LABORATORY
PHYSICS

Third Edition

J. H. AVERY
&
A. W. K. INGRAM

Heinemann

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LABORATORY PHYSICS

By J. H. Avery and M. Nelkon

AN INTRODUCTION TO THE MATHEMATICS OF PHYSICS

(*Heinemann*)

LABORATORY PHYSICS

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To B and D

FOREWORD

'To the making of books there is no end and much study is a weariness of flesh.' It is a long time since these words were written and there is no ground for supposing that if 'the preacher' were alive to-day he would have been shaken in this conviction. Nevertheless while sharing his view about books in general and even thinking it may have a particular application to books on Practical Physics, I am led to commend this one. I do so because here we have not only the fruits of a wide experience, but of an experience which has been made the subject of careful and critical examination so as to extract from it all it has to teach. The result is a collection of experiments which have not been selected from a previous anthology, but have been verily performed, both by the authors and by pupils under their guidance. The pitfalls are scheduled and enough help given to assist the student without relieving him of the salutary necessity of thinking for himself. The new experiments, especially those using valves, will meet a demand which can no longer be evaded and will be welcome to many teachers who have been waiting for this new departure. It is a book which deserves success.

ALEX. WOOD

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PREFACE

The course of laboratory work in Physics set out in this book is designed to cover the needs of those students who study the subject either in the later years of their School life or in the first year at the University. The treatment is practical, and will enable the student to pursue his work without continual explanations of routine matters by the teacher.

We feel strongly that much more precise specification of apparatus is desirable than is to be found in most current publications. Therefore details and exact dimensions of apparatus, together with names of manufacturers, are given wherever useful or necessary. Many publications—of which the *School Science Review* is perhaps the best—give such information; but the details necessary to ensure a reasonable chance of success in some of the routine experiments are nowhere collected together. In some of the conventional experiments the traditional procedures have been modified to overcome the snags which arise in them.

We also believe that the student can profit by making for himself much of the special apparatus needed in certain experiments. We have therefore included some brief instructions on some of the processes which he may be called upon to perform, such as soldering, glass-blowing and glass-drilling.

The question of experimental errors is too often avoided. In consequence (although it is difficult to deal with the subject at this level) Chapter II discusses sources of error and the combination of errors. In Chapter III graphs have been fully treated. Such instruction is essential. Most teachers of Physics are today satisfied as to the importance of the graphical method.

Since 1946 a considerable quantity of ex-government equipment has been made available to the public, often at low prices, and this has encouraged us to include a Part on 'Electronics'.

No tables of constants are to be found at the end of the book, because we believe that abbreviated tables are of little value. Reference to books like *Physical and Chemical Constants* by Kaye and Laby should become the habit of all experimenters.

It is not possible to mention by name all those whom we should thank for their help in the preparation of this book. Included in it would be the authors of standard works as well as many colleagues and pupils who have made suggestions. In particular we should like to express our gratitude to the late Dr. Alexander Wood, Fellow of Emmanuel College, Cambridge, and Mr. M. Nelkon of William Ellis School, London, both of whom read the manuscript and made many helpful suggestions. Mr. W. F. F. Shearcroft, Principal of Peterborough Training College, has also earned our gratitude—his advice was always so readily given. Finally we would thank our publishers for their constant co-operation and unfailing courtesy.

J. H. AVERY
A. W. K. INGRAM

PREFACE TO THE SECOND EDITION

No major changes have been made in this edition but the wording of the instructions to a few experiments has been clarified where experience has shown this to be desirable. The procedures given for Experiments 47 and 62 have been amended and extensions to Experiments 82, 127, 128, 141 and 142 included. A number of diagrams have been redrawn and several misprints corrected.

J. H. AVERY
A. W. K. INGRAM

PREFACE TO THE THIRD EDITION

In preparing this edition much new material has been added and a large number of alterations to the text have been made. These alterations are far too numerous to specify individually—they are the result of further study of the experimental techniques involved, and are made in order to improve the accuracy obtainable in the experiments or to make the physical principles more evident.

The new material comprises experiments on the following: sensitivity of a balance, modulus of rigidity by a statical method, Henning's method for latent heat, Matthiessen's method for the coefficient of expansion of a liquid, the use of conventional apparatus for Charles's Law, Newton's equation for mirrors and lenses, deviation and dispersion by a prism, resistance of a galvanometer, construction of a post-office box, a simple determination of the e.m.f. of a thermocouple, and the determination of pole strength and field strength using a ballistic galvanometer. The electronics section has been expanded by a chapter on transistors. This contains a brief introduction to the theory of their operation, details of standard procedure when using them, and instruction for six experiments on their characteristics. In the section on valves some alterations have been occasioned by some valves becoming obsolete. All the valves suggested are at present obtainable and details of a power pack suited to recent types of valves are given.

The chapters on possible errors and graphical analyses have each been provided with a set of exercises; the answers are accompanied by brief notes on the methods of solution. In the section dealing with practical problems we have added a set of questions taken from recent A-level practical papers set in the examinations of the Northern Universities Joint Matriculation Board. Some discussion of the theoretical aspects of these problems is given at the end of the section; these notes are our responsibility, but they are printed with the approval of the Northern Universities Joint Matriculation Board, to whom we wish to express our gratitude for granting us permission to use the questions in this way.

We would also like to pay tribute to the work done by our own students who have been very patient with us when we have used them as 'guinea pigs'. They have been a fertile source of ideas of which many are included in the text.

To prevent the book from becoming too large, twelve experiments which appeared in earlier editions have been omitted, and the changes which have been made necessitated renumbering pages, chapters, experiments and diagrams.

J. H. AVERY
A. W. K. INGRAM

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PART I

INTRODUCTION

CHAPTER I

GENERAL INSTRUCTIONS

How to Use this Book

Presentation of Experiments

The method adopted for describing the experiments is usually as follows:

HEADING: This is a statement (in heavy type) of the principle being investigated, or of the determination being made.

APPARATUS: This is a list of the apparatus required, omitting such equipment as is commonly to hand such as balances, metre rules, wire, etc. A complete list of the apparatus assumed to be available is on p. 503. Any unusual apparatus or equipment, which requires planning ahead, is printed in large type. Details needed for the construction of apparatus are printed in small type.

THEORY: This is usually a short section (in small type) designed to *refresh the memory* on relevant theory. Occasionally more detail may be given—in cases where a little more help has been found by experience to be needed.

PROCEDURE: Here the actual experimental instructions are given.

RECORD AND CALCULATION: In this section suggestions are often made as to how the observations should be set out in a notebook. These suggestions are by no means obligatory, and should be discarded if a different presentation is preferred. Any guidance needed in the calculation is also given in this section.

At the beginning of each Part, a chapter entitled 'Standard Procedure' is devoted to certain pieces of apparatus, or to aspects of the subject which are of exceptional importance. This introductory material should be carefully studied.

Instructions which Apply to all Experiments

Read the experiment heading carefully and be sure that you have grasped precisely what it means. This is a practical book; at times it reminds you of theoretical points, but it does not pretend to deal with them completely. It is assumed that if you are not familiar with the theoretical matter concerning any experiment, you will take the steps necessary to acquire this knowledge BEFORE BEGINNING THE EXPERIMENT. Thus, the frequent use of the words 'it can be shown' to introduce a formula or expression should be taken as an instruction to find out *how* it is shown, if this is not already known.

Read *right through* all that is given about the experiment, so that you have a clear idea of all that you have to do, the precautions you have to take and the kind of record you have to make.

Examine the apparatus to be used, and if you have any doubts about any of it ask for a demonstration.

Carry through the operations in the order they are given, remembering that this book has not been written for *those who blunder from one operation to the next without having understood the whole experiment.*

Record all observations *in ink in your notebook as you make them.*

Put your apparatus away in its proper place when your experiment is finished.

Your Laboratory Notebook

In your practical notebook, a record of all you do must be kept. The record of each experiment should be started on a fresh page and should normally consist of five main parts:

(1) The heading together with the date.

(2) The observations.

(3) The calculation.

(4) The account of the method, accompanied wherever possible by a diagram.

(5) The statement of the result, including the limits of error.

We will consider these five sections in turn:

(1) *The heading* should be a concise statement of the aim of the experiment, with perhaps a phrase indicating the method to be used. The date is an important part of the heading.

(2) *The observations* should be recorded IN INK in your notebook IMMEDIATELY THEY ARE MADE. This point cannot be overemphasised. The use of loose pieces of paper, and of pencil, is strongly condemned for the following reasons:

(*a*) It is a waste of time, as *all* your observations must be presented in the final record.

(*b*) It is slovenly, and may lead to confusion.

(*c*) It may lead to non-scientific methods of working, by giving you the opportunity to select observations which you think superior to those you reject—without giving any reason for this selection. Usually the motive for this is to 'get the right answer'—whatever that may mean. Remember that there is *no* 'right answer'. Kaye and Laby's tables* tell you what more experienced experimenters have found for the values of many important quantities; and it is certainly worth while to see how your answer compares with the generally accepted value. But if you

* See p. 504.

should happen to 'agree with it' you are more likely to have been lucky than clever. What you should do is to see whether the accepted result lies within the range of values which you obtain, by considering the possible error of your experiment. (See Chapter II.)

Do not omit to record the limits of error of each observation and to state the units in which you are working.

(3) *The calculation* should be neatly set out and intelligible, so that if necessary it can be checked without your being present to decipher it. Do not confuse the observations with the calculations. If a table is used to record both observations and some corresponding calculated quantities, make it clear which are the observed values and which are the deduced ones.

There are many specimen tabulations given in this book which will help you to develop your style in this matter. Modify where you think necessary, and if you are satisfied that you are making an improvement.

(4) *The description of the procedure* has been left until after the observations and calculations, because until you have done the experiment you cannot include any account of the difficulties, etc., which were encountered, and of the methods by which they were overcome. Since the observations must be entered immediately in your notebook, and the calculations naturally follow, this is the only logical position for the description of the method.

When writing the account use the passive voice, e.g. '. . . the calorimeter was half-filled with water . . .' The instructions in this book are not in this form, as the authors are instructing you how to proceed and therefore use the imperative mood. It is usually possible to make the account quite short if attention is paid to a concise style, e.g. do not use the phrase (so common in some students' work) 'So and so *was taken* . . .' Say at once what you did with it.

Usually your description will be made clearer and shorter if a diagram is given. Remember that a diagram is *not* a picture. The test of a good diagram is its simplicity. Introduce only such lines and labelling as are necessary to clarify the point which you are illustrating.

(5) *Conclusions*, which should consist of the following:

(*a*) A comment on any graphs drawn.

(*b*) A statement of your result, giving the value, the limits of error and the units, paying especial attention to the rejection of unjustifiable decimal places.

(*c*) A statement of the accepted value of any universal constant determined, together with the source of reference.

(*d*) A comment on any discrepancy between (*b*) and (*c*), together with suggestions for possible improvement of technique.

If you do not complete an experiment, a statement of the reasons for discontinuing it should be given.

CHAPTER II

MEASUREMENT AND THE COMBINATION OF ERRORS

Observations and Possible Error

Laboratory work in physics involves the use of apparatus to make measurements which can be used for one of two purposes: either to make a definite determination—such as the specific heat of rubber, the focal length of a lens, the resistance of a piece of wire, etc.—or to investigate the validity of a law. In both cases the observations must be faithfully recorded and should be as reliable as possible. It is also necessary to include, in the statement of the result of the experiment, a note on how reliable the experimenter believes that result to be; this chapter accordingly deals with the technique of assessing what might be called the 'reliability factor' of an experiment. Do not make the mistake of assuming that because you, as a student, are performing experiments merely to improve your knowledge of physics, this chapter does not concern you. The pages which follow will show you how to discover whether you have any right to be proud of your results. In fact they will do more than that; they will tell you how to find out just how proud you may be—and pride in an answer which is the best obtainable with the apparatus provided is as justifiable as it is natural.

Our work then is primarily concerned with making measurements. Occasionally we set out to determine a ratio, but this is the exception; usually we determine a quantity, and the final result must therefore consist of a number and a unit. Every time you record an observation ask yourself 'In what units am I working?' The omission of the units from records, calculations, and answers, in physical problems, is perhaps the commonest mistake made. It is certainly the source of a great number of the mistakes in calculations.

It is also necessary to distinguish clearly between the quantity which we set out to determine and the observations which we make in order to compute it.

In all cases we make measurements by observing scale readings.

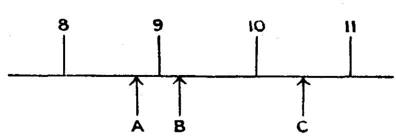


FIG. 1

Scales are engraved with the appropriate units, and our task always consists of making a judgment that some specified point is nearer one line on the scale than another, with the convention that if we judge it to be half-way between two graduations then that one with the higher value shall be recorded. This simple but fundamental point is illustrated in Fig. 1, where A and B are recorded as 9, and C as 11.

This holds even if we employ, as we often do, a method of 'estimation' —by which we mean that we imagine graduations between those actually on the scale. Thus it is usual, when reading a temperature with a thermometer graduated in degrees, to estimate the reading to a tenth of a degree, i.e. to imagine such graduations to exist, and record to which of them we think the specified point—the mercury level—is nearest.

When using a scale as described above, we make a *maximum* possible error of half a scale division. Such an error may be indicated in the record we make as follows :

$$9 \text{ cm.} \pm 0{\cdot}5 \text{ cm.}$$
$$9{\cdot}3 \text{ cm.} \pm 0{\cdot}05 \text{ cm.}$$

The first record indicates that a scale was used which was engraved in centimetres, and the second one that a scale was used engraved with millimetres or that estimation was used. Such a notation expresses the limits within which the observation may lie. Nearly every observation you make can be written in this form—with the possible error stated— and wherever you are able to do so you should record observations in this way. On pp. 24–26 an example is worked out and the method of presentation of the observations should be studied.

The possible error will depend on other factors besides the calibration of the scale you employ. A very important factor, for instance, is the sensitivity of the apparatus. This should always be taken into account, and methods devised by which the possible error can be assessed. As a first example of this type of procedure consider the determination of an unknown resistance by means of a Wheatstone's bridge. The scale by which lengths of the wire are measured may be calibrated in millimetres; but if the galvanometer is not very sensitive you may find that there is a range of say 8 mm. through which no deflection can be observed. You would then record the possible error as $\pm 0{\cdot}4$ cm. In fact the position of balance is sometimes deduced by finding for what positions of the sliding contact, deflections (first one way, and then the other) are *just* detectable, and by using these readings to calculate the mean. As a second example, consider the location of an image by the method of 'no parallax'. Here again there will be a range of distance through which the exploring pin can be moved without apparently leaving the 'no parallax' position. This will almost always be greater than the smallest unit engraved on the scale (usually the millimetre) and in extreme cases is several centimetres. Once again, therefore, a mean position can be found, together with the limits of error. It does not necessarily follow that the arithmetic mean of the two observations is the true value that you are seeking—it depends on the mathematical relationship holding for the related quantities. By the statement that an observation is $x \pm y$, we do not mean 'we believe x to be the value but could only measure it to an accuracy of $\frac{y}{x} \times 100\%$,' but 'we know the value lies between $(x-y)$ and $(x+y)$'.

To increase accuracy therefore, it is important to give attention to the sensitivity of the measuring instruments used. This applies especially to those instruments which are least sensitive, i.e. those which produce the greatest range of possible error, because the final result can rarely be more accurate than the least accurate individual observation. This latter point is discussed in more detail later (pp. 23–24).

Standard (or Probable) Errors

It does not necessarily follow that the actual error of the result is as small as the possible error (i.e. that due to the limitations set by the above errors), because other factors outside the control of the experimenter may influence the observations. The error which takes account of *all* factors affecting the accuracy of the result is known as the 'standard error'. This standard error is not easy to assess and much patient experimenting is needed to effect a marked reduction in its magnitude. The latter depends on the number of independent observations taken, for it can be shown mathematically that if *n independent* observations, each having a probable error of x, are used to calculate an arithmetic mean, then the probable error of that mean is $x/\sqrt{n}$. At first sight it would seem that there is no difficulty in reducing the standard error to a small magnitude. It can be halved by taking four independent readings; and for greater accuracy perhaps a hundred independent readings could be taken—reducing the standard error to one-tenth of the original figure. There is, however, a major obstacle to be surmounted: that of taking readings which are *truly independent of each other*. This is much more difficult than it sounds. As an example, let us consider the determination of the diameter of an object believed to be spherical. The first observation can be taken by using callipers. To take a second reading which is independent of the first, we must not set the callipers across another diameter, because that would merely be investigating whether the object were spherical or not. In fact for this very reason we must be careful to measure the same diameter, and this must be done by placing the callipers across the sphere together with a distance piece, of which the length must also be determined by the callipers. During this process no mental arithmetic must be done, otherwise the second reading may be influenced by the first, and thus would not be independent. It would be quite a long job making a hundred independent determinations; in nearly all experiments at the standard with which we are concerned, the time involved is too great for us to consider taking truly independent observations. In any case we are less concerned with high orders of accuracy than with understanding the principles of the subject. This does not mean that you should give no consideration to errors; but it does mean that the consideration of the 'standard error' is outside your customary range, and that you should usually be content to record the possible errors.

It is often necessary to make a series of observations despite the fact that they will not be independent, for this procedure serves two purposes:

(1) It substantially reduces the likelihood of any major error made when reading the scale remaining undetected;

(2) It serves as a check on the uniformity of the quantity throughout the specimen. Examples of this are to be found in Expts. 1, 8 and many others.

Combining Possible Errors

Various mathematical processes are applied to the observations we make when the final answer is being deduced. It therefore becomes necessary to consider how the error of the final answer can be computed from the errors in the observations.

If quantities are *added* or *subtracted*, the possible error of the result is the *sum* of the errors of each quantity concerned. Suppose the following two temperatures were observed in an experiment, in order to determine the temperature rise:

(i) Initial temperature $= 11 \pm 0{\cdot}5$°C.
(ii) Final ,, $= 39 \pm 0{\cdot}7$°C.

To find the temperature change we subtract 11 from 39 and obtain 28°C. The possible error will be $\pm 1{\cdot}2$°C, obtained by adding the two errors together.

The logic of this is realised when we remember that the above two observations really imply that

(i) Initial temperature is between 10·5 and 11·5°C.
(ii) Final temperature is between 38·3 and 39·7°C.

Now if we were very unfortunate, the initial temperature might have been 10·5°C and the final one 39·7°C, and the temperature rise would have been 29·2°C. We should have been just as unlucky if the temperature had actually changed from 11·5 to 38·3°C, i.e. by an amount 26·8°C. But our original statement admits that either of these changes of temperature was possible; thus our answer must be recorded as the mean of these extreme values $\pm$ half their difference.

If *multiplication* or *division* is used, the actual errors must be converted to percentage errors, and these percentage errors added. Thus, if the observations above were combined by multiplication with a mass of water observed as being 150 ± 3 gm., we should proceed as follows:

The error in the determination of the mass is $\pm 2\%$, whilst that in the temperature range would be $100 \times 1{\cdot}2/28$, i.e. $4{\cdot}3\%$ approx. The error of the answer is therefore $\pm(2+4{\cdot}3)$, i.e. $\pm 6{\cdot}3\%$. The final answer would thus be written $4{,}200 \pm 265$ calories.

It follows that raising a quantity to the nth power multiplies its percentage error by n. This rule also holds for fractional indices. There are two important applications of this which occur commonly in the computation of the possible errors in experimental physics:

(i) *Square roots:* When a square root is taken, the percentage possible error will be halved. This is the unusual case of the accuracy of an observation being improved by mathematical manipulation.

(ii) *Reciprocals:* The percentage possible error in x will be the same as that of $1/x$ (since $1/x$ is x^{-1}), and this finds common application in lens and mirror experiments.

The formal proof of the statements made above may be found in text books on the calculus.

If logarithms are used in the calculation, an error of 1 in 2,500 may be introduced by using four-figure tables. A slide rule, even in experienced hands, may give an error of 1 in 500.

In order to emphasise the points stressed above, and to make quite clear the procedure to be adopted when computing the possible error of the result of any experiment, an example is worked out below. At first sight it looks rather long and complex; but this is only because the explanations of how all the steps are carried out are also included, and often the explanations of mathematical processes are longer than the processes themselves. This is certainly the case here. The portion in italics is explanatory and would not normally be included in the calculation.

Example on the Computation of the Possible Error in the Results of a Determination of the Mechanical Equivalent of Heat by an Electrical Method (Experimental details as in Expt. 62, p. 157).

OBSERVATIONS:

Current	$2{\cdot}5 \pm 0{\cdot}05$ amps.
Resistance of coil used . . .	$11{\cdot}36 \pm 0{\cdot}01$ ohms.
Water equivalent of calorimeter, etc. .	21 ± 1 gm.
Mass of empty calorimeter . .	$157 \pm 0{\cdot}5$ gm.
Mass of calorimeter plus water . .	$312 \pm 0{\cdot}5$ gm.
Initial temperature	$10{\cdot}6 \pm 0{\cdot}2$°C.
Final temperature	$38{\cdot}7 \pm 0{\cdot}3$°C.
Time for which current flowed . .	$298{\cdot}0 \pm 0{\cdot}5$ secs.

CALCULATION:

First we calculate the value of the mechanical equivalent (J) without considering the errors. The equation connecting the above quantities is

$$J = \frac{I^2R}{(W+m)\theta} \times t \text{ joules per calorie.}$$

where I is the current in amps,
R is the resistance of the heating coil in ohms,
W is the water equivalent of the calorimeter, etc., in gm,
m is the mass of water used in gm.,
θ is the rise in temperature in °C,
and t is the time in seconds for which the current flowed.

Hence in this case we have

$$J = \frac{(2 \cdot 5)^2 \times 11 \cdot 36}{(21+155)(38 \cdot 7 - 10 \cdot 6)} \times 298 \cdot 0 \text{ joules/cal.}$$
$$= 4 \cdot 279 \text{ joules/cal.}$$

The answer was calculated using four-figure logarithms. Any reduction of the number of significant figures is made after the consideration of the limits of error, which we consider next:

First consider any quantities which are either added or subtracted during the calculation. These are

(*i*) *the two observations used in finding the mass of water used:* Both of these observations had a possible error of $\pm 0 \cdot 5$ gm., and therefore the possible error in the mass m is $\pm(0 \cdot 5 + 0 \cdot 5)$, i.e. ± 1 gm.

(*ii*) *The mass of water and the water equivalent of the calorimeter:* (*This could actually have been considered along with the foregoing item, since the difference between the observed masses is not manipulated in any way before being added to the water equivalent*). The possible error in the water equivalent is ± 1 gm., which is added to the possible error in m, found above; and therefore ± 2 gm. is taken as the possible error in the value $(W+m)$.

(*iii*) *The observations used to find the temperature-rise:* The initial temperature has a possible error of $\pm 0 \cdot 2$°C, whilst the final one has one of $\pm 0 \cdot 3$°C. Therefore the possible error in the value of θ (the temperature rise) is $\pm(0 \cdot 2 + 0 \cdot 3)$, i.e. $\pm 0 \cdot 5$°C.

We have now found the possible errors in those quantities from which the final answer can be calculated by applying to them the processes of multiplication and division only. At this stage, and not before, we express each actual error as a percentage of the quantity to which it relates. When doing this, great accuracy is not required; we are usually not concerned with fractions less than 0·1 *of* 1%. *Equivalent percentage errors are recorded in the following table:*

Quantity		Possible Error	Percentage Error
Symbol	Value		
I	2·5	$\pm 0 \cdot 05$	2
R	11·36	$\pm 0 \cdot 01$	Negligible
$(W+m)$	176	± 2	1·1
θ	28·1	$\pm 0 \cdot 5$	1·8
t	298	$\pm 0 \cdot 5$	Negligible

The values in the last column were worked out quite quickly using a slide rule (though often a quick mental calculation is good enough). The neglecting of the possible errors in R and t is justified by their smallness compared with the others. We can now find the percentage error possible in the answer. Since I appears in the formula as I^2, the error in this quantity is twice the error in I, and is thus 4%. *This is the only quantity which is raised to any power other than unity in the expression, so we can now add all the possible percentage errors together (including those of the quantities in the denominator) to find the final possible percentage error, which is accordingly*

$$\pm(4+1\cdot1+1\cdot8)\%$$
$$\text{i.e. } \pm 7\% \text{ approx.}$$

Next, we calculate what is the value of 7% *of* 4·279 *(the value of J found in the first part of the calculation).* This comes to 0·295. *The statement* $J = 4\cdot279$ *implies that we know it is between* 4·2785 *and* 4·2795, *i.e. it claims an accuracy of about* 1 *part in* 4,000. *An accuracy of* 7% *is only about* 1 *part in* 16, *so we write our final answer as* $4\cdot3 \pm 0\cdot3$ *joules per calorie.*

'**Result:** The value of J determined by this experiment is $4\cdot3 \pm 0\cdot3$ joules per calorie.'

This result incidentally calls for two other comments:

(i) Had we given no thought to the subject of our possible error and used logarithms (or even long arithmetic) in the calculation, we should perhaps have recorded the result of the experiment as 4·279 joules per calorie. This would have been dishonest as we should have been claiming (by the number of significant figures given) a far higher order of accuracy than in fact we could reach with the apparatus used. Clearly it is not possible to arrive at an honest result to any experiment without considering this question of errors.

(ii) Of the 7% possible error in the final result, 4% were contributed by the error in observation of the current. This was partly due to the fact that the current error was doubled, because I was squared in the formula. It was also due to the fact that the current was only observed to an accuracy of 2%. The experimenter, on analysing these errors, should consider whether he could improve on his result by increasing the accuracy of his least accurate observations—in this case especially the observation of the current, e.g. by using a more sensitive ammeter.

Computation of the Limits of Error when the Result is Deduced from a Graph. Limitations of the Graphical Method.

(Read Chapter III to learn about graphs before studying this paragraph).

As is pointed out in Chapter III, a mean value for a ratio can often be found from a graph (see p. 30). If the possible error for the answer is also expected from the graph, considerable difficulty is experienced. The first point to notice is that the possible errors are not usually plotted on a graph, and thus the limits within which the final result may lie are not shown. The possible errors could of course be plotted if each observation were to be shown by a rectangle. If the values of x were being plotted against values of y, and a particular pair of values gave $(x_1 \pm a)$ and $(y_1 \pm b)$, then the rectangle joining the points $(x_1 - a, y_1 - b)$, $(x_1 + a, y_1 - b)$, $(x_1 + a, y_1 + b)$ and $(x_1 - a, y_1 + b)$ gives the area of the graph in which the point is known to lie. This would, however, only make it more difficult to draw the best straight line; it would not really help us to a solution of our problem, since we should normally have great difficulty in deciding the limits within which lies the line of which we require the gradient. Equal difficulty is likely to be experienced if two lines are drawn so that the maximum and minimum gradients are shown; for there is then more likelihood that only the errors in the initial and final observations will be considered. The conclusion to which we are forced is that, whilst the graph is a good method of enabling us to visualise the results, it is not the best method of finding the final answer. The best method is undoubtedly to use the best set of observations (i.e. those which are consistent with the majority of the observations and which have least % errors), and substitute in the appropriate formula, finding the possible error of the result in the way already described. A graph must be drawn, however, because it enables us to see how closely our results conform to the linear relationship. It ensures that we do not happen to choose a point for the final calculation which is a long way from the mean line, i.e. one which may have been subject to some peculiarity.

To sum up, it is recommended that wherever possible a graph be drawn and analysed to show the consistency of the results, etc. If, however, the aim of the experiment is the most accurate determination of a constant, then this graphical analysis should be supplemented by a calculation based on the most accurate set of observations which is consistent with its fellows. The graphical method of presenting results is very important; but we must not let this prevent us from appreciating the limitations of the method.

How to Reduce the Limits of Error

So far we have considered only the theory of errors; but it is of course equally important to know what precautions to take in the laboratory in order to reduce the possible errors in observations we make. The following suggestions should be carefully studied, and applied whenever possible:

(1) Use the best scale available, i.e. that made as accurately as possible. Scales engraved on wood are usually not as good as those engraved on metal, glass, or ivory.

(2) Choose a *suitable* scale, bearing in mind the accuracy you wish to obtain. Make sure the scale selected is calibrated to meet the demands of accuracy you will make; but do not use one which is giving a much

higher order of accuracy than is required, as you will only waste time taking unnecessarily accurate observations.

(3) If estimation is employed, be sure that you have practised sufficiently to make yourself reliable.

(4) If any devices such as verniers, spherometers, etc., are used, be sure that you understand how they work and how to read them.

(5) Use a lens wherever possible when taking scale readings. This applies especially to reading vernier scales.

(6) Eliminate errors due to parallax, by ensuring that every scale observation is made when the eye, the specified point and its position on the scale are all in a plane normal to the scale. In many pieces of apparatus employing a pointer, a plane mirror is mounted behind (and parallel to) the scale, so that errors due to parallax can be avoided by taking observations when the eye, the pointer, and the image of the latter are in alignment. If a mirror is provided for this purpose it *must* be used.

(7) If the zero graduation is used it should if possible be checked. Many students use the zero graduation without realising that they are doing so—especially in the case of screw gauges, spherometers and electrical recording instruments. If the instrument is a thermometer, the use of ice enables the zero to be checked rapidly—otherwise perhaps there is a thermometer available which has recently been standardised and with which a comparison can be made. In the case of many electrical instruments a zero adjustment is provided and should be used if your instructor has given permission.

Exercises on Limits of Error

(The answers and hints on methods of solution are on p. 505.)

1. The observations to obtain the dimensions of a metal block were as follows:

Length:	position of one end	2·8	($\pm$ 0·05) cm.
	position of other end	12·8	($\pm$ 0·05) cm.
Breadth:	position of one end	1·3	($\pm$ 0·05) cm.
	position of other end	6·3	($\pm$ 0·05) cm.
Thickness:	position of bottom	0·05	($\pm$ 0·05) cm.
	position of top	2·05	($\pm$ 0·05) cm.
The mass was 1,000			($\pm$ 10) gm.

   Calculate the value of the density given by these observations.

2. A metal cube has a side of length 10·0 ($\pm$0·1) cm. and its mass is 8·0 ($\pm$ 0·1) kgm. Calculate its density.

3. In an experiment to determine Young's modulus (see p. 69) the diameter of the wire was 0·40 ($\pm$ 0·01) mm. and its length was 220 ($\pm$ 0·5) cm. A load of 10 kgm. caused an extension of 2·2 ($\pm$ 0·1) mm. If the weights were accurate to 1 %, what was the percentage error possible in the value of the modulus calculated from the data?

4. Using Searle's torsion balance to determine the surface tension of water (see p. 95), the dimensions of the glass plate were determined as 2·00 (± 0·02) mm. and 10·0 (± 0·04) cm. The necessary weight was 1·4 (± 0·01) gm. Ignoring any error made in assessing the pointer position, calculate the surface tension.

5. The bore of a capillary tube was measured by introducing a thread of mercury and determining its length and mass (see p. 55). The observations were:

   Vernier microscope readings:

One end	10·926 (± 0·002) cm.
Other end	4·758 (± 0·002) cm.
Mass of crucible empty	6·610 (± 0·002) gm.
Mass of crucible and mercury	6·884 (± 0·002) gm.

   Assuming that the density of mercury is 13·6 gm./cm³. (to 0·1 %), calculate the diameter of the tube.

6. Within what limits will the periodic time of a simple pendulum lie if its length lies within the values 100 (± 1) cm.?

7. Approximately what variation in length would cause a simple pendulum which has a periodic time of 2·00 seconds to show a variation of a fifth of a second in fifty swings?

8. In an experiment to determine the coefficient of linear expansion of a metal (see p. 133) the following observations were made:

Initial temperature	14·3 (± 0·1)°C.
Final temperature	99·3 (± 0·2)°C.
First reading of micrometer	3·182 (± 0·001) cm.
Final reading of micrometer	3·260 (± 0·001) cm.
Length of rod:	
One end	1·0 (± 0·05) cm.
Other end	51·2 (± 0·05) cm.

   Calculate the coefficient of linear expansion of the metal.

9. Using an optical bench to determine the focal length of a concave mirror by the method of conjugate foci, the readings were as follows:

Object	10·0 (± 0·1) cm.
Pole	50·0 (± 0·1) cm.
Image	30·0 (± 0·1) cm.

   What is the possible percentage error in the focal length?

10. The p.d. across a resistance was measured by a voltmeter which could be read to 0·05 volt and the current through the resistance was measured by an ammeter which could be read to 0·05 amp. The observations were 3·0 volts and 1·5 amps. What value should be assigned to the percentage error in the resistance? What other factor contributes to inaccuracy?

CHAPTER III

GRAPHICAL METHODS

The physicist uses mathematics to express his results in terms free from ambiguity, and to manipulate them in order to obtain conclusions from them which are beyond question.

Obviously the more facile he is in the use of mathematical tools the better he is equipped for his task, and the clearer will be his understanding of what he does, for mathematics simplifies all that it embraces.

It has had to be realised that some who use this book may have little mathematical skill, and hence mathematical considerations have had to be expressed in the simplest manner, which at times appears somewhat clumsy. If you can translate such expositions into the language of the calculus, do so; you will not only achieve neater expressions but also a better appreciation of their significance. To others who do not yet appreciate these matters, it can be said that they make life much easier, and it is worth the trouble to acquire the necessary knowledge.

One of the most useful tools the mathematician uses is the 'graph.' The graphical method of dealing with results is stressed in this book, and where possible it should always be applied.

We use graphs for four main purposes:

(1) To deduce an average value of a ratio,

(2) To investigate how much individual values vary from the mean,

(3) To show how one quantity varies with another, and

(4) To deduce the mathematical relationship between two quantities.

We shall consider these uses in turn.

Deduction of Average Values from Graphs

A common use of graphs is for the purpose of obtaining an average value of a ratio. If we have a number of values of a and b, and require a value for the ratio a/b, then we could work out each ratio and find the average value by arithmetic. It is, however, quicker to plot a against b and find the gradient of the straight line so obtained, which will be the average value required.

For example, in the determination of the reduction factor of a tangent galvanometer, a series of values of current (I) and deflection (θ) is obtained, and the last column of the table of results gives tan θ. (See Expt. 122, p. 305). To find the reduction factor each value of tan θ could be divided into the corresponding value of I, all the answers added together and the total divided by the number of observations. If, however, I is plotted against tan θ, a straight line graph should be obtained;

its gradient is $I/\tan\,\theta$, which is the mean value of the reduction factor.

Variation of Individual Values from the Mean

If all the individual values coincided with the mean, the straight line used to find the mean would pass through every point. The farther a point is from the 'mean line' the greater is the probable experimental error in that observation. Thus at a glance we can see whether a determination is likely to be a reliable one, by noticing how closely the points fall to the mean line. Any point which is clearly a long way from the line may be ignored, as obviously it expresses a result subject to an abnormal error. Time and circumstances permitting, this particular value should be checked. It is thus a good idea to plot the graph immediately the observations have been taken, and whilst the apparatus is still set up.

Graphs which Show how One Quantity Varies with Another

The results of an experiment will often yield a series of corresponding values of two varying quantities. One of these is known in mathematical language as the 'independent variable' (i.e. one which can be given any selected value at the desire of the experimenter), and the other as the 'dependent variable' (i.e. the one which has a value determined by the value of the first one, and which could be calculated if the mathematical relationship were known). It is important to appreciate the significance of these two variables, one of which the experimenter controls, and the other of which is then automatically fixed. Which of the two related quantities is selected as the independent variable in a particular experiment is a matter of convenience.

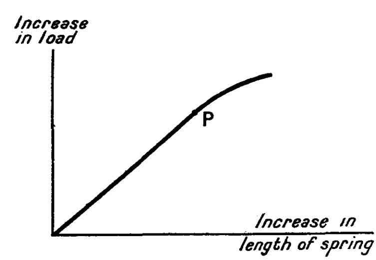


FIG. 2

The series of values referred to are usually set out in a table, but unless the relationship is very simple, figures convey little to one analysing them. Thus one important use of a graph is to draw a 'picture' of the variation. Most people find a relationship easier to understand when presented visually.

Fig. 2 shows how the increase in length of a spiral spring is related to the increase in the load causing the stretching. Since the experimenter could vary the load at will, we may regard this as the independent variable, whilst the increase in extension is the dependent variable. We see immediately that the spring stretches uniformly with increasing load, until a certain point P, after which a large increase in length is produced by a small increase in load.

Many other examples may be found in your theory books and some are to be found in this book, e.g. Fig. 126, p. 266 and Fig. 225, p. 420.

Deduction of the Equation of the Variation

There is always a mathematical relationship between the two variables. It may be simple or it may be complex. Some of the methods used in the deduction of the simple relationships will now be considered.

Graphs may be divided into two groups—those which are straight lines and those which are not. This rather obvious distinction is very important, because a straight line graph is so much easier to interpret than any other. The reason for this is that it is the 'picture' of a direct relationship and can always be assigned a simple equation of the type discussed below.

(1) *Straight Line Graphs*

The equation of a straight line is

$$y = mx + c,$$

where y is the dependent variable, x is the independent variable, m is the gradient (discussed below), and c is the intercept on the axis of y. This is shown in Fig. 3.

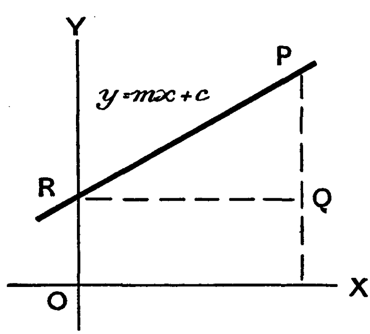


FIG. 3

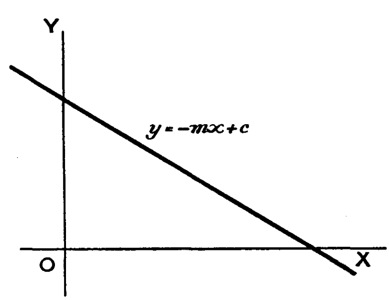


FIG. 4

If then the graph we obtain from our experiment is a straight line, we can, by evaluating the constants m and c, find the equation. We can then claim to have obtained an exact expression for the relationship. This is so important that we must examine the process in a little more detail.

The constant c can be determined by measuring the intercept on the Y-axis, in units of the Y-axis. When the line passes through the origin, c is zero.

The gradient m can be found as follows:

The ordinate corresponding to any convenient abscissa is drawn, and both it and the abscissa are measured in the units of the axis to which they are parallel. The value of c is subtracted from the ordinate and the value so obtained is divided by the abscissa. Thus in Fig. 3 the gradient is PQ/QR. The units of m will be those of the Y-axis divided by those of the X-axis. Sometimes the gradient may be negative, as for example in the case shown in Fig. 4, for which the equation is

$$y = -mx + c$$

The method of determining the equation will be made clearer by studying the following two examples:

EXAMPLE 1

Fig. 5 shows the graphed results of an experiment along the lines of Experiment 6, p. 66. It will be observed that the relationship between

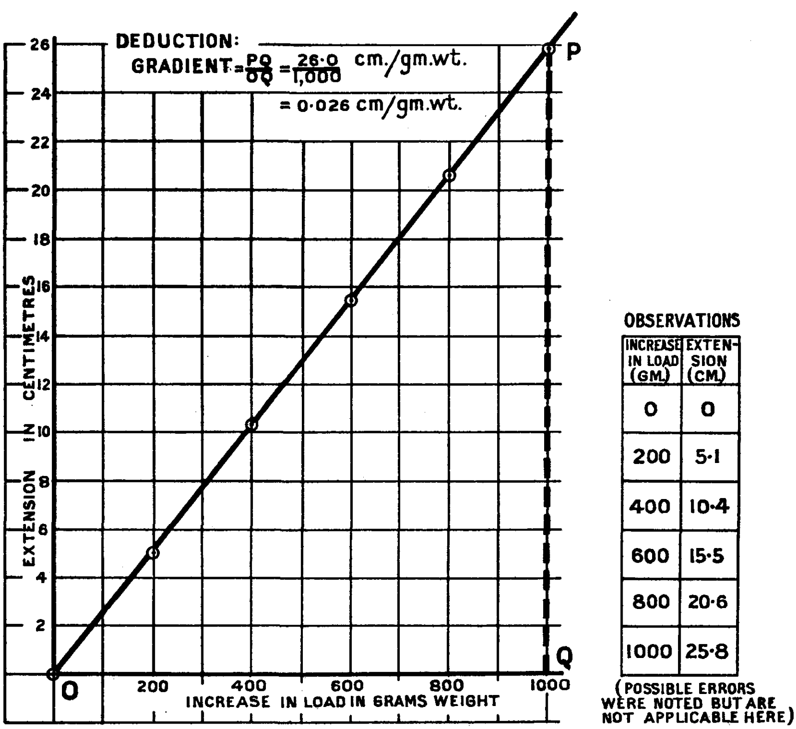


FIG. 5

'load-increase' and 'extension' is 'linear' (i.e. a 'straight line' relationship), and it can therefore be expressed by the equation $y = mx + c$.

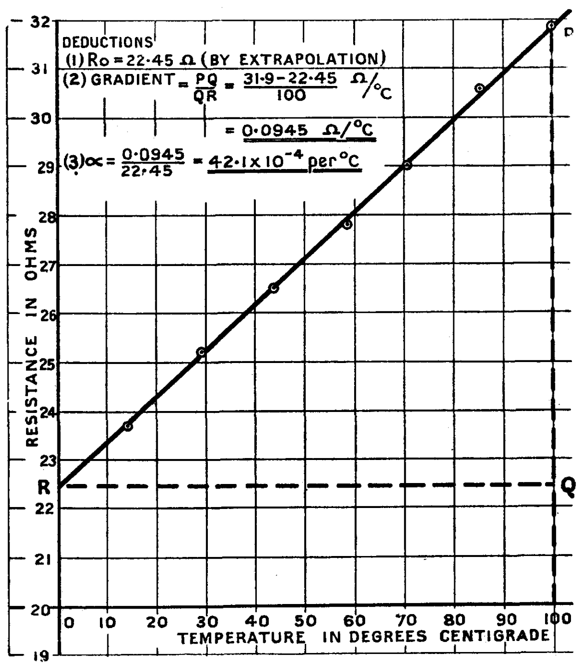
It is seen that the value of c is zero, since the line passes through the origin.

The value of m can be obtained by the process described above. In this case the chosen abscissa was 1,000 gm.wt., and the corresponding ordinate was found to be 26·0 cm. Hence m is 26·0/1,000 cm./gm.wt., i.e. 0·026 cm./gm.wt. Thus if an extension of this spring by l cm. is caused by an increase of load w gm.wt., we can say that the equation for this particular spring is

$$l = 0{\cdot}0260w.$$

EXAMPLE 2

Fig. 6 shows the graphed results obtained in an investigation of the variation of the resistance of a piece of copper wire with temperature through the range 14°C to 100°C (see Experiment 139, p. 330).



OBSERVATIONS

TEMPERATURE (°C)	RESISTANCE (OHMS)
14	23·7
29·2	25·2
43·6	26·5
58·2	27·8
70·5	29·0
85·3	30·6
100·0	31·9

(POSSIBLE ERRORS WERE NOTED BUT ARE NOT APPLICABLE HERE)

FIG. 6

Again the relationship is seen to be linear. It is also to be noted that we have to assume that the linear relationship holds from 14°C to 0°C; for we have to produce the line back to intersect the Y-axis before we can find c. (This extension of the relationship outside the observed values is a process known as 'extrapolation'.) The value of c is found to be 22·45 ohms. A moment's reflection should show you that it is not necessary to show the zero of the resistance scale in order to obtain this value.

Next the value of m is found as follows: the ordinate corresponding to 100°C is drawn and its value found to be 31·9 ohms. The value of c (22·45 ohms) is now subtracted from 31·9 and the answer divided by 100°C. This gives the value of m as 0·0945 ohms per °C.

Thus we have the equation for R_t, the resistance of this wire at t°C, as

$$R_t = 0{\cdot}0945t + 22{\cdot}45 \text{ ohms.}$$

The deduction of the value α is given on the graph, and this quantity is known as the 'coefficient of the increase of resistance with temperature'. A more detailed discussion of the theory of this part of the calculation is given on p. 330.

Evaluation of the intercepts for a Graph of which the origin is not plotted

It is preferable not to show the origin of a graph when a better distribution of the points over the area of the paper can be achieved by limiting the range of the axes. This point is illustrated in Fig. 11, A and B, on p. 39. It is a procedure which leads to a more accurate evaluation of the gradient but makes it more difficult to find the value of the intercepts. There are three ways in which the intercepts can be evaluated under these conditions:

(i) Using the value of the gradient, m, and a pair of values of the dependent and independent variables which lie on the best straight line, substitute in the equation

$$y = mx + c$$

and solve for c.

(ii) Draw a second graph showing the origin and enough of the appropriate axis to include the intercept, using as data the co-ordinates of one point on the line already drawn, and the gradient deduced from the first graph.

(iii) Calculate the value of the intercept, using data obtained from the first graph and applying the principles of similar triangles. A rough sketch should be made of the graph already drawn, showing its relationship to the true origin. From this the geometry can be worked out.

(2) *Graphs which are Not Straight Lines*

If the graph we obtain by plotting our results directly is not a straight line, there still may be a simple equation expressing the relationship, and it is convenient to know what it is. Such relationships can be converted into linear relationships (and hence into graphs which are straight lines) by a process which is known in mathematics as 'changing the variable'. Actually we do not change the quantity which is variable in the experiment at all, the changing process being entirely a mathematical manoeuvre to simplify the analysis. This will be clearer when we consider the results which would be obtained from an experiment to verify Boyle's law. Since this states that

$$pv = k$$

where p is pressure, v is volume and k is a constant, we should not expect the graph of p against v to produce a straight line. The actual curve obtained is shown in Fig. 7. If, however, we plot p against $\frac{1}{v}$ we obtain the graph of the relationship

$$p = kx, \text{ where } x \text{ is } \frac{1}{v},$$

which will be a straight line of gradient k (Fig. 8). Mathematically x is regarded as the new variable, but experimentally v is still the quantity which is varied. The value of this procedure is that it enables us to evaluate k, which we could not have done from the graph of p against v.

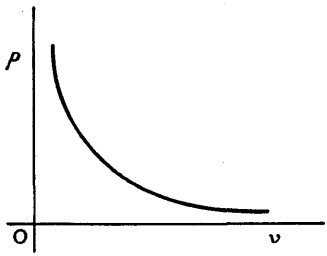


FIG. 7

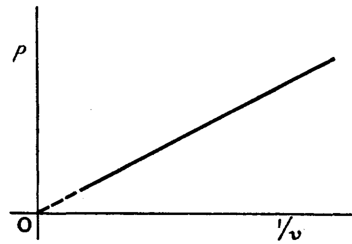


FIG. 8

In practice the matter is often not as simple as this; for suppose we do not know the relationship existing, and have to find it? There are a number of common relationships occurring in Physics, and our curve may not readily convey to us the exact one (especially with experimental errors to make it harder). Thus it is difficult at a glance—if not impossible—to distinguish the graphs of $y = x^2$ and $y = x^3$. The problem may be stated simply as 'how are we to convert a curve of unknown equation into a straight line from which we can deduce that equation?'

We can, of course, always adopt the 'trial and error' method. Thus if we got a curve passing through the origin, such as that in Fig. 9, we could try plotting y against x^2, and if this failed plot y against x^3, and so on. This may be a long job and is not very scientific; so once again we use a mathematical fact to help us. If log y is plotted against log x the gradient of the line gives us immediately the power of x in the original relationship. The theory of this is that if the original relationship is

$$y = kx^m$$

then $$\log y = \log k + m.\log x,$$

i.e. $$\log y = m.\log x + \log k;$$

thus in the new graph the intercept c is the log of the original constant, and the gradient m is the actual power required. (This can be seen more easily if we put $Y = \log y$, $C = \log k$ and $X = \log x$, when the equation becomes $Y = mX + C$). Note that this applies to positive and negative indices as well as to fractional indices, and it is thus a very powerful method. It will work for instance on the Boyle's law curve: if a student not knowing the law, obtained from his experiment the graph shown in Fig. 7, he could by plotting log p against log v obtain the graph given in Fig. 10. The gradient of this is seen to be minus one, and log k can be found from either intercept (since they are equal). Thus he realises that $p = kv^{-1}$ and also knows the value of k. The problem is thus completely solved by drawing two graphs and the solution can be confirmed by plotting p against $1/v$.

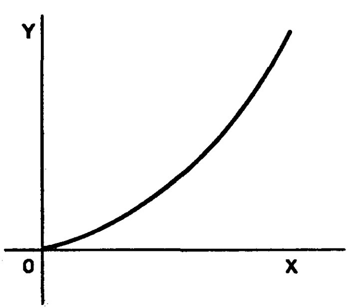


FIG. 9

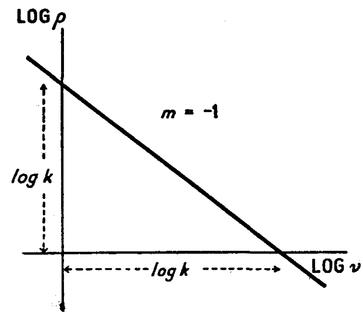


FIG. 10

It is important to remember that the mantissa of a logarithm is always positive, the logarithm of a fraction being given a negative characteristic only. This is important (*a*) when plotting logarithms which have negative characteristics, and (*b*) when deducing the intercept from a logarithmic graph if that intercept has a negative value. The following paragraphs give some guidance on these points:

(*a*) Suppose we wish to locate on a logarithmic graph the point ($\bar{3}{\cdot}2156$, 0). Now $\bar{3}{\cdot}2156$ means $-3 + 0{\cdot}2156$, i.e. $-2{\cdot}7844$. Thus the point we wish to locate is actually ($-\,2{\cdot}7844$, 0). The arithmetic involved in this method can be done more quickly as part of the plotting process by starting with the pencil point on ($-\,3$,0) and moving in the *positive* direction by $0{\cdot}2156$. In general therefore the procedure should be to move from the origin to the point representing the characteristic, *allowing for the sign;* then move a further amount equal to the mantissa, but always carrying out this second stage in the *positive* direction.

(*b*) When deducing an intercept which is negative, similar considerations to those just discussed apply. Thus the procedure becomes:

(i) The characteristic, i.e. the number preceding the decimal point, should be increased by one and given a bar.

(ii) That number following the decimal point should be subtracted from 1·0000 and used as the mantissa when looking up the antilogarithm to find a value for k.

Thus, if, for example, the intercept in such a graph was $-1{\cdot}2540$ then the value for log k will be $\bar{2}{\cdot}7460$, and hence k is 0·05572.

Practical Points for Graphs

The following hints should be carefully studied:

(i) As far as possible choose scales for x and y which are suitable, in that the actual angle (not necessarily the 'gradient') which the line makes with the axis lies between 30° and 60°. There are, however, cases where this is not convenient.

(ii) It should be a general practice to show the origin; but when this results in a figure like that shown at A in Fig. 11 it is better to readjust as shown at B, omitting the origin. Be *exceedingly* careful when calculating gradients and constants in these cases (refer to p. 35).

(iii) When some idea is known of the range of values which will be obtained, the graph paper should be prepared and points plotted as the necessary information is obtained. This will help to avoid the clustering of points so closely together that it is difficult to know what they signify; and it makes it possible to modify the observations taken in order to obtain a really representative set of readings, as well as to check readings of doubtful reliability.

(iv) Locate the points on the graph by small dots in the correct positions, with small circles round them.

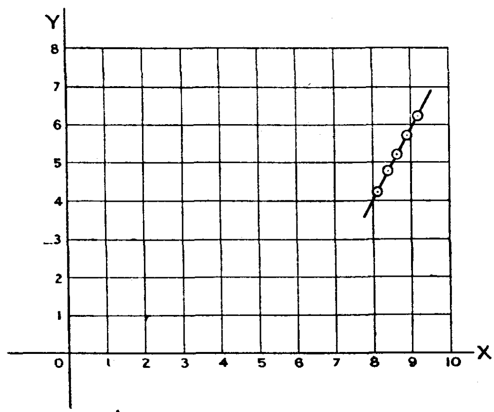
(v) In a graph of any actual set of observations, the points plotted will involve the errors made in each observation. Therefore, whatever the relationship may be of the quantities concerned, the points will not lie on the line, but will lie about it, some on one side some on the other. The line we require is the 'fair' curve drawn through these points, defined as that curve which makes the sum of the distances (measured normally to it) of all the points on one side equal to that of the points on the other side. The drawing of such a curve is a matter of personal judgment, aided usually by one or other of the following methods:

(*a*) A straight line is located by a piece of cotton fastened to two pins. The cotton is stretched along the points and adjusted to what is deemed to be the 'fair' curve, and the pins are then stuck in firmly. Two pencil dots are made beside the cotton, which is then removed. A line is drawn to touch the dots with a straight edge. Alternatively, a celluloid set-square can be used, one edge being made to lie along the 'fair' curve, after which a line is drawn along this edge.

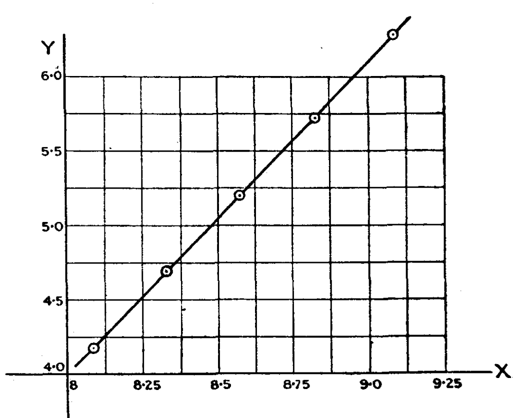
(*b*) If the graph is not a straight line, a number of short lines are drawn here and there among the points, where it is judged the curve should be. They are produced bit by bit till a continuous curve is obtained.

(vi) Five points are usually enough to locate a straight line, but use common sense in the rejection of any points which are manifestly

y	4·2	4·7	5·2	5·7	6·2
x	8·10	8·35	8·60	8·85	9·10



A AXES BADLY SELECTED



B. AXES WELL SELECTED

FIG. 11

wrong. Such points should suggest a repetition of the particular observations from which they were obtained.

(vii) Unless for some special reason it is desired to show a group of curves, a fresh piece of paper should be used for each graph.

(viii) Make sure you have labelled your axes with the quantities plotted along them and the units in which they are measured.

(ix) Do not forget to give the graph a title.

(x) See that the deductions made from the graph appear either on it or very near it.

(xi) When deducing a gradient make sure you obtain the one which is required and not its reciprocal. To do this, rearrange the appropriate equation so that the subject of the formula is the quantity you have plotted along the Y-axis. This ensures that values of the dependent variable are ordinates and thus the gradient (i.e. the value parallel to the Y-axis divided by the value parallel to X-axis) is then the coefficient multiplying the independent variable in the newly-arranged equation.

(xii) Look at Figs. 5 and 6 as examples of one suitable form of presentation.

Exercises on Graphical Analysis

(Answers and hints to aid solutions are on p. 506.)

1. The equation connecting the current in amps. (I), the p.d. in volts (V) and the resistance in ohms (R) applying to a given resistor is $V = I \times R$.

   Draw a graph of the set of observations given below and from it deduce the resistance of the specimen.

V (volts)	0·69	0·90	1·11	1·32	1·57	1·80	2·00	2·20
I (milli-amps.) . .	30·5	40·0	50·1	59·5	70·3	80·0	90·0	99·0

2. The coefficient of expansion of dry air (at constant pressure) was determined by measuring the length of a column of air, trapped in a uniform capillary tube, at various temperatures. The results were:

Temperature (°C.)	23·3	32·0	41·0	53·0	62·0	71·2	87·0	99·0
Length of air column (cm.) .	7·1	7·3	7·5	7·8	8·0	8·2	8·6	8·9

   Plot a graph of these observations and deduce a value for the coefficient of expansion of air (α) given that the equation connecting l_t (the length at t°C.) and l_0 (the length at 0°C.) is $l_t = l_0(1 + \alpha t)$.

3. A spring was extended by loading with weights, and the reading of a pointer attached to the bottom of the spring was observed using a vertical scale. The following observations were recorded:

Load (gm.)	191·0	239·5	288·0	336·5	385·0	433·5
Mean reading of pointer (cm.) . .	31·0	27·6	24·3	21·0	17·8	14·5

Find graphically the force in gm.-wt. needed to extend the spring 1 cm.

4. An unknown resistance was included in the left-hand gap of a metre bridge and a dial resistance box, R, (0–9 ohms) connected across the right-hand gap. The following balance points for different values of R were recorded:

R (ohms)	1	2	3	4	5	6	7	8	9
Position of balance (l cm.)	75·7	60·9	50·9	43·9	38·6	34·4	31·1	28·3	25·9

Draw a graph of $\dfrac{100 - l}{l}$ against R and from it obtain a value for the unknown resistance.

5. The magnification (m) produced by a convex lens of focal length f is connected with the distance from the lens to the image (v) by the equation

$$m = \frac{v}{f} - 1.$$

In an experiment a circular hole 1·00 cm. in diameter was used as an object so that the diameter of the image in cm. was a measure of m. The following observations were recorded:

v (cm.) . .	20·7	23·2	26·3	30·4	34·8	44·5	54
m . . .	1·0	1·25	1·55	1·9	2·35	3·25	4·25

Plot a graph of m against v and deduce the focal length of the lens (i) from the gradient, (ii) from the intercept on the v-axis.

6. A series of values of the current flowing through a tangent galvanometer and the deflection produced was obtained experimentally as follows:

Current (I amps.) . .	0·45	0·72	0·95	1·27	1·60	1·82
Mean deflection (θ) .	26° 30′	38° 30′	46° 45′	54° 30′	61°	63° 30′

The relationship between I and θ is $I = k \tan \theta$ where k is a constant known as the 'reduction factor'. Deduce a value for k from a suitable graph.

•2

7. When a lath of thickness y and width z, supported horizontally and symmetrically by knife-edges distance x apart, is loaded at its centre by weight w, the depression D is given by

$$D = \frac{k \,.\, wx^3}{4zy^3}.$$

In an experiment a fixed weight w was applied and a series of values of D observed as x was varied. What graph would you plot to obtain a straight line and how would you proceed to evaluate k?

8. The periodic time (T) of a rigid pendulum is given by the formula

$$T = 2\pi\sqrt{\frac{h^2 + k^2}{gh}},$$

where h is the distance from the centre of gravity to the point of suspension, k is a constant for the pendulum and g is the acceleration due to gravity.
An experiment provides a series of corresponding values of T and h. How may these be used to obtain a straight-line graph? What will be the gradient of the graph? How may k be obtained?

9. When a series of corresponding values of the object distance (u) and the image distance (v) are obtained with a spherical mirror, or a lens, the student is usually instructed to plot $\frac{1}{v}$ against $\frac{1}{u}$. The equation applying is $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$. By 'changing the variable' in this equation, and comparing the newly formed equation with $y = mx + c$, show (i) how it is that the graph of $\frac{1}{v}$ against $\frac{1}{u}$ is a straight line, (ii) why it slopes 'backwards', (iii) why it has equal intercepts, and (iv) how the focal length (f) is to be obtained.

10. In the 'displacement method' of finding the focal length of a lens an object is set up, and the image formed by the lens located. The object is kept still and the lens moved until it produces an image in the same place as previously. If the lens is moved x cm. when object and image are y cm. apart, the focal length is given by

$$= \frac{y^2 - x^2}{4y}.$$

The experimenter is usually instructed to observe a series of corresponding values of x and y and to obtain the focal length by a graphical method. What graph should be drawn and how is the value of f obtained from it?

11. A resonance tube, with end-correction c, resonates to a tuning fork of frequency f when the length of the tube is l. The relationship is $l + c = \frac{V}{4f}$ where V is the velocity of sound in air. How would you analyse the results of an experiment in which a series of values of l corresponding to various values of f are recorded (both c and V are to be evaluated from the graph)?

12. One method of verifying the inverse square law in magnetism consists in using a ball-ended magnet with one pole vertically over a deflection magnetometer needle and the other to the Magnetic East (or West) of it; the deflection (θ) produced when the lower pole is d cm. from the needle is observed.

If m is the pole strength of the magnet and H_e is the horizontal component of the earth's magnetic field,

$$\frac{m}{d^2} = H_e \tan \theta$$

provided the inverse square law is true. How would you use a series of corresponding values of d and θ to verify the inverse square law?

13. A cell of internal resistance r and e.m.f. E supplies current through a resistance of value R. The equation which applies is

$$r = R \cdot \frac{E - V}{V}.$$

How would you use a series of corresponding values of V and R to obtain (graphically) a value for r?

14. The table below gives corresponding values of the periodic time (T) and the load (M) for a spiral spring executing vertical vibrations. The spring constant (k) was 14·8 gm./cm.

M (gm.)	191·0	239·5	288·0	336·5	385·0	433·5
T (secs.)	0·731	0·816	0·892	0·964	1·030	1·090

The equation connecting T and M is $T = 2\pi\sqrt{\dfrac{M + S/3}{kg}}$, where S is the mass of the spring in gm. and g is the acceleration due to gravity in cm./sec./sec. Plot a suitable graph to obtain a straight line and from it deduce a value for g. How could a value for S be obtained from the graph? Why is this method a good analysis to obtain g but a bad one for finding S?

15. The object distance, u, and the image distance, v, for a concave mirror are connected by the equation

$$\frac{1}{v} + \frac{1}{u} = \frac{2}{r}$$

where r is the radius of curvature of the mirror. The following observations were obtained:

u (cm.) . .	22·8	27·9	33·7	38·0	52
v (cm.). . .	68	43·1	34·5	31·1	25·1

From a suitable graph obtain a value for r.

16. The relationship between the quantities x and y is of the form $y = ax^n$ where a and n are constants.

    Corresponding values of x and y are given in the table below. Plot a graph of log y against log x and from it deduce values for a and n.

x . .	1	2	3	4	5
y. . .	2·5	40	203	640	1,563

17. The relationship between h and l is of the form $h = kl^p$ where k and p are constants. Use the values given in the table below to draw a graph and obtain values for k and p.

l . .	0·063	0·09	1·00	4·00	7·99
h. . .	0·0024	0·003	0·010	0·020	0·028

18. A metal bar was rigidly attached to a vertical wire clamped at its upper end. The bar was allowed to execute oscillations through a small angle in a horizontal plane. The periodic times for a range of different lengths of wire were determined and a summary of the results is given in the table:

Length of wire in cm. (l). . .	20·3	35·9	51·0	79·0	98·0
Periodic time in secs. (T) . .	0·901	1·191	1·425	1·780	1·981

    Given that the relationship between T and l is of the form

$$T = kl^m$$

    where k and m are constants, draw a graph from which k and m can be found and state the exact formula for T in terms of l.

19. Newton's equation for a convex lens is

$$xy = f^2$$

    where x and y are the object and image distances from the first and second principal foci respectively, and f is the focal length. In an experiment the following values of x and y were found:

x (cm.) . .	6·1	11·4	14·5	16·2	20·0
y (cm.) . .	23·6	12·6	9·9	8·9	7·2

    Plot a graph of log x against log y and from it deduce a value for f (make sure before starting to plot that both the intercepts will be on your graph paper—your preliminary rough sketch should help you here).

20. Study questions 51–64, 70–77, 79–81, 83, 84, 86–91 on pp. 480–489 and decide the theoretical significance of the gradients and intercepts, etc. which the experimenter is asked to evaluate.

PART II

MECHANICS AND PROPERTIES OF MATTER

CHAPTER IV

STANDARD PROCEDURE

Measurement of Length

(1) *Vernier Scales*

The commonest instrument for measuring length is the graduated straight-edge, usually called a ruler. But it is subject to the limitations of accuracy imposed by the scale with which it is engraved, as discussed on p. 21. Methods have therefore been devised to increase the accuracy of observations of length. A common device is a vernier scale, which can be moved along the main scale. The principle can best be illustrated by examples:

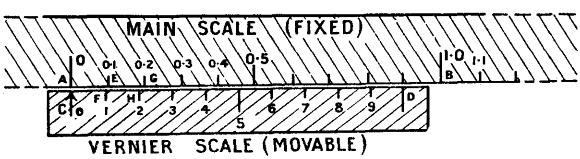


FIG. 12

EXAMPLE 1

Suppose the main scale, AB in Fig. 12, is engraved in cm. and mm. The vernier scale CD is 0·9 cm. long and divided into ten equal parts—each therefore being 0·09 cm. long. Suppose at first A and C coincide. If CD then moves to the right until E and F coincide (i.e. the first marks after the zero), it will be seen that CD has moved a distance (0·1 − 0·09) cm. i.e. 0·01 cm. Similarly when G and H coincide, CD will have moved 0·02 cm., and so on. Now the vernier scale reading corresponding to F is '1' and that corresponding to H is '2'. It is evident that we can in this case read the second decimal place by noting the reading on the vernier scale of that line which is coincident with one on the main scale; there will only be one such line.

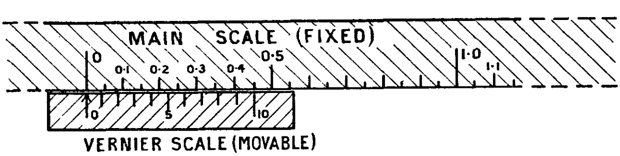


FIG. 13

EXAMPLE 2

The vernier scale need not be constructed by subdividing 9/10 of the whole centimetre unit. It could be made by subdividing 9/10 of 0·5 cm., as shown in Fig. 13.

In this case the 0·05 cm. lines must be engraved on the main scale, and coincidence with *any* line on the main scale is the method of deciding the vernier scale reading. An important distinction here is that the number read on the latter scale must be multiplied by 0·005 cm. This factor is found by considering how much the vernier scale shifts between the positions of coincidence for the zero lines and the next pair, as we did in Example 1. This distance will be (0·05 – 0·45/10) cm. i.e. 0·005 cm.

Many other intervals are used by manufacturers of vernier scales—usually rather more than 1 cm. is chosen as the interval to be subdivided, as this simplifies the process of engraving. Thus a vernier scale reading to 0·002 cm. is often made by dividing 1·2 cm. of the main scale (calibrated to 0·05) into 25 equal parts.* It is evident that you must make a careful examination of the vernier attachment on any apparatus you use so that you discover in what units the vernier readings will be. It is clearly also necessary to decide whether the main scale must be read to the nearest whole unit or the nearest half unit. A good general rule is that usually the main scale must be read to the fullest accuracy which its engraving permits, and the vernier scale reading (multiplied if necessary by the appropriate factor) should be added to this reading.

Scales of angles are often fitted with vernier scales, and usually these read to the nearest $\frac{1}{2}°$ on the main scale and to the minute (up to 30 minutes) on the vernier scale. Most spectrometers are engraved in this way, and the warning given above is therefore applicable here.

Always use a lens to read the vernier scale (see also pp. 27–28).

Finally it must be emphasised that the skill of using a vernier scale can only be acquired by practice, though it does not take long. If you ever have any doubts about any vernier scale, make up your mind what you think is the right method of arriving at the reading, set the scale at random and take the reading. Then ask your instructor to take the reading as a check on your observation. If necessary you can then discuss any difficulties.

(2) *Micrometer Screw-Gauge and Spherometer*

Another common method of increasing accuracy of measurement of length is the use of the screw. This depends on the fact that for one complete revolution a screw moves through a distance equal to the pitch of the thread while any point on the circumference of a screw-head of radius r cm. moves through $2\pi r$ cm. Thus if r is made fairly great (and it can be given any value consistent with convenience of design), the distance given by the pitch of the screw can be subdivided on the circumference of the 'head' with considerable accuracy, owing

* This method is commonly used for vernier microscopes.

to the increased length available. (This is the same type of calculation which occurs in velocity ratio problems of the screw.) The device finds application in many instruments, notably the micrometer screw-gauge and the spherometer.

An examination of the micrometer screw-gauge should enable you to find out in what units the screw head is calibrated.

The use of the spherometer for measuring small distances is described in Experiment 1, p. 57. It is also used commonly to find radii of curvature of spherical surfaces (hence its name). For this purpose the zero reading is observed by using a plane glass block (as before), and the reading is also taken when all four legs make contact with the spherical surface. If x is the difference between these two readings in cm., then the radius of curvature r cm. is given by the formula

$$r = \frac{l^2}{6x} + \frac{x}{2}$$

where l cm. is the length of the side of the equilateral triangle formed by the fixed legs.

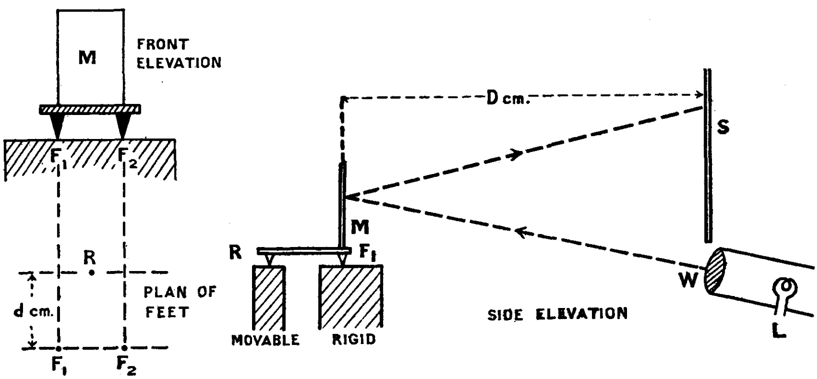


FIG. 14

(3) *The Optical Lever*

This is a simple but effective method of measuring small differences in length or position. It usually comprises a plane mirror, M, mounted on three legs, as shown in Fig. 14, where F_1 and F_2 are the front legs and R is the rear leg. The plane containing the reflecting surface of the mirror must be parallel to the line joining F_1 and F_2. R is mounted on the solid of which the change of position is required, and F_1 and F_2 on a rigid base, so that the mirror can rock about the axis F_1 F_2. L is a lamp house with a cross wire placed just beyond the focus of the lens. An image of the wire is formed on the scale S after light has been reflected from M.

If D and d are the distances shown in Fig. 14, then for any movement of R, the corresponding displacement of the image is $2D/d$ times as much. Thus if D is 1 metre, we can obtain a 'magnification' of say 70 by using an optical lever with a value of d equal to about 3 cm. Using such an arrangement when measuring the coefficient of expansion of brass in the form of a rod one metre long, with a temperature change from about 10°C to 100°C, the image would move over 10 cm. along the scale.

The Determination of Mass. Choice of a Balance

The mass of a body is determined by comparing its weight with that of a known mass. (Known masses are usually referred to as 'weights', which may cause confusion unless the theory behind the process called 'weighing' is thoroughly appreciated.) Mass then is determined by a balance. Several points arise when using this instrument:

(1) Choose a balance which will safely take ALL the loads you intend weighing during the experiment. Watch this especially in experiments in which there is a large increase of load, such as some of the calorimetry work and in density experiments involving mercury.

(2) Choose a balance which is as sensitive as the accuracy demanded, but NOT MORE SO. If you use too sensitive a balance you will merely waste time.

(3) Treat the balance with the care of which an instrument of such precision is worthy.

(4) Always put the box of weights on your right and the weights on the right-hand pan. Add the weights in a logical order, so as to take the minimum time for the weighing.

(5) Never put chemicals on the pan, but weigh them in a previously weighed container.

Experiments 2 and 3 will teach you more about the sensitivity of a balance.

The Measurement of Time

(1) *Simple Harmonic Motion*

Clocks and watches depend for their timekeeping on bodies which are executing what is known as 'simple harmonic motion'. The latter is a very important type of motion and can be defined as follows :

'If a particle moves so that its acceleration towards a fixed point is proportional to its distance from that point, then the motion of the particle is simple harmonic'.

The most important characteristic of such motion is that it is 'isochronous'—i.e. the time for one vibration is a constant and not dependent on the amplitude. True simple harmonic motion is rare. A common case met with in the ordinary laboratory is that of a spiral spring carrying a load which is oscillating in a vertical plane. Many other sorts of vibrations are very nearly simple harmonic, such as those of the simple pendulum, the compound pendulum, the vibration magnetometer. In these cases, however, the periodic time does vary with the amplitude, but the amount of the variation is extremely small, provided the amplitude is small, i.e. not more than 10° from the mean position, and preferably only 5°. Thus when doing experiments involving simple harmonic vibrations, the amplitude used should never exceed these figures for angular displacements, and if possible should be much smaller. The choice of amplitude is, however, controlled to some extent by the energy needed to maintain the vibration for a large number of swings.

(2) *Timing Vibrations*

In quite a number of experiments the determination of the periodic time of vibration is made. It should first be noted that by 'the periodic time', we mean the time taken for the body to move from the mean position to the point of maximum displacement on the one side, back through the mean position to the point of maximum displacement on the other side, and then back to the mean position. The procedure to be adopted to determine a periodic time is as follows:

Make a mark on a piece of paper and fasten it behind the vibrating body, so that the mark is immediately behind some convenient part of the body (e.g. the thread of a pendulum) when in its rest position. As the body vibrates it will pass and repass this mark at its maximum speed. Stand, or sit, directly in line with the mark, and count how many times it is passed. The counting must be done as the body passes the mark always in the same direction, say from left to right in the case of a simple pendulum. Hold the stop watch ready and count thus: 3, 2, 1, 0, 1, 2, 3, . . .' At the '0' start the watch, and stop it when the selected number of swings has been completed.

Unless the amplitude is decaying rapidly, or some other good reason holds, the number of oscillations counted should be such that the watch runs for over a minute, so that the limits of error in timing represent a small fraction of 1% of the total time.

It is necessary to guard against miscounting the number of vibrations and the only way to do this is to use the consistency of the times taken as the criterion of consistency of counting. Thus, after the first timing, a rough value for the periodic time should be calculated. If the next reading differs from the first by an amount comparable with this, it is almost certain that an error in counting has occurred. The third determination should indicate which of the two was the timing with the correct counting, and this must be confirmed by a fourth observation. If after four observations, you are satisfied that three readings are sufficiently consistent to justify the assumption that one was in error (usually this means that three out of the four timings are within about 0·3 secs. of each other), then REJECT THE INCONSISTENT ONE and calculate the average value from those three which are acceptable. If of course three consistent readings are obtained immediately (as indeed they ought to be), then that is good enough to justify your proceeding to the next part of the experiment. Conversely, if four readings have not enabled you to decide what the correct timing observation should be, timing operations must continue until you are ABSOLUTELY SATISFIED as to which value to accept. NEVER TAKE AN AVERAGE OF A SERIES OF TIMINGS WHICH SHOW VARIATION OF AN AMOUNT COMPARABLE WITH THE TIME OF ONE PERIOD, because you do not know how many vibrations this represents.

You should include in your table of observations a column in which n, the number of oscillations counted, can be recorded; the value of n can be chosen to suit each oscillation investigated and can be given a smaller value for the longer time-periods. Thus, in a simple pendulum experiment the larger values of n will correspond to the shorter lengths.

Cleaning Glassware

(i) *Vessels:* modern detergents, e.g. 'Teepol' are often all that are required. If more resistant greasy deposits are to be removed, a concentrated solution of washing soda, a dilute solution of caustic soda, or benzene may be used.

(ii) *Capillary tubing:* The most satisfactory method is to introduce a thread of either caustic soda or nitric acid and to move this liquid to and fro along the tube for some minutes. When the thread of liquid moves down instantly on inverting the tube it is usually a sign that the latter is clean. After rinsing with water, and drying, the tube will be ready for use.

Drying Glassware

The following method is quick and satisfactory :

(i) After rinsing with water and draining, rinse thoroughly with methylated spirit or industrial spirit and drain.

(ii) Rinse with ether and drain. ETHER IS VERY VOLATILE AND HIGHLY INFLAMMABLE.

(iii) Evaporate the ether by passing a stream of air, using a filter pump equipped with a valve—e.g. the type made by Messrs. Edwards. If tube of small bore is being dried, cycle valve rubber can often be used to connect the tube to the ether (or dry air) supply. Insulating sleeving used in electrical work can also be put to this purpose, and has the advantage that it is obtainable in various diameters.

A glass surface will become moist due to condensation from the atmosphere, and if it has to be kept dry for any length of time it should be placed in a desiccator.

Simple Operations with Glass

(1) *Glass-blowing*

It is not intended here to give a full account of the technique of glass-blowing. The subject is too large, and most needs of practical physics, at the standard with which we are concerned, can be met by the aid of simple apparatus and simple technique.

(i) To cut glass tubing proceed as follows:

For short connection-tubing of small diameter make one good cut in the glass with a sharp file and, placing the thumbs one on either side of the cut, break the glass by a gentle bending and pulling action. For tubing of somewhat larger diameter (up to 2 cm.) it may be necessary to make a continuous cut right round the tubing with a file, before breaking by the method described. If the tubing is of diameter greater than 2 cm. the best way is to use a special cutter (which can be obtained for quite a small sum). Otherwise a patient filing process is required. When the 'notch' is *continuous* round the glass—and it should be reasonably deep—heat a piece of iron wire (or a steel knitting needle) to red heat and apply the tip to the notch. The glass should break right round the tube along the prepared line. If it only partially cracks, heat the wire again and apply at the end of the crack; if necessary 'chase' the crack until the tube is cut.

(ii) To bend glass tubing, the ordinary bunsen burner *must* be modified by the addition of a flame spreader. A slightly luminous flame should be used —unless hard glass is being bent (when a hotter flame is required)—and the tubing should be heated for some distance on each side of the proposed bend. The glass should be slowly rotated about its axis whilst this heating is done. When the tubing is quite flexible, bend it firmly to the required angle *outside* the flame.

(iii) To draw out glass tubing, heat it in a slightly luminous bunsen burner flame until soft, and then pull along the axis (without applying any twist) *outside* the flame.

(2) *Grinding Glass*

The rough edges produced when, for example, a bottle has been cut down, may be smoothed in the following way:

Pin a sheet of rough emery paper to a flat piece of wood and pour turpentine on to it. Move the rough glass surface over the emery paper with a circular motion, exerting a firm pressure at the same time. See that the supply of lubricant is well maintained, otherwise the edges will chip. Fine carborundum powder may also be spread on the emery paper to assist the grinding and speed up the work.

(3) *Boring Glass*

What at first sight appears to be rather a difficult operation can be carried out with comparative ease as follows:

(i) Special drills must be made in accordance with the following instructions: These drills are made from silver steel (which can be obtained in 13-in. lengths from most tool shops) of diameter either $\frac{1}{8}''$ or $\frac{3}{16}''$. About three inches should be cut off and about one inch of this heated to bright redness. The end should then be hammered flat to the shape shown in Fig. 15 A and B. The end must next be filed or ground to the shape shown in Fig. 15 C, making the angle between the faces X and Y about 150°. The drill must then be hardened by heating to bright redness again and quickly plunging into cold water to which sodium chloride has been added (this improves the temper). The cutting edges should then be finished by grinding on a fine wheel or using an emery slip, but care should be taken not to overheat the 'bit'. Normally two drills should be made—one of each diameter—as the smaller one is useful for centering.

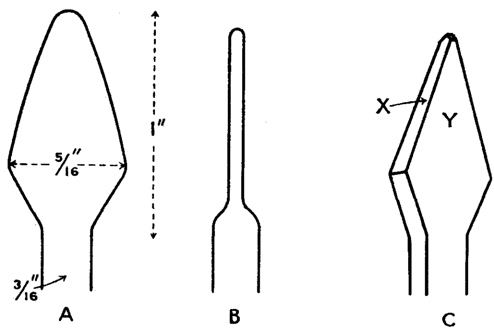


FIG. 15

(ii) To drill a hole proceed as follows: Centre the hole with the smaller drill held in a hand brace, using very light pressure and lubricating continuously with camphor and turpentine. Finish with the larger drill turning at about one revolution per second. Do not drill right through, but, when almost through, turn the glass over and drill from the other side, otherwise the edges will chip. Take care in all drilling operations to ensure a continuous supply of the lubricant and to remove the borings frequently. The drill must also be kept cool. The drilling should be done with the glass resting on fibre-board or soft wood so that splintering of the glass may be avoided by drilling right through into the wood.

Soldering

An electrically heated soldering iron is recommended, as it is easier to manage and the risk of burning the bit is reduced. If available, use multicore solder (i.e. solder in which the flux is incorporated) such as 'Ersin'. Use 'Arax multicore' if iron is to be soldered.

Proceed as follows:

(i) Clean the parts to be soldered with emery paper. If they are very dirty use an old file.

It cannot be too strongly emphasized that time spent in cleaning is time saved. If cleaning is not thoroughly and carefully done, joints will be unreliable.

(ii) 'Tin' the bit, i.e. when the iron is hot, wipe it quickly with a cloth, and apply sufficient multicore solder to give the bit a silvery appearance.

(iii) Tin each part to be joined by applying the bit and solder simultaneously to the work, and covering each part separately with a thin layer of solder.

(iv) Put the tinned parts together, if necessary binding with cleaned thin copper wire, and apply the bit and a little solder simultaneously to the work.

When the solder 'runs', smooth the joint with the bit, remove the bit and hold the parts quite still until the solder has set (the surface will become dull when this takes place).

(v) Give the parts a sharp pull to check that the joint is sound.

Cleaning Mercury

The quickest way of cleaning mercury is as follows: Over the top of a large clean and dry evaporating dish place a clean piece of linen, e.g. a good quality pocket handkerchief. Pour the dirty mercury into the linen and then carefully gather the corners and edges together to make a 'bag' of mercury. Twist the neck of this bag slowly so that the space containing the mercury becomes steadily more and more restricted, with the result that the mercury is forced through the linen and squirts into the dish (hold the bag very near to the dish so that no mercury is lost, for it is *very* expensive). If necessary repeat the process with a fresh piece of linen.

Another method consists in pouring the mercury into a beaker one-third full of plaster of Paris and agitating.

If the mercury is so badly contaminated that the above processes do not succeed, consult a suitable textbook of laboratory technique, e.g. *Modern Physical Laboratory Practice* by J. Strong (published by Blackie), or *Laboratory Workshop Notes* 1953–1955, edited by R. Lang, fourth selection, item 15, pp. 20–21 (published by Arnold). Equipment referred to in the second of these references is manufactured by Messrs. Griffin and George (see their catalogue 56S, p. 430).

Remember that many metals form amalgams on contact with mercury, and it is therefore wise to take special care of valuable objects, especially those involving precious metals (such as fountain pens with gold or silver bands) and if a ring is worn it is always wise to remove it before working with mercury. For the same reason mercury which has been in contact with other metals should be kept apart from the main stock of clean mercury in specially labelled jars—e.g. 'Mercury for Pohl's commutator', 'Mercury for amalgamating zinc rods'.

Testing the Uniformity of Bore of a Capillary Tube and Measuring its Diameter

Introduce a thread of clean mercury, about a centimetre long, into the tube and measure its length with a vernier microscope at different parts of the tube. If the bore is uniform the length will not vary with position.

The internal diameter can be determined by two methods:

(i) Using the thread of mercury already introduced to test the uniformity of the bore, empty the mercury into a clean weighed crucible (or other suitable container) and reweigh to find the mass of mercury used. The diameter of the tube can then be found from the formula

$$d = 2 \times \sqrt{\frac{m}{\pi l D}}$$

where d is the required diameter, in cm.,
m is the mass of mercury, in gm.,
l is the length of the cylindrical thread of mercury in cm.

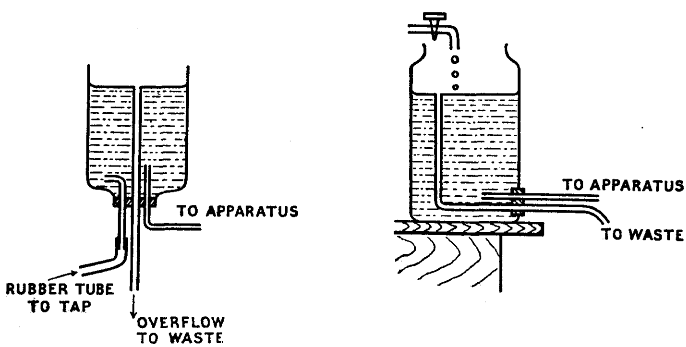
and D is the density of mercury in gm./cm.^{3} at the temperature of the experiment.

This is the best method and the accuracy can be increased considerably if a longer thread is used, though this is undesirable when testing the uniformity of bore.

(ii) Make a number of observations across a cleanly cut end of the tube, with a vernier microscope, and take a mean of the observations.

Constant Head Apparatus

If a supply of water at a constant pressure is required, the pressure at the tap is too variable. This is caused by a number of effects—the chief one being the opening and closing of other taps in the same building. It is necessary therefore to insert between the tap and the apparatus a 'smoothing' device which is known as a 'constant head apparatus'. Various forms can be made quite easily, and two are shown in Fig. 16, which should be largely self-explanatory. The outlet should



(A) (B)

FIG. 16. Constant Head Apparatus.

be a tube of diameter not less than 8 mm. In arrangement A the vessel can conveniently be an inverted broad-necked bottle (such as those in which 'A.R.' reagents are despatched) of which the bottom has been removed and ground down (see p. 53). The inflow tube is bent to the horizontal inside the vessel to reduce the risk of shooting water right out of the apparatus when it is turned on too rapidly, and to reduce the likelihood of a small wave (or pile) of water forming vertically over the inflow tube. In arrangement B an aspirator is used. It needs only two pieces of glass tubing and it is thus rather easier to make. For making water-tight joints 'Bostik B' glazing compound or 'Seelastic' is recommended. Before using a constant head apparatus it is advisable to check that it is delivering water at a constant rate.

CHAPTER V

MEASUREMENT OF MASS, LENGTH AND TIME

Experiment 1. Determination of the Thickness of a Microscope Slide by Several Methods and a Consideration of the Possible Error in Each One

Apparatus: Microscope slide; spherometer; glass block; vernier microscope; micrometer screw-gauge; Archimedes bridge.

THEORY

Reference should be made to Chapter II as this experiment is designed to give practice in combining errors in simple cases. It also introduces you to some important instruments used for measuring lengths, which find many applications in future experiments. This is a good opportunity to become familiar with them, so that later on more complicated experiments are not spoilt by misusing them or misreading the scales on such apparatus. Some guidance on these measuring instruments will be found on pp. 47 – 50.

Procedure: (i) Measure the thickness of the slide in a number of places, using a half-metre rule.

(ii) Repeat, using vernier calipers.

(iii) Place a spherometer on a glass block and screw down until it just does not rock, or until its point is coincident with its own image formed by reflection in the block. Note the scale reading. Screw the point up several millimetres and insert the slide beneath it. Repeat the above process to find a reading from which, by subtraction, a value for the thickness of the slide can be found.

Repeat the operations in different parts of the slide.

(iv) Using a vernier microscope, focus the edge of the slide so that the shortest dimension is perpendicular to the cross-wire. Take the readings of the vernier scale when first the one, and then the other, edge is coincident with the cross-wire.

Repeat for several positions along the four edges.

(v) Measure the thickness in several different places, using the micrometer screw-gauge. Do not forget to observe the zero reading of the screw-gauge and to record it—even if it is truly zero.

(vi) Measure the length and width with a metre rule, and determine the volume by the method of weighing in air and water.

Record and Calculation: Record all observations together with the possible error of each, expressing it thus: '$4{\cdot}6 \pm 0{\cdot}1$ cm.' Calculate the mean value of the thickness, and the possible error of this mean value for each of the experiments (i) to (vi) separately. Arrange the methods in order of merit, giving the most accurate first.

If, in the list, (vi) appears before (i) state why it is that in an experiment in which a ruler was used to make two observations the result was more accurate than when the ruler was used to make only one observation (the ruler is the least accurate instrument used). This is a very important point and you should be sure that you understand it before proceeding to other experiments.

Experiment 2. Verification of the Formula for the Sensitivity of a Balance

THEORY

Part of a balance is shown diagramatically in Fig. 17. A and B are the knife edges supporting the pans and C is that supporting the beam. W_1 and W_2 are weights in the pans.

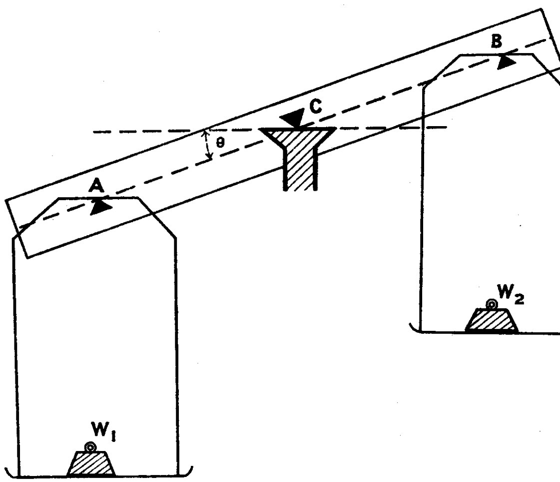


FIG. 17

If the balance beam is deflected through an angle θ due to this difference of weights, then the sensitivity can be measured by the ratio of tan θ to $(W_1 - W_2)$.

In a well-designed balance the three points of contact of A, B and C are made to lie on a straight line, because, if this condition is fulfilled, the sensitivity is independent of the weights of the scale pans. It can be shown that under such conditions the sensitivity is given by the equation

$$\frac{\tan \theta}{(W_1 - W_2)} = \frac{l}{xW}$$

where W is the weight of the beam

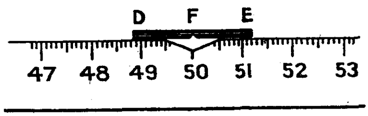
x is the distance from the centre of gravity of the beam to the knife edge C

and l is AB/2.

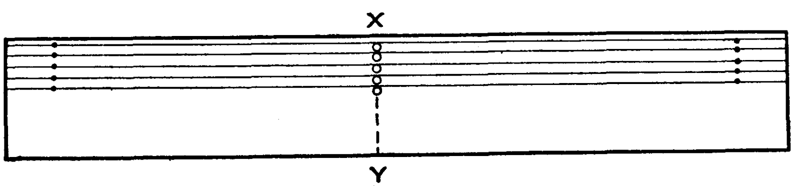
As there are three variables in the R.H.S. of this expression the experiment is conducted in three parts, in each of which two quantities are kept constant and the third varied.

Apparatus

PARTS I AND II. This needs specially making from five or six metre rules (or other lengths of wood, all of which must have similar dimensions to each other). Each of two of the rules is provided with a metal support (DE in Fig. 18A) which must be rigidly attached to the rule. A nick is cut in the under side of DE directly over the 50 cm. mark, and a small triangular piece cut from



(A)



(B)

FIG. 18

the rule to allow the knife edge to support the rule at F. This arrangement ensures that the conditions referred to above will be adhered to in the experiment and the nick prevents the rule sliding when deflected from the horizontal.

Shallow nicks should be cut in the top of the rule at each 5 cm. so that the thread supporting the scale pans will not slide down the rule when it is in the deflected position.

The other three or four rules only require the removal of the triangular portion, as they will be securely fixed to the other two when being balanced (see Part II below).

All the rules are drilled with a hole about 1 mm. in diameter on the centre line of the rule at about the 10 cm. and the 90 cm. marks. This can most easily be done by clamping them all together so that one drilling operation completes the task.

A good knife edge, about 4 cm. long, two scale pans of equal weight and two pieces of screwed brass rod each 3 inches long, fitted with wing nuts, are also needed.

PART III. A smooth piece of $\frac{3}{8}''$ or $\frac{1}{2}''$ board about 3 feet long and 6 inches wide is balanced to find its centre of gravity and the line on its face about which it will balance is drawn carefully (XY in Fig. 18B). Next, five or six holes are drilled as shown in the figure so that the spacing is roughly uniform, and short pieces of glass tubing fitted tightly into the holes. The internal diameter of the glass tubing should be just large enough to allow the knife edge to pass freely through them. Next, a set of lines parallel to the edge of the board and tangential to the tops of the holes is drawn. On each of these lines small holes are drilled at equal distances from the ends—and fairly close to the ends—through which will pass the supporting threads of the scale pans.

Part I

Here W and x are kept constant and l is varied.

Procedure: One of the metre rules fitted with a metal strip is balanced as shown in Fig. 19. If it is not horizontal, wire should be wound

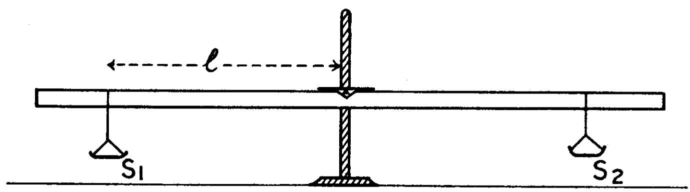


Fig. 19.

round one end (and fixed securely) to correct this. The scale pans, S_1 and S_2, are then supported by threads passing over the top of the rule—thus making sure that the three points referred to in the account of the theory given above are all in one straight line. Devise a suitable method of measuring the deflection (such as making observations at each end of the scale which enable you to find the mean tangent of the deflection). Place the scale pans at the 10 cm. and the 90 cm. marks and make minor adjustments to make the rule horizontal. If the scale pans are truly equal in weight a lateral adjustment of less than half a millimetre should be required. The need for more than this adjustment signifies that the pans are unequal in weight and the rule should be restored to the horizontal by adding a small weight to the lighter pan.

Place 20 gm. in one pan and 21 gm. in the other. Take observations to find the deflection. Remove all the weights from the scale pans and move the latter by about 6 cm. towards the centre. Place them at equal distances from the centre and if necessary adjust the rule to the horizontal by the same process as before—a smaller weight will of course be needed (why?). Next place the 20 gm. and the 21 gm. weight in the pans and measure the deflection again. Continue this process until at least five sets of readings for various values of l have been obtained.

Record and Calculation: Tabulate your observations. Calculate values for tan θ and plot values of tan θ against l (the distance of the scale pans from the centre). State the conclusions you draw from the graph.

PART II

Here x and l are kept constant and W varied.

Procedure: The general method is rather similar to that used in Part I but the distance of the scale pans is kept constant at 41 cm. from the centre. The weight W is altered by varying the number of metre rules composing the beam. First the rule used in Part I is modified by passing through each of the two holes already drilled at the 10 and 90 cm. marks a piece of screwed brass rod 3 ins. long fitted with wing nuts. Wire is again used to bring the rule to the horizontal and the pans are put on at the 9 cm. and the 91 cm. marks, with an appropriate weight, if necessary, to make the beam horizontal. 20 gm. and 22 gm. respectively are put in the pans and observations taken to measure the deflection. The rule (with the two rods) is weighed.

Next the other rule which has a metal bar attached to it is fixed to the first by the two rods so that the metre rules are fixed firmly side by side. The above process is then repeated, including the weighing.

Next a third rule is introduced between the other two rules and the operations repeated.

This process is continued with an additional rule being used each time until all the prepared rules are in use. If the rules are weighed separately, as they are incorporated, mark each one with its weight.

Record and Calculation: Tabulate your results and plot a graph of tan θ against W. State your conclusions. Plot any other graph (or graphs) which you think will aid your analysis (see pp. 35–37) and state your conclusions.

PART III

Here W and l are kept constant and x is varied.

Procedure: Support the specially made beam [described above in *Apparatus*, PART III] by passing the knife edge through the uppermost hole. Hang the scale pans from points near the ends at equal distances from thc centre and on the same line, and adjust (by a small weight in the pan on the lighter side) to make the beam horizontal. This correction is partly (or wholly if the pans are equal in weight) for the inaccuracy in drilling the beam, as it is not normally possible to drill six holes and make the beam balance horizontally about all of them. Put 20 gm. and 25 gm. weights in the pans and observe the deflection. Record the value of x, the distance from the knife edge to the centre of gravity of the beam.

Remove the weights from the pans and support the beam by passing the knife edge through each of the holes in turn. Carry out the operations described in the preceding paragraph for each different value of x, using the appropriate holes for the scale pan threads.

Record and Calculation: Tabulate your observations and plot graphs to analyse your results. State your conclusions.

Experiment 3. Determination of the sensitivity of a balance

Apparatus: The balance; vernier microscope; two boxes of weights including fractions; stop-watch.

THEORY

In the theory section of the preceding experiment, it was noted that the three points of contact, A, B, C (Fig. 17), would be in the same line in a well-designed balance. We shall assume this to be the case in the balance of which the sensitivity is to be determined. This being so, it can be shown that the sensitivity is independent of the masses placed in the pans and, moreover, if the balance is allowed to swing about its mean position, first unloaded (periodic time T_0) and then with equal masses M gm. in each pan (periodic time T), then

$$T^2 - T_0^2 = \frac{8\pi^2 Ml}{g} \cdot k$$

where l is the half-length of the balance beam (AC in Fig. 17) and k is the sensitivity of the balance in radians/gm.

Thus if a series of values of M and T are investigated a graph of T^2 against M should yield a straight line from the gradient of which k can be determined if the other constants are known.

Procedure: Check the zero setting of the balance. Using the standard procedure for the determination of periodic time (see p. 51) obtain a series of corresponding values of T and M, choosing the range of values for M to obtain at least five sets of observations which cover the permissible range of loads for the balance. If on placing the 'equal' loads on the pans they do not balance, make the necessary adjustment by adding appropriate fractional weights or by moving the riders.

Measure the distance apart of the knife-edges ($2l$) which support the pans; this is most easily done if the pans and knife edges are removed and the beam carefully lifted off its support. Before doing so permission should be obtained from your instructor. Care should be taken to reassemble the balance with its parts on the same side as before.

Record and Calculation:

Tabulate the observations as follows:

M gm.	No. of oscillations timed (n)	Stop-watch reading (sec.)				T (sec.)	T^2 (sec.^{2})
		(i)	(ii)	(iii)	Mean		

Plot a graph of T^2 (as ordinate) against M and determine the gradient. Equate the latter to $\frac{8\pi^2 l}{g}k$, using the value of l determined by measurement, and solve for k.

Note: The value of k can be checked by observing the tip of the pointer of the balance with the vernier microscope and noting the distance it moves for the addition of a small fractional weight in the right-hand pan. This distance together with the length of the pointer will lead to a knowledge of the angular deflection in radians caused by the added weight, and hence the value of k can be calculated.

Experiment 4. Determination of the Acceleration due to Gravity, using a Simple Pendulum

Apparatus: Simple pendulum; stop-watch; callipers.

THEORY

The periodic time in seconds (t) of a simple pendulum executing small vibrations can be shown to be given by

$$t = 2\pi\sqrt{\frac{l}{g}}$$

where l is the length in cm.,
and g is the acceleration due to gravity in cm./sec./sec.

This equation transforms to

$$l = \left(\frac{g}{4\pi^2}\right)t^2$$

Thus a graph of l against t^2 will be a straight line and its gradient will be $g/4\pi^2$.

Procedure: Set up a pendulum of length about 40 cm. Measure the length of the string and the diameter of the bob. Determine the time taken for a suitable number of swings (see p. 51), using a small angle of swing. Repeat for various lengths, obtaining at least six sets of observations covering as wide a range as possible—preferably up to lengths of 200 cm.

Record and Calculation: Tabulate results thus:

Diameter of bob	i	. .	cm.
	ii	. .	cm.
	iii	. .	cm.
			cm.
Radius of bob . .		Mean	cm.

n	Length (cm.)			Time of n Swings (secs.)				Period (t) (sec.)	t^2 (sec.^{2})
	String	Radius of Bob	Total	(i)	(ii)	(iii)	Mean		
	$x\pm$	$y\pm$	$(x+y)\pm$						

Plot l against t^2. Find the gradient of the graph and use it to calculate a value for 'g' from the above formula. Deduce also a value for 'g' from the most accurate observations and include in your result a statement of the possible error.

CHAPTER VI

ELASTICITY

Experiment 5. Investigation of the Elastic Properties of a Piece of Wire

Apparatus: Bare copper wire of S.W.G. about 32—certainly not less than 30—insulated wire may be used but see note under 'Procedure' below. Weights of various values, totalling 1,800 gm. for S.W.G. 32 (over 3 kgm. for S.W.G. 30); micrometer screw-gauge; large scale pan (a child's sea-side bucket is suitable); pointer.

The pointer should be fixed rigidly to the specimen of wire and this can best be done by drilling a brass connector to take the pointer (as shown in Fig. 20A) and using the two screws and an internal sleeve to fix it to the wire. It must be fixed *above* the junction of the wire with the sling of the scale pan, so that no variation in position of the latter is recorded. Finally an efficient clamping arrangement at the upper end of the wire is needed and this can easily be made from two steel (or brass) plates which bolt together on to a beam. The wire should be trapped between the two plates and wound round once again as a precaution. The arrangement must ensure that motion of the pointer is the result of extension in the wire and is not affected by any other changes occurring in the apparatus.

Procedure: Measure the diameter of the wire in several places. If insulated wire is used, the actual specimen must on no account be used for diameter measurements, as stripping the insulation involves a stress which will alter the elastic properties of the wire.

Use about 2 metres of wire as the specimen to be investigated. This should be cut from the bobbin with pliers, without applying any longitudinal stress. Weigh the scale pan (which should be a large one which can easily accommodate the total weight to be used) and fix it rigidly to the wire below the pointer. The bottom of the scale pan should have space for extension below it of at least 50 cm. The arrangement is shown in Fig. 20B.

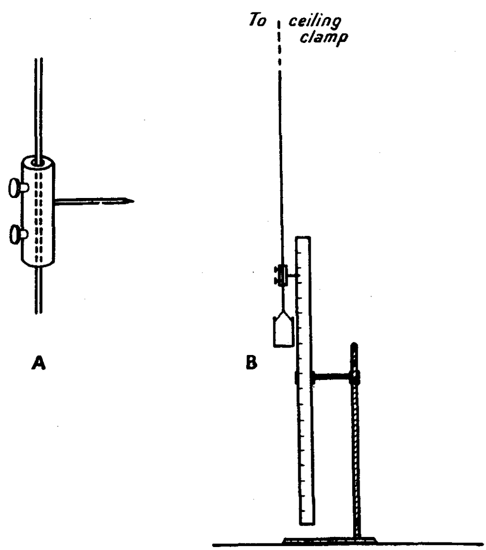


FIG. 20

Determine by a rapid experiment the maximum load (to the nearest 100 gm.) which the wire will support without breaking. It will be about 1,400 gm. for copper wire of S.W.G. 32. The following instructions assume this value for the breaking load and should be amended to meet any variation shown by the specimen you use.

Set up a fresh sample of wire and with only the scale pan as load note the reading of the pointer. Increase the load by increments of 200 gm. until 1,000 gm. is reached, taking the pointer reading for each load. Continue loading by increments of 50 gm. to 1,200 gm. recording the pointer reading for each load. At this stage unload by similar amounts (first 50 then 200 gm.) noting the pointer readings as before. When the load has been reduced to zero repeat the loading experiment exactly as before and after the 1,200 gm. load has been reached continue loading by increments of 10 gm. until the wire breaks. To obtain the best results from this experiment it is very important to allow sufficient time for the extension (or contraction) of the wire to be completed after each change of load. For higher values of the load the time needed for this may be considerable (10 to 15 minutes) and it is wise to note the pointer readings at intervals, continuing until there is no change with time.

Finally measure the diameter of the broken wire in a number of places.

Record and Calculation: Tabulate your results. Plot a graph of extension, as ordinate, against load.

Compare the mean diameters of the wire before and after the experiment.

Discuss the results obtained.

Experiment 6. To Determine if a given Spiral Spring obeys Hooke's Law

Apparatus: Spiral spring; suitable means of support—see Fig. 21 below; weights and hanger, not exceeding the maximum safe load for the spring.

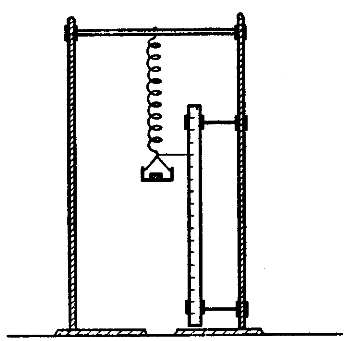


FIG. 21

THEORY

In ordinary usage the term 'elastic' is applied to any body which after being deformed returns approximately to its original shape and size. In physics we use a more precise definition and insist that a body only be described as 'elastic' when the strain produced in it is proportional to the stress applied.

For a spiral spring the strain is the increase in length and the stress is the load; the statement that the one is proportional to the other is known as Hooke's Law. It is not possible to verify Hooke's Law, for the following reason:

If we use a spring which is not elastic—in the strict sense—it will, by definition, not obey Hooke's Law. If we take the precaution to choose one which is elastic the only way we can do this is to ensure that it obeys Hooke's Law, i.e. we have to assume what we aim to verify. Hooke himself was quite vague about the terms he used.

This experiment sets out to investigate whether the spiral spring used obeys Hooke's Law or not, i.e. whether it is 'elastic' in the strict sense.

Procedure: Set up the arrangement shown in Fig. 21. Add just sufficient weights to the scale pan to remove any irregularities in the spring and take the reading of the pointer on the scale. Enquire what is the maximum safe load for the spring and from this decide what increments of load are suitable—you should obtain not less than five sets of observations. Increase the load by these increments recording the pointer reading for each load, until the maximum safe load is reached.

After the last addition unload by the same equal stages, reading the pointer position at each stage until the original load is reached.

Record and Calculation: Tabulate as follows:

Load (gm.)	Pointer Readings			Extension
	Loading	Unloading	Mean	
			a	0
			b	$b-a$
			c	$c-a$
			d	$d-a$
			etc.	etc.

Determine whether the spring obeys Hooke's Law by plotting extension against load—a straight line indicates that the law is obeyed. If the spring proves to be elastic, obtain from the graph a mean value of the force required to produce unit extension of the spring. Determine this quantity also from the best set of readings so that it can be used in the next experiment—which should be done at once, while the apparatus is set up.

Experiment 7. Determination of the Acceleration due to Gravity, using a Vertical Elastic Steel Spring

Apparatus: Elastic spring (see previous experiment); pointer, etc. as for Experiment 6; stop-watch.

THEORY

A loaded elastic spring when displaced vertically from its position of rest and released, executes simple harmonic motion with a periodic time T given by

$$T = 2\pi\sqrt{\frac{M+s/3}{kg}},$$

where M is the mass of the load in gm. (including the scale pan)
s is the mass of the spring in gm.
k is the force required to produce unit extension of the spring in gm.wt./cm.
and g is the acceleration due to gravity in cm./sec.^{2}

Procedure: Set up the arrangement used in Experiment 6 and if the same spring is not being used, determine the value of k for the new spring by the method described on pp. 66–67.

To the spring attach the smallest load used in the determination of k and set the system vibrating in a vertical plane. *Make sure that the coils do not touch when the spring is compressed*—if this is the case use the next increment of load. Find the time (see p. 51) for the greatest number of swings, up to 100, which can be investigated before the usual 'pendulum action' starts. Increase the load by equal increments and determine the periodic time for each one.

Record and Calculation: Tabulate your observations, including in the table a column for T^2.

Plot values of M against values of T^2 and deduce a value for the gradient (see p. 33) which will equal $kg/4\pi^2$. This follows from the result obtained when M is made the subject of the formula given above for the periodic time. Using the known value of k calculate the value of g from the value of the gradient.

Deduce also a value for g, using the most accurate set of values which is consistent with all your observations (see p. 27).

Note: The effective mass ($s/3$) can also be deduced from the graph—it is given by the intercept on the axis of M. If the value so obtained is compared with that found by weighing the spring, close approximation is seldom obtained—mainly due to the fact that the points used are so far from the origin that small variations in the gradient of the 'best straight line' produce large variations in the value of the intercept. This can be avoided to some extent by finding the gradient from a graph which does not show the origin but gives a good distribution of the points over the graph paper, and using the gradient so obtained to draw the best line on a graph which does show the origin (see p. 35).

Experiment 8. Determination of Young's Modulus for the Material of a Piano Wire

Apparatus: In most laboratories there is a permanent apparatus available for this experiment, comprising a pair of steel piano wires securely clamped near the ceiling. One of the wires has the main scale of a vernier arrangement attached to it and the other the movable vernier scale. At least 10 one-kilogram weights are needed to load the latter wire and a micrometer screw-gauge will be required to measure its diameter (which can conveniently be about 0·5 mm.).

THEORY

$$\text{Any modulus of elasticity} = \frac{\text{stress}}{\text{strain}}$$

where stress is a measure of the deforming force and strain is a measure of the deformation caused by it.

In the case in which the force causes elongation, stress is measured as the force per unit cross sectional area and strain is the increase in length of unit length. The modulus is then known as Young's modulus (E) and hence

$$E = \frac{F/A}{l'/l}$$

where F is the force in dynes,
A is the cross sectional area in sq. cm.
l' is the increase in length in cm. caused by F,
and l is the original length of the wire in cm.

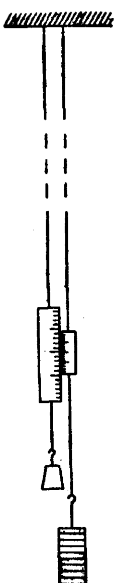


FIG. 22.

Procedure: Suspend from a single clamp (see Fig. 22) two wires. The support must be quite secure and not yield at all to the pull exerted upon it. At a convenient height attach a scale to one wire and a vernier to the other —see diagram. Attach suitable hangers for weights to the ends of the wires. Add weights to each wire to remove any irregularities, and see that the vernier will give readings on the scale. Take the vernier reading and find the length of the wire carrying the vernier from its support to the zero mark on the vernier. Load the measured wire with successive kilogram weights, taking the vernier reading after each addition—a total of about 9 kg. is convenient. Unload kilogram by kilogram, and read the vernier at each stage.

Measure the diameter of the wire at several points along its length and find a mean value. This measurement must be done carefully with a micrometer screw-gauge.

Record and Calculation: Tabulate as follows:

Load in Kg.	Vernier reading		Mean	Extension in cm.
	Loading	Unloading		
w			x_0	
$w+1$			x_1	
$w+2$			x_2	
$w+3$			x_3	
$w+4$			x_4	
$w+5$			x_5	x_5-x_0
$w+6$			x_6	x_6-x_1
$w+7$			x_7	x_7-x_2
$w+8$			x_8	x_8-x_3
$w+9$			x_9	x_9-x_4
			Mean	

(w is the initial weight used to straighten the wire. The table should be extended if more than ($w+9$) kg. is used when loading).

Length of wire = cm.
Zero reading of micrometer screw-gauge . . cm.
Diameter of wire i . . . . . . cm.
ii . . . . . . cm.
iii . . . . . . cm.
iv . . . . . . cm.
Average cm.

From the last column of the above table we get the mean extension for 5 kg., then:

$$\text{Stress} = \frac{5\times 1{,}000\times 981}{\text{Area of cross section}}\ \text{dynes/cm.}^2$$

$$\text{and Strain} = \frac{\text{Mean extension}}{\text{Original length}}.$$

Calculate the modulus in dynes per cm.^{2}.

Experiment 9. Determination of Young's Modulus by Bending a Wooden Lath

Apparatus: Lath (or metre rule); knife edges for supporting it at each end; means of clamping one end—e.g. a G-clamp; vernier microscope or optical lever (see p. 49); weights and hanger.

THEORY

The bending of the bar can be produced by supporting it near the ends and hanging weights at the centre, or fixing it at one end and hanging the weights at the other end.

For the arrangement shown in Fig. 23 A, it can be shown that:

$$\text{Young's modulus} = \frac{wx^3}{4zy^3D}$$

where D is the depression
w is the force in dynes producing it
and the dimensions are as in the diagram.

For the arrangement in Fig. 23 B

$$\text{Young's modulus} = \frac{4wx^3}{zy^3D}.$$

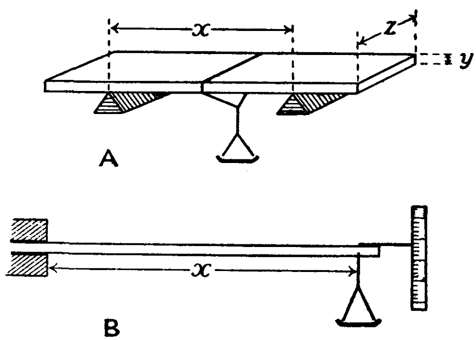


FIG. 23

FIRST ARRANGEMENT (A)

Procedure: A metre rule is a convenient lath to use—which for the first arrangement is supported on knife edges rigidly fixed in some supports. Failing some specially designed supports, triangular files may be secured in clamps. A light scale pan is slung from the centre of the rule by thread.

Find by trial a weight which will give a reasonable depression when added to the pan. Two centimetres is an ample depression. See that when the weight is removed the rule returns to its original position. For this purpose focus a vernier microscope on a marked point in the middle of the rule when in its position of rest, and see that the same reading is obtained before and after the weight is put on. (The optical lever may also be used but rather smaller depressions should be observed).

Make a fresh start and add small equal loads so that the maximum found in the above operation is reached in six stages. Follow the depression with the microscope, and take readings to give the depression of the centre for each added load.

Unload by the same equal stages, taking microscope readings at each stage.

Measure x, y, and z.

Record and Calculation: Tabulate the observations suitably (base your tabulation on that given in Experiment 8, p. 69). Calculate a mean value of w/D and substitute in the appropriate formula to find the value for Young's modulus.

SECOND ARRANGEMENT (B)

The procedure is like that for the first arrangement but the rule is clamped tightly at one end and the scale pan attached at the other, where also the observations of the depression are made, using the pointer and metre scale instead of the vernier microscope.

Experiment 10. Determination of Young's Modulus of a Solid in the Form of a Rod, using a Dust Tube

This experiment is mentioned here for the sake of completeness but until the experiments on 'Sound' have been reached it should be omitted. The details are as for Experiment 100 and the theory is given in Note (1) to that experiment on p. 233.

Experiment 11. Determination of the modulus of rigidity of the material of a rod by the static twisting method

Apparatus: Brass, aluminium or steel rods $\frac{3}{16}''$ in diameter and 20″ long; micrometer screw-gauge; large callipers; strong thin string; weights and hangers up to 3 kgm. by $\frac{1}{2}$ kgm. If a steel rod is used, the

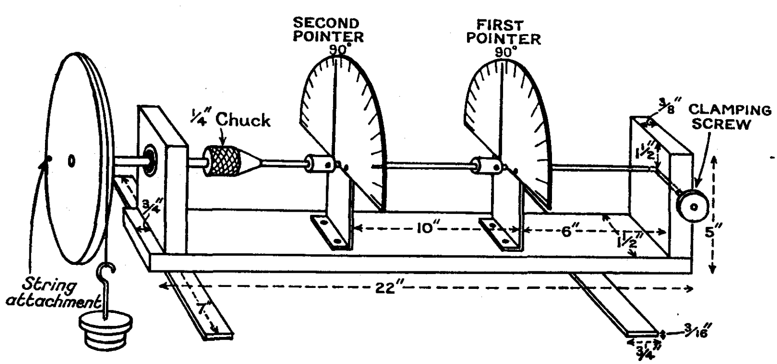


FIG. 24

weights required will be greater, since the modulus for steel is about three times that for aluminium. Standard apparatus as used for twisting a thin horizontal rod by means of a force applied through a large diameter pulley-wheel.

If not available the apparatus can be made from the following details. It forms a useful exercise in apparatus making and is capable of giving quite satisfactory results.

The support is made from $1\frac{1}{2}''$ by $\frac{3}{8}''$ mild steel, to the base of which two $\frac{3}{16}''$ thick mild steel strips, each 7″ long, are bolted to act as 'steadies'. The rod to be twisted fits into a $\frac{3}{16}''$ hole drilled in the support and is clamped by means of a 2 B.A. set screw working in a tapped hole as shown. The front bearing consists of a $\frac{3}{8}''$ wide ball-race, $1\frac{5}{16}''$ outside diameter and with a bore of $\frac{1}{2}''$. This is an easy fit in a hole drilled in the front support, being pushed in and out when the rods are changed. The dimensions of the ball-race are not critical, but its outside diameter must be greater than that of the chuck. The chuck* is 3-jaw $\frac{1}{4}''$, its threaded screw of diameter $\frac{3}{8}''$ being pushed through the ball-race for support, a short piece of copper tubing being used as a sleeve to take up the play in the bore.

The pulley-wheel is attached by two nuts on the threaded screw, or alternatively by soldering the threaded screw into a brass bush which is, in turn, screwed to the wooden pulley wheel.

Meccano brass collars with set screws are drilled out to $\frac{3}{16}''$ diameter and each fitted with a length of 18 S.W.G. brass wire, soldered flush with one end-surface. This can be done by making a light saw cut equal in depth to the diameter of the wire in the end of the collar nearer to the protractor. The outer end of the brass wire is flattened to produce a sharp-edged pointer, and adjusted to move closely over the scale as the rod twists. 6″ diameter protractors are fixed to $\frac{1}{8}''$ brass uprights and bolted to the base.

The large wooden pulley wheel can be turned on the lathe, the outside diameter being $6\frac{1}{2}''$ with a groove $\frac{1}{4}''$ deep round the periphery. Wood $\frac{1}{2}''$ thick can be used, but again these dimensions are not critical.

THEORY

When the rod is twisted statically in the above apparatus, it can be shown that the couple, C, required to produce a twist of θ radians is given by the expression:

$$C = \frac{\pi\eta r^4\theta}{2l}$$

where η is the modulus of rigidity,
r is the radius of the rod,
l is the length of the rod under twist,
θ is the angle of twist in radians.

Experimentally, the angle of twist is measured in degrees, so for an angle of twist of $\alpha°$

$$\theta \text{ radians} = \frac{\pi\alpha}{180} \text{ degrees.}$$

* Drills having suitable chucks are obtainable from Henry Squire and Sons Ltd, Willenhall, Staffs. The full description is: Squire hand-drill machine no. 1200, 0–$\frac{1}{4}''$ 3-jaw chuck. It costs about 10/- complete.

The couple exerted by the load acting at the circumference of the pulley-wheel is given by:

$$C = \frac{Mgd}{2}$$

where M is the load in gm.,
d is the diameter of the pulley wheel,
and g is the acceleration due to gravity.

Hence

$$\frac{Mgd}{2} = \frac{\pi^2 \eta r^4 \alpha}{360 l}$$

$$\therefore \quad \eta = \frac{Mgd \,.\, 360 l}{2\pi^2 r^4 \alpha}.$$

Procedure: Clamp the rod in the stand and ensure that it is firmly held in the jaws of the chuck. Set the pointers to the 90° marks on the protractors, and measure the distance between them, l cm.

Attach the string to an appropriate point on the circumference of the pulley wheel; add successive half kilogram weights, and read the position of each pointer after each addition. Unload in half kilogram steps, again taking the pointer readings. Measure the diameter of the rod at five or six different positions throughout its length, in each case taking two readings at right angles. Because in the equation the radius of the rod is raised to the fourth power, it is important that great care be taken in this micrometer measurement.

Using the callipers, measure the diameter of the pulley-wheel at the position of the string. If the string is thick, make the necessary allowance for it.

Record and Calculation: Tabulate the results as follows:

Load (kgm.)	Pointer readings (degrees)				Twist in degrees at	
	1st pointer		2nd pointer			
	Loading	Unloading	Loading	Unloading	1st pointer α_1	2nd pointer α_2

Length of rod undergoing twisting:

Reading at first pointer . . . . . . cm.
Reading at second pointer . . . . . . cm.
Zero reading of micrometer . . . . . . cm.

Diameter of rod:

(i) (*a*)	(*b*)	cm.
(ii) (*a*)	(*b*)	cm.
	etc.	

Mean diameter (allowing for zero error) . . . . cm.
Diameter of pulley wheel . . . . cm.

Plot on the same axes graphs of M against (i) α_1, (ii) α_2, (iii) $(\alpha_1 - \alpha_2)$. Determine from each, the gradient $\frac{M}{\alpha_1}$, $\frac{M}{\alpha_2}$, $\frac{M}{\alpha_1 - \alpha_2}$, respectively. The third case will correspond to a twisted length of the distance apart of the pointers. This will be the most reliable determination as any 'give' at the clamped end would affect the other two.

Substitute the gradients and the appropriate twisted lengths in the formula given above to obtain three values for η. If there is a significant difference between the value obtained using $\frac{M}{\alpha_1 - \alpha_2}$ and the other two, then these should be discarded as unreliable and the single value accepted.

Experiment 12. Determination of the Modulus of Rigidity of the Material of a Wire

Apparatus: A heavy rectangular bar of dimensions about 15 cm. × 3 cm. × 2 cm., with supporting wire securely fixed to the centre of one of the largest faces (preferably by soldering); stop-watch; micrometer screw-gauge.

THEORY

For the arrangement described above it can be shown that

$$T = 2\pi\sqrt{\frac{2l.I}{\pi\eta r^4}}$$

where η is the modulus of ridigity,
r is the radius of the wire,
l is the length of the wire,
T is the time of vibration of the bar when oscillating through small amplitudes in a horizontal plane,
and I is the moment of inertia of the bar about the axis of suspension (see p. 89).

Procedure: Set up the apparatus, making sure that the upper end of the wire is clamped in a support that cannot yield. This can with advantage be an 'Eclipse' pin-chuck or a similar device, so that the length of the wire which is twisting can easily be varied.

Adjust the length of the wire to be about a metre—or as long as possible with the apparatus available—and obtain three concordant observations of the time taken for a suitable number of oscillations of the bar. Note also the length of the wire used.

Shorten the length being twisted by drawing it through the chuck and reclamping. Repeat the observations. Obtain a set of observations for about six different lengths of wire, covering the available range as fully as possible.

Make the observations which are necessary to enable a value for the moment of inertia of the bar to be calculated—use Routh's Rule (p. 89). When weighing the bar you may assume that the mass of the wire may be neglected, and there is therefore no need to remove the wire from the bar for this process. (If another specimen of the wire is available its mass per unit length can be determined and a correction applied by measuring the length of the wire used in the experiment.) Make a series of observations of the diameter of the wire with the micrometer screw-gauge, and measure the length of the wire.

Record and Calculation: Tabulate your observations and plot a graph of l as ordinate against T^2. The gradient of this line will be $\frac{\eta r^4}{8\pi I}$, from which, knowing r and I, η can be calculated.

Experiment 13. Determination of the Coefficient of Restitution of a Steel Ball Bouncing on Steel

Apparatus: Small steel ball (e.g. out of a ball bearing); electro-magnet with switch and supply; stop-watch. (If the steel ball etc. are not available, the experiment can be performed using a good quality table tennis ball bouncing on a smooth table and released by hand).

THEORY

If a ball drops from a height (h_1) on to a plane, it will not return to its starting point, but will bounce to a height (h_2), owing to loss of energy due to the production of heat, etc., at the time of contact.

From the equation

$$v^2 = u^2 + 2gs$$

we see that:

Velocity with which ball strikes the plane $= \sqrt{2gh_1}$

Velocity with which it leaves the plane $= \sqrt{2gh_2}$

and by definition $\sqrt{2gh_2} = e \times \sqrt{2gh_1}$

where e is the coefficient of restitution.

Therefore

$$h_2 = e^2 h_1$$

In general

$$h_{(n+1)} = e^{2n} h_1 \quad \ldots \quad \text{(i)}$$

where $h_{(n+1)}$ is the height reached after the nth bounce

i.e.,
$$e = \left[\frac{h_{n+1}}{h_1}\right]^{\frac{1}{2n}}$$

Procedure: Use a steel ball and allow it to fall from a measured height on to a piece of steel which has been carefully levelled. The electromagnet should be used to hold the ball. A number of observations should be made to obtain an average value for the height reached after the first bounce.

Then repeat to find the height of the second bounce, then the third and so on.

Record and Calculation: Tabulate:

h_1	h_2	$\sqrt{\frac{h_2}{h_1}} = e$
h_1	h_3	$\sqrt[4]{\frac{h_3}{h_1}} = e$
h_1	h_4	$\sqrt[6]{\frac{h_4}{h_1}} = e$
etc.		

Find the average value of the last column.

Note: An alternative method is to release the ball and find the time for the bouncing to die out completely. The ball settles down quite suddenly. A slightly concave surface of steel is an advantage if available. Using a number of different initial heights the corresponding values of the time taken for the bouncing to die away completely should be obtained.

If when the ball is released from a height h_1 cm. the time taken for the bounces to die out completely is T secs.,
then
$$T = \frac{1+e}{1-e}\sqrt{\frac{2h_1}{g}}.$$

If the values of h_1 are plotted against corresponding values of T^2 we can deduce a value for $\left(\frac{1+e}{1-e}\right)^2 \cdot \frac{2}{g}$ and hence, by assuming a value for g can find e.*

* The proof of the relationship quoted is to be found in *Intermediate Mechanics*, by D. Humphrey, in Chapter III of the 'Dynamics' section. (It is one of the worked examples.)

CHAPTER VII

FORCES AND MOMENTS

Experiment 14. Verification, for Forces, of the Parallelogram Law for the Addition of Vector Quantities

Apparatus: Three sets of weights (1—1,000 gm.) with hangers; two pulleys; drawing board; several sheets of drawing paper; No. 35 thread.

Procedure: Arrange pulleys, weights and strings in front of a sheet of drawing paper pinned to a board, as shown in Fig. 25.

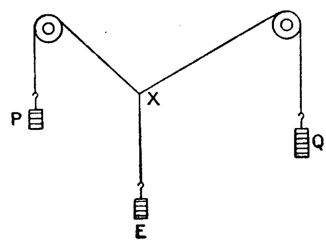


FIG. 25

See that the pulleys run with as little friction as possible, that they both turn in one vertical plane, and the knot in the thread at X is a neat one. Put convenient weights on the hangers *P*. *Q*, and *E*, and allow the system to come to rest. Mark the direction of the threads by two dots placed immediately beneath them and as far apart as convenient, using a plane mirror placed behind the threads to enable you to avoid errors due to parallax (see p. 28).

Record the weights on *P*, *Q*, and *E*, which must include the weight of whatever form of hanger is used.

Repeat several times using different weights and a fresh piece of paper each time.

For each record draw lines through the dots to show the direction of the three forces exerted by *P*, *Q* and *E*.

Record and Calculation: The three forces are in equilibrium and *E* is the equilibrant of *P* and *Q*. It should therefore be equal and opposite to the resultant of *P* and *Q*.

Record your results in a number of small labelled diagrams. Find the resultant for each pair of values of *P* and *Q* by drawing a parallelogram of forces. Express the result as a force in gm.wt. together with a direction measured in degrees from the vertical. Compare these results with the corresponding observed values of E—the angle of which to the vertical is of course always zero. Set out your results in a table as follows :

Experiment No.	Resultant			Difference in magnitude expressed as a percentage of E
	Magnitude		Angle found from parallelogram	
	E	Found from parallelogram		

Note: A useful exercise which is an extension of this experiment is the determination of an unknown weight. The later replaces E and, if P and Q are known, the unknown can be found.

Experiment 15. Verification, for Forces, of the Polygon Law for the Addition of Vector Quantities

Apparatus: Five or six sets of weights (up to 500 gm. each) with hangers; four or five pulleys; drawing board and paper.

Procedure: The verification is carried out as in Experiment 14 above except that more pulleys and weights are used so that more than three forces in equilibrium are considered. One of the forces is applied without the use of a pulley and thus acts vertically downwards; this may conveniently be regarded as the equilibrant of all the others.

Record and Calculation: Label your diagrams as in Experiment 14 and for each result construct a polygon of forces to find the magnitude and direction (expressed as an angle made with the vertical) of the resultant. Compare the values so obtained with the observed equilibrants and summarise the results in a table like that above.

Experiment 16. Determination of the Resultant of Like Parallel Forces and Verification of the Principle of Moments

Apparatus: Specially drilled metre rule (see below; several sets of weights (up to 500 gm.) with hangers.

Procedure: Bore a small hole near the edge of a metre rule about 6 cm. from the centre. Find the centre of gravity of the rule by a careful balancing experiment and note its position. (A knife edge should be used for this). Weigh the rule.

Fit up the arrangement shown in Fig. 26. Supporting the rule by a thread passing through the hole. Loops of thread should be used to support the hangers which carry the weights. Adjust the position of the weights until the rule is horizontal. Note and record the points of application of all the forces acting on the rod, including its weight acting through the centre of gravity.

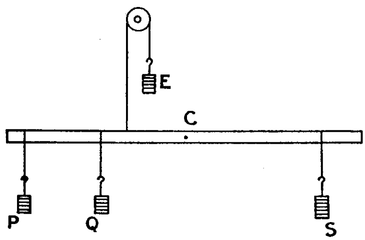


FIG. 26

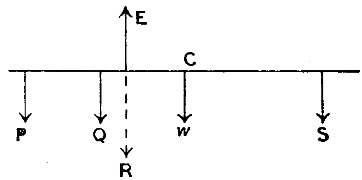


FIG. 27

Repeat several times, varying the values and positions of weights suspended from the rod, making corresponding changes in the supporting weight.

Record and Calculation: Fig. 27 shows a force diagram for an experiment.

For any experiment the resultant of the like parallel forces acting downwards is equal to the upward force E supporting the rod, and

$$R = P + Q + S + \ldots . + w,$$

where

R is the resultant
P, Q, S, etc., are the forces
w is the weight of the rule.

Tabulate thus:

Experiment	Value of R		Difference (as % of calculated value)
	Calculated	Found	

The Principle of Moments states that taking moments about any point:

(Sum of moments in clockwise direction)=
(Sum of moments in anti-clockwise direction).

Take moments about the centre of gravity, and tabulate:

I

Experiment	1	2	3	4
Value of P . . .				
Distance from c. of g. .				
Moment about c. of g. .				
Value of Q . . .				
Distance from c. of g. .				
Moment about c. of g. .				
Etc.				

II

Experiment	Sum of clockwise moments	Sum of anti-clockwise moments	Difference expressed as a % of one of the values

CHAPTER VIII

FRICTION

Experiment 17. Determination of the Coefficient of Statical Friction between two Wood Surfaces

Apparatus: Rectangular wooden block dimensions about $10'' \times 4'' \times 3''$ and with well-planed and smoothed base; well-planed and smoothed wooden surface for this to slide over—that used in Fletcher's trolley apparatus (if of wood) will serve; pulley; set of weights and hanger.

Procedure: Set up the apparatus as shown in Fig. 28. Place weights on the hanger until the block just begins to slide and then reduce them until it just fails to slide. Record this final weight, including that of the hanger. Weigh the block. Repeat the experiment loading the block with various masses, making sure that the same stretch of the baseboard is used for all experiments.

Record and Calculation: Tabulate your results and find the values of reaction forces (R) and the applied horizontal forces (F). Plot F against R and find the coefficient of statical friction from the graph, using the fact that

$$\frac{F}{R} = \mu \text{ (the coefficient of statical friction).}$$

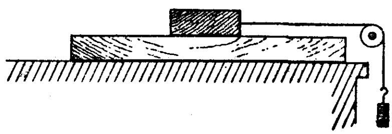


FIG. 28

Notes: (1) An alternative method consists in placing the block on the plane without any pulling force applied in the way described above. The plane is then tilted until the block just fails to slide down under the action of gravity. The angle made by the plane with the horizontal (α) is measured—actually it will probably be simpler to measure its complement using a plumb line—and the coefficient of friction is found from tan α, or cot $(90° - \alpha)$.

(2) Whichever method is used, considerable difficulty will be experienced in obtaining consistent results.

Experiment 18. Determination of the Coefficient of Dynamical Friction between Two Wood Surfaces

Apparatus: As for Experiment 17.

THEORY

In the previous experiment (No. 17) we considered statical friction—i.e. considered the case just before motion occurred. Experience shows that once motion has started the frictional resistance falls to a value somewhat less than that which applied when the body was stationary. The experiment aims at determining the ratio of the friction force to the reaction when movement is just maintained. This ratio is known as the coefficient of dynamical friction.

Procedure: The experiment is performed as in Experiment 17, using either of the two methods given, but the force measured is not that which is applied to the block just before motion occurs but that which is necessary just to move the body with uniform speed.

Record and Calculation: Tabulate the results and calculate a mean value for the required coefficient.

Note: Consistent results are difficult to obtain by this method.

Experiment 19. Determination of the Efficiency of a Pulley System

Apparatus: Two sets of weights and hangers; several pulleys; two pairs of sheaved pulleys.

Procedure: In Fig. 29 several different pulley systems are illustrated. Fit up one of these and balance the load which you put on by an effort consisting of weights on a hanger. Record the values of the load and the effort. Repeat, using a wide range of loads, recording corresponding values of the load and the effort. Set up a pulley system of different velocity ratio and repeat the experiment.

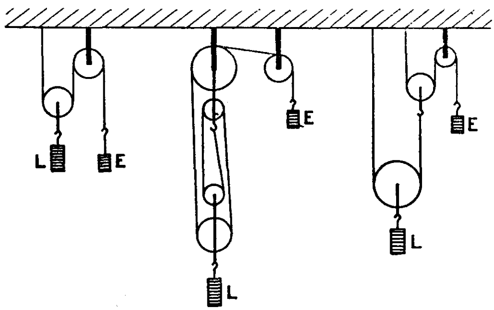


FIG. 29

Record and Calculation: Make a diagram of the system you use and calculate the velocity ratio by considering the number of pulleys and how they are arranged.

Tabulate your observations for each pulley system thus:

Load	Effort	M.A. = $\frac{\text{Load}}{\text{Effort}}$	V.R.	Efficiency % (M.A./V.R.) × 100

Plot efficiency against load and discuss the result.

Experiment 20. Determination of the Efficiency of a Screw Jack

Apparatus: SCREW JACK; set of weights and hanger.

Procedure: Fit up the jack as shown in Fig. 30 and make the effort just sufficient to move the load. Repeat with various weights for loads. Measure the diameter of the screw head and the pitch of the screw. The pitch is best measured by finding the distance between one thread and a corresponding point on a thread, say, ten threads away—one-tenth of this distance will be the pitch.

Record and Calculation: From the diameter, d, of the screw head and the pitch of the screw, p, measured in the same units, calculate the velocity ratio from the formula

$$\text{V.R.} = \frac{\pi d}{p}.$$

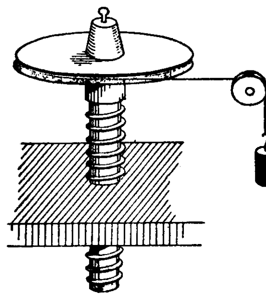


FIG. 30

Tabulate your observation as in Experiment 19 and plot efficiency against load. Discuss the significance of the graph.

Notes: (1) It is instructive to perform the above experiment first with the thread quite dry and secondly with it well oiled. The importance of efficient lubrication of machines will be admirably demonstrated.

(2) If a screw jack is unobtainable a suitable machine can be made from Meccano parts—e.g. a worm wheel drive.

Experiment 21. Determination of the Efficiency of a Series Wound Electric Motor

Apparatus: SPECIALLY PREPARED EQUIPMENT is needed as described below, and shown in Fig. 31.

The belt B is made of asbestos or leather and arranged to hang in a loop in which the pulley of the fractional H.P. motor can be placed. The two ends of the belt are fastened to spring balances, S_1, S_2, graduated in lb. wt.

Some arrangement is required for tightening the belt so that it will act as a brake on the pulley and the braking effect can be varied. The figure shows a simple arrangement for this, consisting of a rigid frame. The screws X and Y, to which the spring balances are fastened, can be raised or lowered and so increase or decrease the pull of the belt on the pulley. When the belt is hanging free the two balances should give the same readings. Some form of revolution counter should be attached to the motor.

A is an ammeter in the circuit which supplies the motor.

V is a voltmeter connected across the terminals of the motor.

THEORY

The fundamental definition of efficiency is the ratio:

$$\frac{\text{Output of energy}}{\text{Input of energy}}.$$

The energy put into the machine is supplied by the electric current, and can be expressed as a horse-power. The power supplied by an electric current is calculated from the formula:

$$\text{H.P.} = \frac{\text{Volts} \times \text{Amperes}}{746}.$$

The output can be found by a measurement of the 'brake horse-power' exerted by the motor, i.e. the horse-power developed when the motor is working against the frictional force of a brake, introduced by the belt round the shaft. If the belt is kept stationary, so that the shaft slips within it, then there will be a difference in tension on the two sides of the belt. If this difference is P pounds weight, the number of revolutions per minute is N, and d is diameter of the pulley in feet:

Then brake horse-power developed $= \dfrac{P\pi dN}{33{,}000}$

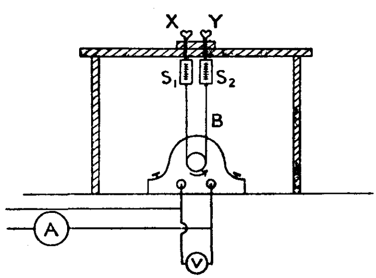


FIG. 31

Procedure: Loosen the belt so that it is hanging free. Start the motor. You will need help to carry out the following operations quickly, so that the various readings are made as nearly as possible simultaneously:

(i) Tighten the belt until it comes into contact with the pulley. One observer should watch the belt and keep it steady.

(ii) Read the voltmeter, the ammeter, and the tensions recorded on the balances.

(iii) Find the number of revolutions per minute. This must be done with the load on.

(iv) Loosen the belt and, if necessary, allow it to cool before doing another experiment.

Repeat the experiment several times with different loads on the motor, i.e. tighten the belt each time. Measure the diameter of the pulley in feet.

Record and Calculation: Tabulate:

Diameter of Pulley $= d$ ft.

Brake horse-power					Energy supplied			Efficiency%
Tension of S_1	Tension of S_2	Difference $=P$	Revolutions per min. (N)	B.H.P. $= \frac{P \times \pi \times d \times N}{33{,}000}$	Volts $=V$	Amp. $=A$	H.P. $= \frac{V \times A}{746}$	$= \frac{100 \times \text{B.H.P.}}{\text{H.P. supplied}}$

Plot efficiency against load, and discuss the result. Plot also B.H.P. against applied volts.

CHAPTER IX

MASS AND INERTIA

Experiment 22. Demonstration of the Truth of the Equation 'Force=Mass × Acceleration', using Fletcher's Trolley

Apparatus:

A brief examination of Fletcher's Trolley should indicate how it works. The 'trolley' can be given various masses by means of removable weights carried in it. The metal lath, when vibrating, executes simple harmonic motion; it thus has a constant periodic time and can be used as a timing instrument. Some laths have the periodic time stamped on them but often this is not the case and an arbitrary time scale is then used—this does not affect the results of the experiment. The brush at the end of the lath should be inked with red ink—this runs more smoothly than blue ink—and it is adjusted to give as fine a trace as possible on a piece of drawing paper pinned to the top face of the trolley. This paper should never be pinned on while the trolley is standing on the base board, as if the latter is of wood it will be made uneven by the pressure transmitted to it through the wheels.

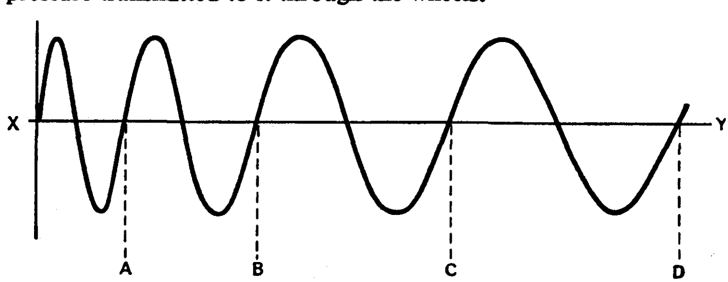


FIG. 32

THEORY

When the trolley is accelerated beneath the vibrating lath the trace obtained will be as shown in Fig. 32. The line XY gives the mean position of the brush and the wave trace will be intersected at equal intervals of time by this line at the points A, B, C, D etc. Thus the acceleration (measured in arbitrary units) is

$$BC-AB = DC-BC = \text{etc.}$$

It is recommended that whole periods not half periods are analysed, for if XY is slightly displaced, as shown in Fig. 33, it is easily possible for $BB'-A'B$ to equal zero giving apparently no acceleration in this half period. If whole periods are examined it does not matter where XY is drawn so long as it is parallel to the mean line. For ease of measurement, however, it should be fairly close to the mean position so that the trace intersects it at the largest possible angle. A further point about this line XY is that it need not be drawn using the stationary brush but may be put in by the experimenter using a ruler and pencil after the trace has been removed from the trolley. It can then be placed to the best advantage.

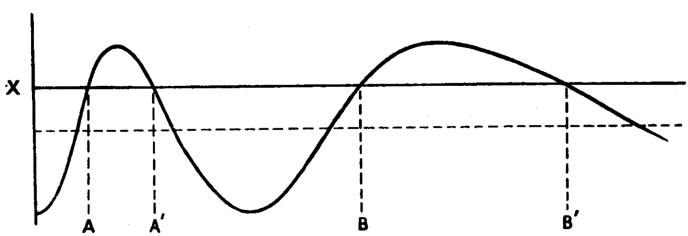


FIG. 33

PART I. VERIFICATION THAT THE ACCELERATION PRODUCED BY A GIVEN FORCE IS PROPORTIONAL TO THE RECIPROCAL OF THE MASS MOVED

Procedure: Start with all the weights in the trolley—i.e. so that it has its maximum mass—and arrange it as shown in Fig. 34.

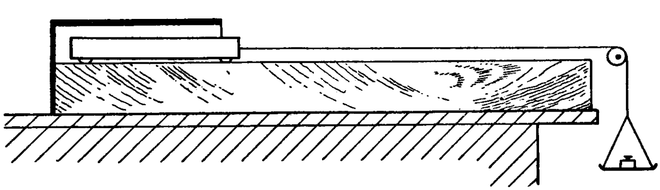


FIG. 34

Find the mass of the trolley plus string and scale pan.

Add just sufficient weights to the pan to move the trolley with uniform velocity, i.e. produce a wave trace with a constant wave length. It is necessary to produce this wave trace, measure the wave lengths and repeat until they are constant.

Add a small additional weight, w, to the pan—sufficient to produce a small though measurable acceleration (this weight is the 'given force' and will later be used to accelerate the trolley when its mass is much less, i.e. when the acceleration is much greater. Hence it is necessary to keep w as small as conveniently possible). Determine the acceleration produced.

Remove all weights from the pan and alter the mass of the trolley by removing one of the cylinders from the side. Find again a small weight necessary to produce uniform motion; add the same additional weight w, and find the acceleration.

Continue the variations of mass of the trolley and for each find the acceleration, using each time the same additional weight to produce the resultant force acting on the moving system.

Record and Calculation: Tabulate the observations obtained from the traces in a manner convenient for calculating the mean value of the acceleration produced in each mass by the given force. Transfer these values of the acceleration to the table below:

Experiment	1	2	3	4	5	
Mass of trolley, string and pan						
Mass of weight to overcome friction						
Mass of pulling weight . .						
Total mass moved . . .						
Acceleration produced . .						

Plot acceleration against the reciprocal of the mass moved—remembering that this must include that of the scale pan and ALL the weights in it. If the equation is true the graph should be a straight line.

PART II. VERIFICATION THAT THE ACCELERATION OF A GIVEN MASS IS PROPORTIONAL TO THE FORCE PRODUCING IT

Procedure: The experiment is carried out in a manner similar to Part I but the mass of the moving system is maintained constant and the pulling weight varied, the acceleration being determined for each value of the latter. The alteration of the pulling force must not effect an alteration of the total mass of the moving system, i.e. weights must be moved from the trolley to the pan. It is usually possible to stand the necessary weights on the trolley so that they do not interfere with the timing lath, and remove them one by one to the pan.

Record and Calculation: Make a suitable tabulation to enable you to calculate the acceleration corresponding to each pulling force Plot force against acceleration—a straight line shows that the results are consistent with the equation.

Experiment 23. Determination of the Moment of Inertia of a Thin Wooden Lath about a Given Axis

Apparatus: A metre rule is a convenient lath. Bore a hole a few cm. from one end, and insert a short length of glass tubing into it, making a tight fit. File a knitting needle to a knife edge (finishing it with a carborundum slipstone) and clamp it rigidly in a horizontal position. This can be slipped through the glass tube and forms a good axis about which the rule can swing. A stop-watch is also required.

THEORY

When a body is rotating, those of its particles which are on the axis of rotation do not move through space. All other particles move round the axis with velocities proportional to their distances from the axis.

It can be shown that if m_1, m_2, m_3 . . . are the masses of particles which are r_1, r_2, r_3 . . . respectively from the axis, then:

$$\text{Kinetic energy of the body is } \tfrac{1}{2}\omega^2\Sigma(mr^2).$$

where ω is the angular velocity of the body measured in radians/sec.

The quantity $\Sigma(mr^2)$ stated in gm.-cm.^{2} or lb.-ft.^{2} is called the Moment of Inertia of the body about the axis of rotation.

It can further be shown that the periodic time of a body swinging in a vertical plane about an axis is given by

$$T = 2\pi\sqrt{\frac{I}{mgh}},$$

where h is the distance of the axis from the centre of gravity,
m is the mass,
I is the moment of inertia about the axis of rotation,
T is the periodic time,
g is the acceleration due to gravity.

Moments of inertia (I) about axes of symmetry may be calculated using the following formulæ which are in accordance with Routh's Rule:

Rectangular Bar, about an axis through the centre of gravity perpendicular to one face

$$I = M\left(\frac{a^2+b^2}{3}\right),$$

where M is the mass of the bar,
$2a$ is the length of the face,
$2b$ is the breadth of that face.

Cylinder, about an axis perpendicular to its length:

$$I = M\left(\frac{l^2}{3}+\frac{r^2}{4}\right),$$

where $2l$ is the length
r is the radius.

An alternative method of defining the moment of inertia is by reference to the 'Radius of Gyration', k, which is defined by the equation

$$I = mk^2$$

where I is the moment of inertia of the body, and
m is the mass of the body.
The value of k applies only to the axis which is considered for I and will vary with the axis of rotation.

Procedure: Find the centre of gravity of the rule by a careful balancing experiment. Hang the rule on the knife edge and find the time of 50 swings (see p. 51). The amplitude (half the angle of swing) must be small—the smaller the better, and it certainly must not exceed 10°.

Measure the distance between the axis of rotation and the centre of gravity (h). Weigh the rod and measure its length and breadth.

Record and Calculation: Tabulate observations and substitute in

$$T = 2\pi\sqrt{\frac{I}{mgh}}$$

to calculate value of I.

Check the results by calculating the moment of inertia from

$$I = m\left(\frac{l^2+b^2}{3}\right) + mh^2,$$

where m is the mass of lath,
$2l$ is the length,
$2b$ is the breadth,
which is obtained from considering Routh's rule and the theorem of 'parallel axes.'

Calculate also the radius of gyration about the axis of rotation and about an axis through the centre of gravity.

Experiment 24. Determination of the Moment of Inertia of a Bicycle Wheel about its Axle

Apparatus: BICYCLE; stop-watch, copper wire.

Procedure: Set up a bicycle so that the front wheel turns freely. Add masses—copper wire is convenient to use—to balance the weight of the valve so that the wheel will come to rest in any position. Fix a small mass (m) to one of the spokes. Measure the distance (d) of this mass from the axis of rotation. Displace the wheel through a small angle and find the period (t) of its vibration as accurately as possible (see p. 51).

Find the periodic times for a series of values of m.

Record and Calculation: Tabulate your observations, and find the moment of inertia from each set of observations by substituting in

$$I = \frac{mgdt^2}{4\pi^2} - md^2$$

where I is the required moment of inertia,
and g is the acceleration due to gravity.

Calculate the mean of your results.

Alternatively plot t^2 against $1/m$ and deduce the result from the graph.

Experiment 25. Determination of the Moment of Inertia of a Flywheel

Apparatus: The flywheel is usually a permanently mounted fitting in the laboratory. In addition weights, a hanger, and a stop-watch are required.

THEORY

The flywheel is accelerated from rest by a weight attached to a string which is in its turn attached to a point near the edge of the flywheel. It is arranged so that the string becomes detached when the weight has fallen a suitable distance—usually to the floor—and the flywheel is allowed to come to rest under the action of the friction couple in the bearings.

Let m be the mass of the suspended load, in gm.,
h be the distance it falls in cm.,
t sec. be the time taken for this descent,
v cm./sec. be the velocity of m after t sec.,
I gm.cm.^{2} be the moment of inertia of the flywheel,
ω rad./sec. be the angular velocity of the flywheel when the string becomes detached,
N be the number of revolutions made in time t sec.,
n be the number of revolutions made after the accelerating force has been detached,
f be the work done against friction in each revolution,
and r be the distance from the axis of revolution to the point at which the string is attached, in cm.

Then the energy given to the flywheel by the mass m will be $mgh - \frac{1}{2}mv^2$.

This is used to endow the flywheel with kinetic energy and to do the work against friction;

Hence $$mgh - \tfrac{1}{2}mv^2 = \tfrac{1}{2}I\omega^2 + Nf \quad \ldots\ldots (1)$$

Also $$\tfrac{1}{2}I\omega^2 = nf \quad \ldots\ldots (2)$$

Eliminating f between (1) and (2) we obtain,

$$m\left(gh - \frac{v^2}{2}\right) = \frac{1}{2}I\omega^2\left(\frac{n+N}{n}\right) \quad \ldots\ldots (3)$$

Now $\omega = \dfrac{v}{r}$,

$$\therefore \quad m\left(gh - \frac{v^2}{2}\right) = \frac{1}{2}I\frac{v^2}{r^2}\left(\frac{n+N}{n}\right) \quad \ldots\ldots (4)$$

By considering the motion of m we obtain,

$$h = \frac{v}{2} \cdot t$$

$$\text{i.e., } v = \frac{2h}{t}.$$

Substituting for v in equation (4) and simplifying we obtain

$$I = \frac{mt^2r^2}{2h}\left(g - \frac{2h}{t^2}\right)\left(\frac{n}{n+N}\right) \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The experiment reduces to a determination of all the quantities appearing on R.H.S. of equation (5).

Procedure: Arrange the apparatus as described in the first paragraph of the section on theory above, taking care to ensure that the string becomes detached as the weight hits the floor. Choose a suitable value for m so that the time of fall can readily be observed. Make a chalk mark on the edge of the flywheel to facilitate counting revolutions.

Spin the flywheel by hand for at least five minutes in order to warm the bearings*; if this is not done, the friction couple will not remain constant during the experiment.

When all is ready, raise the weight to the starting position and release it, starting the watch at the same instant. When the string becomes detached, stop the watch but concentrate on the chalk mark on the flywheel so that the number of revolutions which it makes before coming to rest can be counted. Repeat several times. If inconsistent results are obtained they may be caused by variation in the friction couple, further preliminary spinning possibly being required.

Alter the value of m slightly and repeat.

Observe the value of h and take the necessary observations to enable as accurate a value of r as possible to be deduced.

Record and Calculation: Record for each value of m used, the time of fall, the height, h, the value of m (including the hanger) and the value of n. Record also the observations taken to obtain a value of r and calculate its value. Deduce a value of N from the expression

$$N \times 2\pi r = h$$

(This will be more accurate than counting N).

For each experiment calculate the average time and the average value of n. Substitute in the equation (5) above to obtain a value of I.

Calculate the average value of your results.

Experiment 26. Determination of the Acceleration due to Gravity, using a Rigid Pendulum

Apparatus: Most laboratories have special apparatus available for this experiment. It often consists of a metal bar, about a metre long,

* If a 'viscostatic' lubricant is used this will not be necessary.

drilled with holes at equal intervals and provided with knife-edge supports so that it can be suspended at various distances from the centre of gravity. Another form provides for the variation of the point of support by means of a carriage, to which the knife edge is attached, and which slides along the bar. This carriage can be clamped in any desired position.

A stop-watch is also required.

THEORY

The periodic time of a rigid pendulum is given by the equation:

$$T = 2\pi\sqrt{\frac{h^2+k^2}{gh}}$$

where T is the periodic time in seconds,

h is the distance of the knife-edge support from the centre of gravity of the pendulum, in cm.,

k is the radius of gyration about an axis through the centre of gravity, in cm.,

g is the acceleration due to gravity in cm./sec./sec.

This equation can be rewritten

$$T^2h = \frac{4\pi^2}{g}\cdot h^2 + \frac{4\pi^2 k^2}{g}.$$

Since g and k are constants a graph of T^2h against h^2 will be a straight line with gradient $4\pi^2/g$. The intercept on the axis of T^2h will be $4\pi^2k^2/g$. Thus both g and k can be deduced from this graph.

Procedure: Find the centre of gravity of the pendulum—do not include the knife edge or carriage in this operation.

Support the pendulum with the knife edge at the greatest convenient distance from the centre of gravity and note this distance. Observe the time for a suitable number of oscillations of small angle. Repeat twice, or until consistent observations are obtained in accordance with the instructions given on p. 51. Repeat these observations with the knife edge in at least eight different positions, well spaced along the half-length of the pendulum.

Record and Calculation: Record your observations in a suitable table, including in it columns for the calculated values of T^2h and h^2. Plot a graph of T^2h against h^2 and deduce values for the acceleration due to gravity, and the radius of gyration about the centre of gravity, from the graph.

Notes: (1) If no apparatus is available, moderately satisfactory results can be obtained using a metre rule drilled symmetrically at intervals of 4 cm.

(2) It is also of interest to plot T against h for both positive and negative values of h (i.e. for points of support on both sides of the centre of gravity). A pair of curves symmetrical about the T-axis should be obtained which show minima at $h=\pm k$. The justification for this

statement and further discussion is to be found in theoretical text-books. There is little point in deducing values of g and k from these curves if the method described above has been used.

Experiment 27. Determination of the Acceleration due to Gravity, using a Kater's Pendulum

Apparatus; Kater's pendulum; simple pendulum; stop-watch.

THEORY

It can be shown theoretically that for any rigid body there are two points within it about which it will have the same periodic time of swing. These two points may be situated asymmetrically with regard to the centre of gravity of the body. Further, the distance between these two points is the length of an equivalent simple pendulum, i.e. one having the same periodic time, but without the defects due to its construction.

Kater's pendulum is an instrument designed to find these two points in a compound pendulum, i.e. a rigid body supported so that it will swing about a horizontal axis, the points being situated asymmetrically about the centre of gravity. The pendulum consists essentially of a metal bar which has two knife edges turned inwards towards the centre of gravity and fitted with adjustable weights. In most instruments the knife edges are also adjustable. The instrument available should be examined.

The strict use of Kater's pendulum entails the adjustment of the knife edges or the weights until the periodic time is the same whichever knife edge is used to support the bar. This is a very tedious and lengthy operation and a simplification is usually employed by using Bessel's formula. For this the adjustments are made so that the times of vibration about the two knife edges are reasonably close, and the exact times of vibration are determined for both positions. If t_1 and t_2 are the periodic times for positions of the knife edges, l_1 and l_2 respectively from the centre of gravity, then:

$$\frac{8\pi^2}{g}=\frac{t_1^2+t_2^2}{l_1+l_2}+\frac{t_1^2-t_2^2}{l_1-l_2}.$$

Now (l_1+l_2) is the distance between the two knife edges and can be measured directly with considerable accuracy. The accuracy of the measurement (l_1-l_2) depends on the accuracy with which the centre of gravity can be located, and no methods for doing this with any great degree of accuracy are available.

But the term $\dfrac{t_1^2-t_2^2}{l_1-l_2}$ will be small because the values of t_1 and t_2 have been made very nearly equal, and so an approximate knowledge of the position of the centre of gravity will suffice.

Procedure: Support the pendulum from one of the knife edges and set it swinging. Arrange a simple pendulum so that it swings with the same periodic time as the Kater's pendulum.

Measure the length of the simple pendulum, and fix the second knife edge at this distance from the first. Reverse the pendulum and swing it from the second knife edge.

This adjustment will have altered the period of swing, and the simple pendulum should be altered in length to correspond. Now a further small alteration of the other knife edge will be necessary, after which it will be found that the times of swing for both knife edges are approximately the same. (If the knife edges are not adjustable, the periods of vibration about them are made nearly equal by adjusting the weights.)

Determine accurately the times of swing for both knife edges (see p. 51).

By balancing the pendulum on a knife edge find the position of the centre of gravity.

Measure the distance between the two knife edges and the distance of each from the centre of gravity.

Note that the knife edges must be at different distances from the centre of gravity. Equal periodic times may be obtained for two points for which $l_1 = l_2$ but the fact that l_1 shall not equal l_2 is an essential condition, assumed in the mathematical analysis.

Record and Calculation: Tabulate your results and substitute in Bessel's formula to obtain a value for g.

Note: If a Kater's pendulum is not available an approximate determination of 'g' can be made using a rigid pendulum with fixed knife edges—making all the necessary observations to substitute in Bessel's formula.

A suitable pendulum can be made from two 5-ft. lengths of 3″ × 2″ wood fixed together by two 6 in. nails so that the two parts are about 2 ins. apart. The nails should be driven in at points about 1 ft. and 2 ft. respectively from the centre of gravity (and on opposite sides of it) and should then be filed to knife edges with the sharp edge pointing towards the centre of gravity.

CHAPTER X

SURFACE TENSION

Experiment 28. Determination of the Surface Tension of a Liquid, using Searle's Torsion Balance

Apparatus: The torsion balance, which is usually available as an assembled unit, is an instrument which measures forces by the twist produced in a stretched wire.

A suitable form, designed by G. F. C. Searle, is shown in Fig. 35. Here AB is a light metal bar fixed to a clamp C. C is supported clamped on to a horizontal wire which is not shown as it is at right angles to the plane of the paper. This wire is in turn supported tightly by a metal stand which has three legs, two of which are in the same vertical plane as the wire whilst the third is vertically under the part AC of AB and is adjustable by means of a screw. R is a movable rider, N is a scale pan, P is a pointer and S is a scale.

A petri dish containing the liquid under investigation is placed under N, and a glass slide, attached to N, dips into the liquid.

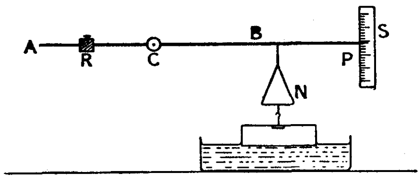


FIG. 35

A micrometer screw-gauge and a thermometer (0–100°C.) are also needed.

Procedure: Adjust the rider R until the arm AB is approximately horizontal.

Clean and dry the glass plate thoroughly (see p. 52). Place it in the holder and arrange it so that it dips in the liquid for about half a centimetre, and the liquid is clinging to it all round. The position is shown in the diagram.

Adjust the screw on the leg of the instrument until the plate just does not leave the liquid, i.e. the downward pull on the plate due to surface tension is just balanced.

Observe the reading of the pointer P on the scale S. Record the temperature of the liquid.

Remove the petri dish and carefully dry the glass plate, with a piece of clean filter paper, without removing it from the clip. Next place on N sufficient weights to depress P until it gives the same reading on the scale as it did when the surface tension force was acting.

Repeat several times to make a check on the readings. Measure the length and thickness of the glass plate.

Record and Calculation: Tabulate the observations and calculate the mean value of the weight which was put into the pan in the last operation. This weight is obviously equal to the force of surface tension acting along a line of length equal to the sum of twice the length and twice the thickness of the glass slide. Thus the surface tension in dynes per cm. at the observed temperature can be calculated.

Experiment 29. Determination of the Surface Tension of a Liquid by Measuring the Rise of the Liquid in a Capillary Tube

Apparatus: The liquid must be one which 'wets' glass—e.g. water, ethyl alcohol, benzene, ether, etc.—otherwise allowance will have to be made for the angle of contact. A capillary tube of uniform bore (see p. 55), a vernier microscope and a thermometer are also required.

THEORY

In Fig. 36 let

r be the radius of the capillary tube in cm.,

h be the height in cm. to which the liquid rises above the free surface of the liquid, the measurement being taken from the bottom of the meniscus.

Then it can be shown that if the angle of contact is zero (i.e. the liquid 'wets' the glass)

$$T = \frac{r}{2}\left(h + \frac{r}{3}\right)Dg$$

where T is the surface tension in dynes per cm.,

D is the density of the liquid in gm./cm^3.,

g is the acceleration due to gravity in cm./sec.^{2}

(The term $r/3$ is added to h to make an allowance for the volume of liquid above the bottom of the meniscus.)

Clearly if r is very small compared with h the expression approximates to

$$T = \frac{rh\,Dg}{2}.$$

Procedure: Test the capillary tube for uniformity of bore and measure its internal diameter (see p. 55). (This avoids the necessity for breaking the tube in order to measure the diameter at the level to which the liquid rises. It should be realised that it is only the diameter at this level that is of importance and, provided this is known, non-uniformity of bore does not affect the result.)

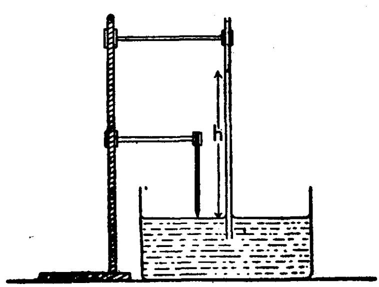


FIG. 36

Flush the liquid through the capillary tube, and then hold it vertically with its lower end dipping into a beaker of the liquid. Keeping the lower end below the liquid, move the tube up and down a few times to check that the meniscus in the tube remains at the same height above the open liquid surface. If this is not the case, the tube is dirty and should be cleaned with caustic soda solution as described on p. 52. It is useless to proceed with the experiment until the meniscus responds to this test. When you are satisfied with the cleanliness of the tube, fix it vertically with its lower end dipping into the liquid. See that there are no bubbles of liquid trapped in the tube above the meniscus.

Measure the height of the meniscus above the surface of the liquid in the beaker. Figure 36 indicates a good method of doing this. A piece of copper wire filed at one end to a point is adjusted so that the point just touches the surface of the liquid some distance away from the edge of the vessel. After taking a reading of the bottom of the meniscus in the tube using a vernier microscope, the beaker of liquid is removed, and a reading of the copper point is taken. Make several independent determinations of the capillary rise. Note the temperature of the liquid.

Record and Calculation: Tabulate observations:

(*a*) *Uniformity of Bore*

Successive readings of mercury thread.

End A	End B	Length
	Mean	

(*b*) *Radius of Tube*

Mean length of mercury thread . . . cm.
Mass of mercury+bottle . . . . gm.
Mass of bottle . . . . . . gm.

Mass of mercury . . . . . . gm.

Radius = cm.

(*c*) *Height of Column*

Meniscus level . . . . . . cm.
Level of liquid in the beaker . . . . cm.
Height, h . . . . . . cm.

Calculate the surface tension from the appropriate formula given above.

Experiment 30. Determination of the Surface Tension of Water by Jaeger's Method

Apparatus: The arrangement shown in Fig. 37 is required. A is a thick-walled capillary tube, of internal diameter about 0·5 mm., which dips into the beaker of water. (The use of a broader tube drawn out to a fine nozzle at the end is not recommended, as the bubbles break away from such a tube in groups. In this experiment the production of a steady stream of single bubbles from A is required.)

B is a manometer filled with water or some lighter non-volatile liquid (of known density). C is a reservoir of air of which the pressure can be altered by allowing water from a constant head apparatus to enter slowly through O. A tap T (or a screw clip) controls the rate of flow of water and therefore the pressure in C. S is for fine control. 5 cm. of capillary tube between S and the manometer will steady the flow.

A vernier microscope, or a cathetometer* may be used to measure the levels of the liquid in B if greater accuracy is sought.

A thermometer (0–100°C.) is also needed.

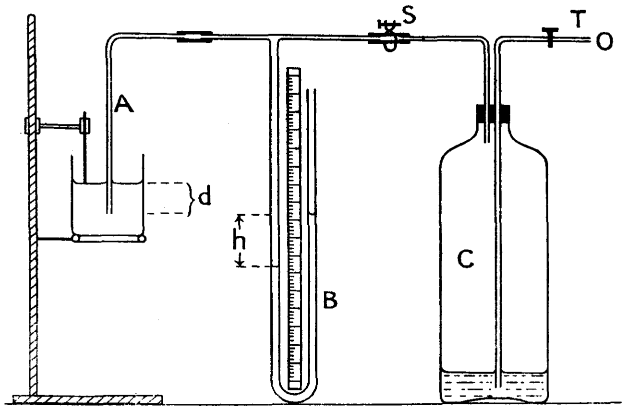


FIG. 37

THEORY

It can be shown that if a bubble is formed *in* a liquid that:

$$T = \frac{R}{2}(p - p_1),$$

where T is the surface tension of the liquid in dynes per cm.,

R is the radius of the bubble in cm.,

p is the pressure inside the bubble in dynes per cm^2.,

p_1 is the pressure outside the bubble in dynes per cm^2.

This is made use of in Jaeger's method, for, as the pressure in C increases, bubbles are formed slowly at the end of the tube. Fig. 38 shows three stages in the growth of a bubble, from which it will be seen that when the bubble is hemispherical its radius is a minimum and is equal to the internal radius of

* i.e. a vernier telescope.

the tube. It follows from the formula above that at this stage the pressure inside the bubble is at a maximum. As the bubble grows and breaks away the pressure falls. The manometer will indicate the rise of pressure to the maximum, and then fall quickly as the bubble grows and breaks away.

Thus observation of the maximum pressure recorded by the manometer combined with the measurement of d (see Fig. 37), gives a value for the excess pressure needed to maintain a bubble the radius of which is that of the end of the tube A.

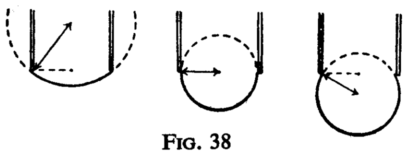


FIG. 38

Procedure: Adjust the pressure by means of the screw clips and the depth of the orifice below the surface so that about one bubble in two seconds is formed, and watch the manometer carefully. Measurements have to be made which will give the difference in level when the maximum pressure is recorded. This can be done either by taking a series of readings of first one side and then the other for successive bubbles, or by adjusting two pieces of paper with straight edges behind the manometer until they mark the positions required, the distance between which is then measured.

Measure the depth of the orifice below the surface of the water—use the same device as in Experiment 29, p. 96.

Measure the diameter of the orifice with a vernier microscope. Take the temperature of the water.

Record and Calculation: Tabulate the observations.

Find the radius of the orifice.

If h is the difference of levels in the manometer at maximum pressure, then the pressure in the bubble is greater than that of the atmosphere by gDh dynes/cm.^{2}, where

g = acceleration due to gravity in cm./sec.^{2}

D = density of the liquid in the manometer in gm./cm.^{3}

The external pressure is that of the atmosphere plus the pressure of the water above the orifice. Let d be the depth of the orifice below water surface and P the atmospheric pressure in dynes per cm.^{2}, then the external pressure is $P+gd$ and the internal pressure is $P+gDh$. Substituting these values in the equation

$$T=\frac{R}{2}(p-p_1)$$

we get

$$T=\frac{R}{2}(P+gDh-P-gd)$$

$$=\frac{Rg}{2}(Dh-d). \;.\;.\;.\;.\;.\; (i)$$

Substitute the values obtained in the experiment to find a value for the surface tension of water at the observed temperature.

Note: A modification has been suggested by R. C. Brown. If the end of tube A is only just in the surface, d becomes zero and a knowledge of the density of the liquid being investigated is not required. Equation (i) reduces to

$$T = \frac{Rg}{2} \cdot Dh$$

This is especially convenient when working with liquids of unknown density, or when investigating the variation of surface tension with temperature.

Experiment 31. Determination of the Variation of Surface Tension of Water with Temperature

The method is that using Jaeger's apparatus described above (Experiment 30, p. 99) with the addition of some arrangement whereby the beaker containing the water can be maintained at various temperatures. If a thermostat is not available the method described on p. 110 can be applied, otherwise a very large water bath would have to be used, but this is not likely to give very satisfactory results.

The surface tension is determined as in Experiment 30 and a graph should be drawn showing surface tension against temperature. Attention is drawn to the note to Experiment 30 above.

CHAPTER XI

VISCOSITY

Experiment 32. Determination of the Coefficient of Viscosity of a Liquid by the 'Rate of Flow' Method

Apparatus: Several litres of the liquid (water is the most convenient); capillary tube with uniform bore (see p. 55); wide glass tube about 50 cm. long by 5 cm. diameter; stop-watch; thermometer (0–50°C. $\times \frac{1}{10}$); mercury.

THEORY

When liquid flows through a capillary tube, as shown in Fig. 39 A and B, the following relationship holds:

$$\eta = \frac{A^2}{8\pi l} \cdot \frac{t}{V} \cdot p$$

where η is the coefficient of viscosity,
V is the volume of liquid passing in cm.^{3},
t is the time for which the liquid flows in seconds,
A is the area of cross-section of the tube in cm.^{2},
l is the length of the tube in cm.,
d is the density of the liquid in gm./cm.^{3},
p is the pressure at the level at which the liquid emerges, in dynes/cm.^{2},
and g is the acceleration due to gravity in cm./sec./sec.

Clearly in the arrangement shown in Fig. 39 A,

$$p = (h + l)dg,$$

where h is the distance shown in cm.; whereas for the arrangement B,

$$p = hdg.$$

Procedure: Set up the apparatus shown in Fig. 39, using either arrangement A or B. That shown at A is preferred, as a better temperature control is maintained. If B is used, grease the end of the tube with vaseline to prevent water running back along the underside of the glass.

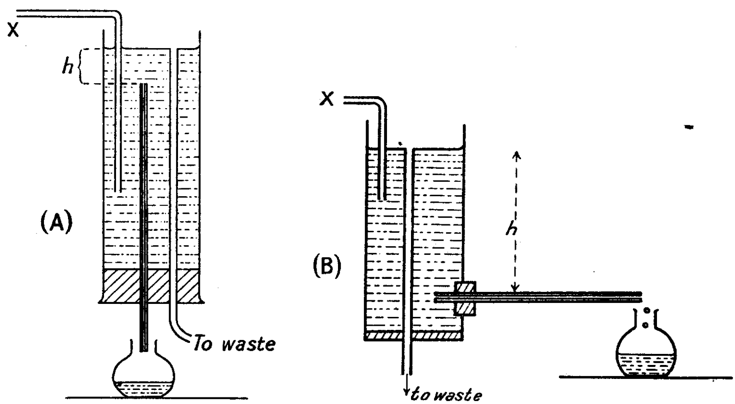


FIG. 39

The arrangements A and B both ensure that a constant head of the liquid is maintained when the tube X is connected to a supply of the liquid. If water is used, X may be joined by rubber tubing to a tap, but in this case the tap should be turned on for at least five minutes before X is connected so as to eliminate the temperature fluctuations which occur in water between the deep mains and the taps.

If water is not used, X must be connected to a large vessel containing several litres of the liquid and, of course, the broad glass tube and capillary tube must be filled with the same liquid. In the latter case a vessel should be provided to catch the liquid from the 'overflow' responsible for maintaining the constant head. The capillary tube should be provided with a cap so that the flow through it can be started and stopped at will.

Test the capillary tube for uniformity of bore and find its cross-sectional area, using mercury (see p. 55). Measure its length.

Fill the capillary tube and place the cap on it. Weigh the flask. Remove the cap, and allow the liquid to flow for a short time until it appears to be flowing steadily. Place the flask under the tube and start the stop-watch.

Allow the liquid to flow for a reasonable time, replace the cap and stop the watch at the same time.

Weigh the flask and liquid. Measure the head of liquid, h. Observe the temperature.

Determine if necessary the density of the liquid. Repeat the experiment, using a different value for h.

Record and Calculation: Record all your observations.

Calculate the volume of liquid which flowed through the tube in time t secs. Calculate the pressure, using the appropriate formula. Using the values obtained substitute in the equation, given above, to find a value for η at the recorded temperature.

Experiment 33. Determination of the Coefficient of Viscosity of Glycerine by the 'Dropping Sphere' Method

Apparatus: Glycerine; 1,000 ml. measuring cylinder; thermometer (0–50°C $\times \frac{1}{5}$); a number of small steel spheres (such as are used in ball-bearings) of various diameters ranging from about $\frac{1}{8}''$ to $\frac{3}{8}''$.

These can be bought at shops where cycle equipment is sold, for about 4d. per dozen, and the quoted diameter may safely be assumed to be accurate to 1 part in 1,000.

THEORY

If a sphere of radius r cm. falls freely through a liquid of density d_1 gm./cm.^{3}, it will, after a time, reach a limiting velocity of v cm./sec. This occurs when the 'viscous drag' is equal in magnitude to the weight of the sphere less the upthrust on it due to the displaced liquid. Stokes showed that the viscous drag was given by

$$6\pi\eta vr$$

where η is the coefficient of viscosity,
v is the velocity of the sphere,
and r is the radius of the sphere.

Hence if the solid has density d_2 gm./cm.^{3},

$$\tfrac{4}{3}\pi r^3(d_2-d_1)g = 6\pi\eta vr.$$

The spheres used in this experiment reach their terminal velocity very rapidly, in fact if dropped into the glycerine from a few millimetres above the surface they enter the liquid at a velocity greater than the terminal velocity and are retarded by the liquid.

Procedure: Fill the measuring cylinder with the glycerine and allow it to stand for long enough to allow all the air bubbles to escape. Select about a dozen balls of equal diameter. Remove any grease from them by washing in sodium hydroxide solution; wash them and dry them carefully. After this, handle them only with tweezers. Weigh a known number of these spheres and record the quoted diameter. Release one of the spheres into the glycerine and time its passage between two graduation marks as far apart as convenient. Repeat with each sphere in turn. Measure the distance apart of the marks.

Repeat the experiment, using another batch of spheres of a different diameter.

Note the temperature of the glycerine.

Either look up the density of glycerine, or determine it.

Record and Calculation: Tabulate your results.

Calculate if necessary a value for the density of the steel of which the balls are made.

Calculate the mean velocity of fall corresponding to each diameter.

Substitute in the equation given above and solve for η, the coefficient of viscosity at the observed temperature.

PART III

HEAT

CHAPTER XII

STANDARD PROCEDURE

Heat Losses in Calorimetry Experiments

In nearly all experiments where temperature changes occur there is a heat exchange between the apparatus and the surroundings. This loss or gain may be

(1) Reduced to a minimum and then ignored, or

(2) Determined experimentally and allowed for in the calculation, or

(3) Eliminated by mathematical analysis of the observations of two (or more) experiments.

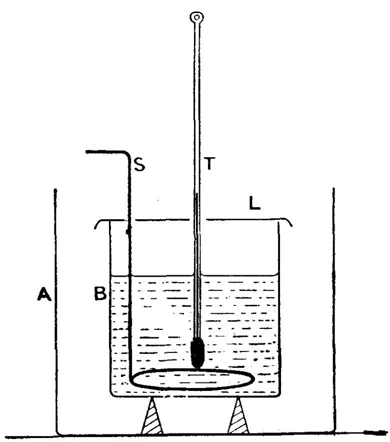


FIG. 40. A is a large outer vessel to shelter the calorimeter B which is supported by corks. S is a stirrer. T is a thermometer. L is a lid.

In most elementary work we adopt method (1) and the apparatus used to minimise heat losses is shown in Fig. 40. This arrangement should be used in all calorimetry experiments unless other instructions are given.

Sometimes we use method (2) e.g. in Experiment 37, p. 113, and complete instructions for the procedure are given there.

Method (3) is rarely applied in work of the standard we are considering but it can be employed when using the constant flow calorimeter—see under Experiment 64, p. 160.

Transmission of Heat

Heat is transferred from one place to another by one of the three processes: conduction, convection or radiation.

(1) *Conduction*

The amount of heat conducted across an area A cm.^{2} of a substance d cm. thick in a time t secs. when the temperature difference between the faces is $(\theta_2-\theta_1)$°C is given by the expression

$$\frac{kA(\theta_2-\theta_1)t}{d} \text{ calories,}$$

where k is a constant known as the 'coefficient of thermal conductivity' of the substance. Experiments 56 to 60, pp. 145 to 154, describe methods by which this coefficient may be determined. In the case of all substances, except metals, k is small, especially in the case of gases. It is clear then that little heat can be lost by this process in the arrangement shown in Fig. 40, p. 107, as cork and air are bad conductors and the temperature differences are never great.

(2) *Convection*

The reason this subject is given little attention, after the very elementary qualitative experiments have been made, is because it is complex and the mathematical treatment is not yet completely worked out. It is, however, the most important means by which bodies at ordinary temperatures lose heat; and some discussion of the laws must be given on this account, even if we do not know the mechanism behind these empirical laws.

The subject can be divided into the two branches: 'natural convection' and 'forced convection'. The former is concerned with convection loss when the body is *not* in a draught, e.g. one which is shielded as shown in Fig. 40. 'Forced convection' is the case which Newton investigated and to which his 'law of cooling' applies. *It is concerned with bodies placed in a draught.* This condition should be noted and care taken to apply Newton's law of cooling only to bodies in a draught. Experiment suggests that very small draughts are sufficient to produce cooling in accordance with Newton's Law and such draughts (which are too small to be felt) are nearly always present in the laboratory. Experiment 34 deals with forced convection, and is placed first amongst the experiments in this Part on account of the importance of the subject in calorimetry.

(3) *Radiation*

The effect of this process is of little importance when the temperature difference between the body and its surroundings is small (i.e. say less than 100°C). It is very important when much higher temperatures are considered. It will not be material in experiments on calorimetry.

The Determination of the Water Equivalent of a Calorimeter, etc.

In most heat experiments the thermal capacity of the vessel employed appears in the expression for the final calculation. An experimental method does not yield consistent results; possible errors in the neighbourhood of 20% are common (and even greater errors not unusual). Thus, wherever a reliable value for the water equivalent is needed in practical physics it should be *calculated* from the mass and the specific heat of the material. The use of a stirrer made of the same material as the calorimeter—usually this will be copper—will enable a single weighing to suffice. The only remaining problem (except in special cases such as Experiment 62, p. 157), is the computation of the water equivalent of the thermometer. This is important as it will represent in the usual arrangement at least 5% of the thermal capacity. By a fortunate coincidence the amount of heat required to raise the temperature of *one cubic centimetre* of glass by 1°C is very nearly the same as that required to raise the temperature of one cubic centimetre of mercury by that amount. For glass (dependent of course on the type) it is about 0·4 calories; and for mercury it is 0·45 calories (depending slightly on the temperature—as the specific heat of mercury varies with temperature). In most experiments the bulb of the thermometer and a relatively short portion of the stem are immersed; and owing to the low thermal conductivity of glass it may be assumed that it is only this immersed part that is of importance. The exact ratio, by volume, of glass to mercury will vary from thermometer to thermometer and from experiment to experiment; but it is probably safe to assume that (except in the case of a short thermometer or of an almost totally immersed one) there is a greater volume of mercury than glass in the immersed portion. Thus, if we assume a value of about 0·45 calories per $cm.^3$ of immersed thermometer we shall not be far out, and will certainly not obtain as close an estimate by experimental methods.

Thus we may summarise the procedure for the determination of the water equivalent as follows:

(1) Use, wherever possible, a calorimeter and stirrer made of the same material. Copper or aluminium are recommended. Determine the mass of these and multiply it by the appropriate specific heat.

(2) Using a 10 ml. measuring cylinder, measure the volume of the thermometer immersed and multiply this quantity (in $cm.^3$) by 0·45. Add the result of this calculation to that obtained from operation (1) to obtain the water equivalent of the calorimeter, stirrer and thermometer.

A Simple Immersion Heater and Thermostat for Use in Water Jackets

In many experiments the temperature has to be varied, and often it is inconvenient to apply heat to a water jacket by means of a bunsen burner. The immersion heater is thus of wide application, and a suitable form can easily be made in the laboratory.

The heating element comprises a coil of nichrome wire (S.W.G. 28 is satisfactory) of resistance about 8 ohms. It should be wound on a cylindrical former a few cm. in diameter and then slipped off. It is a wise precaution to varnish it and bake it so that it is insulated. If this is not done the 'return' lead should be enclosed in a piece of glass tubing, as shown in Fig. 41, so that there is no risk of a short circuit when the heater is in use.

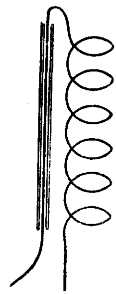


FIG. 41

The supply may be either D.C. or A.C. and is conveniently of the order of 24 volts. The output terminals of the supply are connected to the heater through a switch and a rheostat (see p. 286). With a 24-volt supply and a resistance of 8 ohms the maximum current possible will be 3 amps and you should be able to show that this delivers approximately 17 calories per second. Thus if the water jacket contains 1 litre of water the temperature will rise at about 1°C per minute provided little heat is lost. Thus this heater will enable observations to be taken over the range room temperature to 100°C in about $1\frac{1}{2}$ hours.

It can also be used as a crude thermostat if, after using it to raise the water to the required temperature, the current is reduced by means of the rheostat to such a value that the heat developed in the coil is just sufficient to replace the heat lost to the surroundings.

CHAPTER XIII

CONVECTION COOLING

Experiment 34. Verification of Newton's Law of Cooling

Apparatus: Two thermometers, one 0–100°C, the other 0–50°C$\times\frac{1}{10}$; stop-watch; calorimeter, fitted with lid, stirrer and cork supports.

THEORY

Newton's Law of Cooling states that under conditions of forced convection (see p. 108) the rate of loss of heat from a body is proportional to the difference between its temperature and that of the draught which is cooling it. It can be shown that if the law holds then the rate of fall of temperature as well as the rate of loss of heat will be proportional to the temperature excess, and in this experiment we measure the rate of fall of temperature.

Procedure: Arrange that a draught is blowing over the bench where you will be working, either by opening suitable windows, or (better) by using a fan. A calorimeter should be fitted with a stirrer and lid and through the latter should pass the thermometer which is graduated in tenths. Fill the calorimeter two-thirds full of water at about 45°C and place it, supported on three small corks, on the bench in the draught, as shown in Fig. 42. Place the other thermometer 'upwind' from the calorimeter and at least a foot from it so that the temperature of the draught can be observed.

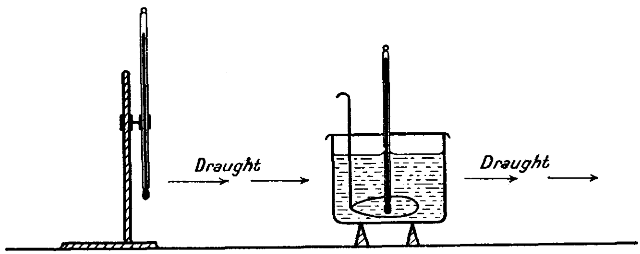


FIG. 42

Record the temperature of the water in the calorimeter each minute until it is within two or three degrees of the draught temperature. The latter should also be observed at convenient intervals to make sure that it is approximately constant. (If this condition is not satisfied the experiment must be repeated).

Record and Calculation: Tabulate your results.

If necessary calculate the mean value of the temperature of the draught—let this be θ_0. Plot a graph of the temperature (θ) of the water and calorimeter, etc. against time. Draw the line $\theta=\theta_0$. (See Fig. 43).

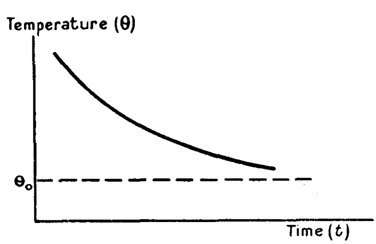


FIG. 43

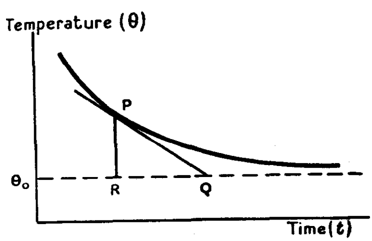


FIG. 44

The rate of fall of temperature at any moment is the slope of the curve at that time. Thus the tangents to the curve are drawn at a number of points. Let one of these points be P, PQ be the tangent, and PR the perpendicular to the $\theta=\theta_0$ line (see Fig. 44).

There are two ways of examining your curve to see whether your results conform to Newton's Law or not:

(i) Tabulate corresponding values of PR/RQ and PR. The first quantity measures rate of fall of temperature and the second the temperature excess. Plot the one quantity against the other. If your results conform to the law the graph should be a straight line.

(ii) Since we expect PR/RQ to be proportional to PR, this is the same as expecting RQ to be a constant. Thus if we tabulate the values of RQ they should be constant if our results verify the law.

CHAPTER XIV

SPECIFIC HEATS

Experiment 35. Determination of the Specific Heat of Brass by the Method of Mixtures

Apparatus: A lump of brass weighing 100–200 gm. Calorimeter etc. as shown in Fig. 40.

Procedure: Find the water equivalent of the calorimeter stirrer and thermometer by the method given on p. 109.

Weigh the brass.

Suspend the brass, by means of thread, in boiling water for about 10 minutes. Meanwhile weigh the calorimeter, stirrer and thermometer. Fill the calorimeter about half full of cold water and weigh again to find how much water has been added.

Arrange the calorimeter as shown in Fig. 40 and when all is ready

(i) Take the temperature of the cold water.

(ii) Take the temperature of the boiling water.

(iii) Quickly remove the brass by the thread, flick off adhering water and lower into the calorimeter.

(iv) Stir, and take the highest temperature reached.

Repeat several times. (Once the apparatus is ready the actual experiment takes very little time.)

(The piece of brass will carry over a little hot water, but at the same time it will lose heat during the transfer. This gain and loss tend to balance each other.)

Record and Calculation: Tabulate your observations.

Calculate heat gained by the calorimeter, etc., and the water in it, from their known masses and water equivalent and the measured rise in temperature.

Heat lost by the brass is given by :

$$H = (m \times s \times t) \text{ cal.}$$

where s is the specific heat of the brass
m is the mass of the brass in grams
t is the fall in temperature of the brass.

Equate heat lost to heat gained and solve for s.

Find the mean of all concordant determinations.

Experiment 36. Determination of the Specific Heat of Paraffin Oil by the Method of Mixtures

Apparatus: Lump of brass weighing 100–200 gm., preferably that used in Experiment 35; paraffin oil; calorimeter, etc.

Procedure: The determination is carried out in the same way as in Experiment 35 except that the paraffin oil replaces the water in the calorimeter and a solid of known specific heat is used. If the piece of brass used in Experiment 35 is available its specific heat may be assumed from the result of that experiment, otherwise it must be looked up in tables.

Record and Calculation: Tabulate your results and calculate the specific heat of paraffin oil.

Experiment 37. Determination of the Cooling Correction

Apparatus: Unshielded calorimeter with cork supports; lid for calorimeter; thermometer (0–50°C$\times\frac{1}{10}$); stop watch. A specimen of a solid which is a bad conductor of heat. This solid should be ring-shaped so that the thermometer will easily pass though the centre of it. The solid itself can then be used as a stirrer in order to eliminate the loss of heat due to evaporation, which is considerable when the usual form of stirrer is used.

THEORY

Whatever precautions may be taken to minimise heat losses it still remains a fact that so long as the temperature of the calorimeter etc. is above that of the surroundings some heat will be lost. In most calorimetry experiments the temperature changes observed are rapid and the heat losses are certainly negligible. If, however, bad conductors of heat are involved in the process of heat transference the temperature changes may take several minutes and the heat loss to the surroundings increases accordingly. In such cases a cooling correction may be applied and this experiment describes the procedure.

There are two further points which should be considered:

(i) The computation of the cooling correction depends on the assumption of Newton's law of cooling and it is thus necessary to ensure that the conditions under which the experiment is performed conform to those stated in the law—i.e. that convection is '*forced*' (see p. 108). The use of a shielded calorimeter is thus prohibited and the experiment should be done in a draught.

(ii) The correction usually amounts to less than 1°C, and often to a small fraction of 1°C; thus in view of the order of accuracy of other observations the labour involved in making the cooling correction is rarely worth while.

If the aim of the experiment is to gain experience in the matter of the cooling correction a solid weighing a few hundred grams and quantities of water of 100–200 gm., in an *exposed* calorimeter should be used. If the aim is to determine the specific heat of a poor conductor an annular solid weighing about 100 gm. and a shielded calorimeter should be used, *the cooling correction being ignored.*

Procedure: Weigh the solid. Tie thread to the solid in such a way that it will be easy to use it as a stirrer, and suspend it so that it is totally immersed in a beaker full of cold water. Raise the temperature of the water in the beaker to boiling point and leave the solid in boiling water for at least half an hour. Meanwhile, calculate the water equivalent of the calorimeter and thermometer (see p. 109), Also weigh the calorimeter, first empty, and then half full of water which is at room temperature. Stand the calorimeter on cork supports and fix the thermometer in a clamp so that it will be ready for use when the transfer of the solid is made.

For the next few minutes you will need the help of another experimenter.

When all is ready take the temperature of the water in the calorimeter (θ_0) and of the boiling water (with another thermometer). Lift the solid out of the beaker, give it one flick to remove excess water and place it immediately in the calorimeter. This transfer must be done as quickly as possible—preferably inside two seconds. Immediately the solid is in the calorimeter the stop-watch must be started and the thermometer slipped into the hole in the specimen. Stirring should be started immediately but the solid must not emerge from the water and splashing must also be avoided. Observations of the temperature of the water in the calorimeter must be recorded every $\frac{1}{4}$ minute until the maximum temperature (θ_{max}) is reached and every minute thereafter. Continue observations of temperatures, stirring all the time, until the cooling has continued for 20 minutes.

Record and Calculation: There are two ways of analysing the results—the first is probably quicker and easier to remember.

METHOD 1

Tabulate your observations.

Plot a graph of temperature of the calorimeter etc. (θ) against time. It should look like the graph in Fig. 45.

Draw the lines corresponding to θ_0 and θ_{max}. AB and CD respectively, C being the peak of the curve. Choose any point E on the curve (somewhere near the end of it).

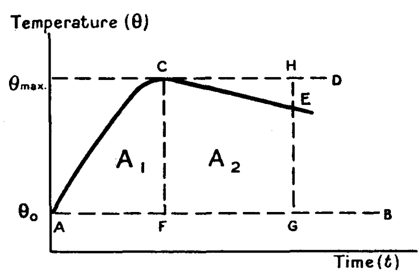


FIG. 45

Draw CF and EG perpendicular to AB. Produce GE to intersect CD at H.

Find the magnitude of the areas between the curve ACE and the line AB bounded by AFC and EGFC. Call these A_1 and A_2 respectively. Find the temperature interval given by EH (θ').

The correction to be added to θ_{max} is then c where

$$c = \theta' \text{ times } A_1/A_2$$

For proof of this a theoretical text book should be consulted.

The value of $(\theta_{max} + c)$ is then used as the 'final temperature' in the usual calculation to find the specific heat.

METHOD 2

This method is most easily understood by reference to an actual example. Tabulate your results in a manner similar to that given below and proceed as indicated:

Temperature Readings

Time in minutes	Temperature in °C.	Mean temperature
0	12·5	
		16·2
1	19·8	
		23·6
2	27·3	
		29·7
3	32·0	
		32·4
4	32·8	
		32·8
5	32·8	
		32·6
6	32·3	
		32·1
7	31·9	
		31·7
8	31·5	
		31·3
9	31·1	
etc.		

Initial temperature of water and room temperature 12·5°C.

Inspection indicates that steady cooling sets in by the end of the 6th minute at the rate of 0·4°C per minute. Assuming that the cooling is proportional to the excess temperature (Newton's Law of Cooling), the graph shown in Fig. 46 is constructed.

To construct this, the point 0·4 on the scale is marked against the temperature 32·1°C—the average temperature for the 7th minute.

A straight line is drawn through this point to cut the axis at the room temperature 12·5°C.

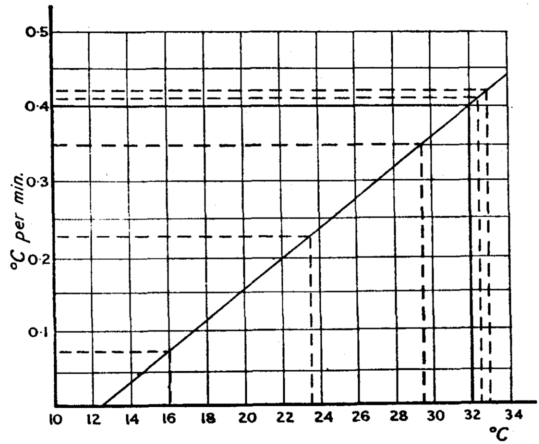


FIG. 46

Using this graph the following table is prepared:

Minute	Temperature correction for each minute
1st . .	0·07°C
2nd . .	0·23
3rd . .	0·35
4th . .	0·41
5th . .	0·42
Total . .	1·48°C

The first value 0·07°C in this table is the value of the ordinate corresponding to 16·2°C, the average temperature for the first minute. Similarly 0·23°C corresponds to 23·6°C, and so on.

If no loss of temperature due to cooling had occurred, then the highest temperature reached in the 5th minute would have been:

$$
\begin{aligned}
&32{\cdot}8°C + (\text{the total correction})\\
&= 32{\cdot}8°C + 1{\cdot}48°C\\
&= 34{\cdot}28°C
\end{aligned}
$$

This value, taken of course as 34·3°C, is used in the usual specific heat calculation.

Note: A close approximation to the cooling correction can be obtained rapidly as follows:

Let t be the time taken to reach maximum temperature. Then the temperature fall in the interval $t/2$ after maximum temperature has been reached is the required cooling correction. This method can usefully be applied in Experiment 62.

Experiment 38. Determination of the Specific Heat of a Liquid by the 'Method of Cooling'

Apparatus: The liquid of unknown specific heat—aniline is suitable; calorimeter etc.; constant temperature enclosure—a simple one can be arranged by the method indicated in Fig. 47; measuring cylinder; stop-watch; thermometer (0–50°C $\times \frac{1}{5}$).

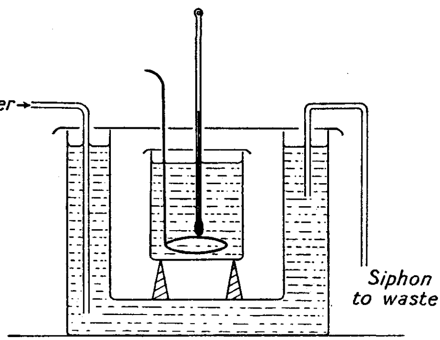


FIG. 47

THEORY

This method which is only applicable to liquids assumes that *some* cooling law exists. If two different liquids are used in turn in the same container then, provided they are of equal volume and their temperatures fall through the same range, it can be shown that

$$\frac{W + m_2s_2}{W + m_1s_1} = \frac{t_2}{t_1}$$

where m_1 and m_2 are the masses of the two liquids
s_1 and s_2 are their specific heats
t_1 and t_2 are the times taken to fall through the selected temperature range
and W is the water equivalent of the calorimeter, etc.

If the specific heat of one liquid is known, that of the other can be calculated.

It must be emphasised that here no *particular* law of cooling is assumed, and that rarely do the conditions of experiment conform to those specified by Newton's Law of Cooling.

The essential precautions are that the above conditions should be observed and that the liquid be adequately stirred, so that the temperature of the bulk of the liquid and the surface of the calorimeter are the same.

Procedure: Weigh the calorimeter and determine the water equivalent of calorimeter, thermometer and stirrer (see p. 109). Introduce into it about two-thirds of its volume of water at about 50°C above room temperature. Place the calorimeter in the prepared enclosure and note the temperature of the water every minute until a fall of 20–30°C has taken place. The stirring must be efficiently maintained all the time. Remove the calorimeter etc. and reweigh it to find the mass (and incidentally the volume) of water used.

Empty and dry the calorimeter. From the measuring cylinder introduce into it a quantity of the liquid equal in volume to the water used. Weigh the calorimeter to determine the mass of this liquid. Warm the calorimeter and its contents to about 50°C above room temperature and place it in the constant temperature enclosure. Note the temperature every minute, stirring constantly, till a fall of about 20–30°C has occurred. If at the starting temperature appreciable condensation has occurred inside the lid, amend the given values for the range of temperature, through which the liquid will cool, in order to avoid this.

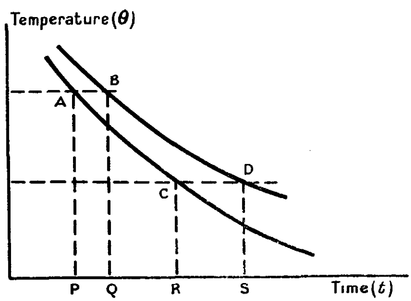


FIG. 48

Record and Calculation: Tabulate the results. Plot a graph of temperature against time for both water and the liquid on the same axes. The two curves should look like those shown in Fig. 48. Draw a pair of lines parallel to the time axis as far apart as convenient and intersecting the curves at A, B, C and D. These two lines define an arbitrarily selected temperature range to be used in the calculation. From the points A, B, C and D draw the ordinates AP, BQ, CR and DS cutting the time axis at P, Q, R and S. Find the time intervals given by PR and QS, which will be the times taken by the two liquids to cool through the selected temperature range, i.e. t_1 and t_2 in the above equation.

Substitute these values, together with the other quantities which have been determined, in the equation, and solve for the unknown specific heat.

Experiment 39. Determination of the Ratio of the Specific Heats of Air by the Method of Clément and Desormes

Apparatus: Special apparatus is required and can be made as follows:

The arrangement is shown in Fig. 49, the large vessel being a carboy, well lagged. The mouth is closed with a tight fitting cork through which pass three tubes, as shown, the tube B being at least 2 cm. in diameter, and provided with an arrangement so that its orifice can be easily and quickly opened and closed. There are several ways in which this can be done—the use of a clip should be regarded as the last resort. Fig. 50 shows a simple method which can be made in the laboratory work shop. Here F is a flange—really part of the tube B—which should be of metal, which is ground with the solid brass cylinder E to give intimate contact all round. The interface of E and F must be smeared with grease. To E is attached the shaft H, about 15 cm. long, which moves up and down in the sleeve D, into which it just fits, leaving enough clearance for a lubricant. S is a spring to keep E and F in close contact. D is securely clamped.

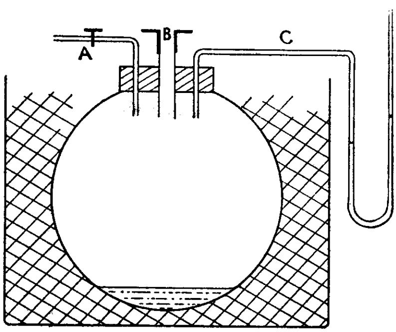


FIG. 49

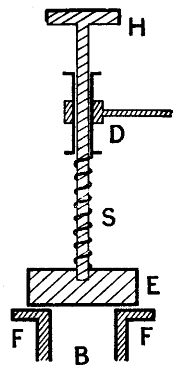


FIG. 50

The tube A is connected to a pump (a bicycle pump will do) and C is connected to a manometer. The apparatus should be made air-tight (use Bostick 'B' on the neck of the carboy, and 'Airtite' elsewhere). The sensitivity of the manometer should be increased by using a liquid of lower density than water but it should be calibrated in cm. of water, unless the density of the liquid is known. A simple way of carrying out this calibration consists in connecting it via a T-tube to a water manometer and performing the calibration by a process rather like that applied in Hare's apparatus. If by any chance no other liquid except water is available for the manometer this may be used, but a calcium chloride drying tube should be included between it and the carboy.

The air under investigation should also be dried by introducing a layer of concentrated sulphuric acid into the bottom of the carboy, and by introducing a calcium chloride drying tube between the pump and A.

THEORY

The value of the specific heat of a gas depends upon whether the determination is made with the gas at a constant pressure, when it will expand during heating, or at a constant volume, when its pressure will increase during heating. The ratio of these two specific heats is

$$\gamma = \frac{C_p}{C_v}$$

where C_p is the specific heat at constant pressure
C_v is the specific heat at constant volume
and γ is a constant for a given gas, its value depending on the atomicity of the gas.

For monatomic gases γ has a value of 1·67; for diatomic gases the value is 1·40. In the case of air which is a mixture of many gases, over 99% of it is composed of diatomic gases—nitrogen and oxygen—and the theoretical value is thus very nearly 1·40.

Procedure: With B closed, pump air slowly into the carboy until the manometer registers a pressure of about 30 cm. of water. The slower the pumping is done the better as this reduces the amount of heating due to compression; in any case it is necessary to wait for the air to cool down to the temperature of the environment after pumping it in. Record the manometer reading (let it be, for reference, h_1 cm. of water).

Open B—or whatever arrangement you are using—'momentarily' i.e. for between 0·5 and 1 second, making sure that on closing it the tube is sealed again, i.e. with the arrangement suggested above press E on to F with a slight turning motion.

Obviously the levels of the liquid in the manometer will become the same when B is opened; but on leaving the apparatus, with B closed, a temperature increase will occur, and a rise in pressure so caused will be indicated by the manometer. (When air expands, work is done. The energy for this will be taken from the air in the carboy itself and therefore the temperature falls below that of the surroundings. On leaving the apparatus the cooled air rises in temperature to that of the room and therefore suffers an increase of pressure. The volume of the air in the manometer is ignored). Take the reading of the manometer when it has become steady—let it be h_2 cm. of water.

If necessary record the pressure of the atmosphere—see discussion below. Let it be P cm. of water.

Record and Calculation: It can be shown that

$$\gamma = \frac{\log p_1 - \log P}{\log p_1 - \log p_2}$$

where p_1 and p_2 are the initial and final pressures in the carboy (measured in the same units as P).

This equation is exact but an approximate one can be deduced from it, which is independent of P, viz.

$$\gamma = \frac{h_1}{h_1 - h_2}$$

Using the second equation will introduce an inaccuracy of only a fraction of 1%, and we are therefore justified in doing so here as such accuracy cannot be achieved with our apparatus.

Record the observations made, substitute in the equation and solve for γ.

Note: The experiment should be repeated with other gases. Coal gas is suitable, as there is a good supply available. Carbon dioxide and oxygen could also be used.

CHAPTER XV

CHANGE OF STATE. HYGROMETRY

Experiment 40. Determination of the Melting Point of Naphthalene by Drawing a Cooling Curve

Apparatus: Naphthalene; test-tube fitted with cork through which pass a stirrer and thermometer (0–100°C); stop-watch, or an ordinary watch provided it has a seconds hand.

THEORY

A liquid placed so that it is at a temperature above its surroundings will lose heat in excess of that received from its surroundings until equilibrium is reached. The loss will be indicated by a fall of temperature to that of the surroundings. If this range of temperature passes through the melting point, solidification will occur, and latent heat will be evolved at such a rate as to balance the loss. Hence, if temperature be plotted against time during such a 'cooling', a horizontal portion of the curve will indicate the evolution of the latent heat of fusion, and correspond to the melting point. It is important to realise that the horizontal part of the curve does not indicate that loss of heat has ceased.

Supercooling may occur in such an experiment and the temperature of the liquid fall below the melting point without solidification taking place or any latent heat being evolved. When solidification does occur, the latent heat is evolved at a rate sufficient to raise the temperature to the melting point quickly. The cooling curve will then proceed horizontally for some time. The melting point is *always* indicated by a horizontal portion of the curve.

Procedure: Fit up the apparatus shown in Fig. 51.

Introduce sufficient naphthalene so that, when it is melted, the bulb of the thermometer will be well covered. No more solid than is necessary for this purpose should be used, for if a large bulk is employed the experiment will be unduly prolonged.

Warm the test tube and its contents in a water bath until the naphthalene is melted. Replace the tube in its position, and take the temperature every minute until the naphthalene has solidified and the temperature is falling steadily. Stir as long as possible.

Record and Calculation: Tabulate the observations. Plot a graph of temperature against time and deduce the melting point from it.

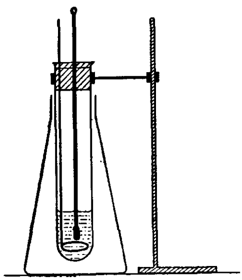


FIG. 51

Notes: (i) It is of interest, if time permits, to repeat this experiment with paraffin wax, which is seldom pure and, therefore, does not have a definite melting point. From the graph produced you will be able to state that melting occurs between two temperatures.

Even under the best possible conditions a strictly horizontal portion of the curve is not likely to be obtained. As the liquid solidifies, stirring becomes impossible, and the curve usually slopes downwards a little during the change. However, with pure substances a distinct break will be observed, and may be taken as a very accurate value of the melting point.

(ii) If sodium thiosulphate is used—the common 'hypo' used by photographers—and the stirring is omitted, it is possible to obtain an interesting curve showing super-cooling.

Experiment 41. Determination of the Melting Point when only a Small Portion of the Substance is Available

Apparatus: The substance—fresh, dry phenol is suitable; a capillary tube of thin glass, about 5 cm. long and bore about 1 mm. with one end sealed; thermometer of suitable range.

Procedure: Grind the substance to a fine powder, and insert enough into the tube to fill it to a depth of 1 to 2 cm.

Arrange the apparatus as shown in Fig. 52.

The beaker contains water or some other liquid which has a boiling point well above the melting point of the substance. The capillary tube will stick to the thermometer, if both are wet, by capillary attraction.

Perform a rapid experiment by heating the water with a medium flame to find the approximate temperature at which melting occurs.

Allow the substance to cool to about 10°C below this temperature and then do a similar experiment with a very small flame and efficient stirring so that a much more accurate reading may be taken.

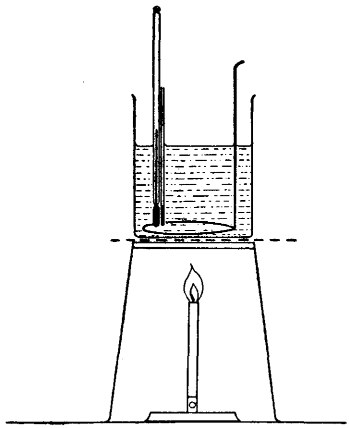


FIG. 52

Note: It is sometimes recommended that after melting, the apparatus should be allowed to cool and a reading of the temperature of solidification taken, and the average of this and the melting point recorded. Supercooling is, however, very likely to occur, and this procedure is not advised.

Experiment 42. Determination of the Vapour Pressure of Water at Various Temperatures

Apparatus: Fit up the apparatus shown in Fig. 53, which should be self-explanatory. The use of round-bottomed flasks is *essential.* If it is available a good exhaust pump should be attached to P, though a

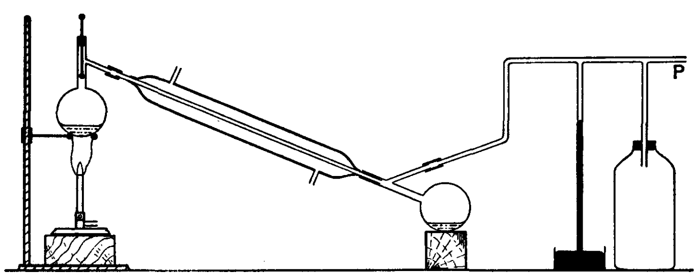


FIG. 53

filter pump, if it is the type fitted with a valve—e.g. the Edwards type 5—is satisfactory and will reduce the pressure to less than 10 cm. of mercury. The manometer should contain mercury and to guard against it entering the main body of the apparatus the manometer should be at least 90 cm. long. Broken porcelain should be used to ensure quiet boiling, and all joints should be made airtight.

Procedure: Reduce the pressure as much as possible by the pump attached to P. See that the apparatus is airtight.

Raise the temperature in the flask until the water boils. Note the temperature and the manometer reading.

Increase the pressure by about 5 cm. of mercury and find the boiling point.

Continue the increases of pressure until atmospheric pressure is reached, finding the boiling point at each change.

Record: Tabulate the observations, and plot boiling points against the pressures inside the apparatus.

Note: An interesting and more compact method is described in the booklet on low-pressure experiments published by Messrs Edwards Ltd., from whom it may be obtained. Briefly, the method is as follows:

A beaker containing the water and a thermometer is heated electrically inside a bell-jar in which the pressure is reduced by a good quality filter pump. The pressure will be recorded by the pressure gauge attached to the base plate assembly, but the accuracy of observations can be improved by incorporating a manometer attached to the appropriate connecting tube in the assembly.

Experiment 43. Determination of the Vapour Pressures of Ether at Various Temperatures

Apparatus: Ether (remember that this liquid is very inflammable); two barometer tubes—or else one barometer tube together with a permanent barometer; 15 cm. of glass tubing of bore about 1 mm. bent as shown in Fig. 54 with rubber tubing of length about 5 cm. and fitted with a clip attached to it; water bath, which can be maintained at various constant temperatures (see p. 109).

THEORY

When a liquid evaporates it produces a vapour, and this vapour exerts pressure. From the moment evaporation begins, this pressure increases until a maximum value is reached—provided of course sufficient liquid is present—and at this stage the vapour is said to be saturated. This maximum pressure is always recorded as the 'vapour pressure' of the liquid at the temperature at which the determination is made.

The value of the vapour pressure depends upon the temperature at which it is measured.

Procedure: Set up the two barometer tubes side by side as shown in Fig. 55. Into one of them introduce liquid ether until there is a distinct, shallow, but permanent layer of liquid on the surface of the mercury. This operation is made fairly easy by using the apparatus shown in Fig. 54, which is filled with ether to within about 2 cm. of the clip. The open end is inserted beneath the barometer tube and ether can be injected by squeezing the rubber. The amount injected can be observed by watching the ether meniscus moving down the tube, and the length of the tube ensures that only ether is injected, i.e. that no air enters.

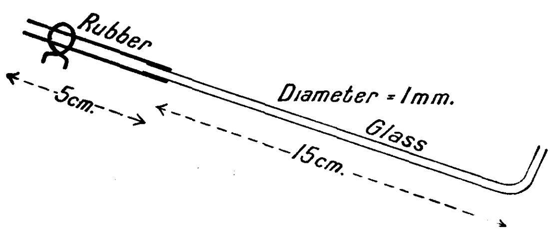


FIG. 54

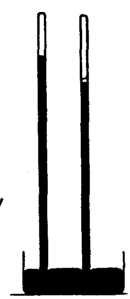


FIG. 55

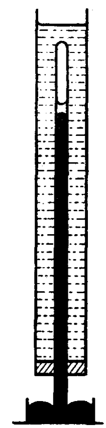


FIG. 56

Surround the barometer tube containing the ether by a water jacket with the immersion heater, making sure that the jacket extends for the whole length of the barometer tube—as shown in Fig. 56. (The immersion heater is not shown in this figure).

Observe the height of the 'true' barometer. Vary the temperature of the water jacket and take a series of observations of corresponding values of the temperature and the height of the mercury column—keeping the water jacket at a constant temperature for at least five minutes before taking each reading.

Record and Calculation: Tabulate your results and plot a graph of temperature against the vapour pressure, expressed in centimetres of mercury. Deduce an approximate value for the boiling point of ether from your graph.

Experiment 44. Determination of the Dew Point and Relative Humidity, using Regnault's Hygrometer

Apparatus: Regnault's hygrometer; aspirator; ether; sheet of glass at least a foot square.

Procedure: Fig. 57 shows the apparatus. Polish the silvered cap at the bottom of the tube.

Pour sufficient ether into A to cover the bulb of the thermometer, and the metallic cup at the bottom of the tube.

It is essential that the observer should not breathe extra supplies of water vapour into the atmosphere near the apparatus. This can be avoided by making all observations through the sheet of glass placed between the observer and the instrument.

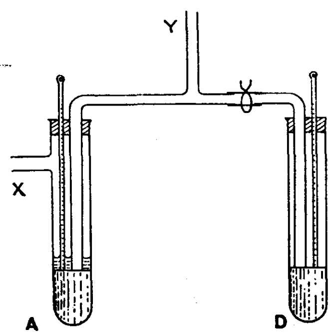


FIG. 57

Draw air fairly rapidly through tube X, which is attached to an aspirator. If an aspirator is not available, then air may be blown through Y by means of small hand bellows. Continue this until a deposit of moisture is obtained on the polished cap.

If an aspirator is used, then the ether vapour produced will be carried away by it. If air is blown through the tube, then a long tube should be attached to carry the ether vapour away from the apparatus. Theoretically the ether vapour should make no difference, but in practice it does.

Allow the apparatus to warm up in the air until the mist has just disappeared. Now let a fairly slow current of air bubble through the ether until once more the mist is observed. Note the temperature recorded by the thermometer in the tube. Allow the temperature to rise, and note the temperature when mist disappears.

Repeat until with care the difference between appearance and disappearance of mist are observed with a temperature difference of 0·5°C or less.

Observe the temperature in control tube D, which is assumed to be at air temperature. If only one tube is provided, take the temperature of the air in the vicinity of the experiment.

Record and Calculation: Record all readings and calculate the average value for the dew point.

Since Relative Humidity is the ratio of the weight of water vapour actually present in a given mass of air at a given temperature to that weight of water vapour required to saturate the same mass of air at the same temperature, it can be shown that it is also equal to the fraction

$$\frac{\text{Vapour pressure at the dew point}}{\text{Vapour pressure at air temperature}}.$$

Look up in tables the vapour pressure at the dew point and at the atmospheric temperature, and substitute in the formula to find the relative humidity.

Experiment 45. Determination of the Absolute Humidity of the Atmosphere

Apparatus: Carboy equipped with tubes as shown in Fig. 58. Two measuring cylinders of large capacity—preferably 1 litre each. Four calcium chloride drying tubes; screw clip.

THEORY

Absolute humidity is defined as the mass of water vapour present in unit volume of the atmosphere. It will vary from day to day by a considerable amount as it depends on the temperature and the relative humidity of the air. This experiment will take at least three hours, and probably over four, and should be performed on a foggy or a wet day in summer, as that is when the absolute humidity will be at a high value. On cold dry days in winter it can fall to a tenth of its maximum summer value, and this experiment will then give no result.

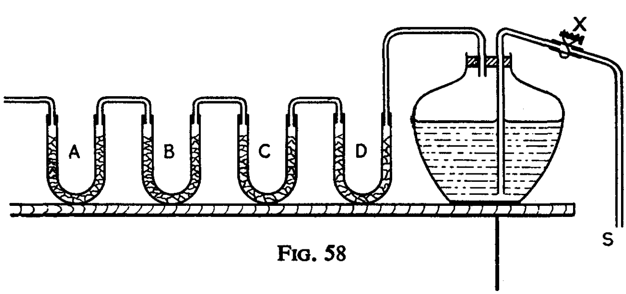


Fig. 58

Procedure: Arrange the apparatus as shown in Fig. 58 and make sure that it is airtight. Suck at the end of the siphon tube S so that water starts to flow into the waste from the carboy. Close the screw clip X. Weigh A and B together. Weigh C. Do not weigh D as it is merely a guard tube to prevent moisture from the water in the carboy affecting C. Record all these weights. Open the screw clip X so that air is drawn slowly through the U-tubes—i.e. at a rate of about 70–100 cm.^{3} per minute. Collect the water delivered from S in the measuring cylinders, replacing the one by the other as each fills, and recording the volumes collected before emptying the contents. Continue until about 20 litres of water has been collected, i.e. that volume of air has been drawn over the calcium chloride. Close X and reweigh A with B; reweigh C separately. If C has gained in weight the experiment must be repeated, as evidently A and B have not collected all the water from the air.

Record and Calculation: Record all weighings and all volumes.

Find the total volume of air examined and the weight of water collected in the tubes A and B when C does not gain in weight. Hence find the mass of water vapour which was present in 1 litre of the air.

Experiment 46. Determination of the Latent Heat of Fusion of Ice at 0°C

Apparatus: Ice; small calorimeter* etc. arranged as described on p. 107, except that no lid is needed.

For many experiments, especially this one, a short (six inch) thermometer is useful as it is more stable when weighing. Such thermometers calibrated 0–100°C are obtainable from Messrs. Baird and Tatlock.

Procedure: Find the water equivalent of the calorimeter (see p. 109).

Break up some ice into small pieces, using a sharp-pointed instrument and have plenty of blotting paper ready with which to dry this ice.

Weigh the calorimeter *together with the thermometer* (the mass of ice added will be relatively small and therefore any water removed on the thermometer would be of importance, so the thermometer is never removed from the calorimeter during the experiment). Fill the calorimeter about two-thirds full of water at about 7 or 8°C above room temperature, and reweigh. Arrange the calorimeter etc. as instructed on p. 107.

Take the temperature of the water, and immediately add pieces of ice, which have been dried with blotting paper. Stir until the ice melts and then add another piece and continue the addition of dry pieces of ice until the temperature has fallen about as much below the room temperature as it started above it. Take a final temperature when the last piece of ice has melted.

The procedure of making the original and final temperatures about the same amounts above or below the room temperature makes a cooling correction unnecessary, as it may be assumed that the heat lost

* So that all weighings can be performed using a chemical balance.

when above room temperature approximately equals the heat gained while below it.

Weigh the calorimeter and its contents.

Perform several experiments, using the same calorimeter, etc.

Record and Calculation: Tabulate observations.

Calculate heat lost by water and calorimeter. This heat will have melted the ice, and the water formed (at 0°C) will have had its temperature raised to the final temperature.

Then, if

m_1 is the mass of water,
m_2 is mass of ice,
W is water equivalent of calorimeter,
l is latent heat of fusion of ice,
t_1 is the original temperature,
t_2 is final temperature,

$$\underset{\text{Heat gained}}{(m_2 \times l) + (m_2 \times t_2)} = \underset{\text{Heat lost}}{(m_1 + W)\,(t_1 - t_2)}$$

Determine by substitution the value each of your experiments yields for the latent heat and find the mean of all your answers.

Experiment 47. Determination of the Latent Heat of Vaporisation of Water at 100°C

Apparatus: Experimental difficulties arise in ensuring that the steam blown into the calorimeter does not carry over any hot water which has condensed in the delivery tube. Various forms of water traps may be inserted in the steam circuit, but the simple apparatus described below places the boiler near the calorimeter and makes the delivery tube fairly short. The ends of the latter should be cut at an angle, as this reduces the likelihood of the formation of drops. Lagging the delivery tube also improves results a little.

Fig. 59 shows the arrangement, which gives fairly satisfactory results. G is a gas ring with an asbestos sheet A to protect the calorimeter from the heating effect of the gas ring. C is the water boiler with a watertight cork, through which the steam delivery tube passes.

A small calorimeter should be arranged as shown in Fig. 40, p. 107, but without the lid. The use of a six-inch thermometer (see p. 129) is recommended here.

Procedure: Place the apparatus some distance away from the calorimeter, light the gas-ring, G, and leave it until the water boils.

Meanwhile use a chemical balance to weigh (separately) the calorimeter and thermometer (of which the water equivalent has been determined). Half fill the calorimeter with water at about 5°C below room temperature (use ice if necessary) and weigh again. When steam is issuing freely from the boiler—the steam should have passed long enough to heat the delivery tube so that no drops of water are formed—take the temperature of the water in the calorimeter. Now arrange the apparatus so that a jet of steam is blown on to the surface of the water in the calorimeter. Continue until the temperature has risen by about 10°C, and then quickly remove the calorimeter, etc. from under the jet of steam, stir the water with the thermometer and record the temperature.

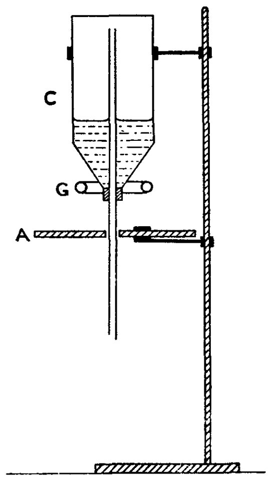


FIG. 59

Weigh the calorimeter and its contents without removing the thermometer. Repeat several times.

Record and Calculation: Tabulate the observations.

Calculate the heat lost and the heat gained and equate, solving for the unknown latent heat. Remember that this latent heat is given out while the steam is condensing, and that an equal mass of water at 100°C will be produced, which will then cool to the final temperature.

Find the mean of all your determinations.

Experiment 48. Determination of the Latent Heat of Vaporisation of Water by Henning's Method

Apparatus: Specially made steam generator and condenser of which details are given below; ammeter, 0–5 amp.; voltmeter, 0–12 volts; rheostat, about 12 ohms, 5 amp.; plug key; supply of current capable of giving a constant current of 3–5 amp., at 12–16 volts, for 15 minutes; stop-watch.

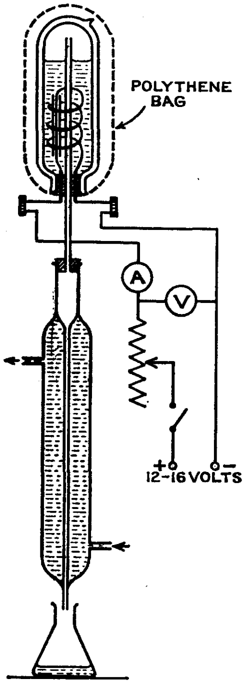


FIG. 60

The steam generator and condenser:

The heating coil should be 38 cm. of bright nichrome wire, S.W.G. 26. The leads for this should be of copper wire, S.W.G. 18. Flatten one end of each lead for about 1 cm. and drill a $\frac{3}{64}''$ hole in each. Pass the leads through a rubber stopper which will fit the steam generator, which should be a 250 c.c. vacuum flask. The holes for the leads should be made with a $\frac{1}{16}''$ drill. Thread one end of the heater wire through the hole in one of the copper leads and solder the contact, using Ersin-cored solder. Slip a piece of glass quill tubing, 5 cm. long, over the nichrome wire and slide it down to the soldered joint.

Now pass the delivery tube, which should be 30 cm. long and 8–9 mm. in diameter, through the central hole in the bung. Wind the heater wire loosely round it, arranging that the coil does not extend more than half-way up the flask. Now solder the free end of the heater wire to the other copper lead in the same way as before, and then wash both of the soldered joints well with boiling water. Fit terminals to the copper leads at the outer ends. Adjust the steam tube so that it nearly reaches the top of the flask and then attach its lower end to a Liebig condenser by means of a cork.

THEORY

If a current of C amps. is passed through the heater at a p.d. of V volts, then the number of calories given to the water in t seconds is VCt/J where J is the mechanical equivalent of heat in joules per calorie.

If in this time M gm. of water are evaporated, then the latent heat of vaporisation, L, is given by

$$L = \frac{VCt}{MJ} \text{ cals./gm.}$$

When a steady state has been reached the rate of evaporation will equal the rate of condensation, thus M can be determined by weighing the distillate.

Procedure: Arrange the apparatus so that the condenser is vertical (see Fig. 60), and connect up the circuit shown. Use thick leads for the wiring (why?) and check that the source of supply is capable of delivering a constant current of 3–5 amps. Fill the flask two-thirds full with boiling distilled water, checking that this is more than sufficient to cover the heater, but also ensuring that the water level is not too near the top of the steam delivery tube when it is inverted.

Switch on the current and allow the apparatus to come to a steady state with a beaker under the condenser. Meanwhile, weigh a conical flask.

Replace the beaker by this flask and at the same time start the stop-watch. Allow 20–25 gm. of water to collect and then remove the flask and simultaneously stop the watch. Reweigh the flask.

While the condensate is being collected, record the readings of the ammeter and the voltmeter.

Take several sets of observations, but do not run the apparatus for so long a time that the water level falls below the top of the coil—it will be possible to keep a check on the quantity of water left in the flask by considering how much has been collected.

Record and Calculation: Record all your observations and substitute each set into the equation given above. Calculate the mean value for the latent heat.

Notes: (i) It is advisable to enclose the flask in a loose polythene bag, tied at the neck, and to *keep this on* when dismantling the apparatus; vacuum flasks have been known to disintegrate after use.

(ii) If the resistance of the ammeter and of the leads between the voltmeter and the heater are determined a more accurate value for the p.d. across the heater can be calculated.

CHAPTER XVI

EXPANSION OF SOLIDS AND LIQUIDS

Experiment 49. Determination of the Coefficient of Linear Expansion of Brass

Apparatus: 50–100 cm. of brass rod; steam jacket; thermometer 0–100°C. Some means of measuring small changes in length is also needed such as a vernier microscope, micrometer screw, spherometer or optical lever. Details of such apparatus will be found on pp. 48–50. Most laboratories have an apparatus permanently assembled incorporating one of these methods, but if time is available it is worth while assembling the apparatus and using the optical lever as the means of measuring the expansion.

Procedure:

USING A VERNIER MICROSCOPE

Measure the brass rod provided to the nearest millimetre.

Insert it in the jacket as shown in Fig. 61.

One end of the rod should rest squarely against the rigid stop, A. Neither end should project very much from the jacket. Observe the temperature. As near as possible to the free end of the rod make a fine scratch with a needle point.

Focus a vernier microscope on this scratch, take the reading and record the temperature given by the thermometer.

Pass steam through the jacket and follow the scratch with the microscope. Take the scale reading when the expansion is complete.

Observe the temperature.

Using a Micrometer Screw

Fig. 61 shows a common form of the apparatus, and the procedure is the same as for the use of a vernier microscope, the expansion being

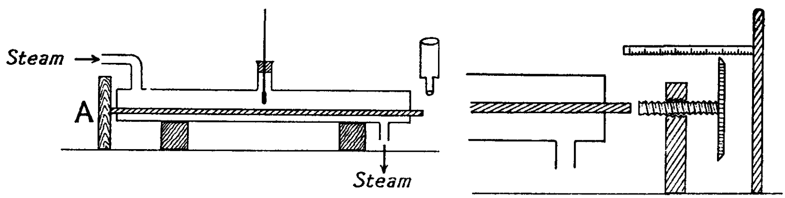


Fig. 61

measured by the screw instead. Before passing the steam through the jacket the micrometer screw should be adjusted so as to leave plenty of room for expansion, otherwise the apparatus will buckle.

Using a Spherometer

Proceed as in the other methods but mount the brass rod vertically and stand the spherometer with its outer legs on a rigid base—which is not affected by the temperature changes—and with its adjustable leg on the top of the brass rod. Screw the adjustable leg well clear of the end of the rod before passing the steam.

Using the Optical Lever

Mount the brass rod vertically and set the optical lever with its front legs on a rigid base (unaffected by the heating) and the rear leg on the brass rod. The expansion can be followed on the scale, and the necessary readings should be recorded.

Record and Calculation: Record all the observations.

Calculate the temperature rise (θ°C) and the expansion (l' cm.).

Substitute these quantities together with the original length (l cm.) in the equation

$$\alpha = \frac{l'}{l\theta}$$

to find the coefficient of linear expansion (α).

Experiment 50. Determination of the Mean Coefficient of Apparent Expansion of a Liquid in Glass, using a Density Bottle

Apparatus: 25 ml. density bottle (unless mercury is selected as the liquid, when a 10 ml. bottle should be used); suitable liquids are paraffin, aniline or chloroform. Thermometer (0–100°C × $\frac{1}{5}$).

Procedure: Clean and dry (see p. 52) the density bottle. Weigh it on a chemical balance. Fill it with the liquid making sure that no air bubbles are trapped in it and put it in a thermostat (or a large beaker of water will suffice), a few degrees above room temperature. After 15 minutes remove the bottle and carefully dry the outside, taking care to handle it as little as possible (certainly not enough to raise its temperature above that of the thermostat). Allow it to cool to room temperature and weigh it again. Note the temperature of the thermostat (t_1°C).

Place it for 15 to 30 minutes in a thermostat at 50°C and then remove, dry and reweigh. Note the temperature of the thermostat (t_2°C).

Record and Calculation: Record the observations as follows:

Weight of empty density bottle . . .	b gm.
Weight of bottle plus liquid which was sufficient just to fill it at t_1°C	a gm.
Weight of bottle plus liquid which was just sufficient to fill it at t_2°C	c gm.

Calculate the coefficient of apparent expansion (α) of the liquid in glass from the formula

$$\alpha = \frac{a-c}{(t_2-t_1)(c-b)}.$$

The proof of this formula may be found in theoretical text books but in any case the student should be able to think it out. The easiest method is to assume the density of the liquid to be ρ gm./cm.^{3} at t_1°C, so that the volume of the bottle becomes

$$\frac{a-b}{\rho}.$$

If then you remember that the final mass of liquid in the bottle occupied $(c-b)/\rho$ cm.^{3} at t_1°C and also expanded to fill the bottle at t_2°C, the result follows. No other density except that at t_1°C has been used in the calculation, and this is eliminated.

Experiment 51. Determination of the Coefficient of Apparent Expansion of Water by Matthiessen's Method

Apparatus: Sensitive balance and support—see below; two boxes of weights; sinker—a glass bulb, of diameter about 3 cm., and weighted with lead shot is usually available for this experiment; 400 ml. beaker; outer container packed with cotton wool into which the beaker will fit; stirrer; thermometer, 0–100°C, calibrated to at least 1/2 deg. C; 50–60 cm. of eureka wire, S.W.G. 47.; 100 ml. pipette.

Drill a 1″ diameter hole in the base board of the balance immediately under the centre of the left-hand pan. Before reassembling the balance, put the base board into the back right-hand corner of the case so that the position of the hole with regard to the base of the case can be marked. Drill a 1″ diameter hole in the base of the case at this point. Reassemble the balance and arrange it in its case as shown in Fig. 62, another balance case with a suitably placed hole in the top could form a suitable lower structure. Paint the inside of the lower enclosure white, or stick white paper in the back, so that the eureka wire suspension will be more easily seen.

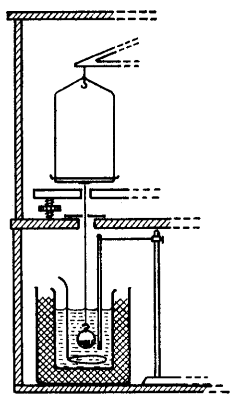


FIG. 62

Tie one end of the eureka wire to the junction of the supports under the left-hand pan. Pass the other end down through the holes, which should be carefully made to register, and tie a loop in the end. Hang the sinker in this loop, the length of the wire being adjusted so that the sinker remains completely immersed when the pans of the balance swing with maximum amplitude. Support the thermometer in a retort stand so that it is near the sinker (but not touching it) and out of the way of the stirrer.

To reduce the possibility of steam condensing on the underside of the left-hand balance pan, cut a slot 5 mm. wide in a square of blotting paper and place it below the base board so that the supporting wire passes through the slot. Secure the paper so that there is no risk of contact with the wire.

Level and adjust the balance, ensuring that it swings freely and can detect a change of 2 mgm.—an ordinary chemical balance should be capable of this, if it is in good condition.

THEORY

The sinker is weighed in air and in water at two or more different temperatures.

Let the weight in air be m gm.,
the weight in water at t_1°C. be m_1,
and the weight in water at t_2°C. be m_2,
then the mean coefficient of apparent expansion, γ, between the temperatures t_1 and t_2 is given by

$$\gamma = \frac{m_2 - m_1}{(m - m_2)(t_2 - t_1)}.$$

Thus, by weighing the sinker as it cools, the mean coefficient over several ranges of temperature can be determined.

Procedure: Place the empty beaker in its insulating container and adjust its position so that the sinker hangs in it. The outer vessel reduces the rate of loss of heat from the contents of the beaker and hence stabilises the temperature, the observations of which are therefore made with greater certainty. Weigh the sinker in air.

Nearly fill the beaker with water at about 90°C and make sure that the sinker remains completely immersed when the balance is brought into action and the right-hand pan is fully depressed. Stir the water well; stop stirring and, when the turbulence has ceased, weigh the sinker in water and note the temperature, using a lens for reading the thermometer. *Leave the balance in action and leave the weights on the right-hand pan* for the whole of the period that the water is allowed to cool, following the procedure described below carefully.

Allow the water to cool; this will cause the density to rise and therefore the left-hand pan will tend to move upwards. To *this* pan add a 50 mgm. weight so that the pan is again depressed and the balance pointer now at the right-hand end of its scale. Stirring gently, watch the pointer and when it is oscillating with small amplitude about the zero mark, record the temperature of the water. Carefully add another 50 mgm. weight to the left-hand pan and repeat the procedure. Continue this process of adding 50 mgm. weights and recording the temperatures at which balance is found until the water is cold.

The method described above avoids the disturbance caused by the usual weighing procedure of adjusting the weights on the right-hand pan and it will be found to be quite sensitive. At the end of the experiment check that no steam has condensed on the underside of the left-hand pan.

The temperature will fall from 80°C to 60°C in about 30 minutes.

To reduce the time taken thereafter, remove 100 ml. of the warm water with the pipette and replace it with 100 ml. of cold water; this should be done after each set of observations.

Record and Calculation: Tabulate your observations as follows:

Weight of sinker in air . . . . gm.

Weight on R.H. pan (gm.)	Weight on L.H. pan (gm.)	Difference	Temperature (°C.)
w	0·000	w	t_1
w	0·050	$w - 0{\cdot}050$	t_2
w	0·100	$w - 0{\cdot}100$	t_3
	etc.	etc.	

Substitute in the equation given under 'theory' above, to find the mean coefficient for a series of temperature ranges.

Note: If β, the coefficient of cubical expansion of the glass used, is known, the factor $\beta\left(\frac{m - m_1}{m - m_2}\right)$ may be added to the calculated result in each case to obtain the coefficient of real expansion of water.

Experiment 52. Determination of the Real Coefficient of Expansion of a Liquid by the Method of 'Balancing Columns'

Apparatus: Some laboratories have apparatus for this experiment already assembled.

If this is not so, one can fairly quickly be made from glass tubing of diameter about 1 cm. Three lengths each about 1 metre long are joined by rubber connections so as to form a U-tube to contain the liquid. One side of the U-tube is 'jacketed' so that it can be maintained at 100°C by steam. Two thermometers (reading 0–100°C.) are also needed.

THEORY

The principle of the method is that the pressure exerted by a liquid depends only on its density and 'head'. The density is related to the coefficient of expansion by the relationship

$$\rho_0 = \rho_t (1 + \alpha t)$$

where ρ_0 is the density at 0°C.

ρ is that at t°C.

α is the coefficient of real expansion of the liquid.

If two columns of liquid, at different temperatures t_1 and t_2, are balancing one another, as in this experiment, then if their heights are respectively h_1 and h_2,

$$\rho_1 h_1 = \rho_2 h_2.$$

$$\therefore \frac{h_1 \rho_0}{(1 + \alpha\, t_1)} = \frac{h_2 \rho_0}{(1 + \alpha\, t_2)}.$$

$$\therefore h_1 + h_1\, \alpha\, t_2 = h_2 + h_2\, \alpha\, t_1.$$

$$\therefore \alpha\,(h_1 t_2 - h_2 t_1) = h_2 - h_1.$$

$$\therefore \alpha = \frac{h_2 - h_1}{(h_1 t_2 - h_2 t_1)}.$$

(If t_1 is made to equal 0°C and $t_2 = t$°C then, $\alpha = \frac{h_2 - h_0}{h_0 t}$.)

Procedure: Set up the apparatus as shown in the Fig. 63. Steam from a suitable source is passed into the hot jacket, the temperature of which can be measured by the thermometer T_2. The temperature of the cold column can be observed by means of T_1 which should be hung near to the unjacketed column. Allow time for the apparatus to reach the steady state and THEN record the temperatures registered by T_1 and T_2. Measure the length of the two columns. The latter is the most difficult part of the experiment and with simple apparatus such as used here a high probable error has to be tolerated, due to the fact that it is not known just how much of the hot column is at the temperature t_2, and no allowance can be made for that portion of the liquid which is at some intermediate temperature between t_2 and t_1. If the reading of T_1 does not alter much during the experiment, probably the best way of finding the value of $(h_2 - h_1)$ is by using a cathetometer focused on the meniscus (i) before the steam is passed in and (ii) after the steady state has been reached. The value of h_1 can be found by a metre rule and from this and $(h_2 - h_1)$ the value of h_2 can be found.

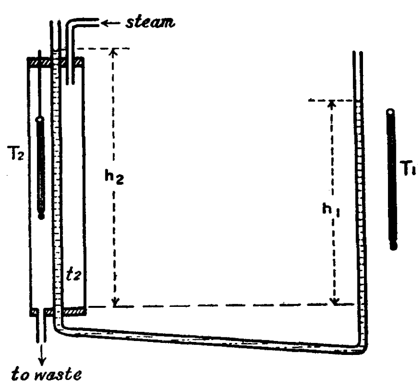


FIG. 63

Record and Calculation: Record all your observations and substitute in the formula to obtain the value of the coefficient of expansion. State your possible error.

Note: The possible error in this experiment may easily be of the order of 20%. There are many causes for this which have arisen because the apparatus is a much simplified form of the one used by Regnault and by Dulong and Petit and others. It is designed to demonstrate the principles of the method and is not intended to yield a satisfactory determination of the coefficient of expansion.

CHAPTER XVII

THE GAS LAWS

Experiment 53. Verification of Charles's Law for Temperatures between Room Temperature and 100°C

Apparatus: About 25 cm. of capillary tubing of uniform bore (about 1 mm.); concentrated sulphuric acid; water jacket which can be maintained at various constant temperatures (see p. 109); thermometer (0–100°C).

THEORY

Charles's Law states that every gas expands by 1/273 of its volume at 0°C. for every one degree C. rise in temperature, provided the pressure is kept constant, i.e. $v_t = v_0 + v_0\alpha t$.

In this experiment the pressure is maintained at atmospheric by using as a specimen of gas a column of air trapped in a capillary tube by a small length of liquid. The lengths of the air column are assumed to be measures of the volumes, i.e. the tube is assumed to be of uniform cross-sectional area.

This being so, it follows that

$$l_t = l_0\alpha t + l_0$$

where l_t is the length of the column at t°C.,
and l_0 is the length at 0°C.

Thus, if Charles's law is true a graph of l_t against t should be a straight line and its gradient divided by its intercept should be 1/273.

Procedure: Test the capillary tube for uniformity of bore (see p. 55.) Dip one end into concentrated sulphuric acid to a depth of about 2 cm. Close the other end with a finger, withdraw the tube and hold it horizontally. Tilt the tube a little so that the acid slides down the tube until it is about 10 cm. from the other end. Bring the tube back into the horizontal and wipe the wet end with an old cloth. Seal the other end in a Bunsen burner flame and leave to cool. In this way a fixed mass of dry air (occupying about 10 cm. of the tube, at room temperature) is confined in the tube. Fix the tube securely to a half metre scale, and place it in the water jacket with the open end uppermost and above the water level. Take a series of observations of corresponding values of the temperature and the length of the air column, making sure that the water is maintained at a constant temperature for a sufficient time for the expansion of the air to have ceased, so that you can be sure that the temperature you record is truly that of the air column.

Record and Calculation: Tabulate your results. Plot a graph of the length (l_t) of the air column against the temperature (t) in °C, and analyse your results by the method indicated under 'Theory' above.

Experiment 54. Determination of the Coefficient of Expansion of Air at Constant Pressure

Apparatus: This is usually available as a complete unit obtained from apparatus manufacturers.

It comprises a graduated vessel C (Fig. 64) connected by rubber tubing to the mercury reservoir R. Vertical movement of R enables the experimenter to maintain the pressure of the air in C at a constant value—that of the atmosphere—by adjusting the level of mercury in C and R to be the same. (Other methods of doing this are met with, one of them being that shown in Fig. 64B, in which mercury is either added to R or drained off at D to maintain the levels the same. The rest of the apparatus is the same.) The amount of dry air in C can be adjusted at the start of the experiment by opening tap T. The temperature of C is controlled by the water bath W which is heated by S, which is also usually used as a stirrer. The temperature of W is recorded by the mercury thermometer M (0–100°C.).

THEORY

Let α be the required coefficient
If v_t is the volume of air at t°C., and
v_0 is the volume of air at 0°C., then provided the pressure is maintained constant,

$$v_t = v_0(1 + \alpha t)$$

Hence

$$v_t = v_0\alpha t + v_0.$$

Thus a graph of v_t as ordinate against t should be a straight line. Its gradient will be $v_0\alpha$ and the intercept on the axis of v_t will be v_0. Thus the required coefficient will be the ratio of the gradient to the intercept.

Procedure: Set up the apparatus as shown in the figure and raise the temperature of the water bath to 100°C by passing through S that current for which it is rated. Adjust the levels in R and C to be the same, if necessary admitting some more dry air into C via T so that the initial volume (at 100°C) is as great as can be measured. This adjustment of levels will be facilitated by viewing them through a telescope and focusing the image of the mercury surfaces to show no parallax with the horizontal cross hair. If a telescope is not available use a horizontal rule placed near the apparatus as a simple sighting device.

Observe the temperature of W and the volume of air in C. Switch off the heater and allow W to cool slowly, stirring continuously. Take a series of corresponding readings of temperature and volume covering the range from boiling point to room temperature, ensuring that the air in W is always at atmospheric pressure when the volume is observed. As a refinement to aid stabilising the temperature of W, a rheostat of suitable rating may be included in the heater circuit and a small current passed through S to compensate for heat lost from W. This will be found especially valuable at higher temperatures (why more so than at lower temperatures?).

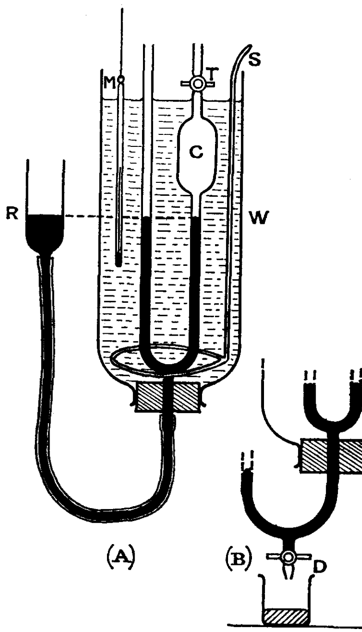


FIG. 64

Record and Calculation: Tabulate all observations. Plot a graph of volume of air (ordinate) against temperature in °C and evaluate the ratio of gradient to intercept as indicated under 'Theory' above.

Notes: (i) If the graph is not linear, or if the result is widely different from the expected value, the explanation may be leakage occuring at T during the experiment. This will mean repeating the experiment after attending to T—greasing is usually all that is needed.

(ii) If time is limited, observations may be taken as the temperature is raised. The method described above usually requires about 2–3 hours, as the cooling in the later stages is slow.

Experiment 55. Use of the Constant Volume Air Thermometer

Apparatus: Large vessel of water fitted with stirrer, or else water jacket which can be maintained at various temperatures (see p. 109); thermometer (0°–100°C); constant volume air thermometer.

The latter is shown in Fig. 65. The bulb contains dry air, and is sealed by a mercury column. By raising or lowering the reservoir, R, the top of this column can be made to coincide with the mark X. All measurements are made with the mercury in this position, and so the volume of the air is always the same.

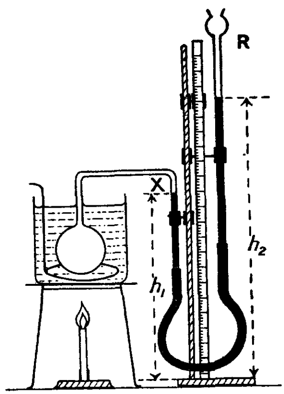


FIG. 65

Procedure: Boil the water in the containing vessel and keep at the boil for 5 minutes. Watch the mercury column, and by raising the reservoir bring the top of the column to the mark. When everything is steady, measure h_1 and h_2 and take the temperature of the boiling water.

Take the burner away and allow the water to cool, stirring vigorously all the time. WATCH THE MERCURY COLUMN, BECAUSE AS THE AIR COOLS IT WILL CONTRACT AND IF THE RESERVOIR IS NOT LOWERED SOME MERCURY WILL BE DRAWN INTO THE BULB, AND A FRESH START WILL BE NECESSARY. At any convenient temperature intervals—say about 90°, 80°, 70°, etc.—adjust the mercury level, measure h_2 and record the temperature.

Continue taking readings until the temperature has fallen to room temperature. If the cooling towards the end is unduly delayed, it may be hastened by adding cold water and thoroughly stirring. A final reading should be taken when the bulb has been in water at room temperature for ten minutes.

Observe the pressure of the atmosphere.

[If time is limited the experiment may be shortened by taking the observations as the temperature is raised. This method usually saves about half an hour.]

Record and Calculation: Tabulate as follows:

Temp. °C	h_1	h_2	Difference	Atmospheric Pressure	Total Pressure

Plot a graph of total pressure (ordinate) against temperature in °C. The relevant equation is

$$p = p_0(1 + \alpha t)$$

where p is the total pressure at t°C.
p_0 is the total pressure at 0°C,
and α is the coefficient of pressure increase at constant volume.

Thus
$$p = (p_0\alpha)t + p_0$$

and the intercept of the line on the p-axis is p_0; α can be calculated by dividing the gradient by the intercept (why?).

Notes: There are several important variations of this experiment:

(i) The coefficient can be determined if observations are taken with the bulb (i) in melting ice and (ii) in boiling water. The coefficient is then calculated, using the equation given above which simplifies to

$$\alpha = \frac{h_{100} - h_0}{100\,(H + h_0)}$$

when t_1 is made equal to zero and t_2 is made equal to 100.

This modification is important because the thermometer used is likely to have been calibrated using a constant volume air thermometer, in other words we are likely to be assuming what we are setting out to verify.

(ii) Using ice and boiling water the instrument can be calibrated as a thermometer and then used either to measure temperatures directly (e.g. to determine a boiling point of a given liquid) or to calibrate a thermometer.

(iii) If a value of α is assumed, the value of the atmospheric pressure can be deduced graphically from two or more observations at known temperatures. This is not a good way to find the atmospheric pressure but the experiment may be set in examinations as an exercise.

CHAPTER XVIII

THERMAL CONDUCTIVITY

Experiment 56. Determination of the Coefficient of Thermal Conductivity of a Metal, using Searle's Apparatus

Apparatus: This is usually available already assembled.

Fig. 66 shows the arrangement. A is a steam chest and heat is conducted along the cylindrical bar B, the temperature-gradient being obtained from the readings of thermometers T_1 and T_2, and their distance apart. C is a metal spiral through which a steady flow of water is maintained by a constant head apparatus (see p. 56). T_4 and T_3 are thermometers used to measure the temperatures at which the water enters and leaves this spiral. The apparatus should be well lagged. A stop-watch and vernier callipers are also required.

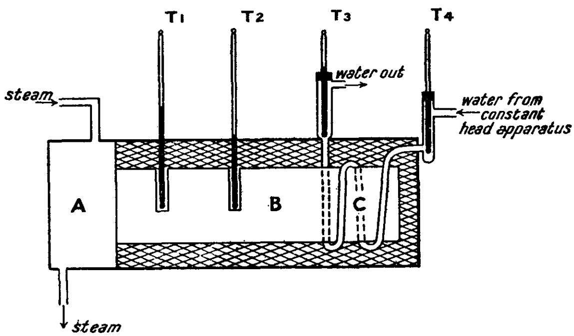


FIG. 66

THEORY

The spiral tube and its thermometers form a 'constant flow' calorimeter. If a mass *m* gm. of water flows through C in a time *t* secs. when the thermometers are registering *steady* values of t_3°C and t_4°C, then the number of calories being delivered per second by B is

$$\frac{m(t_3 - t_4)}{t}.$$

If the cross sectional area of B is *A* cm.², and T_1 and T_2 are *d* cm. apart, reading steady values of t_1 and t_2°C, then

$$\frac{m(t_3 - t_4)}{t} = k.A.\frac{t_1 - t_2}{d}$$

where *k* is the coefficient of thermal conductivity of the metal of which B is made.

Procedure: First measure the distance d and the diameter of B. Pass steam through A and allow a *trickle* of water to pass through C from the constant head apparatus. At intervals of 2 minutes observe the reading of all the four thermometers. When the steady state has been reached, judged by there being no change in the readings of the thermometers for five minutes, record these readings and determine the rate of flow by weighing a suitable vessel (e.g. a conical flask) before and after allowing the water from C to flow into it for a time observed using the stop-watch.

Record and Calculation: Record all observations. Calculate A. Substitute this and the other observations in the equation above and solve for k.

Experiment 57. Determination of the Coefficient of Thermal Conductivity of Rubber in the Form of a Tube

Apparatus: About 80 cm. of Bunsen burner tubing; steam supply fitted with safety tube as shown in Fig. 67; calorimeter of large capacity; stirrer; 20 cm. of glass rod; T-tube of outside diameter to take the rubber tubing; two spring clips; thermometer (0–50°C $\times \frac{1}{5}$); stop-watch; asbestos screen; vernier microscope.

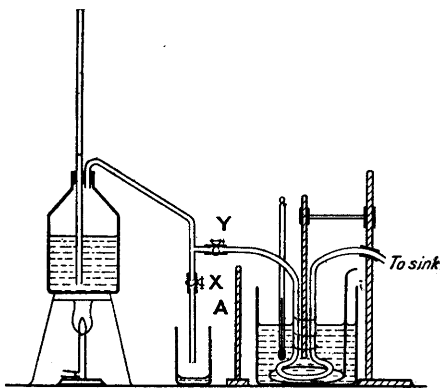


FIG. 67

Procedure: Find the water equivalent of the calorimeter (see p. 109). Fill the calorimeter about two-thirds full of water of which the mass is known. The best way of finding this in the absence of a balance of suitable capacity is to measure its volume; the accuracy obtained will be good enough for this experiment. Introduce the rubber tubing with a *single* coil in it so that about 30 cm. are in the water. A convenient way of securing it is to tie it to the glass rod and to support the latter vertically by means of a clamp and stand (the water equivalent of the immersed glass can be found if desired by multiplying the volume immersed by 0·4—see p. 109). If more rubber is used condensation occurs to a considerable degree in the tubing and consistent results cannot be obtained. Connect one end of the tubing to Y (Fig. 67) and place the other end either over the sink or in a vessel to collect the water which will condense.

Keep X open and Y closed until steam is issuing freely from X and then take the temperature of the water in the calorimeter (t_1°C). Open Y and *immediately afterwards* close X. As Y is opened, start the stop-watch. Allow the steam to pass through the rubber tubing until a rise of temperature of about 15°C has occurred, then disconnect the steam supply by opening X and *then* closing Y. As Y is closed, stop the watch. Stir the water in the calorimeter and record the highest temperature reached (t_2°C).

Remove the tubing and measure the length which was immersed (l cm.). Find the internal and external diameters of the tubing (d_1 and d_2 cm. respectively) but do not cut off a small piece for this purpose, as the cross-section will thereby be warped even more than it was by the single cut made initially.

Record and Calculation: Record all observations. Use the observations made on the calorimeter and the water to calculate the amount of heat (Q) which passed through the walls of the tubing in time t seconds.

The thickness of the walls (d cm.) is taken as half the difference between the diameters, i.e.

$$d = \frac{d_2 - d_1}{2} \text{ cm.}$$

The area of cross-section across which the heat passed is assumed to be the product of the length of the tubing immersed and the mean circumference, i.e.

$$l \times \pi \frac{(d_2 + d_1)}{2} \text{ cm.}^2 = A \text{ cm.}^2$$

The temperature of the inside surface is taken as 100°C, whilst that of the outside surface θ is regarded as the mean of the initial and final temperatures of the water, i.e.

$$\theta = \left(\frac{t_1 + t_2}{2}\right) \text{°C.}$$

Calculate these quantities and substitute in the equation

$$Q = \frac{k.A.(100 - \theta).t}{d}.$$

Notes: (1) The fact that in this experiment steam is passed into a cold tube leads to condensation and even with a short piece of tubing this is a source of error. This difficulty can be overcome as follows:

Drill a hole of the diameter of the rubber tubing in the bottom of one calorimeter, which is thereafter reserved for this experiment. Arrange the apparatus as before but use a coil of rubber tubing led out of the calorimeter through a watertight joint in the bottom. Pass steam through the tube until it is issuing freely at the open end, which should be at least a foot to one side of the calorimeter so that the emerging steam does not cause any heating effects in the calorimeter or its contents. Observe the temperature rise of the water over a measured time interval and deduce the required coefficient in the manner described above.

(2) The heat losses to the surroundings may be important here and if necessary a correction should be applied using the procedure given in Experiment 37, p. 113.

Experiment 58. Determination of the Coefficient of Thermal Conductivity of Glass in the Form of a Tube

Apparatus: About 50 cm. of thick-walled glass tubing—barometer tubing is excellent; glass jacket for this tubing through which steam can be passed; two T-tubes fitted with thermometers as shown in the figure; constant head apparatus (see p. 56); measuring cylinder; stop-watch; vernier microscope. The arrangement is shown in Fig. 68, which

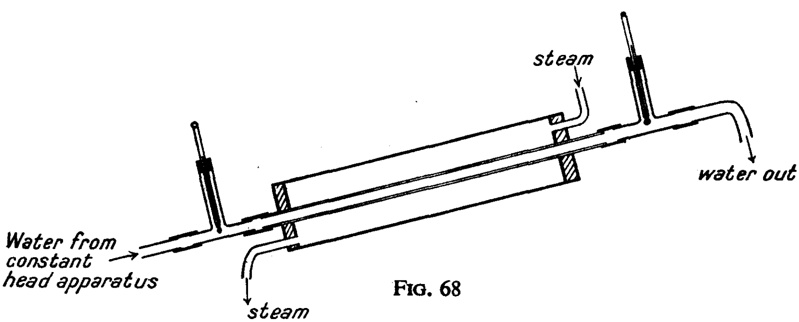


FIG. 68

suggests that a condenser could be used as the glass tubing with the jacket combined. A condenser is unsatisfactory as (i) there is no easy way of measuring the thickness of the glass tubing which actually conducts the heat (it may not be the same inside the condenser as at the ends) and (ii) the glass is usually thin, so that the steam condenses. Thus the jacket temperature may not be even approaching 100°C—unless so slow a rate of flow is used that the temperature rise of the water is of the order of 60–80°C.

Procedure: Pass steam through the outer jacket until the two thermometers are recording constant temperatures—showing that the steady state has been reached. The adjustment of the temperature rise can most easily be done by controlling the rate of flow by the height of the constant head apparatus.

When the steady state has been maintained for several minutes measure the rate of flow of water by measuring either the weight or the volume of water delivered in an observed time, and record the readings of the thermometers.

Measure the internal and external diameters of the tube and the length of the tube which was inside the steam jacket.

Record and Calculation: Record all observations. Calculate the thickness of the glass tubing and the area of it which was conducting heat. Find also the amount of heat received by the water each second. Use these quantities to calculate the coefficient of thermal conductivity of the glass.

Experiment 59. Determination of the Coefficient of Thermal Conductivity of a Solid which is a Bad Conductor by Lees's Disc Method, using a Steam Chest as a Source of Heat

Apparatus: In most laboratories this is available as a complete unit.

Fig. 69 shows the construction and arrangement. Here X and Y are metal discs, about 11 cm. in diameter and 1·25 cm. thick, between which the specimen is placed, and of which the temperatures are measured by the thermometers T_X and T_Y, placed in specially drilled holes as shown. Z is a steam

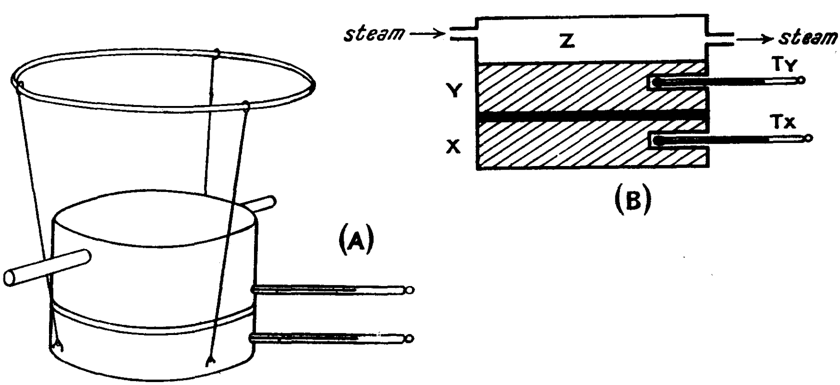


FIG. 69

chamber of the same diameter as X and Y. The whole apparatus is suspended by three strings attached to hooks fixed in X. The specimen should be equal in diameter to X and Y and should be not more than 0·1 cm. thick. Failing any particular material which it is desired to investigate, cardboard is a suitable bad conductor and is easy to cut into the right shape. The thermometers should be calibrated from 0 to 100°C, $\times \frac{1}{5}$. A stop-watch and micrometer screw-gauge are also needed.

THEORY

Steam is passed through Z until a steady state is achieved, i.e. all the heat passing through the specimen is being lost by emission from X. If, when this steady state has been reached, the readings of T_X and T_Y are θ_X and θ_Y respectively then the number of calories passing through the specimen every second (Q) is given by

$$Q = k.A.\frac{(\theta_Y - \theta_X)}{d} \quad . \quad . \quad \text{(i)}$$

where k is the required coefficient of thermal conductivity,
A is the area of one flat surface of the specimen in cm.^{2},
and d is the thickness of the specimen in cm.

In the second part of the experiment the rate of loss of heat from X, with the specimen on top of it, is investigated by observing how long this arrangement takes to cool from a temperature of a few degrees above θ_X to an equal interval of temperature below θ_X. If in this part of the experiment the initial temperature recorded by T_X is θ_1 and the final one is θ_2, then the rate of loss of heat in calories per second from X is

$$\frac{ms(\theta_1 - \theta_2)}{t}$$

where m is the mass in gm. of the disc X (the thermal capacity of the thermometer is ignored),
s is the specific heat of the material of X,
and t is the time taken for the temperature to fall from θ_1 to θ_2.

This amount of heat must be equal to Q—since both represent the amount of heat emitted per second at temperature θ_X. Thus

$$Q = \frac{ms(\theta_1 - \theta_2)}{t} \quad . \quad . \quad \text{(ii)}$$

Procedure:

(i) Having cut the specimen to the required dimensions, measure its thickness with the micrometer screw-gauge, and make a determination of its mean diameter.

Place it between X and Y and arrange the apparatus as shown in Fig. 69. From an apparatus of the usual type pass steam through Z until X and Y have recorded constant temperatures for at least five minutes. Record these temperatures (θ_X and θ_Y respectively).

(ii) Transfer the specimen to the top of Z (to keep it warm) and place Y directly on top of X. (This is the best way to heat X, as if a bunsen burner were used the plating which ensures constant emissivity might be damaged by flaking or oxidation.) When the temperature of X is about 5°C, above the value recorded in part (i) remove YZ and replace it by the specimen. Observe the time taken by X to fall from this temperature to an equal interval below the reading of T_X taken in the first part, recording the initial and final temperatures. Determine the mass of X.

Record and Calculation: Calculate the area in cm.^{2} of the specimen. Substitute the values obtained in the second part of the experiment in equation (ii) above, to find a value for Q. Substitute this value, together with those obtained in part (i) of the experiment, in equation (i) above, and solve for k.

Experiment 60. Determination of the Coefficient of Thermal Conductivity of a Solid which is a Bad Conductor by Lees's Disc Method, using an Electrical Heating Element

Apparatus: This apparatus is often available as an assembled unit, but if there is not one in the laboratory the following instructions should enable you to make one.

A diagram of the apparatus is shown in Fig. 70 in which X, Y, and Z are brass discs about 5 cm. in diameter and 1·3 cm. thick drilled with holes (about 0·6 cm. in diameter) to take thermometers T_X, T_Y and T_Z. The heater consists of 32 cm. of 28 S.W.G. nichrome wire (resistance approximately

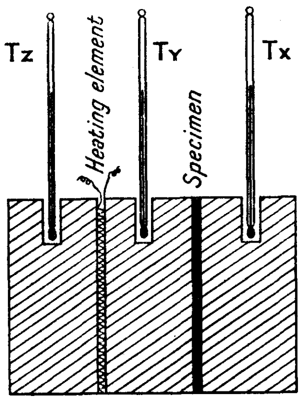


FIG. 70

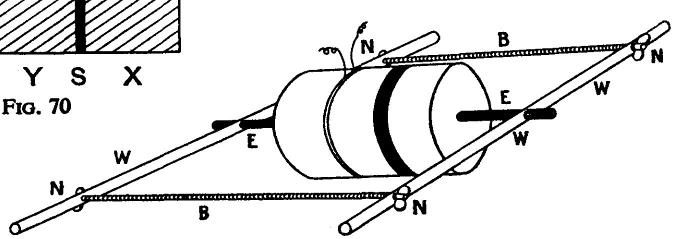


FIG. 71

4 ohms), wound on a mica sheet which is about 4 cm. in diameter, and having a mica sheet about 5 cm. diameter on either side of it.

Finally the whole apparatus should be varnished and baked so as to ensure that the surfaces have constant emissivities.

A cradle should be made to support the apparatus, the only points of contact between the cradle and the discs being made by a pair of ebonite rods of small diameter touching the centres of X and Z. The details of such a cradle are illustrated in Fig. 71 in which E are ebonite rods, W are wooden dowel rods, B are of screwed brass rod, and N are wing nuts.

For the experiment the following instruments are also required:

Voltmeter (0–12 volts); ammeter (0–3 amps); rheostat (0–12 ohms and to carry 3 amps); plug key; steady supply of D.C. at 12 volts (see p. 281); three thermometers (T_X, T_Y and T_Z) calibrated from 0–50°C by $\frac{1}{5}$; another thermometer for recording temperature of the environment.

THEORY

A current is passed through the heating element and when the steady state has been reached the thermometers are read. Suppose at this steady state the temperatures of X, Y, and Z are found to be θ_X, θ_Y, and θ_Z in excess of that of the surroundings, and let e be the rate of emission of heat from the exposed surfaces in calories per cm.^{2} per °C. excess temperature. Then if we assume that the temperature of S, the specimen, is the mean of the temperatures X and Y, the total heat emitted per second is given by

$$e\alpha_X\,\theta_X + e\alpha_s\frac{(\theta_Y + \theta_X)}{2} + e\alpha_Y\,\theta_Y + e\alpha_Z\,\theta_Z$$

where α_X, α_Y, α_Z, and α_s are the areas of X, Y, Z and the specimen respectively which are emitting heat.

This heat is all supplied by the heating element and must therefore be equal to

$$\frac{V.I}{J}$$

where V is the potential drop in volts across the element,
I is the current flowing in amps.,
and J is the mechanical equivalent of heat, which may be taken as 4·18 joules per calorie.

Thus if the other quantities in this equation are known the value of e can be obtained from the equation

$$\frac{VI}{J} = e\alpha_X\,\theta_X + e\alpha_s\frac{(\theta_Y + \theta_X)}{2} + e\alpha_Y\,\theta_Y + e\alpha_Z\,\theta_Z \quad . \quad . \quad . \quad \text{(i)}.$$

The heat flowing through S is given by

$$kA\frac{(\theta_Y - \theta_X)}{d}\text{ calories/sec.,}$$

where A is the area of one flat face of the specimen and d is the thickness of the specimen.

Another expression for this in terms of the emissivity can be found as follows:

All the heat entering S from Y does not pass into X as some is emitted from the curved surface of S; so the heat flowing through S is taken as the mean of the heat entering S from Y and that leaving S for X.

The heat entering S from Y is that which is emitted by S and X together i.e.

$$e\alpha_s\frac{(\theta_Y + \theta_X)}{2} + e\alpha_X\,\theta_X\cdot$$

The heat leaving S for X is that which is emitted by X alone, i.e. $e\alpha_X\theta_X$. The mean of these quantities is

$$\frac{1}{2}\left[e\alpha_s\frac{(\theta_Y+\theta_X)}{2}+2e\alpha_X\,\theta_X\right]$$

and this must therefore equal $\dfrac{kA(\theta_Y-\theta_X)}{d}$.

Hence

$$kA\frac{(\theta_Y-\theta_X)}{d}=\frac{1}{2}e\alpha_s\frac{(\theta_Y+\theta_X)}{2}+e\alpha_X\theta_X \quad . \quad . \quad . \quad . \quad \text{(ii)}$$

From this equation a value for k can be found.

Procedure: Connect the heater into the circuit given in Fig. 72
where A is the ammeter,
V is the voltmeter,
K is the plug key,
R is the rheostat
and S is the supply of current.

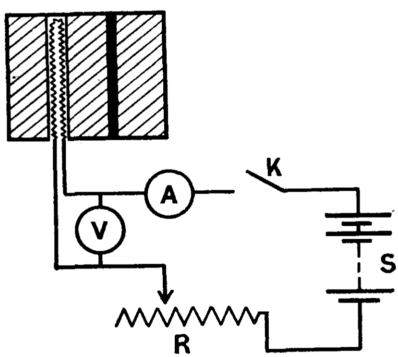


FIG. 72

Adjust R until the current is about $2\frac{1}{2}$ amps. and maintain it at this value until the temperature of Z is about 35°C. Then increase the value of R so that the current is reduced to rather less than one amp., and the voltage of course to a little below 4 volts (for a 4 ohm heater). Maintain this current constant until T_X, T_Y and T_Z have all registered constant temperatures for five minutes and then record their readings, together with those of A and V.

Observe the temperature of the surroundings.

Make the necessary observations to enable you to determine the values of α_X, α_Y, α_Z and α_s, remembering that they are the total areas exposed to the surroundings.

Record and Calculation: Record all your observations.

From the temperature readings calculate the values of the excess temperatures (θ_X, θ_Y and θ_Z).

Calculate the values of α_X, α_Y, α_Z and α_s.

Substitute these quantities together with the observed values of V and I in equation (i) to find a value for e.

Calculate the area A of the flat face of the specimen and substitute this and the other relevant quantities in equation (ii) to find a value for k.

CHAPTER XIX

EMISSIVITY

Experiment 61. Determination of the Surface Emissivity of Nickel in the Form of Wire

Apparatus: 120 cm. of bright nickel wire, S.W.G. 34 with potential leads of thin bare copper wire, each about 3 cm. long, soldered on at about 15 cm. from each end; millivoltmeter (0–10 mV); voltmeter (0–1·5 volts); 2 ohm standard resistance coil; variable resistor (0–500 ohms); 2-volt accumulator; two double-pole-double-throw switches (see p. 289); plug key; thermometer (0–50°C × $\frac{1}{5}$); micrometer screw-gauge.

THEORY

Surface emissivity is defined as the number of calories emitted per second by one sq. cm. of the surface when the excess temperature over that of the surroundings is 1°C. When the temperature of a wire carrying a current becomes steady the rate of loss of heat from its surface must be equal to the rate at which energy is being supplied by the current, i.e. the surface emissivity, e, is given by

$$l\pi d(t_2 - t_1)e = \frac{I^2 R_2}{4{\cdot}2}$$

$$\text{i.e.} \qquad e = \frac{I^2 R_2}{4{\cdot}2} \cdot \frac{1}{l\pi d} \cdot \frac{1}{(t_2 - t_1)}$$

where t_1 is the temperature of the surroundings in °C,
t_2 is the temperature of the wire in °C.
R_2 is the resistance of the wire at temperature t_2, in ohms.
I is the current flowing in the wire in amps.,
l is the length of the wire in cm.,
and d is the diameter of the wire in cm.

Since in the experiment we do not actually measure the current I but the potential drop (V_2') across the wire, it is convenient to eliminate I from the equation by putting $I = V_2'/R_2$ and obtain the form

$$e = \frac{(V_2')^2}{4{\cdot}2 . R_2} \cdot \frac{1}{l\pi d} \cdot \frac{1}{(t_2 - t_1)} \qquad \text{(i)}$$

The only quantities in this equation which are difficult to measure are the temperature t_2 and the 'hot resistance' R_2. These are determined by observing the potential difference across the standard resistance coil and across the wire, when they are wired in series, first at temperature t_1 and then at temperature t_2. Reference to the circuit diagram and the instructions on procedure will tell you how this is done. The mathematics of the deduction is as follows:

At temperature t_1 let the P.D. across S be V_1 and across the wire be V_1'. At temperature t_2 let the P.D. across S be V_2 and across the wire be V_2'.

Then the 'hot' resistance of the wire is obtained at once from

$$R_2 = \frac{V_2'}{V_2}S \quad . \quad . \quad . \quad \text{(ii)}$$

To find the temperature the coefficient of increase of resistance with temperature for nickel must be known—it may be taken as 0·0062 per °C. Let this be represented by the symbol ρ.

Then $\qquad R_1 = R_0(1 + \rho t_1)$

and $\qquad R_2 = R_0(1 + \rho t_2)$

Thus by division we have

$$\frac{R_1}{R_2} = \frac{1 + \rho t_1}{1 + \rho t_2} \quad . \quad . \quad . \quad \text{(iii)}$$

from which t_2 may be calculated since t_1 is observed, and R_1 is calculable from the relationship

$$R_1 = \frac{V_1'}{V_1} \cdot S \quad . \quad . \quad . \quad \text{(iv)}$$

Procedure: Set up the apparatus as shown in Fig. 73 in which ABCD is the wire, the potential leads being attached at B and C,

S is the standard two ohm resistance,
K is the plug key,
R is the 500 ohm variable resistor,
E is the accumulator,
V is the voltmeter, 0–1·5 volts,
MV is the millivoltmeter, 0–10 mV,

and X and Y are the D.P.D.T. switches.

All leads except AE, ER, RK and KS should be of thick copper wire of S.W.G. about 16. Trace the connections through X and Y with great care to ensure that the current flows through V and MV in the correct direction. See p. 290 for further information on setting up circuits.

With all the resistor R in circuit close key K, thus allowing a current of about 4 mA. to flow through S and the wire. Connect Y to MV and use the two positions of X to find (i) the P.D. across S and (ii) the P.D. across the wire between B and C. It may be assumed that the current of 4 mA. is too small to raise the temperature of the wire above that of the surroundings by more than a negligible amount and that these readings correspond therefore to V_1 and V_1'. Now reduce

R to zero so that the current rises to about 1 amp. switching Y so that V is included. When sufficient time has elapsed for the wire to have reached a steady state use the two positions of X as before to find the P.D.'s across S and the wire. These readings will be V_2 and V_2' respectively. Record the temperature of the surroundings. Measure the length of BC and measure the diameter of the wire in a number of places with the micrometer screw-gauge.

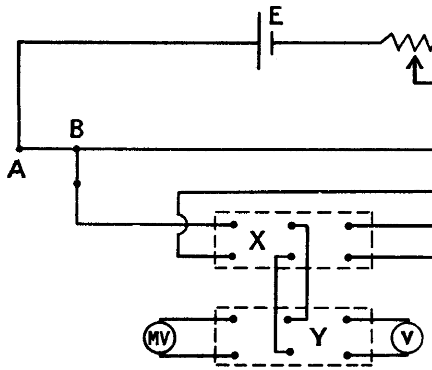


FIG. 73

Record and Calculation: Record all readings.

Calculate the mean diameter of the wire and values for R_1 and R_2 from equations (ii) and (iv).

Calculate t_2 from equation (iii).

Substitute these values in equation (i) to find a value for e.

Note: Consistent results are difficult to obtain with this method; attention is directed to Problem 13 on p. 502.

CHAPTER XX

MECHANICAL EQUIVALENT OF HEAT

Experiment 62. Determination of the Mechanical Equivalent of Heat by an Electrical Method

Apparatus: Copper calorimeter and stirrer; lid for the calorimeter, made of badly conducting material and with a pair of terminals mounted in it, across which, beneath the lid, is connected a heating coil (see Fig. 74).

The coil is usually of resistance 2–3 ohms and should be varnished and baked so as to provide it with an insulating coating. The latter eliminates electrolytic effects and reduces the risk of short-circuiting by the stirrer.

In addition the following:

Thermometer (0–50°C $\times \frac{1}{5}$). Stop-watch; rheostat; 12-volt supply; suitable ammeter and high-resistance voltmeter. The range to be covered by these two instruments will depend on the resistance of the coil and of the electrical supply used. Work out the values of these ranges.

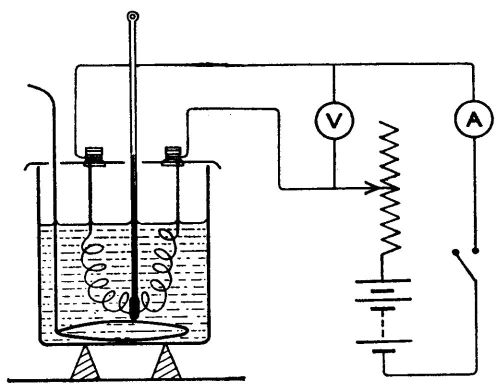


FIG. 74

THEORY

In this experiment the heat is entirely generated by the current in the coil. If the potential difference across the coil is V volts and the current flowing in it is I amps., then the heat generated in t secs. is

$$VIt/J \text{ calories}$$

where J is the mechanical equivalent of heat in joules per calorie.

Assuming that heat losses may be neglected, all this heat is used to raise the temperature of the calorimeter and its contents, from the initial temperature (θ_1) to the final temperature (θ_2). Thus if the mass of water used is m gm. and the water equivalent of the calorimeter, etc., is W gm.

then $$(W + m)(\theta_2 - \theta_1) = VIt/J.$$

So by assuming values for all other quantities appearing in this equation (except J) we can calculate J.

One further problem arises—the computation of the water equivalent of the calorimeter etc. This may be considered under three headings:

(1) The calorimeter, stirrer and thermometer: proceed as instructed on p. 109.

(2) The coil: Reference to a book of tables will show that for most metals, or alloys, of which the coil is likely to be made, the specific heat will be about 0·1. Thus the thermal capacity of the coil can be calculated from its mass, to an order of accuracy sufficient to meet our needs, but in most cases the mass of the coil is so small that its thermal capacity is negligible.

(3) The lid: Since this is made of badly conducting material and the temperature range used in the experiment is only 10°C the actual temperature rise of most of the lid will be extremely small, and the thermal capacity of the lid may thus be neglected.

Procedure: Find the water equivalent of the apparatus by the method indicated above.

Weigh the calorimeter first empty and then containing enough water to cover the coil.

Connect the coil into the circuit shown in the diagram (Fig. 74). Switch on, and adjust the rheostat so that a suitable p.d. is applied to the coil; one of the two instruments should read nearly full-scale deflection and the other one (if you have selected it wisely) almost as great a deflection. Switch off immediately this adjustment is completed. Stir well, and then record the (initial) temperature of the water.

Switch on the current and start the stop-watch simultaneously. Make observations each minute of the voltage and current and if there is any variation restore to the original values by using the variable resistor. (If there is any *marked* variation, the experiment must be abandoned and started again). While the current is flowing, stir the water gently.

When a temperature rise of about 10°C has occurred switch off the current and record the time for which the current has been flowing; *do not however stop the watch.* Record also the temperature at the instant when the current was switched off. Continue taking observations of temperature and time to enable you to calculate a cooling correction using one of the methods given in Experiment 37 (that given in the note at the top of p. 118 is suitable).

Record and Calculation. Tabulate all your observations.

Substitute your observed values in the equation, given above, to find the mechanical equivalent of heat.

Experiment 63. Determination of the Mechanical Equivalent of Heat, using Callendar's Apparatus

Apparatus: The apparatus described here is a modified form of Prof. Callendar's more elaborate one, but is capable of giving very reliable results.

It consists essentially of a brass drum, which acts as a calorimeter and contains a known weight of water. The drum is attached to a spindle and can be rotated by the hand wheel or a small motor can be used. The drum is fitted with a ribbon brake the work from which is converted into heat which is measured in the usual calorimetric way. The apparatus should also be provided with a revolution counter.

Procedure: If the apparatus is to be worked by hand, a preliminary trial is needed. This is necessary in order to adjust the weight hanging on the end of the belt and the rate of rotation, so that the weight 'floats' all the time and a steady rate of revolution is maintained.

The water equivalent of the drum must be known, and it is sufficiently accurate to calculate it from the mass of the drum and the specific heat of brass.

Water is introduced into the drum so that there is as much as possible, but make sure that during rotation none will be spilled. It is quite accurate enough to pipette this water into the drum and assume that each millilitre weighs 1 gm.

The best results are obtained when a start is made with the water at room temperature, and a cooling correction obtained. This can be avoided by starting with the temperature a few degrees below the room temperature and finishing when the temperature has risen an equal amount above it. If this is done care must be taken that a film of moisture is not formed on the outside of the drum, which will make the friction very irregular. For the same reason the silk brake band should be stored in a desiccator when not in use.

Having made all preliminary arrangements, take the temperature of the water, by means of the bent thermometer which fits in the drum. Read the revolution counter and start the drum revolving. At each subsequent minute read the spring balance, the temperature, and the revolution counter.

When the temperature has risen by 10–15°C, stop the motor or other turning agent and remove the weight from the belt. Detach the belt from the spring balance, wrap it round the drum and fasten it. Restart the motor—the drum and the belt now revolve together. Continue the temperature readings every minute until the rate of cooling is constant. Measure the diameter of the drum and record the weight which was suspended from the belt.

Record and Calculation: Tabulate results:

Mass of drum	gm.
Water equivalent of drum	gm.
Mass of water placed in drum . . .	gm.
Temperature of water at start . . .	°C
First reading of counter	
Second reading of counter	
∴ Number of revolutions	
Diameter of drum	cm.
Mass attached to belt	gm.

Time in minutes	Temperature readings	Reading of spring balance
0		
1		
2		
etc.		

Calculate the work done by frictional resistance of the belt from:

Force of friction = (Load on belt − average spring balance reading)
$= F$

Work done $= F \times (\pi \times \text{Diameter of drum}) \times$ No. of revolutions.
Let this be W joules.

Calculate the heat involved in the rise in temperature of water and drum, introducing a cooling correction as in Experiment 37, p. 113. Let this be H calories.

Calculate J from:

$$W = JH.$$

Experiment 64. Determination of the Mechanical Equivalent of Heat, using a Constant Flow Calorimeter

Apparatus: This experiment is a very much simplified form of that due to Callendar and Barnes. The principles involved are the same but the measuring instruments are not so accurate.

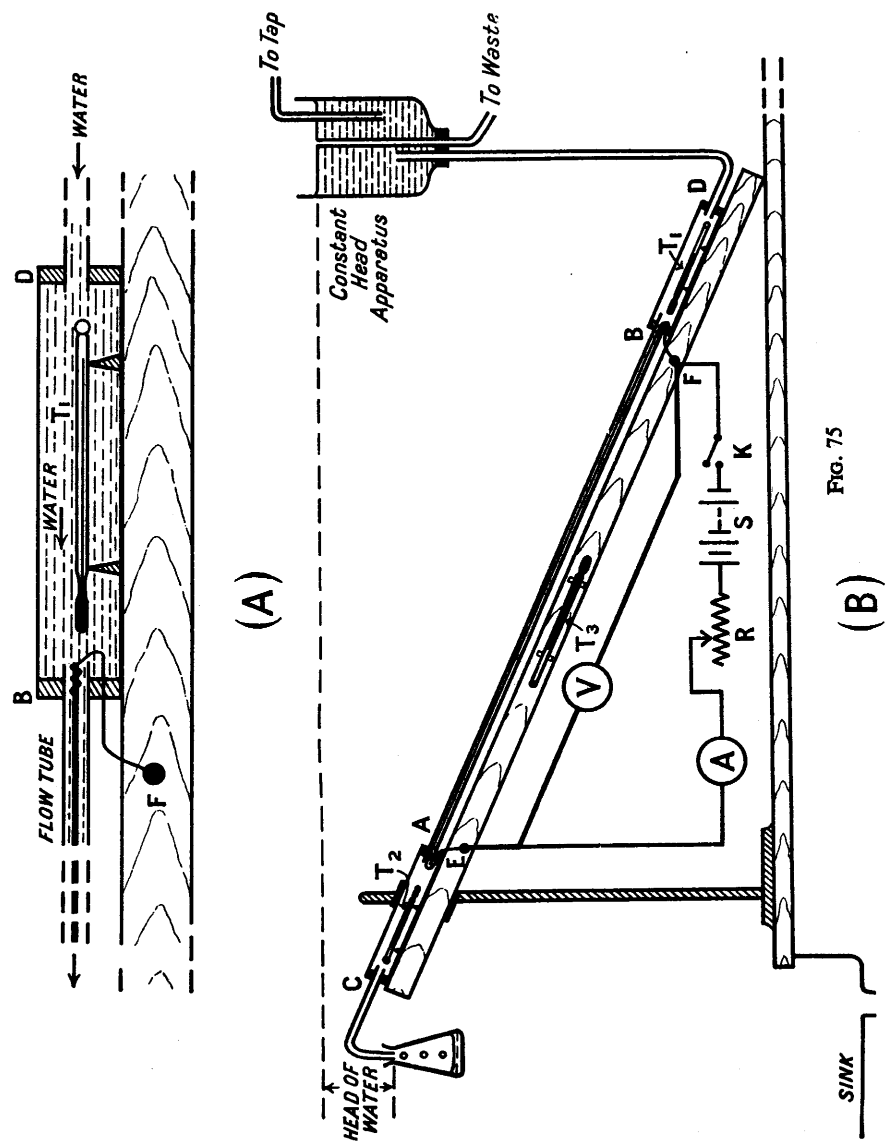

WATER
D
T1
WATER
B
FLOW TUBE
F
(A)
To Tap
To Waste
Constant Head Apparatus
D
T1
B
F
K
S
R
T3
V
A
A
E
T2
C
HEAD OF WATER
SINK
(B)

FIG. 75

If a constant flow calorimeter is not available in your laboratory the following instructions should enable you to make one in about an hour.

The flow tube—AB in Fig. 75B—should be 100 to 150 cm. long and of 4 mm. bore. Cut a piece of bright nichrome wire, S.W.G. 20, of length 10 cm. more than the flow tube, varnish it and bake it, to provide it with an insulating coating. When it is cool introduce it into the flow tube so that all the excess length projects from one end. Carefully remove the insulation from about 3 mm. of the wire at a distance about 5 cm. from the end and fix to this point about 10 cm. of insulated copper wire, S.W.G. about 24, by twisting it securely round to make good electrical contact (oxidised nichrome cannot be soldered but bright nichrome can be—though not easily).

Now draw the nichrome wire towards the other end until all the excess length projects and fix a similar lead at 5 cm. from the other end. Pull the nichrome wire back 5 cm., so that the contacts are just at the ends of the flow tube and remove the unwanted 5 cm. of nichrome wire at each end, using pliers. Turn the copper leads back along the outside of the tube and tie them loosely round the tube to keep them out of your way for the next part of the operation. Next fit the end tubes CA and BD which should be of sufficient internal diameter to take the thermometers (T_1 and T_2) easily as shown in Fig. 75A. Test T_1 and T_2 by the method given under 'Procedure' below, and after inserting them into BD and CA, watertight joints should be made using, say, Bostik B compound. Fit tube BD with an inlet at D of a suitable diameter to take rubber tubing from a constant head apparatus, making the joint watertight; and similarly fit AC with an outlet of the shape shown in Fig. 75B. For ease of storage it is convenient if this outlet is removable—a rubber connection is an easy way to arrange for this.

When this is done the apparatus should be securely mounted on a baseboard so that it can be handled easily without the risk of putting any strain on the watertight joints or the internal electrical connections. The copper leads (which serve as 'potential leads') need to be short and should be connected to two terminals E and F screwed into the baseboard as near as possible to A and B.

For the experiment, in addition to the above, you will need:

Two thermometers (0–50°C $\times \frac{1}{10}$)—thermometers calibrated in fifths *can* be used; stop-watch; constant head apparatus; a source of electric current which can be relied on to give a constant e.m.f. of about 10 volts for at least 20 minutes, and which will supply several amps. without damaging it; a good voltmeter or a good ammeter of range to match the rest of your apparatus; a rheostat; a plug key. (Information on choice of electrical instruments etc. is to be found on p. 285).

THEORY

The principle is to measure the energy dissipated in the heating element in watts, and to equate this to the heat received by the water in unit time, in calories. Thus we obtain a relationship between joules and calories—since one watt is one joule per second.

The heat received per second by the water is found from the rate of flow and the temperature rise.

The energy in watts dissipated in the wire can be found by any one of three ways, whichever is most convenient (depending on the measuring instruments available). Provided two of the three quantities, amperage, potential drop and resistance, in the heating element are known, the watts can be calculated. The resistance of the heating element at room temperature can probably be determined to a higher order of accuracy than the other two quantities—if a bridge method is used (see p. 317), and the change in its value when the wire is hot can be neglected as the temperature coefficient of resistance of nichrome is only $1{\cdot}7 \times 10^{-4}$ per degree C and the mean temperature will differ from that at which the determination of resistance was made by only a few degrees C. There is no reason why both ammeter and voltmeter should not be used, in addition to a knowledge of the resistance, as this presents a check on the accuracy of the instruments.

To eliminate the unknown factor of the heat lost to the surroundings, two separate experiments are made in which different rates of flow of water are used, but by changing the electrical supply the temperature rise is kept the same in both. Since the rate of loss of heat is a function only of the temperature excess, this will be the same for each experiment. The details of the method are as follows:

Let the p.d.'s across the element be V_1 and V_2, the currents passed be I_1 and I_2, the time for each experiment be t secs (this must be the same for both so that the total heat lost in each case is the same), the mass of water passing in t secs be m_1 and m_2, where subscripts indicate first or second experiment.

Let also the temperatures at which the water enters and leaves the flow tube be (in *both* experiments) θ_1 and θ_2 respectively, and the heat lost in t secs be h cals.

Then $$\frac{V_1 I_1}{J} = m_1(\theta_2 - \theta_1) + h$$

and $$\frac{V_2 I_2}{J} = m_2(\theta_2 - \theta_1) + h$$

$$\therefore \qquad \frac{1}{J}(V_2 I_2 - V_1 I_1) = (m_2 - m_1)(\theta_2 - \theta_1).$$

All quantities in the last equation except J are observed in this experiment, and hence J can be determined.

Procedure: Place the thermometers T_1 and T_2 in a beaker of water to check that they give identical readings when at the same temperature. If this is not the case, obtain a pair of thermometers that do give identical readings or else find a correction factor for one of them so that reliable values for the temperature difference of the inflowing and outflowing water can be obtained. This is very important, as the temperature rise will be small and any variation in the thermometers will represent a large percentage error in its value. When this is done insert the thermometers into the end tubes, with a thin piece of thread through their 'rings' to facilitate their removal later.

Provide the constant head apparatus with a supply of water at a steady temperature. This may sometimes be achieved by opening the supply tap for five minutes before making the connection to the constant head apparatus so that deep-mains water is being drawn. In some laboratories this does not succeed and the remedy then is to provide the experiment with an independent water supply contained in a 5–10 gallon storage tank (e.g. a disused oil drum) mounted a few feet above the constant head apparatus. This tank should be filled with water the day before the experiment is to be performed so that the temperature may become stable.

Connect D to the constant head apparatus and raise the level of the other end a few cm. above the bench. Raise the constant head apparatus to a height of at least 50 cm. above the level of C and allow the water to pass at the rate so produced for a few minutes. This is to sweep all the air bubbles out of the flow tube etc. Now increase the slope of the flow tube, and if necessary lower the constant head apparatus, until the rate of flow is reduced to a slow trickle—the water should emerge in isolated drops. Connect the heating element into the circuit shown in Fig. 75B in which

V is the voltmeter, connected to E and F by thick copper leads (of S.W.G. not more than 18),

A is the ammeter,

R is the rheostat,

S is the source of current

and K is the plug key.

Switch on the current; adjust R so that A and V are giving a little more than half-scale deflection. When all the electrical instruments and the thermometers have recorded constant readings for five minutes showing that the steady state has been reached, record their readings and measure the rate of flow of water by allowing it to flow into a weighed vessel for an observed time. The vessel must be reweighed to find how much water passed in the known time. Throughout this collecting operation check that the instruments do not show any variation. If they do, abandon this attempt and wait until the steady state has again been reached before starting a new determination of the rate of flow.

Now adjust R until A and V give nearly full-scale deflection and alter the rate of flow to obtain the same temperature rise as before. When the steady state is established, record all observations as previously.

Record and Calculation: Record all your observations. Substitute the appropriate quantities in the final equation given in the theory paragraph, and solve for the mechanical equivalent of heat.

PART IV

LIGHT

CHAPTER XXI

STANDARD PROCEDURE

White Light Sources

In many cases the light reflected from a polished surface, such as a pin or knitting needle, is used for experimental purposes. Otherwise a beam of light coming from a luminous body is used. An electric lamp is the most convenient luminous body to use, but any lamp will do. The most convenient arrangement is to place the lamp behind an opaque screen in which is a convenient slit. Usually a rectangle is the best shape for the slit, and it is often a help to have thin cross wires stretched across the slit.

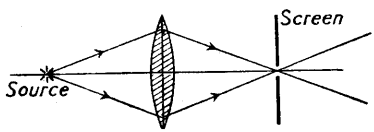


FIG. 76

The lamp may be placed just behind the slit, but then only a very small fraction of the light produced will pass through the slit, and usually the more light we have the more satisfactory the experiment. The arrangement shown in Fig. 76, in which a convex lens is used to concentrate light on to the slit, ensures that the maximum amount of light passes through the slit.

Monochromatic Light Sources

Light of one colour as *judged by the eye* is not a sufficiently precise description for physics; and hence the term monochromatic light is used to mean light of one frequency. Most coloured lights contain many frequencies.

The most readily available source of monochromatic light in the laboratory is one which produces 'sodium light'. Actually the sodium spectrum consists of two very bright lines, the D lines, and thus really is light of two frequencies. This can be shown by an experiment with a diffraction grating (Experiment 95, p. 218). These two frequencies are so nearly the same value that for all our needs sodium light may be regarded as monochromatic. Three methods are available for its production: (i) The commonest consists of soaking in brine a wad of asbestos, bound together with wire, and then arranging the asbestos, by a clamp, in the lower part of a Bunsen burner flame. The wad needs dipping into brine fairly frequently, but otherwise the method is satisfactory. (ii) In place of the asbestos, 'sodium pencils' may be used. These are recommended, and are obtainable from all suppliers of laboratory equipment (at about 20/– per dozen—a number which should last several years). (iii) The sodium vapour discharge lamp, e.g. the standard Mazda 40 watt lamp, is an ideal source, as it provides a much brighter light and requires no attention. There will, however, be a superposed spectrum of the added inert gas (often Neon). This can be eliminated if necessary by using a yellow filter.

Setting up an Optical Axis. The Optical Bench

Experiments on mirrors and lenses involve the setting up of an optical system in which the mirrors, lenses, sources of light, screens, pins etc. appear. Much waste of time, awkward work, and the accompanying poor results can be avoided, if attention is given to the preliminary task of setting out the axis along which the optical elements involved will be placed. Slits through which light streams, plane mirrors and pins should all be in planes at right angles to the axis. The poles of the mirrors, the optical centres of the lenses, the points of the pins, etc., should all lie on the axis.

The optical bench aids this arranging considerably. It is essentially some arrangement so that mirrors, lenses, screens, etc., can be moved backwards or forwards along a straight line which is parallel to the optical axis of the lenses or mirrors used. A scale is attached by means of which the various objects may be located, and various fittings are supplied to hold these objects.

Usually the objects are held in supports which slide along the bench with pointers attached to give readings on the scale. It is, therefore, necessary to determine how the pointer readings are related to the distances it is desired to measure. Thus in Fig. 77 the distance between

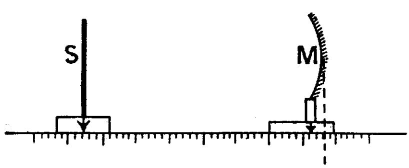


FIG. 77

the pole of the mirror (M) and the screen (S) is not given by the difference of the two pointer readings. Obviously a correction will have to be applied for every measurement made—equal in this case to the distance of the pole of the mirror beyond the pointer.

A convenient method of determining this correction is to use a thin brass rod accurately cut to be, say, 10·0 cm. long. The bar is placed so that it is in contact with the screen and the pole of the mirror, and readings of the two pointers taken. Thus the correction to be applied to subsequent observations is found. The necessary modification for a correction to be applied for measurements from the optical centre of a lens should be obvious.

Optical benches vary from carefully constructed designs with elaborate fittings to the simple arrangement of a metre rule laid on the bench, alongside of which lenses, mirrors, screens, etc., are moved in simple supports, such as wooden blocks with convenient slits cut in them, or small pieces of plasticine into which the objects may be inserted.

Mirrors and Lenses. The Sign Convention

For calculations on problems connected with light it is necessary to adopt a sign convention for the values of the distances measured. There are various sign conventions possible and more than one in common use. The two most usual ones are those known as the 'Real is Positive' (R.P.) and the 'New Cartesian' (N.C.). A useful comparison of these conventions will be found in 'School Science Review', Vol. xxx, No. 110, October 1948; advanced students should study this article. In this book 'R.P.' is used* and a brief summary is given below:

(i) All measurements are made from the pole of a mirror or the optical centre of a lens.

(ii) The measurement made to locate the position of a REAL object or image is POSITIVE.

(iii) The measurement made to locate the position of a VIRTUAL object or image is NEGATIVE.

(iv) Conversely : An evaluation which gives a *negative* result implies a *virtual* object or image, and a *positive* result implies a *real* object or image.

Using this convention it follows that:

(i) The focal length of a convex lens and a concave mirror is positive —for a concave lens and a convex mirror it is negative.

(ii) The equation,

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$$

where v is the distance of the image from the mirror or lens
u is the distance of the object from the mirror or lens,
and f is the focal length,
applies to both mirrors and lenses.

* But diagrams are drawn so that N.C. can also be applied to them.

When using this and other formulæ of a similar nature adhere strictly to the following procedure: while letters are being used do not attach any signs, but when figures are substituted for the letters the correct sign should be introduced.

Further, if I and O are *corresponding* linear dimensions of the image and object respectively, measured perpendicular to the optic axis, then

$$\frac{I}{O} = \frac{v}{u}.$$

All the above deductions assume that:

(i) The mirror or lens has a small aperture-ratio (by which is meant the diameter of the mirror or lens divided by the focal length).

(ii) All measurements are made to the pole of the mirror or the optical centre of the lens.

(iii) In the case of lenses the lens is thin, i.e. the transverse median section approximates to a straight line.

(iv) The sign convention given above is used.

The first three assumptions are of importance in the actual experimental work on lenses and mirrors; and it is well to be familiar with the following methods, by which experimental conditions can be made to approximate to the conditions assumed in the theory:

(1) To produce a small aperture-ratio, the face of the mirror or lens can be masked with a piece of paper or cardboard from which is cut a small circular hole through which the light is allowed to pass.

(2) The pole of the mirror is the point where the optic axis meets the reflecting surface. When using silvered mirrors the pole will be in the back face and if distances are measured to the front face allowance must be made for the thickness of the glass. The latter of course introduces refraction which can normally be neglected because the glass is so thin. The effect can, however, be eliminated by using either polished metal mirrors or else glass mirrors backed with 'dead black' paint so that the major reflection occurs at the front surface.

The optical centre of the lens is that point, within the lens, for which it is postulated that light passing through it suffers refraction but no deviation. In the absence of any other information the optical centre is assumed to coincide with the geometrical centre.

As the optical centre of a lens is within the glass of which it is made it is impossible to make direct measurements from it, and so it is always necessary to make such observations as will give the required length—it is not sufficiently accurate to measure only to the surface of the lens.

(3) For practical work of the standard we are considering, thin lenses should always be used.

How to Plan and Analyse a Lens or Mirror Experiment. Conjugate Foci

The equation $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$ is symmetrical in u and v, and therefore it is possible to interchange v and u. Hence, when an object is placed so that it gives a real image, it is always possible to put the object where the image was and obtain an image where the object was originally. Such interchangeable positions are called 'conjugate foci' of the mirror or lens.

This means that we may make measurements of the positions of an object and its image when the former is at various distances from the lens (or mirror), and use, in any subsequent analysis, each pair of observations twice, calling the value of u a value of v and vice versa. For example, suppose we are using a lens of focal length 20 cm., for positions of the object between 20 cm. and 40 cm. the images will lie between infinity and 40 cm. respectively. In practice we could start with the object at 25 cm. producing an image at 100 cm. and move the object by 3 cm. at a time to 40 cm., at which point it will be the same distance from the lens as the image. If we moved the object any further away, we should be investigating those points which are conjugate to ones in the range already examined. This is a waste of time, as we can use the observations already made for this purpose simply by calling values u 'v' and vice versa. In general then the sensible way to do an experiment of this sort (i.e. one on real images) is to *keep the object inside the range f to 2f,* taking care to cover this range as completely as the measurement of image distances will allow. (For values of u very near f, v will be too great to be measured easily).

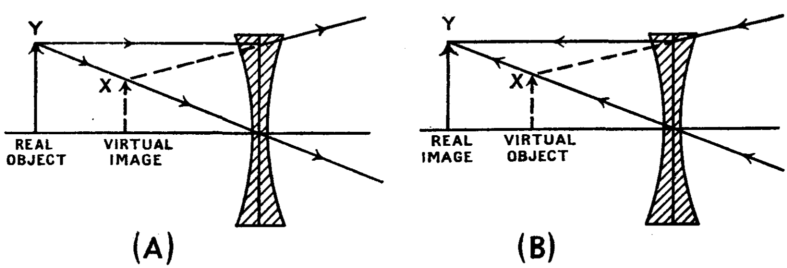
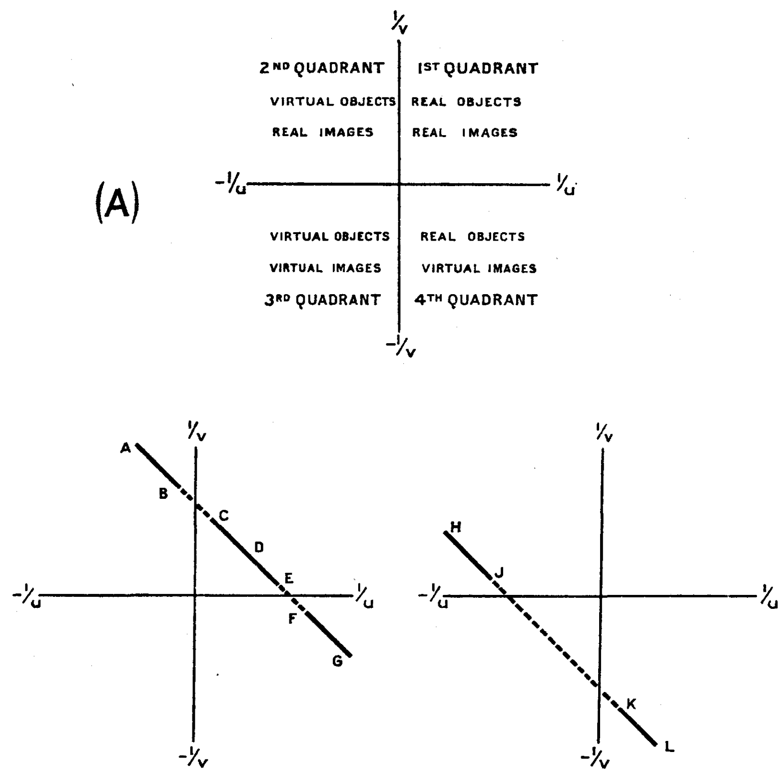


FIG. 78

When virtual images are considered, the values of u and v are still interchangeable, but now the signs must be altered. Fig. 78A shows a real object and its virtual image at X. If the arrows on the rays in Fig. 78A are reversed we get Fig. 78B, where it will be seen that the light converging towards X is diverged by the lens to produce a real image at Y. Further, the light is not actually brought to a focus at X, and so we have in effect a *virtual* object at X. From this it is evident that the case of a real object and its virtual image can be regarded as 'conjugate to' that of a virtual object and its real image. In regarding values of u as values of v as above, and vice versa, it is essential to consider the signs. A similar argument can be applied to all virtual images whether they be formed by converging or by diverging lenses and mirrors. A complete picture can be built up by considering all the possible cases—the student is strongly advised to perform this exercise—and the results can be summarised by the graphs drawn in Fig. 79. It will be seen that points in the first quadrant will have conjugate points also in the first quadrant. Points in the fourth quadrant



Graph of 1/v against 1/u for a converging lens or mirror

(B)

Graph of 1/v against 1/u for a diverging lens or mirror [The part JK cannot be investigated experimentally]

(C)

FIG. 79

will have *their* conjugate points in the *second* quadrant and the points in the third quadrant will have their conjugate points in the third quadrant.

In practice virtual objects cannot be produced without the aid of an auxiliary lens or mirror, and as it is not usual to investigate them, no points are obtained in the third quadrant.

With an experiment on a converging lens or mirror, planned as indicated above, points will be produced along DE and FG in Fig. 79B. The part EF is not obtained as it relates to values of v which are too large to be measured. The rest of the line will be constructed from conjugate points—CD being composed of points which are conjugate to those on ED and AB of points which are conjugate to those on GF.

With a diverging lens or mirror, it is not possible to cover so wide a range since we do not investigate virtual objects. Thus only the section KL is actually investigated (Fig. 79C). The conjugate points, however, yield the portion JH and thus the whole line can be drawn.

The intercepts of these lines on the axes are values of $1/f$ because when

$$v = \infty, \frac{1}{v} = 0. \qquad \therefore \frac{1}{u} = \frac{1}{f}.$$

Also, when $$u = \infty, \frac{1}{u} = 0. \qquad \therefore \frac{1}{v} = \frac{1}{f}.$$

The lines should therefore be drawn so that the intercepts are equal. Both intercepts must therefore be shown on the graph and to make sure that they will be 'on the paper' estimate their value—this should be the first step when planning your graph. The quickest way to do this is to add together a pair of corresponding values of $1/u$ and $1/v$.

How to Determine an Approximate Focal Length Rapidly

To plan an experiment on a mirror or lens a knowledge of the approximate focal length is usually required—see p. 171. For a converging lens or mirror it can be determined rapidly to within 5 to 10% by obtaining a sharp image of a *distant* object on a sheet of paper—or the wall of the laboratory. If the sun is shining it forms the best object, but a laboratory window will do. The distance between the mirror or lens and the image, measured roughly with a metre rule gives the approximate length.

No rapid method for diverging mirrors and lenses is available, but usually this is not a serious handicap.

Location of Images by the Method of 'No Parallax'. Pin-Optics

An object such as a pin can be used to locate an image, by using the fact that if the image and the pin are not in the same plane normal to the optic axis, then, on looking along the optic axis and moving the eye from side to side, the image and the pin will seem to move at different speeds (and perhaps in opposite directions). Only when the pin and the image are in the same plane will they appear to move at the same speed and in the same direction, that is if they are coincident in one position they will appear to be coincident all the time as the eye is moved from side to side. Perhaps the best way of describing the effect is to say that the pin and the image seem to 'stick together'. This technique, of which the applications are numerous, has been given the name 'pin-optics'. Its chief advantage is that it can be used to locate virtual images as well as real ones, whereas the method employing a source of light can only be used to investigate real images. There are other 'advantages', which are of importance to the instructor and the examiner—and hence, incidentally, to the student. They are (i) the apparatus is simple and cheap, i.e. easy to provide, (ii) considerable skill is needed to obtain good results. Since, however, we aim to study light, it is preferred that a source of light be employed wherever possible in investigations, and the method of pin-optics used only when that is not convenient. In the experiments described on lenses and mirrors both methods are given.

Practical Hints on How to Obtain Good Results by the Method of Pin Optics

Success when using the pin method depends largely on the application of common sense to the technique so that good vision is obtained and adjustment made easy. Here are a few suggestions:

(1) Clean the lens or mirror before using it.

(2) Use a brightly polished pin (or pins).

(3) Always have a fairly good idea of the position of an image before you start to locate it—this usually depends on knowing the approximate focal length of the lens or mirror (see p. 173).

(4) It is often a good idea to adjust the apparatus so that you can see the image of your eye and to proceed from this to the use of pins, possibly using a pencil held in the hand as an intermediate step.

(5) When investigating conjugate foci with converging systems always start with the object at twice the focal length and move it by suitable distances (usually about $f/6$) towards the focus. If virtual images are also investigated, start with the object near the lens or mirror and move outwards towards the focus. This can be summarised by saying 'always work towards the focus'; it avoids the difficulty of trying to locate very distant images.

(6) When the magnification becomes about 2 or 3, replace the object pin by a small pin and the exploring pin by a knitting needle. If the

magnification is a fraction, reverse this process, using the knitting needle as the object.

(7) Set up white screens as backgrounds so that the pins stand out clearly. In the case of reflection experiments this can still be done but a small hole through which to look should be made in the screen.

(8) If images are faint, illuminate the object from the side.

(9) If you find yourself confusing two pins make one different from the other by putting a small piece of white paper on it.

(10) Make your final adjustment so that points of pins and images show no parallax; you then have precise points from which to make measurements.

CHAPTER XXII

CONVERGING MIRRORS

Experiment 65. Determination of the Radius of Curvature of a Concave Mirror, and hence the Focal Length, by Coincidence of Image and Object

Apparatus: Concave mirror of radius of curvature 20–30 cm.; optical bench and accessories; optical pin or knitting needle.

THEORY

In the equation:

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} = \frac{2}{r}$$

we have, when image and object coincide, $v = u$,

and $$\therefore \frac{2}{v} = \frac{1}{f}$$

i.e. $$v = 2f.$$

Therefore $$v = u = r.$$

Procedure

Optical Bench Method: Find the approximate focal length of the mirror (see p. 173).

From the optical bench apparatus select the white screen with a circular hole in it fitted with cross wires. The latter form the object when illuminated from behind by a source of white light (see p. 167). The adjacent portion of the screen is used to find the image when the latter coincides with the object.

Adjust the position of the mirror so that an image of the cross-wires is formed near the hole in the screen and is sharply in focus. The image will be the same size as the hole, i.e. the distances u and v will be the same (see Fig. 80).

Measure the distance from the screen to the pole of the mirror. Repeat to obtain an average value.

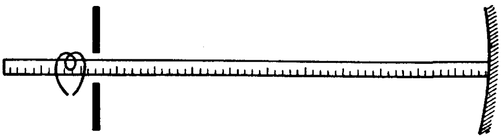


FIG. 80

'NO PARALLAX' METHOD: Find the approximate focal length of the mirror (see p. 173). Place the mirror on the bench or floor and support a knitting needle horizontally over it in a clamp as shown in Fig. 81. Place the needle about twice the focal length from the mirror. On looking down into the mirror, both the needle and its inverted image will be seen—a small triangle of white paper attached to the end of the needle helps (see also p. 174).

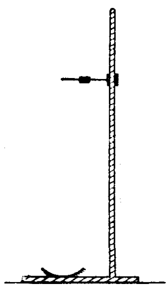


FIG. 81

Move the needle up or down until the tip of the image coincides with the tip of the object, a position indicated by the fact that the image and the object exhibit no parallax.

Measure the distance of the needle from the pole of the mirror—remember that the back of the mirror is usually the reflecting surface.

Displace the needle, and repeat the experiment several times to obtain an average value.

Record and Calculation: Record all observations, calculate an average value for u which will be equal to the radius of curvature, and from this deduce the focal length.

Check your result by using a spherometer (see p. 49).

Experiment 66. Determination of the Focal Length of a Concave Mirror by Conjugate Foci

Apparatus: Concave mirror of radius of curvature 20–30 cm.; optical bench and accessories; two optical pins.

THEORY

Before starting this experiment the matter on pp. 171–173 should be thoroughly understood.

OPTICAL BENCH METHOD

Procedure: Find the approximate focal length of the mirror (see p. 173).

Arrange the light source as in Experiment 65, p. 175. Turn the mirror slightly sideways so that it produces an image on an opaque screen as shown in Fig. 82. The turn should be as little as possible.

Start with the object slightly more than twice the focal length from the mirror, and adjust the screen to obtain a clearly focused image. Make the observations necessary to obtain values of u and v. Move the screen a little nearer the mirror (by about $f/6$), move the object to obtain another clear image, and repeat the observations. Repeat, to obtain a series of readings which will give a reliable graph (see p. 38). At least five sets of observations should be taken.

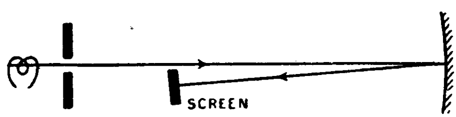


FIG. 82

Record and Calculation: Tabulate your results and find values of u and v. Enter these in a table and add columns for the introduction of $1/u$ and $1/v$. Analyse your results in the manner indicated on p. 172, drawing a graph of $1/u$ against $1/v$. This should be a straight line in the first quadrant (like the part CE of Fig. 79B). The intercepts of this line on the axes—which should be equal—give a value for $1/f$. Calculate f.

'NO PARALLAX' METHOD

Procedure: Find the approximate focal length of the mirror (see p. 173). Set the mirror and a pin to act as an object as shown in Fig. 83 in which O is the object pin, I is the image of O and E is the exploring pin used to locate I.

Place the pin about twice the focal length from the mirror. Adjust the position of the pin so that a real image is clearly seen close to the pin. The image will be more clearly seen if viewed through a small hole cut in a stiff piece of paper. Illuminating the pin by a light on one side of it also helps (see p. 174). Stick another pin—the exploring pin—between the eye and the image, so that object, image and exploring pin appear to be on one straight line; this line should be the

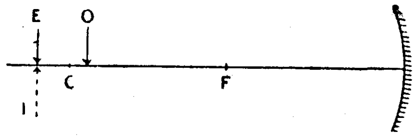


FIG. 83

principal optical axis of the system (see p. 168). Move the exploring pin backwards and forwards until it and the image are coincident as indicated by their exhibiting no parallax (see p. 173).

Record the necessary observations to obtain values of v and u. Move the object pin a little nearer to the mirror (by an amount about $f/6$) and repeat the observations. Take a series of such observations so that u varies over as wide a range of values between $2f$ and f as possible. (For values of u very near to f, v will be too great to be investigated). At least five pairs of corresponding values of u and v should be obtained.

Next the virtual images should be investigated: the object pin is moved close to the mirror and the virtual image is located by placing a pin behind the mirror (and visible over the top of it) so that it shows no parallax with the image seen in the mirror. Make observations to enable you to find u and v. Move the pin a little farther from the mirror and repeat the process. When the object approaches the focus the image will be a long way behind the mirror and it is easier to fix the pin used to locate the image in the approximate position being investigated and to adjust the object pin (which is nearer to the experimenter) so that it produces an image at this position. Several positions of the object pin between the focus and the pole of the mirror should be investigated.

Record and Calculation: Tabulate your results and prepare a table as in Part 1, remembering to give negative signs to the virtual image distances.

Analyse your results by the method given on p. 172, using each pair of values of $1/u$ and $1/v$ twice, bearing in mind the need to consider the signs when plotting virtual image positions.

Points in the 1st, 2nd, and 4th quadrant will be obtained which should lie on a straight line, the (equal) intercepts of which on the axis give a value of $1/f$, from which f may be found (see Fig. 79B).

Notes: (1) The results may be checked using a spherometer to find the radius of curvature, which is twice the focal length. For details see p. 49.

(2) You should also plot the graph of v against u (using the principle of conjugate foci to yield two sets of points). Discuss the significance of the graph so obtained.

Experiment 67. Verification of Newton's Equation for a Converging Mirror

Apparatus: Converging mirror of focal length 10–15 cm.; three optical pins.

THEORY

If the distance of the object from the focus of a mirror is x and the distance of the image from the focus is y, then Newton's equation states that

$$xy = f^2$$

where f is the focal length of the mirror.

This holds for virtual images as well as for real images.

Procedure: Determine the radius of curvature, and hence the focal length, of the mirror, using the method described in Experiment 65.

Set up the mirror with its axis horizontal and place a pin, F, at the focus of the mirror. Set up another pin, O, at a distance just greater than the focal length from the mirror and locate the real image with a third pin, P. Measure and record distances OF and PF, x and y respectively. Move O a little farther from F and repeat. Continue recording corresponding values of x and y, covering as wide a range as possible.

Next repeat the experiment for virtual images, by leaving F in position and placing O between it and the mirror. The image may be located by the method of sighting the exploring pin over the mirror and finding the position of no parallax between it and the image.

Record and Calculation: Tabulate all observations. Plot graphs of y against $1/x$ for (i) real images and (ii) virtual images. In each case the graph should be a straight line passing through the origin.

State (1) the gradient of each graph;

(2) the value of f^2 deduced from the position of F.

CHAPTER XXIII

CONVERGING LENSES

Experiment 68. Determination of the Focal Length of a Convex Lens, using an Additional Plane Mirror

Apparatus: Convex lens; plane mirror; optical bench and accessories; optical pin.

THEORY

The plane mirror is placed behind the lens and a position of coincidence of image and object in front of the lens is found. As object and image coincide the light from the object must have travelled to and from the mirror along the same path. This is only possible if the light reached the mirror normally to its surface, i.e., after reflection by the mirror it returned as a parallel beam of light. This parallel beam suffers refraction as it returns through the lens and is brought to a focus in the focal plane of the lens—see Fig. 84.

Therefore the measurement of the distance from the lens to the position of the image is a direct measurement of the focal length.

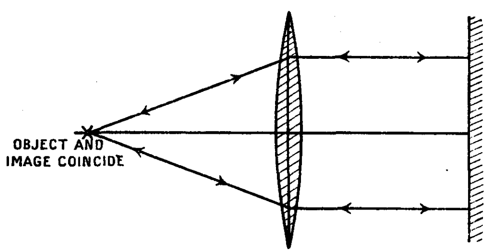


FIG. 84

Procedure

OPTICAL BENCH METHOD: Find the approximate focal length of the lens (see p. 173). As an object, use the hole and cross-wires in a white screen illuminated from behind by a source of white light. When the image coincides with the object the former can be obtained on that part of the screen adjacent to the hole and cross-wires.

Place the plane mirror behind the lens and arrange that both are normal to the optic axis. (Consider whether the distance between the lens and the plane mirror is of importance). Adjust the screen until the position of coincidence of object and image is found, and then make the necessary measurements to obtain a value for the focal length—bearing in mind the facts about the optical centre referred to on p. 170.

'NO PARALLAX' METHOD: Find the approximate focal length of the lens (see p. 173). Put the mirror on the bench or floor and place the lens on it. Above the combination put an optical pin held in a clamp. Stand so that, when looking vertically down, the pin and its image can be seen. Adjust the position of the pin, so that it is in the same horizontal plane as its image, i.e. so that the tip of the pin and the corresponding tip of the image coincide and exhibit 'no parallax'. Make the necessary measurements to find the distance of the pin from the optical centre of the lens (see p. 170).

Repeat several times to obtain an average value.

Experiment 69. Determination of the Focal Length of a Convex Lens by Conjugate Foci

Apparatus: Convex lens of focal length 10–15 cm.; optical bench and accessories; optical pins.

THEORY

This is dealt with in detail on pp. 171–3 which should be thoroughly understood before the experiment is started.

OPTICAL BENCH METHOD

Procedure: Find an approximate value for the focal length (see p. 173). As an object use the screen with cross-wires illuminated from behind by a white light source, and use another screen to locate the image. Place the object at about twice the focal length from the lens and the other screen at about the same distance on the other side. Adjust until a sharp image is obtained and then make the necessary observations to enable u and v to be found—remembering that u and v are measured from the optical centre of the lens (p. 170).

Move the object a little nearer to the lens and adjust the screen to obtain a sharp image. Again obtain values of u and v.

Repeat this process at least three more times (giving not less than five different observations) arranging that the series covers the range $u=2f$ to $u=f$ as adequately as measurements of v (which becomes large as u approaches f) allow.

Record and Calculation: Tabulate your results and calculate values of u and v.

Analyse your results by the graphical method discussed on p. 172 using each pair of observations twice. All the points, which will be in the first quadrant, should lie near a straight line the (equal) intercepts of which on the axes give a value of $1/f$. Hence find the focal length.

'NO PARALLAX' METHOD

Procedure: Find the approximate focal length of the lens (see p. 173).

Place one pin (referred to as the 'object pin') about twice the focal length from the lens. On the other side place the other pin (the 'image pin') at about the same distance and adjust its position so that it coincides with the image of the object pin as judged by the method of 'no parallax'. Make what observations are necessary to find u and v, remembering that these are measured from the optical centre of the lens (see p. 170).

Move the object nearer to the lens by a suitable distance (about $f/6$). Locate its image and take the necessary observations.

Take at least five similar observations with u varying from $2f$ to just over f.

Virtual images should next be investigated as follows: place the object pin near the lens and view it through the lens. A large virtual image will be seen which should be located by a knitting needle viewed over the top of the lens. Take observations to find u and v. Move the object a little farther from the lens and readjust the image pin. Measure u and v. Repeat several times covering as wide a range of values as possible (i.e. from u just less than f, to u nearly zero). For larger values of v it is easier to make the final adjustments to the object pin as in Experiment 66.

Record and Calculation: Tabulate your results and find u and v. Analyse the results by plotting $1/v$ against $1/u$ using the procedure given on p. 172, remembering that when the principle of conjugate foci is applied to virtual images the signs must be considered. Points in the 1st, 2nd and 4th quadrants (see Fig. 79B) should be obtained. They should lie very near a straight line, the (equal) intercepts of which give the value for $1/f$. Calculate f.

Note: You should also plot the graph of v against u (using the principle of conjugate foci to obtain two sets of points) and discuss the significance of the result.

Experiment 70. Verification of Newton's Equation for a Converging Lens

Apparatus: Converging lens of focal length 10–15 cm.; plane mirror; four optical pins.

THEORY

In Fig. 85 let P and Q be the principal foci of the lens. If I is the image of O, then Newton's equation states that

$$OP \times IQ = f^2$$

where f is the focal length of the lens.

This holds for virtual images as well as for real images (see Fig. 85)

Procedure: Set up the lens with its axis horizontal. Place the plane mirror in a vertical plane behind the lens and adjust a pin to show 'no-parallax' with its own image (as in Expt. 68). Call this pin P, *and do not move it or the lens* for the remainder of the experiment. Transfer the plane mirror to the other side of the lens and hence set up a second pin (Q) at the other principal focus. Measure PQ (this is $2f$).

Real images: Using a third pin (O) as an object, and a fourth pin (I) to locate its image by 'no-parallax', investigate as wide a range as possible of object positions with O farther from the lens than P, but always on the same side as P. For each setting record the lengths OP and IQ.

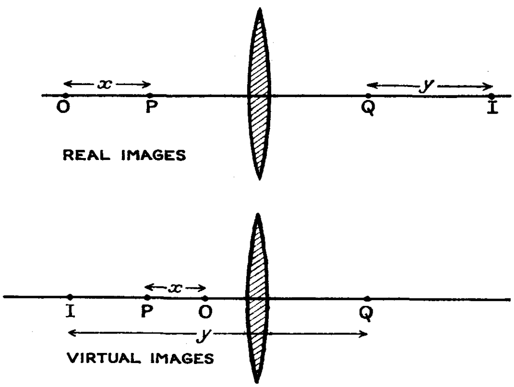


FIG. 85

Virtual images: Repeat the procedure described above but put O between P and the lens. The image pin, I, will now have to be placed on the same side as O and P and will be farther from the lens than P. The image will be viewed through the lens from the Q-side and pin I will be viewed over the top of the lens and adjusted to show no parallax with the image. Record a series of values OP and IQ for as wide a range of IQ as possible. (Be careful to measure IQ and *not* IP.)

Record and Calculation: Tabulate all observations. Plot graphs with OP as ordinate and 1/IQ as abscissa (i) for real images, (ii) for virtual images. If Newton's equation is true these should both be straight lines having gradient equal to f^2.

Experiment 71. Determination of the Focal Length of a Convex Lens by the 'Displacement Method'

Apparatus: Convex lens of focal length about 5–10 cm.; optical bench and accessories.

THEORY

If a lens distance u cm. from an object produces an image at a distance v cm. from the lens, then, by the principle of conjugate foci, if the lens be moved so that it is v cm. from the object the image will be u cm. from the lens. The distance between the object and image in both cases is $(u + v)$ cm. Let the lens be displaced by an amount x cm. to produce this effect, when the object and image are y cm. apart (see Fig. 86).

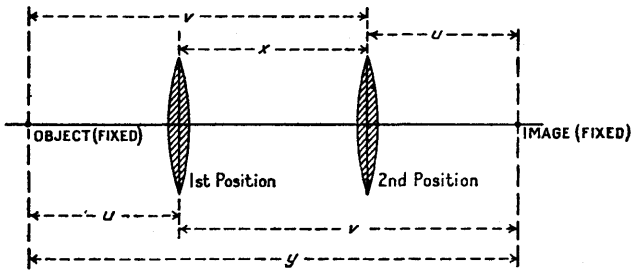


FIG. 86

Then

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$v + u = y \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$v - u = x \quad . \quad . \quad . \quad . \quad . \quad (3)$$

To eliminate v and u, add and subtract equations (2) and (3), i.e.

$$2v = y + x$$

$$\text{and } 2u = y - x.$$

Hence

$$\frac{1}{v} = \frac{2}{y + x}$$

and

$$\frac{1}{u} = \frac{2}{y - x}.$$

Substitute these values in (1),

$$\frac{2}{y + x} + \frac{2}{y - x} = \frac{1}{f}.$$

$$\therefore \frac{4y}{y^2 - x^2} = \frac{1}{f}$$

$$\therefore f = \frac{y^2 - x^2}{4y}.$$

Procedure: Find the approximate focal length of the lens—see p. 173. Use as an object the screen with hole and cross-wires illuminated from behind, and set this up at a little more than twice the focal length from the lens. Locate the image by an opaque white screen. If the image is indistinct and difficulty is experienced in focusing, this will almost certainly be due to spherical aberration. This is eliminated if the lens is fitted with a mask, made of paper, which limits the aperture to, say, 1 cm. diameter. Measure the distance apart of the two screens (y cm.). Keeping both the latter unmoved, displace the lens so that a clear image is again formed on the screen (it will not be the same size). Take the necessary observations to determine the amount by which the lens has been displaced (x cm.). Repeat the process, starting with a greater value of y than before, and take another set of readings of x and y. Repeat these steps until a wide range of values has been investigated.

Record and Calculation: Analyse your results by entering them in a table as follows:

y	x	y^2	x^2	y^2-x^2	$f=\frac{y^2-x^2}{4y}$

Find a mean value of f.

Notes: (1) Devise a graphical method of analysing the same results.

(2) The advantage of this method is that only two easy measurements need be made and the problem of finding the optical centre does not arise. The focal length of a lens enclosed in a tube may be found, using this method.

Experiment 72. Verification of the Formula $\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}$ for the Focal Length of a Combination of Two Lenses in Contact

Apparatus: Two convex lenses of focal lengths about 15 cm. and 25 cm. respectively; optical bench and accessories, or optical pin; plane mirror.

Procedure: Using the method described in Experiment 68 determine the focal length of each lens separately, and of the pair when in contact.

Calculation: Calculate the focal length of the combination from

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}$$

where F is the focal length of the combination and f_1 and f_2 are the focal lengths of the two lenses.

Compare the result with that found by the experiment.

Note: A more accurate formula is

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{x}{f_1f_2}$$

where x is the distance between the optical centres of the lenses.

Clearly the distance x can never in practice be reduced to zero.

CHAPTER XXIV

DIVERGING MIRRORS

Experiment 73. Determination of the Focal Length of a Convex Mirror, using an Additional Convex Lens

Apparatus: Convex mirror of radius of curvature 20–30 cm.; convex lens of focal length about 20 cm.; optical bench and accessories; optical pin.

THEORY

Light which reaches a mirror at zero angle of incidence, i.e., along a normal to the surface of the mirror, is reflected along the incident path. The normal to a spherical surface passes through the centre of curvature. Thus in the arrangement shown in Fig. 87 the centre of curvature of the mirror is at the point where the image was formed before the mirror was introduced. Hence the radius of curvature of the mirror is $(v - d)$.

Procedure: (The instructions given on p. 168 are of particular importance in this experiment).

Using a similar arrangement to that in Experiment 69, p. 181, obtain on a screen an image of a luminous object. Find the distance, v, of this image from the optical centre of the lens (see p. 170).

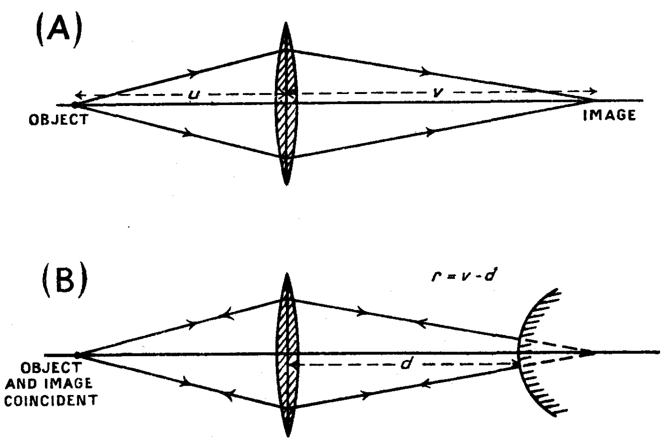


FIG. 87

Arrange that v is greater than the radius of curvature (r) of the mirror.

Keeping the object and lens in the same position, insert the convex mirror between the image and the lens, and adjust its position so that the image formed (by reflection from the mirror and refraction through the lens) coincides with the object, as in Fig. 87B.

Measure the distance between the pole of the mirror and the centre of the lens, d in Fig. 87B.

Repeat with different initial arrangements of the lens and object.

Record and Calculation: Tabulate your results and find for each experiment the value of $(v-d)$. Calculate the mean value of your answer to find the mean determination of radius of curvature. Hence find the focal length.

Notes: (1) A pin can be used as an object and another to locate the image. The notes on p. 174 are relevant here.

(2) The result may be checked using a spherometer (see p. 49).

Experiment 74. Determination of the Focal Length of a Convex Mirror by Conjugate Foci

Apparatus: Convex mirror of radius of curvature 20–30 cm.; an optical pin; thick knitting needle; plane mirror.

THEORY

Refer to pp. 171–3. The images (for all real objects) lie between the pole and the focus of the mirror and they will be virtual and diminished (hence the choice of a thick needle to be used as the object).

Procedure: Since the image is behind the mirror it should be located by one of the following methods:

(i) Place the optical pin behind the mirror and, viewing it over the top of the mirror, adjust its position to show no parallax with the image of the knitting needle seen in the mirror.

(ii) Place the plane mirror a small distance in front of the convex mirror and the optical pin XY between the eye and the plane mirror (see Fig. 88). Adjust the pin (or the plane mirror) until its image (X′ Y′)

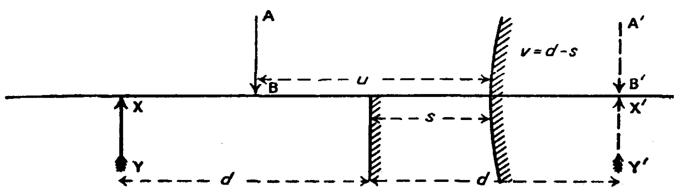


FIG. 88

seen in the plane mirror coincides, as judged by 'no parallax', with the image (A′ B′) of the knitting needle (AB) seen in the curved mirror.

Reference to Fig. 88, which shows the arrangement, will lead to the conclusion that $v = d - s$. Thus, to find v, the distance between the optical pin and the mirror and that between plane mirror and the convex mirror are required.

Using one of these two methods to locate the image, obtain a series of corresponding values of u and v covering as wide a range as possible. At least five different positions should be investigated.

Record and Calculation: Tabulate your results and find corresponding values of u and v.

Analyse your results graphically by the method indicated on p. 173. The points will all lie in quadrants 2 and 4 (the actual observed values being in quadrant 4 and the equivalent conjugate points in quadrant 2). Draw the best straight line through the points—it should cross the third quadrant as shown in Fig. 79C, and give equal intercepts on the axes. Hence calculate the focal length.

Note: This experiment can be done using a single pin if the plane mirror is adjusted so that the images in both mirrors coincide. The difficulty of this method is the smallness of the image formed by the convex mirror compared with that formed by the plane mirror.

CHAPTER XXV

DIVERGING LENSES

Experiment 75. Determination of the Focal Length of a Concave Lens, using an Additional Convex Lens

Apparatus: Concave lens; convex lens which with the latter will produce a converging combination, i.e. one which produces a real image. This can quickly be tested by using a laboratory window as an object and the wall opposite as a screen.

Optical bench and accessories or optical pin; plane mirror.

Procedure: Using the method described in Experiment 68, p. 180, find
(1) the focal length of the convex lens,
(2) the focal length of the combination.

Calculation: Find the mean values of the focal lengths of the convex lens and of the combination from your observations. Let these be f_1 and F respectively. Substitute in the equation

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2}$$

and solve for f_2, the focal length of the concave lens. The latter should of course be negative if the 'Real is Positive' sign convention is used.

Experiment 76. Determination of the Focal Length of a Concave Lens, using an Auxiliary Concave Mirror

Apparatus: Concave lens; concave mirror; optical bench and accessories.

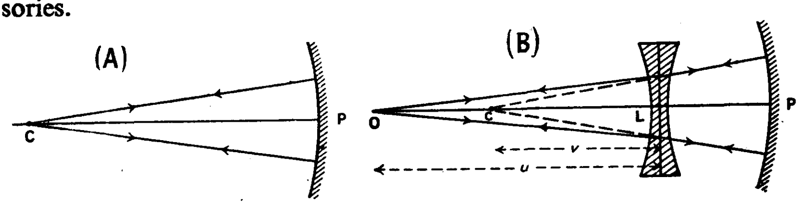


FIG. 89

THEORY

A position of coincidence of image and object is found (i) when the concave mirror is used alone and (ii) when both mirror and lens are used (see Fig. 89). In (A) the object is at the centre of curvature of the mirror and since in (B) the light retraces its path after reflection from the mirror it must have been diverging from C after passing through the lens. Hence C must be the position of the virtual image formed by an object at O. Observations of the positions of C and O with respect to the concave lens will thus yield values of u and v which may be substituted in the usual lens equation.

Procedure: Find the approximate focal length of the mirror (see p. 173).

Using the screen with hole and cross-wires, illuminated from behind, as the object, determine the radius of curvature, CP, of the mirror by the method given in Experiment 65, p. 175.

Introduce the lens between the screen and the mirror and move the screen until a sharp image is once again obtained. Make observations which will enable you to find the distances of the screen from the mirror (OP), and of the optical centre of the lens from the pole of the mirror (LP). Take care that the image formed by reflection at the front face of L is not investigated in error.

Repeat all the observations, using a series of different positions of the lens with respect to the mirror.

Record and Calculation: Tabulate your results as follows:

CP	OP	LP	CP − LP $= v$	OP − LP $= u$	$\frac{1}{v}$	$\frac{1}{u}$

Plot $1/u$ against $1/v$, remembering that virtual image distances have negative signs and applying the principle of conjugate foci as explained on pp. 171–3.

From the intercepts on the axes find the value of the focal length.

Experiment 77. Determination of the Focal Length of a Concave Lens by Conjugate Foci

Apparatus: Concave lens; thick knitting needle; pin; plane mirror.

THEORY

Refer to p. 171, where a discussion of the theory of conjugate foci is given. All the images of real objects are between the lens and the focus and are virtual and diminished—hence the use of a thick knitting needle as the object. These images are all on the same side of the lens as the object and must therefore be located by the method of 'no parallax' using a pin viewed over the top of the lens or else by using the plane mirror method as described in Experiment 74, p. 187. If the method of viewing over the top of the lens is employed, the use of half-lenses will enable you to avoid using the perimeter of the lens for the experiment. This is important, as the theory is dependent on the assumption that the lens is 'thin' and it is therefore necessary to work near the centre of a concave lens. If a whole lens is used, the plane mirror method is thus preferable.

Procedure: Using the appropriate method to locate the images, obtain a series of observations which will lead to a set of corresponding values for u and v, covering as wide a range as possible.

Record and Calculation: Tabulate your observations and analyse your results graphically by the method described on p. 173. Deduce the focal length of the lens.

CHAPTER XXVI

RADII OF CURVATURE OF LENSES

Experiment 78. Determination of the Radii of Curvature of the Faces of a Lens by Boys's Method

Apparatus: Convex lens of focal length 15–30 cm., and preferably not equiconvex; optical pin; mercury—or a dark cloth; micrometer screw-gauge or vernier callipers.

THEORY

Reflection always takes place at the interface of any two transparent substances. Therefore the faces of lenses can be used as mirrors to determine their radii of curvature. In Fig. 90, O represents the object and OAB the path of a ray of light which strikes the back surface of the lens *normally* and so returns along the path of incidence, forming an image also at O. Some of the light will emerge from the lens along BD, without further deviation, and an observer on that side of the lens would see a virtual image of O at C, where DA produced cuts the axis of the lens. Since AB was normal to the face of the lens it is evident that C is the centre of curvature of that face. If the distance XC is r' we have the relationship

$$\frac{1}{r'} + \frac{1}{u} = \frac{1}{f}$$

where u is the object distance (OX),
and f is the focal length of the lens.

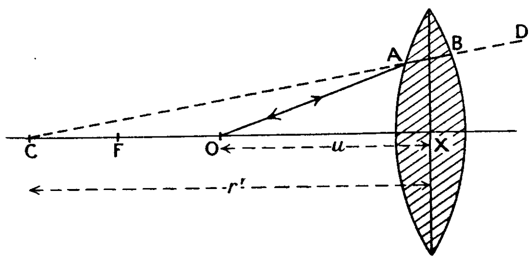


FIG. 90

From this r' can be calculated and hence the radius of curvature of the surface found by adding half the thickness of the lens to r'.

It is important to realise that when the object coincides with its image at O (formed by one internal reflection), O is NOT the centre of curvature of the surface at which reflection is occurring. The radius can only be found by the calculation given above.

Procedure: Find the focal length of the lens (Experiment 68, p. 180) and its thickness.

Clean the faces of the lens and float it in a trough of clean mercury. Place a pin, held in a clamp, above it and adjust its position, by the 'no parallax' method, so that, on looking downwards, the image formed by reflection, and the object are coincident.

Make the necessary measurements to obtain a value of u.

Repeat for the other face of the lens.

Record and Calculation: Record all observations and calculate values for u and f, both measured from the optical centre of the lens. Substitute in the equation given above to find r'. Add half the thickness of the lens to this value to find the required radius of curvature.

Notes: (1) Strictly speaking the addition of half the thickness of the lens in the above calculation only applies to equiconvex lenses. Most lenses conform so closely to this specification that the assumption is justified.

(2) The method can be applied to concave lenses more easily. The reflection takes place, in this case, at the front face and a direct measurement of the required radius of curvature can be made when a position of coincidence of image and object has been found. Obviously the

mercury is not required but a dark cloth is essential to form a background which absorbs light.

(3) The refractive index of the glass of which the lens is made can be found from the data obtained in the above experiment by substituting the values in the equation

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right).$$

One difficulty arises in this process—that of what signs to give to the radii of curvature. For a full treatment of the sign of the radius of curvature and the 'power of a surface' according to the 'real is positive' sign convention a modern text-book of 'Light' should be consulted. If the above formula is used it is sufficient to remember that if the centre of curvature of a surface lies in the space where real images are formed the radius of curvature is taken as positive. Otherwise, it is negative. The image referred to is that formed by the surface considered and not by the whole lens made of the two surfaces.

(4) It is worth remembering that an equiconvex lens made of glass of refractive index 1·5 will have faces of radius of curvature equal to the focal length (the student should prove this for himself). Many lenses, however, are made of glass of much higher refractive index (e.g. 1·65).

Experiment 79. Determination of the Refractive Index of a Liquid, using a Convex Lens and a Plane Mirror (an application of Boys's Method)

Apparatus: Convex lens of focal length about 10 cm.; plane mirror; optical pin; liquid, e.g. glycerine, of which the refractive index is required; mercury.

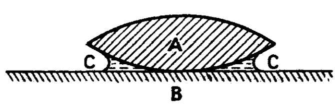


FIG. 91

THEORY

If a liquid, of refractive index μ, is flooded between a convex lens A and a plane mirror B, as shown in Fig. 91, a concave lens made of the liquid is formed between A and B. A determination of the focal lengths of A and of the combination of A with C (the liquid concave lens) enables the focal length of the latter (f_C) to be found from the equation

$$\frac{1}{F} = \frac{1}{f_A} + \frac{1}{f_C}$$

where F is the focal length of the combination
and f_A is the focal length of the convex lens A.

Now the radii of curvature of the faces of the liquid lens are (i) that of the under surface of the lens A and (ii) the plane surface of B. It is thus a plano-concave lens, and the general equation

$$\frac{1}{f_C} = (\mu - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

reduces to

$$\frac{1}{f_C} = (\mu - 1)\frac{1}{r}.$$

where r is the radius of curvature of the under surface of A, ($1/r_2$ is zero since r_2 is infinite).

Thus the determination of the focal lengths of A and of the combination, together with a determination of r, enable the refractive index to be calculated.

Procedure: Using the pin method of Experiment 68, p. 180, find the focal length of the convex lens. Next introduce the liquid between the lens and the plane mirror, making sure that it thoroughly wets the lower surface of A and the upper one of B as this improves the distinction of the image. Find the focal length of the combination. Find the radius of curvature of the under surface of A using Boys's method (see p. 190).

Record and Calculation: Record all your observations and deduce the result by the method given above.

CHAPTER XXVII

MAGNIFICATION

Experiment 80. Determination of the Magnification produced by a Concave Mirror or a Convex Lens

Apparatus: Concave mirror or convex lens of focal length about 10 cm.; optical bench and accessories.

THEORY

Magnification is defined by the ratio

$$\frac{\text{Size of image}}{\text{Size of object}}$$

and with the usual assumptions, it may be shown that:

$$\text{Magnification} = v/u,$$

provided that all measurements of size are made at right angles to the optical axis. The following experiment verifies this conclusion.

Procedure; Find the approximate focal length of the mirror or lens (see p. 173).

As an object use either an illuminated aperture fitted with cross wires to aid sharp focusing, or a pair of parallel pins mounted 6–8 mm. apart in a bull-dog clip. Locate the image either using a screen or by 'no parallax'; in the latter case two pins must be used mounted as before and their distance apart adjusted to coincide with that of the images. Measure the size of object and image and u and v. If appreciable spherical aberration occurs, reduce the aperture of the lens or mirror by a mask with a small hole in it. Obtain a series of about six observations covering as wide a range as possible.

Record and Calculation: Tabulate:

u	v	$\frac{v}{u}$	I	O	$\frac{I}{O}$

The ratios of $\frac{v}{u}$ should equal the corresponding ones of $\frac{I}{O}$.

Note: The focal length of the mirror or lens can be found from the above observations by plotting the values of the magnification (I/O) against the values of the image distance (v). Fig. 92 shows the graph which should be obtained. The slope of the line should be $1/f$ and the intercept on the v-axis should be f. These facts can be proved thus:

Since

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$$

$$1+\frac{v}{u}=\frac{v}{f}.$$

$$\therefore \quad \frac{I}{O}=\frac{1}{f}.v-1.$$

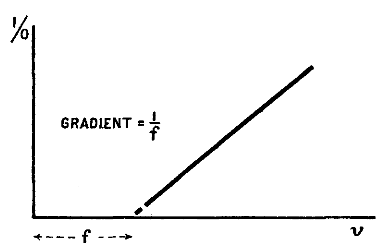


FIG. 92

Hence the slope of the graph of I/O against v is $1/f$. If in the equation we put I/O equal to zero then

$$\frac{1}{f}.v-1=0.$$

$$\therefore \quad v=f$$

hence the intercept on the axis of v is f.

Experiment 81. Determination of the Magnification produced by a Telescope when Image and Object are made to Coincide

Apparatus: Two convex lenses of focal length about 100 cm. and 5 cm. respectively; large sheet of drawing paper; optical pin.

THEORY

The 'magnifying power' of any optical system producing an image, such as a telescope or microscope, may be calculated from the known constants of the lenses or mirrors, having first stated some standard position for the object and the image. Obviously what actual magnification will occur depends upon what focusing adjustments are made when using the instrument. Thus, for example, various magnifications can be obtained by varying the relative positions of the eye, lens and object. For most optical instruments, other than an astronomical telescope used for observing objects so far away that they may be considered to be at infinity, the observer adjusts the instrument so that the image is at the least distance of distinct vision.

In a simple laboratory experiment such as this the precise adjustment is stated and the measurement obtained is the magnification for that adjustment and not the magnifying power.

Procedure: On a strip of paper, make a series of equally spaced lines. It does not matter how far apart these lines are, but the paper has to be hung up as far away from the observer as possible and the lines must be clearly visible to the unaided eye. Having decided where the paper will be placed make appropriate lines. The paper should be at least the full length of the laboratory away, but if a convenient wall or fence can be used at a greater distance and observed through an open window, use this.

Set up a long focus lens, e.g. 100 cm. focal length, and observe that it produces a real, inverted and diminished image of the paper. This image can be located by the 'no parallax' method, using a pin.

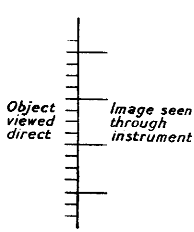


FIG. 93

Use a short focus lens—5 cm. focal length is convenient—as an eye-piece and place this about its focal length in front of the small image produced by the objective lens.

Place one eye close to the eyepiece, and look at the paper with the other eye directly. Adjust the position of the eyepiece by moving it backwards and forwards until judging by the 'no parallax' method, the image seen through the lens, and the object seen directly, are in the same vertical plane (see Fig. 93).

The image will appear magnified, and by slight adjustments of the lenses one of the lines of the image can be made to appear by the side of one of the lines of the object. Count how many spaces on the object correspond to the space between two adjacent lines on the image. If the adjustment has been successfully carried out there will be no strain in viewing both object and image together as they are equally distant from the eyes.

The number obtained in the last operation is the magnification produced under the stated conditions.

Experiment 82. Determination of the Magnification produced by a Compound Microscope when the Image is at the Least Distance of Distinct Vision

Apparatus: Two short focus lenses—preferably both of focal lengths less than 5 cm.; squared paper; optical pin.

THEORY

Normally an observer will so adjust a microscope that the image he observes is at the least distance of distinct vision and usually such a position will not be far removed from that of the object.

Procedure: Use a small piece of squared paper as an object, and place a lens with a focal length of about 3 cm. between 4 and 5 cm. from it, as an objective. A real, inverted and enlarged image will be formed and may be located by the 'no parallax' method using a pin.

Use as an eyepiece a lens with focal length about 5 cm. and place it about 4 cm. from the real image formed by the objective. An enlarged virtual image will be formed.

Place one eye near to the eyepiece, and adjust the position of the eyepiece until the image coincides with another piece of graph paper viewed directly by the other eye, which is placed 25 cm. away from the eyepiece. It may be assumed that the least distance of distinct vision is 25 cm. although it will vary with the observer.

Minor adjustments will enable one line of the image to be made to coincide with one line of the object, and the number of divisions on the sheet viewed directly which correspond to one (or some convenient number of divisions) on the image, can be counted. It will help if one line on the object is ruled in red and another line also ruled in red on the sheet of paper. These two red lines can then be made to coincide.

Record and Calculation: Record the observations made and calculate the magnification.

Note: It is also possible to locate the eye-ring and hence to check that it coincides with the image of the objective formed by the eye-lens.

CHAPTER XXVIII

PHOTOMETRY

Experiment 83. Determination of the Fraction of Incident Light Transmitted by a Sheet of Glass

Apparatus: Two 24-watt 'clear' electric lamps having 'single line' filaments; the sheet of glass; photometer.

The last can easily be made by putting a spot of oil about 1 mm. in diameter on a piece of drawing paper. A pair of plane mirrors may be used, placed one on either side of the screen, and adjusted so that the observer can by means of them view both sides of the screen at once.

Procedure: Arrange the lamps at about 30 cm. from the screen, as shown in Fig. 94A, so that they give equal intensity of illumination on the screen, as judged by the disappearance of the grease spot, or whatever method is appropriate to the photometer used. Note the distance (d_1 cm.) of the lamp L from the screen, i.e. the distance from the centre of the filament.

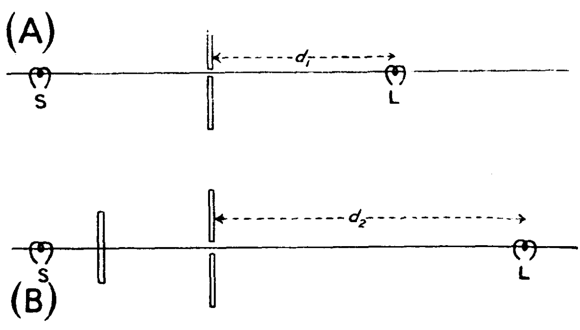


FIG. 94

Next interpose the sheet of glass between the lamp S and the screen and move lamp L until equality of intensity of illumination is restored (see Fig. 94B). It is essential that lamp S be left unmoved relative to the screen. Measure the distance (d_2 cm.) of the new position of L from the screen.

The distance of S from the screen should now be altered and the operations repeated giving another pair of values for d_1 and d_2.

Take a series of observations of corresponding values of d_1 and d_2 covering a wide range of values.

Record and Calculation: Tabulate as below:

d_1	d_2	d_1^2	d_2^2	d_1^2/d_2^2

The mean value of d_1^2/d_2^2 gives the required fraction of incident light transmitted.

The proof of this is as follows:

If L and S are of intensities I_1 and I_2 respectively, and S is at distance d cm. from the screen (both with and without the glass interposed) then

$$\frac{I_1}{d_1^2} = \frac{I_2}{d^2} \quad \text{and} \quad \frac{I_1}{d_2^2} = \frac{fI_2}{d^2}$$

where f is the fraction of incident light transmitted by the glass. Elimination of I_1, I_2 and d from these equations (by division) leads to the result given.

Experiment 84. Investigation of the Relationship between the Current produced by a Photoelectric Cell and the Intensity of Light Incident on it

I. Using a Barrier-layer Type Photoelectric Cell

Apparatus: 150-watt 'clear' electric lamp with suitable holder; micro-ammeter reading up to 100 microamps—preferably of resistance about 100 ohms, but reasonable results can be obtained using one of resistance up to 500 ohms; barrier-layer type selenium photoelectric cell, a suitable size is one having an active area of about 5 cm.[2] (Suitable cells can be obtained from Messrs. Evans Electroselenium Ltd., Bishops Stortford, Herts.).

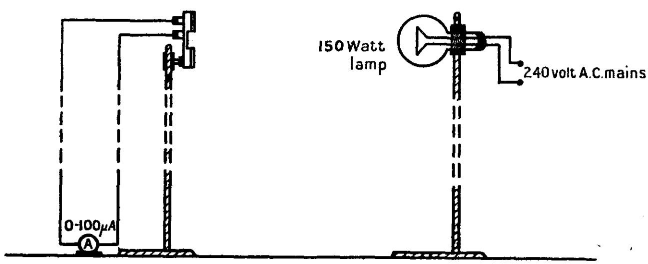


Fig. 95

Procedure: In a dark room set up the apparatus as shown in Fig. 95. Arrange the lamp so that its filament is in a plane perpendicular to the bench and parallel to the plane of the cell. Both the lamp and the cell should be as high above the bench as convenient, to reduce the effect of light reflected from the bench surface—a dark cloth placed on this will also help. Connect the cell directly to the microammeter as shown.

Keeping the planes of the cell and the lamp parallel, adjust the lamp until the current registered is about 10 microamps. Record the current (I) and the distance (d cm.) from the surface of the cell to the filament of the lamp.

Repeat for about 20 microamps, and then continue taking a series of observations up to about 100 microamps.

Record and Calculation: Tabulate your results as follows:

I microamps	d cm.	d^2	$1/d^2$

Plot $1/d^2$ against I. State the conclusion you make from the graph.

II. USING AN EMISSION TYPE PHOTOELECTRIC CELL

Apparatus: Emission type photoelectric cell such as would be used in a 'talkie' film projector—a Mazda PE 7B is suitable—(Maker's ratings for these cells are to ensure stability and very long life. For experimental purposes they can be exceeded for short periods of time); 150-watt lamp and microammeter as used in Part I; fixed resistor of 50,000–100,000 ohms; high-tension supply, 60–100 volts (see pp. 401–3).

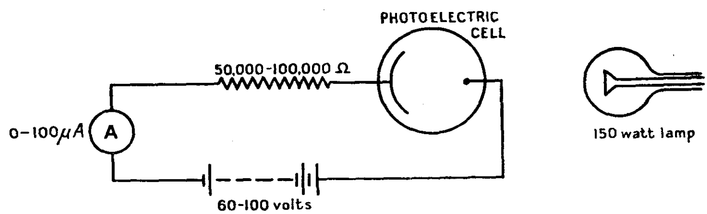


FIG. 96

Procedure: Arrange the apparatus as for Part I, connecting the cell into the circuit given in Fig. 96. The fixed resistor serves to limit the current, but it is still necessary to guard against applying too great a voltage to the cell, for if the latter passes too much current an arc discharge occurs, manifesting itself as a blue glow in the tube between the electrodes. This will probably ruin the cell.

Carry out adjustments and make observations as in Part I.

Record and Calculation: Tabulate the results as for Part I, plot $1/d^2$ against I and state your conclusion.

Compare the performances of the two cells.

CHAPTER XXIX

REFRACTION

Experiment 85. Determination of the Refractive Index of Water by the Real and Apparent Depth Method

Apparatus: Vernier microscope; coin; chalk dust.

Procedure: Place a coin at the bottom of a beaker. Focus a vernier microscope on some clear mark on the upper surface of the coin. Read the microscope scale. Let this reading be x cm.

Pour water into the beaker *so that the position of the coin is not disturbed.* Focus on the image of the same mark on the coin and take the microscope reading (y cm.).

Focus on the surface of the water and read the scale. If any difficulty is experienced in seeing the surface, sprinkle a little of any light powder on the surface and focus on this—lycopodium powder or chalk dust is quite satisfactory. Take the microscope reading (z cm.).

Repeat the whole experiment several times, using various depths of water, taking *all* three readings in each case.

Record and Calculation: Tabulate your results as follows:

x	y	z	$x-z$	$y-z$	$\frac{x-z}{y-z}=$

The mean value of the last column gives the mean value for the refractive index μ. This depends on the fact that

$$\mu = \frac{\text{Real depth}}{\text{Apparent depth}}.$$

Alternatively plot real depth against apparent depth and find the mean value of the ratio from the graph.

Note: This method is also applicable to transparent solids in the form of parallel-faced blocks, which are stood on drawing paper on which a pencil line has been drawn. The distances of this line and of its image below the upper surface are measured by means of the vernier microscope.

Experiment 86. Determination of the Refractive Index of a Liquid, using a Concave Mirror

Apparatus: Glycerine or other liquid of which the refractive index is required; concave mirror of radius of curvature 20–30 cm.; optical pin.

Procedure: Place the mirror on the bench and adjust the optical pin, supported in a clamp, until it coincides with its image formed by the mirror, i.e. is at the centre of curvature of the mirror. Measure its distance from the pole of the mirror (x).

Pour just enough liquid into the mirror to produce a plane surface and again adjust the pin to coincide with its own image. Measure the new distance of the pin from the pole of the mirror (y).

Repeat several times.

Record and Calculation: Tabulate your results and find a mean value of the ratio x/y; this will be the refractive index of the liquid. (The proof of this is left as an exercise for the student. It is given in many theoretical text books, to which reference should be made if necessary.)

Experiment 87. Determination of the Refractive Index of Water, or other Transparent Liquid, by Measuring the Critical Angle

Apparatus: The apparatus consists of a rectangular tank to contain the water. The sides of the tank are preferably made of thin, good quality glass. In the tank is immersed an 'air cell'.

This can be made from two fairly thick microscope glass-slips, cemented together by a thin layer of Canada balsam round their edges. It may be held in a bull-dog clip, and attached to a vertical rod which can be rotated. A pointer is attached to this rod so that it moves over a protractor to measure the angle of rotation. Such an arrangement is shown in Fig. 97A.

In addition to the above a source of monochromatic light is required (see p. 167) and three screens with slits in them.

THEORY

When light passes from a more dense to a less dense medium, *total* internal reflection occurs when the angle of incidence is equal to or greater than the critical angle.

In this experiment light is made to pass through an 'air cell' immersed in the water, and observations made which give a value for the critical angle C and the refractive index calculated from:

$$\mu = \frac{1}{sin\ C}.$$

Referring to Fig. 97B,

$$\frac{\sin \alpha}{\sin \beta} = {}_w\mu_g$$

$$\therefore \sin \alpha = {}_w\mu_g \sin \beta \quad . \quad . \quad . \quad (i)$$

Also

$$\frac{1}{\sin \beta} = {}_a\mu_g$$

$$\therefore \sin \beta = {}_g\mu_a \quad . \quad . \quad . \quad . \quad (ii)$$

Substitute for $\sin \beta$ in (i)

$$\therefore \sin \alpha = {}_w\mu_g \times {}_g\mu_a = {}_w\mu_a$$

$\therefore$ α is the critical angle for a water-air surface.

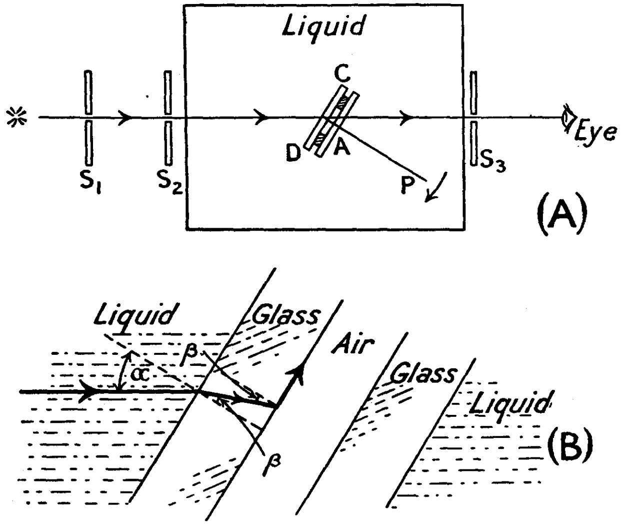


FIG. 97

Procedure: Set up a source of monochromatic light on one side of the tank. Place between it and the tank two opaque screens S_1 and S_2, in each of which has been cut a slit rather less than 1 mm. wide.

On the other side of the tank place a similar screen S_3.

Fill the tank with water and arrange the position of the three screens so that the light reaching the tank through the two slits is normal to the surface, and can be seen through the slit on the other side.

Introduce the air cell CD so that it is approximately at right angles to the beam of light. Check the adjustment made above, and rotate the cell to the right until it is observed that the light is cut off. At this stage read the position of the pointer AP on the protractor.

Rotate the air cell to the left, through its original position, until the light again disappears. Read the position of the pointer on the scale.

Repeat in order to obtain at least six values for each position of extinction of light.

Record and Calculation: Tabulate your results and find a mean value for the critical angle for water. Hence calculate the refractive index.

Experiment 88. Determination of the Refractive Index of Vaseline, using a Wollaston's Refractometer

Apparatus: This is shown diagrammatically in Fig. 98 in which L is a source of monochromatic light (see p. 167), XY is a translucent screen, BC is the base of a glass block which stands on a black base board, AD, attached to a vertical screen in which is cut a horizontal slit, S.

THEORY

The base BC of a glass block is smeared with a little vaseline and placed as shown.

When the block, placed far enough away, is viewed through the slit S the whole of the base appears brightly illuminated, as the light reaching it is totally reflected by the glass-vaseline interface, i.e. the angle of incidence is greater than the critical angle.

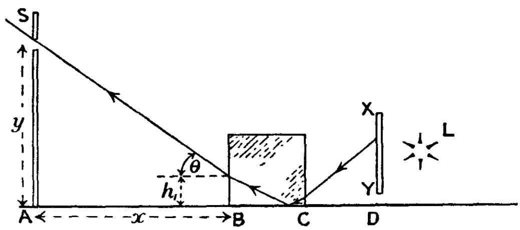


FIG. 98

When the block is moved nearer the slit the light which reaches the slit will have struck BC with a smaller angle of incidence. When this angle is less than the critical angle the light will not be strongly reflected, but will pass through the vaseline and be absorbed by the black surface. This will obviously occur first near B, and therefore if the block is moved steadily towards the slit a black shadow appears on the base, near B at first, and creeps towards C.

Then if x, y and h_1 are the distances as shown in Fig. 98, it can be shown that

$$_{\text{air}}\mu_{\text{vaseline}} = \sqrt{(_{\text{air}}\mu_{\text{glass}})^2 - \frac{(y - h_1)^2}{[x^2 + (y - h_1)^2]}}.$$

The deduction of this equation is to be found in text books on Light.

Procedure: Determine the refractive index of the glass of which the block is made, see Note to Experiment 85, p. 200.

On the side of the block facing the slit make a horizontal mark about 1 cm. from the base. This may be done by sticking a very narrow strip of paper on the glass.

Measure the height (h_1) of the bottom edge of the mark above the base of the block and that of the bottom of the slit above the base board, y.

Smear a layer of vaseline on the base of the glass block and place it on the base board, so that when viewed through the slit the whole of the base appears bright. Move the block little by little towards A—do not *slide* the block along the board. Continue until the edge of the shadow produced, which begins nearest to A, appears to coincide with the horizontal mark.

Measure the distance x (see Fig. 98). Repeat to get a mean value.

Calculation: Find the mean value of x and substitute this and the other quantities in the equation given above.

Note: This method can be applied to any liquid.

Experiment 89. Determination of the Refractive Index of Glass in the Form of a Prism, using the Spectrometer

The Spectrometer and Its Adjustments

The spectrometer, Fig. 99, consists of :

(1) *A collimator, A,* for producing a beam of parallel light.

(2) *A telescope, B,* for observing the beam of light.

(3) *A turn-table, T,* on which is supported a device for producing deviation.

The collimator consists of a metal tube, at one end of which is an adjustable slit S, and at the other a convex lens so arranged that the light passing through it from the slit issues as a parallel beam. This, of course, can only be the case when the slit is so narrow as to approximate to a straight line. In practice the slit is widened to admit enough light to make the image in the telescope easily visible.

The telescope is an ordinary one of small magnifying power with cross-wires, C, mounted in the eyepiece, E. It can be turned in a horizontal plane and the angle through which it swings is measured on a scale of angles engraved on the turn-table. Two verniers, mounted 180° apart, are used to increase the accuracy of the readings. When the telescope is moved from one position to another it is necessary to observe whether the zero line of the scale is crossed. If this happens, record the fact and allow for it when calculating the angle through which the telescope has been turned. Locking screws and fine adjustment screws are provided. The general arrangement is illustrated in Fig. 99, but the actual instrument available should be examined for minor variations.

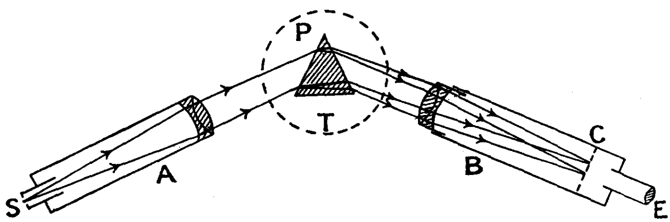


Fig. 99

A number of adjustments must be made to the spectrometer before it is used in any experiment. These are listed below in the order in which they should be made. It is very important not only to adhere to this order but also to be very careful at each stage to avoid altering any adjustment already completed.

Adjustments to be made to the Spectrometer

(1) The Telescope

(i) Point the telescope at a light coloured surface and adjust the eyepiece until the cross-wires are seen sharply without any eye strain.

(ii) Point the telescope at some distant object—clouds in the sky if available or distant trees—and focus until the image and the cross-wires exhibit no parallax. The telescope is now adjusted to focus parallel light on the cross-wires. If it has been removed for these adjustments replace it in its holder.

Place the instrument in the position where it will be used and check that the supporting surface is level.

(2) THE COLLIMATOR

(i) Place a source of monochromatic light (see p. 167) several inches from the collimator slit, and move the telescope until it is in line with the collimator, and the image of the slit can be seen through the eyepiece.

(ii) If necessary, adjust the collimator until the image of the slit exhibits no parallax with the cross-wires, i.e. ensure that a parallel beam of light is emerging from the collimator.

(3) THE TURN-TABLE

This must be levelled, first using a spirit level (this will give an approximate adjustment) and then using the following optical method:

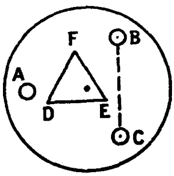


FIG. 100

(i) Place a glass prism DEF, refracting angle DEF, Fig. 100, on its support, with the refracting face DE at right angles to a line BC joining two of the levelling screws, and with the refracting angle close to the centre of the table, as shown in the figure, where A, B and C are the levelling screws. In this position, when the face DE is vertical, movements of the screw A will not alter its plane.

(ii) Looking into the face DE an image of the slit will be seen formed by direct reflection from this face. If necessary move the table to get this image. When found, move the telescope round to view it. Lock the table and adjust screw B until the image is upright and symmetrically placed about the horizontal cross-wire in the field of view.

(iii) Unlock the table, and swing it round to get a reflection from the face EF, and repeat the adjustment by altering screw A. When these adjustments are completed the table should be level. Ensure that this is so by focusing on the first image again and checking that it is in the middle of the field of vision. If it is not, repeat the levelling operations.

THEORY

The experiment is divided into two parts:

(1) the determination of the refracting angle of the prism ($A°$), and

(2) the determination of the angle of minimum deviation of light passing through the prism ($D°$). The refractive index (μ) is given by the formula.

$$\mu = \frac{\sin \dfrac{D + A}{2}}{\sin \dfrac{A}{2}}$$

I. Determination of the Refracting Angle of the Prism

Procedure: Make a careful inspection of the spectrometer so that you become quite familiar with

(i) What each locking screw controls,
(ii) How each 'fine adjustment' works, and
(iii) How the vernier scales are calibrated (see p. 47).

Next adjust the instrument carefully according to the instructions given above. When this is completed turn the table so that the refracting angle of the prism is pointing towards the collimator, and the beam of monochromatic light is incident on the apex of this angle, falling partly on one face and partly on the other. It will be reflected by both. Lock the table.

Locate the image formed by reflection in one face, using the unaided eye, and then move the telescope to a position between the eye and the prism (this saves a great deal of time spent in staring down the telescope when it is a long way from the required position). Lock the telescope and use its fine adjustment to make the centre of the cross-wires coincide with one edge of the image. Read both verniers.

Unlock the telescope and swing it round to receive the image formed by reflection in the other face. Repeat the operations described above to find the vernier readings for the same edge of the image.

Rotate the prism relative to the table and repeat all observations.

Record and Calculation: For each set of observations tabulate as follows:

	Scale A				Scale B			
	1st Position		2nd Position		1st Position		2nd Position	
	Deg.	Min.	Deg.	Min.	Deg.	Min.	Deg.	Min.
Main Scale (to nearest half degree)								
Vernier Scale								
Sum								
Angle between 1st and 2nd Position	......deg. ......min.				......deg. ......min.			

Mean of the two values in the last line (=2A) = deg. min.
Hence angle A = deg. min.

Calculate the mean of the two determinations.

II. Determination of the Angle of Minimum Deviation

Procedure: Unclamp the table and place the prism on it. Rotate the table into a position where the light from the collimator will be refracted.

Locate the image, with the unaided eye, and then rotate the table slowly. Follow the image, with the eye, until a position is found such that whichever way the table is rotated the eye has to be moved away from the 'straight through' position in order to follow the image. In this position the deviation produced by the prism will be at its minimum value. Introduce the telescope between the eye and the prism and locate the image. Using the fine adjustment screws make final adjustments to the table and the telescope so as to locate the position of minimum deviation as accurately as possible. Record the scale readings, using the vernier as before.

Unclamp the telescope, ***but not the table***, remove the prism, and swing the telescope into the 'straight through' position; clamp and use the fine adjustment to obtain the exact position and record both the vernier readings.

Place the prism on the table so that deviation occurs on the opposite side of the 'straight through' position, and repeat the above operations.

Record and Calculation: Record all your observations. From the four sets of readings calculate an average value for the angle of minimum deviation, D.

Substitute this value, together with that found for A in Part I, in the equation

$$\mu = \frac{\sin \dfrac{D + A}{2}}{\sin \dfrac{A}{2}}$$

and hence find a value for the refractive index.

Experiment 90. Investigation of the Deviation produced by a Prism, using a Spectrometer

Apparatus: Sodium vapour lamp; spectrometer (for this experiment a simple calibration is an advantage); prism.

THEORY

(i) *General theory of the prism:*

If i is the angle of incidence,
e is the angle of emergence,
d is the deviation,
and A is the refracting angle of the prism
it is readily shown that

$$d - e = i - A \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

If graphs are plotted of i as abscissa, against e, d and $(d - e)$ in turn, using the same axes, the result should be as shown in Fig. 101.

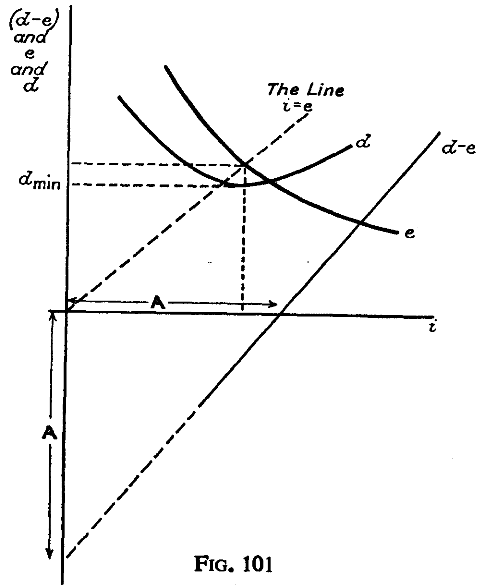


FIG. 101

Notes on the graphs:

(*a*) Clearly as i increases, e must decrease.

(*b*) A minimum value of d should be found, and this should occur for the value of i which corresponds to symmetrical passage, that is where $i = e$ This can be checked from the graphs obtained experimentally.

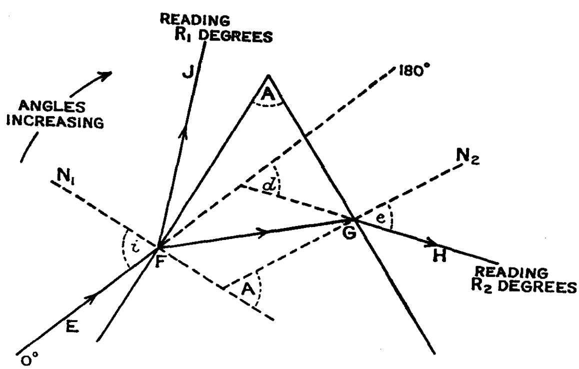


FIG. 102

(c) From equation (1) above it is seen that the graph of $(d - e)$ against i should be linear, since A is a constant for a given prism, and also that the intercepts on the axes should each be equal to A. This can be checked against the value determined by the usual experimental method.

(ii) *Determination of i, d and e:*

In this experiment the 'straight-through' reading is kept at 180° and thus the incident light corresponds to a reading of 0°.

If, in Fig. 102, EFGH represents the path of light through the prism and FJ is the reflected ray, then, if R_1 and R_2 are the *readings* of the reflected and emergent rays for the setting shown, then

$$i = R_1/2 \quad \text{(2)}$$

and

$$d = R_2 - 180° \quad \text{(3)}$$

We can obtain an expression for e by remembering that the normals, FN_1 and GN_2, are at an angle, A, to each other.

Now the reading of FN_1 would be $R_1/2$, and that for GN_2 would therefore be

$$R_1/2 + 180° - A$$

thus

$$e = R_2 - [R_1/2 + (180° - A)] \quad \text{(4)}$$

So, using equations (2), (3) and (4), the values of i, d and e can all be deduced from the readings R_1 and R_2 and the value of A.

Procedure: Carry out all the adjustments to the spectrometer, and measure the angle, A, of the prism in accordance with the instructions given in Experiment 89, p. 204.

Remove the prism and set the telescope to receive the direct beam from the collimator. Lock the telescope. Release the table and rotate it until the reading is exactly 180°. If the instrument has two scales set at 180° apart, use only one of the verniers, but be careful to read only this one throughout the experiment. Use a lens to aid in the settings. Lock the table and *leave it locked for the remainder of the experiment.* Release the telescope.

Replace the prism on the table so that the incidence is as near 'grazing' as possible (i is nearly 90°). Focus the telescope on the reflected light and record the reading, R_1. Leaving the prism untouched, move the telescope to receive the transmitted light and record the reading, R_2.

Rotate the *prism* (NOT the table) a little, and repeat the observations of R_1 and R_2. Continue this process until total internal reflection occurs, taking about ten pairs of readings well spaced throughout the range of angles investigated.

Record and Calculation: Record all observations relevant to the determination of the refracting angle of the prism as shown in Experiment 89, and calculate its value.

Tabulate the other observations in a table as shown below:

R_1	R_2	i $(= R_1/2)$	e $(= R_2 - \frac{R_1}{2} - 180° + A)$	d $(= R_2 - 180°)$	$d-e$

Plot the three graphs referred to in the notes on theory given above and check:

(i) that the minimum deviation occurs when $i = e$,
(ii) that the $(d - e)$ graph is linear;
(iii) that the intercepts of the $(d - e)$ graph are each equal to A.

Note: This experiment is often performed using pins—Problem 27 on p. 477. The pin method is less accurate and the range of values of i which can be investigated is not as great as in the above experiment. (Why is this?)

Experiment 91. Determination of the Dispersive Power of Glass in the Form of a Prism and Verification of Cauchy's Formula

Apparatus: A gas discharge tube, e.g. hydrogen, mercury or mercury-cadmium, giving spectral lines covering the range of the visible spectrum adequately; spectrometer; prism; source of monochromatic light (for preliminary adjustments of the spectrometer).

THEORY

The dispersive power of glass is defined as

$$\frac{\mu_F - \mu_C}{\mu_D - 1}$$

where μ_F is the refractive index of the glass for the F-line of the hydrogen spectrum
μ_C is that for the C-line of the hydrogen spectrum,
and μ_D is that for the sodium D-lines.

In this experiment, data is obtained which can be expressed as a graph of refractive index (ordinate) against wavelength. From the graph the values needed for substitution in the above formula can be obtained using the following data:

Wavelength of F-line $= 4{\cdot}861 \times 10^{-5}$ cm.,
Wavelength of C-line $= 6{\cdot}563 \times 10^{-5}$ cm.,
Wavelength of D-lines $= 5{\cdot}893 \times 10^{-5}$ cm. (mean value).

If a hydrogen tube is used these lines will appear strongly in the spectrum examined, but they do not appear in the other spectra.

Cauchy's formula states that if λ is the wavelength

$$\mu = A + \frac{B}{\lambda^2}$$

where A and B are constants for the glass, their values being in the region of $1{\cdot}6$ and 10^{-10}, respectively, for many types of glass.

Procedure: Using the monochromatic light source, carry out all the preliminary adjustments to the spectrometer as described in Experiment 89, p. 204, and measure the refracting angle of the prism by the method described in that experiment.

Change over to the discharge tube and examine the spectrum produced by the prism, selecting about ten bright lines which cover the visible range well and are also readily identified. Determine the angle of minimum deviation for each line by the method of Experiment 89.

Next, it is necessary to determine the wavelengths corresponding to the selected lines. Data may be available in the laboratory, or in a manufacturer's catalogue, and if time is short such information may well be used. Failing this, the wavelengths should be determined using a diffraction grating in accordance with the instructions given in Experiment 96, p. 219.

Record and Calculation: Tabulate all your observations as described in the experiments on which your methods are based.

When the refractive indices and wavelengths have been obtained, summarize the results in a table as under:

Colour	Brightness	Wavelength (λ)	Refractive Index (μ)

The second column is intended to give only a rough estimate such as 'very bright', 'faint', etc.

Plot a graph showing refractive index as ordinate and wavelength as abscissa. If a hydrogen tube was not used, read from the graph, which should appear as in Fig. 103, the values of μ_F, μ_C and μ_D using the

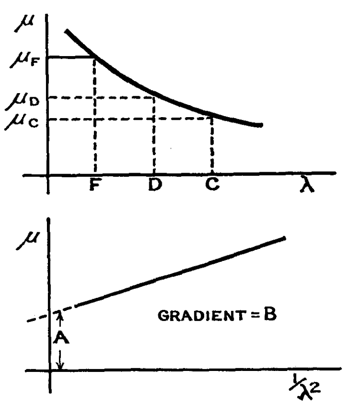


FIG. 103

wavelengths given under 'Theory' above. Hence substitute in the appropriate equation to obtain the dispersive power.

Next, plot a graph of μ as ordinate against $1/\lambda^2$ which should be a straight line, the gradient of which is B and the intercept on the μ axis is A. Determine these values and compare them with the suggested approximate values given under 'Theory' above.

Note: The whole experiment takes a considerable time but with careful work yields extremely satisfying results.

Experiment 92. Verification of the Equation for Refraction at a Single Spherical Surface

Apparatus:

The special vessel shown in Fig. 104 should be made by sealing a 40–50 cm. length of glass tubing of diameter 4–5 cm. into a wide-necked round-bottomed flask of diameter about 10 cm. The bottom of the flask must be spherical—cheap flasks are useless for this purpose. The sealing must make a strong water-tight joint and the use of a glazing compound, e.g. Bostik, round the cork is recommended.

In addition a single-line-filament lamp is needed, operating on a low-voltage supply, e.g. a 24-watt 12-volt motor-car headlamp bulb, or better, a 4-volt 0·8 amp. krypton-filled miner's lamp; this is smaller and has a very bright filament. This lamp is to serve as the 'object' and the flex should be sheathed by a piece of glass tubing slightly longer than the depth of water which will be used. The lampholder should also be coated with wax, from a lighted candle, so that water cannot penetrate to any part of the electrical circuit (this means that wax must also cover the bottom of the glass tubing which sheathes the flex).

THEORY

If the refractive index of water is μ and the radius of curvature of the surface is r, then applying the general equation

$$\frac{\mu_1}{u} + \frac{\mu_2}{v} = \frac{\mu_2 \sim \mu_1}{r}$$

where the symbols have their usual significance, we obtain

$$\frac{\mu}{u} + \frac{1}{v} = \frac{\mu - 1}{r}$$

as the equation applying to light emerging from the apparatus shown.

Thus
$$\frac{1}{v} = -\mu \cdot \frac{1}{u} + \frac{\mu - 1}{r}.$$

If values of u and v are determined and a graph plotted of $1/v$, as ordinate, against $1/u$, then the gradient should be $-\mu$, i.e. $-4/3$. The intercept on the axis of $1/v$ should, moreover, be $\frac{\mu - 1}{r}$.

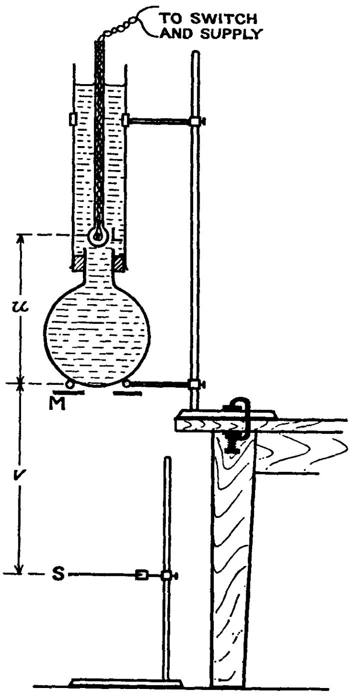


FIG. 104

Procedure: Arrange the apparatus as shown in Fig. 104. The glass tube supporting the lamp, L, must be capable of vertical movement so that a wide range of values of u can be investigated, u being the distance from the filament of the lamp to the lowest part of the surface of the flask. Focus the image of the filament on a screen, S; the sharpness of the image will be improved by reducing the aperture of the refracting surface to a diameter of about 2 cm. by means of a paper mask, M, with a circular hole in it. Obtain a series of corresponding values of u and v covering as wide a range as possible. It will be necessary to keep u greater than $4r$, as for values of u less than $4r$ the image is virtual—you should be able to show that this is so by considering the equation given under 'Theory' above.

Finally, determine the radius of curvature of the lowest portion of the flask, using a small spherometer—why not a large one?

Record and Calculation: Tabulate your results including columns in the table for the calculated values of $1/u$ and $1/v$.

Plot a graph of 1/v, as ordinate, against 1/u. Careful experimenting will produce a linear graph. Evaluate the gradient and compare it with the expected value, which is $-4/3$. Evaluate also the intercept on the axis of 1/v and compare it with the expected value of $(\mu - 1)r$ computed from the value of r determined by means of the spherometer.

CHAPTER XXX

INTERFERENCE

Experiment 93. Determination of the Radius of Curvature of the Surface of a Long Focus Convex Lens, using Newton's Rings

Apparatus: The apparatus is shown in Fig. 105 in which
S is a source of sodium light (see p. 167),
L is the convex lens of long focus—at least 100 cm.
G is a block of optical glass supporting L,
B is any convenient dark background, e.g. dark cloth,
P is a plate of glass which reflects light from S on to L,
M is a vernier microscope,
A is a short focus lens of large aperture.

All glass surfaces should be carefully cleaned before use.

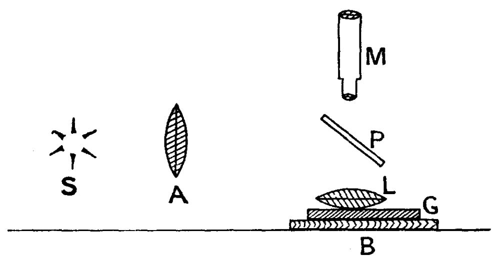


FIG. 105

THEORY

If d_n is the diameter of the nth dark ring then it can be shown that

$$d_n^2 = 4R \, . \, n \, . \, \lambda$$

where λ is the wave length of the light used
and R is the radius of curvature of the lower surface of the lens.

To use this formula it is necessary to know the value of n, which is difficult owing to the indistinctness at the centre, but if d_{n-k} is the diameter of the $(n - k)$th ring, then it follows that

$$(d_n^2 - d_{n-k}^2) = 4R \, . \, k \, . \, \lambda$$

and this can be used to calculate the radius, R, without knowing the number of any ring, provided a value for λ is assumed.

This is the method used in industry for the determination of the radii of curvature of optical surfaces.

Procedure: Before putting the lens L in place, focus the microscope on a piece of paper, or a chalk mark, placed on G. This ensures that the plane in which the rings occur coincides with the focal plane of the microscope and reduces the problem of locating the rings to the relatively easy two-dimensional one. Remove the paper, put L on G, and try to locate the rings by the unaided eye. They will be very small but if the focal length of L is great enough this will be possible. Having located them, move the microscope in a horizontal plane until it is between your eye and the rings. On looking through the microscope some part of the system of rings should be visible—sufficient to enable the final adjustments to be made. Focus so that the rings are distinct and the microscope travels so that measurements made with it will afford values for the diameters of the rings—not chords which are near to them.

The rings very near the centre may not be very distinct, but those farther away should be sharply in focus.

Focus the microscope on the middle of a distinct dark ring. Measurements on about twenty rings are desired, so select a ring which will leave about this number of distinct rings between it and the centre. Read the microscope vernier.

Focus on the next ring nearer the centre, and read the vernier. Continue until twenty measurements have been made on successive rings. The number '20' has no special significance, but it is necessary to measure an even number of rings, and the greater the number the more accurate the final result.

When the last ring has been observed the microscope will still be on one side of the centre. Move it across the centre until it is focused on the same ring at the other end of its diameter. Read the vernier, and proceed outwards until a second set of observations has been made on the twenty rings, from which their diameters can be deduced.

Record and Calculation: Tabulate your observations as below, dividing the table into the two halves as shown.

Number of Ring	Reading		Diameter		Number of Ring	Reading		Diameter		$(d_n^2-d_{n-10}^2)$ etc.
	Right	Left	d_n etc.	d_n^2 etc.		Right	Left	d_{n-10} etc.	d_{n-10}^2 etc.	
n					$n-10$					
$n-1$					$n-11$					
.					.					
.					.					
.					.					
$n-9$					$n-19$					

From the last columns calculate an average value of

$$\frac{(d_n^2 - d_{n-10}^2)}{10}$$

Look up the wave-lengths of the sodium D-lines and use a mean value as the value for λ in the equation

$$\left(\frac{d_n^2 - d_{n-10}^2}{10}\right) = 4R\lambda.$$

Solve this equation for R.

Note: Check your result by finding R by Boys's method (see p. 190).

Experiment 94. Determination of the Wavelength of Sodium Light, using a Biprism

Apparatus: Fresnel's biprism; source of sodium light (see p. 167); vernier microscope; two convex lenses of focal lengths about 5 cm., and 15–20 cm. respectively; optical pin; screen with narrow vertical slit in it. The slit should not be wider than 0·1 mm. and can be made by using two safety-razor blades.

THEORY

The arrangement is shown in Fig. 106 in which

S is a source of sodium light, placed at the focus of lens L,
A is a screen with a narrow slit in it,
B is the biprism.

The biprism, which has an interfacial angle of almost 180°, produces a pair of virtual images of the slit very near together, and it is the light from these images that interferes. The bands extend to infinity but are examined in the focal plane of the microscope, which will show them in sharp focus at once, provided its focal plane lies on the opposite side of the biprism to the slit.

It can be shown that if

λ is the wavelength of the light used, in cm.,
D is the distance, in cm., from the slit in A to the focal plane of the microscope,

and d is the distance apart of the images, S_1 and S_2, in cm., then the fringe width (z) is given by

$$z = \frac{D}{d}\cdot\lambda\,.\,\text{cm.}$$

Thus, to obtain a set of broad fringes, D should be as large as possible. It is usually made about 1 metre. AB should be about 20 cm.

Procedure: Use the source of sodium light and the shorter focus convex lens to illuminate the slit with monochromatic light. Introduce the biprism, at 15–20 cm. from the slit. It should be mounted on a small platform provided with levelling screws. Failing specially provided apparatus the table of the spectrometer can be used. Arrange that the slit and the edge between the faces of the biprism are vertical. The biprism edge can be brought parallel to the slit by observing the images of the slit by the unaided eye and slowly moving the head from side to side; if the adjustment is correct each image will disappear suddenly along the whole of its length, when the eye is moved too much to one side. Place the vernier microscope about 1 metre from the slit so that it will travel horizontally along a normal to the incident light. Exclude all extraneous light—including that from the source which has not passed through the biprism—and move the microscope *slowly* across the field until the fringes appear. No focusing will be necessary—except that of the eyepiece on the cross-wire—and the brightness of the fringes can usually be slightly improved by making minor adjustments to the levelling of the biprism, and the position of S.

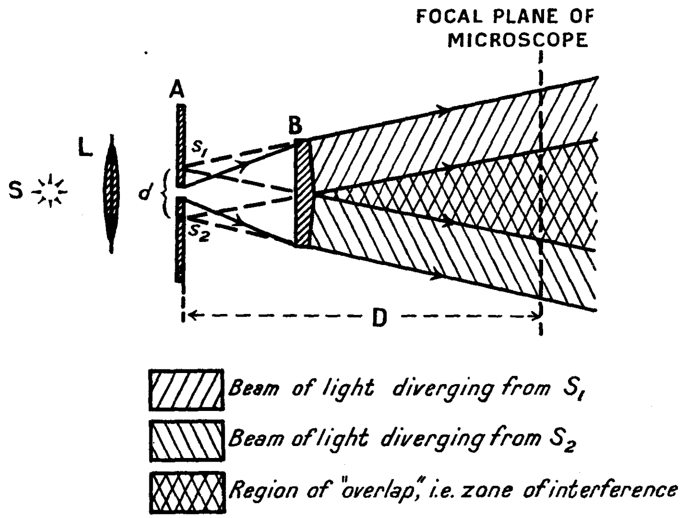


FIG. 106

Before taking observations on the fringes the measurements of d and D should be made as follows:

Place the optical pin vertically so that it is sharply in focus when viewed through the microscope. It is now in the focal plane of the microscope and D can be found by measuring the distance of the pin from the slit. Keeping the pin and microscope unmoved, introduce the longer focus* convex lens between the biprism and the pin and adjust the position of the lens until the real images of the virtual sources S_1 and S_2 show no parallax with the pin. This process will be made easier if a white screen is placed in the focal plane of the microscope, so that the images can be produced on the screen before they are looked for in the microscope. Use the microscope to measure the distance apart of these images (d_1 cm.). Measure also the distance, v, of the lens from

* The focal length must be less than $D/4$—why?

the pin and the distance, u, of the slit from the lens. Remove the lens which has been used to produce the images just investigated and remove also the pin. Be careful to leave all the rest of the apparatus exactly as it was until after the fringe system has been measured. Focus the microscope on a bright line near the edge of the system of fringes and record the vernier reading. Take a series of readings of the positions of bright lines focusing, say, on every fifth line, so that a reliable average value for the fringe width can be obtained.

Record and Calculation: Record the values of D and d_1.

Tabulate your observations on the fringes and find a mean value for the fringe width, z.

Calculate d from

$$\frac{d}{d_1} = \frac{u}{v}.$$

Substitute in $\lambda = \frac{dz}{D}$ to find λ.

CHAPTER XXXI

DIFFRACTION

Experiment 95. Determination of the Wavelength of Sodium Light, using a Diffraction Grating

Apparatus: Spectrometer; diffraction grating; source of sodium light (see p. 167).

THEORY

In this experiment the deviation produced by a grating on which is ruled a known number of lines is observed for sodium light. The first order spectrum and, if visible, the second order spectrum should be used. It can be shown that for the first order spectrum produced by a grating of spacing d

$$d \sin \theta = \lambda$$

and for the second order $$d \sin \theta = 2\lambda.$$

Thus if N is the number of lines per cm. on the grating,
λ is the wavelength in cm. of the light used,
and θ is the angle of deviation,
we can substitute $1/N$ for d and obtain

(i) for the first order $\sin \theta = N\lambda$

(ii) for the second order $\sin \theta = 2N\lambda$.

Procedure: If you have not used a spectrometer before, perform Experiment 89, p. 204, before attempting this one.

Make the preliminary adjustments to the spectrometer, see p. 204.

The grating must be exactly normal to the incident light, and to make this adjustment the following operations are carried out:

(i) Place the telescope in the 'straight through' position and read both verniers.

(ii) Turn the telescope through 90°. This is done by calculating the correct vernier readings and moving the telescope to this position. Clamp it.

(iii) Place the grating on the table and turn the latter so that a reflected image of the slit coincides with the cross-wires in the telescope. Read the verniers.

(iv) Turn the table through exactly 45°, keeping the telescope clamped. The grating is now normal to the incident light. Clamp the table and unlock the telescope.

Focus on the 'straight through' position and read the verniers.

Focus on the first order spectrum on each side of the 'straight through' position and again read the verniers.

If the second order spectrum is visible, then make similar readings for it.

Record and Calculation: Tabulate your results and calculate the average deviation for each spectrum investigated. Substitute in the appropriate formula to find the wavelength.

Note: The sodium spectrum has two lines and with a good instrument, well adjusted, separation of these 'D-lines', as they are called, can be effected, and measurements made on each line. The second order spectrum gives greater separation.

Experiment 96. Examination of the Spectrum emitted by a Gas-Discharge Tube

Apparatus: The gas discharge tube, e.g. hydrogen, neon, or mercury-cadmium; if only a sodium tube is available this may serve, as many lines of the sodium spectrum are often bright enough for easy observation. Spectrometer; source of sodium light; diffraction grating.

Procedure: Using the source of sodium light carry out all the preliminary adjustments to the spectrometer and to the grating as described in Experiments 89 and 95, pp. 204 and 218.

Replace the sodium light by the gas-discharge tube and for each line of the spectrum, except the very faint ones, take observations of the deviation on each side for the first order spectrum. Record also the 'straight-through' position.

Record and Calculation: Tabulate and analyse the results as under:

Number of lines per cm. of the grating (N) =

Colour	Estimate of brightness	Vernier readings			Mean θ	Wavelength λ
		left	'straight through'	right		

The wavelength is calculated from $\lambda = \frac{\sin \theta}{N}$.

Note: If Experiment 91 has not previously been done it can profitably follow this one immediately, as the data obtained is needed in Experiment 91.

PART V

SOUND

CHAPTER XXXII

STANDARD PROCEDURE

Tuning

In many sound experiments it is necessary to tune one source of sound to have the same frequency as another. The trained musical ear is surprisingly accurate in judging when two notes have the same frequency, but even the best musicians make mistakes, and it is therefore better to be as sure as possible by employing some more or less mechanical aids such as:

(*a*) *The Phenomenon of Beats.* The sounding sources are tuned as closely as possible by ear, and beats are listened for when both sources are sounding. The tuning process is continued in such a way that the rate at which beats occur is diminished, until none are produced. The two sources have then the same frequency.

If the tuning is carried out to determine the frequency of one source, the other being known, then matters are so arranged that well-marked beats are heard at a rate which can be counted easily. The number of beats per second is determined, and this number is the difference in frequency between the two sources and has to be added or subtracted to find the unknown frequency. If on slightly raising the pitch of the unknown source the rate at which beats are heard increases, then the difference must be added; it must be subtracted if the rate of beats decreases.

(*b*) *Using the Phenomenon of Resonance.* If when one source is sounded another 'picks up' the note in resonance then both must have the same frequency. Care must be taken that the resonance is not caused by any overtones. As an example, a stretched wire can be made to vibrate by sounding a tuning fork of the same frequency. The fork should be rested on the end of the wire as shown in Fig. 107.

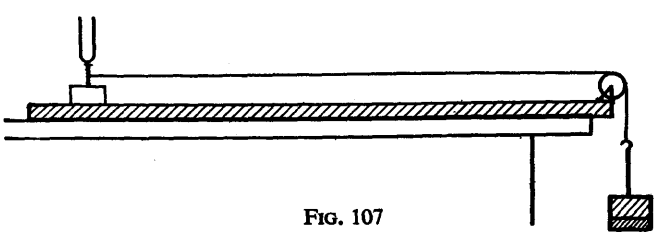


FIG. 107

Small paper riders may be placed on the wire, and they will be violently agitated and probably thrown off the wire when resonance is obtained.

In the case of the resonance tube (see below), after the level of water has been adjusted to within a few millimetres of the resonating position the final adjustment can be made to a high order of accuracy if the tuning fork is given a very small 'flick'—so small that the unaided ear has difficulty in hearing the sound. The tube in correct adjustment will respond to these small vibrations and the note will 'sing out' from the tube quite loudly.

Resonance Tubes

Any closed tube resonates to a frequency that bears a close relationship to the length of the tube—see the theory of Experiment 98, p. 229. Investigation of the phenomenon requires a tube the length of the air column in which can be easily varied at will. Such a tube is known as a 'resonance tube'. The method most commonly used consists in altering the length of the air column in the tube by introducing varying quantities of water into it. The simplest form of a resonance tube would thus be, for instance, a gas jar or measuring cylinder into which water is poured to vary the volume of air. This method is not rapid enough

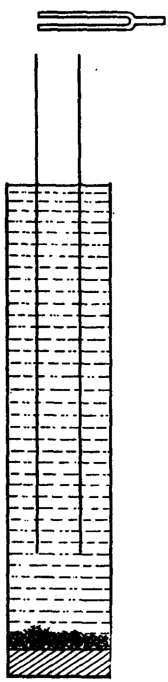


FIG. 108

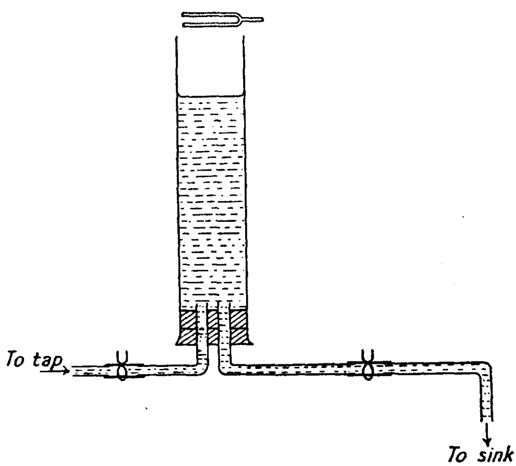


FIG. 109

and such vessels are not long enough. Two better methods are suggested.

(1) About 1 metre of glass tubing about 5 cm. in diameter is supported vertically in a vessel of water at least 1 metre deep (see Fig. 108). Clearly vertical motion of the tube presents a quick method of achieving the object in view.

There is sometimes difficulty in obtaining the vessel into which to put the resonance tube. A wide tube securely corked at the lower end will serve. A pad of cotton wool should be placed at the bottom of the tube so that if the resonance tube slips it does not break. The outer tube should be *filled* with water so that the upper end of the resonance tube is well clear of the outer tube.

If such apparatus is not available the second method is recommended:

(2) Fig. 109 is almost self-explanatory, the level of water being controlled by opening and closing the two clips. The disadvantage of this method is that to drain water into the sink the experiment has to be conducted on a bench, and the top of the tube is rather high above the experimenter.

CHAPTER XXXIII

VIBRATING STRINGS

Experiment 97. Verification of the Laws of Vibration of Stretched Strings

Apparatus: Sonometer; at least five tuning forks of various known frequencies, and covering as wide a range of frequencies as possible; weights and hanger (totalling 20 kgm.); several metres of wires of different materials but of the same diameter.

THEORY

It can be shown that for a stretched string executing transverse vibrations that

$$V = \sqrt{\frac{T}{m}}$$

where V is the velocity in cm./sec. of a transverse wave travelling along the string fastened at each end, and sounding its fundamental,
T is the tension of the stretched string in dynes,
m is the mass per unit length of the string in gm./cm.,

This statement is true only if the string is so thin that no complications are introduced by its stiffness, and if the lateral displacement is small.

Combining this with

$$V = n\lambda$$

we get

$$n = \frac{1}{2l}\sqrt{\frac{T}{m}} \quad . \quad . \quad . \quad . \qquad \text{(i)}$$

where l is the length of the wire in cm.; from which it follows that:

I. If T and m are constant:

$$n \propto \frac{1}{l}$$

II. If l and m are constant:

$$n \propto \sqrt{T}$$

III. If l and T are constant:

$$n \propto \sqrt{\frac{1}{m}}.$$

The following experiments verify these relationships in turn.

I. The Frequency of a Stretched String Varies Inversely as its Length, provided the Tension and the Mass per Unit Length are kept Constant

Procedure: Stretch a thin wire on a sonometer provided with a movable bridge (see Fig. 110). Apply the tension by means of weights attached to the end of the wire which passes over the pulley provided.

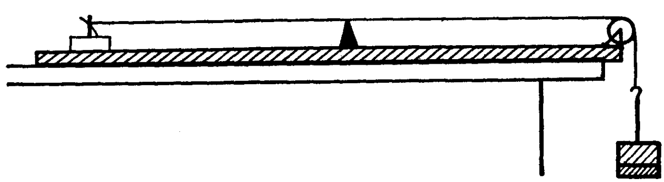


Fig 110

Adjust the tension until the note given out by the wire has the same frequency as the standard tuning fork of lowest frequency (see p. 223 for advice on methods of tuning). Measure the length of the wire. Keep the tension constant and introduce the movable bridge beneath the wire. Adjust the position of the bridge until one part of the wire vibrates with the same frequency as another standard tuning fork. Record the length of this piece of the wire. Repeat this procedure with a number of tuning forks, using not less than five altogether.

Record and Calculation: Tabulate as follows:

Frequency of fork (n)	Length of wire (l)	$1/l$

Plot n against $1/l$. If the relationship given above is true, the result should be a straight line.

II. The Frequency of a Stretched String varies directly as the Square Root of the Tension, provided the Length and Mass per Unit Length are Constant

Procedure: Select the standard tuning fork which has the highest frequency and place the maximum load on the sonometer wire. If this load is insufficient to raise the frequency of the wire to that of the tuning fork reduce the length of the vibrating part of the wire by means of the movable bridge until tuning is effected. If, without the use of a bridge, the load has raised the frequency of the wire above that of the tuning fork, reduce the load until tuning is effected, using the whole length of the wire. Record the load and frequency. Keep unaltered the length of the wire which is vibrating and, by varying the tension, tune the wire to emit the same notes as the tuning forks taken in turn. Record the tension and frequency in each case.

Repeat the whole experiment to obtain a check on your readings.

Record and Calculation: Tabulate as follows:

Frequency (n)	Tension (T)			n^2
	(i)	(ii)	Mean	

Plot n^2 against T. If the relationship given above is true the result should be a straight line.

III. The Frequency of a Stretched Wire Varies Inversely as the Square Root of the Mass per Unit Length, provided the Length and Tension are kept Constant

THEORY

To do this experiment a number of wires are used since the mass per unit length of a particular wire cannot be varied. Thus the frequency has to be determined for each one. This cannot be done by direct comparison with a standard tuning fork, as the number of standard forks available is limited and the intervals between them considerable. We therefore tune the wire to a standard fork by varying the length and then calculate the frequency that the wire would have had if the length had been left unaltered. If we wish to know what the frequency would have been if the length had been l' instead of l, we multiply by the ratio l/l'. This is justified by the result of Part I.

Procedure: Determine the mass per unit length of each wire by weighing a measured length of each one.

Using the wire which has the least value for 'm', stretch it on the sonometer and adjust the tension until it vibrates with the frequency of a selected tuning fork. Measure the length vibrating (l'). Replace the wire by one of the other wires, apply the same tension, and tune it to the same frequency by reducing the length by means of the bridge. Record the length vibrating (l).

Repeat this operation for all the wires.

Record and Calculation: Tabulate your observations as follows:
(i) Determination of mass per unit length of wires:

Material	Length Weighed	Mass	Mass/cm. (m)

(ii) Determination of frequency:

Length of wire before introduction of bridge (l' cm.). Frequency of fork used (n').

Material	l	$\frac{n' \times l}{l'} (= n)$	n^2	m	$\frac{1}{m}$

Plot n^2 against $1/m$. If the relationship given above is true the result should be a straight line.

Note: The above is a strict approach in which the square of frequency is plotted against the reciprocal of mass per unit length. Since n was found by the formula $\frac{n'l}{l'}$ in which n' and l' are both constants, obviously the result could be demonstrated by plotting l^2 against $1/m$.

CHAPTER XXXIV

DETERMINATION OF THE SPEED OF SOUND

Experiment 98. Determination of the Speed of Sound in Air, using a Resonance Tube and one Tuning Fork

Apparatus: Tuning fork—preferably of high frequency, say 512; resonance tube (see p. 224).

THEORY

For all forms of wave motion $V = n\lambda$, where V = velocity, n = frequency and λ = wavelength.

A closed pipe will resonate when its length is approximately $\lambda/4$ and again when its length is $3\lambda/4$ and so on. This is because the air at the closed end is still and this end is therefore a node, whilst the open end is an antinode; so that stationary waves are set up in the tube whenever its length is an odd number of quarter-wavelengths.

In practice, however, the open end is not quite coincident with the antinode and an 'end correction' must be applied. This is dealt with fully in the next experiment. In the present one we arrange to eliminate it.

Consideration of the diagrams in Fig. 111 will show that if the lengths of the tube resonating to frequency n are l_1, l_2, l_3, etc. corresponding to

$$\frac{\lambda}{4}, \quad \frac{3\lambda}{4}, \quad \frac{5\lambda}{4},$$

then, if the end correction is c

$$l_1 + c = \frac{\lambda}{4}; \quad l_2 + c = \frac{3\lambda}{4}; \quad l_3 + c = \frac{5\lambda}{4}, \text{ etc.,}$$

$$\therefore \quad l_2 - l_1 = \frac{\lambda}{2}; \quad l_3 - l_2 = \frac{\lambda}{2} \text{ etc.,}$$

But $$\lambda = \frac{V}{n} \text{ (see above)}$$

$$\therefore \quad l_2 - l_1 = l_3 - l_2 = \frac{V}{2n}.$$

Hence $$V = 2n\,(l_2 - l_1) = 2n(l_3 - l_2) = \text{etc.}$$

In this experiment a series of resonating lengths are found for a single frequency and the values substituted in the equations deduced above.

Procedure: Set up the resonance tube and adjust the amount of water in it until the shortest possible length resonates to the frequency of the fork, which is sounded and held horizontally over the top of the tube. The sounding of the fork should be done by a bow or by the fingers—it should NEVER BE BANGED as this process will in time cause a slight change in frequency. Record the length of the tube which is resonating, i.e. the level of the water below the open end.

Next find the second resonance position—corresponding to $3\lambda/4$ and repeat the measurements. Continue this process to obtain as many readings as possible.

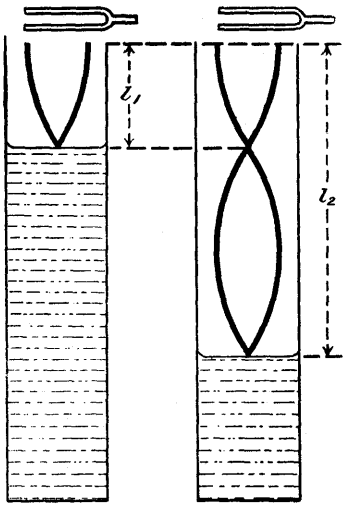


FIG. 111

Record and Calculation: Record the frequency of the tuning fork—it should be stamped on it. Tabulate as follows, and calculate a mean value for the velocity of sound at room temperature.

Lengths	$\lambda/2$	$\lambda/2$
l_1		
l_2	$l_2 - l_1$	Mean
l_3	$l_3 - l_2$	Value

Experiment 99. Determination of the Speed of Sound in Air and of the End Correction for a Resonance Tube

Apparatus: Resonance tube (see p. 224); at least five tuning forks of various frequencies covering as wide a range as possible.

THEORY

In the previous experiment it was pointed out that the true equation for a resonating tube involved the end correction, and the equation

$$l + c = \frac{\lambda}{4}$$

was given. But $\lambda = V/n$ and thus if a series of forks is used, so that n is varied, and the first resonance position investigated we have a general equation connecting the length resonating, the frequency, and the velocity:

$$l + c = \frac{V}{4} \cdot \frac{1}{n}.$$

Thus a graph of l against $1/n$ will be a straight line (Fig. 112). The gradient of this line will be $V/4$ and the (negative) intercept on the l-axis will be the end correction (see p. 32).

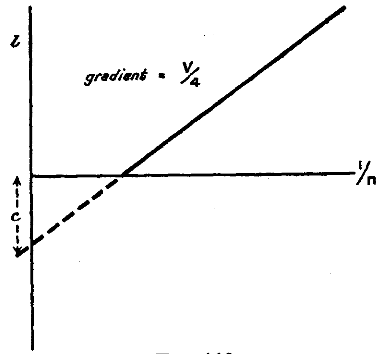


FIG. 112

Procedure: Starting with the fork of highest frequency, find the shortest length of tube which will resonate to the fork held horizontally over the top. Record the value of n and l.

Repeat using the fork of next highest frequency and continue observations until as many readings as possible have been made. Several determinations of the length resonating to each frequency should be made so that a mean for each one can be found.

Record and Calculation: Tabulate your results as follows:

n	LENGTH (l)				$\frac{1}{n}$
	(i)	(ii)	(iii)	Mean	

Plot mean values of l against $1/n$ and deduce the velocity of sound in air at room temperature (T° Absolute) and the value of the end correction from this graph.

The value of the velocity at 0°C may be computed using the equation

$$V_O = V_T\sqrt{\frac{273}{T}}$$

and compared with that quoted in books of tables, e.g. Kaye and Laby's 'Physical and Chemical Constants'.

Experiment 100. Determination of the Speed of Sound in Air, using a Dust Tube

Apparatus: This apparatus is usually available as an assembled unit.

Fig. 113 shows the arrangement in which a long glass tube (not less than 1 metre in length) is closed at one end by a 'stop' CB, and at the other by a disc, D, attached to a sounding rod, A, which is made of brass, wood, or glass. This rod must be tightly clamped at exactly its midpoint between a pair of jaws which are almost knife edges, as it will be assumed that it vibrates with a frequency such that the length of the rod is half a wavelength. It is sounded by stroking with a resined cloth or, better, by a resined leather gauntlet. Dry lycopodium powder is sprinkled in the tube.

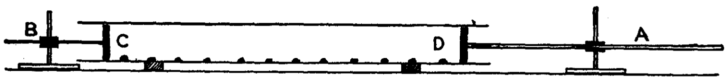


FIG. 113

THEORY

The lycopodium powder is very light and is disturbed by the air motion in the tube when the rod A is sounded. If the distance between C and D is a whole number of wavelengths stationary waves will be set up in the tube and the lycopodium powder will gather at the nodes, where there is no disturbance of the air. It will be violently agitated elsewhere. The distance apart of the heaps of lycopodium powder leads to a direct determination of the wavelength in air of the note, since the distance apart of the nodes in a stationary wave-motion is half the wavelength.

Procedure: Success in this experiment depends on both the tube and the powder being quite dry, so pay great attention to this before starting. For methods of cleaning and drying glassware see p. 52. To dry the powder sprinkle it on paper and warm gently for about an hour. Be careful not to burn it.

Set up the apparatus as indicated above and stroke A from the centre towards you. Adjust the position of C until the air column in the tube resonates to the note emitted by A. Continue gentle stroking and make final adjustments to C so that the powder collects in heaps. Measure CD. Remove the tube and empty it of nearly all the powder by holding it vertically and tapping it over a sheet of paper. Replace the tube, making CD the same length as before, and repeat the tuning operations. This time the adjustment is more critical and the powder will settle in quite thin lines at the nodes when CD is a whole number of wavelengths. Measure the distance apart of the first and the last line of powder and count the number of half wavelengths to which this distance is equivalent.

Determine the frequency of the note emitted by the rod by the method of Experiment 101, p. 234.

Record and Calculation: Record all observations. Calculate the frequency of the note (n) and the wavelength (λ) of the note in air.

Substitute in

$$V = n\lambda$$

and hence find the speed of sound in air at room temperature.

Notes: (1) This apparatus can be used to determine Young's modulus for the material of the rod as follows: The apparatus is tuned as described above and the wavelength of the note in air found by the usual method. Let this be λ. Next the speed of sound in air at room temperature is found by looking up in tables the speed at 0°C (V_0) and substituting in the equation

$$V_t = V_0 \sqrt{\frac{273 + t}{273}}$$

in which V_t is the speed of sound in air at room temperature, and t is room temperature in °C.

This value V is substituted with the value for λ found from the experiment in

$$V_t = n\lambda$$

to find a value for n, the frequency of the note.

So far we have concentrated on the sound waves in the air column. Now let us think about those in the rod. They will have a different speed and a different wavelength but the frequency will be the same.

The wavelength is assumed to be twice the length of the rod. Thus if we substitute n and l in the equation

$$V = 2nl$$

we can find the speed of sound in the rod at room temperature.

It can be shown that this value V' is also given by the equation

$$V' = \sqrt{\frac{E}{\rho}}$$

where E is Young's modulus for the material of the rod,

and ρ is the density of the material of the rod.

The density must be determined and its value, together with that of V', substituted in this equation to find E.

(2) If a tube of the shape shown in Fig. 114 is used then it may be filled with other gases and the speed of sound in these determined.

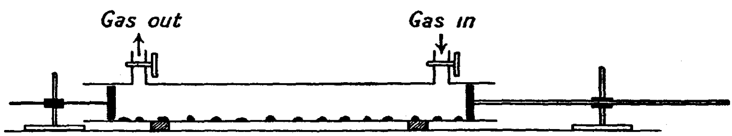


FIG. 114

(3) A telephone energised by an oscillator may be used as the source of sound and by this means a number of other interesting effects demonstrated. The details of the method used by Prof. E. N. Da C. Andrade may be found in Proc. Royal Soc. Vol. 159, p. 507, 1937.

CHAPTER XXXV

DETERMINATION OF FREQUENCY

Experiment 101. Determination of the Frequency of the Note Emitted by a Given Source of Sound

Apparatus: Source of sound of which the frequency is required, e.g. unmarked tuning fork, stretched string, dust-tube sounding rod (see Experiment 100); sonometer with usual accessories; tuning fork of known frequency.

THEORY

The method depends on the fact that if the mass per unit length and the tension of a wire are kept constant then the frequency is inversely proportional to the length vibrating. The mathematics are given on pp. 225–6.

Procedure: Tune the wire of the sonometer by altering the tension and the length until it emits a note of the same frequency as the fork of known frequency. Record the length (l). Next tune the same wire, by *altering the length,* but *not* the tension, until its frequency is the same as that of the unknown source. Record the length of the wire which is vibrating (l').

Repeat all observations several times using different initial tensions and lengths.

Record and Calculation: Tabulate as follows:

Frequency of known tuning fork . . . . . n

l	l'	l/l'

Calculate a mean value for l/l' and multiply this by n to find the frequency of the unknown source.

Experiment 102. Determination of the Frequency of a Tuning Fork by a Chronographic Method

Apparatus: Gramophone; stop-clock; hog's bristle, or piece of fine stiff wire; tuning fork of unknown frequency.

Procedure: Cut a piece of thick white cardboard to fit the gramophone turn-table, cover it with as even a layer of soot as possible—waving it above burning turpentine will do this. Fasten the smoked cardboard to the turn-table so that it does not slip when the table is rotating—one or two drawing pins inserted through the paper into the usual baize covering will do this.

Fasten a thin piece of wire or a hog's bristle to a tuning fork as shown in Fig. 115. A wire can be soldered to the fork with the merest spot of solder; the bristle can be fastened with wax. As little extra load as possible should be added to the fork, as any load will decrease its frequency. Wind up the gramophone motor as much as possible, and find the time for 50 complete revolutions.

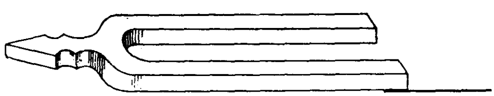


FIG. 115

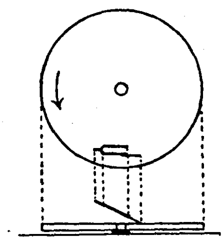


FIG. 116

Re-wind the motor and arrange the fork as shown in Fig. 116. The bristle should make a distinct mark—a white line—on the smoked cardboard when the table is turning. Start the motor—so that the turntable has time to reach a constant speed. Set the fork vibrating and lower it gently so that the bristle just touches the cardboard, making a wave-trace round at least a quarter of the circumference.

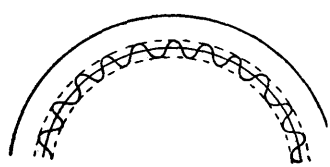


FIG. 117

Calculation: Remove the cardboard and pin it on to a drawing board. Draw the 'mean line', using a pair of compasses.

The cardboard will look like the diagram in Fig. 117.

From two corresponding, well-marked points of intersection of the 'mean line' and the wave trace, draw lines to the centre of the cardboard. Measure the angle between them.

Count the number of waves between the two points.

Calculate the time of one complete revolution of the table.

Let θ be the angle in degrees between the lines,
t be the time of one revolution of the table,
and n be the number of waves counted.

Then time occupied in making trace between selected points $= \left(\frac{\theta}{360} \times t\right)$ sec.

$= x$ sec.

Frequency of fork $= \frac{n}{x}$.

Experiment 103. Determination of the Frequency of a Tuning Fork by the 'Dropping Plate' Method

Apparatus: Various forms of apparatus are available for this experiment. Essentially a short style, made of thin wire or a hog's bristle, is attached to a fork so that when the fork is vibrating the bristle traces out a wavy curve on a falling smoked plate.

Procedure: Examine whatever form of apparatus is provided. See that the plate is falling freely, and that the bristle makes contact with it.

With the fork silent allow the smoked plate to fall, producing a straight-line trace.

Sound the fork. An electrically maintained fork is best, but otherwise the fork should be sounded with a well-rosined bow. The arrangement should be such that the bristle while moving makes a mark on the stationary plate. Allow the plate to fall.

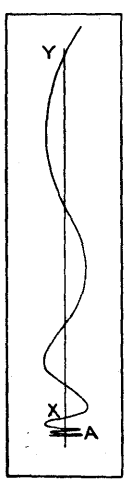


Fig. 118

Calculation: The trace obtained will appear somewhat like that shown in Fig. 118.

Although the starting point will be clearly marked, the first few waves will be too small or indistinct to count.

Make two marks at convenient places on the trace as shown at X and Y in Fig. 118. Measure the distance XY, and count the number of waves between X and Y.

Using the equation

$$s = \tfrac{1}{2}gt^2,$$

calculate the time of fall from X to Y.

The number of vibrations made in this time is equal to the number of waves counted, hence the required frequency can be calculated.

The possible error will be great. (Why?)

Note: If the frequency of the tuning fork is known, this experiment can be made the basis of a determination of the acceleration due to gravity, but it is subject of course to as great an error as the determination of n, and is of value only for instructional purposes.

Experiment 104. Determination of the Frequency of a Source of Sound, using a Siren

Apparatus: The source of sound of unknown frequency could conveniently be a violin string, an organ pipe, or other wind instrument. A stop-watch and a siren will be required also.

The siren will be found to consist of a metal plate with a number of holes bored obliquely near its circumference. This plate is mounted on a spindle so that it can rotate immediately above a similar plate fixed over a wind chest. When air is forced into the latter the top plate is caused to rotate and a loud note is produced, the frequency of which depends on the speed of rotation of the plate and the number of holes in it. The speed of rotation is determined by means of a revolution counter attached.

Procedure: Count the number of holes in the top plate. Engage the revolution counter and start forcing air into the wind chest of the siren. Sound the source of unknown frequency and increase the air pressure in the chest until the two sources are producing beats sufficiently slowly to be counted. Determine the number of beats per second by counting the number of beats heard during an observed time. Note also whether the frequency of the note emitted by the siren is greater or less than that emitted by the other source—see p. 223 for the method. Finally record the time taken for an observed number of revolutions, using the moving hand on the dial of the revolution counter to aid precise starting and stopping of the watch.

Record and Calculation: Record all the observations:

Number of holes in plate	x
Number of beats counted	b
Time for which beats were counted	t' secs.
Time for which revolution counter was engaged .	t secs.
Number of revolutions counted	y

Frequency of the siren note is given by xy/t.

Therefore the frequency of the source is

$$xy/t \pm b/t'.$$

PART VI

MAGNETISM

CHAPTER XXXVI

STANDARD PROCEDURE

The Magnetic Field of Your Laboratory

Since all experiments in this part are carried out in a laboratory without any special screening devices, there will be lines of force of the Earth's magnetic field passing through your laboratory and affecting ALL your experiments.

The lines of force of the Earth's field are not horizontal (except along a line circling the Earth in the Tropics, known as the 'magnetic equator'), and the angle that they make with the horizontal is known as the 'angle of dip'. This is determined by Experiments 115 and 156, pp. 263 and 366. We are not usually concerned with the total value of the Earth's magnetic field, but with the horizontal component, the determination of which is described in Experiments 114 and 156, pp. 262 and 366.

The line which gives the direction of the Earth's magnetic field is known as the 'magnetic meridian', and this rarely points towards geographic north. The angle between the magnetic meridian and true north is known as the 'declination'. This is measured in degrees and may be east or west of true north. Declination is subject to many variations (consult theoretical textbooks for details of these) but unless affected by local concentrations of magnetic materials, e.g. a cupboard or drawer where magnets are kept, its value in Great Britain is usually between 10° and 20° west.

The direction of the magnetic meridian is of great importance in all magnetic experiments; and in this work the first step should always be to plot the magnetic meridian at the spot where the experiment is to be performed, using a plotting compass with jewelled bearings. Having done this, it is naturally an elementary precaution to see that no ferromagnetic materials, such as iron stands and clamps, galvanometers, steel pen knives, steel drawing pins (most drawing pins are ferromagnetic nowadays), etc., are brought nearer than six to ten feet of the place selected. Wooden stands should always be used where supports are needed. It is worth remembering that there are many quite powerful small magnets sold cheaply in the shops, and you should try to ensure that any of them possessed by you or your friends are not brought into the vicinity of your experiment.

The magnetic field through your laboratory will show considerable variation in all the elements. It is interesting to co-ordinate the work of the practical class by allotting to each experimenter his particular spot for investigation, so that, when all the results are available, a map of the laboratory showing the values of the various magnetic elements in the different places can be drawn.

Magnetising and Demagnetising Apparatus

Although permanent magnets will form part of the equipment of the laboratory, an apparatus for magnetising and demagnetising specimens of iron and steel is also needed. If such an apparatus is not available, the information required to make one is to be found in *The Science Masters' Book, Part I, Physics* (John Murray) pp. 133–4.

In order to magnetise a given specimen, it is placed inside the solenoid and the apparatus connected to the A.C. mains. A sharp tap is given to the key so that the alternating current flows momentarily through the solenoid. The polarity cannot be forecast (why not?) but this rarely matters. If polarity is of importance, and the first attempt magnetises the specimen in the wrong sense, demagnetise as instructed below and remagnetise. Test the polarity and continue demagnetising and magnetising until the polarity is the right way round.

To demagnetise, hold the magnet in the solenoid, switch on the current, and withdraw the specimen to a great distance along the axis of the solenoid. Then switch off.

You should think out the explanations of these processes—reference to theoretical textbooks may be necessary but p. 270 of this book may suffice.

Determination of the Position of Poles of a Magnet

The usual magnet provided for experiments in magnetism is either cylindrical or rectangular and is about 12 cm. long. This is quite suitable for most work but it must be realised that the magnetic length in such magnets is often between 10% and 20% different from the geometric length. The location of poles thus becomes a process of major importance. The method of plotting several lines of force leads to large errors—so large that such a method is almost a waste of time. It is suggested therefore that the following method, due to F. A. Meier, be applied *in all cases*. The complete account, including theory, is to be found in *The Science Masters' Book, Part I, Physics*, on pp. 163–5. A shortened version is given here, without the theoretical justification:

Locate the poles approximately by finding where, near the end of the magnet, a plotting compass, which has jewelled bearings, must be placed so that the needle makes a right angle with the axis of the magnet. Measure the approximate magnetic length.

Place a piece of foolscap paper (or exercise book paper will do) so that its lines are in the magnetic meridian (see p. 241). On the top line of the paper place the compass at a distance of 1/3 of the magnetic length from the marginal line. (This figure is convenient for magnets of length about 12 cm. but may need modifying for others—see Meier's original article.)

Place the magnet so that its axis lies along the marginal line and slide it up the line until the needle of the compass is not deflected from the magnetic meridian. The arrangement will then appear as in Fig. 119 in which C is the compass, A and B the ends of the magnet, and D the foot of the perpendicular from C on to AB. Let the position of the pole be P. It can be shown that

$$DP = CD/9,$$

thus by measuring AD and CD the position of the pole is found.

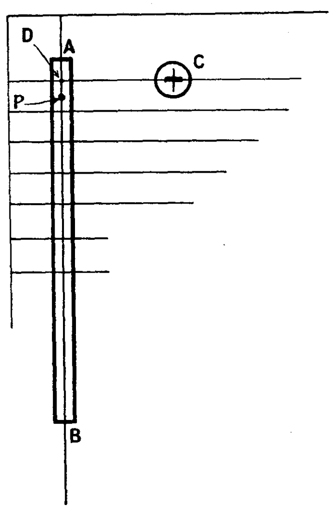


FIG. 119

Choosing a Magnet

Usually the best magnet to use for the experiments which follow is the cylindrical type about 10 cm. long and 0·6 cm. in diameter. The bar magnet is not so suitable, as there is more likelihood of the magnetic axis not being coincident with the geometric axis. In magnetometry this effect could be eliminated by the method given on p. 246, but this is not usually done.

Deflection Magnetometer

This instrument consists essentially of an arrangement by which deflections of a freely suspended magnet can be measured. It provides a small magnet, referred to as the needle, mounted to swing in a horizontal plane. A light pointer is fixed to the needle at its centre and at right angles to its axis. The ends of the pointer move over a scale. The needle, pointer and scale are mounted in a glass-topped box. At the bottom of the box there is usually a mirror so that parallax errors in reading the pointer can be eliminated.

More often than not this box is mounted on a wooden base to which two 'arms' are attached which bear scales alleged to be graduated so that they give direct distances from the point of support of the needle.

Cheap forms of this instrument are often unreliable.

The instrument is occasionally used for a 'null method', when two fields—other than the Earth's field—are applied so as to be equal and opposite in their effects on the needle. Usually, however, a deflection is recorded when the needle is in equilibrium under the influence of two fields mutually at right angles, one of which is that due to the Earth, and the other due to a magnet. The ordinary bar magnet can be used to produce a field at right angles to the magnetic meridian in one of two simple ways (there *are* others which call for more complex mathematical treatment). These are known as the Gauss 'A' and 'B' positions, often referred to as the 'end-on' and 'broadside on' positions respectively. The two arrangements are shown in Fig. 120, 'A' and 'B'.

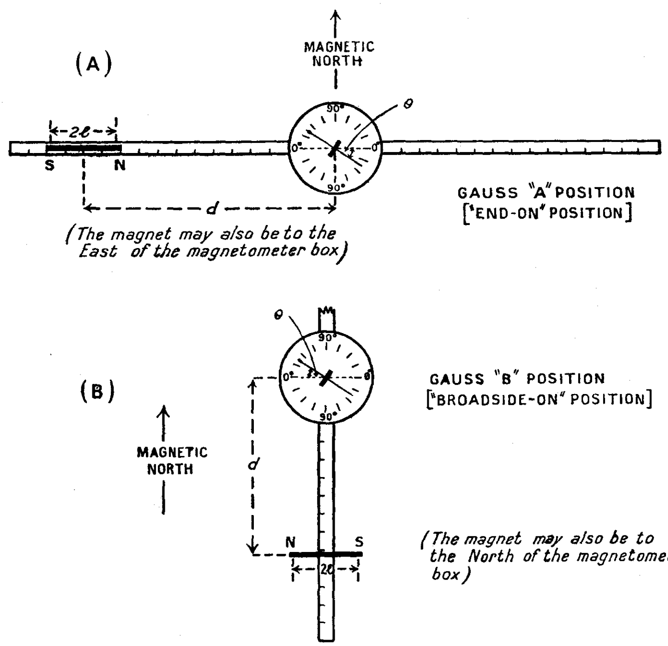


FIG. 120. Gauss 'A' and 'B' positions for the Deflection Magnetometer

Let a magnet of moment M c.g.s. units and magnetic length $2l$ cm., be placed so that its magnetic centre is d cm. from the needle of a magnetometer, and let the horizontal component of the Earth's field be H_e oersteds. Then, for the 'A' position, the deflection, θ, will be given by the equation

$$\frac{2Md}{(d^2-l^2)^2}=H_e \tan \theta;$$

and for 'B' position

$$\frac{M}{(d^2+l^2)^{3/2}} = H_e \tan \theta.$$

When using the instrument it is important to adjust matters so that the deflection is never outside the range 25° to 65° and preferably it should be between 30° and 60°. This is because the value of θ is to be used in the form tan θ and an effect which can be called 'error magnification' arises. The matter will be made clear by considering the following examples:

Suppose the deflection can only be observed with an accuracy of half a degree. Let us consider how this possible error will affect the values of the tangents of deflections 10°, 25°, 30°, 45°, 60°, 65°, and 80°.

Reference to tables will show that

$$\tan 10^\circ\, 30' = 0{\cdot}1853$$
$$\tan 9^\circ\, 30' = 0{\cdot}1673$$
$$\text{thus } \tan 10^\circ\, 30' - \tan 9^\circ\, 30' = 0{\cdot}0180$$
$$\text{Now } \tan 10^\circ\, 00' = 0{\cdot}1763$$

Thus an observation of $\theta = 10^\circ \pm 0{\cdot}5^\circ$ leads to a statement that

$$\tan \theta = 0{\cdot}1763 \pm 0{\cdot}0090$$

This represents a possible error of over 5% in tan θ.

If similar calculations are made for the other angles the results will be as recorded in the table below:

DEFLECTION (θ)			TAN θ		
Mean Value	Possible Error		Mean Value	Possible Error	
	Actual	Percentage		Actual	Percentage
10°	±0·5°	±5%	0·1763	±0·0090	±5·1%
25°	±0·5°	±2%	0·4663	±0.0107	±2·3%
30°	±0·5°	±1·7%	0·5774	±0·0116	±2·0%
45°	±0·5°	±1·1%	1·0000	±0·0158	±1·6%
60°	±0·5°	±0·8%	1·7321	±0·0349	±2·0%
65°	±0·5°	±0·8%	2·1445	±0·0489	±2·3%
80°	±0·5°	±0·6%	5·6713	±0.2902	±5·1%

An examination of this table will show why the range 30° to 60° is suggested for value of the deflection. The table is based on a constant actual error in θ, rather than a constant percentage error in θ because the former is the usual state of affairs in an experiment.

Observations to be made when using the Deflection Magnetometer

The deflection magnetometer is subject to two defects in construction for which correction can be made by taking the mean of a number of readings. These are:

(1) The pointer may not be suspended at the centre of the circular scale of angles and therefore both ends of the pointer are read.

(2) The needle may not be supported at the centre of the linear scale and therefore readings are taken with the magnet first on one arm and then with its centre at the same reading on the other arm.

In addition, the magnets used are rarely symmetrically magnetised in that (i) the poles are neither at the ends nor equidistant from the ends, and (ii) the magnetic axis (i.e. the line joining the poles) is not coincident with the geometric axis. The first of these is allowed for by takings readings first with the north pole nearer the compass box and then with the south pole nearer the compass box, keeping the reading of the midpoint the same. It is not customary to make allowance for the fact that the magnetic axis may not coincide with the geometric axis but, if great accuracy is sought, readings should be taken with the axis in each of four positions obtained by rotating it through 90° about its axis, keeping all other distances constant. This means that instead of the usual eight readings thirty-two would be obtained.

The Vibration Magnetometer

If a freely suspended magnet is placed in a magnetic field it will come to rest with its axis along a line of force of the field. If it is given a displacement from this position there will be a couple on it due to the field in which it is placed which will tend to restore it to the 'rest' position. If the magnet is released after being displaced it will execute simple harmonic motion (see p. 50) *provided the angle of displacement does not exceed* 10°. If the period of the vibration (i.e. the time for one *complete* swing) is T secs. then

$$T = 2\pi\sqrt{\frac{I}{MH}}$$

where I is the moment of inertia of the magnet in c.g.s. units,
M is the moment of the magnet in c.g.s. units,
and H is the field in which it is swinging, in oersteds.

This presents us with an easy and remarkably accurate method of comparing the intensities of magnetic fields, the only observations needed being the time taken for a known number of oscillations of a given magnet. The instrument using this principle is called the 'vibration magnetometer'. Since it is T which is to be measured it is desirable to make it as large as possible. The length of the magnet must be as small as possible so that it may be regarded as swinging wholly in a field of uniform intensity. This reduction of length reduces I (see p. 89) and would reduce T. The 'Searle's vibration magnetometer' (Fig. 121)

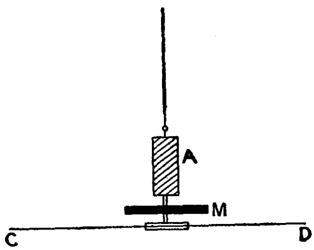


FIG. 121

overcomes this difficulty by mounting a short magnet M under a mass of brass A (which increases the moment of inertia of the system), and attaching a light pointer CD to facilitate the counting of vibrations. It should be suspended in a glass vessel to shield it from draughts, and a pad of cotton wool should be placed in the bottom of the vessel to protect it from breakage in the event of the suspension breaking.

For such an instrument I and M will be constant and the equation given above reduces to

$$T = \sqrt{\frac{\text{constant}}{H}}$$

$$\text{or } H = \frac{k}{T^2} \text{ where } k \text{ is a constant.}$$

In practice the field we investigate is always superposed on that due to the Earth. If the horizontal component of the Earth's field is H_e and T_e is the periodic time of the vibration magnetometer when oscillating in this field, then

$$H_e = \frac{k}{T_e^2}.$$

If the field to be investigated is H and the periodic time in the combined fields when they act in the same direction is T,

then $$H + H_e = \frac{k}{T^2}$$

$$\therefore \quad H = k\left(\frac{1}{T^2} - \frac{1}{T_e^2}\right).$$

If the fields act in opposite directions it is necessary to know which field is the greater. So many errors are made on account of this that it is recommended that the *sum* of the fields always be investigated. This can be done by making sure that the needle

(i) does not reverse when the second field is superposed on that due to the Earth and

(ii) has a shorter periodic time in the combined fields than in the Earth's field alone.

CHAPTER XXXVII

THE INVERSE SQUARE LAW

Experiment 105. Verification of the Inverse Square Law for the Force Exerted between Two Magnetic Poles, using Hibbert's Magnetic Balance

Apparatus: Hibbert's magnetic balance—as shown in Fig. 122.

It being impossible to isolate a magnetic pole, the forces acting in this experiment are actually the resultants of those due to two poles, but by using long magnets the effect of one pole in each magnet is reduced to a negligible amount. (This does not assume the law we set out to verify but it does assume that the law is an inverse one). Ball-ended magnets are often provided for this experiment and their poles may be assumed to be approximately at the centres of the balls. Their exact position can be found by the method given on p. 242.

Both magnets are placed horizontally, as shown in Fig. 122, one being fixed to a vertical rod, up and down which it can be moved. The other magnet is balanced on a knife edge at its centre of gravity and carries a small rider R. The adjacent poles of the magnets must be kept the one vertically over the other.

THEORY

Let w be the weight of the rider R,
x the distance in cm. of R from the knife edge,
l the distance in cm. from the pole at end B to the knife edge,
and F the force of repulsion between the poles when they are d cm. apart.
Then, applying the principle of moments:

$$wx = Fl$$

$$F = \frac{wx}{l}$$

But both w and l are constant for a given magnet and

$$\therefore \quad F \propto x.$$

If the inverse square law holds,

$$F \propto \frac{1}{d^2}$$

$$\text{i.e. } x \propto \frac{1}{d^2}.$$

The experiment sets out to verify the law by examining the relationship between x and d^2.

Procedure: Locate the poles of the magnets to be used as accurately as possible (see p. 242).

Arrange the apparatus as shown in Fig. 122, balancing the lower magnet before introducing the upper one. When the latter is put into place, repulsion will depress the end B of the lower one and the rider R must be adjusted to restore the magnet to the horizontal. Tabulate a series of observations of d and x, for various positions of the upper magnet.

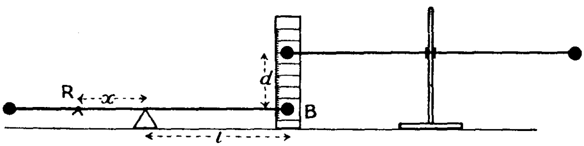


FIG. 122

If possible repeat the whole experiment, using a different pair of magnets.

Record and Calculation: Tabulate as follows:

x	d	$\frac{1}{d^2}$

Plot x against $1/d^2$. State your conclusion.

Experiment 106. Verification of the Law of Inverse Squares, using a Deflection Magnetometer

Apparatus: Deflection magnetometer (see p. 243); Robison (*i.e.* ball-ended) magnet.

THEORY

The magnet is arranged so that one pole is vertically over the point of suspension of the needle of the magnetometer and the other pole is either magnetic east or magnetic west of this point and in the same horizontal plane as the needle (see Fig. 123). In this way the field due to the upper pole is arranged to be vertical in the region of the magnetometer needle. The latter will therefore find an equilibrium position along the direction of the resultant of the fields, due to (i) the Earth and (ii) the magnetic pole which is in the same horizontal plane as the needle itself.

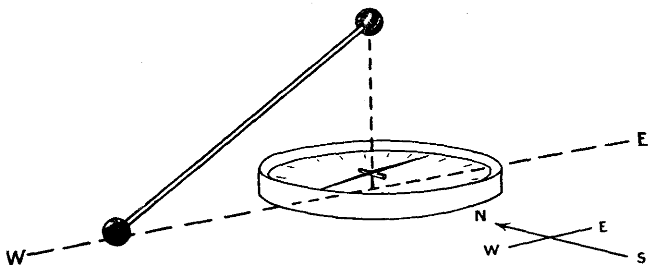


FIG. 123

If the pole strength is m and the distance from the pole to the magnetometer needle is d cm., then, if the inverse square law holds good,

$$\frac{m}{d^2} = H_e \tan\theta$$

where H_e is the horizontal component of the Earth's field and θ is the deflection.

If we vary d, θ should also vary in such a way that

$$\frac{1}{d^2} \propto \tan\theta, \text{ i.e. } d^2 \propto \cot\theta.$$

Thus a graph of $\cot\theta$ against d^2 should produce a straight line passing through the origin if the inverse square law is true.

Procedure: Locate the poles of the ball-ended magnet as accurately as possible. Plot a line of the Earth's field in chalk on the bench, and set up the magnetometer so that its linear scales are at right-angles to this line. Rotate the magnetometer box so that the ends of the needle read zero, or as near so as possible, when undeflected. Record these 'zero' readings. Using a wooden clamp arrange the ball-ended magnet as shown in Fig. 123, so that one pole is exactly over the point of suspension of the magnetometer needle, and the other pole is resting on the western arm of the magnetometer, at a distance d cm., such that the deflection is about 60°. Observe the reading of each end of the pointer and the value of d.

Reverse the magnet and observe the two readings of the ends of the needle again. Repeat all four observations with the magnet on the east side of the magnetometer box, but with the same value for d. Increase d so that the deflection changes to about 55° and repeat the above processes to obtain eight readings for the corresponding deflections. Continue to alter d by suitable amounts until the deflection is only 30°, taking eight readings for each value of d.

Record and Calculation: Tabulate thus:

d cm.	POINTER READINGS IN DEGREES								MEAN VALUE FOR θ [allowing for zero reading]	Cot θ	d^2
	END ONE				END TWO						
	'ZERO' =				'ZERO' =						
	EAST		WEST		EAST		WEST				
	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)			

Plot d^2 against cot θ and state your deduction.

Experiment 107. Verification of the Law of Inverse Squares, using a Vibration Magnetometer

Apparatus: Searle's vibration magnetometer (see p. 247); Robison (ball-ended) magnet; stop-watch.

THEORY

The ball-ended magnet is used in a way rather similar to that of the previous experiment (p. 249). This time the variation of the horizontal field due to the lower pole is investigated by a vibration magnetometer. If the periodic time of the magnetometer when vibrating in the Earth's field alone is T_e and H_e is the horizontal component of the Earth's field, then

$$H_e = \frac{k}{T_e^2}$$

where k is the constant for the magnetometer (see p. 247).

If now the ball-ended magnet is placed with its north pole vertically over the suspension of the magnetometer and with its south pole d cm. to the magnetic north of the magnetometer needle (and in the same horizontal plane as the latter), the field due to the Earth will be acting in the same direction as that due to the south pole of the magnet. Since the two fields reinforce, the new periodic time (T secs) will correspond to a total field of $\frac{m}{d^2} + H_e$, provided the inverse square law holds good.

$$\therefore \quad \frac{m}{d^2} + \frac{k}{T_e^2} = \frac{k}{T^2}.$$

$$\therefore \quad \frac{1}{d^2} = \frac{k}{mT^2} - \frac{k}{mT_e^2}.$$

Thus if a series of values of d and T are recorded and a graph of $1/d^2$ against $1/T^2$ drawn, the result should be a straight line. It will not pass through the origin but will have an intercept $(-k/mT_e^2)$ on the axis of $1/d^2$.

Procedure: Locate as accurately as possible the poles of the ball-ended magnet (see p. 242).

Plot the magnetic meridian (see p. 241).

Set up the ball-ended magnet so that the north pole is vertically over the suspension of the magnetometer and the south pole is to the magnetic north of this point. Observe the time for a convenient number of small vibrations. The total time taken should be several minutes; Three independent readings consistent to about 1/5 sec. should be obtained (see p. 51 on 'Timing Vibrations'). Make observations to enable the distance d of the pole from the magnetometer to be deduced.

Alter the value of d and repeat all the observations. Continue this process until five or six sets of readings covering as wide a range as possible have been recorded.

Record and Calculation: Tabulate as follows:

d cm.	Time for n swings				n	Periodic time (T)	T^2	$\frac{1}{T^2}$	$\frac{1}{d^2}$
	(i)	(ii)	(iii)	Mean					

Plot $1/d^2$ against $1/T^2$. State the result.

Another method of verifying the inverse square law is given in note (2) to Experiment 108, p. 253.

CHAPTER XXXVIII

COMPARISON AND DETERMINATION OF MAGNETIC MOMENTS

It is suggested that the same pair of magnets be used for all the experiments described in this chapter so that (i) only a single determination of the positions of the poles need be made and (ii) the results of the experiments can be compared.

Experiments 108 to 117 should all be done at the place in the laboratory allocated to you (see suggestion on this on p. 241).

The two magnets will be referred to as X and Y and their properties indicated by the suffixes X and Y.

Thus M_X is the magnetic moment of X, $2l_X$ is the magnetic length of X, I_Y the moment of inertia of Y and so on.

Experiment 108. Comparison of the Magnetic Moments of Two Magnets, using the 'Two Neutral Points' Method

Apparatus: The magnets X and Y; compass box with jewelled bearings and fitted with glass top and bottom.

THEORY

(1) A magnet placed in the magnetic meridian with its south pole pointing towards magnetic north will at some point on its axis (produced) be causing a magnetic field which is equal and opposite to that of the Earth. At this point there will be no resultant field and it is thus referred to as a 'neutral point'. There will be one neutral point to the north of the magnet and another to the south. They will each be a cm. from the magnetic centre of the magnet (i.e. $2a$ cm. apart) such that

$$\frac{2Ma}{(a^2 - l^2)^2} = H_e$$

where H_e is the horizontal component of the Earth's field in oersteds,
M is the moment of the magnet
and $2l$ is the magnetic length.

$$\therefore \quad \frac{2M_X a_X}{(a_X^2 - l_X^2)^2} = H_e$$

and

$$\frac{2M_Y a_Y}{(a_Y^2 - l_Y^2)^2} = H_e.$$

$$\therefore \quad \frac{M_X}{M_Y} = \left(\frac{a_X^2 - l_X^2}{a_Y^2 - l_Y^2}\right)^2 \cdot \frac{a_Y}{a_X}.$$

(2) If the magnet is placed in the magnetic meridian with its north pole pointing north, then the neutral points will occur at a distance b cm. to the east and west of the midpoint of the magnet such that

$$\frac{M}{(b^2 + l^2)^{3/2}} = H_e.$$

Hence

$$\frac{M_X}{(b_X^2 + l_X^2)^{3/2}} = H_e$$

and

$$\frac{M_Y}{(b_Y^2 + l_Y^2)^{3/2}} = H_e.$$

$$\therefore \quad \frac{M_X}{M_Y} = \left(\frac{b_X^2 + l_X^2}{b_Y^2 + l_Y^2}\right)^{3/2}.$$

Procedure: Determine the positions of the poles of the two magnets (see p. 242) and record the magnetic lengths ($2l_X$ and $2l_Y$). Plot a line of the Earth's magnetic field. Place the magnet X, with its axis on this line so that its south pole points to the north. Locate the two neutral points using the compass. (Quite close to the point and nearer to the magnet the compass will show that the field due to the magnet is the stronger, and on moving through the neutral point the direction of the needle will reverse. At the neutral point it sometimes sets at 90° to the meridian and sometimes slowly turns round and round—especially if *very lightly* tapped with a pencil.) Measure the distance apart of the two neutral points ($2a_X$ cm.)

Turn the magnet round so that its north pole points northwards, find the neutral points and measure their distance apart ($2b_X$ cm.).

Repeat the experiments with the second magnet to find $2a_Y$ and $2b_Y$.

Record and Calculation: Record all the observations.

Calculate values for a_X, b_X, a_Y, and b_Y, and substitute in the appropriate equation above to find two values for the ratio $\dfrac{M_X}{M_Y}$.

Find the mean of the two determinations.

Notes: (1) If the value of the horizontal component of the Earth's magnetic field (H_e) were known at the place where the experiment was conducted a value for M_X and M_Y could be found by using the equations

$$\frac{2M_X a_X}{(a_X^2 - l_X^2)^2} = H_e\,; \qquad \frac{M_X}{(b_X^2 + l_X^2)^{3/2}} = H_e$$

$$\frac{2M_Y a_Y}{(a_Y^2 - l_Y^2)^2} = H_e\,; \qquad \frac{M_Y}{(b_Y^2 + l_Y^2)^{3/2}} = H_e.$$

(2) The equations quoted above are deduced, making the assumption that the inverse square law holds good. Thus, if the values for the ratio of the magnetic moments found in the two parts of the experiment are consistent within the limits of experimental error that in itself is a verification of the law.

Alternatively, since

$$\frac{2Ma}{(a^2 - l^2)^2} = H_e = \frac{M}{(b^2 + l^2)^{3/2}}.$$

$$\therefore \quad \frac{(a^2 + l^2)^2}{a(b^2 + l^2)^{3/2}} = 2.$$

Thus a verification can be made by substituting the values of *a*, *b*, and *l* for either magnet in the left-hand side of this expression and checking that the value so obtained is 2. This method means that the inverse square law can be checked, using one magnet.

(3) The student could with profit consult *The School Science Review* No. 139, June 1958, pp. 484–5, where E. M. Somekh describes a method using 'Parity Points', i.e. points at which the field due to the magnet is equal to that due to the earth but is perpendicular to it.

(4) Problem 36 on p. 478 is concerned with Owen's Method for neutral points and reference should be made to this.

Experiment 109. Comparison of the Magnetic Moments of Two Magnets by the 'Null' Method

Apparatus: The magnets X and Y; deflection magnetometer (see p. 243).

Procedure: Locate the poles of the magnets (see p. 242), unless their position is already known—see note at the start of this chapter. Record the magnetic lengths and mark the magnetic centre of each magnet.

Plot a line of the Earth's magnetic field and place the deflection magnetometer on it so that the linear scales are at right-angles to this magnetic meridian and also so that the pointer reads zero on the scale of angles. Place the magnets one on either side of the magnetometer box and orientate them so that their axes lie along the linear scales, and the poles are such that they would have produced deflections of the needle in opposite directions. Adjust the distances of the magnets from the needle until the resulting deflection is zero. The final judgment will be aided if the glass of the magnetometer box is lightly tapped near the edge—do not tap it over the suspension of the needle.

Measure the distances of the magnetic centres from the point of support of the needle (d_X and d_Y).

Repeat several times with the magnets at different distances from the needle.

Record and Calculation: Tabulate as follows:

MAGNET : X. Magnetic length = $2l_X$ cm.					MAGNET : Y. Magnetic length = $2l_Y$ cm.					M_X/M_Y
d_X	d_X^2	l_X^2	$d_X^2 - l_X^2$	$(d_X^2 - l_X^2)^2$	d_Y	d_Y^2	l_Y^2	$d_Y^2 - l_Y^2$	$(d_Y^2 - l_Y^2)^2$	$\frac{(d_X^2 - l_X^2)^2}{(d_Y^2 - l_Y^2)^2} \cdot \frac{d_Y}{d_X}$

The result quoted in the last column follows from the expression for the field strength in the Gauss 'A' position (see p. 244). The experiment may be performed using the Gauss 'B' position, when the expression will be

$$\frac{M_X}{M_Y} = \left(\frac{d_X^2 + l_X^2}{d_Y^2 + l_Y^2}\right)^{3/2}.$$

Note that in this position the linear scale must lie in the magnetic meridian and the magnets are at right-angles to it (see Fig. 120, p. 244).

Experiment 110. Comparison of the Magnetic Moments of Two Magnets, using the Deflection Magnetometer

Apparatus: The magnets X and Y; deflection magnetometer (see p. 243).

Procedure: Locate the poles of the magnets by the method given on p. 242, unless their position is already known (see p. 252). Record the magnetic lengths of the magnets and mark their magnetic centres. Plot a line of the Earth's field and place the magnetometer on this line with its linear scale at right-angles to the magnetic meridian and with the pointer reading zero on the scale of angles. Place magnet X on the western arm as shown in Fig. 120A, p. 244, at such a distance that the deflection is about 30°. Record the distance from the magnetic centre to the point of suspension of the needle and the readings of both ends of the pointer. Turn the magnet round without altering its distance from the needle and again record the two pointer readings. Transfer the magnet to the eastern arm and place it so that its magnetic centre is the same distance as before from the point of suspension of the needle. Take the pointer readings, reverse the magnet (as before) and record two more pointer readings. Repeat the above operations to obtain eight more pointer readings for a smaller value of d_x, giving a deflection in the neighbourhood of 45°, and finally take a third set of observations for a deflection of about 60°.

Perform a similar series of operations with magnet Y.

Record and Calculation: Tabulate the readings for magnet X as follows:

Magnetic length $= 2l_x$ cm.

$\therefore\ l_x =$ cm.

EXPERIMENT NUMBER	d_x (cm.)	POINTER READINGS IN DEGREES									$\tan\theta$	$\frac{(d_x^2-l_x^2)^2}{2d_x}\tan\theta$
		END ONE				END TWO				MEAN DEFLECTION (allowing for Zero) θ		
		'ZERO'=				'ZERO'=						
		East		West		East		West				
		(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)			
1												
2												
3												

From the three values in the last column of the table calculate the mean value for

$$\frac{(d_x^2 - l_x^2)^2}{2d_x} \tan \theta.$$

Let the value of this mean be x.

Tabulate the values for magnet Y in an identical manner and obtain the mean value of

$$\frac{(d_Y^2 - l_Y^2)^2}{2d_Y} \tan \theta.$$

Let the value of this mean be y.

It follows that the ratio $M_X/M_Y = x/y$.

Notes: (1) A similar experiment can be done using the Gauss 'B' position, the values in the last column of the table then being

$$(d_X^2 + l_X^2)^{3/2} . \tan \theta \quad \text{and} \quad (d_Y^2 + l_Y^2)^{3/2} . \tan \theta.$$

If the mean values obtained from the last columns are again x and y the ratio of M_X/M_Y is again x/y.

(2) If the value of the horizontal component of the Earth's magnetic field is known, then a value for M_X and M_Y can be calculated.

Experiment 111. Comparison of the Magnetic Moments of Two Magnets by the Vibration Method

Apparatus: The magnets X and Y; large glass vessel, e.g. a large bell jar; stop-watch.

THEORY

The experiment depends on the fact that the time of vibration of a freely suspended magnet, oscillating through small angles (not more than 10°) in a field of intensity H oersteds is given by

$$T = 2\pi\sqrt{\frac{I}{MH}}$$

where I is the moment of inertia of the magnet in gm.-cm.^{2}
and M is its magnetic moment in c.g.s. units.

If for magnet X these values are T_X, I_X, M_X, and for magnet Y they are T_Y, I_Y, M_Y,

then
$$M_X H = \frac{4\pi^2 I_X}{T_X^2}$$

and
$$M_Y H = \frac{4\pi^2 I_Y}{T_Y^2}.$$

$$\therefore \quad \frac{M_X}{M_Y} = \frac{T_Y^2}{T_X^2} . \frac{I_X}{I_Y}.$$

Using this equation a value for the ratio of the magnetic moments can be obtained without the need for finding the poles, as the magnetic length does not appear in the expression used. For magnets of regular geometric shape the moment of inertia is easily found, using Routh's rule, and the periodic time is easily determined to a high order of accuracy. The method is therefore a very good one, once it can be assumed that the vibrating magnet lies wholly in a field of uniform intensity.

Procedure: Measure the mass, the geometric length and the breadth of magnet X. Suspend magnet X from a wooden stand so that the magnet is inside the bell jar. (If the latter is inverted put some cotton wool in it—to break the fall of the magnet if the suspension should break.) A satisfactory suspension can be made in the form of a stirrup of copper wire of S.W.G. about 16–20 attached to eureka wire of S.W.G. 40–47.

Set the magnet horizontal and motionless. Observe—or make—a mark whereby this position can be remembered. Bring magnet Y slowly into the vicinity so as to produce a deflection of about 5° in X. Remove Y to a considerable distance—so that it has negligible effect on X. Make the necessary observations to enable you to deduce a reliable value for the periodic time of vibration of X, as it oscillates under the influence of the Earth's field. See p. 51 for details of the method to be used.

Repeat ALL the above operations interchanging X and Y.

Record and Calculation: For each magnet record the mass and dimensions and calculate the moments of inertia about the axis of suspension (which may be assumed to be through the centre of gravity), using Routh's rule (p. 89).

Tabulate the observations on the periodic time thus:

	Number of Swings	Time taken in secs.				Periodic Time (T)	T^2
		(i)	(ii)	(iii)	Mean		
Magnet X							
Magnet Y							

Substitute in the equation

$$\frac{M_X}{M_Y}=\frac{T_Y^2}{T_X^2}\cdot\frac{I_X}{I_Y}$$

to find a value for the required ratio.

Notes: (1) If the magnets are of identical dimensions and mass, the moments of inertia need not be calculated.

(2) If the horizontal component of the Earth's field (H_e) is known,

the actual values for the magnetic moments can be found by using the equations

$$T_X = 2\pi\sqrt{\frac{I_X}{M_X H_e}} \quad \text{and} \quad T_Y = 2\pi\sqrt{\frac{I_Y}{M_Y H_e}}.$$

(3) An alternative method is to bind the two magnets together so that like poles are adjacent and find the periodic time of vibration of the combination (T_1). Then bind the magnets so that unlike poles are adjacent and find the periodic time of the new arrangement (T_2). It follows that

$$M_X + M_Y = \frac{k}{T_1^2}$$

and

$$M_X - M_Y = \frac{k}{T_2^2}.$$

From which it follows that

$$\frac{M_X}{M_Y} = \frac{T_2^2 + T_1^2}{T_2^2 - T_1^2}.$$

This method has the important advantage that the moments of inertia need not be determined. The only measurements made are therefore of periodic times which can be found to a high order of accuracy.

Experiment 112. Comparison of the Magnetic Moments of Two Magnets, using a Searle's Vibration Magnetometer

Apparatus: The magnets X and Y; Searle's vibration magnetometer (see p. 247); glass vessel in which to suspend the magnetometer.

Procedure: Locate if necessary (see p. 252) the poles of the two magnets by the method described on p. 242. Record the magnetic lengths and mark the magnetic centres.

Plot a line of the Earth's field on the bench.

Determine the periodic time of the magnetometer at a point on this line when it is influenced only by the field due to the Earth. (Refer to p. 51 on 'Timing Vibrations' if necessary.)

This done, place the magnet X to the south of the vibration magnetometer, with its axis along the meridian and its north pole pointing north. (There are other arrangements which can be used but this one ensures that the fields are acting in the same direction at the magnetometer, and as pointed out on p. 248 it is essential to be sure of this.) Check that the magnet is placed correctly by the method given on p. 248. Determine the periodic time of vibration of the magnetometer needle. Record the distance from the point of suspension of the magnetometer needle to the magnetic centre of the magnet (d_X).

Repeat for various values of d_X.

Repeat all the operations, using magnet Y instead of X.

Record and Calculation: Record as follows:

Time for n swings in the Earth's field alone

(i)	secs.
(ii)	secs.
(iii)	secs.
Mean =	secs.
T_e (Periodic time) =	secs.
Hence $1/T_e^2$ =	secs.$^{-2}$

For magnet X tabulate the observations made, using the magnetometer as follows:

Magnetic length $= 2l_X$ cm.

d_X cm.	$\frac{(d_X^2 - l_X^2)^2}{d_X}$	Number of swings (n)	Time (secs.) (i)	(ii)	(iii)	Mean	Periodic time (T_X)	$\frac{1}{T_X^2}$	$\frac{1}{T_X^2} - \frac{1}{T_e^2}$	$\frac{(d_X^2 - l_X^2)^2}{d_X} \cdot \left(\frac{1}{T_X^2} - \frac{1}{T_e^2}\right)$

Calculate the mean value of the entries in the last column.

Make a similar table for magnet Y and find a mean value for

$$\frac{(d_Y^2 - l_Y^2)^2}{d_Y} \cdot \left(\frac{1}{T_Y^2} - \frac{1}{T_e^2}\right).$$

Calculate the value for the ratio of the magnetic moments from the equation

$$\frac{M_X}{M_Y} = \frac{\dfrac{(d_X^2 - l_X^2)^2}{d_X} \cdot \left(\dfrac{1}{T_X^2} - \dfrac{1}{T_e^2}\right)}{\dfrac{(d_Y^2 - l_Y^2)^2}{d_Y} \cdot \left(\dfrac{1}{T_Y^2} - \dfrac{1}{T_e^2}\right)}.$$

Notes:

(1) The deduction of the above result is as follows:
If the field due to magnet X is H_X, then

$$H_X = \frac{2M_X d_X}{(d_X^2 - l_X^2)^2}.$$

Also
$$H_X + H_e = \frac{k}{T_X^2}$$

where H_e is the horizontal component of the Earth's field.

But $$H_e = \frac{k}{T_e^2}.$$

$$\therefore \quad H_X = k\left(\frac{1}{T_X^2} - \frac{1}{T_e^2}\right).$$

$$\therefore \quad \frac{2M_X d_X}{(d_X^2 - l_X^2)^2} = k\left(\frac{1}{T_X^2} - \frac{1}{T_e^2}\right).$$

i.e. $$\frac{2}{k} \cdot M_X = \frac{(d_X^2 - l_X^2)_2}{d_X} \cdot \left(\frac{1}{T_X^2} - \frac{1}{T_e^2}\right).$$

Similary $$\frac{2}{k} \cdot M_Y = \frac{(d_Y^2 - l_Y^2)^2}{d_Y} \cdot \left(\frac{1}{T_Y^2} - \frac{1}{T_e^2}\right).$$

From these two equations the result quoted follows immediately.

(2) The magnets can be placed to the east or the west of the magnetometer and the equation

$$\frac{M_X}{(d_X^2 + l_X^2)^{3/2}} = H_X$$

made use of in a calculation similar to the one above. Care must be taken to be sure in which direction the field due to the magnet is acting and to know which is the greater field—that due to the magnet or that due to the Earth.

Experiment 113. Determination of the Magnetic Moment of a Magnet

Apparatus: The magnet; deflection magnetometer (see p. 243); stop-watch.

THEORY

If the horizontal component of the Earth's magnetic field at a given point is H_e and the moment of the magnet is M then using a deflection magnetometer in the Gauss 'A' position (p. 244) a value of M/H_e can be found.

If the periodic time of oscillation of the magnet suspended at the same point (so that H_e is the same) is found, a value for MH_e can be calculated using the equation

$$T = 2\pi\sqrt{\frac{I}{MH_e}} \quad \text{i.e.} \quad MH_e = 4\pi^2 \cdot \frac{I}{T^2}$$

in which I is the moment of inertia of the magnet about the axis of suspension.

If the value of M/H_e is multiplied by that of MH_e, the quantity H_e is eliminated and a value for M^2 obtained, from which M is found.

Procedure: If one of the magnets X or Y, used in the previous experiments is the one of which the moment is required, much, if not all the experimental work is saved. If Experiments 110 and 111 were performed at exactly the same spot in the laboratory the appropriate data from these experiments can be used. If this essential condition did not hold, the whole experiment described below should be performed using the magnet of which the moment is required.

The experiment is divided into two parts:

(1) Make observations in accordance with the instructions in Experiment 110, p. 255, to enable you to construct a table of values for the magnet like that given for magnet X on p. 256.

(2) Make observations in accordance with the instructions given in Experiment 111, p. 257, to enable you to find the periodic time of vibration of the magnet when it is vibrating in the Earth's field at the same spot as that in which part (1) was carried out. Make also observations to enable the moment of inertia of the magnet to be calculated.

Record and Calculation: Tabulate the results as instructed above. Calculate mean value for M/H_e from

$$\frac{M}{H_e} = \frac{(d^2 - l^2)^2}{2d} \tan \theta,$$

i.e. find the mean value of the last column in the table made in Part (1).

Calculate MH_e from the equation

$$MH_e = 4\pi^2 I/T^2.$$

Hence find M by the method indicated under 'Theory' above.

Note: The mean value of M/H_e can also be deduced from deflection experiments using the Gauss 'B' position (see p. 244) when

$$\frac{M}{H} = (d^2 + l^2)^{3/2} \cdot \tan \theta.$$

CHAPTER XXXIX

TERRESTRIAL MAGNETISM

Experiment 114. Determination of the Horizontal Component of the Earth's Magnetic Field at a Given Spot in the Laboratory

Apparatus: Magnet; deflection magnetometer; stop-watch.

THEORY

It was seen in Experiment 113 that values for M/H_e and MH_e can be found for a given magnet at a given spot. If these values are divided instead of multiplied (as they were in Experiment 113) then M is eliminated and a value of H_e^2 obtained.

Procedure: The instructions are identical with those given for Experiment 113, p. 261. Naturally the experiment must be conducted at a given spot. It is an interesting exercise to co-operate with the rest of the practical class and 'survey' the laboratory with respect to its variations in the horizontal component of the Earth's magnetic field, rather than to determine this quantity at a point chosen at random.

Record and Calculation: Record and tabulate as in Experiment 113, p. 261.

Find the mean values of M/H_e and MH_e. Divide the latter by the former and solve for H_e.

Notes: (1) The note at the foot of Experiment 113, p. 262, applies here also.

(2) The tangent galvanometer can also be used to determine H_e. Refer to Experiment 123, p. 308, for details.

(3) The method using the Earth Inductor for the determination of H_e is given in Experiment 156, p. 366.

Experiment 115. Determination of the Angle of Dip at a Given Spot in the Laboratory

Apparatus: Dip circle.

This consists of a magnet suspended about a horizontal axis passing through its centre of gravity. Under the influence of the Earth's field the needle will take up a position along a line of force and make an angle with the horizontal. Behind the needle is a mirror and a scale of angles. The whole is contained in a box with a glass front, mounted on a stand so that it can be turned about a vertical axis.

Three screws are provided for levelling the instrument.

Care is required when handling so delicate an instrument and the following precautions should be observed:

(*a*) Use forceps to handle the needle—damp fingers may deposit moisture on it.

(*b*) Remove and replace the magnet on its supports gently and the correct way round.

(*c*) Rotate the instrument slowly to prevent a movement which might make the needle roll off its knife-edge supports.

(*d*) Remagnetising should be done using a solenoid (see p. 242) as the use of a permanent magnet will almost certainly result in damage to the spindle of the needle.

THEORY

No instrument is perfectly made and the effect of the imperfections must be as far as possible eliminated by the way the instrument is used. The following is a list of the possible sources of error in the dip circle together with a note of how each is eliminated:

(*a*) The suspension of the needle may not coincide with the centre of the scale of angles. Therefore both ends of the pointer should be read.

(*b*) The magnetic axis of the needle may not coincide with the geometric axis. Therefore reverse the needle in its bearings and repeat the above readings.

(*c*) The zero line of the scale of angles may not be horizontal. Therefore rotate the instrument through 180° and repeat the above four readings.

(*d*) The point of suspension of the needle may not be at the centre of gravity of the needle. Therefore demagnetise the needle, remagnetise with the opposite polarity, and repeat the above eight readings.

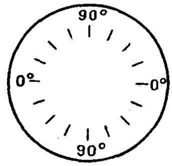


FIG. 124

The instructions below refer to an instrument for which the horizontal scale of angles is calibrated as shown in Fig. 124. Other ways of engraving the scale are in use and if the instrument you use is engraved differently it may be necessary to modify instruction (iv) of the group which relates to the preliminary adjustments of the instrument given below.

Procedure: Carefully level the instrument.

Rotate the instrument until the plane of the needle is in the magnetic meridian.

This can be done as follows, if a horizontal scale of angles is provided :

(i) Rotate until the needle appears to be vertical. Adjust until the top of the needle is at the 90° mark. Read the horizontal scale. Repeat for the bottom of the needle and read the horizontal scale.
(ii) Rotate through 180° and repeat.
(iii) Reverse the needle and repeat all four readings.
(iv) Calculate the average of the eight readings and rotate through exactly 90° from this value. Clamp to prevent further movement.

Take the following readings:

(*a*) Read both ends of the needle.
(*b*) Reverse, i.e. turn the needle over and read both ends.
(*c*) Rotate through 180° and repeat all four readings.
(*d*) Remove the needle and demagnetise it—see p. 242.
Remagnetise it so that its polarity is reversed and repeat the eight readings as above.

Calculation: The average of the sixteen readings is the angle of dip.

Note: The angle of dip can also be determined using the earth inductor. For details of this method refer to Experiment 156, p. 366.

CHAPTER XL

PROPERTIES OF FERROMAGNETIC MATERIALS

The student should be familiar with procedure used in electrical experiments before attempting the work in this chapter. Special attention is directed to Chapter XLI.

Experiment 116. Determination of the Susceptibility of a Given Ferromagnetic Specimen for Various Values of the Magnetising Field

Apparatus: Many laboratories have apparatus already assembled to meet the needs of this experiment. Ask for details of such apparatus. If one is not available the following data should enable you to construct one. It is designed to work off a 24-volt D.C. supply.

On a thin cylindrical 'former' 2 cm. in diameter and 50 cm. long wind four layers of D.C.C. Copper wire of S.W.G. 26, to make the solenoid which will be used for magnetising. This will have about 15 turns per cm. length. On a similar former about a quarter of the length wind a similar series of turns of the same wire. This will be connected in series with the first one and will act as a compensating coil—see below. Mount these solenoids on a base board with their ends about 16 cm. apart. The magnetometer compass box should be mounted on a block of wood which can slide between the solenoids along the base board without lateral movement. The thickness of the block should be such that the magnetometer magnet lies in the horizontal plane containing the axis of the solenoids.

To achieve satisfactory results it is almost essential to make a rheostat to match this apparatus. This should be of the dial type and the following is a list of the resistances in ohms which should be included between successive studs:

680, 240, 76, 56, 27, 18, 9, 9, 4, 3, 2·5, 1·5, 1·5, 1·5, 1·5, 0·8, 2·7.

If the specification of the solenoids is altered, or the voltage of the supply, these values will need amending.

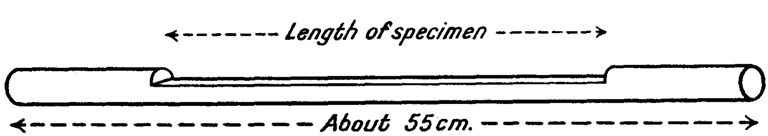


FIG. 125

The specimen can conveniently be a piece of $\frac{1}{8}''$ mild steel rod about 35 cm. in length. (This is known to give excellent results.) A piece of iron wire of S.W.G. about 16 could also be used. The specimen is mounted in a special carrier of length about 55 cm.—the ends must protrude from the solenoid when the specimen is in the middle of the latter. This carrier can be made from dowel rod of such a diameter that it will slide easily but not loosely in the solenoid. The central portion should be cut away as shown in Fig. 125 so that the specimen just fits into the 'cradle' so formed.

In addition to the above the following will be needed: deflection magnetometer box; ammeter (to match apparatus); plug key; 24-volt D.C. supply; micrometer screw-gauge.

THEORY

(1) *General:* If M is the moment of a magnet and V cm.^{3} is its volume, then, if it is uniformly magnetised, we define the 'intensity of magnetisation' (J) as the magnetic moment per unit volume

$$\text{i.e.}\quad J = \frac{M}{V}.$$

The 'susceptibility' of a substance (k) magnetised by a field H oersteds is defined by the equation

$$k = \frac{J}{H}.$$

If magnetism is induced in an initially unmagnetised specimen of a ferromagnetic substance by a field the intensity of which is slowly increasing, and the values of the inducing field (H) plotted against the intensity of magnetisation (J) produced by this field, a graph as shown in Fig. 126 will be obtained. Notice that a 'saturation' point is reached where further increase in field strength causes no appreciable increase in the intensity of magnetisation. The corresponding graph for susceptibility is shown in Fig. 127.

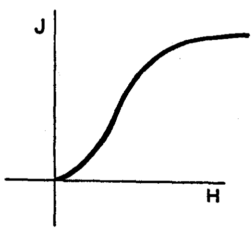


FIG. 126

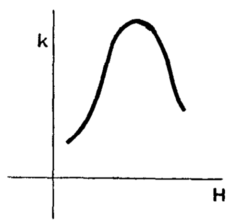


FIG. 127

(2) *Finding H:* The magnetising field, H, is produced in this experiment by the long solenoid. If this has n turns per cm. length (allowing for the fact there are several layers—i.e. in the one described above n is 4×15), then when it is carrying a current of I amperes the field inside it will be

$$\frac{4\pi nI}{10}\ \text{oersteds.}$$

But $4\pi n/10$ is a constant for the solenoid and can be calculated once n is known. This constant will from now on be referred to by the symbol K_1 and the field can be found by observing the reading of an ammeter in series with the solenoid and multiplying it by K_1.

There is, however, one complicating factor which may lead to errors of the order of 10%. This is, that the magnetism induced in the specimen opposes the magnetic field producing it. A correction for this effect can be introduced by substituting the value

$$\frac{H}{1 + \alpha k} \text{ instead of } H,$$

where k is the susceptibility and α is a constant, known as Maxwell's constant, and given by the table:

$\frac{\text{Length of specimen}}{\text{Diameter of specimen}}$	α
50	0·01820
100	0·00540
200	0·00160
300	0·00075
400	0·00045
500	0·00030

Since the correction depends on k an approximate value of k must first be found and the correction applied using this value. This new value of k must then be substituted in the original equation to find a more accurate correction factor. This technique is known as the 'method of successive approximation'.

(3) *Finding J:* The magnetometer needle is influenced by four fields in this experiment:

(i) that due to the horizontal component of the Earth's field (H_e).
(ii) that due to the poles induced in the specimen
(iii) that due to the magnetising solenoid, and
(iv) that due to the smaller coil.

The last two are arranged so that their fields in the region of the needle are equal and opposite; this is the reason for referring to the smaller coil as the 'compensating coil'.

The deflection θ is therefore caused by the two fields (i) and (ii) and gives the direction of their resultant. The ratio of these two fields will thus be $\tan \theta$.

The field due to the specimen can be evaluated as follows:

From the definitions of J and M, given above, it follows that the pole strength of the specimen is $\pi r^2 J$ where r is the radius of the specimen in cm.

If the distances from the point of suspension of the magnetometer needle to the poles of the specimen—assumed to be at the ends—are x cm. and y cm., then the field due to them at the needle is

$$\frac{\pi r^2 J}{x^2} - \frac{\pi r^2 J}{y^2} = \pi r^2 J\left(\frac{1}{x^2} - \frac{1}{y^2}\right) \text{ oersteds}$$

$$\therefore \quad \frac{\pi r^2 J\left(\frac{1}{x^2} - \frac{1}{y^2}\right)}{H_e} = \tan \theta$$

$$\therefore \quad J = \frac{H_e}{\pi r^2 \left(\frac{1}{x^2} - \frac{1}{y^2}\right)} \cdot \tan\theta$$

$$= K_2 \tan\theta$$

where K_2 is clearly another constant for the experiment calculable in terms of H_e, x, y and r.

Procedure: If it is not known, determine the horizontal component of the Earth's field at the spot where the experiment is to be conducted—see Experiment 114, p. 262, for details.

Determine the diameter of the specimen in a number of places using the micrometer screw-gauge.

Determine the value of n—the number of turns per cm.—of the long solenoid, S_1, by counting the number of turns in, say, 10 cm.

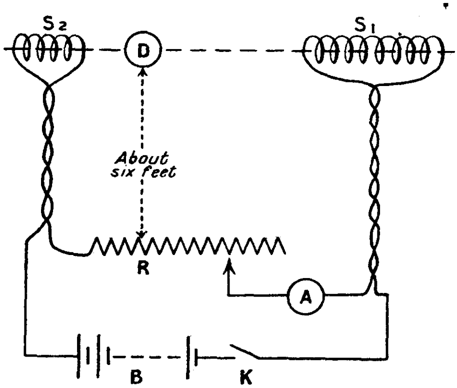


FIG. 128

Set up the circuit shown in Fig. 128 in which

S_1 is the magnetising solenoid
S_2 is the compensating coil
D is the deflection magnometer box
A is the ammeter
B is the supply of D.C.
R is the rheostat
K is the plug key

Arrange that the axis S_1DS_2 is at right-angles to the magnetic meridian. Rotate the compass box so that the ends of the pointer read zero. Record the 'zero' readings. Make sure that all leads and other apparatus carrying current, except S_1 and S_2, are so far from D that they have negligible effect on the needle. For this purpose the leads between the rest of the apparatus and S_1 and S_2 should be twisted together; flex is useful here. See also that the directions of the currents in S_1 and S_2 are such that the fields due to them at D are in opposite directions.

Without the specimen in the solenoid adjust the position of D until with maximum current flowing in it there is no deflection of the needle. This ensures that the field due to the solenoid S_1 alone is neutralised by that due to S_2, at D.

Switch off the current.

Demagnetise the specimen (see p. 242), and test it for the absence of magnetism by placing a few iron filings on a piece of paper and testing by attraction. If any filings stick to the specimen, demagnetise again and repeat the test.

Place the specimen in its holder and record the distances from the ends of the latter to the ends of the specimen. See that about equal lengths of the holder protrude from the solenoid so that the specimen is symmetrically placed in it. Measure the distances from the ends of the holder to the point of suspension of the magnetometer needle — so that x and y can be found.

Insert the maximum resistance provided by R and switch on the current. Observe the reading of the ammeter (I amps.) and the deflection of the needle (θ). Reduce the value of R by steps, noting the current deflection for each stage. DO NOT DECREASE THE CURRENT AT ANY STAGE, NOR SWITCH IT OFF (until the experiment is finished). If a hitch does occur, switch off, remove the specimen, demagnetise completely and start again. Continue reducing R step by step until the maximum current is flowing, taking as many observations of I and θ as the design of R permits.

Record and Calculation: Record all observations. Calculate values for K_1 and K_2.

Tabulate the observation of I and θ as follows:

I (amps)	Pointer Readings			tan θ	J (K_2tan θ)	H ($=K_1I$)	Approximate Susceptibility $k'\left(=\frac{J}{H}\right)$	α	$1+\alpha k'$	k $=k'(1+\alpha k')$
	End one Zero =	End two Zero =	Mean (θ)							

Plot graphs showing (i) how J varies with H.
(ii) how k varies with H.

Note: Proceed to Experiment 117 before dismantling the apparatus.

Experiment 117. Determination of the Retentivity, the Coercive Force, and the Hysteresis Loss during a Cycle of Magnetisation for a Specimen of Ferromagnetic Material

Apparatus: As for Experiment 116, together with a reversing key.

THEORY*

In Experiment 116 care was taken to increase the magnetising field steadily. This was done because the graph for demagnetisation does not coincide with that for magnetisation. There is always a lag between the magnetic properties produced and the magnetic field responsible for the magnetisation. This phenomenon is known as 'hysteresis'. It is easily possible to take the specimen through a complete cycle of magnetisation by increasing the applied field to a positive maximum then decreasing it to a negative maximum and finally increasing it again to the positive maximum—a process which involves reversing the current twice. If this cyclical operation were carried out the result would be as shown in Fig. 129 where AB represents the first part of the path, up to saturation and BCDE the path followed as the magnetising field is reduced to the negative maximum. At C the applied field is zero but the material still retains some magnetism. AC measures the residual magnetism or 'retentivity'. The material is demagnetised completely at point D at which the applied field has a value AD. This field required to reduce the magnetisation of the specimen to zero is known as the 'coercive force'. The completion of the cycle is along the path EFB and the whole loop is referred to as the 'hysteresis loop.'

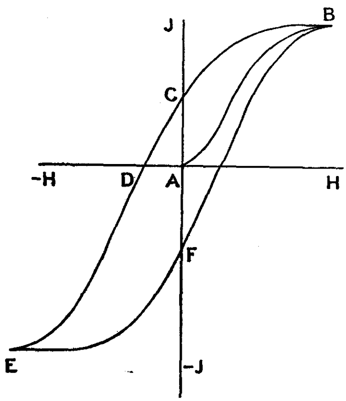


FIG. 129

It can be shown that the area, in c.g.s. units of the hysteresis loop is numerically equal to the energy lost in ergs/cm.^{3} of the specimen during the cycle of operations. Thus a graph of J against H enables us to find:

(1) The retentivity: this will be the intercept on the J-axis and will be in c.g.s. units of magnetic moment per unit volume of the specimen.

(2) The coercive force: this will be the intercept on the H-axis and will be in oersteds.

* Students should be familiar with the 'Theory' of Experiment 116 before proceeding with this experiment.

(3) The energy loss during the operations: this is found from the area of the loop, but attention must be paid to the units in which it is measured. The safest method is to use c.g.s. units throughout (the oersted is a c.g.s. unit). Having plotted the *J-H* graph, decide what is the relationship between one square of the graph paper and the units used. The area can then be counted in squares and converted, by the factor already determined, into ergs/cm.^{3}.

It is not essential to plot the *J-H* curve itself and time can be saved if a graph of I against $\tan \theta$ is drawn. From this it is still possible to obtain the values required. The retentivity is the intercept on the $(\tan \theta)$-axis multiplied by K_2. The coercive force is the intercept on the I-axis multiplied by K_1. The hysteresis loss is the area of the I-$(\tan \theta)$ loop expressed in units used for the axes and then multiplied by $K_1 \times K_2$.

Note that all the data obtained from this experiment refers to one cubic centimetre of the specimen.

Procedure: Much of the basic data for the apparatus can be assumed from the results of Experiment 116 if it has been done recently. Otherwise it is necessary to determine the value of n, r and H_e by the methods given on p. 268.

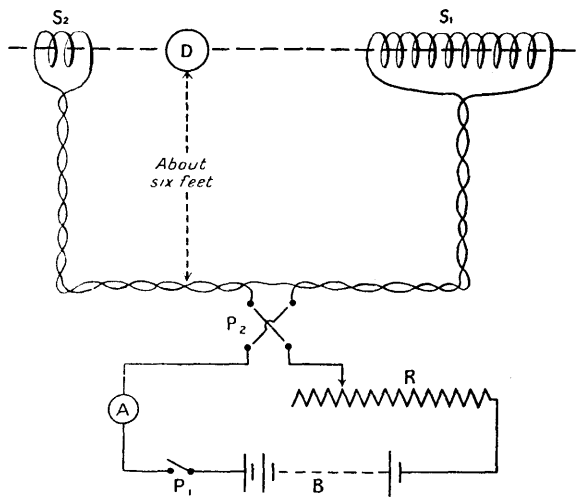


FIG. 130

Set up the circuit shown in Fig. 130 where

S_1 is the magnetising solenoid
S_2 is the compensating coil
D is the deflection magnetometer box
A is the ammeter
B is the supply of D.C.
R is the rheostat
P_1 is the plug key
P_2 is the reversing key

Arrange that the axis of S_1DS_2 is at right-angles to the magnetic meridian. Rotate the compass box so that the ends of the pointer read zero and record these 'zero' readings. Keep all the rest of the apparatus at least six feet from the solenoids and D, using flex for the leads connecting S_1 and S_2 into the circuit. See that the directions of the currents in S_1 and S_2 are in opposite directions.

Without the specimen in S_1 switch on the current and adjust the position of D so that when maximum current is flowing there is no deflection of the magnetometer needle; this ensures that the field due to S_1 alone is neutralised at D by that due to S_2. Switch off the current.

Mount the specimen in its holder and measure the distance from the ends of the latter to the ends of the specimen. Introduce the specimen into S_1 and arrange that it lies symmetrically inside. Measure the distances of the ends of the holder from the point of suspension of the magnetometer needle so that x and y can be deduced.

Switch on the current and adjust R to a minimum so that the maximum current is flowing. Using P_2, reverse this maximum current about 100 times so that the specimen is taken through a magnetising cycle about 50 times. This should be sufficient to ensure that the magnetic history of the specimen is unlikely to have any effect on the results and brings the specimen into what is termed 'the cyclic state'.

With maximum current flowing read both ends of the pointer in the magnetometer and record the current. Reduce the current by the steps for which the rheostat was designed, noting the pointer and ammeter readings at each stage. When the current is at its minimum move P_2 to its other position, thus reversing the current, and then increase the current again step by step, taking observations as before. After maximum current has been reached continue taking observations as the current is reduced by the same steps, reversing at the minimum and completing the loop by increasing to the positive maximum again. It is necessary to take a reading for every value of the current obtainable at all stages of the cycle and it is also necessary to carry out the operations in the order given above without any interruptions or reversals—except those specified. If any hitch does occur the cycle must be started again.

Record and Calculation: Tabulate the results. Calculate the values for K_1 and K_2 (see pp. 266–268). Plot I against $\tan\,\theta$ and deduce retentivity, coercive force and energy loss from the curve by the method given above.

PART VII

ELECTRICITY

CHAPTER XLI

STANDARD PROCEDURE

Electrical Supplies

(1) *Alternating Current*

In most laboratories at least two A.C. supplies are available. One will be the usual 'mains' supply at 240 volts, and the other will be this supply transformed to 12 or 24 volts. The 240-volt supply, which is that used for lighting, heating, etc., is capable of giving a serious shock—serious enough on occasions to cause death—and it should therefore never be carried by exposed wires. Flex should be used in wiring and all connections covered with insulating tape. There are not many occasions when this supply will be used, as most experimental work in electricity is concerned with direct current. Chapter LIII is devoted to the study of alternating current.

(2) *Direct Current*

This is obtained from various sources—cells, accumulators, rectifiers working off low-voltage A.C., or from dynamos. Cells and accumulators are used extensively and the use of rectifiers is increasing rapidly.

STORAGE CELLS (i.e. ACCUMULATORS): The 'acid accumulator', or lead accumulator, is in common use and gives a steady current for long periods. The e.m.f. when fully charged is just over 2 volts, which would fall to about 1·85 volts if completely discharged. The acid accumulator consists of a number of specially prepared plates immersed in a solution of sulphuric acid and instructions for maintenance are usually provided by the manufacturers. If this is not so, the following instructions will be useful. The specific gravity of the acid should not exceed 1·25 when fully charged. As the accumulator is discharged the specific gravity of the acid falls and it should never be allowed to fall below 1·18. *The specific gravity of the acid is the best test for the condition as to the state of charge of an accumulator, as the voltage should never be allowed to fall below* 2 *volts.*

With proper attention to maintenance the accumulator has a long life; the following points should receive constant attention:

1. Pure acid at the specified concentration should be used.
2. The level of the liquid, which tends to decrease during charging, should always be maintained at the level indicated on the glass container—distilled water should be used for this purpose.
3. Charging and discharging should never exceed the specified correct rate—too rapid rates may lead to buckling of the plates.

4. An accumulator should never be discharged below a voltage of 2. It will continue to give a current until its voltage falls to about 1·85 volts, the decrease below 2 volts occuring rapidly towards the end of the life of the charge.

5. Accumulators should never be left in an uncharged condition; on the contrary they should be kept as fully charged as possible.

THE LECLANCHÉ CELL: This cell has an e.m.f. of 1·5 volts, and gives a current which, although it falls off rapidly, recovers when the cell is left for a short time. As it is cheap and easy to maintain it is therefore very useful when current is required for a short time only, such as in 'Null' methods.

It consists of a positive pole of carbon embedded in depolarising material in a porous pot. This requires no attention at all and lasts for a long time. The porous pot is placed in a jar containing a saturated solution of ammonium chloride (salammoniac), together with a rod of amalgamated zinc which acts as the negative pole.

When not in use the porous pot and the zinc rod should be removed and stored dry.

THE DANIELL CELL: The usual form of Daniell Cell, which has an e.m.f. of rather more than 1·1 volts consists of a copper vessel containing a saturated solution of copper sulphate, in which stands a porous pot containing an approximately 5% solution of sulphuric acid. In this acid is immersed an amalgamated zinc rod, which is the negative pole. The copper vessel is provided with a 'shelf' on which should be placed copper sulphate crystals so that the strength of the copper sulphate is maintained. The disadvantage of this form of the cell is that the internal resistance rises due to polarisation. Much more satisfactory results will be obtained if the porous pot is filled with a saturated solution of zinc sulphate and a few pieces of granulated zinc dropped in. The e.m.f. is a little lower—about 1·08 volts but remains remarkably constant. The internal resistance is higher but does not vary much provided the cell is short-circuited for about ten minutes before use, and a porous pot is used which has been previously well soaked.

Both forms of cell should be dismantled immediately after use and the solutions returned to bottles reserved for the purpose. The zinc rods should be washed well under the tap and brushed (with an old tooth brush) and then stored dry. If attention is paid to these last instructions the need for re-amalgamating a zinc rod rarely arises. If it does become necessary, dip the rod into dilute sulphuric acid for 30 seconds, and then hold the rod in a horizontal position while a small quantity of mercury is poured over it into a receptacle. A small quantity of the mercury will adhere to the zinc and this should be spread over the whole surface by rubbing, preferably with the finger.

It will not be found necessary to use any more mercury than that which adheres in the first instance.

THE STANDARD CELL: For standardisation of instruments a source of e.m.f. which is constant and of which the value is known to a high order of accuracy is required. WE CANNOT RELY ON THE 2-VOLT ACCUMULATOR HAVING AN e.m.f. OF 2·000 VOLTS. For this purpose a 'standard cell' is used and, though a number of different types have been designed, the Weston Standard Cell is nearly always used nowadays mainly due to the advantage which it has over other cells in that the variation of its e.m.f. with temperature is very small—so small that for our purposes we need rarely concern ourselves with the extent of the variation, provided we use it at temperatures experienced in the usual laboratory.

The e.m.f. of a Weston Cell is 1·0183 international volts at 20°C. If the temperature at which the cell is working is different from this value, and work of a very high order of accuracy is being performed, a temperature correction will be needed. In this case reference should be made to books of tables to find the temperature coefficient for the cell.

Any standard cell will fail to maintain its quoted e.m.f. if it is not treated with great care. The most important point to remember is that it must never be allowed to give more than infinitesimal current—and *that* only for a very short time, i.e. less than a second. When using such a cell a resistor of at least 10,000 ohms should be wired in series with it, to 'guard' it. It is convenient to use a wireless type resistor. In many cells this resistor is incorporated and you should enquire whether this is so in the cell you are given to use. If there is any doubt on the matter, include the resistor externally.

This cell is used in conjunction with a potentiometer (see Ch. XLVIII) and the small current which passes when the sliding contact is not at the balance point will be difficult to detect. A 5–0–5 microampere galvanometer should be used if it is available, and for preference it should be of the reflecting type. Reasonably satisfactory results are obtainable with a 20–0–20 microampere instrument, even if it is the pointer type, but of course the balance points are much less sharply determined. If only an instrument rated at about 500–0–500 microamperes is available it will be necessary to reduce the series resistance from 10,000 ohms to 1,000 ohms when the balance point has been determined as carefully as possible using the higher resistance. When the lower guarding-resistance is in circuit, take great care to tap the potentiometer wire:

(i) lightly, (ii) momentarily, and (iii) near to the expected balance point.

(3) *Rectification of Alternating Current*

Various forms of rectifier are obtainable and some can be made in the workshop. The subject is too wide to be dealt with fully here. Information on valve rectifiers should be sought in text books on Electronics (i.e. 'radio') and forward reference should also be made to Experiment 168, pp. 396–8 and to pp. 401–2.

The metal rectifiers which are now available are very useful in the laboratory; they are fairly cheap and are easy to use. The two most common ones are the 'copper oxide' and the 'selenium-iron' rectifiers but the use of germanium and silicon rectifiers is increasing rapidly because of their higher current-carrying capacity and small size.

The metal rectifier has a low resistance in one direction and a high resistance in the other. Thus in the case of the copper oxide rectifier current flows easily from the oxide to the copper but only with difficulty in the opposite direction. In the selenium rectifier the current flows much more readily from the iron to the selenium than from selenium to iron. (An experimental investigation of this effect is described on p. 396.) The direction in which the current flows more easily is called the 'forward direction' and the conventional symbol for a rectifier is as shown in Fig. 131. It will be noted that the forward direction is indicated by the direction of the arrow.

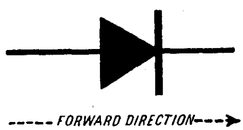


FIG. 131

Before using the rectifier the circuit should be thoroughly understood and the following notes (pp. 278–81) should therefore be studied.

HALF-WAVE RECTIFICATION. In Fig. 132 the function of a single rectifier element is shown. In diagram A the way in which it would be connected across the A.C. mains is shown, T being the transformer which steps down the voltage to the value for which the rectifier element is rated. Diagram B is a graph of current against time for the supply which enters the element whilst C shows the corresponding graph for the current which would flow in a circuit connected across the output terminals of the element. The mechanism will be understood when it is remembered that the part of the graph B which is above the axis represents the current which is flowing in the opposite direction to that drawn below the axis. It has been assumed that the positive currents correspond to the 'forward direction' of the rectifier. Such rectification is referred to as 'half-wave rectification'.

SMOOTHING: The output is intermittent and variable, which does not matter in many demonstration experiments but is inconvenient when quantitative work is involved. The conversion of this type of output into a continuous current is a process known as 'smoothing'. If currents of a few milliamperes are required this can be effected by connecting an 8-microfarad capacitor in parallel with the output

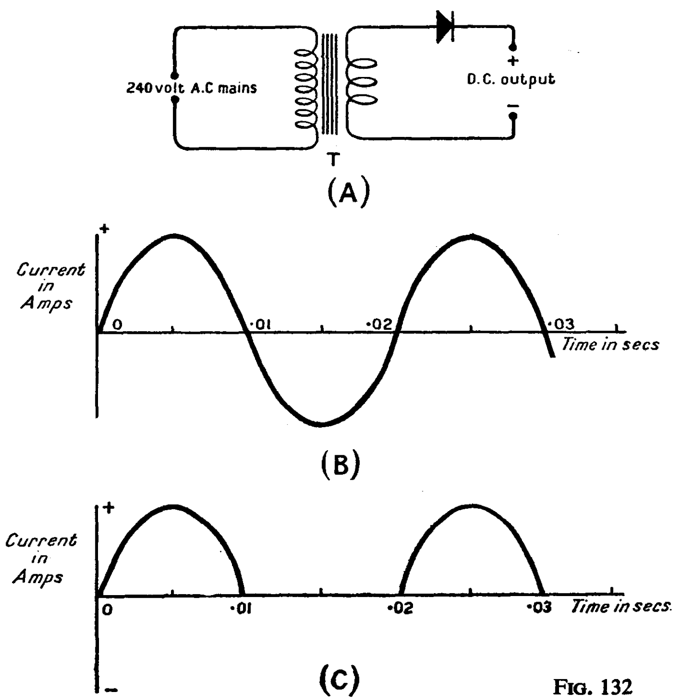


FIG. 132

terminals, as shown in Fig. 133A. For heavier currents this can be replaced by a battery of accumulators, see Fig. 133B. When this is done it is important to be careful to connect the positive pole of the battery to the positive terminal of the output. Failure to do this will result in serious damage to the battery. The e.m.f. of the battery used should be less than a third of the peak voltage of the element's output. The reason for this will be appreciated when the following explanation of the details of the process has been studied.

In Fig. 134 the half-wave output of a rectifier working off 12 volts A.C. is shown, this time as a voltage. The line A′G′ represents the (steady) e.m.f. of the battery. During the time intervals represented by AB, CD, EF, etc. the voltage of the rectifier (which is in parallel with the battery) is below that of the battery and it is therefore the latter which supplies the external circuit with current at its own e.m.f. During the time intervals represented by BC, DE, etc., the output voltage of the rectifier exceeds that of the battery but the voltage applied to the external circuit remains the same as before, provided the resistance of the battery is very small compared with that of the external circuit. During these intervals (BC, etc.) the excess energy

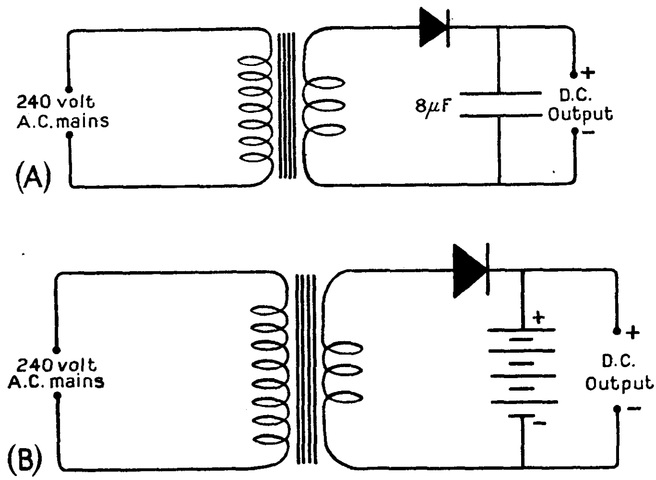


FIG. 133

from the rectifier is being absorbed by the battery which is thus being charged. The process can thus be summed up by saying that those parts of the graph shaded with vertical lines represent the amount of energy *supplied by* the battery whilst those shaded with horizontal

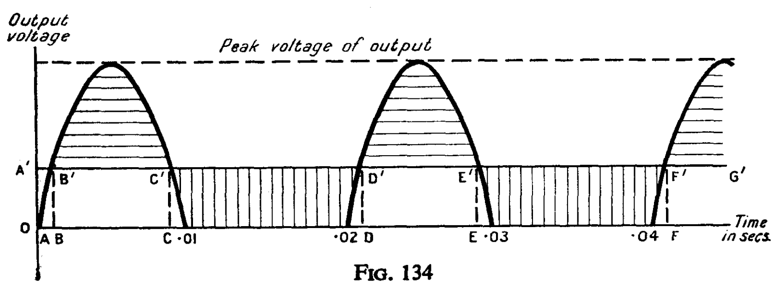


FIG. 134

lines represent the energy *absorbed by* the battery. Clearly the best arrangement will be that in which the energy amounts are equal. This occurs when the e.m.f. of the battery is $1/\pi$ times the peak of the output voltage*. Such an arrangement ensures that the battery is *just* receiving

* Putting a voltmeter across the output terminals will not give the 'peak voltage' but the 'R.M.S. voltage'. The former can be found by multiplying the voltmeter reading by 1·414.

as much charge as it delivers. It may be asked why the rectifier need be used, since the steady voltage achieved is that of the battery. The answer is that for short experiments there is no advantage unless very heavy currents are needed; if the latter are required the rectifier should be used, as it saves heavy discharge of the battery. An intermittent heavy discharge will not damage the battery as a continuous one would do. Secondly when a fairly heavy current is needed for several hours there would almost certainly be a fall in e.m.f. of the battery if the latter were unaided by the rectifier.

For purposes of smoothing it is important to use a battery of accumulators. The internal resistances of the other types of cell available are too high.

FULL-WAVE RECTIFICATION: Full-wave rectification can be obtained by using a circuit composed of four rectifier elements arranged as shown in Fig. 135. Diagram A shows the conventional circuit diagram

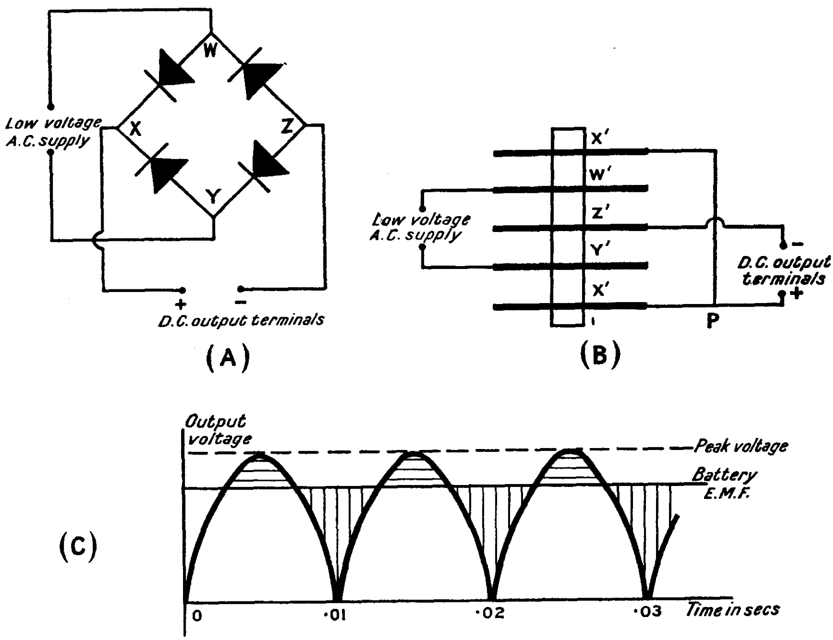


FIG. 135. FULL-WAVE RECTIFICATION.

whilst B shows how this arrangement is achieved in practice. (This is the usual form of rectifier obtained from suppliers.) Diagram B can be obtained from diagram A by 'opening out' the arms WX and YX at X and rejoining them by the leads X′ P, as shown in diagram B.

To smooth the output of such a rectifier the same methods can be used as for the single element. The 8 μF capacitor is quite satisfactory for small currents but a battery is necessary for heavier ones.

Since twice as much energy is now available from the rectifier the e.m.f. of the battery may now have any value up to $2/\pi$ times the peak voltage of the output. This fraction should not be exceeded, as this would cause a slow discharge of the battery.

For a full-wave rectifier giving a R.M.S. output of 12 volts the peak voltage will be $12 \times 1{\cdot}414$, i.e. nearly 17. Thus the battery e.m.f. required to smooth this must not exceed 10·8 volts. In practice this means that not more than five accumulators should be used with such a rectifier. Fig. 135 (C) illustrates the smoothing process and should be compared with Fig. 134.

Further information on rectifiers can be obtained by consulting the pamphlets published by Messrs. Westinghouse Brake and Signal Co., Standard Telephones and Cables Ltd., B.T.H. Co. Ltd., G.E. Co., and Mullards.

Measuring Instruments

(1) *Galvanometers*

Galvanometers are the most important of the measuring instruments because, in addition to their intrinsic uses, they are used to make ammeters and voltmeters by the addition of shunts and series resistors. Except for the tangent galvanometer (see p. 305) they are usually designed to measure only very small currents, i.e. of the order of microamperes, and they are therefore delicate and expensive; they should be handled very carefully.

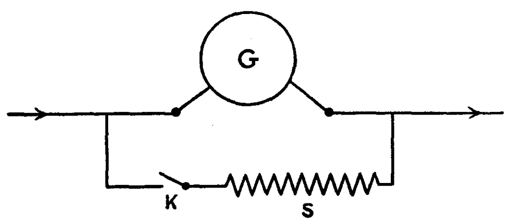


FIG. 136

Usually a galvanometer is employed in a 'null' method (e.g. experiments in chapters XLV – XLVIII) and when this is the case it is a wise precaution to guard the galvanometer by introducing a low-resistance shunt as shown in Fig. 136. If for example the galvanometer had a resistance of 100 ohms the use of a shunt, S, of resistance about 0·1 ohm ensures that until the key K is opened, only about 1/1,000 of the current in the circuit concerned passes through the galvanometer. While preliminary adjustments are being made, the sensitivity can be decreased by including resistance S, which for this purpose can conveniently be 10 cms. of eureka wire of S.W.G.22. For the final stage of the experiment K is opened and the full sensitivity restored.

The construction of galvanometers of the moving coil and moving magnet types should be studied in theoretical text books on Electricity. Your instructor will no doubt be willing to remove the covering from some of the instruments available. Do not attempt to do this for yourself unless you have obtained permission and have been told how to proceed.

An important modification is sometimes introduced in order to allow a quantity of charge to pass practically instantaneously through the coil of the galvanometer. This is done by reducing damping to a very small amount by winding the coil on a non-conducting core to eliminate eddy currents. When this is done, practically all the charge passes before the coil has moved appreciably. Such a galvanometer is known as a 'ballistic galvanometer'.

Most ballistic galvanometers are of the moving coil type and all instructions in this book relate to this design.

When a charge passes through a ballistic galvanometer the coil gives a rapid 'throw' or 'kick' until it is checked by the torsional forces of the suspension. The latter then restore it to its mean position by a series of decaying oscillations. It is the initial throw, corrected as shown below, which is proportional to the charge passed.

Though the occurrence of induced currents may have been eliminated by the design, the resistance to motion of the coil offered by the air will produce some damping. It is usually undesirable that the damping be reduced to such small proportions that the instrument becomes difficult to manage due to its prolonged time in coming to rest. The first throw will thus be less than that which theoretically would have been produced by the charge in an undamped system. Correction for this involves the determination of the 'logarithmic decrement' and advanced students should consult appropriate textbooks on this subject. A good treatment is to be found in *Practical Physics* by T. G. Bedford (Longmans Green) paragraphs 530, 531. A simpler method is available which, whilst it is an approximation, is nevertheless sufficiently accurate to meet the needs of experiments at the standard with which we are concerned. It consists in observing the first throw and the next throw *on the same side.* Let these observations be θ_1 and θ_2. An approximate value for the corrected throw is then

$$\theta_1 + \frac{\theta_1 - \theta_2}{4}.$$

For a proof of this refer to *Practical Physics* by T. G. Bedford, paragraph 532.

Immediately after each observation has been made it is convenient to bring the coil to rest by short-circuiting it (electro-magnetic damping). Thus the ballistic galvanometer should be connected to the centre pair of terminals of a double-pole double-throw switch with a shorting strip across one outer pair of terminals and the leads from the rest of the circuit connected to the other outer pair. (See Figs. 189, 190, 192, etc.)

When using a ballistic galvanometer it is essential to keep the switches, keys, capacitors, etc., free from dust. If this is not done the variation in charges involved makes it difficult to obtain either consistent or accurate results.

(2) *Reflecting Galvanometers and their Adjustments*

In many galvanometers provision is made for observing the deflection (or the throw) by an optical method. A mirror is attached to the suspension and from it a beam of light is reflected on to a scale placed usually at one metre from the mirror. It is essentially an 'optical lever' method and reference to p. 49 should be made if the principle is not understood. When a galvanometer is used ballistically the optical system MUST be employed. Linear deflections of the spot of light will be observed, and it may be assumed that if two deflections are comparable in magnitude the ratio of the linear deflections is equal to the ratio of the angular deflections.

This type of system is very susceptible to vibration and a galvanometer of the reflecting type must therefore be placed on a rigid support, preferably a shelf fixed to a wall. If this is not possible the galvanometer lamp and scale should be set up on a table separate from the other apparatus.

It is further advisable to stand a ballistic galvanometer on an insulator such as paraffin wax or alkathene, and to use leads from it about two metres long, made of well-insulated wire, connected to a double-throw switch. In this way the galvanometer can be isolated from the rest of the circuit while the adjustments are made, and the leakage of charge during the experiment is also minimised.

To set up the optical system proceed as follows:

Place the scale so that the centre zero is on the normal from the galvanometer window and is as nearly as possible 100 cm. from the galvanometer mirror. Ensure that the scale is parallel to the galvanometer window. Adjust the centre of the lamp so that it is immediately under the zero of the scale. Unclamp the galvanometer suspension and by means of the zero adjuster bring the image of the cross-wire on to the zero of the scale. Make final adjustments to the focusing so that a sharp image of the cross-wire is obtained on the scale. Check the zero again by setting the coil swinging and making sure that the image of the cross-wire returns to the zero mark when the oscillations have ceased.

(An easy and safe way to set the coil swinging is to hold the junction of a copper-eureka thermocouple between the fingers and touch the galvanometer terminals with the other ends of the leads.)

Experiments on the sensitivity of galvanometers will be found in Chapter LI.

(3) *Ammeters*

An ammeter is a galvanometer provided with a shunt through which most of the current passes. The mathematics of design is simple and should be studied in appropriate books. Clearly the resistance of an ammeter will be low and it is usually safe to assume that the introduction of an ammeter into the circuit will have negligible effect on the current flowing. You should, however, always remember that an ammeter has *some* resistance and in certain low-resistance circuits allowance may have to be made for it.

(4) *Voltmeters*

A voltmeter is a galvanometer which has a high resistance connected in series with the coil. Again theoretical textbooks should be consulted for details of the design. It is used to measure the potential difference between two points in the circuit and should be connected across those two points, in parallel with the main circuit. Usually it may be assumed that the current taken by the voltmeter is negligible and that the main circuit is undisturbed, but if there is any high resistance involved in the main circuit the effect of the voltmeter on the current flowing may be appreciable, and careful consideration should be given to the matter.

(5) *Choice of Instruments*

Before collecting the instruments which you intend to use in any electrical experiment you should have done some estimating of the currents likely to be flowing, and the potential differences occurring, in each part of the circuit. Exact values are rarely needed and are in any case rarely calculable, but it is no use going to a cupboard containing ammeters, etc., of a wide variety of ranges without knowing whether your maximum current will be 10 amps., 2 amps., or 5 milliamps. As far as possible select an ammeter, voltmeter, milliammeter or millivoltmeter which has a full-scale deflection just above the maximum value likely to occur in the part of the circuit with which it is concerned. If the experimental instructions state a range, do not accept this without thought. It may be that your other apparatus is of different specification from that referred to in the rest of the experiment and that on that account you need an instrument of different range.

Unless you have had reasonable experience in practical electricity it is wise to ask your instructor to check your calculations before selecting the instruments—but he will do you a disservice if he does those calculations for you.

Wherever possible a moving coil instrument should be selected, but remember that such an instrument cannot be used for A.C. unless a rectifier is incorporated in the instrument—a practice which is becoming increasingly common. Details of such rectifiers may be found in pamphlets published by the firms mentioned on p. 282.

Resistors

(1) *Variable Resistors or Rheostats*

These are usually constructed of lengths of wire of high resistance wound on suitable formers and provided with sliding contacts so that different lengths of the wire may be introduced into the circuit. The winding should be non-inductive (see p. 330). Do not choose a rheostat haphazardly any more than you would select a measuring instrument at random. The maximum safe current and the maximum resistance of the rheostat should be stamped on it and you should be satisfied that the one selected is suitable to meet the demands which will be made of it.

(2) *Resistance Boxes*

A rheostat affords control of the current but the exact value of the resistance inserted is unknown. If this information is needed a resistance box may be used. This consists of a number of coils of known resistance mounted in a box. The method of introducing the coils into the circuit may be by removing brass shorting plugs from the brass bar to which the coils are connected (as shown in Fig. 137)

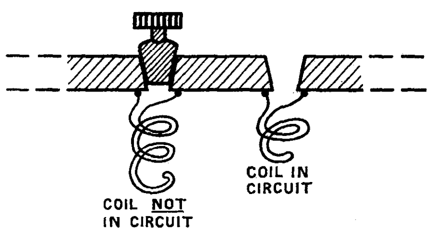


FIG. 137

or else by moving a rotating switch. If the first method is used the box is said to be of the 'plug type'; this is commonly met with in school laboratories. If the other method is employed the box is said to be of the 'dial type'; this is used extensively in industrial laboratories, mainly because the change of resistance can be effected so much more rapidly. Notice that the resistance offered by the plug type box is the sum of the resistances of the coils for which the plugs are removed.

It is customary, too, to include an 'infinity plug' which is simply a gap in the brass bar which affords almost infinite resistance when the plug is removed and which is in effect a plug key. Plugs should be inserted *and removed* with a right-hand screwing action; it will be necessary to tighten the plugs next to those removed.

Care should be taken not to pass too great a current through any coil in the resistance box. For either type a reasonable maximum is about 0·05 amp. It is useful to remember that if an e.m.f. of 1·0 volt is used to supply the current the minimum value inserted by the resistance box should be about 20 ohms if there is no other appreciable resistance in series with it and the box is taking the main current.

All resistance boxes should have certificates giving more accurate values for the coils than the ones stamped on the box, which must be regarded as the approximate values. The limits of error will be included with the resistance of each coil. They should be included in your record, and used when calculating the possible error of the final answer.

(3) *Standard Resistance Coils*

For more exact work than the use of resistance boxes allows, standard resistance coils should be used. These consist of bobbins specially wound with high-resistance wire and with the resistance which is included between the terminals stamped on them. Although wire with a low temperature-coefficient will be used when making them it must be remembered that the resistance *will* depend on the temperature and for this reason the current passed through them should never be enough to raise their temperature appreciably.

(4) *Lamp Resistors*

These are sometimes used when controlling A.C. and take the form of a number of lamp sockets (mounted on a board) into which lamps are inserted to pass the current. The sockets are wired in parallel so that the greater the number of lamps in use the greater is the current passing.

Keys and Switches

Various types of keys and switches are commonly used, and detailed descriptions of the simpler ones are unnecessary as each has its fairly obvious advantages and the choice is not difficult.

Bad switches and keys—especially dirty ones—lead to many disappointments and special attention should be paid to the cleanliness of the contacts. When including plug keys in a circuit remove the plugs before connecting, so that no current flows until all your attention is focused on the effect of that current on the instruments (see also a note on this below).

The reversing key may present difficulties but if a four-way plug key is used the wiring is as shown in Fig. 138. Do not forget to remove ALL the plugs before wiring.

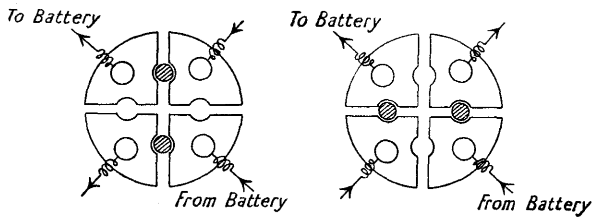


FIG. 138

Pohl's Commutator

Another important piece of apparatus used for reversing currents, and other purposes, is Pohl's commutator. This is shown diagrammatically in Fig. 139(A) and (B), in which A, B, C, D, E and F are pools of mercury connected by thick copper wire or strip to terminals mounted on a base board. AF and BE are joined by pieces of copper strip.

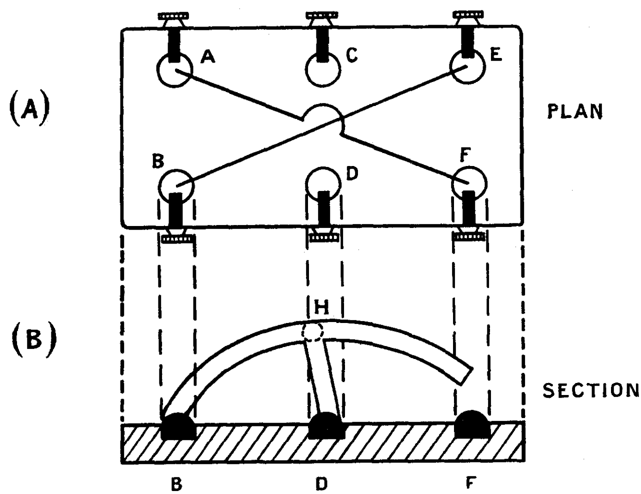


FIG. 139

Two bridges, made of copper, stand, as shown in the section (Fig. 139B), one with its central support in C and the other in D. They are connected by an insulating bar H. These bridges are not shown in the plan. If the commutator is to be used as a reversing key the part of the circuit in which the current is to be reversed is connected to B and F and the supply to C and D. The current can then be reversed by moving the bridges from one position to the other (see Fig. 140).

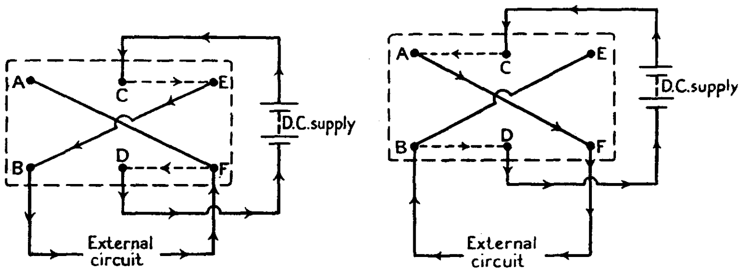


FIG. 140

Wiring it in this way ensures that there is no change in resistance in the circuit when reversal occurs—provided strips AF and BE are equal in resistance. If the outside circuit had been joined to A and B there would have been a change of resistance equal to the sum of the resistances of the strips AF and BE when reversal occurred.

Cleanliness is essential when using this commutator, as dirty mercury will give rise to inconsistent results.

Double-pole Double-throw Switches (*D.P.D.T.*)

If the copper strips AF and BE are removed the Pohl's commutator becomes a double-pole double-throw switch, so called because it can control two leads in two circuits. The terminals C and D can be introduced into a circuit connected to A and B, or to another circuit connected to E and F, at will.

Double-pole Single-throw Switches (*D.P.S.T.*)

This type of switch controls two leads of a single circuit and would be obtained if the terminals E and F of Pohl's commutator, shown in Fig. 140, were left unused.

Single-pole Double-throw Switches (*S.P.D.T.*)

This type of switch controls one lead in each of two circuits—serving the purpose of a two-way key. Again the diagram can be obtained from Fig. 140 if the terminals B, D and F are left unused; C can then be connected either to A or to E at will.

Single-pole Single-throw Switches (*S.P.S.T.*)

As its name implies this type of switch controls one lead of a single circuit, i.e. it is the equivalent of a plug key. Diagrammatically it could be obtained from Fig. 140 by leaving the terminals B, D, F and E unused.

It is not necessary to use the 'mercury pool' type of switch for any of the above four purposes, in fact the usual type consists of metal blades making contact with metal clips to which the terminals are connected.

Setting up a Circuit; Choice of Wires

When setting up a circuit observe the following instructions:

(1) Arrange the apparatus neatly and in such a way that any part which you will need to reach is readily accessible and near to where you will be sitting.

(2) Set the recording instruments so that the dials can be seen from your position so that *when you switch on they are all easily visible.* This enables you to switch off the current with minimum delay should there be anything wrong with the circuit, such as an instrument being overloaded or connected wrongly with respect to polarity.

(3) Remove the plugs from plug keys and the 'infinity' plugs from resistance boxes before starting the wiring.

(4) Give thought to the choice of leads. The following points should be borne in mind in this matter:

(i) Copper wire should always be used. Other materials, such as iron or nichrome, are used as 'specimens' in experiments, or for introducing definite resistances into a particular part of the circuit, but NEVER merely as connecting leads.

(ii) If the resistance of the leads will not matter use D.C.C. copper wire of S.W.G. about 24—provided that that gauge will carry the current required. It is worth remembering that the safe maximum currents quoted in most tables of data on wires can be exceeded by a wide margin (certainly several 100%) when the wire is fully exposed, as it is when used for leads. In fact copper wire of S.W.G. 24 has a carrying capacity suitable for practically all the experimental work described in this Part of the book.

(iii) If the resistance of the leads must be kept to a minimum—e.g. when introducing standard resistance coils to a Wheatstone's bridge circuit—use, for preference, copper strip, but if this is not available use D.C.C. copper wire of S.W.G. 16 or less. For this purpose use the shortest leads possible and, if thick copper wire is used, be careful to avoid subsequent movement of these leads, as they act as 'spanners' on the terminals and loosen the connections.

(iv) In some experiments—such as the Wheatstone's bridge work, or Post Office box—some leads should be of S.W.G. 24 and others of low resistance. It is convenient to remember that the resistance of copper wire of S.W.G. 24 is about 0·07 ohm per metre.

(v) If the magnetic effect of the current carried by the leads, must be eliminated, flex should be used. If this is not available twist the wires to be used together (they must of course be insulated).

(5) Having set out the apparatus and chosen the connecting wires, connect up the various circuits involved, checking each one independently before uniting the apparatus into one circuit. Make sure that all connections are 'good' by tugging at them. When wiring on to a terminal either make a loop in the bare end of the wire and slip it over the thread of the screw before putting on the nut, or else make sure that the wire passes round the thread in such a way that the nut tends to tighten the wire on the thread and not 'undo' it.

(6) When joining two wires use a terminal connector if one is available, otherwise twist the bare wires securely together. When joining two leads to the same terminal they should be twisted together before they are put on to the terminal. For permanent joints soldering should be used—see p. 54.

The Potentiometer

The essentials of a potentiometer are:

(i) a piece of uniform wire,
(ii) a source of constant e.m.f.

By uniform wire we mean one of which the resistance per unit length is constant—no matter how small a unit of length is considered. In the notation of the calculus this would be that dR/dl is constant where R represents resistance and l length. The source of constant e.m.f. is *always* a fully charged accumulator, or a battery of accumulators if conditions demand it (see below).

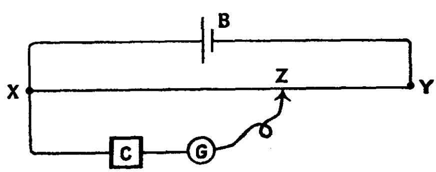


FIG. 141

In Fig. 141 the arrangement of a potentiometer circuit is shown. Here B is the source of constant e.m.f. and XY the uniform wire. Since the value of dR/dl is constant it follows from the usual mathematical expression for Ohm's law that the fall in potential per unit length of XY is also constant, i.e. dV/dl is constant, where V represents potential. In other words the p.d. between any two points on XY is proportional to their distance apart. Thus if the potential drop over the whole (or any known length) of XY were known, the e.m.f. of any subsidiary source 'C' could be determined, using the circuit shown in Fig. 141, by finding at what distance along the wire the sliding contact Z needed to be placed so that when contact was made the galvanometer G showed no deflection.

We cannot, however, assume a value for the e.m.f. of B to any high order of accuracy. The only cell of which the e.m.f. is known with the necessary accuracy is a standard cell (see p. 277) and such a cell must not be allowed to give more than a very small current, and that for very short periods. A standard cell can therefore only be used in position C and NEVER as the source of constant e.m.f. The details of the use of the standard cell for calibrating the wire in volts per cm. are given in Chapter XLVIII. Very often the wire can be used without it being calibrated, as many experiments are comparison experiments (these are given in Chapter XLVII). In such experiments two e.m.f.'s are compared by finding the positions of Z whereat zero deflection of the galvanometer occurs. If these are Z_1 and Z_2 then the ratio of the e.m.f.'s is XZ_1/XZ_2.

Detailed instructions which apply to individual potentiometer experiments will be found in the relevant parts of the text but the following practical considerations apply to all potentiometer work and should be applied in all such experiments:

(1) Make sure that the accumulator (or battery of accumulators) used at B is fully charged.

(2) Since the uniformity of the wire is important the contact between Z and the wire must always be light. NEVER PRESS THE SLIDING CONTACT ON THE WIRE. If a light touch is insufficient to indicate whether the balance point has been reached or not the remedy is to clean the sliding contact and the wire. If this is necessary the following method should be used:

(*a*) Clean the sliding contact with fine emery cloth.

(*b*) Clean the wire by gently rubbing it with a clean cloth followed by *very gentle* rubbing with fine emery cloth. Then remove the metal dust with a clean cloth. The wire of a potentiometer needs replacing at intervals but do not do this without permission and instruction.

(3) Set up the potentiometer circuit and the subsidiary circuit separately and test each individually before proceeding to the main part of the experiment. Introduce a voltmeter in series with the potentiometer circuit to test the BXY section, but test the subsidiary circuit by means of the shunted galvanometer (see notes on guarding the galvanometer in the preliminary stages, on p. 282).

(4) When both circuits are continuous unite them and test again by observing the direction of the deflection in the galvanometer when contact is made first at one end of XY and then at the other.

If these two deflections are in opposite directions the circuit is satisfactory, as a balance point can be found somewhere along XY.

If they are in the same direction one of several faults has occurred. First make sure that since the individual tests were made no break has occurred in either circuit. If they are both still 'good', shunt the galvanometer with a *very low* resistance—e.g. a short piece of copper wire of S.W.G. about 16. Now observe whether the deflection increases or decreases as Z is moved from X towards Y.

(i) If it increases as Z approaches Y the source of e.m.f. 'C' is connected the wrong way round. The simplest remedy is to reverse the poles of B. If C is a cell—as is usually the case—LIKE POLES of C and B should be joined to X. If the source C is a thermocouple

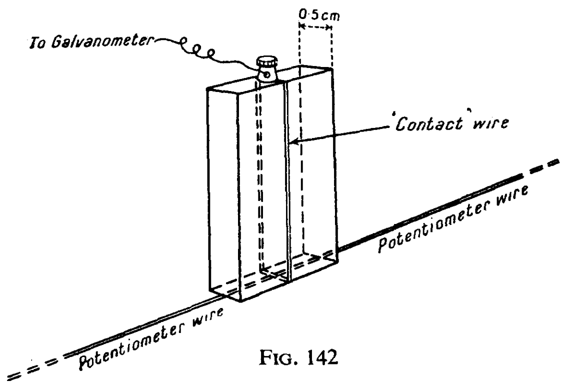


FIG. 142

for which the direction of the e.m.f. is unknown this test enables you to decide whether it is connected correctly or not.

(ii) A decrease in the amount of deflection as Z approaches Y indicates that the e.m.f. of B is less than that of C. This is corrected by increasing the number of accumulators, used at B, by an appropriate number.

(5) If inconsistent results are being obtained the explanation may be found in the production of contact potentials at Z due to the sliding contact and the wire being of dissimilar metals. This applies especially in experiments with thermocouples. It can be overcome by making a sliding contact by winding a piece of wire of the same material as that of XY round a strip of wood about 0·5 cm. thick. This is used in such a way that the two wires are at right-angles to each other when contact is made—as shown in Fig. 142.

'End Correction' for the Potentiometer

If great accuracy is sought with the potentiometer a correction should be made for the error which arises due to the resistance of the soldered joints between the wire XY and the terminals at each end. There are two ways to deal with this problem:

(1) Use two accumulators for B and find 'balance points' for each of two cells—e.g. a Leclanché cell and a Daniell cell—separately. Let these be distance l_1 and l_2 from X. Now connect the two cells in series and find the new balance point—let it be distance l_3 from X.

If l is the length of the wire which is equivalent to the resistance of the soldered contact at the end X then

$$l = l_3 - (l_1 + l_2).$$

The proof of this is as follows:

Let the potential drop per unit length of XY be k volts.
Then, if the e.m.f. of the first cell is E_1 and of the second is E_2,

$$E_1 = k(l_1 + l) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and $$E_2 = k(l_2 + l) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

When connected in series the equation for the cells is

$$E_1 + E_2 = k(l_3 + l) \quad . \quad . \quad . \quad . \quad . \quad (3)$$

A value of $E_1 + E_2$ can be obtained by adding equations (1) and (2).

i.e. $E_1 + E_2 = k(l_1 + l_2 + 2l)$.

Hence $k(l_1 + l_2 + 2l) = k(l_3 + l)$

$$\therefore \quad l = l_3 - (l_1 + l_2).$$

(2) The above method of finding the end correction is convenient only when two cells of different e.m.f. are already involved in the experiment. If this is not the case the best procedure is to eliminate the necessity for the end correction as follows:

Use two sliding contacts of the type shown in Fig. 142 and connect the source of e.m.f., C, to them, through the galvanometer, as shown in Fig. 143. Make contact with one of them (Z_1) a few cm. from X and find where the second one (Z_2) must be placed for the galvano-

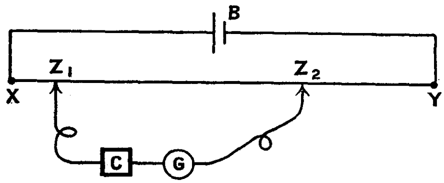


FIG. 143

meter to give no deflection. Observe the distance which they are apart (Z_1Z_2) and use this in your calculation instead of the length XZ. This method uses a length of the wire where soldering has not been carried out and eliminates contact potentials as well. It is rather a longer technique and in the elementary experiments such as 140 and 141, pp. 332–5, the usual method should be used. This refinement can be applied with advantage in experiments in which the wire is calibrated by use of a standard cell.

The Wheatstone's Bridge

If the circuit shown in Fig. 144 A is set up and the values of R_1, R_2, R_3 and R_4 adjusted so that on closing the key K the galvanometer shows no deflection then it can be shown (from Kirchhoff's laws) that

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}.$$

If any three of these resistances are known, the fourth can be determined.

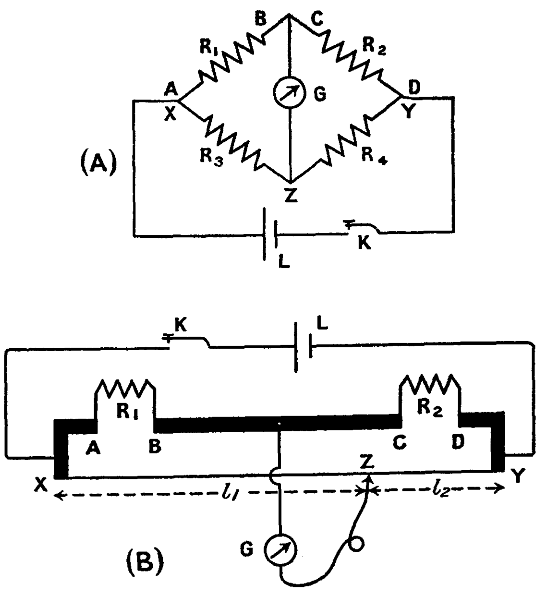


FIG. 144

This is known as the 'Wheatstone's Net Principle' and it finds many applications in electrical determinations. In experiments where the principle is used the 'net' which corresponds to the circuit used should always be drawn. The piece of apparatus that is most often used to apply this principle is known as the 'Wheatstone's Bridge'. The arrangement is shown in Fig. 144B where XY is a piece of uniform wire (i.e. dR/dl is constant—see p. 291) and A, B, C and D are terminals connected by copper strip as shown. R_1 and R_2 are connected across the gaps AB and CD, and the midpoint of BC is connected through a sensitive galvanometer to a sliding contact Z. A comparison of Figs. 144A and 144B will show that the portion of the wire XZ becomes R_3 and ZY becomes R_4. Hence when Z is placed so that G shows no deflection we have

$$\frac{R_1}{R_2} = \frac{\text{Resistance of XZ}}{\text{Resistance of ZY}}.$$

But since the wire is uniform the right-hand side of this equation is the ratio of the length XZ to the length ZY

$$\text{i.e.} \quad \frac{R_1}{R_2} = \frac{l_1}{l_2}.$$

Thus if either R_1 or R_2 is known, the value of the other resistor can be determined. The usual procedure is to make R_2 a standard resistance coil (see p. 287) so that R_1 can be determined to a high order of accuracy from

$$R_1 = R_2 \cdot \frac{l_1}{l_2}.$$

Although details vary from one experiment to another there are a number of considerations which are common to all Wheatstone's bridge experiments. The following notes should be studied before such experiments are attempted:

(1) The uniformity of the wire is just as important here as it is in the potentiometer and thus all the instructions relating to the wire about light touch with the sliding contact, and cleaning the wire, etc., apply with equal importance. Refer to general instruction (2) on the potentiometer given on p. 292 for details of these matters.

(2) An important difference between this apparatus and the potentiometer arises when the source of electric current is considered. There is no need here for a source of constant e.m.f. But it is not merely unnecessary to use an accumulator, it is undesirable, on account of its low internal resistance. The Leclanché cell is preferable as its e.m.f. is high enough to give the required sensitivity and its internal resistance is high enough to limit the current to a safe maximum.

(3) When the circuit is complete, test it by observing the deflection of the galvanometer when contact is made first at one end of XY and then at the other. If the circuit is wired correctly these deflections will be in opposite directions.

(4) When seeking the 'null' point the key K should be closed before contact is made with Z—this avoids deflections due to induction effects.

(5) If the balance point is not near the centre of the wire, i.e. for a metre bridge within 10 cm. of the midpoint, replace the standard resistance coil by one which has a value nearer to the unknown resistance (which will have been determined approximately by the position of the first balance point).

(6) For work of a high order of accuracy two other effects must be considered:

(i) Thermal effects may affect the deflections and hence the position of the null point. This can be eliminated by introducing a reversing key between the battery and the rest of the circuit so that balance points can be found with the current flowing in both directions. The thermal e.m.f.'s will act in the same direction in each case and thus a slight variation in balance point will be detected. The mean of the two positions is assumed to be a balance point which is independent of thermal effects.

(ii) Contact potentials may interfere with the results and these can be dealt with as in the case of the potentiometer by using a sliding contact made of the same material as the wire. For details refer to instruction (5), p. 293, and Fig. 142.

End Corrections for the Wheatstone's Bridge

As in the case of the potentiometer the resistances of the soldered contacts at the ends of the wire XY should be allowed for, if work of a high order of accuracy is being carried out. We saw that in the case of the potentiometer it was possible, by using two sliding contacts, to eliminate the necessity for finding the values of the corrections. This method is not applicable here for, although it is possible to design a circuit using the idea, the complication is too great, and as much accuracy would be lost in the process as it was hoped to gain by finding the correction. It is therefore necessary to *determine* the end correction for each end of the wire. There are two ways in which this can be done:

(1) Replace the unknown resistance by a standard resistance R_2 comparable with R_1 but not equal to it. Find the balance point. Let it be at distance x_1 from X and y_1 from Y.

Then

$$\frac{R_1}{R_2} = \frac{x_1 + l}{y_1 + l'}$$

where l is the length of wire equivalent to the resistance of the contact at X and l' is the length equivalent to the contact at Y.

Next interchange R_1 and R_2 (including their leads) and find the new balance point. Let the new values be x_2 and y_2.

Then

$$\frac{R_2}{R_1} = \frac{x_2 + l}{y_2 + l'}.$$

If we put R_1/R_2 equal to k (a known constant) these equations can be solved for l and l' as follows :

$$k(y_1 + l') = x_1 + l \quad . \quad . \quad . \quad \text{(i)}$$

and $$y_2 + l' = k(x_2 + l) \quad . \quad . \quad . \quad \text{(ii)}$$

Hence $$ky_1 + kl' = x_1 + l \quad . \quad . \quad . \quad \text{(i)}$$

and $$ky_2 + kl' = k^2x_2 + k^2l \quad . \quad . \quad \text{[Equation (ii) multiplied by } k\text{]}.$$

By subtraction $k(y_1 - y_2) = x_1 - k^2x_2 + l(1 - k^2)$

whence $$l = \frac{k(y_1 - y_2) + k^2x_2 - x_1}{(1 - k^2)}.$$

Similarly $$l' = \frac{k(x_2 - x_1) + k^2y_1 - y_2}{(1 - k^2)}.$$

All the quantities in the right-hand sides of these two expressions are determined in the experiment, hence the values of the corrections l and l' can be found.

(2) Use the wire XY as the uniform wire of a potentiometer circuit and proceed as in the first method of finding the end correction for the potentiometer wire, details of which are given on p. 293.

Two separate experiments must be performed—one for each end of the wire.

CHAPTER XLII

ELECTROCHEMISTRY

Experiment 118. Determination of the Electrochemical Equivalent of Hydrogen

Apparatus: 2-volt accumulator; ammeter (0–2 amps.); rheostat (0–10 ohms); plug key; stop watch; water voltameter.

A simple water voltameter is shown in Fig. 145. The electrolyte is water acidified with dilute sulphuric acid. Hydrogen and oxygen are liberated at the electrodes and are collected in graduated tubes. The electrodes (see Fig. 146) are of platinum connected to a mercury column by a platinum wire fused into the glass. The copper leads from the rest of the circuit dip into the mercury and are not allowed to make contact with the electrolyte.

Procedure: Arrange the apparatus as shown in Fig. 145 and connect it into the circuit shown diagrammatically in Fig. 147, in which

K is a plug key
B is the accumulator
A is the ammeter
R is the rheostat and
V is the voltameter.

Remove the graduated tubes, switch on the current and allow it to run for some time. Adjust the variable resistor R until a suitable steady current is flowing and bubbles of gas are being evolved at a moderate rate. When these adjustments are complete, switch off the current while the graduated tubes are filled and put in position. Switch on the current as soon as the apparatus is ready and start a stop-watch at the same moment.

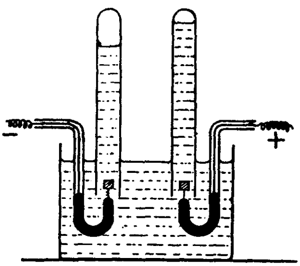


FIG. 145

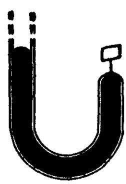


FIG. 146

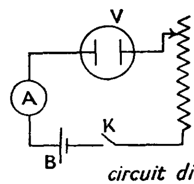


FIG. 147

Record the readings of the ammeter every half minute in order to ensure that a steady current is maintained throughout the experiment. If any appreciable variations occur, repeat the experiment, using a better supply. Continue until the hydrogen collected has driven the water level inside the tube down to that of the level of liquid outside it. Switch off the current and stop the watch simultaneously.

Observe the volume of the hydrogen—if the levels inside and outside the tube are not the same then make the necessary adjustment to obtain this condition before reading the volume. Observe the temperature in the neighbourhood of the experiment and the atmospheric pressure.

Record and Calculation: Tabulate the ammeter readings, and if necessary calculate a mean current.

Record all other observations.

Calculate the partial pressure of the hydrogen by subtracting the water vapour pressure (at the appropriate temperature) from the atmospheric pressure.

Calculate what volume the hydrogen collected would occupy at

S.T.P. and hence calculate its mass. At S.T.P. 1 ml. of hydrogen has a mass of 0·00009 gm. From the mean current and the time for which it flowed calculate the number of coulombs that liberated this mass of hydrogen.

Hence find the E.C.E. of hydrogen.

Notes: (1) No allowance has been made for the fact that some of the hydrogen evolved may dissolve in the water. This will not be a large source of error but it could be eliminated by using water which has been electrolysed for some time so that it had become saturated with hydrogen.

(2) If the volume of oxygen is observed a similar calculation for this gas can be carried out to find the E.C.E. of oxygen.

Experiment 119. Determination of the Electrochemical Equivalent of Copper

Apparatus: 6-volt battery of accumulators; ammeter (for range see instructions below regarding suitable current); 2 ohm rheostat capable of carrying the selected value of current; fuse rated at ammeter f.s.d.; plug key; copper voltameter with four electrodes; stop-watch.

A copper voltameter consists of a pair of copper electrodes dipping into a vessel containing a solution of copper sulphate acidified with dilute sulphuric acid. This electrolyte should contain about 150 gm. of pure sulphate per litre and should be acidified by adding, slowly, 25 ml. of concentrated sulphuric acid per litre. It should be reserved for voltameter work and not used in other experiments (e.g. in a Daniell cell) as it may become contaminated with other chemicals. The voltameter is usually provided with a double anode so that the cathode can be placed between the two anode plates as shown in Fig. 148.

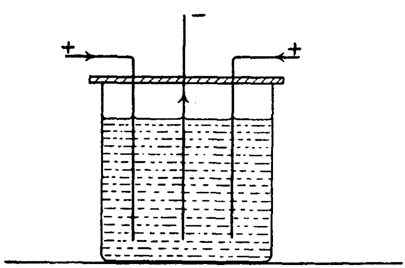


FIG. 148

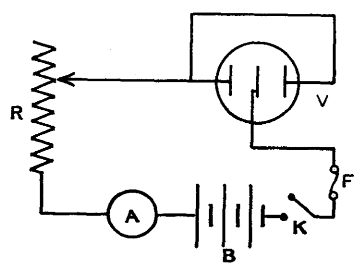


FIG. 149

To obtain a reliable result a deposit of copper which weighs between 1 and 2 gm. is desirable, and a current strength which will give such a deposit in a reasonable time should be employed. A current of 5 amp. is convenient, but in order to obtain a firm deposit it is essential to make the cathode of such submerged area that the 'current density' is not more than 0·02 amp. per $cm.^2$ of cathode surface, e.g., for a current of 5 amp. a total area of 250 $cm.^2$ is necessary. Remember that an electrode has two faces, and copper will be deposited on both.

Procedure: Set up the circuit given in Fig. 149 where
K is a plug key
B is a battery of three accumulators
A is an ammeter
R is a variable resistor
V is the copper voltameter
F is the fuse.

(F is introduced to guard the ammeter in the event of the electrodes accidentally being brought into contact.)

Introduce a 'test' cathode between the two anodes in V and fill to the correct level with electrolyte. Set R at its maximum resistance and close K. Adjust R until the required current is flowing, then switch off.

Clean the cathode to be used with fine emery cloth and finish with a clean duster. If the electrode is so contaminated as to make this method inadequate, proceed as follows (a perfectly clean cathode is essential):

If there are any greasy patches on it remove them by dipping for a few minutes in sodium hydroxide (caustic soda) solution. Wash well under the tap, dry, and then clean with fine emery cloth. Next dip it for about half a minute into dilute nitric acid, wash well under the tap, and finally dry with filter paper.

Weigh the cleaned dried cathode and then put it in the voltameter in place of the test cathode. Switch on the current and at the same instant start the stop watch. Keep a check on the constancy of the current, controlling it if necessary by means of R or, if the voltameter is of suitable design, by making slight variations in the separation of the electrodes.

After a suitable time has elapsed (i.e. when 1–2 gm. have been deposited) switch off the current and simultaneously stop the watch. Record the time for which the current was flowing, and then remove the cathode from the solution. Carefully dab it dry with filter paper (do not rub it) and then reweigh it.

Record and Calculation: Calculate the mass of copper deposited and the number of coulombs which were passed. Hence deduce the electrochemical equivalent.

Experiment 120. Calibration of an Ammeter, using a Copper Voltameter

Apparatus: As for the previous experiment (No. 119) except that the ammeter to be calibrated replaces the reliable ammeter—A in the circuit diagram, Fig. 149.

THEORY

The experimental procedure is similar to that in Experiment 119 but here the electrochemical equivalent of copper is assumed to be 0·00033 gm./coulomb and the current flowing is calculated from the mass of copper deposited in an observed time.

Procedure: Proceed as in Experiment 119, performing the experiment several times—once with nearly full-scale deflection on the ammeter, then about three-quarters f.s.d., then half f.s.d., and finally about quarter f.s.d.

Record and Calculation: Tabulate and record the results of each experiment as instructed in Experiment 119. Calculate the true current flowing in each experiment. Plot a graph showing the true current against the reading of the ammeter. This is the calibration graph. Sometimes it is preferred to plot a graph of correction against ammeter reading.

Note: This method is a tedious one. An alternative method which is rather quicker is described in Experiment 144, p. 340.

CHAPTER XLIII

MAGNETIC EFFECTS OF A CURRENT

Experiment 121. Investigation of the Magnetic Field Produced by a Current flowing in a Long Straight Wire, using a Deflection Magnetometer

Apparatus: Not less than 20 ft. (continuous) of copper wire S.W.G. 20–24. Supply of current capable of delivering a steady current of about 3 amp. for about an hour at an e.m.f. of six volts; rheostat of about 10 ohms, capable of carrying several amps.; ammeter, 0–3 amp.; plug key; reversing key; wooden stands; magnetometer box.

THEORY

The long straight wire when placed in the magnetic meridian and carrying a current I amp., will produce a field at right angles to the magnetic meridian of value $2I/10r$, where r is the distance from the wire to the point considered. If a deflection magnetometer box is placed r cm. vertically below the wire this will cause a deflection θ where

$$\frac{2I}{10r} = H_e \tan \theta \qquad . \quad . \quad . \quad . \quad (1)$$

H_e being the horizontal component of the earth's magnetic field.

In this experiment the value of r cannot be measured, as the glass top of the magnetometer box prevents access to the compass needle. If, however, the height, h, of the wire above the glass is measured the result can be obtained as follows:

Let d be the depth of the compass needle below the glass; then $r = h + d$.

Hence

$$\frac{2I}{10(h + d)} = H_e \tan \theta$$

which can be rewritten

$$\frac{I \cot \theta}{5H_e} = h + d.$$

Hence

$$h = \frac{I}{5H_e} \cot \theta - d \quad . \quad . \quad . \quad (2)$$

Thus, if two separate experiments are performed, the relationship between I and θ can be investigated by keeping h constant, and the relationship between h and θ can be investigated by keeping I constant.

For constant position, the graph of I against $\tan \theta$ should be a straight line (equation 1).

For constant current the graph of h against $\cot \theta$ should be a straight line and from its gradient and the value of I the magnitude of H_e can be deduced (see equation 2). The intercept on the h-axis is a value of d, though the points will not usually lie so close to a single line as to make this a very reliable intercept.

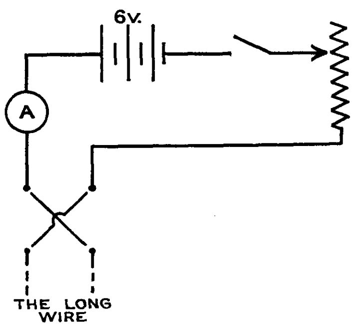


FIG. 150

Procedure: Set up the circuit shown in Fig. 150, using as great a length of wire for the 'long straight wire' as possible and in any case not less than six feet. Keep all the rest of the apparatus as far as convenient from the compass box so that stray magnetic fields in its vicinity are reduced to a negligible amount. A good arrangement is to put only the compass box in the middle of the table (see Fig. 151) with the wire, supported in wooden stands, passing over it, and to place the remainder of the apparatus on the floor just to one side of the table.

PART I. Adjust the magnetometer box so that the pointer reads zero. Set up the wire horizontally over the compass box and as near to it as possible. Employ an anti-parallax method, using the mirror of the compass box, to set the wire in the magnetic meridian.

Switch on the current and adjust the rheostat until a deflection of 60°–65° is obtained. Record the current and the reading of each end of the pointer. Reverse the current and record two more values of θ. Reduce the current slightly and take the four corresponding values of θ. Continue this process until the deflection is about 30°, taking about six separate values for the current.

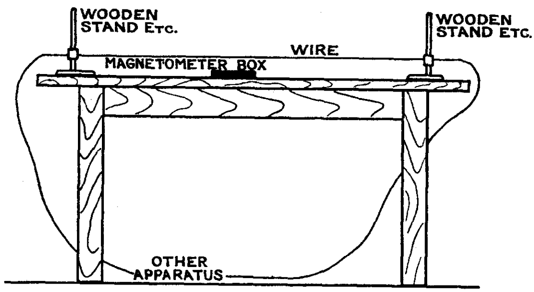


FIG. 151

PART II. Restore the current to its initial value. Measure h the distance of the glass of the magnetometer box below the wire.

Record the readings of the ends of the pointer. Reverse the current and record the new pointer readings. Raise the wire, keeping it horizontal, until the deflection has fallen to about 55°. Take pointer readings again for both directions of the current. Continue this process, recording for each position the value of h and the four pointer readings. Record the value of the current (I).

Record and Calculation: Record the observations in tables as under:

PART I.

Current (I) (amp.)	Pointer readings				Mean θ	Tan θ
	Direct		Reversed			
	(i)	(ii)	(i)	(ii)		

PART II. Value of current used = amp.

h (cm.)	Pointer readings				Mean θ	Cot θ
	Direct		Reversed			
	(i)	(ii)	(i)	(ii)		

Plot graphs of I against tan θ and of h against cot θ. These should be linear as explained in the theory paragraph. From the gradient of the second graph deduce a value for H_e. If in the second graph the points lie close to the straight line drawn, record the value of the intercept on the h-axis and consider whether it is a reasonable value for d.

Experiment 122. Determination of the Reduction Factor of a Tangent Galvanometer

Apparatus: Tangent galvanometer; ammeter (0–2 amps.); rheostat (0–10 ohms); 2-volt accumulator; plug key; reversing key.

THEORY

The magnetic field produced at the centre of the coil is given by

$$F = \frac{2\pi nI}{10a} \quad . \quad . \quad . \quad \text{(i)}$$

where F is the field strength in oersteds,
I is the current flowing in the coil in amperes,
a is the radius of the coil in cm. and
n is the number of turns used.

The direction of the field at the centre of the coil is at right-angles to the plane of the coil, and therefore if the coil be placed in the plane of the meridian, the field (F) due to the current will be acting at right-angles to the Earth's field (H_e). If θ is the angle of deflection of the magnet when a current is flowing through the coil, then

$$\frac{F}{H_e} = \tan\theta \quad . \quad . \quad . \quad \text{(ii)}$$

From (i) and (ii) we get

$$\frac{\pi nI}{5aH_e} = \tan\theta$$

or

$$I = \frac{5aH_e}{\pi n}.\ \tan\theta$$
$$= K.\tan\theta$$

where K is a value known as the *reduction factor* of the instrument. It must be remembered that this reduction factor depends upon the strength of the field in which the instrument is set—the reduction factor at one position in a laboratory is not necessarily correct for any other position.

Further, as

$$K = \frac{I}{\tan \theta}$$

if values of I are plotted against values of $\tan \theta$, a straight line should be obtained provided the magnetic field in which the instrument is set does not change during the experiment.

Since the instrument depends for its use on calculations of the tangents of the deflections, the considerations set out on pp. 245-6 apply here, and θ should not therefore be less than 25° nor more than 65°. Preferably it should be between 30° and 60°.

Procedure: (These instructions regarding the rating of the ammeter, the number of turns used, etc., relate to a coil of diameter about 15 cm.

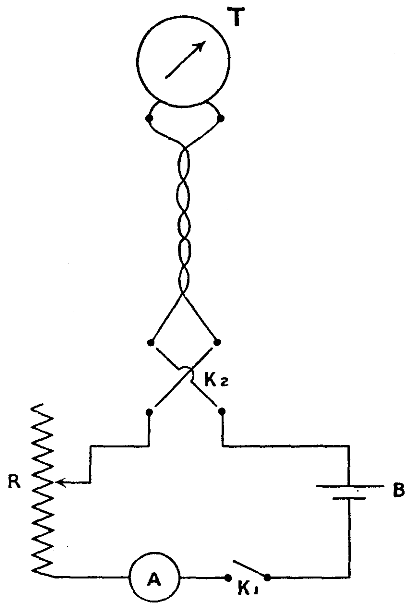


FIG. 152

If the galvanometer you use is of different dimensions these figures will need amending.) Set up the circuit shown in Fig. 152 in which

T is the tangent galvanometer with the flex connected to the terminals marked '2'—i.e. so that 2 turns are used—

K_1 is the plug key

R is the rheostat

A is the ammeter

K_2 is the reversing key

B is the accumulator.

The galvanometer must be so far from the rest of apparatus that the magnetic effects due to (i) the current flowing in R, etc., (ii) the ammeter magnet, are reduced to negligible amounts. This is why flex is used to introduce the galvanometer into the circuit—so that the resultant magnetic effect of the current flowing *to* the galvanometer is equal and opposite to that due to the current flowing *from* the galvanometer.

Rotate the galvanometer until the plane of the coil is in the magnetic meridian—the ends of the pointer should now read zero. Switch on the current and adjust R so that a deflection of about 30° is obtained. Record the pointer readings and the current (I). Reverse the current, check that its value has not altered and record the pointer readings again. Increase the current until the deflection has altered by about 6° and repeat the observations. Continue increasing the current step by step, taking four pointer readings for each value of I, and arranging that about six sets of observations are taken covering a range of deflections from 30° up to 60°.

Record the number of turns used. Measure the diameter of the coil.

Record and Calculation: Record the diameter of the coil and the number of turns used.

Tabulate the observations of I and θ as follows:

CURRENT in amps. (I)	POINTER READINGS				MEAN DEFLECTION (allowing for zero) (θ)	Tan θ
	END ONE		END TWO			
	"ZERO"=		"ZERO"=			
	(i)	(ii)	(i)	(ii)		

Plot I against tan θ and deduce a value for the reduction factor from the graph.

Calculate the reduction factor from the best set of observations and state the possible error of the answer.

Note: (i) The diameter of the coil was measured as it is required in the next experiment, the procedure for which is the same as in this one and for which the calculation can now be carried out using the results obtained above.

(ii) Refer to problem 90 on p. 489 to consider the field due to a coil at a point on its axis but not at its centre.

Experiment 123. Determination of the Horizontal Component of the Earth's Magnetic Field, using the Tangent Galvanometer

Apparatus: As for the previous experiment (No. 122).

THEORY

On p. 305 it was shown that the reduction factor (K) for the tangent galvanometer was given by the expression

$$K = \frac{5aH_e}{\pi n}.$$

The value of K has been determined experimentally by Experiment 122 and if this is substituted in the equation together with the measured values of a and n the value of H_e can be found.

Procedure: As in Experiment 122.

Record and Calculation: Record and tabulate the observations as for Experiment 122. Calculate the radius of the coil and the reduction factor of the instrument. Substitute to find a value for H_e.

Experiment 124. Calibration of an Ammeter, using a Tangent Galvanometer

Apparatus: As for Experiment 122, replacing the ammeter, A, by the one which is to be calibrated.

Procedure: Arrange the apparatus in accordance with the instructions given in Experiment 122 on pp. 305–7, setting it up at a place where the horizontal component of the Earth's magnetic field is known (see p. 262).

Carry out the observations in exactly the same way as described in Experiment 122.

Record and Calculation: Record all observations and tabulate the observations of current and deflection in a table similar to that given on p. 307.

From the formula $K = 5aH_e/\pi n$ calculate the reduction factor and use it to convert the values of $\tan \theta$ (in the last column of the table) into currents by the formula $I = K \tan \theta$.

Plot the ammeter readings against the calculated values of the currents. This is the calibration graph.

Note: This method of calibration depends on a knowledge of H_e. Another method (other than the tedious one of Experiment 120) is described in Experiment 144, p. 340. For purposes of standardising instruments the method of Experiment 144 should be used.

Experiment 125. Determination of the Resistance of a Tangent Galvanometer by the 'cot θ and R' Method

Apparatus: Tangent galvanometer; set of resistance coils of known values, 5–100 ohms, capable of carrying the necessary current; 2-volt accumulator; plug key; reversing key.

THEORY

The circuit to be used is shown in Fig. 154. Suppose that in this arrangement the e.m.f. of the accumulator is ε volts, its internal resistance is r ohms, the galvanometer has resistance G ohms and a standard resistance of R ohms is included. If then the current flowing is I amps. we have

$$I = \frac{\varepsilon}{R + r + G} = K \,.\, \tan \theta$$

where K is the reduction factor of the galvanometer.

Hence $$R + r + G = \frac{\varepsilon}{K} \cdot \cot \theta.$$

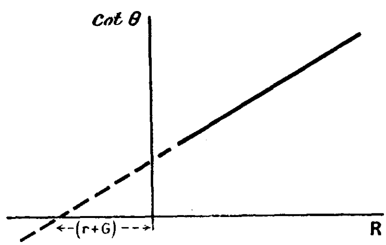


FIG. 153

Since in the experiment ε is maintained constant, the graph of R against cot θ should be a straight line (both r and G being also constants) as shown in Fig. 153. Thus, by plotting such a graph, a straight line is obtained, and a value for $(r + G)$ found from the intercept on the R-axis (it will be a negative intercept). If the galvanometer resistance is large compared with r—which it will be unless the tapping introducing the smallest number of turns is used—then this intercept may be taken as being almost equal to G, r being neglected.

Procedure: Set up the circuit shown in Fig. 154 in which

T is the tangent galvanometer, connected by using flex as usual

B is the 2-volt accumulator

K_1 is the plug key

K_2 is the reversing key

R is composed of the known resistances.

Use the tapping on the galvanometer which introduces 50 turns (most galvanometers have resistances of several ohms with this tapping).

Set the galvanometer with its coil in the magnetic meridian and record the readings of the ends of the pointer. Introduce a known resistance so as to make the deflection about 60°. The value required will probably be between 20 and 30 ohms. Record the pointer readings. Reverse the current and record the pointer readings again. Note also the value of *R*.

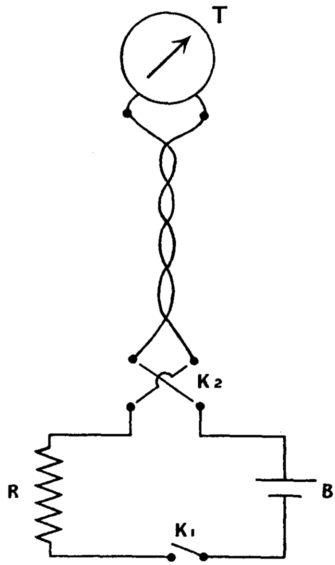


FIG. 154

Increase the value of *R* by about 10 ohms and repeat the operations above. Continue this process, using values of *R* up to about 90 ohms—the deflection will then be down to about 30°.

Record and Calculation: Tabulate the results as follows:

R (ohms)	POINTER READINGS				MEAN DEFLECTION (allowing for zero) θ	Cot θ
	END ONE		END TWO			
	"ZERO" =		"ZERO" =			
	(i)	(ii)	(i)	(ii)		

Plot cot θ against R and deduce the resistance of the galvanometer, assuming that the internal resistance of the accumulator can be neglected.

Note: If the reduction factor of the galvanometer is known—i.e. if the experiment is conducted at a place where the value for the horizontal component of the Earth's magnetic field is known—a value for the e.m.f. of the accumulator can be deduced from the gradient of the graph.

Experiment 126. Comparison of the e.m.f.'s of a Daniell Cell and an Accumulator by the Sum and Difference Method

Apparatus: Tangent galvanometer; Daniell cell (see p. 276); 2-volt accumulator; resistance box; plug key; reversing key.

THEORY

The deflection of the galvanometer needle is observed first when the cells are assisting each other (in series) and secondly when they are in opposition in what is otherwise the same circuit.

If their e.m.f's are ε_1 and ε_2 and the deflections corresponding to the e.m.f.'s $(\varepsilon_1 + \varepsilon_2)$ and $(\varepsilon_1 - \varepsilon_2)$ are θ_s and θ_d respectively, then, if the resistance of the circuit is the same in both cases,

$$\frac{\varepsilon_1 + \varepsilon_2}{\varepsilon_1 - \varepsilon_2} = \frac{K \tan \theta_s}{K \tan \theta_d}$$

whence
$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{\tan \theta_s + \tan \theta_d}{\tan \theta_s - \tan \theta_d}.$$

Procedure: Set up the circuit shown in Fig. 155 in which

T is the tangent galvanometer
R is the resistance box
K_1 is the plug key
K_2 is the reversing key
B is the battery formed of the accumulator and the cell.

Set the coil so that its plane is in the magnetic meridian and connect it into the circuit, using flex to keep it well away from the rest of the apparatus. Use the tapping which introduces 500 turns. Remove all the plugs from the resistance box (except the 'infinity' plug) and with the cells assisting one another (as shown in Fig. 155) switch on the current. Reduce the value of R until the deflection has risen to between 60° and 65°. Record the pointer readings. Reverse the current and record the pointer readings again.

Turn the Daniell cell round so that it opposes the accumulator and, keeping the value of R the same, record the pointer readings. Reverse the current and record the pointer readings again.

Record and Calculation: Record all observations. Calculate the mean values for θ_d and θ_s and substitute in the equation given above to find a value for the ratio of the two e.m.f's.

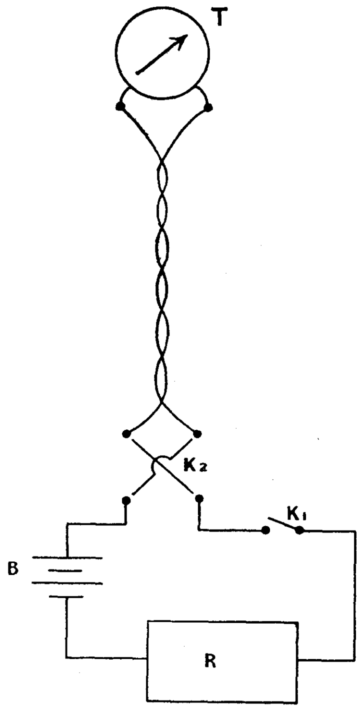


FIG. 155

Note: The experiment is sometimes set for a Daniell and a Leclanché cell. It is more difficult to obtain good results with these two cells, as the ratio of $(\varepsilon_1 + \varepsilon_2)$ to $(\varepsilon_1 - \varepsilon_2)$ is about 5 : 1 and there is considerable difficulty in obtaining deflections within the range for which the tangent galvanometer gives satisfactory accuracy. With the Daniell cell and the accumulator the ratio of $(\varepsilon_1 + \varepsilon_2)$ to $(\varepsilon_1 - \varepsilon_2)$ is only 3 : 1.

CHAPTER XLIV

ELEMENTARY METHODS FOR THE DETERMINATION OF RESISTANCE

Experiment 127. Determination of an Unknown Resistance by the Method of Substitution

Apparatus: 2-volt accumulator; rheostat (0–120 ohms) resistance box; milliammeter (0–20 mA.); tapping key; two-way plug key; the unknown resistance.

If the experiment is being performed for practice a suitable unknown resistance can be made by winding about 5 metres of eureka wire of S.W.G.26 on to a glass former. The winding should be non-inductive so that the result of this experiment can be confirmed by a 'bridge' method later.

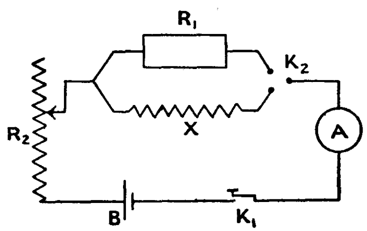


FIG. 156

Procedure: Set up the circuit shown in Fig. 156, in which

- X is the resistor of which the resistance is to be determined
- R_1 is the resistance box
- R_2 is the rheostat
- B is the accumulator
- K_1 is the tapping key
- K_2 is the two-way key
- A is the milliammeter.

Adjust R_2 to its maximum value and set K_2 so that X is included in the circuit. Depress the tapping key and alter R_2 until a reasonable current is flowing—i.e. a current of nearly 20 milliamps. Note the reading of the milliammeter.

Release K_1 and move K_2 so that R_1 is included in the circuit. Remove all the plugs except the infinity plug from the latter and close K_1. Adjust the value of R_1 until the same current is flowing as before. Record this value of R_1. Repeat the operations once or twice with different values of the current. The final value of R_1 which gives the same current as when X was in circuit is obviously the value of X.

Note: This method can be used for the determination of the resistance of an electrolytic solution contained in a glass tube about 3 cm. in diameter and 80 cm. long. Electrodes of the same metal as the positive radical of the electrolyte must be used, e.g. copper electrodes with copper sulphate. By varying the distance apart of the electrodes a graphical method can be applied to eliminate end error.

Experiment 128. Determination of the Internal Resistance of a Cell or Battery, using a Voltmeter

Apparatus: The battery: this can conveniently be a pair of NiFe cells connected in series by means of a 20 ohms radio-type resistor, thus creating an 'artificial' internal resistance; this battery will have an e.m.f. of about 2·6 volts. High-resistance voltmeter (0–3 volts); resistance box; tapping key.

THEORY

This experiment assumes that the voltmeter takes so small a current that this can be neglected. Let the e.m.f. of the cell be ε volts and its internal resistance r ohms. If when it is connected across a resistance of R ohms the p.d. across the latter is V volts and the current flowing is I amps., then

$$I = \frac{V}{R} \text{ and } I = \frac{\varepsilon}{R+r}.$$

Hence $$\frac{V}{R} = \frac{\varepsilon}{R+r}.$$

Thus $$r = R\frac{(\varepsilon - V)}{V}.$$

If we assume that the internal resistance of the cell is so small compared with the resistance of the voltmeter that the latter will record the e.m.f. of the cell when connected across its terminals, all the quantities in this equation except r can be determined experimentally.

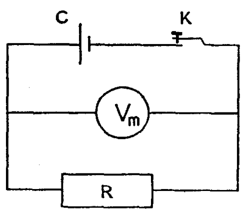


FIG. 157

Procedure: Set up the circuit shown in Fig. 157 in which
C is the cell
R is the resistance box
K is the tapping key, and
V_m is the voltmeter.

Remove the infinity plug from R, close K, and record the reading of V_m. This will be the e.m.f. of the cell (ε) since the latter is on open circuit.

Replace the infinity plug and remove the 100 ohm plug. Close K and record the voltmeter reading again.

Continue taking readings of V_m and R for various values of R down to 5 ohms.

Record and Calculation: Tabulate the results as follows:

R	Reading of Voltmeter	$(\varepsilon - V)$	$r=R\left(\frac{\varepsilon - V}{V}\right)$
∞	ε	—	—
100	V_{100}	$(\varepsilon - V_{100})$	$100\left(\frac{\varepsilon - V_{100}}{V_{100}}\right)$
etc.	etc.	etc.	etc.

Calculate the mean value of the last column.

Alternatively plot $1/R$ against $1/V$ and deduce the value of r from the graph.

Note: This experiment can, with profit, be followed immediately by No. 141.

Experiment 129. Determination of the Resistance of a Galvanometer

Apparatus: the galvanometer; two resistance boxes, one of about 10,000 ohms ($\times 1$ ohm) and the other of about 50 ohms (it must be slightly more than the resistance of the galvanometer) and capable of giving values at 1 ohm intervals, or better 0·1; accumulator, fully, but not freshly, charged; plug key; reversing key.

THEORY

The circuit to be used is shown in Fig. 158. R_1 is the high resistance which reduces the current through the galvanometer to safe values. If the f.s.d. of the instrument is about 0·5 mA the value given under 'apparatus' above will be suitable. If the instrument is more sensitive (for instance it may be a reflecting galvanometer of sensitivity 0·2 micro-amperes per cm. at 1 metre) then much higher values of R_1 will be required and radio type resistors can well be introduced into the circuit in place of R_1, as the exact value is not important. Thus for such a reflecting instrument a 1 Meg. and a 500 K.

would be suitable. The first step should be to calculate the order of magnitude of R_1 needed to protect the instrument. The f.s.d. of the galvanometer is usually marked on it, and this, though not always accurate, is near enough to serve as a guide.

The principle of the circuit is to obtain a deflection on G with K_2 open and then to cause the deflection to fall to half of this value by closing K_2 and adjusting R_2. When the adjustment is complete the value of R_2 will be the value of the galvanometer resistance, provided R_1 is very great compared with R_2—so that it can be assumed that the total current flowing is the same whether K_2 is closed or open.

Procedure: Set up the circuit shown in Fig. 158, using components suited to the galvanometer which is being investigated. Starting with R_1 at its largest value, close K_1 and observe the galvanometer reading.

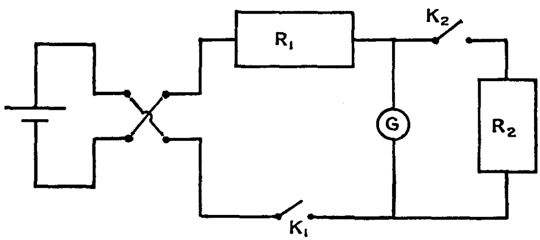


FIG. 158

If it is less than, say, a third of full-scale deflection adjust R_1 appropriately. Record the deflection and the value of R_1. Close K_2 and adjust R_2 so that the galvanometer reading is halved. Reverse the current and repeat. Open K_2 and by adjusting R_1 increase the deflection of the galvanometer and repeat the above operations. Continue this process until full-scale deflection is reached, taking about four sets of readings, so that a mean value of eight determinations of R_2 can be found.

Record and Calculation: Record *all* observations as follows:

R_1	Galvanometer reading θ (K_2 open)	$\theta/2$	R_2
	(direct)		
	(reversed)		

Calculate the mean value of the last column.

Note: It is often convenient to determine the sensitivity by the method of Experiment 152 p. 358, immediately this experiment is completed. The values given in Experiment 152 should be modified as necessary to suit the instrument being used.

CHAPTER XLV

APPLICATIONS OF THE WHEATSTONE'S NET PRINCIPLE

The Wheatstone's net principle is discussed on p. 295 and the more important practical aspects which apply to most of the experiments based on it are given. Before starting the experiments described in this chapter this general information should be mastered. The matter on 'end corrections' may be left for a time, as a knowledge of this subject will not be wanted until more accurate experimental work is attempted.

Experiment 130. Determination of an Unknown Resistance, using a Wheatstone's Bridge

Apparatus: The unknown resistance (if the experiment is being performed merely to gain experience the resistor used for Experiment 127 may be used, as its approximate resistance will be known from that experiment); Wheatstone's bridge; sliding contact (see p. 296); set of standard resistance coils; Leclanché cell; sensitive galvanometer with centre zero and an arrangement for varying its sensitivity as described on p. 282; tapping key.

Procedure: Set up the circuit shown in Fig. 159 in which

R_1 is the unknown resistance
R_2 is a standard resistance coil (or combination of several) which has a value near to that of R_1
K is the tapping key
L is the Leclanché cell
Z is the sliding contact which can be moved along XY
G is the galvanometer.

The arrangement for varying the sensitivity of the galvanometer is not shown but it should be used throughout the experiment in accordance with the instructions given on p. 282.

Close K and test the circuit by observing the direction of the deflection of the galvanometer needle when contact is made with Z first at X and then at Y. If the deflections are not in opposite directions there is a fault in your wiring. When the circuit is correct find the point on XY at which contact with Z can be made (when K is closed) without causing any deflection in the galvanometer. If this point is distant from the middle of XY by more than a tenth of the total length of XY, replace R_2 by another standard resistance coil to adjust the position of balance appropriately. Note the position of the balance point and

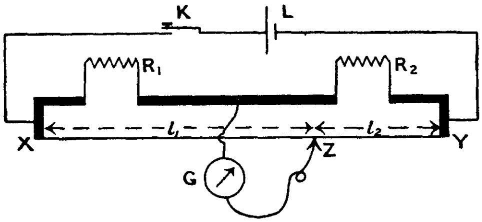


FIG. 159

the value of R_2. Interchange R_1 and R_2 and find the new balance point. Replace R_2 by another standard resistance coil of nearly the same value and repeat the operations.

If a high order of accuracy is sought, determine the end corrections to be applied to the observations by one of the methods described on pp. 297–8.

Record and Calculation: Tabulate your results and calculate a value for R_1 from each set of observations. Find the mean of these determinations.

Note: This is an experiment in which it is easy to determine the possible error. The length of XY through which Z can be moved without any deflection being produced in the galvanometer is twice the possible error of the reading. With a good galvanometer operating at full sensitivity a balance point on a metre bridge should be found to within 1 millimetre.

Experiment 131. Demonstration of the Principle of the Post Office Box by Constructing one from its Components

Apparatus: Resistance box, preferably dial type, giving values up to 1,000 ohms by 1 ohm intervals; two 1 ohm, one 10 ohm and one 100 ohm resistance—all wire wound radio-type of 1% accuracy; centre-reading galvanometer with sensitivity control; Leclanché cell; two tapping keys; unknown resistance of value about 20 ohms.

THEORY

First study carefully the theory of the Wheatstone's net (see pp. 295–299) and read the theory section of the next experiment (132). This experiment is intended to emphasise the fact that the P.O.B. is only a Wheatstone's net in a box. Often the P.O.B.'s are made with terminals labelled so that a determination of resistance can be made and the user remain quite ignorant of the principle involved. It cannot be too strongly emphasised that the P.O.B. must always be thought of as a *net*; and the net itself should be pictured as four resistances joined in series to form a closed circuit shaped like a 'diamond' or a 'kite'. Across the diagonals of this kite (i.e. along its 'sticks') are connected a battery and a galvanometer, each provided with a tapping key. See Fig. 160A.

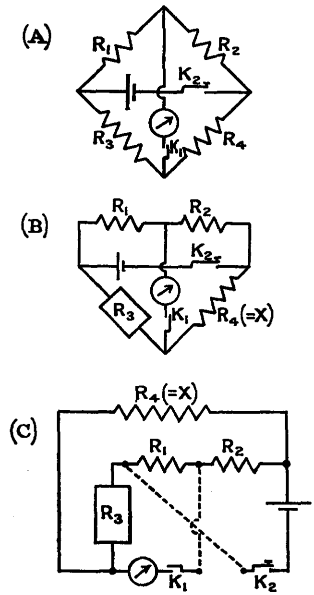


FIG. 160

The ratio-arm of the home-made P.O.B. used here consists of the wireless-type resistors, used in pairs so as to give in turn 1:1, 1:10 and 1:100 ratios. These are R_1 and R_2 in the figures 160, A, B and C. The resistance box forms the rheostat arm, R_3. Thus the net shown in Fig. 160A will become the circuit shown in Fig. 160B.

To see how the conventional P.O.B. shown in Fig. 161B follows from these circuits, we can redraw Fig. 160B as shown in Fig. 160C. If then R_1, R_2 and R_3 are enclosed in a single box, and tapping keys are fitted with concealed leads as shown by dotted lines, then the arrangement shown in Fig. 161B follows. But the reader should understand that all five diagrams are of the SAME circuit.

Procedure: Make the first ratio arm by joining the two 1-ohm radio resistors in series. Connect this in series with the resistance box, R_3, and the unknown resistance, $X(=R_4)$, forming the 'kite'. Across one diagonal of this circuit connect the cell with its tapping key, and across the other one the galvanometer with its tapping key. Make sure the contact points of the keys are clean (use emery cloth if necessary).

Set R_3 at zero and with the galvanometer shunt included to reduce its sensitivity, momentarily close K_1 and K_2. Note the direction of the deflection.

Set R_3 at its highest value and repeat; if the circuit is correctly wired up, the deflection should be in the opposite direction.

Next adjust R_3 so that on closing the tapping keys no deflection occurs. Remove the sensitivity control from the galvanometer and make final adjustments to R_3 to obtain as accurate a setting for its balance value as can be found with the 1:1 ratio. The value of R_3 is now equal to the unknown resistance to the nearest ohm. This value should be recorded.

Now the ratio arm should be changed to give a value of 10:1, using the 10-ohm resistor, and R_3 should be increased to ten times the value determined in part (i). With the sensitivity of the galvanometer reduced, find a balance value for R_3, and then repeat with full sensitivity restored. Record this value.

Finally, repeat the operations with a ratio of 100:1.

Record and Calculation: Tabulate your observations, giving the values of the ratio and the values obtained for R_3 when the galvanometer gave no deflection. The value of the unknown resistance can be stated to two places of decimals by considering the final determination. It is likely, however, that the sensitivity of the adjustment will not support such accuracy, as it may be found that no deflection is detectable for a range of values of R_3, e.g. 2,230 ($\pm$ 5) ohms. This would lead to a result 22·30 ($\pm$ 0·05) ohms, which could be written 22·3 ohms.

Experiment 132. Determination of an Unknown Resistance, using a Post Office Box

Apparatus: The resistor of unknown resistance; Post Office box (see further notes on this below); sensitive galvanometer with centre zero, and an arrangement for varying its sensitivity as described on p. 282; Leclanché cell.

THEORY

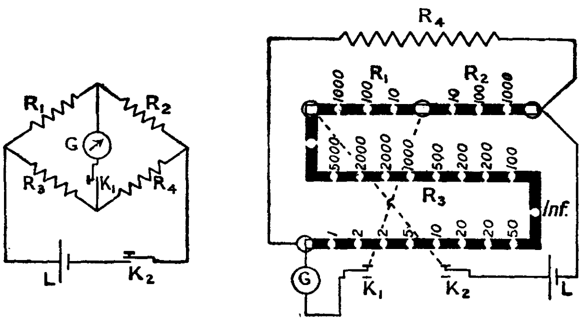
A Post Office box is an arrangement in which three of the arms of a Wheatstone's net are included in one instrument. Two of the arms are the ratio arms and the other is a resistance box usually called the rheostat arm. Fig. 161 illustrates the arrangement diagrammatically and also shows the conventional diagram.

The arms R_1 and R_2 are so arranged that the removal of the plugs inserts resistances of 10, 100 and 1,000 ohms so that $\frac{R_1}{R_2}$ can be made to assume the values $\frac{1}{100}$, $\frac{1}{10}$, 1, 10 or 100.

The keys K_1 and K_2 are connected as shown by the broken lines.

The rheostat arm has resistances usually from 1 to 5,000 ohms and also a gap which inserts an air gap (resistance = infinity).

Procedure: Examine the Post Office box which you will be using and if it is different from the one illustrated in Fig. 161 work out the equivalent Wheatstone's net and, after wiring the circuit, have it checked. Make R_4 the unknown resistance and control the sensitivity of the galvanometer as instructed on p. 282. When the circuit is ready remove the 10-ohm plugs from the ratio arms (R_1 and R_2) and the infinity plug from the rheostat arm (R_3). Depress the battery key and THEN the galvanometer key momentarily; release the battery key AFTER the galvanometer key. Note the direction of the deflection.



[A] FIG. 161 [B]

Replace the infinity plug and repeat the operations to observe the new direction of the deflection. If this is not in the opposite direction to that obtained with the infinity plug removed, there is a fault in the circuit. Trace the fault and test again.

When the circuit is correctly wired find the value of R_3 for which the galvanometer shows no deflection when the keys are depressed in the way described above. Adopt an orderly method of removing the plugs from R_3. Since for this part of the experiment $R_1 = R_2$ this value of R_3 will be the value of the unknown resistance to the nearest ohm. Using this knowledge, select a value for the ratio R_1/R_2 which will enable the most accurate determination of R_4 to be made. Remove the appropriate plugs from the ratio arms and find what value of R_3 is needed to give no deflection in the galvanometer when the keys are depressed. Determine the possible error by noting through what range of values R_3 can be varied without the galvanometer showing any deflection.

Record and Calculation: Record your final value for R_3 and the values of the ratio arms. Hence calculate the value of the unknown resistance together with the possible error.

Notes: (1) Dial boxes (see p. 286) are commonly used in industrial laboratories and you should, if possible, carry out a determination using one.

(2) Another device for increasing the sensitivity of the Post Office box is to replace the Leclanché cell by a 9-volt grid bias battery. This means that in positions other than those of balance more current flows through the galvanometer and the method is correspondingly more sensitive. This is a valuable method when high resistances are to be determined.

Experiment 133. Determination of the Resistance of a Galvanometer, using a Post Office Box

Apparatus: The galvanometer (no sensitivity control can be used here); resistance box (up to at least 10,000 ohms); Post Office box; Leclanché cell.

THEORY

If the Wheatstone's net shown in Fig. 162 were set up, it is evident that there would always be a deflection recorded by G so long as K_2 were closed. On closing K_1 as well there would normally be a change in the deflection due to the passage of current along BC. If the resistances of R_1, R_2 and R_3 were such that the potential of B equalled that of C no current would flow along BC on closing K_1, and the galvanometer would show no change in deflection. This is the method employed here and though it cannot be called a 'null' method it is as good as one and may be thought of as a method of 'NO CHANGE' in deflection. When this condition is realised

$$\frac{R_1}{R_2} = \frac{R_3}{G},$$

where G is the resistance of the galvanometer.

Thus if the three resistances R_1, R_2 and R_3 are known G can be calculated.

The Post Office box circuit, which is equivalent to the 'net' shown in Fig. 162, is given in Fig. 163. If your box is similar to the one shown, try to invent the circuit diagram for the box before examining Fig. 163. To ensure that a deflection to about half full-scale is obtained the high resistance R is placed in series with the cell.

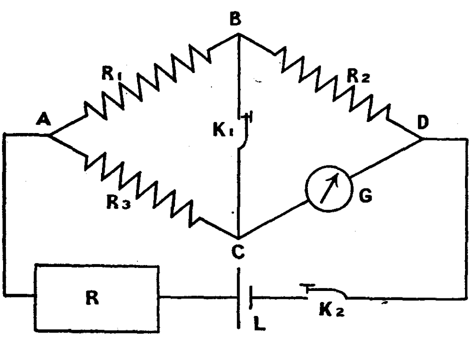


FIG. 162

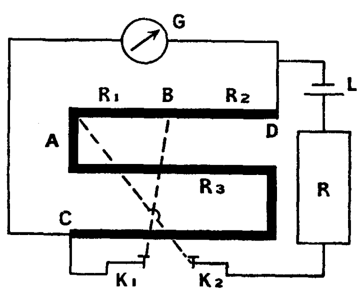


FIG. 163

Procedure: Set up a circuit similar to that given in Fig. 163 in which
L is the Leclanché cell
R is the resistance box
G is the galvanometer of which the resistance is required.

To obtain satisfactory results the reflecting system of the galvanometer should be used, if it has one, otherwise arrange a lens so that the pointer can be observed through it. Information on setting up reflecting galvanometers will be found on p. 284.

Remove the 10-ohm plugs from the ratio arms (R_1 and R_2) and adjust the value of R until the galvanometer gives about half-scale deflection when K_2 is closed.

Check the circuit by making sure that the change in deflection of the galvanometer is in opposite directions when $R_3 = 0$ and when $R_3 = \infty$.

Now find the value of R_3 for which there is no change in deflection of the galvanometer when K_1 is closed (K_2 being kept closed).

Sometimes it is possible to alter the value of the ratio arms so that a 10 : 1 ratio can be used, but this depends on the instrument being investigated.

Record and Calculation: Record the value of R_3 which was found in the last part of the experiment and the values of the ratio arms. From these calculate the resistance of the galvanometer by the method given in the theory above.

Notes: (1) This method can be used to find the resistance of any ammeter or voltmeter. If a microammeter is being investigated, great care should be taken to ensure that R is large enough to keep the current down to a suitable value.

(2) A Wheatstone's bridge can be used for this experiment—the circuit diagram follows directly from the 'net' given in Fig. 162.

Experiment 134. Determination of the Internal Resistance of a Cell, using the Post Office Box (Mance's Method)

This experiment is similar to the previous one except that the battery and the galvanometer are interchanged. This means that the high resistance R is now in series with the galvanometer. The method is again a 'NO CHANGE in deflection' method. The theory and procedure are the same.

Experiment 135. Determination of the Resistivity of the Material of a Wire

Apparatus: A length of uniform wire of which the resistivity is required—this should be such that its resistance is at least 10 ohms, thus 2 metres of insulated Manganin, S.W.G. 30 would serve, and there are available special high-resistance alloys which with similar gauge will give resistances of about 20 ohms per metre. Apparatus for determining resistance—either Wheatstone's bridge and accessories (see Experiment 130) or Post Office Box and accessories (see Experiment 132). Micrometer screw-gauge.

THEORY

The resistivity or specific resistance of a material is the value of the constant ρ in the equation

$$R = \frac{\rho l}{A}$$

where A is the area of cross-section of the wire in cm.^{2},
l is the length of the wire in cm.
and R is the resistance in ohms of this length of wire.

Thus, if a range of five or six different lengths is used and their resistances determined, a graph of R against l can be plotted. This should be a straight line passing through the origin and having a gradient of value ρ/A. From this gradient and a knowledge of A the resistivity can be deduced.

Procedure: Determine the resistance of the greatest length of wire available by the method selected. This done, press the wire upwards at each terminal to make a right-angle kink in it and then remove the wire and measure the distance between these kinks, which will be the length of which the resistance was determined. Introduce a shorter length of wire into the circuit and repeat. Do this about six times, covering as wide a range of resistances as can reasonably be determined by the method chosen. If a bridge is used, the value of the standard resistance should be changed as the experiment proceeds, in order to keep the balance point near the middle of the bridge wire.

Finally, remove the insulation in several places along the wire and measure the diameter with the micrometer screw-gauge.

Record and Calculation: Tabulate your observations in a way appropriate to the method chosen. Hence, obtain a table of corresponding values of length and resistance. Record also the micrometer readings, and from them calculate the area of cross-section of the wire.

Plot a graph of R, as ordinate, against l and determine its gradient. Multiply the latter by the area of cross-section to obtain the resistivity.

Experiment 136. Determination of an Unknown Resistance, using a Carey Foster Bridge

Apparatus: Carey Foster Bridge—this is similar to a Wheatstone's bridge except that it has four 'gaps' in it instead of two; a standard 1-ohm coil; two standard coils of equal resistance (2-ohm coils will serve very well); Leclanché cell; tapping key; sliding contact—preferably of the type described on p. 293 and illustrated in Fig. 142;

sensitive galvanometer with centre zero and sensitivity control as described on p. 282; the unknown resistance and a standard resistance coil of almost the same value.

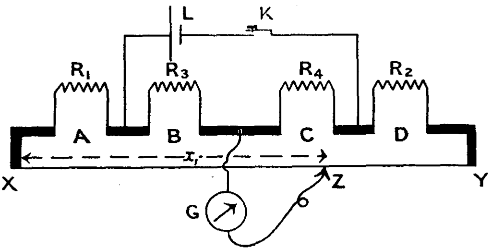


FIG. 164

THEORY

The accuracy of the normal wire bridge is limited by the shortness of the wire. Wires longer than 1 metre are inconvenient. The Carey Foster bridge achieves an artificial lengthening of the wire by the arrangement shown in Fig. 164.

Here R_1 is the unknown resistance and R_2 the known resistance, and both effectively form part of the wire used in determining a balance point. If R_3 and R_4 are equal and a balance point is obtained at x_1 cm. from X then

$$\frac{R_1 + (x_1 + l)r}{R_2 + (100 - x_1 + l')r} = \frac{R_3}{R_4} = 1 \quad . \quad . \quad . \quad . \qquad \text{(i)}$$

where l and l' are the end corrections (see p. 297) in cm. and r = resistance per cm. of the wire.

If now R_1 and R_2 are interchanged, and a new balance point at x_2 obtained, then

$$\frac{R_2 + (x_2 + l)r}{R_1 + (100 - x_2 + l')r} = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad \text{(ii)}$$

Equation (i) may be written

$$R_1 + rx_1 + rl = R_2 + 100r - rx_1 + rl'$$

and equation (ii) reduces to

$$R_2 + rx_2 + rl = R_1 + 100r - rx_2 + rl'.$$

By subtraction we obtain

$$R_1 - R_2 + r(x_1 - x_2) = R_2 - R_1 + r(x_2 - x_1)$$

i.e.
$$2(R_1 - R_2) = 2r(x_2 - x_1)$$

$$\therefore \quad R_1 = R_2 + r(x_2 - x_1) \quad . \quad . \quad . \quad . \quad . \qquad \text{(iii)}$$

Three facts are of importance in this equation:

(i) The values of R_3 and R_4 do not appear in it and do not need to be known PROVIDED THEY ARE EQUAL.

(ii) The end corrections do not appear in it and therefore need not be determined in the experiment.

(iii) The resistance per cm. of the wire must be determined. This is usually made the first part of the experiment and can be done by making use of the result proved above provided R_1 and R_2 are in this case known. Usually R_1 is replaced by a standard 1-ohm coil (or one of lower resistance if the wire requires it) and R_2 is reduced to zero by means of a shorting strip of copper. If under these conditions a balance point is obtained at x cm. from X with the 1-ohm coil in gap A and at x' cm. from X when it is in gap D (gap A being then 'shorted'), then by substituting in equation (iii) we obtain

$$1 = 0 + r(x' - x)$$

$$\therefore \quad r = \frac{1}{(x' - x)} \text{ ohms per cm.}$$

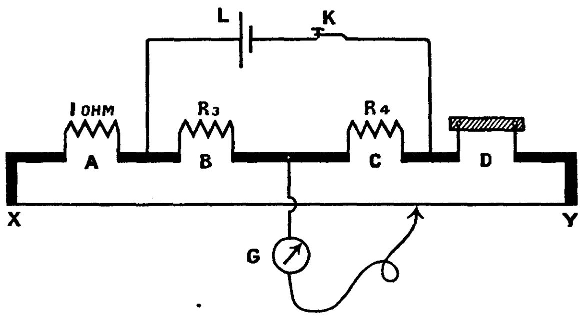


FIG. 165

Procedure: Set up the circuit given in Fig. 165 where

R_3 and R_4 are the equal standard coils

K is the tapping key

L is the Leclanché cell

G is the galvanometer. The sensitivity control is not shown but it should be used as instructed on p. 282.

The shorting strip should have short thick leads as shown. Use this circuit to determine the resistance per unit length of the wire (r ohms/cm.) as follows:

Find the balance point (x cm. from X).

Interchange the shorting strip and the 1-ohm coil but DO NOT INTERCHANGE THEIR LEADS (this is the reason for including leads with the shorting strip, as if this were not done the 1-ohm coil could not be introduced across the gap D). Find the new balance point (x').

Now remove the shorting strip from gap A and introduce the unknown resistance R_1. Replace the 1-ohm resistance in gap D by the standard resistance coil R_2 which must be of nearly equal value to R_1 (i.e. of such a value that the balance point is within 20 cm. of the centre of the wire if it is a metre bridge). The circuit should now be that shown in Fig. 164.

Determine the balance point (x_1 cm.).

Interchange R_1 and R_2 without moving the leads and find the new balance point (x_2 cm.).

Record and Calculation: Record all your observations.

Calculate the value of the resistance per centimetre of the wire and substitute this and the other necessary values in the equation (iii), above, to find the value of the unknown resistance.

CHAPTER XLVI

THE VARIATION OF RESISTANCE WITH TEMPERATURE

Experiment 137. Investigation of the Relationship between the Resistance and the Applied Voltage for an Electric Lamp

Apparatus: 12-volt 18-watt car headlamp bulb; rheostat (0–30 ohms) capable of carrying 2 amps.; voltmeter (0–15 volts); ammeter (0–2 amps.); switch ; 16-volt supply—if this is A.C. make sure that instruments designed to measure A.C. are used (see p. 286).

THEORY

Ohm's Law is only true if the temperature of the conductor through which the current is flowing remains constant. As the current passed by the filament of the lamp increases, the temperature rises and thus a graph of applied voltage against current flowing will not be a straight line. The departure from the linear relationship between current and voltage when the temperature varies can thus be demonstrated by this experiment.

Procedure: Set up the circuit shown in Fig. 166 in which:

L is the lamp
V is the voltmeter
A is the ammeter
R is the rheostat
and K is the switch.

Adjust R until it has its maximum value and switch on the current. Note the readings of A and V. Reduce R by suitable amounts so that a series of corresponding values of current and potential difference for the lamp is obtained. It is safe to 'over-run' the lamp for short periods so that higher temperatures than those at which it would normally operate can be investigated. In selecting the values of the current for which to observe the p.d. remember that the temperature changes considerably before the filament begins to glow and therefore several readings should be taken in that range.

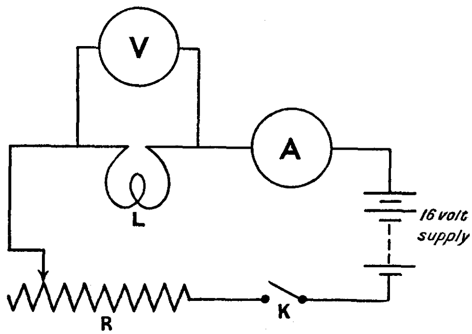


FIG. 166

Record and Calculation: Tabulate the observations as follows:

Current in amps (I)	p. d. in volts (V)	Resistance in ohms $= \frac{V}{I}$	Power in watts (VI)

Plot a graph of I against V and on the same axes plot a graph of resistance against V.

Discuss the results.

Plot the power dissipated (in watts) against volts, making the latter the abscissae. Discuss the result.

Experiment 138. Investigation of the Effect of the Temperature on the Resistance of the Filament of (i) a Metal Filament Lamp and (ii) a Carbon Filament Lamp

Apparatus: 240-volt, 15-watt metal filament lamp; 240-volt, 16-watt carbon filament lamp; standard B.C. lamp holder; variable resistor (0–1,500 ohms) capable of carrying 0·3 amps; A.C. voltmeter (0–240 volts); A.C. ammeter (0–0·3 amps.); switch.

THEORY

This is an extension of Experiment 137 and investigates the same phenomenon. In most cases the resistance of a material increases with rising temperature but this is not so with carbon, which is said to have 'a negative characteristic' of resistance. This is demonstrated by comparison with a metal filament lamp which has the usual positive characteristic.

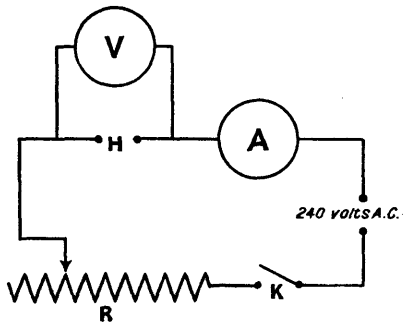


FIG. 167

Procedure: Set up the circuit shown in Fig. 167 in which
H is the lamp holder
V is the voltmeter
A is the ammeter
R is the rheostat
K is the switch.

Place the metal filament lamp in the holder, adjust R to give its maximum resistance and switch on the current. Remember that 240 volts A.C. is being used and that care should therefore be taken not to touch any uninsulated parts of the circuits whilst the switch is closed.

Note the readings of A and V. Reduce R by suitable amounts and obtain a series of readings of A and V, covering as wide a range as the meters allow. Be careful to cover the low-temperature part adequately.

Replace the lamp by the carbon lamp and repeat the operations.

Record and Calculation: Tabulate the observations as follows:

METAL FILAMENT LAMP			CARBON FILAMENT LAMP		
CURRENT in amps (I)	P.D. in volts (V)	RESISTANCE in ohms ($= V/I$)	CURRENT in amps (I)	P.D. in volts (V)	RESISTANCE in ohms ($= (V/I)$)

Plot graphs of resistance (as ordinates) against volts for each lamp. Plot these on the same axes with the scale of voltage common but a different scale for resistance—this enables the results to be more clearly seen.

Discuss the results.

Experiment 139. Determination of the Coefficient of Increase of Resistance with Temperature

Apparatus: ICE—this is not essential but is an advantage; Wheatstone's bridge; Leclanché cell; tapping key; sensitive galvanometer with centre zero and sensitivity control (see p. 282); water bath—or better a bath of liquid of much higher boiling point, such as glycerine or engine oil; thermometer of suitable range.

The coil of wire, of which the resistance is to be investigated, should be wound non-inductively, i.e. the length of wire to be used should be 'folded' in two and then wound on to an insulating core. Thick copper leads should be soldered to it and it should then be fixed into a boiling tube together with the thermometer. If platinum wire is available in sufficient quantity, or nickel, these are excellent. If these are not to hand, copper will serve, if only the range 0°–100°C is to be investigated. About 20 metres of D.C.C. copper wire of S.W.G. 36 will provide a resistance of about 10 ohms which is the order of magnitude required. When the coil is made, select a standard resistance coil of a comparable value for use with it in the Wheatstone's bridge.

THEORY

Experiments 137 and 138 demonstrated the variation of resistance with temperature. The quantitative relationship which exists is of the form

$$R_t = R_0(1 + \alpha t + \beta t^2)$$

where R_t is the resistance at t°C,
R_0 is the resistance at 0°C
and α and β are constants.

In some cases the value of β is so small compared with that of α that the term βt^2 can be neglected if a limited range of temperature is considered. The equation then reduces to

$$R_t = R_0(1 + \alpha t)$$

and α is known as the 'coefficient of increase of resistance with temperature' for the material considered. For metals α is positive but, as Experiment 138 demonstrated, for carbon it is negative.

A set of results for this experiment is given on pp. 34–5 and some discussion of graphs is given. It should be noted that the drawing of a straight line through the observations of R_t and t, when graphed, is an assumption of the linear relationship, i.e. of the fact that βt^2 may be neglected. The deduction of α from the graph involves first the determination of R_0 because the value of the gradient is $R_0\alpha$.

Procedure: Set up the circuit shown in Fig. 168, in which

L is the Leclanché cell
K is a tapping key
R is the standard resistance coil
G is the galvanometer
C is the coil of which the resistance is being investigated
L′ are compensating leads.

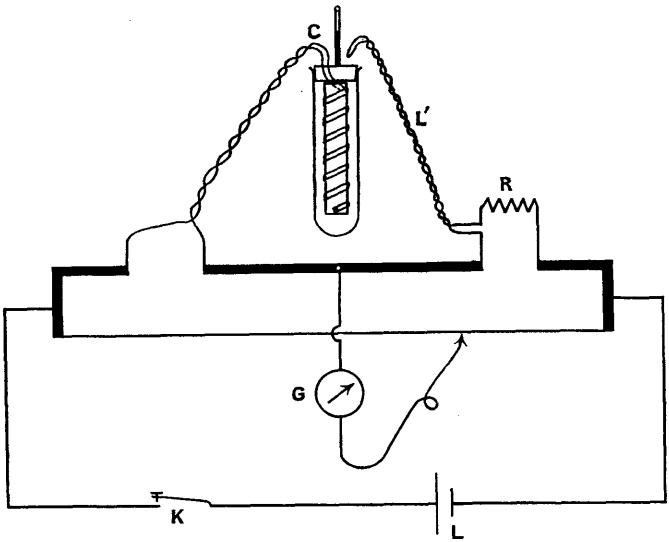


FIG. 168

Connect C into circuit by 5-amp. flex, and cut an equal length of flex to serve as the compensating leads. Without such leads the error in determining the resistance of the coil will be at least equal to the resistance of its leads, and this error will rise as the temperature rises. The use of L′ reduces this error considerably provided the balance point remains near the centre of the slide-wire throughout the experiment. The ends of L′ near C should be joined together—NOT connected to C.

If ice is available surround C with melting ice and determine the resistance of the coil by the usual Wheatstone's bridge method (see pp. 317–18) but do not interchange R and C to obtain a check on your readings.

Next surround C with whatever bath is to be used and make a series of determinations of the resistance of the coil at a number of temperatures, covering as wide a range as possible.

Record and Calculation: Tabulate the results as follows:

t (°C)	R (ohms)	l_t (cm.)	$(100-l_t)$ (cm.)	$R_t = \frac{l_t}{100-l_t} \cdot R$

Plot R_t against t and deduce a value for α from the graph.

If a reading was taken in melting ice the more accurate method of finding α is to use the formula

$$\alpha = \frac{R_{100} - R_0}{100R_0}.$$

If this method is employed the graph should nevertheless be drawn.

CHAPTER XLVII

SOME USES OF THE UNCALIBRATED POTENTIOMETER

The principle of the potentiometer and the more important practical aspects are discussed on pp. 291–5, to which reference should be made before any of the experiments described in this chapter are attempted.

Experiment 140. Comparison of the e.m.f.'s of a Daniell and a Leclanché Cell, using a Potentiometer

Apparatus: Daniell and Leclanché cells—see p. 276; potentiometer; sliding contact; plug key; two-way key; fully charged 2-volt accumulator; sensitive galvanometer with centre zero and sensitivity control (see p. 282).

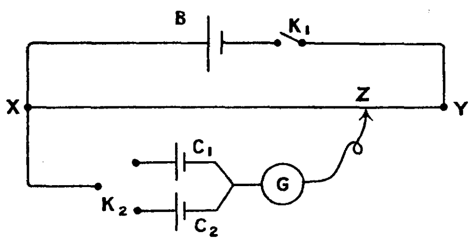


FIG. 169

Procedure: Set up the circuit shown in Fig. 169 in which

XY is the potentiometer wire
Z is the sliding contact
B is the accumulator
K_1 is the plug key
K_2 is the two-way key
C_1 is the Daniell cell
C_2 is the Leclanché cell
G is the galvanometer (the sensitivity control is not shown but should be used throughout in accordance with the instructions given on p. 282).

Check the circuit by the method given on p. 292.

Put the Leclanché cell circuit into operation, close the potentiometer circuit, and as quickly as possible obtain a balance point and note the scale reading. Switch the Daniell cell circuit into operation and again find balance point and scale reading. Repeat until three independent readings have been obtained for each cell.

The need for being as quick as possible, *consistent with accuracy*, in these operations, is due to the fact that significant alterations of e.m.f. are likely to occur if the cell circuits are closed for any length of time. Switching backwards and forwards from one circuit to the other allows several readings to be taken without either cell being in action very long.

For this reason, too, it is an advantage if the galvanometer is moderately damped—i.e. not so unstable as to take a long time to come to rest.

Introduce a small resistance, R,—about a tenth of that of the potentiometer wire—between B and X so that a second set of balance points can be obtained. This resistance could be several cm. of resistance wire, e.g. eureka wire S.W.G. about 24.

Record and Calculation: Record all observations, and for each set of balance points find the mean value of the ratio of l_1/l_2. This will be the ratio of the e.m.f.'s. Calculate the average value of this ratio.

Explain why the balance points moved towards Y when R was introduced and state in general terms the limiting value of R.

Note: Whilst this apparatus is set up it is convenient to determine the end-correction for the potentiometer wire by the method described on pp. 293–4. If further experiments using the potentiometer have to be done, the same instrument can be used and the end corrections will be known.

Experiment 141. Determination of the Internal Resistance of a Cell or Battery, using a Potentiometer

Apparatus: Potentiometer and accessories; the cell—the special battery described in Experiment 128 can be used with advantage here; tapping key; resistance box.

THEORY

If reference is made to p. 314 a proof will be found of the relationship

$$r = \frac{R(\varepsilon - V)}{V}$$

for a cell of e.m.f. ε volts and internal resistance r ohms which produces a p.d. of V volts across an external resistance of R ohms.

In this experiment instead of measuring V by means of a voltmeter we measure it by the potentiometer. For a cell of e.m.f. about 1·5 volts the circuit shown in Fig. 170 could be used. If the e.m.f. is less than this a suitable resistance should be included in series with the accumulator and the potentiometer wire. Its value should be calculated using as data the e.m.f. of the accumulator (assumed to be 2 volts) and the resistance of the potentiometer wire. If a battery is used in place of the cell and its e.m.f. exceeds 2 volts, then more than one accumulator will be required in the potentiometer circuit and perhaps a series resistance as well. The potentiometer circuit should be designed to meet the demands of the experiment, that is, a balance point near the end of the wire should be obtained when the cell or battery is on open circuit.

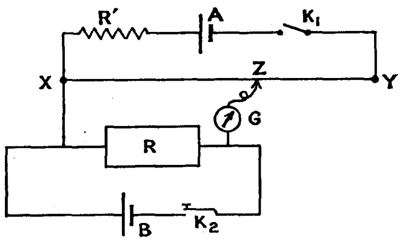


FIG. 170

Suppose the 'open circuit' balance point is l_∞ and the balance point corresponding to a value of R ohms in the resistance box is l, then it follows from the relationship given above that

$$r = \frac{R(l_\infty - l)}{l}$$

whence

$$\frac{1}{R} = \frac{l_\infty}{r} \cdot \frac{1}{l} - \frac{1}{r}$$

Thus a graph of $1/R$, as ordinate, against $1/l$ will be linear and have a (negative) intercept on the $1/R$ axis of value $1/r$. The value of r can, however, be obtained to a higher order of accuracy by evaluating the gradient and using the value of l_∞ obtained experimentally.

Procedure: Set up the circuit shown in Fig. 170 in which

XY is the potentiometer wire
Z is the sliding contact
A is the accumulator
K_1 is the plug key
B is the cell or battery

R′ is the series resistor introduced if necessary to ensure that the 'open circuit' balance point is near to Y
R is the resistance box
K_2 is the tapping key
G is the galvanometer with the sensitivity control.

Take the 'infinity' plug out of R and find the position of balance (l_∞). Give R a value of 100 ohms and find the new balance point. Record the value of R and the distance of the balance point from X. Reduce the value of R by stages, finding the balance point for each resistance. Do not reduce R below 15 ohms without consulting your instructor, as otherwise you may burn out one of the coils in the box. Take at least six readings.

Record and Calculation: Tabulate your observations as follows:

R ohms	XZ (l) cm.	$1/R$	$1/l$

Plot $1/R$ as ordinate against $1/l$ and deduce a value of r from the intercept and from the gradient as instructed in the theory paragraph above.

Note: The maximum power theorem can be verified using the data obtained in this experiment by plotting l^2/R as ordinate against R as abscissa. The graph should appear as shown in Fig. 171.

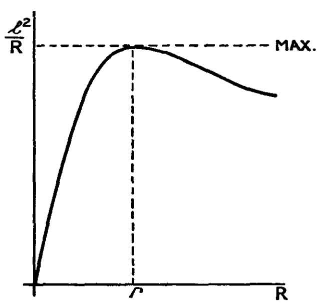


FIG. 171

Since l is a measure of the p.d. across R, l^2/R is a measure of the power dissipated in R. Thus if the maximum power theorem is true the maximum of the graph obtained in the experiment should occur at $R = r$. Thus the theorem can be verified.

Experiment 142. Comparison of Two Resistances of Approximately Equal Value, using a Potentiometer

Apparatus: Potentiometer; two 2-volt accumulators; resistance box (0–1,000 ohms); fixed resistance of about 50 ohms (this need not be known accurately); two plug keys; sensitive galvanometer with centre zero and sensitivity control; sliding contact; the two resistances.

THEORY

If a constant current is sent through the two resistors in turn, the fall in potential across each one will be proportional to the resistances.

In this experiment this condition is established by connecting the two resistors in series with an accumulator (and perhaps a series resistor to limit the current) and the lengths of the potentiometer wire equivalent to the p.d.'s across each one found. The resistances will be in the ratio of these lengths.

For maximum sensitivity the p.d. across the potentiometer wire should be only slightly more than the p.d. across the larger resistance of the two which are to be compared.

The circuit to be used is shown in Fig. 172. If R_2 and R_3, which are to be compared, exceed about 10 ohms each, then the resistance R_4, which is used to limit the current through them, will not be required. In such a case the p.d. across R_2 and across R_3 will be about a volt. To obtain balance points near the end of the potentiometer wire it will be necessary to give R_1 a value of slightly less than that of XY. (Why?)

Often the resistances to be compared are so small that if they were connected across the accumulator, damage to all components would result, and even if this did not occur there would be a serious risk of the rise in temperature in R_2 and R_3, caused by the heavy current, giving rise to an increase in their resistance. Thus R_4 becomes essential. Its value is not critical but it must be enough to limit the current to less than 1/20 amp.

In order to plan the circuit intelligently the following data is required:

(i) The value of R_4 to within a few ohms;

(ii) The values of R_2 and R_3* to within about 5%;

(iii) The resistance of the potentiometer wire.

By applying Ohm's law for the complete circuit to the B_2-R_4-R_2-R_3 circuit, assuming the e.m.f. of B_2 to be 2 volts, the p.d. across R_2 or R_3 must be calculated. Let this be V volts (approx.). Similar considerations must now be applied to the potentiometer circuit to deduce the value of R_1 which is required so that the p.d. across XY is slightly greater than V.

Final adjustment of the balance point can be carried out after the circuit is completed, by slight variations in R_1, which can be either a resistance box or a rheostat.

* This is not a case of knowing what we wish to determine. An approximate value is sufficient and this experiment must be regarded as a second stage in resistance determination—the one in which the accuracy is considerably improved.

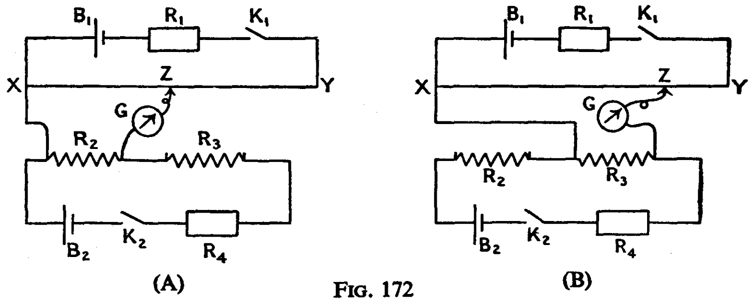


FIG. 172

Procedure: Set up the circuit shown in Fig. 172 in which
XY is the potentiometer wire
Z is the sliding contact
R_1 is the resistance box
B_1 is one accumulator
K_1 is one plug key
R_2 and R_3 are the two resistances
B_2 is the other accumulator
K_2 is the other plug key
R_4 is the fixed resistance of about 50 ohms
G is the galvanometer of which the sensitivity should be controlled as usual (see p. 282).

Give R_1 a rather lower value than calculated—so that the balance points are some distance from Y—and then by a rough experiment determine which is the larger, R_2 or R_3. Connect the larger one across X and G and adjust R_1 until the balance point is nearly at Y. With the

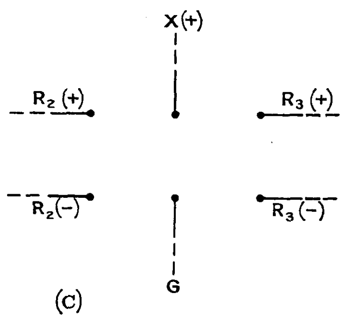


FIG. 173

galvanometer set at its full sensitivity, determine and record this balance point. Now connect the other resistance across X and G *leaving everything else unaltered* and determine the balance point.

Let the balance point obtained with R_2 in circuit be l_2 and with R_3 in circuit be l_3. Reduce R_1 a little and obtain another pair of values for l_2 and l_3. Continue this process until about six pairs of values have been obtained, but keep all balance points between Y and the middle of the wire.

The operations described above entail a good deal of moving of leads, and this can all be eliminated if R_2 and R_3 are connected to X and G by a double-pole double-throw switch. The wiring of this is illustrated in Fig. 173 and the use of it will enable R_2 and R_3 to be included at will. Care must be taken to see that the positive ends of R_2 and R_3 are connected to the positive ends of the potentiometer wire. The best way to wire such a circuit is to set up both potentiometer circuit and 'resistance' circuit completely and *separately* first, supplying R_2 and R_3 with leads at each end. *Then* unite the circuits through the d.p.d.t. switch.

Record and Calculation: Tabulate corresponding values of l_2 and l_3. Plot a graph of l_2 against l_3. The gradient of this graph is the ratio of R_2 to R_3.

Notes: (i) If great accuracy is required, apply an end correction (see pp. 293–4).

(ii) If one of the resistors is known, the other can be determined.

CHAPTER XLVIII

SOME USES OF THE CALIBRATED POTENTIOMETER

In the previous chapter various ways in which the uncalibrated potentiometer can be used are described. All these methods use the fact that the p.d. between any two points on the potentiometer wire is proportional to their distance apart, but in none of the experiments was the actual voltage drop per cm. determined. If the potentiometer is to be used to *measure* p.d., as distinct from making a comparison of two p.d.'s, then it must be calibrated—i.e. the factor by which distances along the wire must be multiplied to convert them into equivalent voltages must be determined. In this chapter some experiments demanding calibration of the wire are described and whilst each has its own particular circuit the principle used is the same in all cases, the variations being introduced because in some cases p.d.'s of the order of a volt are to be measured and in others p.d.'s of a millivolt or less are involved.

Before calibrating a potentiometer wire decide the order of magnitude of the p.d.'s which you wish to measure. Then include in series with the accumulator supplying the potentiometer wire a resistance which bears such a relationship to the resistance of the wire that the p.d. per cm. will be about that which is required. Let the maximum p.d. to be determined be V volts, the resistance of the wire be r ohms, the e.m.f. of the battery employed be ϵ volts, and the series resistance required be R. Then the current in the potentiometer wire is

$$\frac{V}{r} = \frac{\epsilon}{R + r} \qquad \text{(Ohm's law for the complete circuit)}$$

from which R can be calculated.

If V is small, then usually R is so large compared with r that the latter may be neglected, so that *in this case* $R = \epsilon r/V$.

The first step is therefore to determine roughly the resistance of the potentiometer wire (a more accurate value may later be needed) and then to compute the value of the series resistance needed. Normally this is included as a variable resistor so that adjustments can be made to cover the exact range demanded, or sometimes to arrange that the p.d. per cm. of the potentiometer wire is a simple number.

If the e.m.f. of the accumulator could be assumed to be exactly 2·00 volts, the p.d. across the wire could be calculated from the known values of R and r, and the wire would thus be calibrated.* Unfortunately, this assumption is liable to an error of up to 5% even with a good-quality accumulator. A standard cell—preferably a Weston cell—is not subject to this probable inaccuracy provided it is treated correctly (refer to p. 277), and the calibration process is completed by the use of such a cell. In the experiments in this chapter an e.m.f. for the cell of 1·0183 volts has been assumed; if the cell with which you are provided has a different e.m.f. it will, of course, be necessary to modify the figures given in the text.

Experiment 143. Determination of the E.M.F. developed by a Copper-Eureka Thermocouple

Apparatus: The thermocouple, which can be made by twisting together the *clean* ends of pieces of copper and eureka (contra) wire each of S.W.G. about 26; ICE; two thermometers, 0–100°C (× 1°C); potentiometer and accessories, including a resistance box of suitable range—see under 'Theory' below.

* This method is demonstrated in Experiment 143 which must be regarded as an introductory experiment rather than a satisfactory method.

THEORY

Such a thermocouple with its hot junction at 100°C. and its cold junction at 0°C. will produce an e.m.f. of about 4·7 mV. Ascertain the resistance of the potentiometer wire which you will be using and hence calculate the value of the resistance which must be placed in series with it and an accumulator of e.m.f. 2 volts so that the p.d. across the wire becomes about 5 mV. (See p. 339). This will ensure that balance points will be spread well along the wire.

Procedure: Set up the potentiometer circuit which has been designed to measure p.d.'s up to 5 mV. Immerse one end of the thermocouple in a water bath, the temperature of which can be varied, and connect this junction to the positive end of the potentiometer wire. Immerse the other junction in melting ice and connect this junction to the sliding contact through a sensitive centre-reading galvanometer. Put a thermometer in each bath. Record a series of balance points and the temperatures of the hot junction to which they correspond, covering the range up to 100°C adequately and checking that the cold junction remains at 0°C throughout.

Finally measure the e.m.f. of the accumulator with a voltmeter.

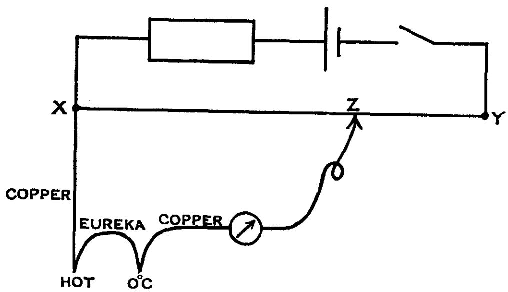


FIG. 174

Record and Calculation: Plot a graph of l (the balance point), as ordinate, against the hot-junction temperature.

From the values of the resistances in the potentiometer circuit and the e.m.f. of the accumulator, deduce the p.d./cm. which occurs along the potentiometer wire. Hence calculate the e.m.f. generated at 100°C.

Experiment 144. Calibration of an Ammeter, using a Potentiometer

Apparatus: The ammeter which is to be calibrated (this is assumed in the following instruction to be of range 0 to 2 amps.); potentiometer; three 2-volt accumulators; three plug keys; one two-way key; a sliding contact; Daniell cell; STANDARD CELL (see p. 277); fixed resistor of at least 10,000 ohms, unless it is certain that such a resistor is incorporated in the standard cell; rheostat (0–20 ohms) capable of carrying 2 amps.; standard 1-ohm coil; sensitive galvanometer with centre zero and sensitivity control (see pp. 277 and 282).

THEORY

This experiment is one which virtually employs the potentiometer to measure current. It does this by using the potentiometer to determine the p.d. across a known resistance through which the current to be measured is flowing. If the known resistance is of value 1 ohm the p.d. in volts is numerically equal to the current in amps. Otherwise the relationship

$$\text{amps.} = \frac{\text{volts}}{\text{ohms}}$$

must be used to find the current.

Procedure: Set up the circuit shown in Fig. 175 in which

B_1 is a 2-volt accumulator
K_1 is a plug key
XY is the potentiometer wire
K_2 is the two-way key
C_1 is the Daniell cell
C_2 is the standard cell
R_2 is the fixed high resistance (this may be incorporated in C_2)
G is the galvanometer (sensitivity control not shown)
Z is the sliding contact
A is the ammeter
R_1 is the standard 1-ohm coil
R_3 is the 20-ohm variable resistor
K_3 and K_4 are plug keys
B_2 is a 4-volt accumulator.

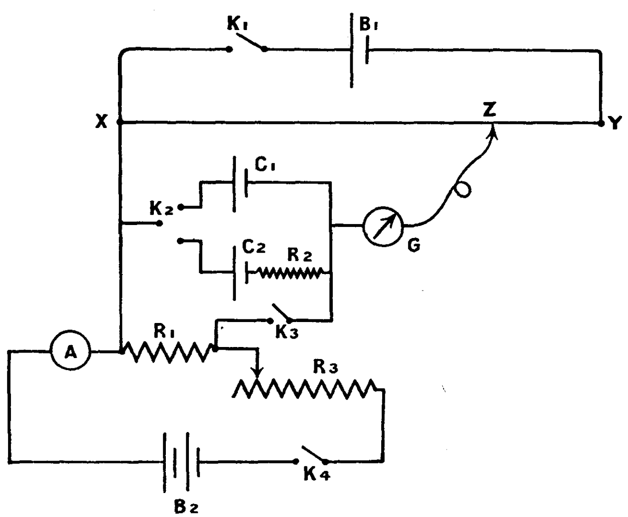


FIG. 175

PART I. CALIBRATING THE WIRE: Leave K_3 and K_4 open throughout this part of the experiment, as only the 'calibration circuit' is needed. Switch K_2 so that the Daniell cell is included in the circuit, close K_1 and find the balance point, on XY, with Z. Move K_2 so that the Daniell cell is replaced by the standard cell and find the new balance point, using the technique described on p. 277. Record the distance of the balance point from X (l cm.).

PART II. CALIBRATION OF THE AMMETER: Remove both plugs from K_2 so that neither C_1 nor C_2 is included in the circuit during this part of the experiment. Give R_3 its maximum value and switch on with K_4; close K_3 and find the balance point on XY. Record the position of this balance point together with the corresponding ammeter reading. Reduce R_3 so that a change of about 0·25 amps occurs in the reading of A, record the latter and find the new balance point. Record the distance of this from X. Continue reducing R_3 by stages, taking corresponding readings of the current and the position of the balance point until full-scale deflection of A is reached.

Record and Calculation:

Record the observations as follows:

PART I: e.m.f. of standard cell = ε volts.
Balance point at l cm. from X.

PART II: Tabulate as follows:

Reading of Ammeter (amps.)	XZ (cm.)	p.d. $\frac{XZ}{l} \times \varepsilon$ (volts)	Current $\frac{XZ}{l}\,\varepsilon \times \frac{1}{R_1}$ (amps.)

Plot the calculated current against the recorded current—this is the calibration graph. Sometimes the correction to be applied is plotted against the ammeter reading.

Notes: (1) If R_1 is not 1 ohm the last column will not be the same numerically as the preceding column. Even when R_1 is unity it is not a wise procedure to omit the last column, as there is the matter of units and dimensions to consider. The third column gives values of p.d.'s and these cannot be measured in amps.

(2) If the range of the ammeter is not 2 amps. the values for R_1 and R_3 will need amending suitably and B_2 must consist of sufficient accumulators to supply the current required to give full-scale deflection

of the ammeter. Care must also be taken to 'match' the fall of potential across R_1 with the p.d. across XY.

(3) A voltmeter can be calibrated by this method, as it is only an ammeter which takes minute currents. Unless R_1 is given a very high value (comparable with that of the voltmeter) the wire XY will have to be calibrated by the method described in Experiment 145 because the p.d. across R_1 will be small.

Experiment 145. Determination of the e.m.f. in Microvolts of an Iron-Copper Thermocouple for Various Temperature Differences between the Junctions

Apparatus: Potentiometer; 2-volt accumulator; plug key; tapping key; two-way key; two resistance boxes (each 0–1,000 ohms); sliding contact; Daniell cell; STANDARD CELL; fixed resistor of at least 10,000 ohms—unless one is incorporated in the standard cell; sensitive galvanometer (preferably reflecting type) with centre zero and sensitivity control; ICE—not essential but desirable; thermometer (0°–100°C); thermometer (0°–360°C, or higher if available); copper-iron thermocouple with arrangement to raise one junction to a high temperature. A satisfactory method is described here but an engine-oil bath can be used if the electrical heater is not available.

Details of the thermocouple and the heater:

Clean the ends of a piece of iron wire, 80–100 cm. long, with emery cloth and then to each one solder a length of copper wire, also cleaned at the ends.

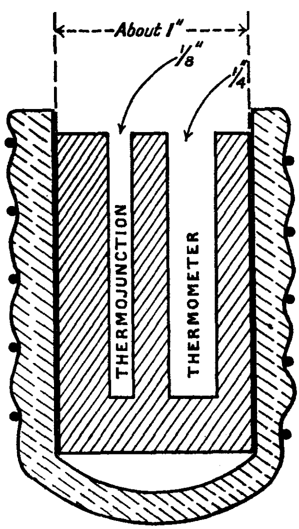


FIG. 176

In a cylinder of brass, of diameter one inch and of length two inches, drill two holes, one of diameter an eighth of an inch and the other of diameter a quarter of an inch as shown in Fig. 176. These holes are to take one of the thermo-junctions and the thermometer respectively. Before drilling the second make sure that a quarter of an inch is sufficient to take the thermometer (0°–360°) which you will be using. Mount this brass cylinder in the heating element of a 600-watt bowl-type electric fire, as shown in Fig. 176. Into the smaller of the two holes introduce one of the thermojunctions and fix the other one in a test tube by means of a cork through which the thermometer (0–100°C) passes.

To obtain balance points at the higher temperatures, it is necessary to reduce the rate of loss of heat by providing the heater with a suitable screen, e.g. a cylinder of asbestos of diameter about 3″.

THEORY

This subject is too complex to be dealt with shortly here. Reference to advanced textbooks on electricity should be made and the subject thoroughly studied before this experiment is conducted. A suitable book for this purpose is *Electricity and Magnetism for Advanced Students* by S. G. Starling, of which Chapter VIII is relevant.

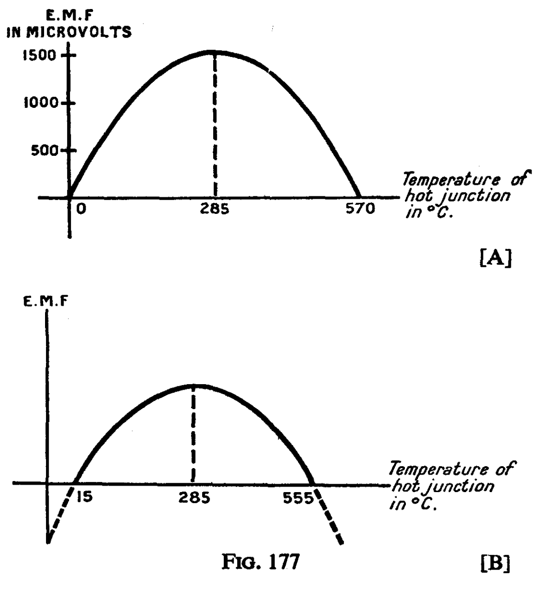


FIG. 177

Reference to tables on this subject will confirm the view that the subject is not as simple as many elementary books imply—many students fail to realise for instance that the *direction* of the thermoelectric e.m.f. can change with temperature conditions at the junctions.

For a copper-iron thermocouple with one junction at 0°C and the other at a higher temperature (up to 570°) the e.m.f. is such that the current would flow from the copper to the iron through the hot junction. Thus the cold junction must be connected to the positive end of the potentiometer wire (imagine the thermocouple replaced by a cell connected so that it would send a current in the same direction).

The curve showing the relationship between the temperature of the hot junction and the thermoelectric e.m.f., when the cold junction is kept at 0°C, is given in Fig. 177[A]. Notice that a maximum e.m.f. of 1,500 microvolts is obtainable, and that this occurs when the temperature of the hot junction is 285°C. The e.m.f. falls to zero again by 570°C, and in fact the curve is a parabola symmetrical about the ordinate corresponding to 285°C. This important temperature is known as the 'neutral temperature' and is a constant for a given pair of metals. It should be understood that it is NOT the *difference* in temperature between the junctions required to produce maximum e.m.f. but is a temperature *for the hot junction* at which maximum e.m.f. is produced. This will be better understood if Fig. 177[B] is examined. Here the thermoelectric e.m.f.'s are plotted against the temperatures of the hot junction with the changed condition that the cold junction is no longer at 0°C but at, say, 15°C. This curve is obtainable from Fig. 177[A] by sliding the temperature axis upwards until it intersects the parabola at the 15°C mark—or whatever the temperature of the cold junction happens to be. The 'new' curve is thus a part of the old one and is symmetrical about the same line.

Experimentally it is just as simple to find the neutral temperature when the cold junction is kept at room temperature as when it is kept in melting ice. In both cases it will be given by the temperature of the hot junction which corresponds to the maximum e.m.f. But as room temperature rises the thermoelectric e.m.f. obtainable will fall, i.e. the sensitivity of the experiment falls.

Since the curve of e.m.f. against temperature of the hot junction is a parabola the graph of the slope of the curve against temperature of the hot junction will be a straight line. Since also the gradient changes from a positive one to a negative one at the neutral temperature this straight line will intersect the axis of temperature at the neutral temperature. This is shown in Fig. 178.

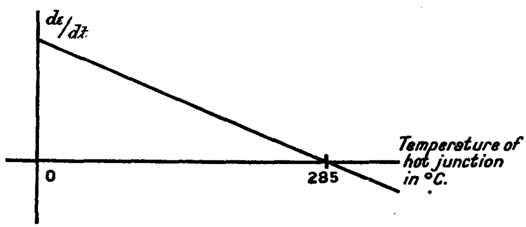


FIG. 178

To measure such small e.m.f.'s the potentiometer must be calibrated so that balance points near the end of the wire correspond to e.m.f.'s of the order of 2,000 microvolts, i.e. about 1/500 volt. To achieve this a high resistance is placed in series with the potentiometer wire and the accumulator, and the considerations given on p. 339 will show that the value of this resistance must be about 1,000 times the resistance of the potentiometer wire. The details of the theory of the calibration are included with the instructions below.

Procedure:

PART I: CALIBRATION OF THE POTENTIOMETER WIRE:

Determine the resistance of the potentiometer wire. Let it be *r* ohms.

Connect the wire XY into the circuit shown in Fig. 179 in which

B is the 2-volt accumulator
K_1 is the plug key
R_1 is one resistance box
R_2 is the other resistance box
XY is the potentiometer wire
C_1 is the Daniell cell
C_2 is the standard cell with its high resistor, R
K_2 is the two-way key
K_3 is the tapping key
G is the galvanometer (sensitivity control not shown).

Give R_1 and R_2 each a value of $500r$ ohms. Set K_2 so that the Daniell cell is included in the circuit and then alter the value of R_2 until there is no deflection in the galvanometer on closing the key K_3.

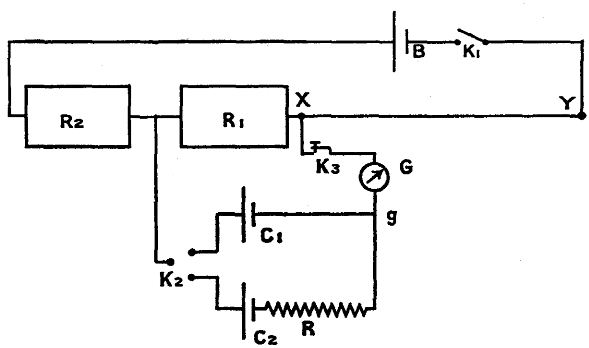


FIG. 179

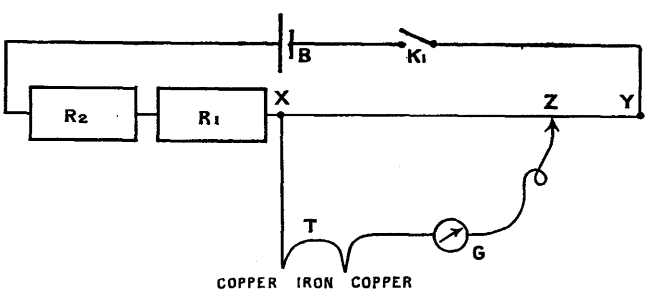


FIG. 180

Now set K_2 so that the standard cell is in circuit and make the necessary adjustments to R_2 so that there is no deflection in the galvanometer when K_3 is closed *momentarily* (Refer to p. 277).

The p.d. across R_1 is now equal to the e.m.f. of the standard cell. If this be ε volts, then the p.d. across the wire XY is

$$\frac{1}{500} \cdot \varepsilon \text{ volts.}$$

PART II: DETERMINATION OF THE THERMOELECTRIC E.M.F.'S AT VARIOUS TEMPERATURES OF THE HOT JUNCTION:

Arrange the thermocouple with its cold junction in ice, if this is available, and its hot junction in its container connected to a 240 volts mains point with a switch included. Connect it into the circuit shown in Fig. 180 in which B, K_1, R_1, R_2, and XY are left exactly as they were at the end of the calibration experiment, and

T is the thermocouple
G is the galvanometer
Z is the sliding contact.

The calibrating circuit may be left intact if it is desired but this is not necessary. It is fairly easy to design a circuit which incorporates both parts—one way is to connect the sliding contact to the point *g* (in circuit 179) through the thermocouple and to close K_3 when seeking the balance point with Z.

Switch on the current in the heating element and allow the temperature to rise until it is about 40° below the maximum temperature which the thermometer can safely record. The temperature will continue to rise a little and by switching the current on and off it will be possible to adjust the temperature of the hot junction to a value near to the maximum which the thermometer will record.

Find a balance point for the highest temperature possible; record the length XZ and the temperature. As the hot junction cools take a series of corresponding observations of the position of the balance point and the temperature, noting the latter when the balance point has been located, not before.

Record and Calculation:

Record the observations as follows:

PART I:

Resistance of potentiometer wire . .	ohms.
Length of potentiometer wire . .	cm.
e.m.f. of standard cell	volts.
Value of R_1 when G gives no deflection, with standard cell in circuit . .	ohms.
Hence p.d. per cm. along the wire XY .	microvolts.

PART II : Tabulate as follows:

Temperature of hot junction (°C)	Balance position (XZ) in cm.	Thermoelectric e.m.f. in microvolts

Plot the values of the thermoelectric e.m.f. against the temperature of the hot junction and from this graph deduce the neutral temperature. Plot also a graph of the gradient of the microvolts–C° curve against temperature of the hot junction and deduce the neutral temperature from this.

Notes: (1) The iron wire used in making the thermocouple may not be pure but may contain some carbon. The amount of this will vary from one specimen to another and this will cause a variation in the value of the neutral temperature.

(2) If a standard cell is not available the neutral temperature can be found by using an uncalibrated potentiometer wire and plotting the lengths of XZ against the temperatures for the hot junction. It will still be necessary to have about 1,000*r* ohms in circuit with the accumulator so that the p.d. per cm. of the wire is of the right order to give balance points at reasonable positions along XY.

CHAPTER XLIX

EFFICIENCY

Experiment 146. Investigation of the Relationship between the Efficiency of an Electric Lamp and the Voltage of the Supply

Apparatus: 100-watt, 240-volt, electric lamp (assuming you have the usual mains supply available). Suitable rheostat for inclusion in a 'mains' circuit; A.C. ammeter reading to 1 amp.; A.C. voltmeter reading to 250 volts. Suitable lamp holder and leads, etc. Photometer (see p. 197) another lamp (if possible a standard lamp) but otherwise a clear lamp with a single-line filament.

THEORY

The ordinary gas-filled lamp used for interior illumination converts a very small amount of the energy it consumes into light, but dissipates most of it as heat. The efficiency of a lamp can be measured in terms of the candle power it provides per watt of energy used. Unless your laboratory has a lamp of standard candle power it will not be possible to determine the candle power of the lamp in question, but we can find the values of a quantity to which its candle power is proportional and thus investigate how the candle power per watt varies with voltage of supply.

Procedure: Set up the circuit shown in Fig. 181 in which

L is the lamp
V is the voltmeter
A is the ammeter
R is the rheostat
K is a D.P.S.T. switch.

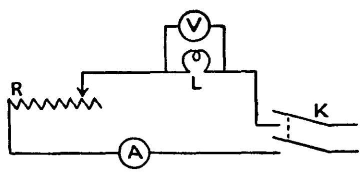


FIG. 181

Incorporate the lamp L as the source of unknown candle power in a photometric arrangement such as that shown in Fig. 182 in which P is the photometer, and L′ is either the standard lamp or else the lamp with which L is to be compared.

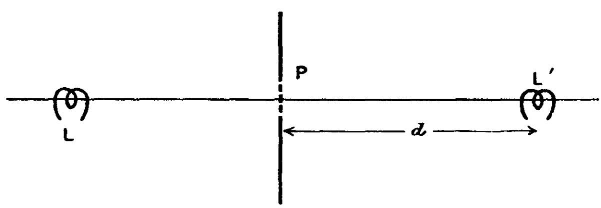


FIG. 182

Keep the distance of L from P constant and, as its candle power is varied by alterations of the voltage, adjust the position of L′ so that equal intensities of illumination are produced at P. The candle power of L will then be proportional to $1/d^2$, and if L′ is a standard lamp the actual candle power of L is given by $LP^2 \times (c/d^2)$ where c is the candle power of L′ and d is the distance from P to the filament of L′. Starting with a value of R which is great, so that the brightness of L is small, find the position of L′ such that P is equally illuminated by both lamps. Record the readings of the ammeter and the voltmeter as well as the distance d. Decrease R somewhat and repeat the adjustments and observations. Continue this process until R is zero.

Record and Calculation: Tabulate the results as follows:

d	Volts V	Amps. I	Watts $W = I \times V$	$\frac{1}{d^2}$	$\frac{1}{d^2 W}$

The values in the last column are proportional to the candle powers per watt for the lamp L.

Plot these values against the voltages and discuss the result.

Experiment 147. Verification of the Maximum Power Theorem

Apparatus: Several metres of wire of resistance about 3 ohms per metre. The resistance per cm. of the wire must be known and if necessary must be determined by the use of a Wheatstone's bridge. The latter together with accessories (see Experiment 130) may therefore also be required.

Daniell cell—the zinc sulphate cell described on p. 276 should be used here, as it has a higher internal resistance than the sulphuric acid cell. The internal resistance of this cell must also be known and the apparatus for Experiment 141, p. 333, may therefore also be needed.

In addition to the above you will need a 2-volt accumulator, a milliammeter (0–250 mA.), a tapping key and some arrangement for including definite amounts of the resistance wire in the circuit. This could take the form of a pair of wooden blocks each having two terminals screwed into them, the terminals on each block being joined by copper strip. These blocks can then be fixed to the bench by G-clamps and the wire stretched from a terminal on one to a terminal on the other. The second terminals are used to include the arrangement in the circuit (see Fig. 183).

THEORY

The maximum power theorem states that maximum power is dissipated in the external circuit when the resistance of the latter is equal to the internal resistance of the source of e.m.f. To verify this we shall first determine the internal resistance of the Daniell cell and then take a series of observations which will enable us to plot a graph of watts dissipated in the external circuit against the resistance of the external circuit. To do this the external circuit is arranged so that all the effective resistance is offered by the resistance wire of which the resistance per cm. is known. Thus the resistance can be found by measuring the length of wire included. The power dissipated can be found by measuring the current flowing, and using the formula

$$\text{watts} = (\text{amps.})^2 \times \text{ohms}.$$

If the maximum power theorem is true the graph of watts dissipated in the wire should show a maximum at the point where the resistance of the wire is equal to the internal resistance of the cell.

Procedure:

PART I. Determine the internal resistance of the Daniell cell, using the method given in Experiment 141, p. 333.

PART II: Determine the resistance per cm. of the resistance wire by finding the resistance of a measured length of it (several metres) using the Wheatstone's bridge (see Experiment 130, p. 317).

Next include the wire in the circuit shown in Fig. 183 in which

PQ is the wire, of which length T_1T_2 is included in the circuit
T_1 and T_2 are the terminal blocks clamped to the bench
A is the milliammeter
C is the Daniell cell
K is the tapping key.

Adjust T_1 and T_2 so that all the wire is included in the circuit, measure its length and record the current which flows when K is closed. Reduce the distance apart of T_1 and T_2 by suitable amounts, pulling the resistance wire tight between the terminals for each position, and hence obtain a series of observations of corresponding values of length of wire included in the circuit and the current flowing.

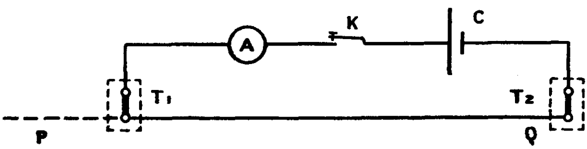


FIG. 183

Record and Calculation: Record all the observations made in PART I and find the internal resistance of the Daniell cell by the method given on p. 335.

Calculate the resistance per cm. of the wire (r ohms) from the observations using the Wheatstone's bridge.

Tabulate the results of the last part of the experiment as follows:

Current I amps.	Length l cm.	Resistance lr ohms	Watts I^2lr

Plot the values of I^2lr against lr (making the latter the abscissae). This graph should show a maximum. From the graph find the value of lr which corresponds to this maximum and compare it with the internal resistance of the cell found in Part I.

Note: For an alternative method of verification see note to Experiment 141, p. 335.

CHAPTER L

MOTORS AND DYNAMOS

Do not attempt any of the experiments described in this chapter until you have studied the subject under consideration by referring to theory books. The motors to be used can conveniently be of about 1/16 h.p. and the instructions relate to such motors. Obviously if the motor with which you are provided does not conform to this specification the ranges of the instruments required, etc., will have to be amended.

Experiment 148. Investigation of the Relationship between the Torque and the Armature Current for a Shunt Wound Motor of which the Field Current is kept Constant

Apparatus: 12-volt shunt wound D.C. motor taking total current of about 5 amps; two ammeters (0–3 amps.); two rheostats (0–6 ohms, capable of carrying 5 amps.); two plug keys; 12–16 volts D.C. supply; spring balance (0–100 gm.); metal disc of diameter about 20 cm. which can be fixed to the armature spindle of the motor by a set-screw. A hole must be drilled in this disc at about 8–9 cm. from the centre. The drilled disc commonly used for sirens is admirable for this purpose.

THEORY

When current passes through the armature windings, the magnetic field produced will react with the field produced by the current in the field windings,

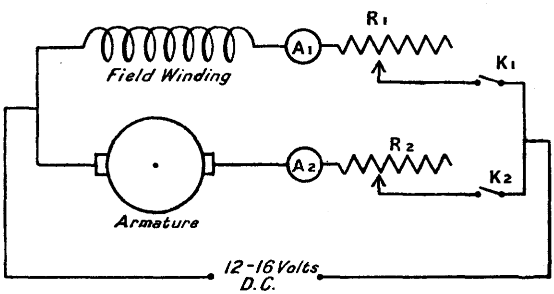


FIG. 184

and (in accordance with the Left-hand Rule) a force will be produced which will cause motion. If the armature is held still, this force may be measured by causing the torque to register a pull on a spring balance.

Torque is proportional to the product of armature current and field current, so if field current is constant the torque will be proportional to armature current. The experiment sets out to verify this linear relationship.

Procedure: Set up the circuit shown in Fig. 184, arranging the disc and the spring balance as shown in Fig. 185.

In Fig. 184,

A_1 and A_2 are the ammeters
R_1 and R_2 are the rheostats
K_1 and K_2 are the plug keys.

Fasten the disc to the armature spindle and attach the spring balance so that the string joining it to the hole in the disc is perpendicular to a radius of the disc. Make a mark x where the radius through the hole intercepts the circumference of the disc and adjust a pointer y to coincide with this mark.

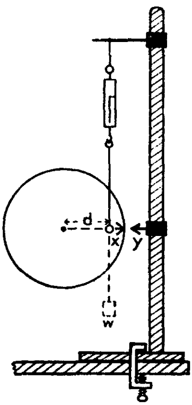


FIG. 185

In order to obtain steady readings it may be advisable to hang a small weight w, on the string to produce a standing deflection on the balance.

Close K_1 and adjust R_1 so that the field current is about 1·5 amps. Note the reading of the spring balance, and switch on the armature current by closing K_2; adjust R_2 so that the current flowing gives a small torque. Raise the spring balance support until the marks x and y coincide again and then read the balance and the two ammeters. Increase the current through the armature, keeping the field current constant, adjusting the balance and taking the necessary readings for each value of the current. Cover as wide a range as the motor will allow.

Measure the distance d from the centre of the disc to the point of attachment of the string; this is the 'torque arm'.

Record and Calculation: Tabulate the results as follows:

Torque arm = d cm. Field current (constant) = amp.

Armature current amps.	Balance reading		Pull gm. wt. $(s-z)$	Torque gm. cms. $d(s-z)$
	No current flowing z	Current flowing s		

Plot torque as ordinate against current as abscissa. This should be a straight line cutting the current axis a little to the right of the zero. What is the significance of this intercept?

Repeat the experiment with a different value of field current.

Experiment 149. Investigation of the Relationship between the Torque and the Current for a Series Wound Motor

Apparatus: 12-volt series wound D.C. motor—that used in Experiment 148 with the field and armature windings connected in series would be suitable; ammeter (0–3 amps.); rheostat (0–6 ohms, capable of carrying 5 amps.); plug key; 12–16-volts D.C. supply; spring balance (0–100 gm.); disc torque-arm as used in Experiment 148.

THEORY

Since the field and the armature windings are connected in series they take the same current. The torque, which depends on the product of the armature current and the field current, will therefore depend on the square of the current taken by the motor. The experiment sets out to verify this relationship, the torque being measured by exactly the same method as in Experiment 148.

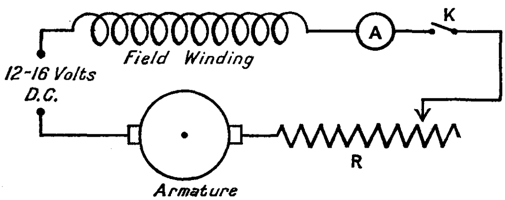


FIG. 186

Procedure: Set up the circuit shown in Fig. 186, in which

A is the ammeter
R is the rheostat
K is the plug key.

Arrange the disc and spring balance as described in Experiment 148 and shown in Fig. 185.

Close K and adjust R so that a small torque is produced, adjusting the spring balance so that the marks x and y coincide. Record the readings of the ammeter and of the spring balance.

Gradually increase the current through the motor by decreasing the value of R, and take a set of corresponding readings of the spring balance and the current up to the safe limit for the motor. Measure the torque arm (d) as for Experiment 148.

Record and Calculation: Record the observations as follows:
Torque arm, $d =$ cm.

Current (amps.) I	Balance reading		Pull (gm. wt.) $(s-z)$	Torque (gm.–cm.) $d(s-z)$	I^2
	No current flowing z	Current flowing s			

Plot torque (as ordinate) against the square of the current.
State your conclusion.

Experiment 150. Investigation of the Relationship between the Speed and the Armature Voltage for a Shunt Wound Motor of which the Field Current is kept Constant

Apparatus: 12-volt shunt wound D.C. motor, taking total current of 5 amps.; ammeter (0–3 amps.); ammeter (0–5 amps.); two rheostats (0–6 ohms, capable of carrying 5 amps.); two plug keys; voltmeter (0–15 volts); 12–16-volt D.C. supply; revolution counter together with stop-watch, or else a speedometer.

If a revolution counter is used the 'Veeder' type obtainable from Messrs. Philip Harris & Co. is suitable. For this experiment the revolution counter is not recommended, as the increase in load when the revolution counter is started is found to change all the meter readings. Thus the speedometer is more satisfactory.

THEORY

This experiment provides a means of illustrating Faraday's Law of Electromagnetic Induction, which states that the e.m.f. induced in a conductor moving in a magnetic field depends on the rate at which the lines of force are cut. In this experiment the field is constant and thus the rate of cutting lines of force depends on the speed of rotation of the armature, which should therefore bear a linear relationship to the applied voltage.

The experiment also can be used to illustrate the rather unexpected effect of the increase of speed of the motor when the field current is decreased.

Procedure: Set up the circuit shown in Fig. 187 in which

A_1 and A_2 are the ammeters, the latter of range 0–5 amps.
R_1 and R_2 are the rheostats
K_1 and K_2 are the plug keys
V is the voltmeter.

A_2 is not strictly necessary, but it is useful as a check on the current should it become too high for any reason.

Connect the speedometer to the armature spindle by the driving band. Switch on K_1 and adjust R_1 so that the field current is between 0·5 and 1·0 amp. Switch on K_2 and adjust R_2 so that the motor is running steadily at its lowest speed. It will probably be necessary to adjust the field current again to the predetermined value, or to choose another value of it better suited to the working conditions. Note this field current and keep it constant throughout the remainder of the experiment. Read the speedometer and the voltmeter. Increase the p.d. across the armature by varying R_2, adjust the field current to its correct value, and again read the speedometer and voltmeter. Obtain a series of readings covering as wide a range of values as the apparatus permits.

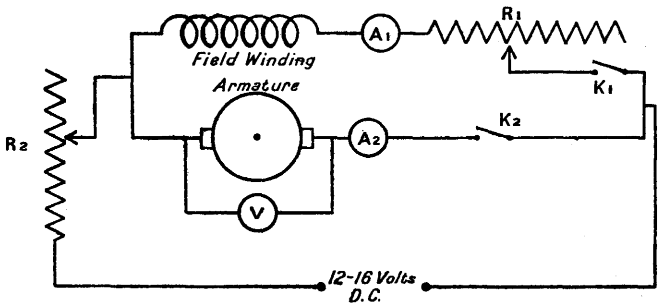


FIG. 187

Record and Calculation: Tabulate the results as follows :

Field current (constant) =   amps.

Armature volts	Speedometer reading (r.p.m.)

Plot a graph of speed as ordinate against armature volts as abscissa. It should be a straight line, cutting the abscissa to the right of the zero.

What is the significance of this intercept?

Repeat the experiment with a different value for the field current, plotting the results on the same axes as the first set of results.

State your conclusion, and account for the observed facts.

Experiment 151. Investigation of the Relationship between the Terminal Potential Difference and the Load Current for a Shunt Wound Dynamo

Apparatus: 12-volt, 6–10 amp., shunt wound D.C. dynamo; suitable motor for driving this generator at constant speed; rheostat (0–6 ohms, capable of carrying 10 amps.); ammeter (0–10 amps.); voltmeter (0–15 volts); plug key.

THEORY

In a shunt wound generator the current produced has to flow through the armature windings and since these have a resistance there will be a drop in voltage across them which will increase as the current increases. This potential drop is referred to as 'the lost volts'. Thus the terminal p.d. will be less than the generated e.m.f. Since also the field windings are in parallel with the armature, the field current will also be reduced, and this in turn reduces the generated e.m.f. and therefore the terminal p.d.

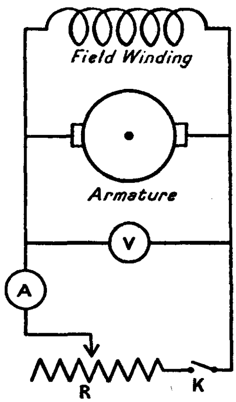


FIG. 188

Procedure: Set up the circuit shown in Fig. 188 in which

A is the ammeter
V is the voltmeter
K is the plug key
R is the rheostat.

Adjust R so that it has its maximum value, i.e. so that the load on the generator is a minimum. Start the motor which is to drive the dynamo (the former is not shown in Fig. 188) and when the dynamo is running at constant speed, close K and record the readings of A and V. Decrease R gradually, taking readings of the current and terminal p.d. for each value of the load current. Be careful not to reduce R to so small a value that the generator is overloaded, as this may burn out the windings.

Record and Calculation: Tabulate the observations as follows:

Terminal p.d. (volts)	Load current (amps.)

Plot terminal p.d. (as ordinates) against load currents.

Note: If the laboratory has a generator for providing current for charging accumulators the apparatus may be used for the experiment above.

Switch on the generator and adjust the field-regulating resistor to a value which can be kept constant during the charging of accumulators. The best results will be obtained if the accumulators used do require charging. Record the generator voltage on open circuit before switching in the accumulators. Record the voltage and the current flowing and continue recording these at five minute intervals for the first hour of charge, and after that at hourly intervals. Plot a graph as instructed above.

CHAPTER LI

SOME USES OF THE BALLISTIC GALVANOMETER

The introductory matter on Galvanometers in general and on ballistic galvanometers in particular, given on pp. 282–5, should be studied before any of the experiments in this chapter are attempted. The first experiment can be applied to any type of galvanometer but it is conveniently performed with this group of experiments, as the time spent in setting up the instrument can be saved if all the experiments described are done before it is dismantled.

Experiment 152. Determination of the Current Sensitivity of a Mirror Galvanometer

Apparatus: Mirror galvanometer of known resistance (if necessary this must be determined by the method of Experiment 129, p. 315); two resistance boxes (each of 0–10,000 ohms); standard 1-ohm and 2-ohm resistance coils; fully charged 2-volt accumulator; reversing switch; d.p.d.t. switch; plug key; lamp and scale for galvanometer.

THEORY

The current sensitivity is defined as the deflection in millimetres produced on a scale 100 cm. away from the galvanometer mirror when a current of 1 microampere flows through the instrument.

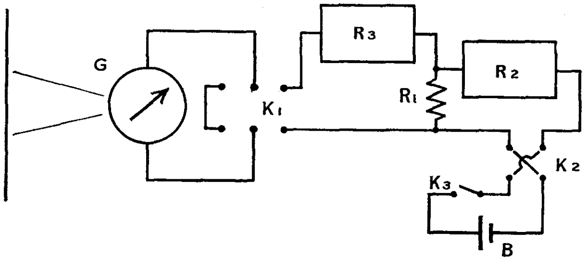


FIG. 189

The circuit which is to be used is shown in Fig. 189 and reference to this circuit diagram should enable you to see that if ε volts is the e.m.f. of the accumulator, then the current through R_1 is

$$\frac{\varepsilon}{R_1 + R_2} \text{ amps.}$$

But if R_2 is much larger than R_1 (which in the experiment is the case, since R_1 is the 1-ohm coil and R_2 is 2,000 ohms) this approximates to ε/R_2 amps.

Thus the p.d. across R_1 is $\frac{\varepsilon . R_1}{R_2}$ volts.

This is the p.d. applied to the galvanometer circuit which has a total resistance of

$$R_1 + R_3 + G \text{ ohms}$$

which approximates to $R_3 + G$ ohms when R_3 is of the order of 1,000 ohms.

Thus the current through the galvanometer is

$$I_g = \frac{\varepsilon . R_1}{R_2} \div (R_3 + G) \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \text{(i)}$$

In the experiment, $R_1 = 1$ ohm
$R_2 = 2{,}000$ ohms
and $R_3 = (1{,}000 - G)$ ohms
while $\varepsilon = 2$ volts.

This makes the current flowing through the galvanometer equal to $\frac{2}{2{,}000 \times 1{,}000}$ amps, which is 1 microampere.

The deflection in millimetres produced by this current is therefore the current sensitivity.

Other values of R_1 can be used if corresponding changes are made in R_2, and if necessary in R_3.

The general formula for the current given by equation (i) can be used to invent suitable combinations.

Procedure: Set up the galvanometer and arrange the optical system in accordance with the instructions given on pp. 284–5.

Determine, if not already known, the resistance of the galvanometer.

Connect the galvanometer into the circuit shown in Fig. 189 in which

K_1 is the d.p.d.t. switch
K_2 is the reversing key
K_3 is the plug key
R_2 and R_3 are the resistance boxes
R_1 is a standard resistance coil of low value—start with 1 ohm
B is the accumulator.

Give R_2 and R_3 the values chosen (see under 'Theory'), close K_1 and check that the image of the cross-wire is still on the zero mark. Close K_2 and K_3 and when the deflection is steady, record it. Reverse the current by means of K_2 and when the deflection is steady again, record it. Carry out several reversals to obtain a set of observations.

Change the value of R_1 to 2 ohms, adjust R_2 and R_3 so that the current through the galvanometer is once again 1 microampere and repeat the observations.

Record and Calculation: Tabulate the observations as follows:

R_1	R_2	R_3	G	Position of 'zero'	Deflection		Mean Deflection
					Left	Right	

Calculate the mean value of the last column—this is the sensitivity of the galvanometer.

Notes: (1) For higher accuracy the e.m.f. of the accumulator should be checked against a standard cell by means of a potentiometer (the method is given in Experiment 140, but the circuit will be complicated by the need of a Daniell cell to find an approximate balance point before including the standard cell). When ε is known more accurately the values of R_2 and R_3 will need altering accordingly.

(2) If R_2 and R_3 are made of the order of 10,000 ohms the galvanometer resistance can be neglected in most cases, i.e. when it is small compared with 10,000. In this case the e.m.f. of the supply will have to be increased to 50–100 volts, depending on the sensitivity of the galvanometer.

(3) If the deflection produced by a microampere is not measurable to a high order of accuracy—i.e. it is only a few centimetres—the

values of R_2 and R_3 may need altering so that the current is several microamperes. It is then convenient to make R_1 a dial resistance box, 0–9 ohms.

Experiment 153. Comparison of Two Capacitors

Apparatus: Ballistic galvanometer with lamp and scale; the two capacitors (these can conveniently be of capacitance about 0·5 and 1·0 μF.); 2-volt accumulator or Weston cell; D.P.D.T. switch; reversing key; two-way plug key; paraffin wax or alkathene blocks (see p. 284).

THEORY

In the ballistic galvanometer the corrected throw (see p. 283) is proportional to the charge passed. In this experiment each capacitor is charged to the same potential so that if their capacitances are C_A and C_B farads the charges acquired are C_AV and C_BV coulombs.

Thus, if the mean corrected throws are respectively θ_A and θ_B we have

$$\frac{C_AV}{C_BV}=\frac{\theta_A}{\theta_B}.$$

Hence the ratio of the corrected throws is the ratio of the capacitances. For satisfactory deflections the capacitances must be of the same order.

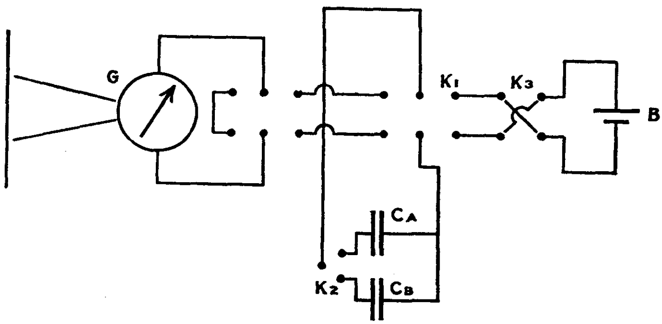


FIG. 190

Procedure: Set up the circuit shown in Fig. 190 in which

C_A and C_B are the capacitors
K_1 is a double-pole double-throw switch
K_2 is the two-way plug key
K_3 is the reversing key
B is the accumulator
G is the galvanometer.

Stand both capacitors, the switches, and the cell on insulating blocks of paraffin wax or alkathene. Keep all leads clear of the bench.

Introduce one of the capacitors into circuit by means of K_2 and charge it by connecting it to B for at least one minute.

Check the zero reading of the galvanometer and then switch over K_1 so that the capacitor discharges through the galvanometer. Record the first throw and the next throw in the same direction.

Recharge the capacitor with the same polarity, and repeat the observations a number of times, so that a mean may be found.

Using the reversing switch, charge the capacitor in the reverse direction and obtain another series of readings, the throws being on the opposite side of the zero due to the reversed polarity.

Now replace this capacitor by the other, by means of K_2, and repeat the cycle of operations.

Record and Calculation: Tabulate your observations as follows:

CAPACITOR A:

POSITION OF CROSS-WIRES ('zero')	DEFLECTION		CORRECTION (c)	CORRECTED THROW	MEAN THROW	FINAL MEAN (θ_A)
	First Throw θ_1	Second Throw θ_2	$c = \frac{\theta_1-\theta_2}{4}$	$\theta=\theta_1+c$		$\theta_A=\frac{\theta_L+\theta_R}{2}$
					LEFT	
					θ_L	
					RIGHT	
					θ_R	

Make a similar table for capacitor B. Calculate the ratio of the capacitances from the ratios of the mean corrected throws.

Note: If the capacitance of one of the capacitors is known, that of the other can obviously be determined.

Experiment 154. Determination of the Quantity Sensitivity of a Ballistic Galvanometer given a Known Capacitance

Apparatus: As for Experiment 153, replacing the two capacitors by one of known capacitance.

THEORY

The quantity sensitivity of a galvanometer is defined as the deflection in millimetres produced on a scale at a distance 100 cm. from the galvanometer mirror when a charge of 1 microcoulomb passes.

If a capacitor of given capacitance, C farads, is charged to a potential of V volts, the charge acquired is CV coulombs. If on passing this charge through a ballistic galvanometer a corrected throw of θ millimetres is produced, then the quantity sensitivity of the instrument is clearly

$$\frac{\theta}{CV \times 10^6} \text{ mm./microcoulomb.}$$

Procedure: Arrange the circuit as for Experiment 153, introducing the known capacitance in place of C_A and omitting C_B—the two-way key will not be needed.

Carry out an experiment with this capacitor in accordance with the instructions of Experiment 153 which apply to C_A.

Record and Calculation: Record the known capacitance and the voltage to which it was charged.

Tabulate the observations with the galvanometer as for Experiment 153 and find the mean corrected throw.

Substitute in the formula given above to find the quantity sensitivity.

Experiment 155. Determination of the Quantity Sensitivity of a Ballistic Galvanometer, using a Known Inductance

Apparatus: Ballistic galvanometer with lamp and scale; ammeter (0–0·5 amps.); rheostat (0–50 ohms); two 2-volt accumulators; double-pole switch; reversing key; the inductor, which can be made as follows:

Wind carefully 1,000 turns of D.C.C. copper wire of S.W.G. 22 in two layers of 500 turns each on to an insulating former of diameter 1·5 cm. and length 70 cm. The layers will occupy about 50 cm. of the length. Cover the complete solenoid by transparent adhesive tape. During the construction the overall diameter of both of the layers, the length of each layer and the total number of turns in each should be recorded for future reference.

Wind the secondary coil (using similar wire) over the centre part of the primary, making one layer of 100 turns first, and then over that another layer of 100 turns tapped at 50, 20, 20 and 10 turns. This makes the apparatus more 'flexible' and allows for reasonable throws when magnetic material is placed in the primary coil.

Mount the whole on a base board and solder the primary and secondary windings to terminals mounted on it. Record the data concerning the primary coil (noted above) clearly and indelibly on this base board.

Fig. 191 shows the construction diagrammatically.

THEORY

The quantity sensitivity of the ballistic galvanometer is defined above.

The field due to the current flowing in the primary coil is $4\pi ni$ oersted, where n is the number of turns per unit length of the primary coil, and i the current in absolute units.

The total flux in the primary is therefore $4\pi niA$, where A is the area of the cross-section of the primary coil. This flux cuts all the secondary turns. If there are N turns in the secondary coil, then the effective flux cutting it when the current is stopped or started is $4\pi niAN$; if the current is *reversed*, the flux cutting the secondary is $8\pi niAN$.

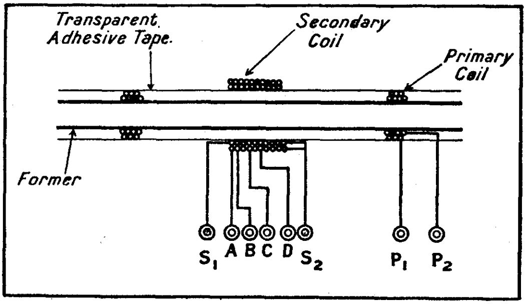


FIG. 191

If the total resistance in the secondary circuit, including the galvanometer is r, then the quantity of electricity passing

$$q = \frac{8\pi niAN}{r} \text{ abs. units.}$$

If the current is measured in amps. (symbol I) and the resistance in ohms (symbol R), this expression must be multiplied by 10^{-1} to convert the current to e.m.u., and it must be divided by 10^9 to convert ohms to absolute units. The charge will still be in absolute units, as we have arranged that the expression is unaltered. Thus

$$q = \frac{8\pi nIAN}{R.10^{10}} \text{ absolute units of charge.}$$

This expression must be multiplied by 10 to convert it to coulombs, i.e.

$$q = \frac{8\pi nIAN}{R.10^9} \text{ coulombs.}$$

If this quantity of electricity produces a deflection θ millimetres the quantity sensitivity will be

$$\frac{\theta}{\left(\frac{8\pi nIAN}{R.10^9} \times 10^6\right)}$$

i.e. $$\frac{\theta.R.10^3}{8\pi nIAN} \text{ millimetres per microcoulomb.}$$

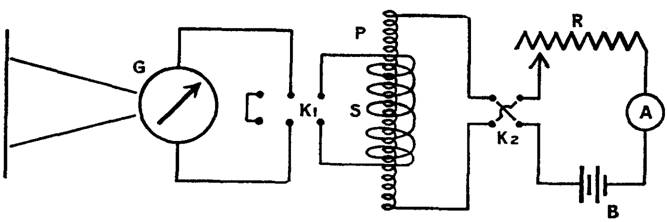


FIG. 192

Procedure: Set up the circuit shown in Fig. 192 in which

G is the galvanometer
K_1 is the d.p.d.t. switch
S is the secondary winding and
P the primary winding of the inductor
K_2 is the reversing key
R is the rheostat
A is the ammeter
B is the 4-volt battery.

The galvanometer, inductor and ammeter should all be as widely separated as possible.

Open K_1; close K_2 and adjust the current through the primary to about 0·1 amp. Open K_2; close K_1; close K_2; this will give a throw on the galvanometer, due to the growth of the field in the primary coil. It will be roughly half the throw which will be produced when the current is reversed. Allow the light spot to become steady and check the position of the zero. By means of K_2 reverse the current, noting the first throw and the next throw in the same direction. When the spot has again become steady, reverse the current again and note the throws as before. They will be in the opposite direction to the first set of readings. Check that the primary current has remained constant, and repeat the above sequences so that a mean value of the throw may be obtained.

Repeat for further values of the current up to about 0·5 amp.

The low resistance of the secondary winding leads to appreciable damping unless the secondary circuit is opened within a small fraction of a second of the discharge through the galvanometer taking place. This can be done (with practice) using a tapping key, but a more satisfactory method is to connect the secondary to a 4 microfarad capacitor through a germanium diode (to prevent the capacitor discharging through the secondary). The capacitor is then discharged *immediately* afterwards through the galvanometer and *if the components are kept free from dust and moisture* the loss of charge by this temporary storage is negligible.

Record and Calculation: Tabulate your results as follows:

Primary current amps	Position of cross-wires	Throws				Correction $\frac{1}{2}(\theta_1-\theta_2)$		Corrected throw		Mean	Final Mean for each current
		Left		Right							
		First θ_1	Second θ_2	First θ_1	Second θ_2	Left C_1	Right C_2	Left θ_1+C_1	Right θ_1+C_2		

Plot a graph of mean corrected throw (as ordinate) against current.

From the graph determine the throw for a given current; substitute in the formula above to find the quantity sensitivity in millimetres per microcoulomb.

The result should be compared with that obtained in Experiment 154. Close agreement is not to be expected, as there are so many quantities involved in the above experiment which are difficult to measure with accuracy.

Experiment 156. Determination of (a) the Angle of Dip, (b) the Horizontal Component of the Earth's Magnetic Field and (c) the Vertical Component of the Earth's Magnetic Field, using an Earth Inductor

Apparatus: Ballistic galvanometer with lamp and scale; double-pole double-throw switch; compass; resistance box; earth inductor—this can be made as follows:

Wind 300 turns of D.S.C. copper wire of S.W.G. 36, on to a circular wooden disc 23 cm. in diameter and 2 cm. thick. The windings should be made inside a slot, which should be about 1 cm. wide and 1 cm. deep, in the periphery of the disc. Connect the ends of the wire to terminals screwed

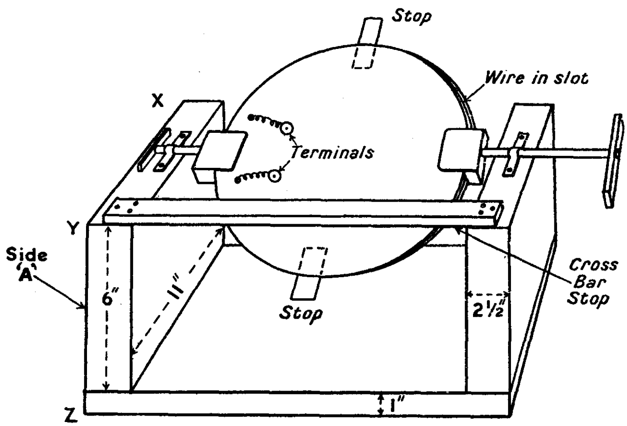


FIG. 193

into the face of the disc. The coil will have a resistance of about 120 ohms. Arrange that the coil is held by brass supports so that it pivots inside a wooden frame and can easily be rotated through 180°. It will be necessary to fit stops (which will strike the crossbar) to ensure accurate rotation through this angle. The wooden frame must be substantial and heavy so that the coil can be rotated without disturbing the position of the coil supports when the coil hits the stops. The side 'A' (see Fig. 193) should be plane so that the apparatus can be stood firmly on it. The side members should be about 2½ inches thick and the base about 1 inch thick.

The main features and dimensions are shown in Fig. 193.

THEORY

Suppose the plane of the coil to be vertical and perpendicular to the magnetic meridian. The flux linked with the coil will be $H_e AN$ lines where

H_e is the horizontal component of the Earth's magnetic field in oersteds

A is the area of the coil in square centimetres

and N is the number of turns in the coil.

If the coil is rotated through 180° about the vertical axis the change of flux linked with the coil will be $2H_e AN$ lines. If the total resistance of the circuit (including the galvanometer) is R ohms, then the quantity of electricity passing through the galvanometer will be q' where

$$q' = \frac{2H_e AN}{10^8 R} \text{ coulombs} \quad . \quad . \quad . \quad (1)$$

Similarly if the coil is placed with its axis perpendicular to the meridian and its plane horizontal, a rotation of 180° will cause a charge of q'' through the galvanometer where

$$q'' = \frac{2VAN}{10^8 R} \text{ coulombs} \quad . \quad . \quad . \quad (2)$$

the vertical component of the Earth's magnetic field being V oersteds.

From these two equations the three elements—angle of dip and horizontal and vertical components of the Earth's field—can be found as follows:

(*a*) *Angle of Dip* ($d°$):

If equation (2) above is divided by equation (1) we obtain

$$\frac{q''}{q'} = \frac{V}{H_e}$$

But $$\frac{V}{H_e} = \tan d, \text{ and hence } \tan d = \frac{q''}{q'}.$$

The corrected throws of the ballistic galvanometer corresponding to q' and q'' are θ' and θ'' mm. then

$$\frac{q''}{q'} = \frac{\theta''}{\theta'} = \tan d.$$

Thus the angle of dip is $\tan^{-1}\left(\frac{\theta''}{\theta'}\right)$ . . . . . (3)

(*b*) *The Horizontal Component* (H_e):

If K is the quantity sensitivity of the galvanometer (see definition on p. 363 and determination in Experiments 154 and 155) then

$$\theta' = Kq' \times 10^6 \quad .$$

Hence, combining this with equation (1), we have

$$\frac{\theta'}{K10^6} = \frac{2H_e AN}{10^8 R} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

H_e can thus be found if all the other quantities in this equation are determined—including K.

(*c*) *The Vertical Component* (V):

By a similar argument to that given in (*b*) it can be shown that

$$\frac{\theta''}{K10^6} = \frac{2VAN}{10^8 R} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Thus V can be found.

A more detailed discussion is to be found in theoretical textbooks.

Procedure: If it is not already known, determine the quantity sensitivity and the resistance of the galvanometer.

Include the Earth Inductor in the circuit shown in Fig. 194 in which

E is the inductor
r is the resistance box
K_1 is the double-pole double-throw switch
G is the galvanometer.

Use flexible leads to connect the earth inductor to the rest of the apparatus, and keep it at a considerable distance from the galvanometer and any other magnetic apparatus.

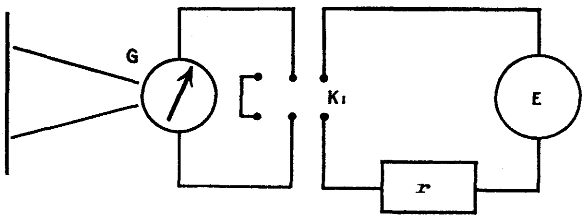


FIG. 194

PART I: DETERMINATION OF THE VERTICAL COMPONENT

Arrange E so that the axis of rotation is horizontal and the plane of the coil is horizontal. Adjust the stops so that one is against the crossbar. Open K_1, give r its minimum value (i.e. zero) and check that the light spot is on the zero of the scale. Close K_1—there should be no deflection of the light spot.

Rotate the coil through 180° with a smooth firm twist, avoiding as far as possible any 'bounce' at the end of its travel. Note the first throw and the next throw in the same direction.

If the throw is off the scale, include resistance from the box in the circuit until a reasonable deflection is obtained. It should be nearly full scale if possible, as the throw for the horizontal component is much less.

Allow the spot to come to rest, and then turn the coil back through 180°, noting the throws as previously. They will be in the opposite direction.

The spot can be rapidly returned to zero by using the short thick piece of copper wire across one pair of terminals of K_1.

Obtain a series of readings from which a mean can be calculated.

Vary the series resistance r and repeat the operations.

PART II: DETERMINATION OF THE HORIZONTAL COMPONENT

Determine the direction of the magnetic meridian by means of the compass. Place the earth inductor so that the axis of rotation is vertical, the plane of the coil perpendicular to the magnetic meridian and one of the stops against the crossbar stop.

With the apparatus described, the frame will be standing on side 'A' and the edge YZ will be approximately in the magnetic meridian.

With K_1 open, check that the light spot is on the zero of the scale. Include in the circuit the same series resistance used in the first set of results for (1) above. Close K_1. There should be no deflection. Rotate the coil through 180° as previously, noting the first throw and the next in the same direction.

Allow the spot to come to rest, and then turn the coil back through 180°, noting the throws as previously. They will be in the opposite direction.

Obtain a series of readings from which a mean can be calculated. Alter the series resistance to the values used in (1) above and repeat.

When the coil is perpendicular to the magnetic meridian the throw will be a maximum. This may be used as a check on the orientation of the coil, as displacements of a few degrees should cause a reduction of the throw.

Make the necessary observations to enable you to determine the mean diameter of the coil (hence the value of A), the number of turns in the coil (N) and the resistance of the coil (R_C).

Record and Calculation: Record the observations as follows:

Resistance of galvanometer . . .	G ohms
Resistance of the coil	R_C ohms
Quantity sensitivity of the galvanometer	K mm/micro-coulomb
Number of turns in coil . . .	N
Diameter of the coil	cm.

Tabulate the observations for Part I as follows:

Series Resistance r (ohms)	Total Resistance of circuit R $(=Rc+G+r)$	Galvanometer Readings					Correction $\left(\frac{\theta_1-\theta_2}{4}\right)$		Corrected Throw $\theta_1+\left(\frac{\theta_1-\theta_2}{4}\right)$		Mean
		Position of zero	Throws								
			Left		Right						
			1st θ_1	2nd θ_2	1st θ_1	2nd θ_2	Left	Right	Left	Right	θ''
r_1											
r_2											
etc.											

Construct a similar table for PART II.

(*a*) Find the mean value for d by using equation (3) given above—remember to use values for the throw that were obtained using the same value for r.

(*b*) Find H_e by substituting the appropriate quantities in equation (4), given above, and taking the mean of the consistent determinations.

(*c*) Find V by a similar method, using equation (5).

Note: It is instructive to compare the values for H_e and d found by this experiment with the values obtained at the same spot, using the tangent galvanometer and the deflection magnetometer.

Experiment 157. Determination of a High Resistance, using a Known Capacitance and a Ballistic Galvanometer

Apparatus: Ballistic galvanometer with lamp and scale; good quality capacitor (oil-filled-paper or mica) of capacitance 1 or 2 μF; high resistance (to be determined) of the order of 5 megohms; 2-volt accumulator (or perhaps a standard cell—see under 'Procedure'); well-insulated double-pole double-throw switch; two tapping keys; reversing key; stop-watch.

THEORY

If a charged capacitor of capacitance C farads is discharged through a resistance of R ohms, then the charge which is still on the capacitor after t secs. is Q coulombs where

$$Q = Q_0 e^{-\frac{t}{CR}} \quad . \quad . \quad . \quad . \quad (1)$$

In this equation Q_0 is the charge when $t = 0$, i.e. before the discharge started, and e is the base of Naperian logarithms.

If the capacitor were to be discharged through a ballistic galvanometer, the resistance of the latter is so low that t may be taken as zero for the whole discharge (this is inherent in the design of the galvanometer) so that the galvanometer records a throw which corresponds to a charge Q_0. Let the corrected throw for this be θ_0.

If the capacitor is recharged with Q_0 coulombs and is connected across a high resistance R ohms for t seconds before being connected across the ballistic galvanometer again, it can be shown that the corrected throw θ is given by

$$\log_{10}\theta = -\frac{t}{2{\cdot}3\,CR} + \log_{10}\theta_0 \quad . \quad . \quad . \quad (2)$$

This equation is of the form $y = mx + c$,

$$\text{where } y = \log_{10}\theta,$$

$$m = -\frac{1}{2{\cdot}3\,CR},$$

$$x = t$$

$$\text{and } c = \log_{10}\theta_0.$$

Thus if $\log_{10}\theta$ is plotted against t (as abscissae) a straight line is obtained which will have a gradient equal to $-1/2{\cdot}3CR$. Since C is known R can be found.

An alternative method of obtaining R is as follows:

From equation (1) it can be shown that the charge decreases by 63% of its maximum value in CR seconds. It follows therefore that 37% of the charge remains after CR seconds. The product CR is called the 'time-constant' of the circuit. For a capacitor to charge or discharge slowly the time constant must be great. The value of CR can be obtained by plotting the corrected

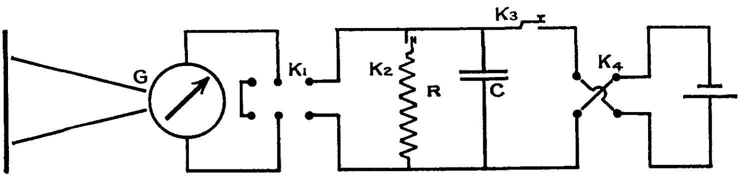


FIG. 195

throw (as ordinate) against t (as abscissa). This graph will be an exponential curve and the value of t for which θ has decreased to 37% of its maximum value can be deduced from it. This value will equal CR and hence, since C is known, R can be found.

Procedure: Set up the circuit shown in Fig. 195 in which

G is the galvanometer
C is the capacitor
R is the high resistance
K_1 is a double-pole double-throw switch
K_2 and K_3 are tapping keys with carefully cleaned contacts
K_4 is the reversing key.

With the galvanometer connected to its shorting strip, charge the capacitor by closing K_3, meanwhile open K_1 and check the zero of the spot of light. Open K_3 and *immediately* afterwards connect C to the galvanometer by K_1. Record the first throw, and the next throw in the same direction. Repeat several times. *Be careful to take G out of circuit before charging the capacitor.*

Reverse K_4 and repeat the above. The corrected mean throw will give θ_0. If the throw is off the scale use a standard cell in place of the accumulator. If the spot is still off the scale apply the p.d. to the capacitor through a potentiometer connected across an *accumulator* (see p. 403). In all cases the capacitor must be allowed to charge for at least half a minute.

Recharge the capacitor; by means of K_2 connect R across C and as the key is closed start a stop-watch. After 5·0 seconds open K_2 and immediately afterwards discharge C through the galvanometer by means of K_1. Repeat the operations, and then carry out two more determinations with K_4 reversed.

Now carry out the operations described in the preceding paragraph for time intervals of 10 secs., 15 secs., etc. until the deflections are too small for satisfactory measurement.

Record and Calculation: Tabulate the observations as follows:

<table>
<tr><th rowspan="4">Time in secs. (t)</th><th colspan="5">Galvanometer Readings</th><th colspan="2" rowspan="2">Correction $\frac{\theta_1-\theta_2}{4}$</th><th colspan="2" rowspan="2">Corrected Throw $\theta_1+\frac{\theta_1-\theta_2}{4}$</th><th rowspan="3">Mean</th><th rowspan="4">$\text{Log}_{10}\theta$</th></tr>
<tr><th rowspan="3">Position of 'zero'</th><th colspan="4">Throws</th></tr>
<tr><th colspan="2">Left</th><th colspan="2">Right</th><th rowspan="2">Left</th><th rowspan="2">Right</th><th rowspan="2">Left</th><th rowspan="2">Right</th></tr>
<tr><th>θ_1</th><th>θ_2</th><th>θ_1</th><th>θ_2</th><th>θ</th></tr>
<tr><td>0</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>θ_0</td><td></td></tr>
<tr><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>θ_5</td><td></td></tr>
<tr><td>10</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>etc.</td><td></td></tr>
<tr><td>etc.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Plot a graph of $\log_{10}\theta$ (as ordinate) against t and from the gradient of the line so obtained deduce a value for R by the method indicated above.

Plot also a graph of θ (as ordinate) against t and determine the value of t for which θ is 37% of its maximum value. Hence find a value for R.

Note: The resistance of the capacitor can be determined with the above apparatus.

Charge the capacitor; open K_4 and K_3. After about 2 or 3 minutes switch K_1 over so that the capacitor discharges through the galvanometer. Let the corrected throw be θ_t. The capacitor will have lost charge due to leakage through itself, and if R_x is the capacitor resistance, it can be shown from equation (1) that

$$R_x = \frac{t}{2{\cdot}3\,C\log_{10}\left(\frac{\theta_0}{\theta_t}\right)}$$

R_x can therefore be calculated since all the other quantities are known. For a good capacitor the value should be of the order of 500 megohms or more.

Experiment 158. Use of a Ballistic Galvanometer to Determine (i) Field Strength, (ii) Pole Strength

Apparatus: Ballistic Galvanometer with lamp and scale; resistance box giving values up to about 10,000 ohms; large permanent horse-shoe magnet giving a field strength between its poles of a high value—e.g. a magnetron magnet (which may have a field of up to 30,000 oersteds between its poles); cylindrical magnet with as high a pole strength as available—e.g. a 12 cm. magnet with magnetic moment several thousand c.g.s. units; search coils to match these magnets, i.e. which will give suitable throws on the galvanometer when used as described below.

The coils should be wound from thin copper wire (D.C.C., S.W.G. 32–36). Count the number of turns as the coil is wound and record it on a small label attached to one of the leads. Wind the turns on a thin cardboard cylinder of suitable dimensions, so that the area of cross-section can easily be determined.

THEORY

If the flux linked with a circuit changes by ϕ maxwell-turns and the circuit has a total resistance of R ohms, the total charge passed round the circuit due to the induced e.m.f. is

$$\frac{\phi}{R \times 10^8} \text{ coulombs}$$

(If this is not familiar it is essential that reference be made to theoretical books.)

In part (i) of the experiment the flux is due to the field, H oersted, between the pole pieces of the permanent magnet. The circuit to be used is shown in Fig. 196[A]. If the coil has n turns and area of cross-section A cm.^{2}, when it is removed from between the pole pieces to a reasonable distance away (say several feet), then the change in flux linked with it is nAH maxwell-turns. The charge passed is thus

$$\frac{nAH}{R \times 10^8} \text{ coulombs,}$$

where R is the total resistance of the circuit. This charge is passed through the ballistic galvanometer and the throws are observed. Let the sensitivity to charge be k mm/microcoulomb at a metre (determined previously—see Experiments 129 and 154) and the mean corrected throw be θ. Then the charge causing this throw will be

$$\frac{\theta}{k} \times 10^{-6} \text{ coulombs.}$$

Hence

$$\frac{nAH}{R \times 10^8} = \frac{\theta}{k} \times 10^{-6},$$

from which a formula for H can be obtained.

In this experiment, R is varied and a graph of R_1 as ordinate against $1/\theta$ is plotted. From the relationship deduced above it will be seen that if the resistance of the rest of the circuit (excluding R_1) is r,

$$r + R_1 = \frac{nAkH}{100} \times \frac{1}{\theta}.$$

$$\therefore \qquad R_1 = \frac{nAk}{100} . H . \frac{1}{\theta} - r.$$

This graph will therefore have a gradient of $\frac{nAk}{100} \cdot H$ and hence from this, knowing n, A and k the value of H can be found.

In Part II the flux is due to one pole (of strength m c.g.s. units) of the cylindrical magnet. The circuit is shown in Fig. 196(B). Now 4π lines emanate from unit pole, and thus the flux linked with the search coil is $4\pi\ mn$ maxwell-turns.

Hence
$$\frac{4\pi mn}{R \times 10^8} = \frac{\theta}{k} \times 10^{-6}$$

i.e.
$$r + R_1 = \frac{4\pi nk}{100} m \cdot \frac{1}{\theta} \cdot$$

Thus the gradient of a graph of R_1, as ordinate, against $1/\theta$ will be $\frac{4\pi nkm}{100}$, from which, knowing n and k, m may be determined.

Procedure:

PART I. DETERMINATION OF FIELD STRENGTH

Set up the circuit shown in Fig. 196(A), using a quickly prepared search coil of, say 20 turns, and cross-sectional area 1–2 cm². Insert a value of R_1 equal to 5,000 ohms. Hold the coil between the poles of the magnet and with its plane normal to the field, and then move K_1 so that G is

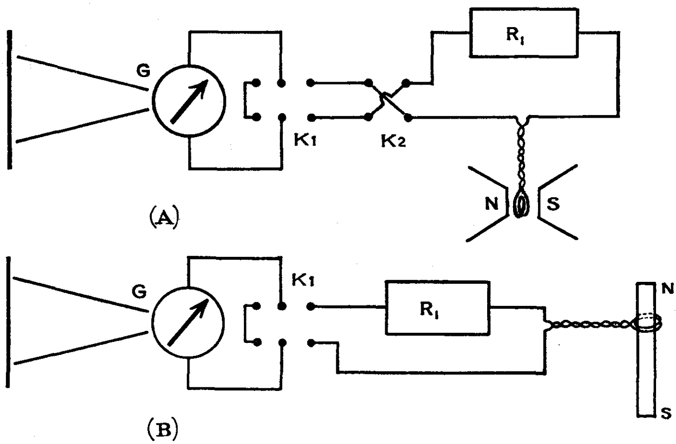


FIG. 196

included in the circuit. Move the search coil fairly quickly out of the field of the magnet and observe the first throw. From this reading decide how many turns are necessary for the search coil which is to be used in the careful experiment, and then make it in accordance with the instructions given under ‘apparatus’ above.

When the coil is prepared, record the number of turns and measure its diameter in a number of directions. Next include it in the circuit in place of the test coil. Give R_1 a suitable value—so that the throw will be about 100 mm. and with G shorted through its shunt, place the coil between the poles of the magnet. Move K_1 to include the galvanometer and then remove the coil from the field. Observe the first throw (θ_1) and the second throw in the same direction (θ_2). Short the galvanometer again and operate K_2 so that the throw will be reversed. Replace the coil between the poles and repeat the observations.

Give R_1 a smaller value so that the throw will be about 150 mm. and repeat the two observations of throw in each direction. Continue this process until as wide a range of values of R_1 and θ as possible has been covered, taking about six sets of readings altogether.

Part II. Determination of Pole Strength

Carry out the instructions given for Part I above but obtain the change of flux by removing the coil from the end of the magnet—it should be about 1 cm. from the end when in its ‘rest position’. In this Part the reversals of throw are produced by using both ends of the magnet. The pole strength will, of course, be the same at each end. The circuit diagram is given in Fig. 196B.

Record and Calculation: Part I: Tabulate your results as follows:

Number of turns on search coil (n) =
Diameter of search coil (i)
(ii)
(iii)
Hence mean diameter =
Hence area of cross-section (A) =
Sensitivity to charge of galvanometer (k) =

R_1 (ohms)	Galvanometer Readings					Correction $\frac{\theta_1-\theta_2}{4}$		Corrected Throw		Mean θ	$1/\theta$
	Position of zero	Throws									
		Left		Right							
		θ_1	θ_2	θ_1	θ_2	Left	Right	Left	Right		

Plot a graph of R_1 against $1/\theta$ and deduce H, the field strength, from the gradient by the method discussed in the ‘Theory’ paragraph.

Part II:

Number of turns on the search coil (n) =
Sensitivity to charge of the galvanometer (k) =

R_1 (ohms)	Galvanometer Readings					Correction $\frac{\theta_1 - \theta_2}{4}$		Corrected Throw		Mean θ	$1/\theta$
	Position of zero	Throws									
		N-pole		S-pole							
		θ_1	θ_2	θ_1	θ_2	N	S	N	S		

Plot a graph of R_1, against $1/\theta$ and deduce the pole strength from the graph.

CHAPTER LII

THE QUADRANT ELECTROMETER

Setting up and Adjusting the Quadrant Electrometer

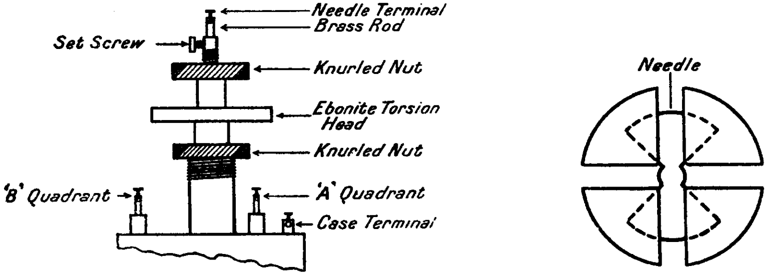
The theory of the quadrant electrometer should be studied in appropriate textbooks before any work described in this chapter is attempted. All the instructions given apply to the Dolezalek quadrant electrometer—the commonest form in use.

The support is of primary importance. The apparatus is very sensitive to vibration and consistent work is impossible unless the support is quite rigid. A convenient and satisfactory arrangement is a shelf made of slate about four feet long and a foot wide fixed into a corner of the laboratory formed by two walls and at a height of about 4′ 6″ from the floor. It is a complete waste of time to use an ordinary bench. The only apparatus placed on this shelf is the electrometer, the lamp and the scale; ALL other apparatus should be placed on an adjacent bench.

It must be emphasised that the instrument is very delicate and easily damaged and the utmost care must be taken when making adjustments.

Level the instrument roughly by means of the levelling screws and then remove the outer protecting case. Check whether the needle is free or is resting on the bottom of the quadrants. If the latter is the case, very carefully raise it by means of the knurled nut at the top of the torsion head until it is free, the weight being taken by the suspension (see Fig. 197A). Open the quadrants by the short brass handle provided and USING A PAIR OF TWEEZERS very carefully unhook the needle from the suspension—under *no* circumstances must the quadrants or insulators be touched by the fingers. Put the needle in a previously prepared box in a safe place. Damage to the needle in any way will make it impossible to obtain consistent results.

Unclamp the centre brass rod by loosening the set-screw (see Fig. 197A), gently lower it, and remove the suspension with the tweezers. Place it on white paper and put into another prepared box in a safe place.



[A] FIG. 197 [B]

The electrometer is usually supplied with three different suspensions. With a p.d. of 1 volt between the quadrants the least sensitive one will give about 250 mm. deflection on a scale at 100 cm. distance, when the needle is raised to a potential of 100 volts.

Examine in detail the mechanical adjustments of the instrument, and make quite sure that you understand them (if this is done with the needle and suspension in place, damage to one or both is almost certain to occur).

Replace the suspension on its top hook. Carefully put the needle between the quadrants, and adjust the height of the suspension by means of the rod until the bottom hook engages with the needle hook. Clamp the rod by the set screw.

(1) Adjust the height of the needle by the top knurled nut so that it is swinging roughly midway between the top and bottom of the quadrants.

(2) Holding the brass rod steady, unclamp the set screw and turn the rod so that the needle hangs roughly symmetrically along one of the 'open diameters' between the quadrants. Clamp the rod. Unlock the bottom knurled nut, and by adjusting the ebonite torsion head set the needle as accurately as possible (by eye) symmetrically with regard to the above 'open diameter' (Fig. 197B). Clamp the lock nut.

(3) Adjust the top knurled nut so that the needle is accurately midway between the top and bottom of the quadrants.

(4) Close the quadrants.

(5) Adjust the main levelling screws so that the upright needle support hangs centrally between the quadrants as viewed along both the 'open diameters'.

(6) Replace the case, making sure that the window is as nearly as possible parallel to the suspension mirror.

(7) With a dry soft brush dust the top of the case, the terminal supports and the torsion head.

(8) Set up the lamp and scale at 100 cm. from the mirror, and adjust so that the light spot is at the centre of the scale. The scale should be 100 cm. long (see p. 284 for details of the arrangement).

Connecting the Quadrant Electrometer into a Circuit

In a clean block of paraffin wax measuring 6″ × 2″ × 1½″ drill eight holes ¼″ diameter and ½″ deep as shown in Fig. 198, in which *a, b, c, d, e, f, g* and *h* are the holes. Scrape the surface of the block to make sure that dust and dirt are removed and then fill the holes with clean mercury.

Connect the electrometer terminals to the holes by using bare copper wire of S.W.G. 18, using the stiffness of the wire to make self-supporting leads which touch nothing else except the terminals and the mercury. Keep the leads well apart. Connect the needle to *d* through a 1 or 2 megohm resistor of the 'wireless type'. This will prevent damage to the suspension in the event of an accidental short circuit between the needle and the quadrants. If such a resistor is not available, use a water resistor made by filling a 6″ U-tube with water and providing it with corks carrying the leads.

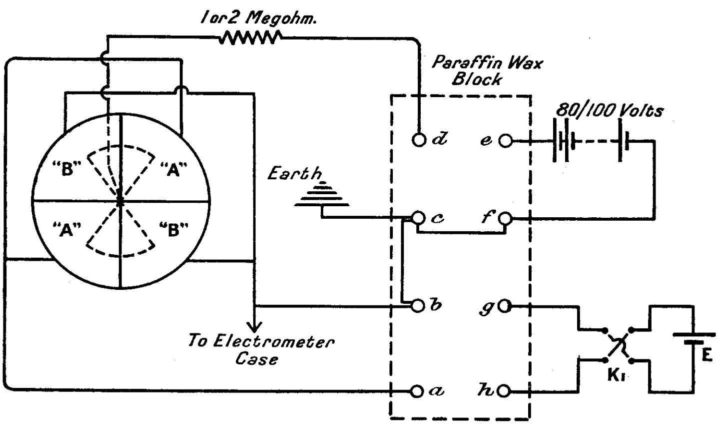


Fig. 198

Connect the 'A' quadrants to *a*, the 'B' quadrants and the case to *b*. The contact *c* is connected to earth by means of a wire soldered to a water pipe. It is important that this earth contact should be good and merely wrapping the lead round a water pipe is not enough—it must be *soldered* to the pipe. Connect *b* to *c* by a short piece of bare wire. The other apparatus is connected to *e*, *f*, *g* and *h* as required by the particular experiment.

To make contact between holes, prepare pieces of bare copper wire, each about 4″ long, and bent into a U shape, and push them into the holes as required. The holes *a* and *h* will sometimes have to be connected without either of them being earthed; for this purpose prepare a contact with an insulated handle by winding a piece of bare copper wire round an insulating cylinder (e.g. an alkathene rod) and bending the ends into a U shape so that they can be pushed into the holes.

Adjusting the Quadrant Electrometer to Zero

Earth the needle, the quadrants, and the case, by connecting *a* to *b* and *c* to *d*. When the light spot is steady, adjust the scale so that the spot is on the zero. This determines the 'mechanical zero'.

Keeping the quadrants 'A' and 'B' earthed, charge the needle by connecting it to the positive end of a high-tension battery of e.m.f. 80 to 100 volts. The negative end of the battery is earthed as shown in Fig. 198. There should be no movement of the light spot when *d* is connected to *e*, if the 'electrical zero' corresponds to the 'mechanical zero'. In general there will be movement, and the object of these adjustments is to make the two zeros coincide, so that the spot remains in the same position whether the needle is charged or earthed.

If the light spot has moved, bring it back towards the mechanical zero by small adjustment of the main levelling screws. Earth the needle by breaking contact between *c* and *f*, and making contact between *c* and *d*. The alteration of the levelling screws may have changed the mechanical zero. Note its new position. Charge the needle again, and by further alterations in the levelling screws, earthing the needle and checking the mechanical zero, make the two zeros coincide. If this is not possible, work can be carried out with a difference of 5 mm. between them.

When the adjustments are satisfactorily completed, arrange the scale so that the light spot is on the zero of the scale.

If the light spot goes right off the scale when it is first connected to the H.T. supply, and will not come back with small alterations of level, the preliminary mechanical adjustments for symmetry and centre of the needle should be repeated with more care.

Now connect the cell E in the circuit by means of a good quality well-insulated reversing switch K_1. Use either an accumulator or a Weston standard cell. Through the contacts *g* and *h* this can charge the 'A' quadrants relatively to the 'B' quadrants, *g* being connected to *b* and *h* to *a*.

With the 100 volts still on the needle, check that the deflection is the same on both sides of the zero when the cell is reversed. If it is not, then carefully adjust the levelling screws until this is so.

It will be necessary to re-check the mechanical and electrical zeros if the level has been changed, until both these and the deflections on both sides of the zero are satisfactory.

Quite good results can be obtained without the use of the reversing switch. The above adjustments are exacting and sometimes exasperating; they cannot be hurried, but the results obtained will repay the time and determination given to them.

Experiment 159. Investigation of the Relationship between the Sensitivity of a Quadrant Electrometer and the Potential of its Needle when the Quadrant Potential is Constant

Apparatus: Quadrant electrometer connected to paraffin wax block as shown in Fig. 198, p. 378; lamp and scale; Weston standard cell; reversing switch of good quality and with well-insulated segments; high tension supply up to 200 volts, or more if available; voltmeter reading to the maximum value of the H.T. supply and having a high resistance, not less than 200 ohms per volt; 4 or 5 paraffin wax blocks on which to stand the various pieces of apparatus.

THEORY

Reference should be made to the textbooks for the complete treatment. With the 'B' quadrants earthed, let the needle be at potential V volts, and the 'A' quadrants at v volts with respect to earth.

The deflection θ is then very nearly proportional to V and v, that is

$$\theta = kVv,$$

where θ is the deflection. If v is kept constant the deflection is nearly proportional to V, provided it is not too high.

In fact the deflection increases proportionally with needle potential at first, it then begins to fall off, finally decreasing after passing through a maximum. This is in the region of 500 volts on the needle.

When the instrument is connected as above, i.e. with the needle at a high potential with respect to both of the quadrants, it is said to be used 'Heterostatically'.

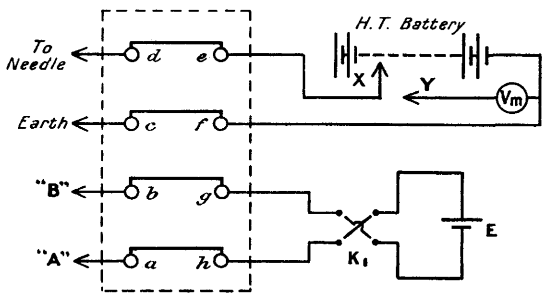


FIG. 199

Procedure: Set up the circuit shown in Fig. 199 in which

E is the standard cell

K_1 the reversing switch

V_m is the voltmeter

X and Y are the movable contacts concerned with the needle potential

a, *b*, *c* and *d* are connected to the quadrant electrometer in accordance with Fig. 198, p. 378.

It is assumed that the preliminary adjustments described on pp. 376–9 have all been carefully done.

Stand the pieces of apparatus on the wax blocks.

Connect *a* to *h*, *b* to *g*, *c* to *f*, and *d* to *e* by the copper U-pieces. Plug X into the lowest voltage contact of the H.T. battery. Obtain the value of this voltage by touching the contact Y on to X and reading the voltmeter. Disconnect Y from X, and when the light spot is steady read the deflection. Reverse K_1 and note the deflection in the opposite direction.

Repeat for all available voltages up to the limit of the H.T. supply.

Good results can be obtained without the use of the reversing switch.

Record and Calculation: Record the observations as follows:

e.m.f. of standard cell . . . . . 1·018 volts

Needle Potential (Volts)	Electrometer Readings			Mean Deflection θ	Deflection per volt $(\theta/1{\cdot}018)$
	Position of 'zero'	Deflections			
		Left	Right		

Plot a graph of deflection per volt (as ordinate) against needle potential. The result should be a shallow curve which approximates to a straight line.

Experiment 160. Investigation of the Relationship between the Sensitivity of a Quadrant Electrometer and the Quadrant Potential when the Needle Potential is kept Constant

Apparatus: Quadrant electrometer connected to paraffin wax block as shown in Fig. 198, p. 378, with lamp and scale. 100-volt H.T. battery; 2-volt accumulator; reversing switch; two resistance boxes (each 0–10,000 ohms); high-resistance voltmeter (0–100 volts); paraffin wax blocks.

THEORY

In the previous experiment it was pointed out that the deflection depended on the product of the needle potential and the quadrant potential. In this experiment the same argument holds but now it is V which is maintained constant while v is varied. The relationship between θ and v will be similar in nature to that between θ and V in the last experiment.

Procedure: Set up the circuit shown in Fig. 200 in which
R_1 and R_2 are the resistance boxes (which act as a potentiometer)
K is the reversing key
E is the accumulator.

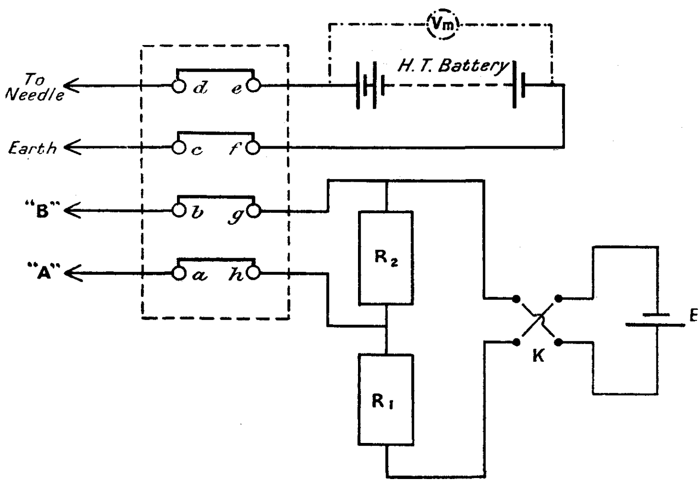


FIG. 200

It is assumed that the preliminary adjustments to the electrometer have been made as described on pp. 376–9.

Connect *a* to *h*, *b* to *g*, *c* to *f*, and *d* to *e* by the copper U-strips.

By means of the voltmeter find the voltage of the H.T. battery; record it and then disconnect the voltmeter.

Give R_1 a value 9,000 ohms and R_2 a value of 1,000 ohms. Close K and note the deflection. Reverse K and note the deflection (in the opposite direction).

Change R_1 to 8,000 ohms and R_2 to 2,000 ohms, and repeat the operations. Continue the reduction of R_1 and the increase of R_2 by 1,000 ohms increments, keeping their sum always 10,000 ohms, and taking observations of the deflections in each case. Cover as wide a range of values as is permitted by the apparatus.

Determine the e.m.f. of the accumulator by comparing it with a standard cell, using a potentiometer (see Experiment 140, p. 332).

Alternatively the e.m.f. may be found, using the method of the next experiment (No. 161).

Record and Calculation: Record the observations as follows:

Potential of the needle . . . . . volts
e.m.f. of the accumulator . . . . . ε volts

R_1	R_2	Quadrant Potential $= \frac{ER}{R_1 + R_2}$	Electrometer Readings			Mean Deflection
			Position of 'zero'	Deflections		
				Left	Right	
9,000	1,000					
8,000	2,000					
etc.	etc.					

Plot a graph of deflection (as ordinate) against the potential of the 'A' quadrants. It should approximate to a straight line passing through the origin.

Note: The proof that $\varepsilon R_2/(R_1 + R_2)$ is the quadrant potential is left as an exercise for the student. It is based on reasoning similar to that used in Experiment 152, p. 358.

Experiment 161. Comparison of the e.m.f.'s of an Accumulator and a Weston Standard Cell, using the Quadrant Electrometer

Apparatus: Quadrant electrometer connected to paraffin wax block as shown in Fig. 198, p. 378, with lamp and scale; 100-volt H.T. battery; 2-volt accumulator and Weston standard cell—or other cells of which the e.m.f.'s are to be compared; reversing key; paraffin wax blocks.

THEORY

If one terminal of a cell is connected to the 'A' quadrants of the electrometer, and the other terminal is earthed, the quadrants will be charged to a certain potential, but no continuous current flows. Hence, by definition, the p.d. between the terminals will be the e.m.f. of the cell.

With a constant high potential applied to the needle,

$$\theta \propto \varepsilon,$$

where θ is the deflection, and ε the e.m.f. of the cell.

If θ_1 is the deflection for cell with e.m.f. ε_1 volts
θ_2 is the deflection for cell with e.m.f. ε_2 volts

then

$$\frac{\theta_1}{\theta_2} = \frac{\varepsilon_1}{\varepsilon_2}.$$

Procedure: Set up the circuit shown in Fig. 201 in which
E is one of the cells
K is the reversing key.

Stand the apparatus on the wax blocks.

The connections from *a*, *b*, *c* and *d* are as usual and it is assumed that the preliminary adjustments have been made in accordance with

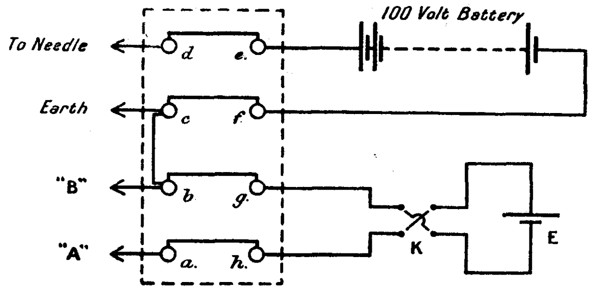


Fig. 201

the instructions on pp. 376–9. Connect *a* to *h*, *b* to *g*, *c* to *f*, and *d* to *e* by the copper U-strips. Close K and observe the deflection. Reverse K and note the deflection (in the opposite direction).

Substitute the other cell and repeat the observations.

Record and Calculation: Record the observations as follows:

Potential of needle . . . . . . volts

For each cell, tabulate as follows:

TYPE OF CELL :—			
ELECTROMETER READINGS			MEAN DEFLECTION
Position of 'zero'	Deflections		
	Left	Right	

Find the ratio of θ_1 to θ_2—this is the value for $\varepsilon_1/\varepsilon_2$.

Note: The method is a very reliable one as the results obtained should justify a claim of accuracy better than 1%. Further, it is the only method of checking standard cells for constancy of e.m.f.

Experiment 162. Comparison of the Capacitances of Two Capacitors, using the Quadrant Electrometer

Apparatus: Quadrant electrometer connected to paraffin wax block as shown in Fig. 198, p. 378, with lamp and scale; 100-volt H.T. battery; 2-volt accumulator (or Weston standard cell); reversing key; well-insulated double-pole double-throw switch; paraffin wax blocks; the two capacitors of which the capacitances are to be compared. A suitable order of capacitance for this experiment is 0·5 – 1·0 μF. The capacitors should be of good quality, otherwise leakage of charge will occur and prevent consistent results being obtained.

THEORY

If one of the capacitors, of capacitance C_1, is charged to a potential of V_1, and is then connected in parallel with the second capacitor, of capacitance C_2, since theoretically there is no loss of charge, the potential will drop to V_2. Hence,

$$Q = C_1V_1 = (C_1 + C_2)V_2 \, ,$$

provided the capacitance of the electrometer can be neglected.

$$\therefore \qquad C_1(V_1 - V_2) = C_2V_2$$

or,

$$\frac{C_2}{C_1} = \frac{V_1 - V_2}{V_2} = \frac{\theta_1 - \theta_2}{\theta_2}$$

where θ_1 is the deflection when the first capacitor (alone) is connected to the electrometer, and θ_2 is the deflection when the two capacitors (in parallel) are connected to the electrometer.

Procedure: Set up the circuit shown in Fig. 202 in which

C_1 and C_2 are the capacitors
E is either the accumulator or the standard cell
K_1 is the reversing key
K_2 is the double-pole double-throw switch.

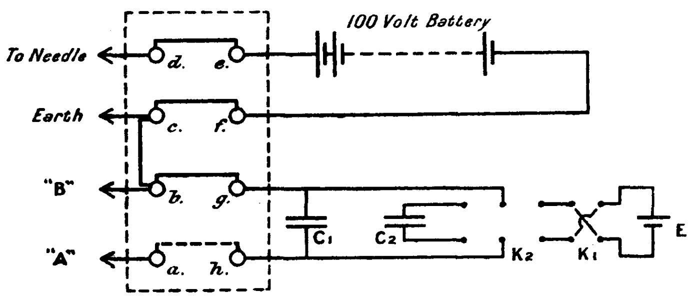


FIG. 202

It is assumed that the usual connections to the electrometer have been made and that the instrument has been adjusted in accordance with the instructions given on pp. 376–9.

It is very important to stand all the apparatus on paraffin wax blocks, and to keep the terminals of C_2 shorted until it is connected to C_1.

Connect *b* to *g*, *c* to *f*, and *d* to *e*. Do NOT connect *a* to *h* yet.

Close K_1, and put K_2 over so that the capacitor C_1 is charged, leaving it in the charge position for at least half a minute. Open the switch K_2, and at the same time connect *a* to *h* by means of the insulated holder carrying the bare copper wire (see p. 379). The charge on the capacitor will raise the potential of the 'A' quadrants, and a deflection will be produced. Record this when it is steady (θ_1).

Just before connecting *a* to *h* it is advisable to connect the 'A' quadrants to earth by connecting *a* to *b*, removing the connecting wire just before *a* is put in contact with *h*.

Now close K_2 so that the charge on C_1 is shared with C_2, taking particular care that no part of the d.p.d.t. switch is touched except the insulated handle. The light spot will be seen to move towards the zero. Record the deflection when it is steady (θ_2).

Disconnect *a* from *h*, discharge both the capacitors by shorting them with a wire for 10 seconds or more. Reverse K_1 and repeat the above sequence.

Obtain a series of readings from which means can be calculated.

Record and Calculation: Record the observations as follows:

Needle potential . . . . . . volts
e.m.f. of cell used . . . . . . volts

ELECTROMETER OBSERVATIONS					Mean Deflection for C_1 alone	Mean Deflection for (C_1+C_2)
Position of 'zero'	DEFLECTIONS					
	Left		Right			
	C_1 only (d_1)	(C_1+C_2) (d_2)	C_1 only (d_1')	(C_1+C_2) (d_2')	$\frac{(d_1+d_1')}{2}=\theta_1$	$\frac{(d_2+d_2')}{2}=\theta_2$

Substitute θ_1 and θ_2 in the equation deduced above to find the ratio of C_1 to C_2.

Note: It was pointed out in the deduction of the equation that the capacitance of the quadrant electrometer was assumed to be small compared with C_1 and C_2. This assumption is justified until capacitors of capacitance of the order of 10^{-12} farads are considered. If experiments are conducted using such capacitors, the capacitance of the electrometer must be determined and allowance made for it.

Experiment 163. Calibration of a Quadrant Electrometer for Idiostatic Use, and the Determination of the Value of an Alternating Potential

Apparatus: Quadrant electrometer connected to paraffin wax block as shown in Fig. 198, p. 378, with lamp and scale; battery, giving range of 0–20 volts, in steps of 1·5 volts—two 9-volt grid bias batteries connected in series are suitable; voltmeter reading up to the maximum e.m.f. of the battery; reversing key; two wander leads; paraffin wax blocks; source of alternating potential the value of which is to be determined—e.g. the output of a 240-volt mains transformer, provided it is inside the range quoted for the battery.

THEORY

If the 'B' quadrants are earthed and the 'A' quadrants are connected to the needle the instrument is said to be used idiostatically. In this case the deflection (which is proportional to the product of quadrant p.d. and needle potential) will be proportional to the square of the applied potential. The quadrant electrometer can thus be used to measure alternating potentials.

Procedure: Set up the circuit shown in Fig. 203 in which
V_m is the voltmeter
K is the reversing key
X and Y are 'wander' leads.

The connections from *a, b, c* and *d* are as usual (Fig. 198) and it is assumed that the preliminary adjustments have already been made in accordance with the instructions given on pp. 376–9.

Connect *c* to *f*, *d* to *e*, and *a* to *d*. The contacts *g* and *h* are not used.

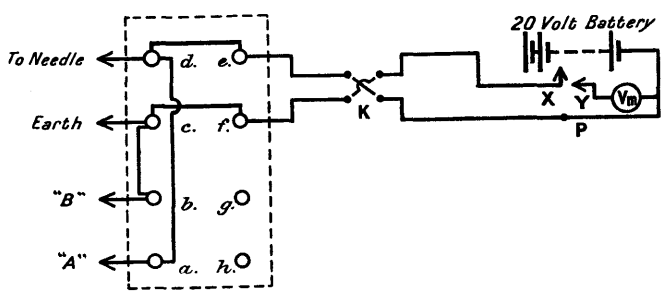


FIG. 203

PART I. CALIBRATION: Plug X into the highest voltage tapping of the battery, and check that the light spot does not go off the scale when steady. If it does, the voltage must be reduced. Touch Y on X and take the reading of the voltmeter; disconnect Y as soon as this has been done. Read the deflection when it is steady. Reverse K and check that the deflection is the same as previously, and in the SAME direction.

Obtain the deflection for the range of voltage provided by the battery.

Record and Calculation: Tabulate the observations as follows:

Potential applied to needle and 'A' quadrants	Electrometer observations			Mean Deflection θ	$\sqrt{\theta}$
	Position of 'zero'	Deflections			
		Left	Right		

Plot a graph of (*a*) Deflection, as ordinate, against potential.
(*b*) Square root of the deflection, as ordinate, against potential.

The first graph will give a curve, while the second will be a straight line through the origin. It should be found that 90% of the points lie on the line.

PART II. DETERMINATION OF AN ALTERNATING POTENTIAL: Connect one end of the transformer secondary to the point P, and the other end to X. Note the deflection when the spot is steady.

From the graph determine the value of the applied potential.

CHAPTER LIII

ALTERNATING CURRENT

Experiment 164. Determination of the Frequency of the A.C. Mains, using a Sonometer

Apparatus: Sonometer with steel wire of diameter about 0·7 mm. Slotted kilogram and half kilogram weights (up to 5 kg.) and hanger; electromagnet with suitable A.C. supply. If the latter is about 6 volts a suitable electromagnet can be made as follows:

An iron core of diameter $\frac{3}{8}''$ and length $2\frac{1}{4}''$ is required; on this core put a layer of insulation tape and then wind on 400–500 turns of No. 26 enamel covered copper wire to occupy about 1½″ of its length. No special care is needed in the winding. Slip lengths of sleeving over the ends of the wire, and protect the windings by a layer of insulating tape. The magnet will have a resistance of about 3 ohms, and on 6 volts A.C. will take just over 1 amp.

THEORY

If a wire of mass m gm. per cm. and length l cm., is stretched with a tension of T dynes it will emit a note of frequency f, where

$$f = \frac{1}{2l}\sqrt{\frac{T}{m}}.$$

In this experiment the note emitted by the sonometer wire is tuned to be the same as the mains 'hum' by adjusting the tension until resonance in the wire is produced by the attraction and repulsion of the wire by the electromagnet.

Thus, as T and l can be measured, if m is known, f can be calculated. The value of the mass per unit length can be determined either by making measurements of the diameter and assuming the density of steel to be 7·7 gm./cm.^{3}, or else by the method of weighing a measured length of the wire. Wire of diameter 0·7 mm. is specified, as it enables a number of readings to be obtained with the same wire.

Procedure: Set up the apparatus shown in Fig. 204 in which
ω is the sonometer wire
M is the electromagnet
F is the fixed bridge of the sonometer
B is the movable bridge
W are the weights for altering the tension.

Support the magnet in a retort stand and fix it between 8 and 10 cm. from F and about 2 or 3 mm. above the wire.

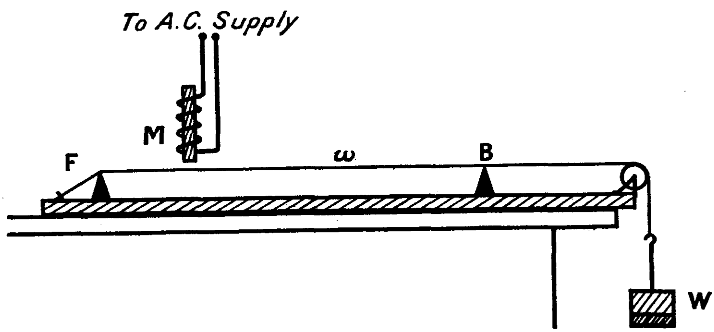


FIG. 204.

Give W a value of 1 kg. and switch on the A.C. supply. Carefully slide B along the wire towards F until the wire starts to vibrate. Make minor adjustments until the amplitude is a maximum and then record (i) the length of wire vibrating (FB) and (ii) the value of W (this will be T when expressed in dynes). Repeat this process with values of W up to 5 kg., by half kilograms.

Determine the mass per cm. of the wire by one of the methods given above.

Record and Calculation: Record the observations as follows:

(i) Data for the determination of m

(ii) Tabulate thus:

Load on wire W gm.	Length FB. cm. (l)	W × 981 dynes (T)	$\sqrt{T}$
1,000			
1,500			
etc.			

Plot a graph of $\sqrt{T}$ (as ordinate) against l. The result should be a straight line through the origin. The slope of this line will be $2f\sqrt{m}$, from which a mean value for f can be calculated. The frequency determined in this experiment, using the above formula, will be twice the mains frequency (why?)

Experiment 165. Determination of the Frequency of the A.C. Mains by Melde's Method

Apparatus: Mains transformer with secondary output of 6 or 12 volts; A.C. ammeter (0–2 amps.); rheostat (0–6 ohms, capable of carrying 5 amps.); plug key; weights and hanger (or scale pan); pulley; 500 cm. of No. 24 cotton; flat copper strip about 2 by 1″ by 1/64th inch with a fine hole bored in it near one end, just large enough for the cotton to pass through; vibrating reed made from a 10″ by ½″ hacksaw blade or from a 10″ length of flat strip. The electromagnet used for the previous experiment (details given on pp. 388–9) is also needed. The vibrator must be rigidly fixed to a support, with the magnet near to it, but capable of adjustment.

The arrangement shown in Fig. 205 is easily made and quite effective. The base and vibrator support are made of wood. The vibrator is held firmly in place by the pieces of steel strip, A and B; it can be adjusted by loosening the screws, *c*. The magnet is held down by the strip of wood W, and can be adjusted for position by the screws, *s*. W is 15 cm. by 2 cm. by 0·5 cm.

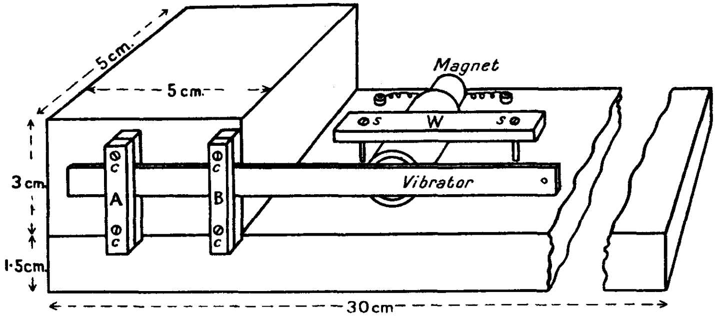


FIG. 205

THEORY

If a string is attached to a vibrating reed so that it is perpendicular to the reed and in the plane of vibration, it will be set into vibration in tune with the reed. Well-marked nodes and anti-nodes will appear as the tension on the string is changed. If the length of the string is varied, for a given tension it will be found that for a certain length the amplitude of vibration of the string is a maximum, and the nodes and anti-nodes well marked. The wave-length can therefore be measured for a particular tension on the string. The frequency of vibration can then be calculated by applying the formula:

$$f = \frac{1}{\lambda}\sqrt{\frac{T}{m}} = \frac{1}{\lambda}\sqrt{\frac{Mg}{m}}$$

where f is the frequency in vibrations per second
λ is the wavelength in cm.,
T is the tension in the string in dynes,
M is the load on the string in gm.,
g is the acceleration due to gravity in cm./sec./sec.
m is the mass per unit length of the string in gm./cm.

In this experiment the iron reed is set vibrating by means of the electro-magnet which takes its supply from the A.C. mains, the frequency of which is to be determined. A series of values of λ and M is observed and a graph plotted of $\sqrt{M}$ (as abscissa) against λ. The slope of this graph will be $\frac{1}{f}\sqrt{\frac{g}{m}}$, from which f can be found, since g is known and m has been determined.

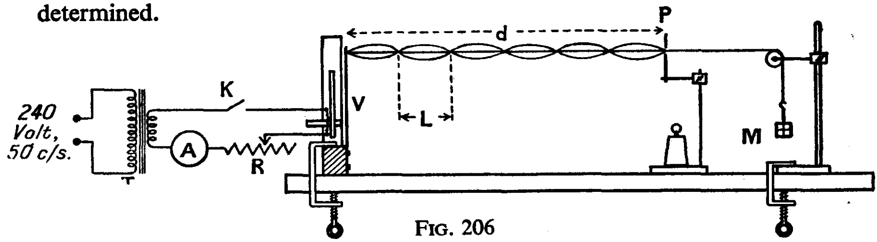


FIG. 206

Procedure: Arrange the apparatus as shown in Fig. 206 in which

T is the transformer
R is the rheostat
A is the ammeter
K is the plug key
V is the vibrating reed with the string attached to it
P is the plate in which is the small hole through which the string passes.
M is the mass producing the tension in the string.

Make sure that the vibrator and the pulley holder are securely clamped to the bench and that the support for the plate is rigid.

The distance d should be about 200 cm. It will vary during the experiment. Load the cotton with a 20 gm. weight, close K and adjust the length of the reed and the position of the magnet until the amplitude is a maximum. Now adjust P so that the nodes and anti-nodes are well marked and the amplitude a maximum again. Count the number of loops between V and P, and measure the distance d.

Repeat with increasing loads, adjusting the position of P for each load so that the nodes are well marked and the amplitude a maximum. It will be necessary to move the magnet nearer to the reed for each load, to obtain maximum amplitude.

Weigh a known length of cotton, not less than 500 cm., on a good balance.

Record and Calculation: Tabulate the results as follows:

Load M gm.	$\sqrt{M}$	Number of loops $= z$	Distance d (cms.)	$\lambda = \frac{2d}{z}$

Length of cotton weighed . . . . . cm.
Weight of cotton . . . . . . gm.
Therefore mass of unit length of cotton is . gm./cm. (m)

Plot λ against $\sqrt{M}$ and find the slope of the best straight line drawn through the points. Hence calculate the value for f.

Note: It is worth while repeating the experiment with the reed rotated through 90° so that it vibrates in a plane perpendicular to the length of the cotton. Explain the results obtained in this experiment.

Experiment 166. Determination of the Frequency of the A.C. Mains, using Known Capacitances

Apparatus: Moving iron ammeter (0 – 1·0 amp.); double-pole switch; four capacitors, two of capacitance 1 μF and two of 2 μF. These must be of good quality—the oilfilled paper type is suitable. 10 K. resistor mounted on insulating handle for discharging capacitors.

THEORY

If a circuit has capacitance only, i.e. the resistance and inductance can be neglected, the relationship between current and potential difference is

$$I = \frac{\varepsilon}{X_C}$$

where I is the alternating current flowing (i.e. the r.m.s. value),
ε is the alternating e.m.f. applied (i.e. the r.m.s. value)
and X_C is a constant for the circuit known as the 'Reactance' (in this case it is 'capacitative reactance').

It can be shown that for a capacitor of capacitance C farads to which is applied an alternating e.m.f. of frequency f cycles per second the capacitative reactance is given by

$$X_C = \frac{1}{2\pi fC}.$$

Combining this with the above relationship we obtain

$$\frac{\varepsilon}{I} = \frac{1}{2\pi fC}.$$

Thus if ε and I are measured, C being known, f can be found.

Procedure: Set up the circuit shown in Fig. 207 in which

C is one of the capacitors of known capacitance
A is the ammeter guarded by a 1 amp. fuse in series with it
K is the double-pole switch.

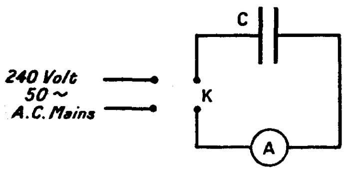


FIG. 207

Start with C being the capacitor of 1 μF capacitance, switch on with K, and record the reading of the ammeter.

Switch off and discharge the capacitor with the 10 K. resistor, checking that the discharge is complete by shorting the terminals of the capacitor with a screw-driver. (The reason for this precaution is that if by chance the switch was opened when the mains voltage was at its peak, the capacitor terminals would remain at a p.d. of 340 volts approx. In fact it will be the rare case when the capacitor has no residual charge after switching off).

Replace the capacitor by a 2 μF. capacitance; switch on and record the current.

Switch off and discharge; replace the 2 μF capacitor by a 1 μF and a 2 μF in parallel and repeat the observation. Repeat again with two 2 μF capacitors in parallel, giving an effective capacitance of 4 μF. Continue changing the capacitance of the circuit and take as many observations of the current as possible with the capacitors available. Using a suitable meter, measure the mains voltage. It may be assumed that this is the p.d. across the capacitor.

Record and Calculation: Tabulate the observations as follows:

Voltage of supply . . . . . volts

Capacitance (μF)	1	2	3	4	5	6
Current (amps.)						

Plot a graph of current (as ordinate) against capacitance. The slope of this graph—which should be a straight line—is $2\pi f\varepsilon$, from which f can be found, since ε has been determined.

Note: If f can be assumed this method can be used to determine C.

Experiment 167. Determination of the Inductance of an Air-cored Solenoid

Apparatus: Mains transformer with output of 5–10 volts at 1–2 amps.; two 2-volt accumulators; moving iron ammeter (0–1 amp.); moving iron voltmeter (0–5 volts); double-pole switch; non-inductive rheostat (0–20 ohms, capable of carrying 1 amp.), such as the carbon plate pressure type; the solenoid.

The latter can conveniently be the 800 turn coil from the Stenzl apparatus supplied by Messrs. Reynolds and Branson, Leeds. It has a resistance of about 2·6 ohms.

THEORY

When an alternating e.m.f. is applied to a circuit which has inductance and resistance (but not capacitance) the relationship between the current and the e.m.f. is

$$I = \frac{\varepsilon}{Z}$$

where ε is the alternating e.m.f. applied,
I is the current in amps. flowing
and Z is a constant for the circuit known as the *impedance*.

This quantity can be calculated from the equation

$$Z^2 = R^2 + X_L{}^2$$

where R is the resistance of the circuit in ohms
and X_L is another constant for the circuit known as the 'inductive reactance'—compare with the capacitative reactance mentioned on p. 393.

If now direct e.m.f. is applied, and the direct current so caused is measured, the resistance of the circuit can be found, since

$$\frac{\text{Direct voltage}}{\text{Direct current}} = \text{Resistance } (R).$$

Thus by measuring the current produced first by a known direct e.m.f. and then by a known alternating e.m.f., both R and Z can be found and hence X_L calculated.

But X_L is related to the inductance of the circuit by the following equation:

$$X_L = 2\pi fL$$

where f is the frequency of the alternating supply
and L is the inductance of the circuit in henries.

If f is known L can be found, using this equation.

The power factor, cos δ, is also obtainable from the relationship

$$\cos \delta = \frac{R}{Z}$$

and hence δ, the angle of lag, can be found.

Procedure: Set up the apparatus shown in Fig. 208 in which
L is the solenoid of which the inductance is to be measured
V is the voltmeter
A is the ammeter
R is the rheostat
T is the transformer
K is the double-pole switch.

PART I: Adjust R to its maximum value and switch on the current. Note the readings of A and V. Decrease R by convenient steps and record the p.d. and the current for each value of R.

PART II: Switch off, remove the transformer and connect the circuit in series with a 4-volt battery (the two accumulators in series). This should be connected across P and Q. Repeat the variation of R and record the p.d. and the current for each value again.

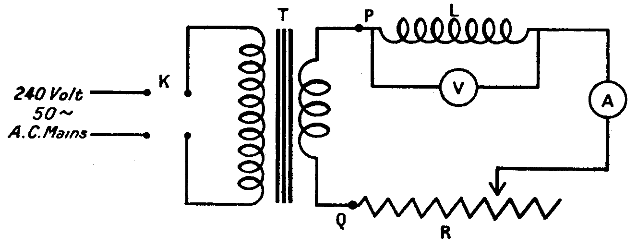


FIG. 208

Record and Calculation: Tabulate the observations as follows:

PART I. A.C.		PART II. D.C.	
p.d. (volts)	Current (amps.)	p.d. (volts)	Current (amps.)

Plot current (as abscissae) against p.d. for both the alternating and the direct current, using the same axes for them both.

From the slope of the straight lines so obtained find values for Z and R.

Hence find X_L and calculate a value for L, assuming that f is 50 cycles per second. L will be in henries.

Calculate also the power factor and the angle of lag.

Experiment 168. Investigation of the Relationship between the Current Passed by a Metal Rectifier and the Applied Voltage

Apparatus: Metal rectifier; 2-volt accumulator; plug key; 100-ohm potentiometer; voltmeter (0–1·5 volts); two milliammeters (one 0–15 mA., the other 0–150 mA.).

The ranges of these instruments are suitable for a copper oxide rectifier element of diameter 3·5 cm. The potentiometer may be of the wireless type, wire wound.

THEORY

An account of the mode of operation of metal rectifier elements is given on pp. 277–82.

Procedure:

CURRENT IN FORWARD DIRECTION: Set up the circuit shown in Fig. 209 [A] in which

B is the 2-volt accumulator
K is the plug key
A is the milliammeter, *reading to* 150 *mA*,
V is the voltmeter
P is the potentiometer
F is the rectifier.

Connect the oxide to the positive terminal of the potentiometer. Increase the p.d. applied to the element through the range 0–1 volt (approximately) and record corresponding readings of A and V for about six different values.

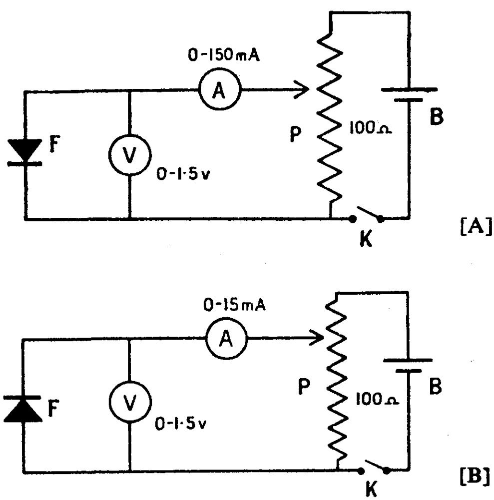


FIG. 209

CURRENT IN REVERSE DIRECTION: Rearrange the circuit by connecting the oxide to the negative terminal of the potentiometer and replacing the milliammeter by the one of range 0–15 mA, as shown in Fig. 209 [B].

Take a series of observations similar to those recorded in Part One.

Record and Calculation: Tabulate the observations as follows:

FORWARD DIRECTION		REVERSE DIRECTION	
p.d. (volts)	Current (amps.)	p.d. (volts)	Current (amps.)
+0·1		−0·1	
+0·2		−0·2	
+0·3		−0·3	
etc.		etc.	

(i) Plot current (as ordinate) against p.d. Is Ohm's law obeyed?

(ii) From the graph determine the resistance of the rectifier for various voltages and plot resistance (as ordinate) against voltage. State your conclusions.

Note: The circuit given above can be modified so that a junction rectifier can be investigated. With such a rectifier it is necessary to guard against overloading and the maker's specifications should be consulted when the circuit is being designed. Thus, if an A.E.I./B.T.H. SJDX12B is used the circuit shown in Fig. 210 could be employed. For this rectifier the peak inverse voltage is 200 and the maximum current allowable is

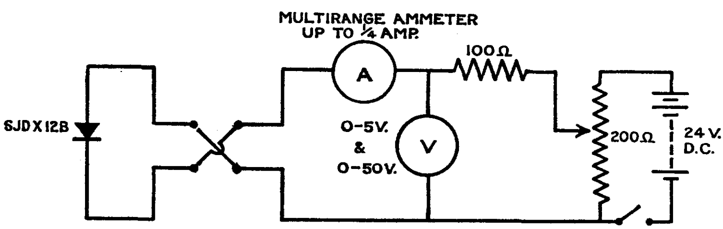


Fig. 210

0·5 amp. The 100 ohm series resistance offers an effective guard against overloading the rectifier as it restricts the current to ¼ amp. It will be found that a multirange ammeter is an advantage and the voltmeter should have at least two ranges (in this case 0–5 V. for the forward direction and 0–50 V. for the reverse direction).

PART VIII

ELECTRONICS

CHAPTER LIV

STANDARD PROCEDURE

Before attempting any of the electronic experiments, the following notes should be carefully read and considered. Ask your instructor for help on those matters which you do not understand. It is very easy to damage apparatus if incomplete consideration is given to circuits and component values, and in particular a careful check before switching on H.T. power is most necessary.

The theory textbooks should be read before starting any experiment, as no attempt has been made to give anything but the barest outline of the principles involved.

High-Tension Voltage Supply

(1) H.T. batteries: The dry cell type of 120-volt battery is suitable for some experiments, but not for all. It is not capable of delivering current of the order of 10 mA for very long. Milnes H.T. batteries, which can be recharged in the same way as an accumulator, are very effective and will last for many years if treated with reasonable care.

(2) Metal Rectifiers: Either the copper oxide or selenium-iron type can be used. The latter have a lower internal resistance and can pass a higher current without overheating. A transformer is required to supply the correct input voltage. They do not appear to deteriorate in any way with time. Reference should be made to Chapter XLI, pp. 277–82, for more information on rectifiers.

(3) Valve Rectifiers or 'power packs': In this method a double diode rectifier valve is fed from a transformer, the output being freed from ripple by means of a reservoir and a smoothing capacitor across the output. Details of a power pack with a fixed output voltage (suitable for supplying the potentiometer chain of a cathode ray tube) are given on pp. 438–40. For work with valves a lower output voltage is needed and the experiments also demand that this H.T. supply shall be variable. The motor generators discussed on pp. 402–3 afford the best method of achieving this, but the power pack described below will also be found of value for voltages exceeding 50 V.

The circuit is shown in Fig. 211. The A.C. supply to the anode is from one half of the 350–0–350 secondary winding of the transformer, this being of the 'wireless type' giving output current of 80–100 mA. The heater voltage must be that for which the valve is rated. The slider of the $\frac{1}{4}$–$\frac{1}{2}$ Meg. potentiometer, which is connected across the 350-volt winding, varies the bias on the grid of the valve and so controls the output voltage. It is important to use an insulated knob for this slider and as an added precaution it should be fixed to the potentiometer spindle by means of an insulated sleeve or spider connector. A high-resistance voltmeter across the output enables the voltage to be measured and serves to discharge the capacitors after use. If no voltmeter is fitted a 'bleeder resistance' of value 200K–500K. should be wired in its place.

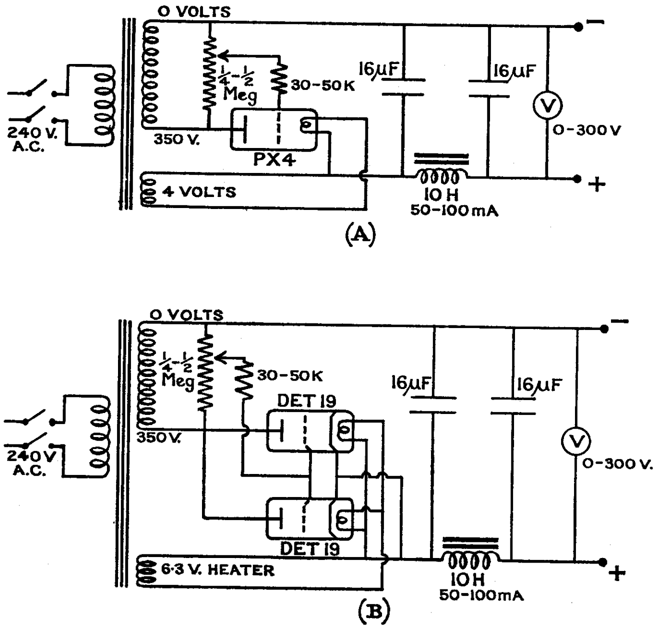


FIG. 211

A PX4 valve may be used as shown in Fig. 211[A], and this will give 220 volts at 50 mA. with a load of 4·5 K. It has a directly heated cathode (see p. 405) which takes 1 amp at 4 volts. The base is British 4-pin.

Alternatively, two DET19 valves in parallel can be used as shown in Fig. 211[B]. These will give 175 volts at 45 mA with a load of 4·5 K. These valves are indirectly heated (see p. 405) and the heaters each take 0·8 amp. at 6·3 volts. The bases are small UX7. These valves can usually be obtained for a few shillings (see advertisements in 'Wireless World').

An alternative power pack to the above is described by A. H. B. Walker in 'Wireless World' for September 1952. It is rather more complicated but forms a useful constructional exercise.

(4) Rotary Transformers (Rotary Converters or Motor Generators): These are combined electric motors and generators. The armature has a commutator on each end. One commutator is fed with low-voltage D.C. at about 12 or 24 volts, and the other, which has many

more segments on it than the first, supplies D.C. at about 200 volts. The speed of the motor can be controlled by a rheostat of about 6 ohms carrying 5 amps., the motor requiring about 2·5 amps. By the speed control the output voltage can be varied from about 10 to 200.

For most purposes (especially school work) this method is the most satisfactory because the rheostat controlling the speed affords control of the output voltage, and potentials below 50 volts can be obtained and controlled equally easily. Motor generators can be bought relatively cheaply (in the range 15/– to 40/–) from suppliers who advertise in 'Wireless World'. A careful study of the advertisements and comparison of the prices quoted for the same article is desirable. The time spent is well repaid in the economy which can be achieved when purchasing. This advice in fact applies to the purchase of most electrical equipment, including meters, transformers, rectifiers, resistors, etc.

Potentiometers

The voltage applied to the valve electrodes in the following experiments has to be varied. This can be done by using a wander plug and moving it from tapping to tapping of the H.T. battery. In some

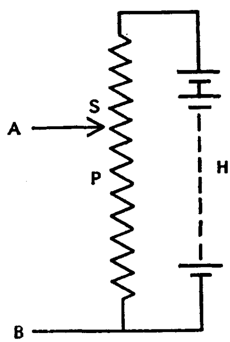


FIG. 212

cases, however, the voltage has to be varied and must not be switched off while this is being done. A potentiometer is therefore connected across the H.T. supply to provide the variable voltage. The potentiometer takes the form of many turns of high-resistance wire wound on a former. The supply is connected to the two ends of the wire. By means of a sliding contact which can move up and down the wire, in contact with it, the potential between the slider and either end of the wire can be continuously varied. Fig. 212 shows the arrangement. H is the H.T. battery, P the potentiometer, S the slider. By moving S up or down the wire the potential between the points A and B can be varied. A motor generator can be used instead of H; care must be taken to choose a potentiometer which will carry the output current safely.

Voltmeters

For measuring the H.T. and grid bias voltages applied to the valves, voltmeters of high resistance and good quality will be needed. If the resistance is low the drain on the H.T. battery due to the voltmeter alone may be more than the current taken by the valve. For example, if a voltmeter of resistance 10,000 ohms is used across a high-tension battery of e.m.f. 100 volts the current through the meter will be 10 mA. This together with the valve current may be more than the battery can deliver without seriously reducing its life.

CHAPTER LV

THERMIONIC VALVES

The simplest type of thermionic valve has two electrodes and is called a *diode*. One electrode, the cathode, is a wire filament similar to that of an ordinary electric lamp. The other, the anode, is an open-ended metal box surrounding the cathode, but not in contact with it. The electrodes are enclosed in an evacuated glass envelope, the pressure being of the order of 10^{-7} mm. of mercury.

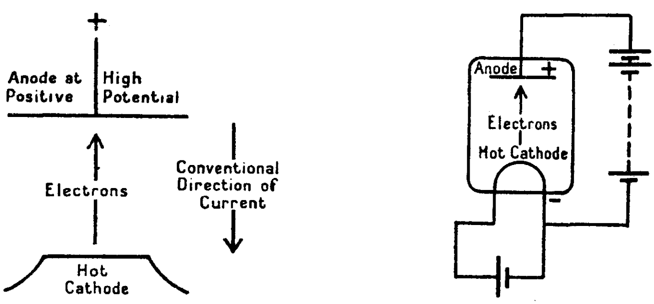


FIG. 213

They are called valves because they have the property of conducting electricity in one direction only. This is done by the transfer of electrons from the heated cathode to the anode, which is maintained at a high positive potential in order to attract the electrons. Fig. 213 shows this diagrammatically.

If the cathode is heated by passing a current through it, the valve is said to be 'directly heated', and the arrangement is shown in Fig. 213. More often the cathode is provided with an independent heater through which A.C. is passed. The valve is then said to be 'indirectly heated', and is often called a 'mains' valve. Fig. 214A and B shows the arrangement of the electrodes and the method of indirectly heating the cathode.

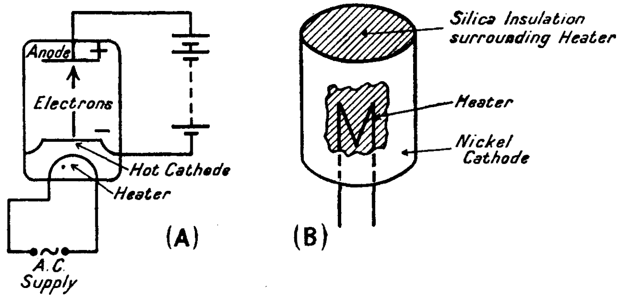


FIG. 214

In conventional diagrams the electrode connections are shown as coming from the top, bottom and sides of the valve. In fact in the majority of cases the wires from the electrodes are brought out to metal pins in the bottom cap of the valve. Connection to the valve is made by means of a valve holder—an assembly of sockets into which the valve fits. Each socket is connected by a metal strip either to a terminal or solder tag on the holder. The circuit wiring is connected to these terminals or tags.

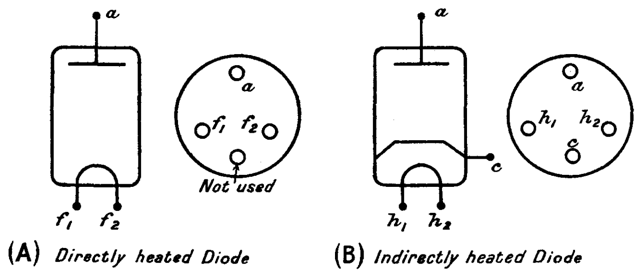


FIG. 215

It is a saving of time to fix some of the commoner holders on to square pieces of paxolin or ebonite, and to wire the sockets to terminals on this insulating base.

The relative position of the pins depends on the make and type of valve. There is no standard method of arrangement. It is therefore necessary to consult makers' lists and catalogues to be sure of identifying the electrodes. The 'Wireless World Valve Data Book' is recommended for this purpose.

The diagrams show the arrangement as seen when the pins are pointing towards the observer.

Fig. 215A and B shows a directly heated and an indirectly heated diode, with the electrodes and valve sockets correspondingly labelled. The holder in each case is a standard British four-pin type. *a* is the

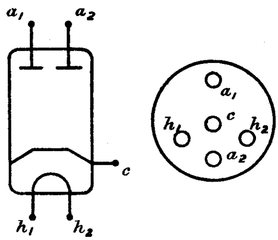


FIG. 216

anode connection and its socket; f_1 and f_2 the filament connections and sockets. In B, *c* is the cathode connection and socket, whilst h_1 and h_2 are the heater connections and sockets; in A the cathode connection would be made to the end of the filament which is connected to the negative pole of the heater current supply.

Fig. 216 shows the arrangement for an indirectly heated double diode. The holder is a standard British five-pin type, the cathode being connected to the centre socket.

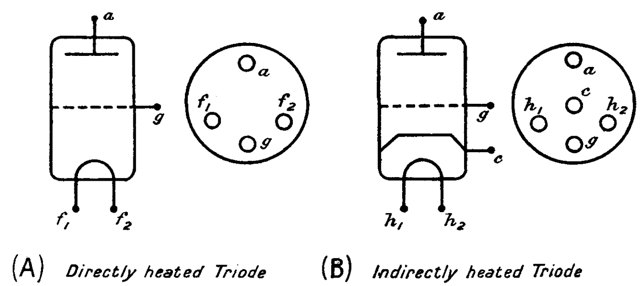


FIG. 217

The electrode connections and holders for a triode valve are shown in Fig. 217A and B. It will be noted that either the standard British four- or five-pin holder is used.

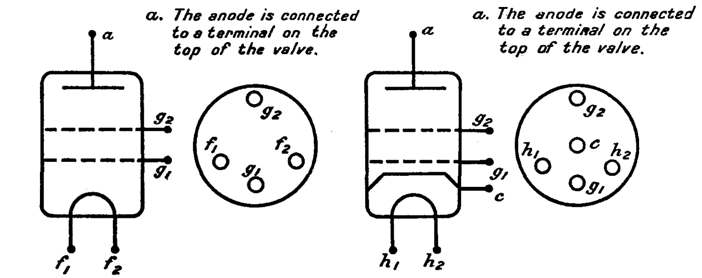
For the tetrode and pentode valves, Figs. 218A and B and 219A and B give the connections and arrangement of the electrodes.

It will be seen that the indirectly heated pentode has a seven-pin base. The type shown is the standard British seven-pin holder, one of the sockets not being used.

Other common types of valve base are I.O. (International Octal), and M.O. (Mazda Octal). Details of these will be found in the '*Wireless World Radio Valve Data Book*'.

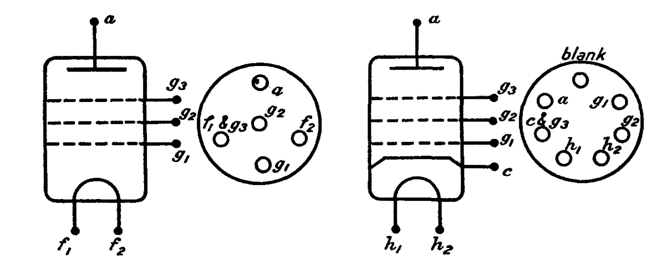
The majority of valves used in commercial radio are B7, B8 or B9 types. They are much smaller, the connections being made via small pins sealed through the glass bases. They are not recommended for school use because the pins are easily bent accidentally and the base connections leave little room for soldering.

It is again emphasised that the arrangement of the electrodes differs from maker to maker and it is always necessary to check the connections against a catalogue description.



(A) *Directly heated Tetrode* (B) *Indirectly heated Tetrode*

FIG. 218



(A) *Directly heated Pentode* (B) *Indirectly heated Pentode*

FIG. 219

Experiment 169. Investigation of the Relationship between the Anode Current and the Filament Current for a Diode Valve of which the Anode Voltage is Constant

Apparatus: H.T. supply (see p. 401); three ammeters (one, 0–5 mA $\times \frac{1}{10}$, another 0–150 mA, and a third, 0–3 amps. $\times \frac{1}{10}$); voltmeter to read to the maximum value of the H.T. supply; rheostat (0–6 ohms to carry 5 amps.); plug key; double-pole double-throw switch; wander plug or crocodile clip; cathode heater supply. Diode valve and valve holder.

For this experiment the choice of the valve is important. A valve with a directly heated filament should be used. With the indirectly heated types there is a considerable time-lag between the alteration of the heater-current and steady temperature conditions of the cathode, and they are unsuitable for this experiment.

Directly heated filament diodes operating at suitable low voltages are now unobtainable but good results can be achieved with a Mazda HL23 directly heated triode. If the grid is connected to the anode the valve will act as a diode. The anode voltage is about 150 and the anode current, although rated at 1·5 mA., can be raised for experimental purposes to 8–10 mA. These valves are obtainable on the surplus market for about 10*s*.

If apparatus is available for supplying higher voltages and currents the directly heated 5Y3 on an I.O. base passes 125 mA. at 350 volts. The filament current is 2 amps. at 5 volts.

The Ferranti GRD7 directly heated diode is especially designed for this investigation. Without the guard-ring in circuit, 200–250 volts on the anode give saturation at filament currents of 1·9, 2·0 and 2·2 amps. The makers supply with the valve (which costs about £3) a graph showing filament temperature against filament current.

The Ferranti KE10 is another directly heated diode which is at present being developed (January 1961). It is primarily designed to investigate the magnetron effect and is likely to differ from the GRD7 in that (i) it will have a split anode, and (ii) it will not have a guard-ring.

THEORY

Thermionic emission depends on the nature of the surface and on the temperature. With rise in temperature the emission is very small at first, but after a certain temperature, depending on the surface, it increases rapidly with further rise in temperature.

If the anode of the valve is made positive with respect to the cathode, the emitted electrons will be attracted to it, so constituting a current called the anode current.

By varying the current through the filament or heater, the cathode temperature can be altered and the effect on the anode current observed.

Procedure: Set up the circuit as shown in Fig. 220 in which

T is the valve
H is the H.T. battery
L is the low-tension supply for heating the cathode
A_1 and A_2 are the anode current meters
A_3 is the filament current meter
V is the voltmeter
R is the rheostat
K_1 is the double-pole double-throw switch
K_2 is the plug key
W is the wander plug.

In Fig. 220A

a_1 and a_2 are the valve base terminals to which the anodes are connected

f_1 and f_2 are the terminals to which the filament is connected

f_2, it will be noted, is also the cathode connection, since it is connected to the negative end of the H.T. battery

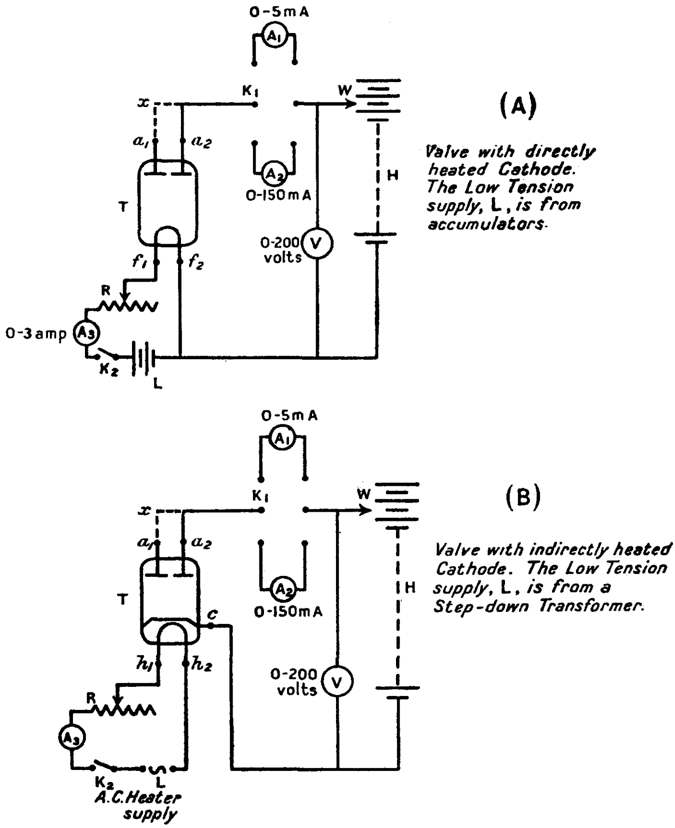


FIG. 220

In Fig. 220B

a_1 and a_2 are again the valve base terminals to which the anodes are connected

h_1 and h_2 are the terminals to which the heater is connected

c is the cathode terminal.

If the valve is a double diode, either a single anode may be used, the other being left disconnected, or they can be connected together and treated as one anode, as at x in the diagram. In the latter case the anode current will be approximately doubled.

Switch on K_2 and adjust R so that the minimum heating current flows; Plug the wander lead into the 80- or 100-volt tapping of the H.T. battery, and switch K_1 so that the 5 mA meter is in circuit. It is quite possible that no current will be registered by it. Keeping the anode voltage constant, increase the filament current *gradually* until a reading is obtained on the anode current meter. Record the filament current and the anode current. Increase the filament current by small steps, and read the anode current for each value. Check that the anode volts remain constant throughout. Continue the readings up to the safe limit of filament current, changing over to the 150 mA meter when the range covered by the smaller instrument has been reached. This arrangement of meters allows the lower values of current to be measured with greater accuracy.

If a valve with an indirectly heated filament is used it will be found necessary to wait at least two minutes between each alteration of heater current to allow the temperature to become steady.

Record and Calculation: Tabulate the observations as follows:

Anode voltage . . . . . . volts

Filament Current I_f (amps.)						
Anode Current I_a (mA)						

Plot a graph of anode current, I_a, (as ordinate) against the filament current, I_f. State your conclusions.

Experiment 170. Investigation of the Relationship between the Anode Current and the Anode Voltage for a Diode Valve of which the Filament Current is Constant

Apparatus: As for the previous experiment (No. 169, p. 407).

THEORY

When the cathode of the valve is heated, electrons are emitted from it. This leaves the cathode positively charged. If the anode potential is zero, the electrons will be attracted back to the cathode. The emitted electrons surrounding the cathode form what is known as a 'space charge'.

If the anode potential is made positive, some of the electrons will penetrate the space and reach the anode, thus producing a small current. As the anode potential rises, more electrons will reach the anode, so increasing the anode current, until finally all the electrons emitted by the cathode are attracted to the anode. The anode current is then a maximum, and is known as the saturation current. Further increase of the anode potential will not increase the current through the valve to any great extent.

In this experiment we investigate the effect of the variation of anode voltage for three different values of the filament current. One type of valve gave the curves shown in Fig. 221 and the shape of these 'characteristics', as they are called, is typical for all diodes.

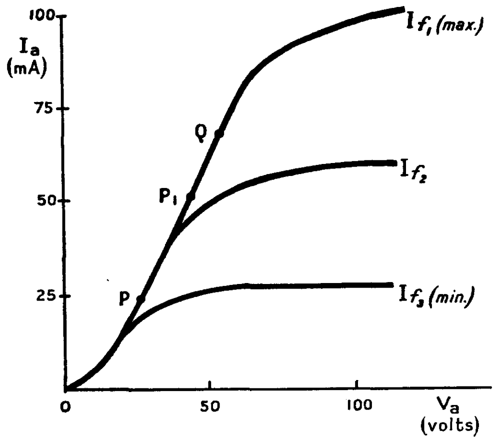


FIG. 221

For the straight part between P and Q, the change in I_a for a given change in V_a must be constant. This constant is known as the 'slope resistance' of the valve; it is sometimes called the 'A.C. resistance' or the 'A.C. impedance' of the valve. It is denoted by the symbol r_a or R_a. It is equal to the reciprocal of the slope of the graph over the straight part indicated.

Thus, for the straight part of the graph,

$$r_a = \frac{\text{change in } V_a}{\text{change in } I_a} = \frac{dV_a}{dI_a}.$$

Note that this is not the same as the abscissa of the point P_1 divided by the ordinate of P_1. This would give the D.C. resistance of the valve, which is not constant, and is of little practical interest.

Procedure: Set up the circuit as shown in Fig. 220 and described on pp. 408–10. Switch on K_2 and adjust the heater current by means of R until it is the correct value for normal working of the valve, as given in the maker's specification.

Put the wander plug in the lowest voltage tapping of the H.T. battery, i.e. at about 10 volts. By means of K_1 switch the 150 mA meter into the circuit and note the current. If it is below 5 mA, change over to A_1. Note the reading of the voltmeter V ($=V_a$), and the reading of the ammeter A_1 or A_2 ($= I_a$). Increase V_a steadily up to the maximum of the H.T. supply or that permissible for the valve, noting the corresponding values of I_a. Check that the heater current remains constant throughout the observations.

Repeat the readings with the heater current reduced by 0·1 amp. and by 0·2 amp. from the normal value.

Record and Calculation: Tabulate the results as follows:

Filament Current I_f (amps.)	Anode Voltage V_a (volts)	Anode Current I_a (milliamps)
First value		
Second value		
etc.		

Plot a graph of I_a (as ordinate) against V_a for each value of I_f, Plotting all the curves on the same axes. State your conclusions.

Experiment 171. Investigation of the Anode Characteristic Curves and Determination of the Valve Constants for a Triode Valve.

Apparatus: H.T. supply; grid bias battery (9 volts); two ammeters (0–5 mA and 0–15 mA); two voltmeters (0–15 volts and 0–150 volts); double-pole double-throw switch; reversing switch; plug key; cathode heater supply to suit the valve used; triode valve and valve holder; two wander-plugs.

The valve can be the HL23 as previously used, or the indirectly heated 6J5 which has an I.O. base.

THEORY

The space charge produced by the electrons emitted from the cathode of a diode is situated quite close to the cathode. The triode valve has a third electrode between the anode and the cathode, very close to the cathode.

It consists of a mesh of fine wire wound round the cathode, but not touching it.

Potentials applied to this electrode, known as the 'control grid', have therefore a big effect on the space charge, and since it is so much nearer to the cathode than to the anode, changes in the potential of the control grid have a far greater effect on the anode current than similar changes in anode potential.

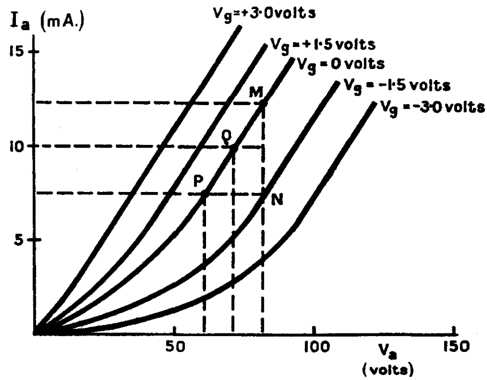


FIG. 222

It is this controlling effect which the experiment demonstrates, by means of the curves shown in Fig. 222 where I_a (the anode current) is plotted against V_a (the anode voltage) for various values of the grid bias (V_g). These are referred to as 'anode characteristic curves', and from them three important valve constants (or 'parameters') can be found. They are

(1) The A.C. resistance (r_a)
(2) The amplification factor (μ), and
(3) The mutual conductance (g_m).

The method by which these parameters can be deduced from the curves will be made clear by reference to Fig. 222, in which actual values have been plotted.

(1) THE A.C. RESISTANCE OF THE VALVE, r_a, can be found from the graph in the same way as for the diode in Experiment 170. The grid bias must, however, be constant.

So

$$r_a = \frac{dV_a}{dI_a}$$

for the straight part of the graph, and with V_g constant.

In Fig. 222, P and Q are two points on the $V_g = 0$ curve. Between these points V_a has changed from 60 to 70 volts, and I_a from 7·5 to 10 mA.

$$\therefore \quad r_a = \frac{10}{2{\cdot}5 \times 10^{-3}} = 4{,}000 \text{ ohms.}$$

The straight part of any of the curves can be used to calculate r_a, since they will be found to be parallel.

(2) THE AMPLIFICATION FACTOR, μ, is defined as

$$\frac{\text{change in } V_a \text{ needed to cause a given change in } I_a}{\text{change in } V_g \text{ needed to cause the same change in } I_a}.$$

So, $\mu = \dfrac{\delta V_a}{\delta V_g}$, and it is a number with no units.

In Fig. 222 between the points P and M on the $V_g = 0$ curve, I_a changes from 7·5 to 12·5 mA, i.e. by 5 mA.

This change in I_a could be brought about by a change in V_a from 60 to 80 volts, V_g being constant at zero.

It could also be brought about by moving from N to M, V_a being constant at 80 volts, but V_g changing by 1·5 volts.

$$\therefore \quad \mu = \frac{20}{1 \cdot 5} = 13 \cdot 3.$$

(3) MUTUAL CONDUCTANCE, g_m is defined as

$$\frac{\text{change in } I_a}{\text{change in } V_g} \quad \text{when } V_a \text{ is constant.}$$

Thus $g_m = \dfrac{\delta I_a}{\delta V_g}$. It is usually expressed in mA per (grid) volt.

As previously, from N to M, I_a changes by 5 mA, and the bias changes by 1·5 volts.

$$\therefore \quad g_m = \frac{5}{1 \cdot 5} = 3 \cdot 3 \text{ mA per volt.}$$

It will be seen that

$$\mu = g_m \times r_a ,$$

providing that g_m is expressed in amps. per volt.

Procedure: Set up the circuit as shown in Fig. 223 in which

T is the valve
H is the high-tension battery
G is the grid bias battery
L is the low-tension supply for the cathode heater
A_1 and A_2 are the anode current meters
V_1 is the anode-volts meter (0–150 volts)
V_2 is the grid-volts meter (0–15 volts)
K_1 is the reversing switch
K_2 is the plug key
W_1 and W_2 are the wander leads
a is the valve base terminal to which the anode is connected
f_1 and f_2 are the terminals to which the filament is connected
g is the grid terminal.

The points *x* and *y* will be referred to in subsequent experiments.

Close K_2 so that the normal heater current flows. Open K_1 so that the grid battery is not connected. The potential of the grid will then be zero with respect to the cathode, or more briefly, the grid 'bias' is

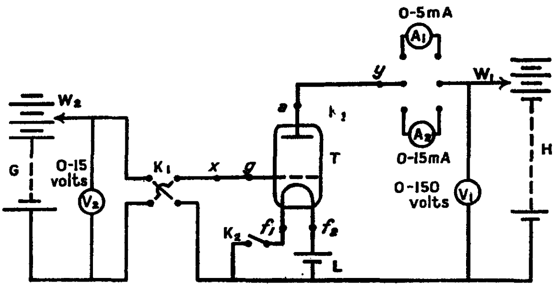


FIG. 223

zero. Put the wander plug W_1 in the lowest tapping of the H.T. battery which gives a measurable reading on the anode current meter, A_1. Record the reading of V_1 ($= V_a$), and the reading of A_1 ($= I_a$). Increase V_a up to the limit of the H.T. battery, or until I_a reaches the maximum permissible value for the valve used, switching in A_2 when necessary. Record the corresponding values of V_a and I_a. Disconnect W_1 from the H.T. battery, and put wander plug W_2 in the 1·5-volt tapping of the grid bias battery. Switch on K_1 so that the grid is negative with respect to the cathode. Put W_1 in the lowest tapping which gives a measurable deflection on A_1. Record the reading of A_1 ($= I_a$), V_1 ($= V_a$) and V_2 ($= V_g$).

Keeping the value of the grid bias constant, increase the anode voltage up to the permissible limit as previously, recording the corresponding values of V_a and I_a. Repeat the observations with the grid bias $+ 1·5$ volts by switching over K_1. Keep a careful watch on the anode current when the bias is positive to ensure that it does not exceed the limit for the valve. Use A_1 or A_2 as necessary. Repeat the observations for grid bias values of plus and minus 3 volts.

Record and Calculation: Tabulate the observations as follows:

Grid Bias (V_g) volts	Anode Voltage (V_a) volts	Anode Current (I_a) milliamps
0		
−1·5		
etc.		

Plot I_a (as ordinate) against V_a for each value of V_g, plotting all the curves on the same axes.

The result should be similar to that shown in Fig. 222. From the curves deduce the values of the three parameters discussed above.

Experiment 172. Investigation of the Mutual Characteristic Curves (Static and Dynamic) of a Triode Valve

Apparatus: As for the previous experiment (No. 171) and in addition: one 10,000 ohm, 2–3 watt wireless type resistor.

THEORY

If a graph of anode current passed by a triode is plotted against grid bias the results are as shown in Fig. 224, where several curves obtained for a series of fixed values of anode voltage are given. The curves are known as 'mutual characteristic curves'. It will be noticed that they are altered by variation of the 'load resistance', i.e. the resistance through which the anode current is made to pass. In part (i) of this experiment, using the circuit shown in Fig. 223 there is virtually zero load resistance and the three curves A, B, C apply to this condition. They are known as 'static' characteristic curves. When the load resistance becomes appreciable—as in part (ii) of

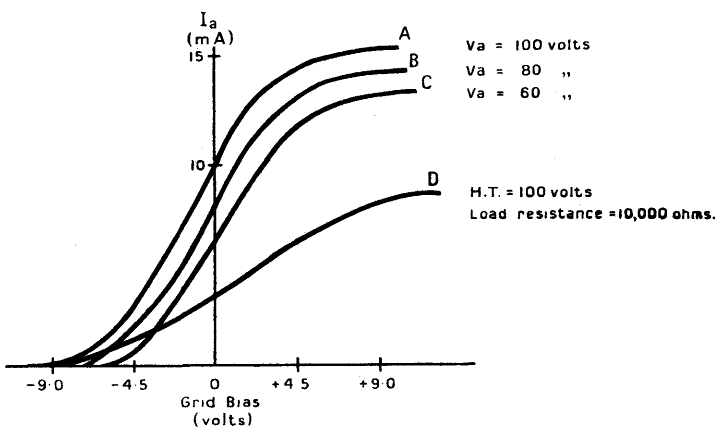


FIG. 224

this experiment, where 10,000 ohms is included in the anode circuit, the curve changes to that shown at D and is known as a 'dynamic' characteristic curve. This curve is of importance, as it represents the characteristic curve which applies when the valve is being put to a useful purpose. The explanation of the reduction in I_a is that there is a voltage drop across the load resistance which must be subtracted from the e.m.f. of the H.T. battery to obtain the value of V_a.

Procedure:

PART I. STATIC CHARACTERISTIC CURVES

Set up the circuit described on p. 414 and shown in Fig. 223.

Close K_2 so that the normal heater current flows. Put the wander plug W_2 in the 9-volt tapping, and switch K_1 so that the grid is biased negatively by this amount. Put the wander plug W_1 in the 60-volt tapping of the H.T. battery. Switch in A_1 and read V_2 ($= V_g$) and A_1 ($= I_a$). Switch over to A_2, and change K_1 so that the grid is biased positively by 9 volts. Read V_2 ($= V_g$) and A_2 ($= I_a$). By means of W_2 reduce the bias voltage to 7·5, 6·0 . . . 1·5, reading I_a for each value of bias, both negative and positive. Finally, read I_a when the bias is zero, by switching K_1 off.

Keep a careful watch on the anode current when the bias is positive, to ensure that it does not exceed the limit for the valve or for the ammeter.

Repeat the observations for V_g and I_a with values of anode voltage, V_a, equal to 80 and 100 volts.

PART II. DYNAMIC CHARACTERISTIC CURVES

Introduce the 10,000-ohm resistor between y and a (Fig. 223) to provide a load resistance for the valve. Put W_1 in the 100-volt tapping of the H.T. battery and take a series of observations of I_a for the same series of values of V_g as was used in Part I.

Record and Calculation:

PART I. Tabulate the observations as follows:

Anode Volts V_a (volts)	Grid Bias negative V_g (volts)	Anode Current I_a (milliamps)	Grid Bias positive V_g (volts)	Anode Current I_a (milliamps)
First value				
Second value				
etc.				

Plot on the same axes values of I_a (as ordinate) against V_g (as abscissa) for each value of anode voltage, V_a.

The curves obtained should be similar to those shown in Fig. 224. They are called mutual characteristic curves.

From the curves determine the mutual conductance and the amplification factor. Hence calculate a value for the A.C. resistance of the valve.

If the same valve was used as in the previous experiment, check the results with those previously obtained.

PART II. Enter the observations in a table similar to the one used in Part I and plot a graph of I_a against V_g on the same axes as those used for Part I. State your conclusions.

Experiment 173. Investigation of the Relationship between the Grid Current and the Grid Voltage in a Triode Valve

Apparatus: The same as for Experiment 171, p. 412, with the addition of another ammeter which should read from 0 to 1 milliamp., by intervals of 50 microamps.

THEORY

Under some circuit conditions the grid of a valve has a positive potential with respect to the cathode. This increases the anode current considerably. Some of the electrons will strike the grid and produce a very small current in the grid circuit. In practice the positive grid bias is kept low so that the grid current is only of the order of microamps. If the positive bias becomes too great, excessive electron emission from the cathode will take place and it will burn out.

Procedure: Set up the circuit described on p. 414 and shown in Fig. 223, but include the third ammeter between the points g and x.

Close K_2 so that the normal heating current flows. Put W_2 in the 1·5-volt tapping and switch K_1 so that the grid is biased negatively by this amount. Put W_1 in the 100-volt tapping of the H.T. battery, and switch in A_2. It will probably be found that the grid current meter, A_3, shows no reading, if so reduce the bias to zero and read A_3. It may be found again that no current flows. Switch K_1 so that the bias is 1·5 volts positive; read V_2 ($= V_g$), and A_3 ($= I_g$). Repeat for increasing values of V_g, noting the corresponding values of I_g. Increasing the positive bias will increase the anode current very rapidly, so watch the anode current meter, A_2, and ensure that the maximum permissible current for the valve is not exceeded.

Repeat for a value of $V_a = 50$ volts.

Record and Calculation: Tabulate the observations as follows:

Anode Voltage V_a (volts)	Grid Voltage V_g (volts)	Grid Current I_g (microamps)
100		
50		

Plot the curves showing I_g (as ordinate) against V_g for each value of the anode voltage, on the same axes, and state your conclusions.

Experiment 174. Investigation of the Relationship between the Anode Current and the Anode Voltage, and between the Screen Current and the Anode Voltage for a Tetrode Valve

Apparatus: H.T. battery (0–120 volts); 9-volt grid bias battery; four ammeters (two 0–15 mA and two 0–5 mA); three voltmeters (two 0–150 volts and one 0–15 volts) see p. 404; two double-pole double-throw switches; reversing switch; plug key; three wander plugs; cathode heater supply to suit the valve used; Screened grid valve and valve holder; a suitable valve is Cossor 215 SG or equivalent types.

THEORY

The triode valve is not a satisfactory amplifier at radio frequencies, due to the fact that the capacitance between the grid and the anode, though small, acts as a comparatively low reactance to A.C. at high frequencies. The A.C. output from the anode circuit will therefore be fed back to the grid input circuit via this low reactance. This produces unstable conditions, and the valve may start to oscillate.

To overcome this defect, the grid-anode capacitance must be reduced, and this is done by placing a screen in the form of a wire mesh, between the grid and the anode. The lead from the screen is connected to a tapping on the H.T. battery to give a potential on the screen of about one-third of the anode potential. Electrons can therefore still pass through to the anode, but the resistance of the H.T. battery is so low that for all practical purposes the screen is at the same potential as the cathode as far as A.C. is concerned. The grid is, therefore, almost completely shielded electrostatically from the anode, and variations on the one do not affect the other to any appreciable extent. The introduction of this fourth electrode changes the characteristic curves, as will be seen from Fig. 225 in which I_a (the anode current) and I_s (the screen current) are plotted as ordinates against anode voltage.

The peculiar 'kink' between X and Y will be noted. Over this part of the characteristic the anode current is falling as the anode voltage rises. This is said to show a negative resistance, and over this part of the curve the valve can be made to oscillate. When used thus it is known as a 'dynatron oscillator'.

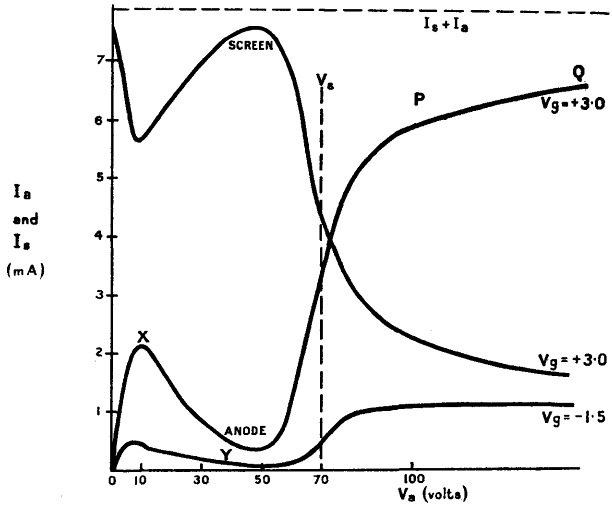


FIG. 225

It will be seen that the screen current is a maximum when V_a is zero. All the electrons from the cathode are being attracted to the screen, none reaching the anode. Increasing V_a causes a slight rise in anode current at first, followed by a fall. At an anode voltage of about 10, the electrons reaching the anode have sufficient energy to cause secondary electrons to be emitted from the anode These are attracted to the screen because it is at a higher potential than the anode. Consequently I_s increases and I_a decreases. When the anode voltage approaches the screen voltage, however, the anode current begins to increase rapidly, while the screen current diminishes.

Under working conditions the straight part of the curve PQ is used. As the slope is so much less than in the case of the triode the A.C. resistance is correspondingly very much greater, being of the order of 200,000 ohms.

Procedure: Set up the circuit as shown in Fig. 226, in which

T is the valve
H is the H.T. battery
G is the grid bias battery
L is the low-tension supply for the cathode heater

A_1 and A_2 are the anode current meters
A_3 and A_4 are the screen current meters
V_1 is the anode voltmeter
V_2 is the grid voltmeter
V_3 is the screen voltmeter
K_1 is the reversing key
K_2 is the plug key
K_3 and K_4 are the double-pole double-throw switches
W_1, W_2, and W_3 are the wander plugs
S is the screen terminal.

Close K_2 so that the normal heater current flows. Put W_2 in the 1·5-volt tapping and switch K_1 so that the grid is biased negatively by this amount. Put W_3 in the 70-volt tapping and switch in A_4. Switch in A_1, and put W_1 in the lowest available tapping of the H.T. battery. This should be of the order of 1·5 volts. Read V_1 (= V_a), A_1 (= I_a), V_3 (= V_s), A_4 (= I_s), V_2 (= V_g).

Keeping V_s and V_g constant, increase V_a, reading corresponding values of I_a and I_s up to the maximum value of I_a.

Repeat with the grid bias set at zero, + 1·5 and + 3·0 volts, the screen voltage being constant all the time at the original value. Observe the usual precautions against excessive anode current and grid current, when the grid has a positive bias.

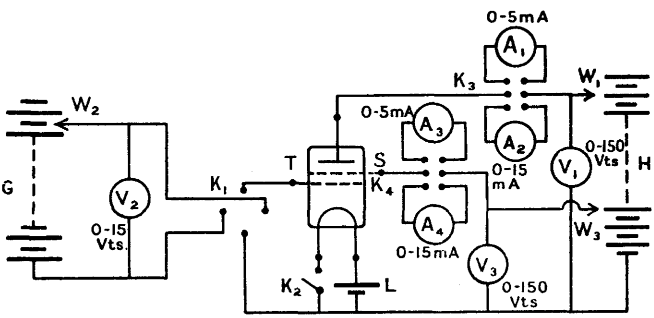


FIG. 226

Record and Calculation: Tabulate the observations as follows:

Screen Volts V_s (constant)	Grid Bias V_g volts (constant)	Anode Volts V_a	Anode Current I_a (milliamps)	Screen Current I_s (milliamps)

Plot graphs of I_a (as ordinate) against V_a (as abscissa) for each value of V_g. On the same axes plot I_s as ordinate against V_a as abscissa, using the same scales as for the first set of curves. Draw a perpendicular through the point $V_a = V_s$.

Find the sum of I_a and I_s for each value of V_a, and draw a line through these plotted points. It should be parallel to the abscissa.

The curves will appear similar to those shown in Fig. 225.

Note: The mutual characteristic curves may be obtained with the circuit as above by finding I_a for various values of V_g (V_a and V_s being kept constant).

With V_s unchanged, repeat for other values of V_a. Plot the curves as in Experiment 172.

They will be found to have almost the same slope as the triode curves, thus giving similar values for g_m. But it will also be found that the curves are much closer together, showing again that the A.C. resistance is much higher than for the triode.

It therefore follows that the amplification factor, μ, is much greater for the tetrode.

Experiment 175. Investigation of the Relationship between the Anode Current and the Anode Voltage, and between the Screen Current and Anode Voltage for a Pentode Valve

Apparatus: H.T. battery (0–200 volts); 9-volt grid bias battery; four ammeters (two 0–15 mA, two 0–5 mA); three voltmeters (two 0–150 volts and one 0–15 volts); two d.p.d.t. switches; reversing switch; three wander plugs; cathode heater supply to suit the valve used.

Pentode valve and holder; an indirectly heated valve which would be suitable is a Mazda AC/Pen. or any equivalent type.

THEORY

The secondary electrons emitted from the anode of a screened grid valve and attracted to the screen produce the 'kink' in the I_a–V_a characteristic as shown in Experiment 174. This leads to anomalous variation in I_a when V_a varies, and so gives rise to a distorted output.

The screened grid can be prevented from attracting the secondary electrons to it by placing a third grid between it and the anode. The valve then has five electrodes, and is called a pentode.

The third grid, known as the 'suppressor', is put at cathode potential by connecting it to the cathode of the valve. Thus the anode is at a high positive potential with respect to the suppressor and all the secondary electrons will be attracted back to the anode. For this reason no kink will appear in the characteristic curves.

Electrons from the cathode, however, still have sufficient energy to reach the anode, being slowed down between the screen grid and the suppressor, but accelerated between the suppressor and the anode.

Procedure: Set up the apparatus shown in Fig. 227, in which

T is the valve, shown in the diagram as indirectly heated
H is the H.T. battery
G is the grid bias battery
h_1 and h_2 are the valve base terminals to which the heater low-voltage supply (not shown) is connected
A_1 and A_2 are the anode current meters
A_3 and A_4 are the screen current meters
V_1 is the anode voltmeter
V_2 is the grid voltmeter
V_3 is the screen voltmeter
K_1 is the reversing switch
K_2 and K_3 are the d.p.d.t. switches
W_1, W_2, W_3 are the wander plugs
a is the valve base terminal to which the anode is connected
c is the valve base terminal to which the cathode is connected
g_1 is the valve base terminal to which the control grid is connected
g_2 is the valve base terminal to which the screen grid is connected
g_3 is the valve base terminal to which the suppressor is connected (if it is not internally connected to the cathode).

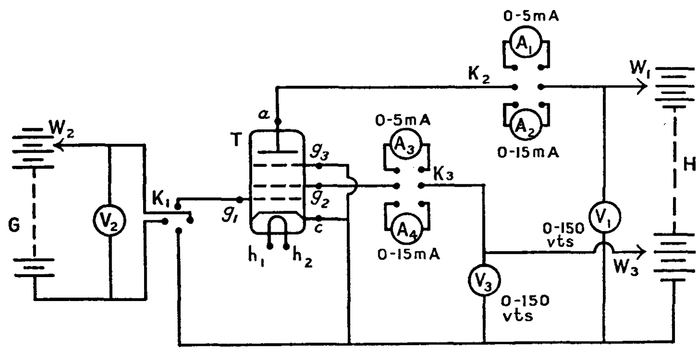


FIG. 227

Switch on the heater supply so that the normal current for the valve is passed through the heater. Put W_2 in the 3-volt tapping and switch K_1 so that the control grid is biased negatively by this amount. Put W_3 in the 75-volt tapping of the H.T. battery and switch in A_4. Switch in A_1 and put W_1 in the lowest available tapping of the H.T. battery.

Record the readings of V_1 ($= V_a$), A_1 ($= I_a$), A_3 ($= I_s$), and V_2 ($=V_g$). Keep V_g and V_s constant, increase V_a, recording corresponding values of V_a, I_a and I_s for a series of values up to the maximum for I_a.

With the screen voltage at the same values repeat these observations with grid bias values of (− 1·5), zero, (+ 1·5), (+ 3·0) volts.

Observe the usual precautions against excessive anode current and grid current, when the grid has a positive bias.

Record and Calculation: Tabulate the observations as follows:

Screen voltage . . . . volts.

Grid Bias V_g (volts)	Anode Volts V_a (volts)	Anode Current I_a (milliamps)	Screen Current I_s (milliamps)
− 3·0			
− 1·5			
etc.			

Plot graphs of I_a and I_s (as ordinates) against V_a on the same axes for each value of V_g. Draw the vertical line representing V_s. The results should be similar to those given in Fig. 228. There should be no kinks

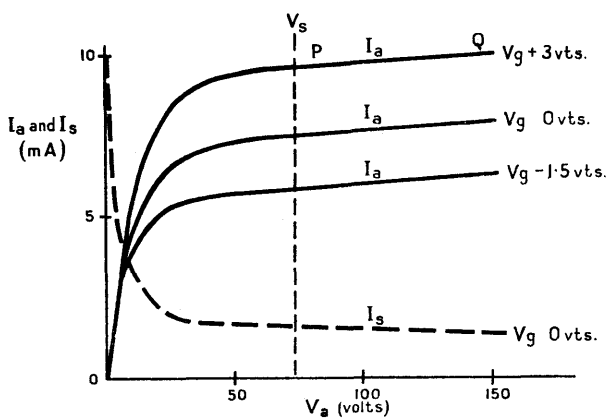


FIG. 228.

in them. Under working conditions the straight part of the curve PQ is used. The slope is much less than for the triode (this was noted in the case of the tetrode) and the A.C. resistance is correspondingly higher.

Notes: Two further points of interest arise in connection with the pentode:

(1) The anode characteristics show that over the straight part of the

curve the anode voltage has little effect on the anode current, the slope being so small that the current does not vary much. The valve is therefore sometimes referred to as a 'constant current valve'.

(2) It follows from the above that a load resistance in the anode circuit will have very little effect on the anode current. If, therefore, the above experiment is repeated to determine the mutual characteristic curves by finding I_a for various values of V_g (V_a and V_s being maintained constant), it will be found that the dynamic curves obtained when the anode load is put in circuit differ little in slope from the static curves.

Experiment 176. Investigation of the Characteristics of a Gas-filled Triode, or Thyratron, Valve

Apparatus: 200-volt H.T. battery; 9-volt grid bias battery; three ammeters (0–15 mA, 0–150 mA, 0–500 μA); two voltmeters (one 0–150 volts, the other 0–15 volts); potentiometer (4,600 ohms, capable of carrying 0·3 amps); two wireless type resistors (one 10,000 ohms, 1 watt, the other 5,000 ohms, 2–3 watts); plug key; wander plug; cathode heater supply to suit the valve used.

Gas-filled triode, argon type, Osram GT1C, or mercury vapour type Mazda Thyratron T41 are suitable. The former has a British standard 5-pin base, the latter a Mazda octal base. Both have 4-volt heaters.

The H.T. supply needs consideration: First the variation cannot be effected by the wander plug method as there must be no interruption in the applied voltage—the reason for this is given under 'Theory' below. If an H.T. battery be used it will require a potentiometer (see p. 403). As the output may be 20–30 mA, the battery itself must have a large capacity. It is evident that the use of a battery is inadvisable if other methods are available. The power-pack method can be used (see pp. 401–2) but care must be taken to ensure that the potentiometer is suited to the output so that it is not overloading the pack nor carrying more than its own rated current. The best solution is to use the rotary transformer (see pp. 402–3).

THEORY

The common types of thermionic valves are 'hard' valves, i.e. they have a high degree of vacuum, of the order of 10^{-7} mm. of mercury. They are characterised by a comparatively low anode current, of the order of tens of milliamps, which can be controlled completely by variation of grid potential.

If a small quantity of inert gas, usually mercury vapour or argon, is introduced into a triode valve, the characteristics are completely changed. The anode current can rise to hundreds of milliamps., but the grid has only a very restricted control of its operation.

The electrons emitted from the cathode of the gas-filled triode, or 'thyratron' as it is commonly called, ionise molecules of the gas. The heavy positive ions travel to the negatively charged grid, and so tend to neutralise its effect by making it more positive. More electrons are therefore emitted from the cathode which in their turn produce further ions. The anode current rises very rapidly indeed, and unless limited by a series resistor in the anode circuit will cause the cathode to burn out in a fraction of a second.

The grid bias alters the voltage at which the valve begins to conduct, or 'fire' but variation of the grid potential after the valve has fired has little effect on the anode current, neither can it cause deionisation. This can only be done by reducing the anode voltage below a certain value, or by switching off the H.T. supply.

The voltage at which the valve fires is known as the 'breakdown voltage', and the voltage at which it ceases to conduct is the 'extinction voltage'.

The valve therefore acts as an infinite resistance up to the breakdown voltage and thereafter as a low resistance.

The breakdown voltage is directly proportional to the grid bias; and the ratio

$$\frac{\text{change in breakdown voltage}}{\text{change in grid bias}}$$

is known as the 'control ratio' of the valve.

Procedure: The following precautions should be noted (*failure to observe them will ruin the valve*):

(1) The heater must be switched on at least two minutes before any anode voltage is applied.

(2) A 5,000-ohm resistor must be kept in the anode circuit to limit the current to a safe value. For normal working I_a is about 300 mA. This current will not be approached in the following experiments with the component values as suggested.

(3) The bias must not be allowed to become positive, and the grid current should be limited to a safe low value by the use of a high resistance in the grid circuit. 10,000 ohms is adequate.

Set up the circuit as shown in Fig. 229, in which

T is the valve
H is the H.T. battery
G is the grid bias battery
A_1 is the anode current meter (0–15 mA. initially)
A_2 is the grid current meter
V_1 is the H.T. voltmeter
V_2 is the grid voltmeter
R_1 is the resistor to limit anode current
R_2 is the grid resistor
P is the potentiometer
K_1 is the plug key
W is the wander plug
a is the valve base terminal to which the anode is connected
g is the valve base terminal to which the grid is connected
c is the valve base terminal to which the cathode is connected
h_1 and h_2 are the valve base terminals to which the heater is connected.

PART I. DETERMINATION OF BREAKDOWN VOLTAGES AND OF THE CONTROL RATIO FOR THE VALVE

Switch on the heater current and wait for the two minutes (see above). Put W in the ($-1{\cdot}5$) volt tapping of the grid bias battery. Move the slider of the potentiometer so that the minimum value of the H.T. is applied to the anode, and switch on K_1. Steadily and *slowly* increase the anode voltage, watching the anode current meter and the anode voltmeter at the same time. At first no current will flow, but at about 18 to 20 volts the needle will suddenly jump to a reading of the order of 0·5 mA. Note the anode voltage and the grid bias. Change the bias to ($-3{\cdot}0$) volts and repeat to find the breakdown voltage for this bias. Continue up to the limit of the bias battery.

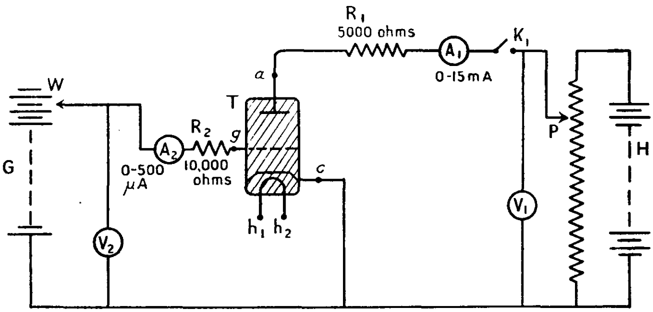


FIG. 229

For bias values of (-6) volts and more, it will be necessary to change the anode current meter to one with a higher range, as at (-9) volts bias, the current is about 30 mA. for a GT1C valve, with an anode voltage of approximately 180.

Record and Calculation: Tabulate the observations as follows:

Grid Bias V_g (volts)	$-1{\cdot}5$	$-3{\cdot}0$	$-4{\cdot}5$	etc.	
Breakdown (voltage)					

Plot a graph of breakdown voltage (as ordinate) against grid bias and from the slope of the straight line so obtained deduce the control ratio for the valve.

PART II. DETERMINATION OF THE ANODE CHARACTERISTIC

Set the grid bias at ($-4\cdot5$) volts and start with the anode voltage well below the breakdown voltage for this bias. Increase V_a until the valve 'fires' and then note V_a and I_a. Increase the anode voltage by steps and record a series of corresponding values of anode voltage (V_a) and anode current (I_a) up to a maximum value of about 15 mA. Reduce V_a by steps to zero, recording corresponding values of I_a and V_a.

Repeat with grid bias values of ($-3\cdot0$) and ($-1\cdot5$) volts, taking readings both as V_a is increased and decreased.

Record and Calculation: Tabulate the observations as follows:

Anode load . . . . R_1 ohms

Grid Bias V_g. (volts)		Anode Voltage (including load) V_a (volts)	Anode Current I_a (mA)	Voltage drop across anode load $R_1 \times I_a$	Voltage drop across the valve $(V_a - R_1 I_a)$
$-4\cdot5$	Increasing				
	Decreasing				
$-3\cdot0$	Increasing				
	Decreasing				
etc.					

What is the significance of the last column?

Plot graphs of I_a (as ordinate) against V_a for each value of V_g and state your conclusions. The curves should each be similar to the one shown in Fig. 230.

PART III. DETERMINATION OF THE GRID CURRENT

Give the grid a bias of $(-1{\cdot}5)$ volts and the H.T. voltage a value between 60 and 80. Note the grid current. Maintaining the H.T. voltage constant, change the bias to $(-3{\cdot}0)$ volts, $(-4{\cdot}5)$ volts, etc., and record corresponding values of the grid current (I_g).

Repeat with a different value for the H.T. voltage.

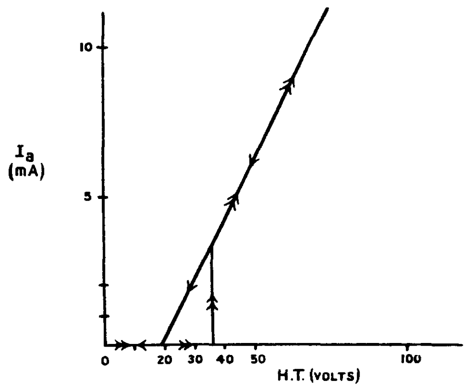


FIG. 230

Record and Calculation: Tabulate the observations as follows:

H.T. Voltage V_a (volts)	Grid Bias V_g (volts)	Grid Current I_g (microamps)
First value		
Second value		

Plot a graph of I_g (as ordinate) against V_g and state your conclusions.

Experiment 177. Determination of the Ionisation Potential of a Neon Lamp and of the Relationship between the Applied Voltage and the Current Passed by the Lamp

Apparatus: 200-volt H.T. battery; ammeter (0–15 mA); voltmeter (0–200 volts); potentiometer, 4,600 ohms and capable of carrying

0·3 amps.; plug key; the neon lamp, which can conveniently be an Osram 240-volt, 5-watt 'Osglim'; standard lamp holder.

If a rotary transformer is available use this as the H.T. supply instead of the battery and potentiometer (see discussion of this on pp. 402–3).

THEORY

The neon lamp contains two electrodes in an atmosphere of neon at low pressure. If the electrodes are connected to a source of direct current, any stray electrons in the gas will be attracted to the positive electrode. If the speed of the electrons becomes sufficiently high some of the gas molecules will be ionised by collision. As in the case of the thyratron, the effect is cumulative and the lamp will conduct, as seen by the characteristic red neon glow when the current flows.

To prevent excessive current the lamp has a ballast resistor, in the base, of about 2,000 ohms. This limits the current to a safe value.

The potential at which the lamp starts to conduct is called the 'striking potential'. If the potential is now steadily reduced it will be found that the lamp will not go out until the potential has dropped substantially below the striking value, the difference being of the order of 30 volts or so.

Deionisation thus takes place at a lower potential than ionisation. The lamp thus acts as a very high resistance up to the striking potential, and then as a low resistance between striking and extinction potentials. It is this property which has led to its use as a time base for cathode ray oscillographs, though it is not very satisfactory as such.

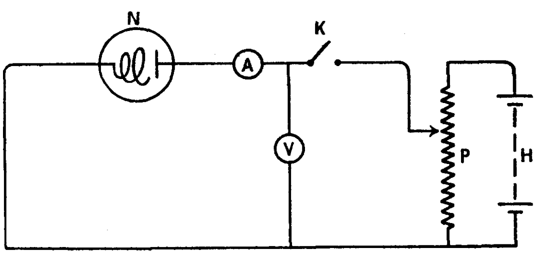


FIG. 231

Procedure: Set up the apparatus shown in Fig. 231 in which

N is the neon lamp
H is the H.T. battery (or other H.T. supply)
A is the ionisation current meter
V is the voltmeter
P is the potentiometer—this will not be needed if a rotary transformer is used
K is the plug key.

Close K, and starting with the voltmeter reading about 120 volts, gradually increase the p.d. across the lamp until it strikes, as seen by the appearance of the red glow. Read the ionisation current, *I*, and the voltmeter reading, V_1. This voltage is the striking voltage of the lamp.

Increase the p.d. across the lamp up to the maximum available, recording a series of readings of A and V. Without switching off the H.T. reduce the voltage steadily, recording corresponding values of current and voltage until the lamp goes out. The voltage at which this takes place is the extinction voltage, V_2.

Record and Calculation: Tabulate the observations as follows:

H.T. Voltage (volts.)	Increasing						Decreasing					
Ionisation current (mA)												

Plot a graph of ionisation current (as ordinate) against applied voltage. Compare the result with that obtained with the thyratron.

Experiment 178. Investigation of the Relationship between the Voltage applied to an Emission Type Photo-electric Cell and the Current passed by the Cell when the Intensity of Illumination is Constant

Apparatus: 100-volt H.T. battery; voltmeter (0–150 volts); ammeter (0–100 μA); wireless type fixed resistor of value about 100,000 ohms; wander plug; 240-volt, 150-watt pearl electric lamp and holder; 240-volt mains supply; Emission type photo-electric cell complete with holder —the Mazda PE7B is suitable. The maker's ratings for these cells are to ensure stability and very long life. For experimental purposes they can be exceeded for short periods of time.

THEORY

The incidence of light on the surface of many metals causes electrons to be liberated and this property is made use of in the emission type photo-electric cell. The cathode consists of a metal plate covered with a thin layer of the emitting substance which may be potassium, sodium, rubidium or caesium. (Different metals respond to different wavelengths). The anode is a wire fixed in front of the cathode. The electrodes are contained in an evacuated envelope.

The emitted electrons falling on the anode produce a very small current in an external circuit. If the anode is given a positive potential with regard to the cathode the electrons will be attracted to the anode and an increased current produced.

An experiment has already been described in which the current through the cell was made to vary by altering the light falling on it (Experiment 84, II). If the light intensity is kept constant, then the current will vary with the applied voltage.

Procedure: Set up the apparatus as shown in Fig. 232 in which

P is the photo-electric cell
H is the H.T. battery
A is the ammeter
V is the voltmeter
R is the resistor to limit the current
W is the wander plug
L is the 150-watt lamp
a is the base terminal to the anode of the cell
c is the base terminal to the cathode of the cell.

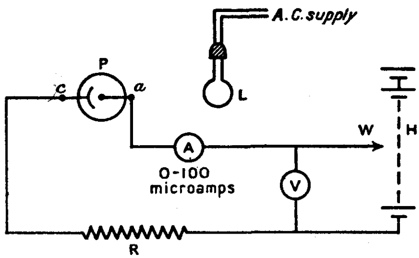


FIG. 232

Adjust the position of the lamp in front of the cell so that it is between 50 and 100 cm. from it and is on the normal from the cell cathode. Put the wander plug in the 100-volt tapping and note the current. It will be of the order of 20 microamps. Carefully bring the lamp nearer to the cell until the current is about 70 to 80 microamps. Watch the cell carefully to ensure that it does not give a blue glow. This glow indicates excessive current, and the ensuing arcing will ruin the cell.

Note the reading of the voltmeter and the ammeter. Keeping the position of the lamp constant, reduce the voltage in 10-volt steps recording the corresponding values of current.

Record and Calculation: Tabulate the observations as follows:

p.d. across the cell (volts)						
Current (microamps)						

Plot a graph of current (as ordinate) against p.d.

The graph should be a straight line at first but at higher values of the H.T. the current should tend to a maximum.

CHAPTER LVI

THE CATHODE RAY OSCILLOGRAPH

The Cathode Ray Tube

The cathode ray tube is a piece of apparatus which provides a beam of electrons focused on to a fluorescent screen, so that a spot of light 0·5 to 1 mm. in diameter is formed. By applying magnetic or electrostatic fields in the vicinity of the beam it can be deflected and the spot of light made to move over the face of the screen. Thus a visible pattern is traced which is determined by the potential causing the electrostatic field or the current producing the magnetic field.

The common form of tube used in the laboratory has electrostatic deflection and it is this type which will be required in the experimental work described in this chapter. Reference should be made to the more detailed descriptions to be found in the theoretical textbooks. As in the radio valve the source of electrons is a hot cathode, indirectly heated, the heater usually requiring 1 amp. at 4 volts. The cathode is surrounded by a metal shield in the form of a cylinder with a hole at the end further from the cathode. This cylinder is given a negative potential with respect to the cathode, so that the electrons are repelled from it, and form a beam which passes through the hole. This electrode is called the 'grid', 'shield' or 'modulator', and by varying the negative potential on it the emission of electrons from the cathode can be controlled, and so the brightness of the spot varied. This control is usually labelled 'brightness' or 'brilliance'.

The beam of electrons from the shield passes through a series of electrodes known as first, second and third anodes, all of which are at positive potentials with regard to the cathode. The electric fields between these electrodes can make the electron beam converge or diverge according to the potentials applied. They act, in fact, rather like a lens system. The usual arrangement is to make the first and third anodes at the highest potential with respect to the cathode, while the second anode is lower than the other two, but higher in potential than the cathode. The second anode can have its potential varied, and by this means the spot of light can be focused on the screen. The potentiometer controlling its potential is labelled 'Focus', see Fig. 233. The screen is usually coated with zinc silicate, which, when bombarded with electrons, emits green light.

Between the final anode (A_3) and the screen, the deflector plates are fixed, with the X-plates which produce the horizontal deflection, nearer to the screen than the Y-plates which produce the vertical deflection.

Since the beam is composed of electrons, the application of a p.d.

between the X-plates will make the beam move from left to right or right to left according to the polarity of the X-plates, the spot moving towards the plate with the more positive potential on it. Potentials applied to the Y-plates will cause the beam to move up or down in the same way.

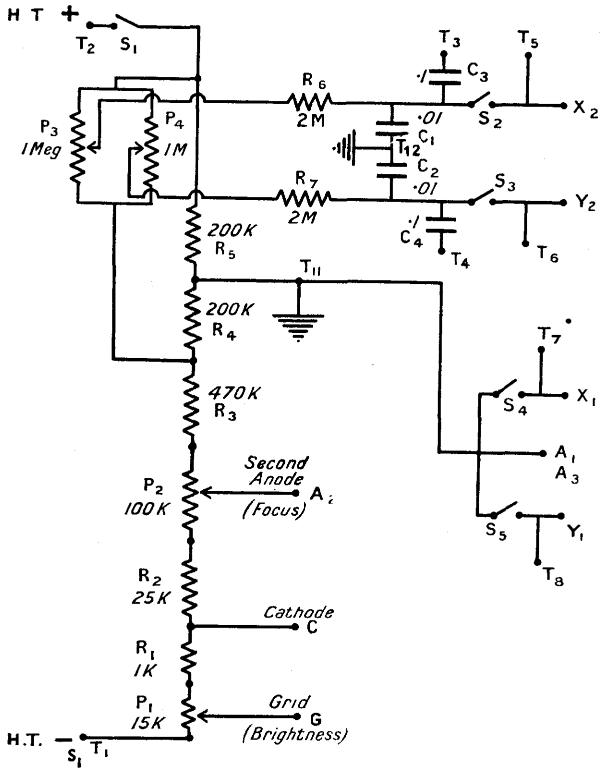


FIG. 233

An important point in connection with the application of electrode voltages should be particularly noted: it is customary to earth the final anode so that the plates are not in the vicinity of high potentials which would cause the spot to behave in an erratic manner, and might, under certain conditions, prove dangerous. This means that the cathode end of the tube is at a negative potential with respect to the earth of some 1,000 volts or so, depending on the size of the tube. Thus the cathode and its heater, the heater transformer windings, and the focusing anode (A_2) are DANGEROUS TO HANDLE when the tube is working. Care should therefore be taken to SWITCH OFF THE H.T. SUPPLY BEFORE ADJUSTMENTS ARE MADE.

It is neither difficult nor expensive to set up the cathode ray tube and its associated apparatus. The arrangement described here gives satisfactory results and no other tube is needed to perform all the experiments described.

The Cathode Ray Tube Assembly (see Figs. 233–7).

This consists of the potentiometer chain and the various controls for the tube. The apparatus required is as follows:

(1) The tube: either a Mullard ECR30 or a G.E.C. E-4205-B7, having screens 3″ in diameter (quite adequate) and needing only 900–1,000 volts for the final anode, is suitable. A base holder to fit the tube used is also required.

(2) Resistors: all $\frac{1}{2}$ or 1-watt type. ('K' = 1,000 ohms, 'Meg' or 'M' = 1,000,000 ohms).

R_1.	1K.	R_5.	200K.
R_2.	25K.	R_6.	2 Meg.
R_3.	470K.	R_7.	2 Meg.
R_4.	200K.		

(3) Potentiometers: 2 or 3-watt insulated type.

P_1.	15K. (Brightness)	P_3.	1 Meg. (X shift)
P_2.	100K. (Focus)	P_4.	1 Meg. (Y shift)

(4) Capacitors: all 500-volt working, tubular, paper.

C_1.	0·01 μF	C_3.	0·1 μF
C_2.	0·01 μF	C_4.	0·1 μF

(5) Switches:

S_1. d.p.s.t. (H.T. ON/OFF.)

S_2, S_3, S_4, S_5, S_6, s.p. (ON/OFF.)

(6) Terminals:

Insulated type, T_1 to T_{10}.

Non-insulated, T_{11}, T_{12} (earth connections).

(7) Other equipment:

Coloured p.v.c. connecting wire of about 22–24 S.W.G. The use of different coloured wires will assist in identifying the various parts of the circuit.

Two one-foot lengths of single-core screened lead for heater wiring.

Solder terminal strip, eight contacts.

Two strips of paxolin or similar insulating material, $1\frac{1}{2}$″ wide and 9″ long; these will act as terminal supports. Four Meccano angle brackets. Metal chassis; this can be easily made by bending a piece of aluminium 19″ long and $7\frac{1}{4}$″ wide so that it forms a wide U of dimensions as shown in Fig. 237.

Wooden block, 2″ × $1\frac{1}{2}$″ × 5″, with groove $1\frac{1}{2}$″ in diameter cut out of the centre to accommodate the tube.

Notes on Procedure when Assembling

The circuit is shown in Fig. 233. Slight variations from the values of resistances given will probably not affect performance. R_1 however should not be less than 1K, since its purpose is to ensure that the grid is always slightly negative with respect to the cathode.

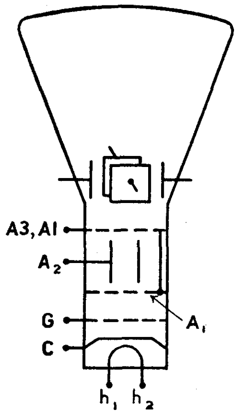


FIG. 234

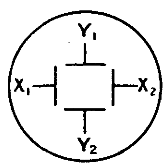


FIG. 235

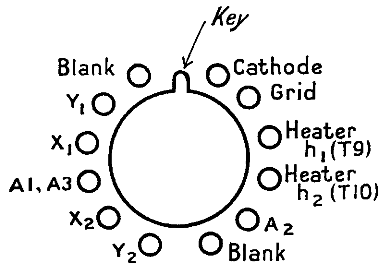


FIG. 236

S_2 and S_3 enable the X_2 and Y_2 plates to be isolated from the 'shift' controls, P_3 and P_4. The input terminals will then be T_5 and T_6. When A.C. is applied to the plates, S_2 and S_3 will normally be closed, and the input connected to T_3 and T_4.

Similarly, S_4 and S_5 can be opened to isolate X_1 and Y_1 from A_3 and earth, and voltages can then be applied to these plates through T_7 and T_8. Normally S_4 and S_5 will be closed. When S_4 and S_5 are open it may be found that the spot becomes unstable due to X_1 and Y_1 picking up charge from the beam. This can be cured by connecting X_1 and Y_1 to earth, each through a 2 Meg. resistor.

Fig. 234 shows the arrangement of the electrodes diagramatically, while Fig. 236 gives the base connections for the Mullard tube, the letters corresponding to the circuit diagram labelling. The arrangement of the plates as seen from the *screen* end of the tube is given in Fig. 235.

The base connections for the particular tube used should be checked, as there are different arrangements, notably the interchange of grid and cathode pins.

Fig. 237 shows the mounted tube and the disposal of the components between the chassis uprights.

The wooden block is screwed to the top of the chassis, and the tube held in place by two wide rubber bands fixed to hooks in the block. Leads to the tube base pass through a hole in the chassis just under

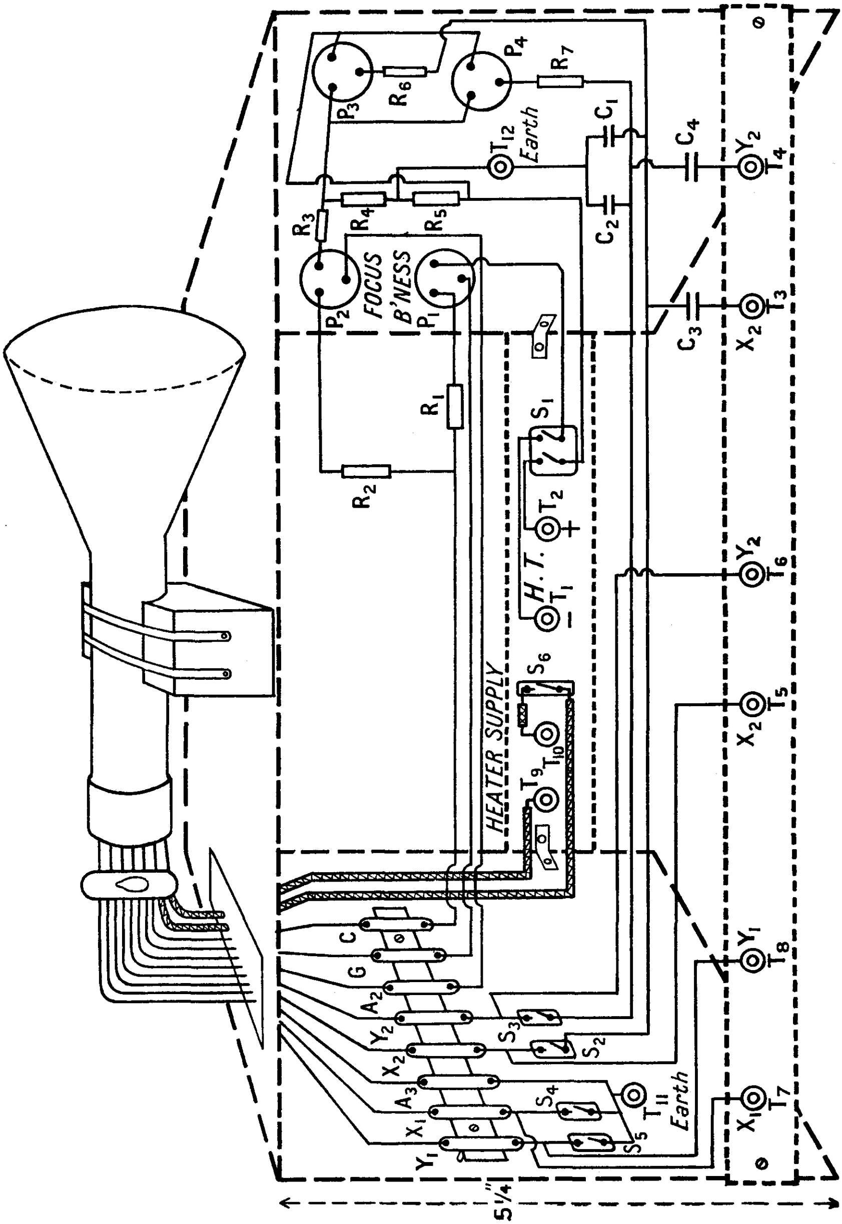

P3
R6
P4
R7
C1
T12
Earth
C4
Y2
T4
R3
R4
R5
C2
P2
FOCUS
B'NESS
P1
C3
X2
T3
R1
S1
R2
T2
+
H.T.
T1
–
Y2
T6
HEATER SUPPLY
S6
T9
T10
X2
T5
C
G
A2
Y2
X2
A3
X1
Y1
S3
S2
S4
S5
T11
Earth
Y1
T8
X1
T7
5¼"

FIG. 237

the end of the tube. With 22 or 24 gauge wire the resistors and capacitors may be 'hung' in the wiring.

Wires are soldered to the screening round the heater leads and connected to the earth terminal T_{11}. These are not shown in the diagram.

The earth terminals are bolted straight on to the chassis; one of them is then connected by a wire to a water pipe, to ensure good earth contact.

The two paxolin strips are bolted to the chassis by the Meccano angle brackets.

The open construction allows the components to be easily seen and replaced, and helps to dispel the atmosphere of mystery surrounding the totally enclosed commercial types of instrument.

The trace on the screen can be shown up in daylight if the contrast is increased by fixing a black paper sleeve round the front end of the tube.

The Power Pack Assembly

This consists of the components required to provide the high voltage for the tube, and the heater voltages for the tube and for the rectifying valve.

Apparatus: Transformer, input 240 volts, 50 c.p.s., output 350–0–350 volts at 60 mA, 4 volts, 1 amp., 4 volts 1 amp. (this is a standard radio type of mains transformer); high-voltage rectifying valve, Osram U17 or equivalent; standard British 5-pin valve base to fit U17, but must

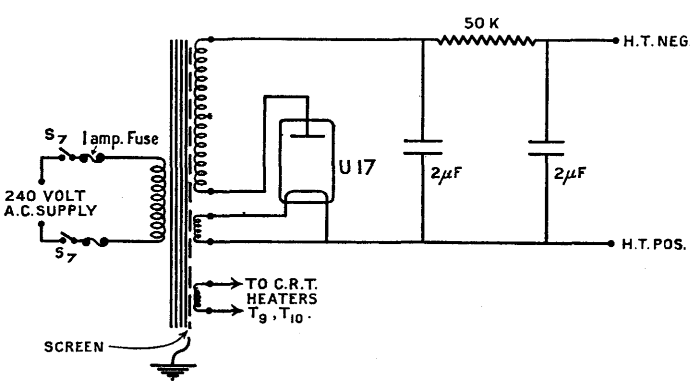


FIG. 238

be high-insulation type; two 2μF. (1,000–1,500-volt working) capacitors, oil-filled paper are satisfactory; 50K 1 or 2 watt, wireless type resistor: twin fuse holder and 1 amp. fuses; d.p.s.t. (on/off) switch; four insulated terminals: one bare terminal for the earth connection; length of twin flex and 3-pin plug to fit mains socket; paxolin strip 3″ wide and 8½″ long; two fixing nuts and bolts; metal chassis, about 9″ × 7″ × 2″, but these dimensions will depend on the size of the transformer used; 22 or 24 gauge rubber-covered copper connecting wire.

Notes on Procedure

The circuit is shown in Fig. 238. It will be noted that the centre tap of the transformer is not used, the full output from the secondary being applied across the valve. The rectifier is directly heated, so one pin of the filament is H.T. positive. Fig. 239 gives the base connections

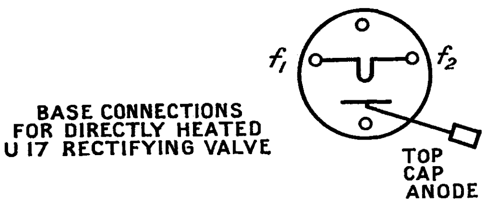


FIG. 239

for it, the valve having a top anode. A hole will have to be cut in the chassis to take the holder. Fig. 240 gives a plan view of the layout of components.

The third pin of the mains plug is connected to the chassis—this is not shown in the figure. It is assumed that the third pin is earthed.

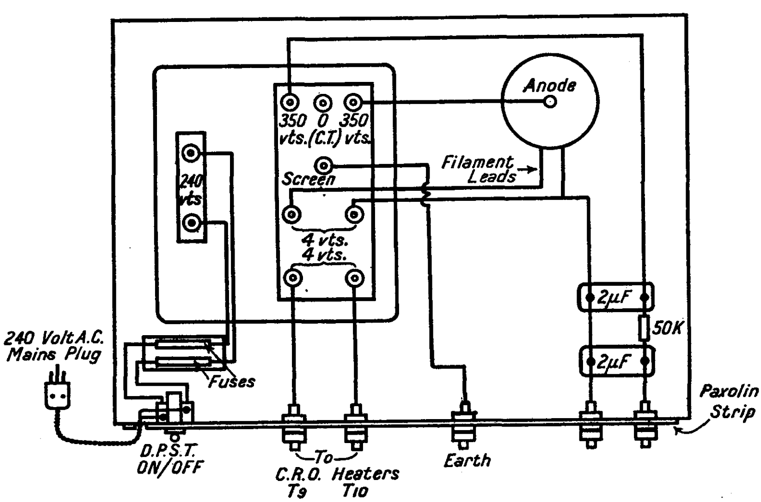


FIG. 240

The paxolin strip is bolted to the side of the chassis as shown in Fig. 241.

Good quality rubber covered wire should be used for making connections between the power pack and the C.R.T.

Remember that the heater terminals on the power pack are at 1,000 volts below earth potential.

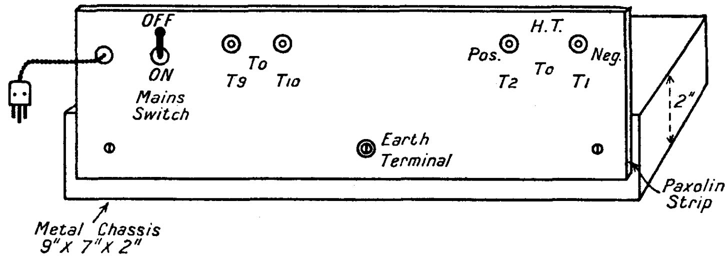


FIG. 241.

When the power pack is switched off, the capacitors will be charged to about 900 volts. It is therefore dangerous to touch any of the wiring until they have been discharged. This may be done by shorting each capacitor in turn with a 500K resistance held in an insulating handle. They will take a few seconds to become completely discharged.

Power Supplies from A.C. Mains

The warnings given previously about the dangerous nature of electric shocks from the A.C. mains applies here and all the usual precautions should be taken. In addition to the risk to yourself there is a risk to the apparatus, for if this is connected wrongly damage will result. The instructions should therefore be most carefully carried out.

In some of the following experiments alternating voltages from the mains supply will be applied to the deflector plates of the C.R.T. Thus one of the leads from the mains will have to be connected to X_1 or Y_1 and so, therefore, to earth.

In order to avoid short circuits it will be necessary to identify the mains lead which is at earth potential, and to ensure that this is the lead which is connected to earth on the C.R.T.

The earth lead can be identified by connecting a wire from one terminal of a 240-volt A.C. voltmeter to earth, and touching each main lead in turn with an insulated wire from the other voltmeter terminal. The 'live' lead will show a reading of 240 volts, while the other should show no reading, or at the most 3 or 4 volts; this is, of course, the earthed lead of the mains supply.

The above procedure is satisfactory if the mains supply is from a 'star' connected source, since the star point will be earthed. A few localities, however, have the mains supply from a 'delta' connected source, in which case neither of the mains wires is at earth potential, and so neither of them may be earthed without causing a short circuit. The voltmeter connected as above will show a high voltage to earth when either of the leads from the supply is connected to it. The type of supply should therefore be ascertained before carrying out any of the A.C. experiments.

If the supply is from a 'delta' connected source, a mains transformer with a ratio of primary to secondary turns of one to one may be used to isolate the supply, one end of the secondary being earthed. This may, however, produce unwanted phase changes. For further information on this matter the appropriate theoretical text-books should be consulted.

Experiment 179. Determination of the Voltage Sensitivity of a Cathode Ray Tube. The Use of the Cathode Ray Tube as an A.C. Voltmeter

Apparatus: Cathode ray oscilloscope and power pack as described on pp. 433–41; 240-volt A.C. supply; 0–100-volt H.T. battery or variable H.T. supply (see pp. 401–3); high-resistance voltmeter (0–100 volts D.C.); wander plug; transparent scale graduated in cms. and mms. one edge of a celluloid set square is suitable for the purpose.

THEORY

If one plate of a pair of plates is made positive with respect to the other, then the electron beam will be attracted to the more positive plate, the deflection of the beam causing the light spot to move across the screen. The deflection will depend on the difference of potential between the plates and the experiment is to show how the deflection varies with applied voltage.

If D.C. potentials are used, then the spot will move from the centre position to a point either to the left or right of the centre, depending on the polarity of the plates and the potentials applied. If the potentials are applied to the Y plates then the spot will be deflected up or down for the same reasons.

If alternating voltages are applied, it should be clear that the spot will be drawn out into a line. The length of this line is a measure of the peak to peak voltage applied. The D.C. voltage corresponding to the sum of the maximum deflections on each side of the centre (i.e. to the length of the line) is $2\sqrt{2}$ times the R.M.S. voltage—the voltage indicated by an A.C. voltmeter.

PART I. DETERMINATION OF THE VOLTAGE SENSITIVITY

Procedure: Connect the power pack to the A.C. mains supply and to the C.R.O., and adjust the controls so that a small clearly focused spot is obtained in the centre of the screen. Once the preliminary adjustments have been made, the only quantities to be varied are the voltages applied to the plates. The power pack and the C.R.O. have been omitted from Fig. 242 in order to simplify the diagram.

Set up the circuit shown in Fig. 242 in which

H is the H.T. battery or variable H.T. supply
V is the voltmeter
W is the wander plug
S is the screen
X_1, X_2, Y_1, Y_2 are the deflecting plates
E is the earth connection.

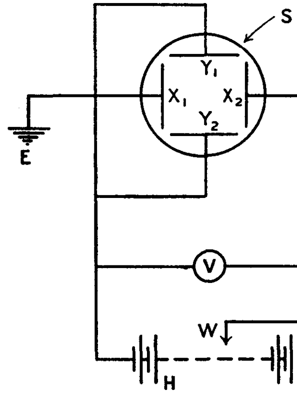


FIG. 242

(i) Horizontal Sensitivity

Earth Y_2 and the negative end of the H.T. battery. Earth X_2 by connecting W to the negative end of the H.T. battery. Clamp the transparent scale horizontally in front of the screen so that the spot is just above it, and so that it is a 'diameter' to the screen. Adjust the scale so that the spot is at some convenient graduation mark. Put the wander plug into the 10-volt tapping of the H.T. battery, and note that the spot has moved to the right. Read the voltmeter and the position of the spot on the scale. Increase the voltage by steps of 10, noting the corresponding reading of the deflection.

Now reverse the battery, connecting the positive end to earth and the negative end to the wander plug. Repeat the observations of voltage and deflection, noting that the latter is now to the left. Since the voltmeter will almost certainly be a moving coil instrument the connections to its terminals will also have to be reversed.

(ii) Vertical Sensitivity

The same sequence is carried out for the Y plates. X_2 and the negative end of the H.T. are earthed, and the wander plug connected to Y_2. The scale is adjusted as before, but in the vertical direction. The downward and upward deflections are observed, the polarity being changed as before.

Record and Calculation: Tabulate the results as follows:

Reading of voltmeter (volts)	Zero position of spot (cms.)	Deflected position of spot (cms.)	Deflection (cms.)
X_2 positive			
X_2 negative			
Y_2 positive			
Y_2 negative			

Plot graphs, on the same axes, of applied volts (plus and minus) as ordinate against deflection (right and left), for the X and for the Y plates.

The graphs should be straight lines through the origin. Determine the deflection in mm./volt for each set of plates. These are the voltage sensitivities of the tube.

Note: For the Mullard ECR30 tube the X and Y sensitivities will be found to be very nearly the same, and this has certain advantages—e.g. Experiment 180 (see under 'Theory'). In general the Y plates are more sensitive than the X plates because the latter are nearer to the screen in most tubes.

PART II. DETERMINATION OF THE RELATIONSHIP BETWEEN THE PEAK VOLTAGE OF AN A.C. SUPPLY AND THE READING OF AN A.C. VOLTMETER

Procedure: Apply various alternating voltages (up to a maximum of 70 volts R.M.S.) simultaneously to the X-plates and to an A.C. voltmeter. Record the lengths of the traces and the readings of the voltmeter. Repeat, using the Y plates.

Calculation: Plot voltmeter readings against deflections on the same axes as used in Part I, above. From this graph deduce a series of corresponding values of direct and alternating voltage, i.e. those values which produce equal deflections. Tabulate your results and discuss their significance.

PART III. USE OF THE C.R.O. AS AN A.C. VOLTMETER

Procedure: Apply the alternating voltage to the X plates and measure the length of the trace on the screen. Repeat, using the Y plates.

Calculation: Convert the lengths of traces into 'peak to peak' voltages, using the calibration graphs obtained in Part I, and hence calculate the R.M.S. voltage.

Experiment 180. Comparison of Two 'In-Phase' Voltages by Means of the Cathode Ray Tube

Apparatus: Cathode Ray oscilloscope and power pack as described on pp. 433–41; 240-volt A.C. mains supply; 80-volt A.C. supply; two 1,200-ohm, 20-watt potentiometers; transparent celluloid protractor; Post Office box and accessories, for determination of resistance.

THEORY

Provided the wavelength is the same, two quantities are in-phase with one another when, at a given instant they are:

(1) changing at the same rate.
(2) changing in the same sense or direction.

When an alternating voltage is applied to two resistors in series, the voltage across one resistor will be in phase with the voltage across the other. If therefore the voltage from each resistor is applied to the X and to the Y plates, the beam will be deflected by both plates, and a straight line will be produced, inclined to the horizontal. If the voltages have the same value, then clearly the line will be inclined at an angle of 45 degrees with the horizontal, from top left to bottom right, *provided the plate sensitivities are the same*. If the latter condition holds good but the applied voltages are different then the slope of the line, expressed as the tangent of its angle of inclination will give the ratio between the vertical and horizontal voltages. In this experiment we shall assume that the sensitivities are equal. (The Mullard ECR30 tube is thus a good one to use.)

Procedure: Set up the power pack and the C.R.O. and adjust so that a clearly focused spot appears in the centre of the screen.

Set up the circuit shown in Fig. 243 in which

P_1 and P_2 are the potentiometers
X_1, X_2, Y_1 and Y_2 are the deflecting plates
T_1 and T_2 are the 80-volt supply terminals.

(The power pack and C.R.O. are omitted for simplicity.)

Adjust the potentiometer P_1 until the trace, which should be a straight line, is of reasonable amplitude. Support the protractor in front of the screen and nearly touching it, so that the trace lies along the horizontal zero line, with its centre at the centre of the protractor. Vary the position of the slider on P_2, and check that the trace coincides with the degree lines throughout its travel. It will be noticed that the trace shortens from the horizontal position as it moves up, reaches a minimum length and then increases again to a maximum.

Adjust P_2 so that the trace is at 10 degrees with the horizontal. Switch off the 80-volt supply, and by means of the Post Office box, determine the resistance between the slider of P_2 and the point S. Let this be r_1 ohms. Disconnect the P.O.B., switch on the 80-volt supply, and adjust P_2 so that the inclination is now 20 degrees. Carry out the same sequence to measure the resistance r_1 between S and the slider again. Repeat for angles up to 90 degrees, when the value of the total resistance of P_2 will be determined.

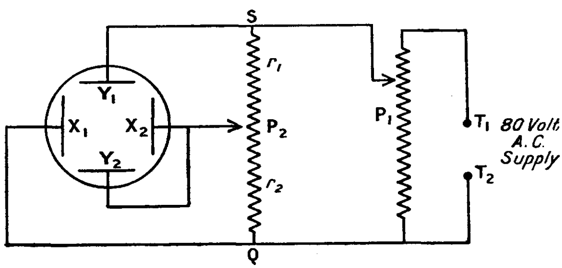


FIG. 243

Record and Calculation: Tabulate the results as follows:

Inclination of trace θ	Tan θ	Resistance r_1	Resistance r_2	Ratio of voltages r_1/r_2

The value of r_2 is obviously found by subtracting the value of r_1 from the total resistance of the potentiometer, which in turn is the value for r_1 determined when the angle was 90°.

Plot a graph of voltage ratio against tan θ, and state your conclusions.

Experiment 181. Determination of the Frequency of the A.C. Mains Supply by Producing a Circular Trace on the Screen of a C.R.T.

Apparatus: Cathode ray oscilloscope and power pack as described on pp. 433–41; 240-volt A.C. mains supply of nominal frequency 50 c.p.s. transformed to between 50 and 80 volts; known 3 μF capacitance; one 1,200-ohm, 20-watt potentiometer; one 1,200-ohm, 20-watt rheostat; A.C. supply of between 50 and 80 volts; Post Office box and accessories for determining resistance; 'gridded' transparent screen made from a 3″ square of celluloid on which is ruled lines 2 mm. apart in the same way as on graph paper.

THEORY

When A.C. is applied to the terminals of a capacitor, the current through the capacitor leads the voltage across it by 90 degrees. If a resistor is connected in series with the capacitor, then the voltage across the resistor will lead that across the capacitor by 90 degrees. The voltages are said to be '90 degrees out of phase'. If the voltages across the resistor and capacitor are applied to the X and Y plates of a C.R.T., then the spot will in general trace out an ellipse. If the voltages across the resistor and capacitor are equal and the X and Y sensitivities are equal, the axes of the ellipse will be equal, and so the spot will trace out a circle.

If the value of the series resistor is adjusted so that a circle is produced, then, since the voltages are equal, the impedance of the capacitor, X_C will be equal in value to the resistance, R, in series with it.

Therefore, since

$$X_C = \frac{1}{2\pi f C}$$

f can be calculated, as all the other quantities are known.

Procedure: Set up the power pack and the C.R.O. and adjust so that a clearly focused spot appears in the centre of the screen.

Set up the circuit as shown in Fig. 244, in which

P is the potentiometer
R is the rheostat with slider, S,
C is the capacitor
X_1, X_2, Y_1, Y_2 are the deflecting plates
T_1 and T_2 are the 50–80-volt A.C. supply terminals.

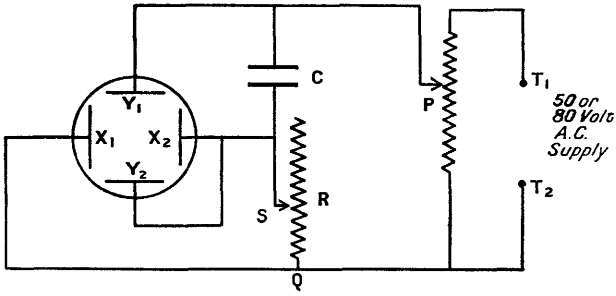


FIG. 244

Switch on the supply to the potentiometer, and adjust the latter until the amplitude of the trace is satisfactory, i.e. about 2/3rds the diameter of the tube. Vary the resistance of R and note the changes in the form of the trace. Adjust R carefully until the trace is a circle. This is checked by using the transparent screen as a background, and counting the number of squares making up each diameter.

Without altering the position of the slider on the rheostat, disconnect it from the circuit and measure the resistance between the slider and the end Q.

Record and Calculation: Record the results as follows:

Capacitance of C = farads.
Resistance of R = ohms (= X_C).

Substitute in the formula above, and calculate the value of f, the frequency of the mains.

Experiment 182. Demonstration of the Characteristics of a Metal Rectifier, using a C.R.O.

Apparatus: C.R.O. and power pack as described on pp. 433–41; 240-volt A.C. mains supply; mains transformer with output of anything between 50 and 100 volts; 3,000-ohm, 1-watt wireless type resistor, Westinghouse H.T. metal rectifier, type H17 or similar type.

THEORY

A graph of current against voltage for a metal rectifier can be obtained by the method of Experiment 168, p. 396. The curve can also be produced on the screen of a C.R.O. by applying an A.C. voltage across the rectifier and a resistor in series with it. The voltage across the series resistor will be proportional to the current through the rectifier. If this is applied to the Y plates, and the voltage across the rectifier to the X plates, a curve similar to that obtained in Experiment 168 will be seen on the screen.

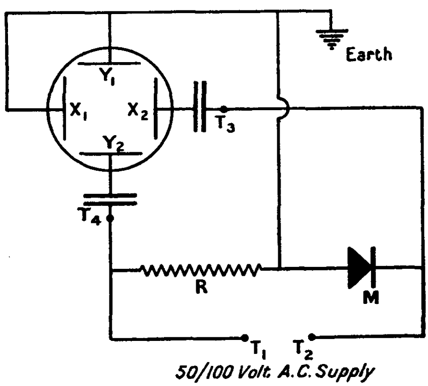


FIG. 245.

Procedure: Set up the power pack and the C.R.O. and adjust so that a clearly focused spot appears in the centre of the screen. Set up the circuit as shown in Fig. 245, in which

R is the 3,000-ohm resistor
M is the metal rectifier
T_1 and T_2 are the input terminals of the 50–100-volt A.C. supply
X_1, X_2, Y_1, and Y_2 are the deflecting plates
T_3 and T_4 are the C.R.O. input terminals, see Fig. 233, p. 434.

Switch on the supply to the terminals T_1 and T_2. Observe that the form of the trace produced on the screen is the same as that obtained in Experiment 168.

Experiment 183. Demonstration of the Mutual Characteristic Curves of a Triode Valve, using a C.R.O.

Apparatus: C.R.O. and power pack as described on pp. 433–41; 240-volt A.C. mains supply; mains transformer with output of anything between 50 and 100 volts; 120-volt H.T. battery; 9-volt grid bias battery; wander plug; 1,200-ohm potentiometer; 100K wireless type potentiometer; plug key; Osram MS4B screened grid valve. It is convenient to use this valve, with the screen and anode connected together, as a triode (it will be used as a tetrode in Experiment 185, p. 451); suitable supply for valve heater—either accumulators or small transformer.

THEORY

The mutual characteristic curves, or I_a/V_g curves for a triode were determined in Experiment 172. These curves can also be obtained on the screen of a C.R.T. If an alternating potential is applied between grid and cathode of a valve, and the voltage between the two electrodes applied to the X plates, the spot will move horizontally and follow the variations of the voltage applied to the grid. Vertical deflections depending on anode current can be obtained by connecting the Y plates across the valve.

Procedure: Set up the power pack and the C.R.O., and adjust so that a clearly focused spot appears in the centre of the screen. Set up the circuit as shown in Fig. 246 in which

H is the H.T. battery
G is the grid bias battery
W is the wander plug
R is the 100K potentiometer used as a variable series resistor
P is the 1,200-ohm potentiometer
K is the plug key
T_1 and T_2 are the input terminals of the 50–100-volt A.C. supply
X_1, X_2, Y_1, Y_2 are the deflecting plates
T_3 and T_4 are the C.R.O. input terminals, see Fig. 233, p. 434
h_1 and h_2 are the valve base terminals to which the heater is connected.

Switch on the valve heater current. Adjust the grid bias to (−1·5) volts, and the slider of the potentiometer P so that it is in the centre of its travel. Switch on the supply to T_1 and T_2—observe that the spot is drawn out to a line. Vary P and note the effect. Switch on the H.T. by means of K, and observe that the trace is of the form shown in Fig. 224. By means of P adjust the A.C. input voltage to a low value e.g. 10 to 15 volts. Vary the bias and confirm the effect produced with the curves of Fig. 224.

Note: Phase changes in the circuit may cause the trace to be inverted. The simple remedy is to turn the oscilloscope upside down.

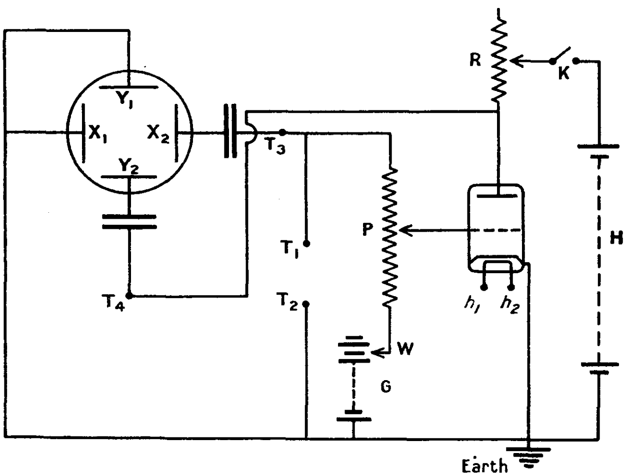


FIG. 246

Experiment 184. Demonstration of the Anode Characterisic of a Triode, using a C.R.O.

Apparatus: C.R.O. and power pack as described on pp. 433–41; 240-volt A.C. mains supply; transformer with output of anything between 50 and 100 volts; 0 to 120-volt H.T. battery; 9-volt grid bias battery; two wander plugs; 1,200-ohm, 20-watt potentiometer; 50K potentiometer, 3-watt type; plug key; Osram MS4B screened grid valve, with screen and anode connected together; suitable supply for valve heater—either accumulators or small transformer. The MS4B will be used as a tetrode in the next experiment. W_3 will be referred to in the next experiment.

THEORY

The anode characteristic curves for a triode were determined in Experiment 171. These curves can also be obtained on the screen of a C.R.O. An alternating voltage of peak value approximately equal to the H.T. voltage is connected between the H.T. positive and the anode load resistor. The voltage across the valve is applied to the X plates to produce the horizontal deflection. The p.d. across the load resistor, which is proportional to the anode current, is applied to the Y plates to produce the vertical deflection.

Procedure: Set up the power pack and C.R.O. and adjust so that a clearly focused spot appears in the centre of the screen. Set up the circuit as shown in Fig. 247 in which

H is the H.T. battery
G is the grid bias battery
W_1 and W_2 are wander plugs
P_1 is the 1,200-ohm potentiometer
P_2 is the 50K potentiometer
K is the plug key
T_1 and T_2 are the input terminals of the 50–100-volt A.C. supply
X_1, X_2, Y_1, Y_2 are the deflecting plates
T_3 and T_4 are the C.R.O. input terminals, see Fig. 233, p. 434
h_1 and h_2 are the valve base terminals to which the heater is connected.

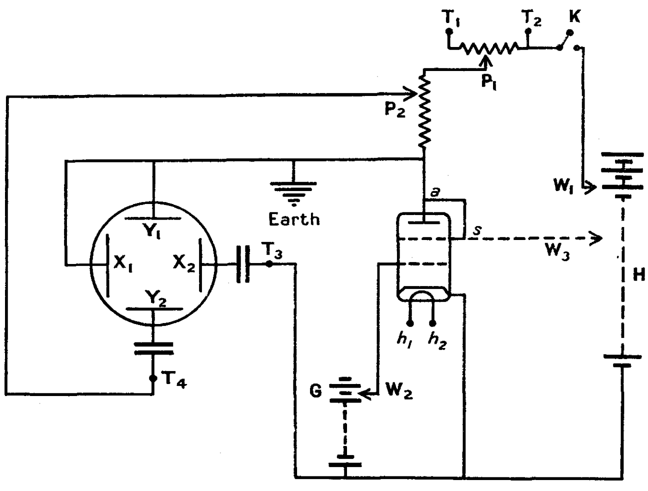


FIG. 247

Connect the screen *s* of the valve to the anode *a* as shown.

Switch on the valve heater current. Adjust the grid bias to zero, and the slider of P_1 so that it is in the centre of its travel. Set P_2 so that maximum resistance is in circuit, and plug W_1 into the 100-volt tapping.

Switch on K and connect the supply to T_1 and T_2. Observe the curve produced, and make adjustments to P_1 and P_2 so that the trace is the best possible. Vary the bias between $+ 3{\cdot}0$ volts and $- 3{\cdot}0$ volts and observe the effect on the curves. Confirm that the form of the curves is similar to that obtained in Experiment 171.

Experiment 185. Demonstration of the Anode Characteristic of a Screened Grid Valve, using a C.R.O.

Apparatus: As for Experiment 184, with the addition of the wander plug, W_3 in Fig. 247.

THEORY

This is the same as for the previous experiment (No. 184), with the additional fact that the provision of a fixed potential on the screen of the valve will alter the trace of the triode to give that of the screen grid valve as previously obtained in Experiment 174.

Procedure: As for Experiment 184, with the modification that the lead from the screen *s* to the anode *a* is disconnected, and the screen is connected to the 70-volt tapping on the H.T. battery, see Fig. 247.

Vary the bias as previously and observe the effect on the curves. The 'kink' should be clearly seen on the trace.

Experiment 186. Demonstration of the Anode Characteristic of a Pentode Valve, using a C.R.O.

Apparatus: As for Experiment 185, but substituting a pentode valve for the tetrode. This may be a Mazda AC/Pen, a Mazda SP41 or a Mullard EF50. If an AC/Pen is used it will be found that the suppressor grid is internally connected to the cathode; with the other two valves it will be necessary to connect the cathode to the suppressor externally.

THEORY

This is as for Experiment 185.

Procedure: This is the same as for the tetrode. The trace will be seen to have lost its 'kink', and variation of the bias will give curves similar to those obtained in Experiment 175. The very gradual slope of the curve after the initial steep rise should be noted.

Experiment 187. Demonstration of a Time Base, using a Gas-filled Triode (or Thyratron) and a C.R.O.

Apparatus: C.R.O. and power pack as described on pp. 433–41; 240-volt A.C. mains supply; transformer with output of anything between 50 and 100 volts; 120-volt H.T. battery; 9-volt grid bias battery; two 1,200-ohm, 20-watt potentiometers; 1 megohm potentiometer; 500-ohm resistor, 2 watts; two 0·1 μF capacitors; two plug keys; 25K, 1-watt resistor;

Mazda T41 mercury vapour thyratron, or Osram GT1C argon-filled triode.

THEORY

One of the great advantages of the C.R.T. is its ability to indicate very short time intervals, and so to record variations of voltage with time.

It has already been seen that the application of an alternating voltage across the Y plates of a C.R.T. produces a vertical line, due to the spot executing simple harmonic motion under the influence of the alternating voltage.

If the wave form of the alternating voltage is to be examined, the spot must be made to traverse the screen as well as move up and down. This may be done by applying a uniformly increasing potential difference between the X plates. This will cause the spot to move across the screen with constant speed.

Suppose the frequency of the alternating voltage applied to the Y plates is 50 c.p.s. Then, if the spot can be made to move between the X plates at the same frequency, one complete cycle of the Y voltage will appear on the screen. If the spot moves between the X plates with a frequency of 25 c.p.s. then two complete cycles of the Y waveform will appear.

The p.d. applied to the X plates to obtain this horizontal movement of the spot is called the 'time base voltage', and the equipment used to produce it is referred to as a 'time base'.

If the time base produces uniform movement of the spot it is said to be linear.

A simple time base to illustrate this effect can be set up, using a gas-filled triode or thyratron, but it will not be quite linear in its action.

A capacitor is charged through a resistor from an H.T. battery, with the thyratron connected in parallel with the capacitor. The thyratron fires at a voltage equal to the product of the grid control ratio and the grid bias, see Experiment 176. The capacitor thus discharges through the conducting thyratron until its voltage is equal to the extinction voltage. It then begins to charge again and the operation is repeated.

If the X plates are connected across the capacitor, the spot will be deflected by the varying voltage, returning to its original position when the capacitor discharges. This latter excursion is known as the 'fly back' or the 'back stroke'.

The time base is not linear, since the charging of the capacitor takes place exponentially.

The time base can be observed by applying the time base voltage to the X plates, and an alternating voltage at nominal mains frequency of 50 c.p.s. to the Y plates.

Procedure: Set up the power pack and the C.R.O. and adjust so that a clearly focused spot appears in the centre of the screen. Set up the circuit as shown in Fig. 248 in which

H is the H.T. battery
G is the grid bias battery
P_1 and P_2 are the 1,200-ohm potentiometers
P_3 is the 1-megohm potentiometer used as a series resistor
R_1 is the 500-ohm resistor
R_2 is the 25K resistor
C_1 and C_2 are the 0·1 μF capacitors
K_1 and K_2 are the plug keys
T_1 and T_2 are the input terminals of the 50–100-volt A.C. supply
X_1, X_2, Y_1, Y_2, are the deflecting plates
T_3 and T_4 are the C.R.O. input terminals, see Fig. 233, p. 434
h_1 and h_2 are the valve base terminals to which the heater is connected.

CAUTION—On no account must the thyratron be allowed to work with zero bias, and the heaters must be switched on at least TWO MINUTES before H.T. is applied, see Experiment 176.

Switch on the valve heater current. Adjust the bias to $-4{\cdot}5$ volts, and set P_3 so that maximum resistance is in circuit. Switch on K_1. Observe that the trace is now a horizontal line. Vary the bias carefully, and watch the effect on the amplitude.

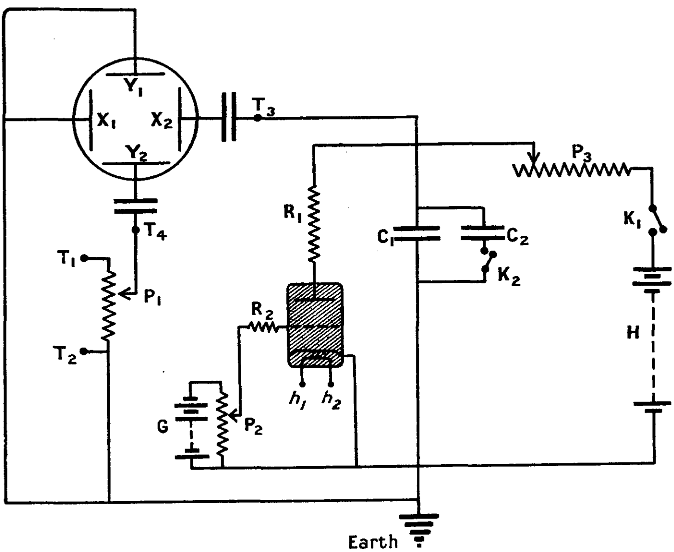


FIG. 248

Adjust P_1 in the centre of its travel and switch on the supply to T_1 and T_2. Note that the trace is now elongated in the vertical direction, and probably shows a complicated 'sine-wave' pattern. Adjust P_1, P_2 and P_3 until a single sine-wave is produced. Vary the setting of P_3 and note the frequency change produced. Switch in C_2 by means of K_2. Observe that the range of frequency has gone down. Stationary patterns should be produced when the time base frequency is a multiple or sub-multiple of the mains frequency.

The non-linearity of the trace will be shown up by the fact that the wave-length of a series of cycles will be observed to be progressively increasing when measured from one end of the trace.

Experiment 188. Demonstration of a Transitron Linear Time Base, using a C.R.O.

Apparatus: C.R.O. and power pack as described on pp. 433–41; 240-volt A.C. mains supply; transformer with output anything between 50 and 100 volts; 250-volt D.C. H.T. supply, preferably from a power pack; plug key; two-way switch; capacitors, (one 0·1 μF, two 0·01 μF, one 0·001 μF); resistors (one 2-megohms, one 200K, one 47K); potentiometers (two 1-megohm, 3-watt; two 100K, 3-watt; one 1,200-ohms, 20-watt); pentode valve, either Mazda SP41, Mullard EF50 or 6J7.

Suitable supply for valve heater.

Base board on which to mount the components, approximately 15 cm. square, with a sheet of paxolin fixed at right-angles to it also about 15 cm. square. The potentiometers can be mounted on this paxolin.

THEORY

For the detailed theory of the transitron oscillator, reference should be made to the theory text books; details will be found in Puckle's *Time Bases*, published by Chapman and Hall, and in an article by W. T. Cocking in the June 1946 number of *Wireless World*.

Procedure: Set up the power pack and the C.R.O., and adjust so that a clearly focused spot appears in the centre of the screen. Set up the circuit as shown in Fig. 249, in which

H is the H.T. supply, 250-volts D.C.
C_1 is 0·01 μF — R_1 is 2 Meg.
C_2 is 0·01 μF — R_2 is 200K
C_3 is 0·001 μF — R_3 is 47K
C_4 is 0·1 μF
P_1 is 1 meg., fine frequency control
P_2 is 1 meg., synchronising control
P_3 is 100K
P_4 is 100K amplitude control
P_5 is 1,200-ohm, 20-watt input amplitude control
K is the plug key
S is the two-way switch
T_1 and T_2 are the input terminals of the 50–100-volt A.C. supply
X_1, X_2, Y_1, Y_2 are the deflecting plates
T_3 and T_4 are the C.R.O. input terminals, see Fig. 233, p. 434
h_1 and h_2 are the valve base terminals to which the heater is connected.

Mount the components on the base board; the capacitors and resistors 'hang' in the wiring.

Switch on the heater current supply, and switch in C_2 by means of S.

Switch on with K, and note that a horizontal trace is produced on the screen. Check that the amplitude can be varied by means of P_4. Set P_3 in the centre of its travel.

Switch on the supply to T_1 and T_2. Note that a pattern is now produced.

Adjust the frequency by means of P_1 until the pattern is stationary, or nearly so. Adjustment of P_3 may be necessary.

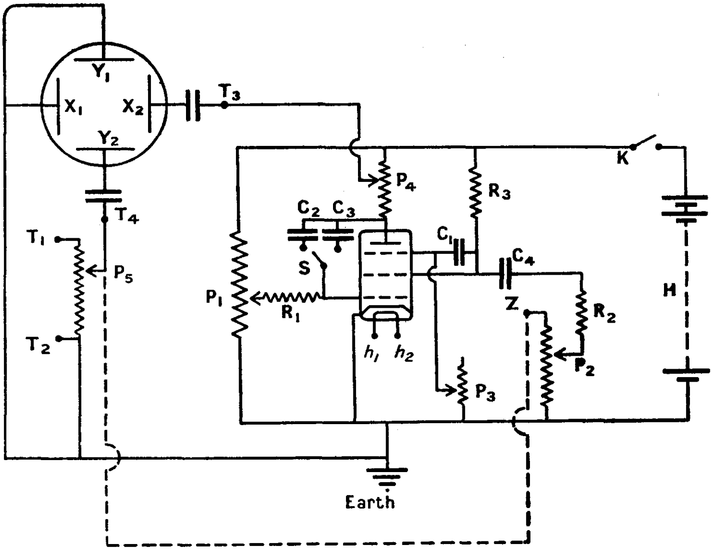


FIG. 249

Note that the trace is now linear, the wavelength of a series of cycles being constant.

To ensure that the pattern remains stationary, some of the 'work' voltage from the input is applied to the screen grid of the valve by connecting the free end, Z, of P_2 to the slider of P_5. This should 'lock' the pattern, due to the synchronising effect of the input voltage. Switch in C_3 and note that the frequency has increased. Higher frequencies may be obtained by replacing C_3 by capacitors of lower values.

It should be clear that any voltage wave-form can be examined by connecting it in place of the 50 c.p.s. input between T_1 and T_2 and adjusting the time base speed by means of C_1, C_3, etc. and P_1.

CHAPTER LVII

TRANSISTORS

The energy possessed by an electron in an atom determines the orbit in which it will move, and in order to jump from an orbit nearer the nucleus to one farther away it must be given the appropriate amount of energy. The quantum theory shows that the process is not continuous but that there are definite restricted zones of energy and these are known as 'bands'. The outermost electrons in a normal atom constitute the valency electrons and are in the 'valency band'. Conduction of electricity is mainly the result of the movement of electrons and these must usually be even farther away from the nucleus than the valency band, and so we have to consider the relationship between the valency band and the 'conduction band'. In good conductors, like the metals, the valency band and the conduction band overlap, so that there are always electrons available for conduction. In insulators there is a considerable gap between the minimum of the conduction band and the maximum of the valency band. This is illustrated in Fig. 250(A) and (B) in which (A) shows the general case and (B) shows the special case which applies to metals.

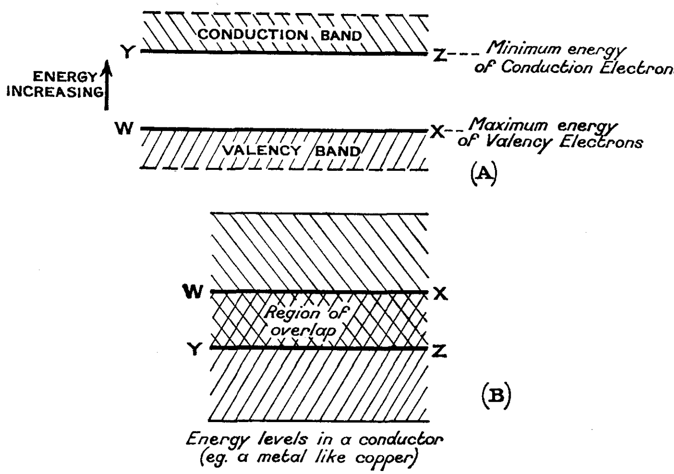


FIG. 250

In the case of the elements Germanium and Silicon (Group IV of the periodic table) the gap between the bands is too large for electrons to jump unless extreme energies are available, and these materials are therefore non-conductors. If, however, traces of elements are introduced into otherwise pure Germanium or Silicon these impurities can act as 'stepping stones' between the valency and conduction bands. The processes are as follows:

(i) *N-type semi-conductors:*

If the impurity is an element from Group V of the periodic table, e.g. arsenic or antimony, this will have five electrons in its valency band. Moreover, the maximum energy of the valency band of the impurity element is greater than that in the germanium or silicon, and electrons can thus more readily move from this band into the conduction band of the group IV element. The material thus becomes semi-conducting and because the conduction is due to the enrichment by negative ions it is known as 'N-type'. Some conduction is due to positive ions in this material but most is due to electrons and these are referred to as the 'majority carriers' (in N-type materials). Refer to Fig. 251.

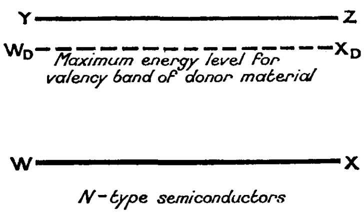


FIG. 251

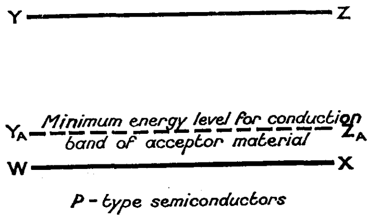


FIG. 252

(ii) *P-type semi-conductors:*

If the impurity is an element from Group III of the periodic table, e.g. boron or indium, it will have only three electrons in its valency band and, moreover, the minimum energy of its conduction band is lower than that of the group IV elements. Thus electrons can more easily

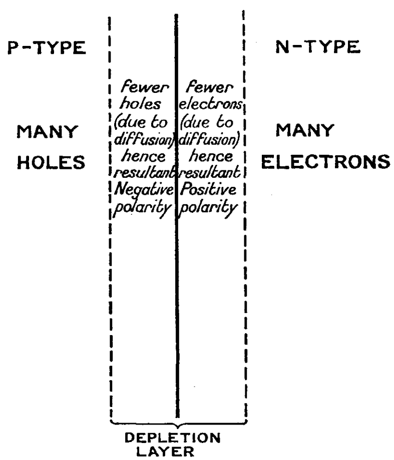


FIG. 253

jump from the valency band of the germanium or silicon into the conduction band of the boron or indium. This process creates a positive ion, by the loss of the electron, and as this is a 'vacancy' for another electron it is usually referred to as a 'hole', and the material is known as a 'P-type' semi-conductor. In such materials most of the conduction is by the positive holes and thus in this case the electrons are the *minority* carriers. The process is illustrated in Fig. 252.

The effect of a junction: If a P-type material and an N-type material are put into contact there will be diffusion at the junction caused by the random movement of the ions, due to thermal agitation, and this will be more marked at higher temperatures. Thus, electrons will diffuse into the P-type material and holes will diffuse into the N-type material. In each case these will meet ions of opposite sign in profusion after crossing the junction and will unite to form electrically neutral atoms. Thus near the junction there will be a shortage of ions and this region is therefore called a 'depletion layer'. It is illustrated in Fig. 253. Within the depletion layer a polarity will be established, negative in the P-type and positive in the N-type, and this will favour the movement across the junction of minority carriers. So there is a leakage current across the junction and this is investigated in Experiments 189 and 190. Because the effect is caused by diffusion, the leakage current will be highly sensitive to temperature—hence the precautions described on p. 460 to ensure temperature stability.

The Transistor: The practical application of these qualities resulted in the production of the device known as a 'transistor'—a 'transfer-resistor'. It may be a thin plate of P-type between two pellets of N-type, or a thin plate of N-type between two pellets of P-type. The former is referred to as an N-P-N transistor and the latter, which is at present the more common, the P-N-P transistor.

The effect of this construction is to produce two depletion layers, as shown in Fig. 254. A transistor in operation is always biased in the

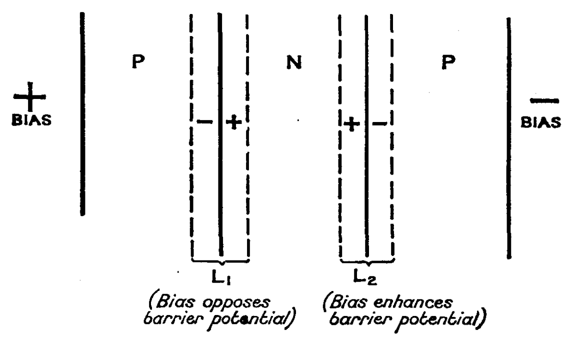


FIG. 254

way indicated, which it will be seen is such as to oppose the barrier potential in one depletion layer (L_1), and to enhance it in the other (L_2). Hence there will be a small resultant p.d. across L_1 and a large one across L_2. Thus L_1 becomes a low resistance layer and L_2 a high resistance layer. As the current passing through L_2 is nearly the same* as that through L_1, the power dissipated in L_2 is much greater than that dissipated in L_1.

* It is usually about 98% of it.

In the pellets of P-type the majority carriers are the holes and the central region of N-type is made very thin so that any holes crossing L_1 have an excellent chance of reaching L_2 before meeting an electron and so being 'neutralised'. Once across L_2 the risk of a hole meeting an electron is very much less. So the P-N-P transistor will rely almost entirely on holes for conduction through it.

The thin layer of N-type material is known as the 'base' and the positively biased pellet of P-type is known as the 'emitter'. The other pellet of P-type, biased negatively, is known as the 'collector'. The reason for the choice of these terms lies in the explanation of the mechanism of the transistor. A (small) base-emitter current will control the forward bias in L_1 and hence control the number of holes attracted into the base. Most of these holes are attracted by the negative bias of the collector; thus one pellet is *collecting* the holes *emitted* by the other pellet, provided always that the base is thin enough. This control of collector current by means of variations in the base-emitter current is investigated in Experiment 192.

In the N-P-N transistor, electrons are emitted from a pellet of N-type material into a thin layer of P-type material (the base). Nearly all of these electrons are collected by the second pellet of P-type material before they encounter a 'hole' in the base. Thus, in contrast to the P-N-P transistor, the N-P-N transistor relies on electrons for most of its conduction and accordingly the bias is reversed from that of the P-N-P type.

Fig. 255 shows the practical form and Fig. 256 shows the conventional diagram. A transistor behaves in a manner similar to that of a thermionic

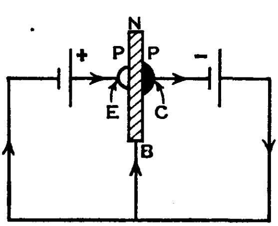


FIG. 255

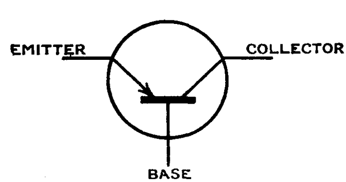


FIG. 256

valve, but both the power consumption and the applied voltages are substantially lower. It is, in fact, sometimes helpful to compare the emitter, base and collector with the cathode, grid and anode of a valve, but it is necessary to remember that whereas the valve has a positive potential applied to its anode, the transistor has a negative potential applied to its collector.

A triode valve is a voltage-operated device, quite small changes in grid potential producing large changes in anode current; the input impedance is very high but the output impedance is relatively low. A transistor is a current-operated device, the input impedance being low—of the order of 20 to 100 ohms—and the output impedance is high—50K to 500K ohms, the precise value depending on the mode of operation. A small change in input current produces a change in output current, but *at a much higher impedance*. There is thus a *power* gain.

A transistor can also be looked upon as two diodes, these being formed by (i) the emitter-base, and (ii) the collector-base junctions; the emitter is biased positively with respect to the base, and the collector negatively with respect to the base, as in Fig. 255.

The connections to the base, emitter and collector are made by means of wire sealed through the glass end-support. The wires are conventionally spaced as shown in Fig. 257A. and B. The base connection is the middle wire; the space between the collector and the base is greater than that between the emitter and the base. The collector can also be

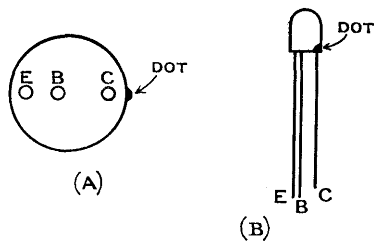


FIG. 257

identified by a coloured dot on the transistor placed next to the collector lead. In some makes, e.g. B.T.H./A.E.I., the collector lead is about $\frac{1}{8}''$ shorter than the other two wires.

As was pointed out on p. 458 the device is highly temperature sensitive, and every precaution must be taken to ensure that the current flowing, and the power dissipated, do not exceed the manufacturer's figures. They are usually referred to a maximum temperature of 25°C. It is found that the collector-base leakage current doubles for a temperature rise of approximately 10°C, and the collector-emitter leakage current doubles for a rise in temperature of approximately 8°C.

To stabilise the temperature during experiments the transistor should be placed in a hole drilled in a small brass block. The hole should be just deep enough to allow the case of the transistor to 'bottom' in the hole. The Mullard OC.71 transistor needs a hole $\frac{13}{64}$ inch in diameter and the B.T.H./A.E.I. GT31/32 a hole $\frac{3}{16}$ inch diameter.

If the transistor is soldered into a circuit the lead wires must *not* be shortened and during soldering operations it MUST be held in a 'heat shunt'. The latter consists of a heavy pair of pliers holding the lead wires between the glass seal and the point at which the solder is applied. Crocodile clips with small copper blocks soldered to the jaws will also serve. Failure to observe these precautions will certainly damage the transistor.

The risk of damage can be reduced if the lead wires are clamped between two 6BA nuts on a 6BA bolt fitted with a solder tag to which the circuit wires have previously been soldered. Three such nut and bolt assemblies should be mounted on a paxolin strip and spaced correctly so that the emitter, base and collector can be readily identified. This

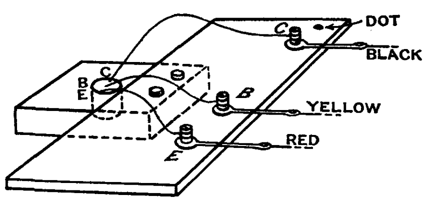


FIG. 258

will reduce the risk of connections of wrong polarity being made—another certain way of destroying the transistor. The paxolin strip should then be bolted to the temperature-stabilising brass block as shown in Fig. 258. Finally, label the tags by appropriate letters on the paxolin, and add the coloured spot by the collector tag. The circuit leads should then be coloured as shown (use coloured sleeving). It cannot be too strongly emphasised that application of the wrong polarity will burn out the transistor *in a fraction of a second.*

A further point that must be remembered is that if a resistance-measuring meter is used to check the transistor, the meter terminal or socket marked red is connected to the *negative* of the internal battery. Thus any transistor terminal requiring a *positive* supply must be connected to the *black* terminal of the meter being used for the resistance test.

The general polarity scheme for the transistor is shown in Fig. 255.

Fig. 259A gives some idea of the usual applied voltages and Fig. 259B, some idea of the current values. These figures should be compared with the far greater requirements of the thermionic valve.

Transistor Experiments: In the experiments which follow, quite small voltages and currents have to be measured, if significant graphical results are to be obtained. A high-resistance meter with f.s.d. 1·0 volt which can be read to 0·01 volt will be required—an AVO model 7 is suitable. Currents of 1 microamp. to 5 microamp. can be measured on a meter with f.s.d. 20 microamp., or even 50 microamp. A meter with f.s.d. 100 microamp., or 200 microamp., will also be needed. It may not be possible to measure currents of less than 5 microamp. on meters of this type but with care it can be done with the 100 microamp. instrument.

It should be realised that meters with low f.s.d. values are very delicate and costly. They should be treated with the utmost care both mechanically and electrically. They can often be obtained for a few pounds each from suppliers advertising in *The Wireless World.*

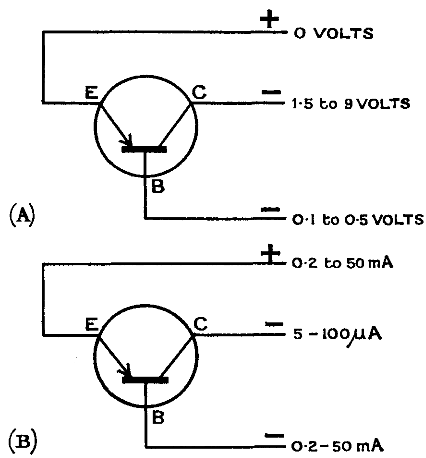


FIG. 259

The performance of transistors varies significantly with the operating conditions, there being considerable 'interaction' between the electrodes, quite unlike the behaviour of thermionic valves. Furthermore, individual transistors of the same make and type can, and do, vary considerably in their parameters. For example, one manufacturer gives the following values for current amplification in the common emitter circuit:

minimum	value	45
typical	,,	60
maximum	,,	100

The transistors used in the experiments described are standard Mullard and B.T.H./A.E.I. types. Other transistors can be obtained at about one-third of the cost of these (they are known as 'red spot', 'white spot', etc.) and they are usually specimens which have not come up to the required standards in all the parameters and so have been discarded by the makers. They can be quite satisfactory in some respects but for specific purposes they must be individually tested.

Before attempting any laboratory work with transistors the student should refer to standard works on this subject. For instance 'The British Transistor Manual' and 'Transistors for the Experimenter' (Mullards) can be strongly recommended. When referring to literature on transistors the term 'common' and 'grounded' are often to be found where in other electrical literature the word 'earthed' would be used.

Experiment 189. Investigation of the collector-base leakage current of a P-N-P type junction transistor

Apparatus: 9-volt grid bias battery; 10 K. potentiometer—radio type with carbon or wire wound track; high-resistance voltmeter, 0–1 volt, calibrated to 0·01 volt (see p. 461); microammeter, 0–20 μA. or 0–50 μA., (see p. 461); two s.p.s.t. switches; Mullard OC71 or B.T.H./A.E.I. GT31 or GT32 transistor, fitted into a support, etc. as described on pp. 460–1.

THEORY

As discussed on pp. 459–60, the junction formed by the collector and base acts as a diode, biased so that the collector is negative with respect to the base.

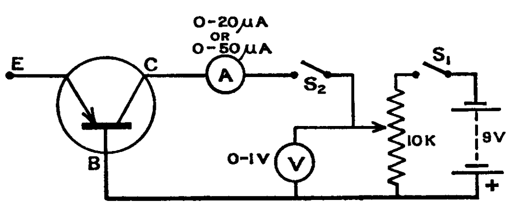


FIG. 260

Procedure: Set up the circuit shown in Fig. 260, the emitter not being connected. Close S_1 and adjust the potentiometer so that the voltmeter reads 0·01 volt, i.e. so that the slider is at the most positive end of the potentiometer. Close S_2, watching the microammeter carefully; it should read about 1 μA. Carefully raise the applied voltage to 0·02 volt, 0·03 volt, etc. and note the corresponding readings of the microammeter. Continue changing the voltage by 0·01 volt until you are sure that the 'knee' has been passed (see Fig. 261), and then change the applied voltage by increments of about 0·1 volt, continuing until a maximum of 1 volt is reached.

If possible repeat with another type of transistor.

Record and Calculation: Tabulate your observations and plot a graph of collector current, I_c, against collector volts, $-V_c$. It is customary in these experiments to plot the negative applied voltage along the abscissa in the normal positive direction. The form of the graph should then appear as in Fig. 261. Note the scale of the abscissa and that the 'knee' will be missed if during the experiment the low voltages are not carefully applied.

If a second transistor was used, plot a similar curve and compare the two transistors (a note on variations to be expected is to be found on p. 462).

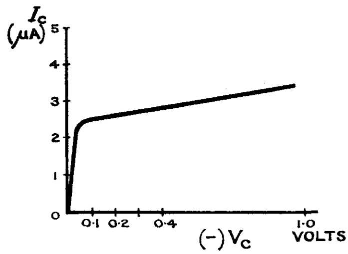


FIG. 261

Experiment 190. Investigation of the emitter-collector leakage current of a P-N-P type junction transistor

Apparatus: As for Experiment 189 except that the microammeter used should now have a range of 0–100 μA.

THEORY

It will be seen from the circuit diagram (Fig. 262) that the current flows from the emitter to the collector via the base. The current through the emitter-base diode will cause an amplified current to flow in the collector-base circuit. The leakage current, determined in Experiment 189, will therefore be increased by this transistor action.

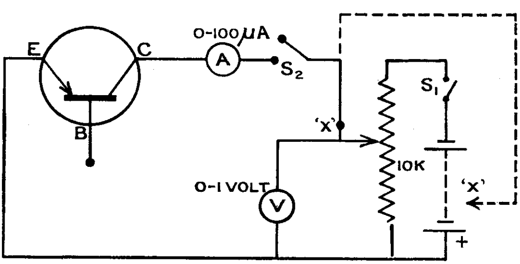


FIG. 262

Procedure: Set up the circuit shown in Fig. 262, the base not being connected. Close S_1 and adjust the potentiometer for the minimum reading as in Experiment 189. Close S_2. Notice that the current is greater than it was for the same potentiometer setting in Experiment 189—it should now be of the order of 2–5 μA. Carefully increase the applied voltage by steps of 0·01 volt to 0·1 volt, noting the corresponding currents. Next investigate the effect of applied voltages greater than 1 volt by disconnecting the slider and voltmeter at X and plugging X in turn into the 1·5, 3·0 volts, etc. tappings of the battery, continuing this process until a p.d. of 9 volts is applied.

If possible repeat with another type of transistor.

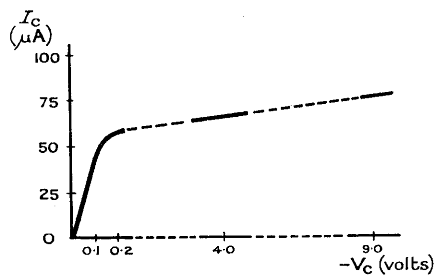


FIG. 263

Record and Calculation: Tabulate your observations and plot a graph of collector current, I_c, against collector volts, V_c, plotting the negative values of the latter in the positive direction of the abscissa, as previously. The result should be similar to Fig. 263. Notice that once again the 'knee' will not be evident unless initial voltages are small.

Experiment 191. Investigation of the collector-current—emitter-current characteristics and of the current gain of a P-N-P type junction transistor with its base earthed

Apparatus: Two 9-volt grid bias batteries; one 25 K. and one 10 K. radio type potentiometer or variable resistor; two milliammeters, either 0–5 mA or 0–10 mA; s.p.s.t. switch; Mullard OC71 or B.T.H./A.E.I. GT32 junction transistor fitted into a support etc., as described on pp. 460–1.

THEORY

When the voltage on the collector is held constant at a suitable negative value, changes in the emitter current cause changes in the collector current of approximately the same order. If these changes are respectively denoted by δI_e and δI_c, then the 'current gain', α, is defined as $\frac{\delta I_c}{\delta I_e}$, and this is one of the important transistor parameters.

Procedure: Set up the circuit shown in Fig. 264. The two variable resistors are connected in series so that they may be used as coarse and fine controls. With maximum resistance in the emitter-base circuit set the collector voltage to $-1{\cdot}5$ volts by plugging the wander plug X into the appropriate tapping of the grid bias battery. Close S and adjust the variable resistor so that the emitter current is 0·5 mA, and read the corresponding value of the collector current. Increase I_e by steps of 0·5 mA, up to 5 mA, and record corresponding values of I_c.

Repeat for values of the collector voltage of $-4{\cdot}5$ and $-9{\cdot}0$ volts.

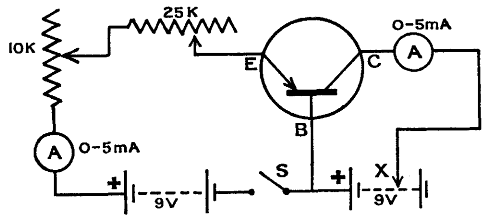


FIG. 264

Record and Calculation: Tabulate your observations as follows:

COLLECTOR VOLTAGE					
− 1·5		− 4·5		− 9·0	
Emitter Current I (mA)	Collector Current I_c (mA)	I_e (mA)	I_c (mA)	I_e (mA)	I_c (mA)
0·5					
1·0					
etc.					

Plot graphs of I_c as ordinate against I_e for each value of V_c, and from these graphs deduce a value for α.

Experiment 192. Investigation of the collector-current—base-current characteristics and of the current gain of a P-N-P junction transistor with its emitter earthed

Apparatus: Two 9-volt grid bias batteries; one 25 K. and one 100 K. radio type potentiometer or variable resistor; microammeter, 0–100 μA; milliammeter, either 0–5 mA, or 0–10 mA; s.p.s.t. switch; Mullard OC71 or B.T.H./A.E.I. GT31 junction transistor fitted into a support, etc. as described on pp. 460–1.

THEORY

As described on p. 459, when the voltage on the collector is held constant at a suitable negative value, very small changes in the base current produce large changes of current in the collector circuit. If these changes are denoted respectively by δI_b and δI_c, then the current gain, α' (or sometimes denoted by β) is defined as

$$\alpha' = \frac{\delta I_c}{\delta I_b}$$

This is another of the important transistor parameters.

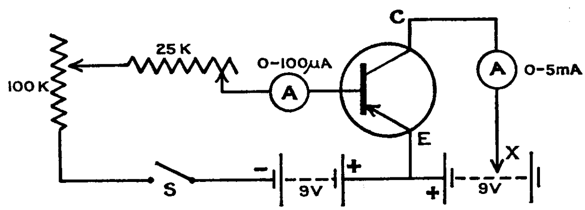


FIG. 265

Procedure: Set up the circuit shown in Fig. 265. The variable resistors are connected in series so that they can be used as coarse and fine controls for the base current. With maximum resistance in the base circuit, set the collector voltage to $-1{\cdot}5$ volts by plugging the wander plug X into the appropriate tapping of the grid bias battery. Close S and adjust the variable resistors so that the base current is 10 μA and record the reading of the milliammeter, this will be I_c. Keeping the collector voltage constant at $-1{\cdot}5$ volts increase the base current to 100 μA, by steps of 10 μA, and record the corresponding values of the collector current.

Repeat the above observations with the collector voltage set at $-3{\cdot}0$ volts, $-4{\cdot}5$ volts, etc., but be careful not to exceed the recommended ratings for the transistor you are using.

Record and Calculation: Tabulate your observations as follows:

COLLECTOR VOLTAGE					
$-1{\cdot}5$		$-3{\cdot}0$		$-4{\cdot}5$	
Base Current I_b (μA)	Collector Current I_c (mA)	I_b	I_c	I_b	I_c
10					
15					

Plot graphs of I_c against I_b for each value of the collector voltage, V_c. The results should be as shown in Fig. 266. From the graphs determine α' for various values of I_c. Plot a graph of α' against I_c and state your conclusions.

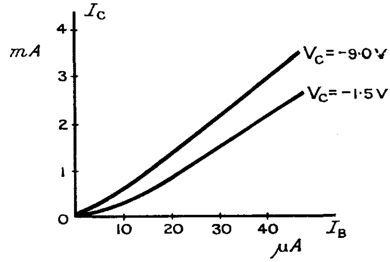


FIG. 266

Experiment 193. Investigation of the collector-current—collector-voltage characteristic of a P-N-P junction transistor with its base earthed

Apparatus: Two 9-volt grid bias batteries; one 100 K., one 25 K. and one 10 K. radio type potentiometers or variable resistors; milli-ammeter, 0–5 mA; 5–0–5 mA meter or else 0–5 mA meter with a reversing switch; voltmeter, 0–10 volts; two s.p.s.t. switches; reversing switch; Mullard OC71 or B.T.H./A.E.I. GT31 or GT32 transistor.

THEORY

When the emitter current, I_e, is held constant at a suitable value, the collector current, I_c remains almost constant for the negative values of the collector voltage, V_c, but very small positive collector voltages have a large effect on the collector current.

Procedure: Set up the circuit shown in Fig. 267. If the milliammeter used to record the collector current is centre reading, the switch S_4 will not be required.

Close S_1 and adjust the 10 K. potentiometer so that the collector voltage will be —9·0 volts; this will be registered by the voltmeter. Take care that the polarity is correct. Close S_3 and adjust the 100 K. and the 25 K. resistors so that the emitter current, I_e is 1·0 mA. Keeping this current constant, change the collector voltage in turn to —8·0, —7·0 volts, etc. and record the corresponding values of the collector current, finally applying zero voltage to the collector.

Reverse S_2; reverse the voltmeter connections (if an Avometer with a reverse polarity switch is used as this voltmeter, this switch should be used). Check that V_c is still zero. If S_4 is in circuit, reverse it. Check that I_e has remained constant at 1·0 mA. Carefully increase V_c in the positive direction in steps of 0·1 volt until 0·5 volt is reached. For each setting record the value of I_c, noting too that at some low value of $+ V_c$ the collector current reverses.

Repeat the whole of the above procedure with the emitter current set at 2·0 mA and at 4·0 mA, taking great care when increasing V_c in the positive direction. Notice that the maximum permissible value of $+ V_c$ rises as I_e is raised.

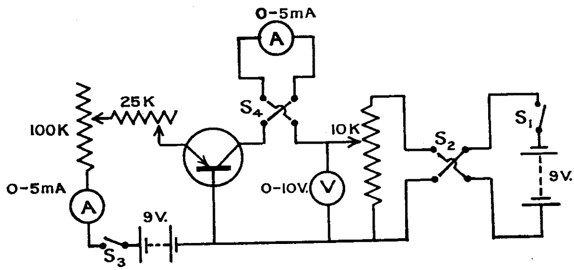


FIG. 267

Record and Calculation: Tabulate your observations as follows:

EMITTER CURRENT (I_e)					
1 mA		2 mA		4 mA	
Collector Volts $\pm V_c$	Collector Current I_c (mA)	V_c	I_c	V_c	I_c
− 9·0 − 8·0 ⋮ 0		− 9·0 − 8·0 ⋮ 0		− 9·0 − 8·0 ⋮ 0	
+ 0·1 ⋮ + 0·5		+ 0·1 ⋮ + 0·7		+ 0·1 ⋮ + 1·0	

Plot graphs of I_c against $-V_c$ for each value of I_e and comment on your results.

Experiment 194. Investigation of the collector-current—collector-voltage characteristic of a P-N-P junction transistor with its emitter earthed

Apparatus: Two 9-volt grid bias batteries; one 100 K., one 25 K. and one 10 K. radio type potentiometers or variable resistors; microammeter, 0–100 μA; milliammeter, 0–5 mA; voltmeter, 0–10 volts; two s.p.s.t.

switches; Mullard OC71 or B.T.H./A.E.I. GT31 or GT32 P-N-P junction transistor.

THEORY

When the base-current is held constant at a suitable value, the collector-current varies with the collector-voltage, the rate of change being considerable for low values of the collector-voltage, but much less for the higher values of V_c.

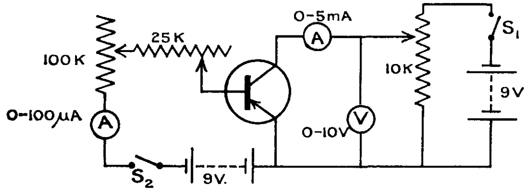


FIG. 268

Procedure: Set up the circuit shown in Fig. 268. Set the 10 K. potentiometer slider at the positive end (so that the voltmeter reads zero) and then adjust the 100 K. and 25 K. resistors so that the base current is 20 μA. Switch on S_1. Increase the collector volts by steps of 0·05 volt or 0·1 volt, recording in each case the value of the collector current, I_c. It will be found that after V_c has become $-0{\cdot}5$ to $-1{\cdot}0$ volts the increments used can be of the order of 1·0 to 1·5 volts.

Repeat the process for values of I_b 40 μA, 60 μA, 80 μA, and also for I_b zero.

Record and Calculation: Tabulate your observations as follows:

BASE CURRENT				
I_b = 20 μA		I_b = 40 μA		etc.
$-V_c$ (volts)	I_c (mA)	$-V_c$ (volts)	I_c (mA)	

Plot a graph of I_c against $-V_c$ for each value of I_b. Note again the 'knee' which appears in each curve.

CHAPTER LVIII

EXERCISES

The majority of the exercises in this chapter are direct applications of the methods described in the text. Where applicable, the number of the experiment on which the exercise is set is given in brackets at the end of the statement of the exercise. No variation of technique is required from that given in the instructions for the experiment on which the exercise is based. It is not suggested that all these exercises be performed, as the time required would be too great, and the problems given in the next two chapters are much more interesting. A selection of the exercises should be carried out and the student should satisfy himself that he *could* do all of them without reference to the experimental instructions. In fact a revision of the practical physics course can be made by writing down the method to be used and the precautions to be taken, and by drawing a diagram of how the apparatus would be assembled. This need only be done in the form of notes, but it should be *written*; it is only by committing oneself by the written word that a real test of knowledge can be made and the gaps which exist exposed; a circuit diagram is often more difficult to produce than one expects it to be. On this subject it is worth mentioning that it is a waste of time to try to memorise circuit diagrams. It is the principles which should be memorised and understood; the circuit diagrams can then be designed to meet the needs of the experiments.

1. Determine the volume of 2 metres of bare copper wire of about S.W.G. 14.
2. Determine the density of iron.
3. Determine the density of methylated spirits.
4. Determine the density of oak.
5. Determine the acceleration due to gravity, using a thick piece of rubber (catapult rubber) as a vertical spring, (7).
6. Determine Young's modulus for nichrome wire, (8).
7. Determine Young's modulus for steel, using a steel vibrator from Fletcher's trolley apparatus, (9).
8. Determine the moment of inertia about an axis through the centre of gravity of a piece of wood which measures about 2 ft. by 6 inches by 1 inch, (23).
9. Determine the surface tension of benzene, (29).
10. Determine the specific heat of iron, (35).
11. Determine the specific heat of aniline by the method of mixtures, (36).
12. Determine the specific heat of glass, (37).
13. Determine the specific heat of aniline by an electrical method, (62).
14. Determine the specific heat of turpentine by the 'method of cooling', (38).
15. Determine the coefficient of linear expansion of iron, (49).
16. Determine the mean coefficient of apparent expansion of paraffin in glass, (50).

17. Determine the coefficient of expansion of air, (53).
18. Determine room temperature, using a constant volume air thermometer, given some ice, (55).
19. Determine the coefficient of thermal conductivity of rubber in the form of a tube, (57).
20. Determine the radius of curvature and the focal length of a concave mirror, (65).
21. Determine the focal length of a convex lens, (68).
22. Determine the focal length of a convex lens by the method of displacement, (71).
23. Determine the focal length of a convex mirror, using an auxiliary convex lens, (73).
24. Determine the focal length of a convex mirror, using an auxiliary plane mirror, (74).
25. Determine the focal length of a concave lens, using an auxiliary convex lens, (75).
26. Determine the focal length of a concave lens, using an auxiliary concave mirror, (76).
27. Determine the radii of curvature of the faces of a convex lens and the refractive index of the material of which the lens is made, (78).
28. Determine the radii of curvature of the faces of a concave lens and the refractive index of the material of which the lens is made, (78, note 2).
29. Determine the refractive index of water given only 0·5 ml. of it, (79).
30. Determine the focal length of a convex lens from a graph of magnification against distance of image, (80, note).
31. Determine the fraction of incident light transmitted by a sheet of perspex, (83).
32. Determine the refractive index of methylated spirits by the 'real and apparent' depth method, (85).
33. Determine the refractive index of the material of a glass prism, using a spectrometer, (89).
34. Determine the number of lines to the centimetre in a given diffraction grating, assuming a value for the wave-length of sodium light, (95).
35. Determine the velocity of sound in air at room temperature, (98).
36. Determine the end correction for the given resonance tube, (99).
37. Determine the frequency of the given tuning fork, (101).
38. Compare the magnetic moments of two magnets by (i) finding the neutral points for the 'A' and 'B' positions and (ii) a null method using a deflection magnetometer, (108 and 109).
39. Compare the magnetic moments of two magnets by a vibration method, (111).
40. Magnetise a steel knitting needle and determine its magnetic moment, (113).
41. Determine the horizontal component of the earth's magnetic field, (114).
42. Determine the electrochemical equivalent of chlorine, (118).
43. Calibrate an ammeter, using a copper voltameter, assuming a value for the electrochemical equivalent of copper, (120).
44. Determine the horizontal component of the earth's magnetic field, using a tangent galvanometer, (123).
45. Determine the e.m.f. of a Leclanché cell by a 'sum and difference method'. Compare it with a pair of accumulators in series, assuming the e.m.f. of such an arrangement to be 4 volts, (126).
46. Determine the value of a 10,000-ohm wireless type resistor, using a Post Office box, (132, note 2).
47. Determine the resistivity of eureka wire, (135).

48. Compare the e.m.f.'s of an accumulator and a pair of Leclanché cells (wired in series), using a potentiometer, (140).
49. Determine the internal resistance of a Daniell cell, using a potentiometer, (141).
50. Calibrate an ammeter, using a potentiometer, (144).

CHAPTER LIX

ELEMENTARY PROBLEMS

In the practical papers of examinations two types of questions are encountered. The first involves the use of a standard method and is of the type given in the previous chapter. The second type of question demands a little more ingenuity even though the question is based on a standard method. This last type is met particularly in Scholarship papers, and so that the student may gain experience in this work a collection of such problems is given here. Usually the whole experiment, including the written record and calculation must be completed in 1½ hours. Such time allowance is sometimes inadequate and a good experimenter who wastes no time may have considerable difficulty in doing himself justice when asked to work against the clock. However, the student must accept the conditions of the examination for which he enters and if necessary must adapt his methods suitably. The most important thing is to plan the whole experiment before starting it. Have a clear idea of what must be done and what the range of the observations will be. Failure to attend to the latter often results in too much time being devoted to observations at one end of the range whilst the other end is neglected due to shortage of time. If a graph is to be used, try to plot the points as the experiment proceeds so that suitable values can be observed and doubtful results checked immediately. If experimental work is temporarily held up, perhaps while a temperature variation is being effected, use the time to do some of the written work. Work at such a speed that accuracy is not impaired—that is, do not increase your speed so much that you become hasty. By practice in this sort of work you will discover just how fast you can work without spoiling the results.

1. *Apparatus:* Simple pendulum with as long a thread as possible, e.g. one suspended from the ceiling and almost touching the floor; stop-watch; metre rules.
   Problem: Determine the length of the pendulum, without measuring it directly, by two methods:
   (i) Displace the bob by an amount d cm., measured along the chord joining the mean position to the new position. Record this distance and the amount of vertical displacement (x cm.) which the bob has

suffered. Plot a graph of d^2 against x and deduce the length of the pendulum from it.

(ii) Find the periodic time of vibration of the pendulum when it is swinging through a small angle. Assume that the acceleration due to gravity is 981 cm./sec./sec., and calculate the length of the pendulum from the result.

2. *Apparatus:* Spiral spring; weights and hanger—not exceeding the maximum load for the spring; simple pendulum; (no timing instrument); metre rule.

   Problem: Load the spring with a small weight and set it oscillating in a vertical plane. Adjust the length of the simple pendulum so that its periodic time is the same as that of the spring. Record the load on the spring and the length of the pendulum. Repeat for various loads up to a safe maximum. Plot the values of load against length of equivalent pendulum and deduce values for (i) the load needed to extend the spring 1 cm., (k), (ii) the effective mass of the spring.

   Check your value for k by another method.

3. *Apparatus:* Metre rule of known weight (about 100 gm.); piece of glass of about the same weight (not given); knife edge; thread; beaker. (No weights are provided).

   Problem: Find the density of glass.

4. *Apparatus:* Two sets of weights and hangers (each 0–500 gm.); solid denser than water, of weight (not given) about 300–400 gm.; two pulleys; drawing board; paper; thread; plane mirror; drawing instruments; beaker.

   Problem: Determine the density of the given solid, using the principle of the parallelogram of forces, and Archimedes' principle.

5. *Apparatus:* Tangle of uniform bare wire; Archimedes' bridge; micrometer screw-gauge.

   Problem: Find the length of the wire, without untangling it, by a hydrostatic method.

6. *Apparatus:* Large boiling tube; lead shot; metre rule; liquid of unknown density—methylated spirits is suitable; ruler; gas jars (no balance).

   Problem: Load the tube with lead shot and record the depths to which it is immersed when it floats in water and in the liquid. Repeat with various loads. Use a graphical method to deduce the density of the liquid.

   Note: The graphical method eliminates the need for a correction for the rounded end of the tube which would be necessary if a series of separate values were calculated and the mean found. You should prove mathematically that this is so.

7. *Apparatus:* Spiral spring; set of weights and hanger (not exceeding the maximum load for the spring); liquid of unknown density—methylated spirits is suitable; solid of unknown density and weight less than the maximum load for the spring (weight not given); metre rule, thread; beaker.

   Problem: Calibrate the spring for use as a spring balance and use it to determine the densities of the given solid and liquid.

8. *Apparatus:* Spiral spring; liquid of unknown density and solid of unknown weight and density—the weight not to exceed the maximum load for the spring; metre rule; thread; beaker.

   Problem: Determine the densities of the solid and the liquid.

9. *Apparatus:* ICE; specific gravity bottle; methylated spirits; chemical balance; beaker.

   Problem: Determine the density of ice by finding the density of that mixture of methylated spirits and water which has the same density as ice.

10. *Apparatus:* ICE; bare copper wire of about S.W.G. 24; micrometer screw-gauge; thermometer; chemical balance; metre rule.
Problem: Determine the density of ice by the following method: Find the mass per unit length of the wire and its cross-sectional area. Choose a large piece of ice and wrap sufficient wire round it so that it will float in water at about 4°C. Leave it until the ice (and wire) just submerge completely and then quickly remove the lump, dry on blotting paper and place in a weighed vessel. Find the weight of this ice. Measure the length of wire used. Repeat several times.
11. *Apparatus:* Apparatus for verifying Boyle's Law; metre rule.
Problem: Determine the pressure of the atmosphere (use a graphical method).
12. *Apparatus:* Piece of wood of irregular shape but of uniform thickness. The area should be several square feet, the thickness about one inch, and a hole (H) should be drilled about 9 inches from the centre of gravity, so that a knife-edge can pass easily through it; a balance on which to weigh the piece of wood, a stop-watch and a knife-edge are also needed.
Problem: Suspend the wood by passing the knife-edge through H and find the periodic time (T) for small oscillations. Without making any further holes in the wood take any other observations, and perform any constructions, needed to enable you to find ALL the points of suspension about which the wood has a periodic time T.
13. *Apparatus:* Uniform metal bar measuring about 25 cm. × 3 cm. × 3 cm.; thread; stop-watch; metre rule.
Problem: Suspend the bar by a pair of equal vertical threads attached to the bar at equal distances from its ends. Displace the bar through a small angle in a horizontal plane (actually the bar must, of course, lift a little) and release it. Investigate how its periodic time of vibration is related to
(i) The distance apart of the strings
(ii) The length of the strings.
Note: Each part will take about 1½ hours, i.e. the problem should be regarded as two separate ones. The second part is a good example of the application of the logarithmic method of analysis referred to on pp. 36–8.
14. *Apparatus:* Long lath—a metre rule will serve, though a metal one is preferable; G-clamp; optical lever or vernier microscope; set of small weights and hanger.
Problem: Clamp one end of the lath securely to the bench and hang various weights on to the other end. Determine the relationship between the load applied and the depression it produces.
15. *Apparatus:* As for problem 14 together with a metre rule.
Problem: Clamp one end of the lath securely to the bench and hang a weight at the other end. Observe the depression produced. Keeping the weight constant and still at the end of the lath, allow less of the lath to protrude from the clamp. Observe the new value of the depression. Continue this process, taking a series of readings of corresponding values of the length of the lath used (x cm.) and the depression produced (D cm.).
The relationship between D and x is of the form
$$D = kx^n,$$
where k and n are constants. Find values for k and n, from your experiment, for the lath used.
Note: The value of n is the same for all laths but k depends on the dimensions of the lath.

16. *Apparatus:* Metal bar about 1 metre long, 2–3 cm. wide and several millimetres thick; G-clamp; rigid *vertical* support in which to mount the bar; stop-watch; metre rule.
Problem: Clamp the lath securely at one end so that its greatest and its least dimensions are horizontal—i.e. as in the case of the Fletcher's trolley lath. Find the periodic time of the lath when vibrating through small angles in a horizontal plane. Reduce the length free to vibrate, and repeat the timing. Take sufficient observations to enable you to determine how the periodic time is related to the 'free length'.

17. *Apparatus:* Two wall clamps with a horizontal wire stretched tightly between them; scale pan and weights; thread; vernier microscope.
Problem: Load the midpoint of the wire with various weights (w). Determine how the depression (d) of the midpoint of the wire, below its undisturbed position, is related to w.

18. *Apparatus:* Two capillary tubes of different but uniform bores; mercury; benzene; vernier microscope; metre rule; chemical balance; weighing bottle.
Problem: Compare the diameters of the given tubes by two methods. (Use mercury first.)

19. *Apparatus:* Funnel; short piece of rubber tubing; screw clip; paraffin wax; glass tubing of diameter several millimetres, and length a few centimetres; vernier microscope; chemical balance.
Problem: Coat one end of the glass tubing with wax and join the other end to the funnel by means of the rubber tubing. Put some water in the funnel and control its rate of flow by means of the screw clip on the rubber tubing. Use this apparatus to determine the surface tension of water at room temperature, making use of the fact that the weight in grams of a drop of liquid of diameter d cm. is

$$\frac{1{\cdot}9\, d \times S}{g}$$

where S is the surface tension of the liquid in dynes/cm., and g is the acceleration due to gravity (981 cm./sec./sec.).

20. *Apparatus:* Normal solutions of sulphuric acid and sodium hydroxide; thermos flask; thermometer (0–50°C × 1/5); two burettes. 100-200 gm. of copper (S.Ht. = 0·09).
Problem: Determine the heat of neutralisation of the solutions provided, assuming that the water equivalent of the thermos flask is negligible.
Note: A 'normal solution' contains the equivalent weight in grams of the chemical dissolved in enough water to make the volume of the solution 1 litre. The 'heat of neutralisation' is the amount of heat liberated (or absorbed) when one gram equivalent of the acid is neutralised by one gram equivalent of the base.

21. *Apparatus:* Ammonium chloride; thermos flask; test-tube; thermometer (0–50°C × 1/5); measuring cylinder; chemical balance.
Problem: Determine the heat of solution of ammonium chloride. Make sure that the powder and the water are at the same temperature before mixing, by floating the test-tube, containing the ammonium chloride to be used, in the water to be used, for some time before the experiment.
Note: The heat of solution is defined as the amount of heat liberated when one gram-molecule of a substance is dissolved in water. The molecular weight of ammonium chloride is 53·5.

22. *Apparatus:* ICE; constant volume air thermometer; large beaker; stirrer; (no thermometer).
Problem: Determine the pressure of the atmosphere, assuming that the pressure of the gas is proportional to its absolute temperature.
23. *Apparatus:* ICE; constant volume air thermometer; liquid of boiling point between 100°C and 200°C (to be determined); large beaker.
Problem: Use the apparatus provided to find the boiling point of the given liquid.
24. *Apparatus:* ICE; uncalibrated mercury-in-glass thermometer; constant volume air thermometer; large beaker.
Problem: Calibrate the given thermometer.
25. *Apparatus:* ICE; constant volume air thermometer; ammonium chloride (or sodium chloride will do); large beaker; (no other thermometer).
Problem: Determine the minimum temperature obtainable with the freezing mixture formed of ice and the given powder.
26. *Apparatus:* Rectangular block of glass; four pins; drawing paper; drawing board; ruler; protractor.
Problem: Make observations to enable you to draw a graph showing how the displacement of a ray of light passing through the glass block depends on the angle of incidence.
27. *Apparatus:* Glass prism; four pins; drawing paper; drawing board; protractor.
Problem: Make observations to enable you to plot graphs of (i) angle of emergence against the angle of incidence, and (ii) the angle of deviation against the angle of incidence, for light passing through the prism. Measure the refracting angle of the prism.
Plot the graphs referred to on the same axes and from them (*a*) show that for the position of minimum deviation the angle of emergence is equal to the angle of incidence and (*b*) find the refractive index of the glass of which the prism is made.
28. *Apparatus:* Convex lens of focal length 10–15 cm.; stiff cardboard—preferably Bristol board; metre rule.
Problem: Make two scales on the cardboard. Use one of them as an object. Locate (by the method of 'no parallax') the image of this scale formed by the lens, by means of the second scale. Take a series of observations of magnification (m) and image distance (v). Plot m against v and deduce the focal length of the lens from the graph.
29. *Apparatus:* Convex lens of focal length 10–20 cm.; two pins; metre rule.
Problem: Use one pin as the object and the other pin to locate the image of the first one formed by the lens. Investigate real image positions only and record a series of corresponding values of the distance (u) of the object pin from the lens and the distance apart of the pins (d). Plot d against u and deduce the focal length of the lens from the graph.
30. *Apparatus:* Watch glass; pin; liquid of unknown refractive index; plane mirror; metre rule.
Problem: Determine by an optical method the radius of curvature of the watch glass. Put some of the liquid in the watch glass—the minimum amount which is needed to produce a *plano*-convex lens of the liquid. Determine the focal length of this liquid lens and hence find the refractive index of the liquid.
31. *Apparatus:* Lens of large diameter; bright source of light; screen; metre rule.
Problem: Set up the source of light at a great distance from the lens and locate the real image by means of the screen. Make the observations needed to enable you to find the focal length of the lens. Next locate

the images formed by light which suffers (i) one internal reflection (ii) two internal reflections in the lens and measure their distances from the lens. Use the data obtained to calculate the refractive index of the lens.

32. *Apparatus:* Convex lens; plane mirror; one pin; metre rule; a liquid of unknown refractive index; water (refractive index 1·33).
Problem: Determine the refractive index of the liquid using the apparatus provided.

33. *Apparatus:* Sonometer; tuning fork of given frequency; set of weights and hanger (up to 20 kg.); block of stone weighing about 10 kg. (weight not given); bucket large enough to hold the stone easily; metre rule.
Problem: Use the tuning fork and weights to calibrate the wire for the determination of tensions. Then use the calibrated wire to determine the weight of the stone in air and in water. Hence find the density of the stone.

34. *Apparatus:* Sonometer; set of weights and hanger (up to 20 kg.); vernier microscope; micrometer screw-gauge; metre rule; G-clamps to fix the sonometer rigidly to the bench.
Problem: Determine Young's modulus for the wire of the sonometer measuring the extensions by means of the vernier microscope. (What is the largest source of error in this method?)

35. *Apparatus:* Sonometer; five or six tuning forks of known frequency; set of weights and hanger (up to 20 kg.); vernier microscope; metre rule.
Problem: Using a constant length of wire adjust the load so that the wire is in tune with each of the tuning forks in turn. With the vernier microscope observe the extensions caused by the changes of load, regarding the first position (i.e. that of lowest frequency) as the 'zero'. Use a graphical method to determine the relationship between frequency of the note emitted and the extension of the wire.

36. *Apparatus:* Short powerful magnet; plotting compass; large sheet of graph paper; drawing board.
Problem: Fix the graph paper to the drawing board and, using the compass, adjust the paper so that one set of lines is parallel to the magnetic meridian. Place the magnet near the middle of the paper, with its axis in the meridian and with its S-pole pointing north. Use the compass to construct the loci of points at which the needle sets (i) perpendicular, (ii) parallel, to the earth's field. From the intersection of the loci determine the positions of the two neutral points and hence, given H_e, determine the moment of the magnet. (The theory of this method is well described in *Higher Physics* by Nightingale, pp. 545–6.)

37. *Apparatus:* Wheatstone's bridge and accessories; standard resistance coils of values 2 to 10 ohms; resistance box; Daniell cell—no other source of e.m.f.
Problem: Determine the internal resistance of the cell.

38. *Apparatus:* Wheatstone's bridge and accessories; standard resistance coil of resistance comparable with that of the galvanometer provided; resistance box (0–10,000 ohms).
Problem: Determine the resistance of the galvanometer.

39. *Apparatus:* Wheatstone's bridge and accessories, or Post Office box and accessories; micrometer screw-gauge; tangle of insulated copper wire of resistance several ohms.
Problem: Determine the length of the given wire without untangling it. You will be told the resistivity of copper.

40. *Apparatus:* Wheatstone's bridge and accessories; two lengths of wire of

the same material but of different diameters, each being several metres long and of resistance several ohms; standard resistance coil to 'match' the wires; metre rule.
Problem: Determine the ratio of the diameters of the wires.

41. *Apparatus:* Post Office box and accessories; standard 1-ohm coil; resistance box to provide resistance of 10,000 ohms; grid bias battery (9 volts); unknown resistance of value about 1 megohm.
Problem: Determine the value of the unknown resistance which is of the order of 1,000,000 ohms, using the apparatus provided. Connect the 1-ohm coil in series with one ratio arm, and the resistance box in series with the other ratio arm so that the ratio is 10,000 : 1. Discuss the accuracy of the method.

42. *Apparatus:* Several metres of wire of resistance about 3 ohms per metre; Wheatstone's bridge and accessories; Daniell cell; ammeter (0–0·25 amp.); tapping key; metre rule.
Problem: Determine the resistance per cm. of the given wire without cutting it. Use it to determine the internal resistance of the Daniell cell, using the maximum power theorem.

43. *Apparatus:* Accumulator; resistance box; voltmeter (0–2 volts).
Problem: Connect the accumulator, the resistance box and the voltmeter in series. Vary the resistance of the circuit and record corresponding readings of the voltmeter (V) and the resistance box (R). Plot $1/V$ against R and from the graph deduce the resistance of the voltmeter.

44. *Apparatus:* Tangent galvanometer with removable magnetometer box; constant source of D.C.—the output of a metal rectifier smoothed by accumulators is most suitable, but a battery of accumulators will do; rheostat; plug key; reversing key; ammeter (0–2 amp.); metre rule.
Problem: Investigate how the magnetic field at a point on the axis of the coil, produced by a current flowing in the coil, depends on the magnitude of the current.

45. *Apparatus:* Constant source of D.C.—as used in problem 44; tangent galvanometer with magnetometer box removed; vibration magnetometer; rheostat; plug key; ammeter (0–2 amps.); stop-watch; metre rule.
Problem: Investigate how the magnetic field at a point on the axis of the coil, produced by a current flowing in the coil, depends on the distance of the point from the coil itself—not from the centre of the coil.

46. *Apparatus:* Tangent galvanometer; 4-volt accumulator; reversing key; rheostat (0–10 ohms, 3 amps.); copper voltameter; stop-watch.
Problem: Use the apparatus provided to find the horizontal component of the earth's magnetic field. The electrochemical equivalent of copper is 0·00033 gm. per coulomb.

47. *Apparatus:* Copper voltameter; voltmeter (0–3 volts); 4-volt accumulator; standard 2-ohm coil; rheostat (0–10 ohms); plug key; stop-watch.
Problem: Calibrate the voltmeter, assuming that the electrochemical equivalent of copper is 0·00033 gm. per coulomb.
Note: The resistance of the voltmeter may be assumed great compared with that of the standard 2-ohm coil.

48. *Apparatus:* Potentiometer and accessories; Leclanché cell; stop-watch.
Problem: Investigate the recovery of the Leclanché cell from polarisation using the following method: Find a balance point for the cell unpolarised and then short circuit the cell for 5 minutes. Find the new balance point. At intervals of 1 minute—or if this is too short, an interval of 2 minutes—find new balance points. Plot the position of the balance point against time and discuss the result.

49. *Apparatus:* Tangent galvanometer; accumulator; ammeter (0–2 amps.) rheostat; reversing key; plug key.
Problem: Arrange the circuit as though the reduction factor of the galvanometer were to be determined in the usual way. When the current is switched on rotate the *coil,* keeping the magnetometer box unmoved, until the reading is zero. Switch off and note the pointer reading when it has come to rest—this will be the angle through which the coil was turned. Using the instrument in this way vary the current and take a series of readings of current (I) and deflection (θ). Plot a graph of I against sin θ and from it deduce a value for the horizontal component of the earth's magnetic field.
Note: This instrument is known as the 'Sine galvanometer' because

$$I = K \sin \theta.$$

The value of K in this equation is given by

$$K = \frac{5aH_e}{\pi n}$$

where H_e is the horizontal component of the earth's magnetic field, in oersted,
a is the radius of the coil, in cm.
and n is the number of turns used.
(The student should deduce this equation theoretically.)

50. *Apparatus:* Copper-iron thermocouple; oil bath; ICE; potentiometer and accessories—the resistance of the potentiometer wire to be given to the student; resistance box; thermometer (0–360°C).
Problem: Assume that the e.m.f. of the accumulator supplied with the potentiometer accessories is 2 volts and that its internal resistance is zero. Put the cold junction of the thermocouple in ice and vary the temperature of the hot junction between 0 and 350°. Take observations to enable you to plot a graph of thermoelectric e.m.f. against temperature of the hot junction. Deduce the neutral temperature.
Note: The thermoelectric e.m.f. will not exceed 2,000 microvolts.

Questions taken from recent A-level papers in Practical Physics set by the Northern Universities Joint Matriculation Board

In many cases the apparatus required is obvious from the wording of the question. Where this is not the case a brief note is given at the end of the question.

It is of interest, and sometimes an advantage, to know the theory behind the questions and some guidance on this will be found on pp. 490–501, to which reference should be made *after attempting the question.* In an examination the student does well to avoid spending more than a few minutes considering the theory, for the time available is usually only just adequate for the practical work involved. He should concentrate on doing the question as presented to him, and *then,* if time permits, considering the significance of the quantities which he has been asked to evaluate.

51. Determine the mass of a loaded rule and locate the section through its centre of mass by balancing the rule on a knife edge in the following way.
By means of a strong elastic band securely fix one 100 gm. brass weight

underneath the 80 cm. graduation mark of a metre rule, the flat base of the weight being in contact with the face of the rule. Let the mass of this loaded rule be M.

Attach a small loop of thread to the second 100 gm. brass weight and suspend this weight at a distance x from the zero end of the rule. Balance the rule on a knife edge and note the distance y of the knife edge from the zero end of the rule. Use **ten** values of x from 15 cm. to 95 cm.

Plot a graph with y as ordinate and x as abscissa. Find the gradient of the graph and the intercept on the y axis. Hence deduce a value for M and the distance of the centre of mass of the loaded rule from the zero end. Check the latter value by direct balancing. (1959)

52. Make a bifilar suspension for a metre rule and examine the effect of varying the distance apart of the suspensions on the time period of the rule.

Suspend a metre rule horizontally, graduated face upwards, from a horizontal fixed metre rule, graduated face towards you, by means of two vertical threads, each approximately 50 cm. long and equidistant (d cm.) from the centres of the rules. Determine the time period (T sec.) of the rule for small angular oscillations about its central vertical axis. Repeat for FOUR more values of d.

Plot a graph having log T as ordinate and log d as abscissa. Find the gradient of the graph. (1956)

53. Make a bifilar suspension for a symmetrically loaded metre rule and examine the effect of varying the distribution of the load on the time period of the rule.

Suspend a metre rule horizontally, with its graduated face upwards by means of two equal vertical threads, each about 50 cm. long and equidistant (about 10 cm.) from the centre of the rule. Place two 50 gm. brass weights on the rule, at equal distances, x cm., from its centre. Determine the time period (T sec.) of the loaded rule for small angular oscillations about its central vertical axis. Repeat for FOUR more values of x.

Plot a graph having T^2 as ordinate and x^2 as abscissa. Find the gradient (G) of the graph and the intercept (A) on the T^2 axis. Evaluate A/G. (1956)

54. Arrange a metre rule as a cantilever and determine a value of Young's modulus Y for the wood of the rule in the following way.

Clamp a metre rule along the top of the bench with its graduated face upwards so that a length of 80 cm. projects over the edge. Apply a load W at a point 1 cm. from the free end of the rule and measure the depression d of the rule at this point. Use **six** values of W from 50 gm. wt. to 300 gm. wt. Note the distance l between the edge of the bench and the point of loading of the rule. Measure the breadth b and thickness t of the rule.

Plot a graph with d as ordinate and W as abscissa. Find its gradient G. Evaluate Y in gm. wt. cm.$^{-2}$ from the formula

$$Y = \frac{4}{Gb}\left(\frac{l}{t}\right)^3. \qquad (1959)$$

55. Support a metre stick with its flat face resting on two knife edges which are equidistant from its centre and a distance L cm. apart in the same horizontal plane. At a point 5 cm. from each end hang a load of M gm. wt. Note the distance p between each knife edge and the nearer weight. Measure the elevation, h, produced at the centre of the stick. Do this for L = 80 cm., 70 cm., 60 cm., 50 cm., and 40 cm. Plot a graph with h/p along the x-axis and L^2 along the y-axis and determine the gradient of the line so obtained.

Hence find the value of E in the equation

$$E = \frac{3}{2} \cdot \frac{Mg}{ab^3} \cdot \frac{L^2p}{h},$$

where a cm. is the width of the stick, and b cm. is the thickness. The magnitude of M will be given by the supervisor.

State the units in which the value of E is expressed.

[A suitable value for M is 1 kgm. The rule should be drilled at the 5 cm. and 95 cm. mark to permit secure attachment of the loads by means of wires at these points.] (1951)

56. Examine the relation between the depression of the centre of a loaded beam and the distance apart of the supports.

Fix a pin at the 50 cm. mark of a metre rule which is supported on a pair of knife edges initially set at the 30 cm. and 70 cm. marks. Mount a second rule in order to measure the depression of the centre of the beam using the pin as a pointer. Load the beam by suspending the weight from the centre and note the depression, d. Repeat for at least five different values for the distance apart of the knife edges, a, and plot a graph of log d against log a.

In your account give a brief description of the way you set up the apparatus and the precautions you took to ensure reliable results; deduce as much information as you can from the graph.

[A load of about 1 kgm. is suitable.] (1950)

57. Find the specific gravity of the solid provided by the following method. Balance the metre rule, graduated face upwards, on the knife edge with the solid suspended at a distance d cm. from the 'zero' end of the rule. Measure the distances x cm. and y cm. of the knife edge from each end of the rule, y being the distance from the zero end. Repeat for FOUR other values of d less than 50 cm.

Repeat these observations with the solid immersed in water.

Plot a graph with x–y as ordinate and y–d as abscissa for each set of observations, the two graphs being drawn on the same sheet of graph paper and to the same scale. Find the gradient of each graph, and hence calculate (*a*) the weight of the solid (*b*) its specific gravity. (The mass of the rule will be given to you.) (1955)

58. Determine a value for the acceleration due to gravity by means of a simple pendulum.

Use a 50 gm. brass weight as the bob of the pendulum and tie a knot in the thread about 10 cm. above the weight. Measure the distance l between the point of suspension and the knot and determine the time period T of small oscillations of the pendulum in a vertical plane. Use six values of l between 30 cm. and 100 cm.

Plot a graph with T^2 as ordinate and l as abscissa. Find the gradient of the graph and the intercept on the l axis. Use the former to determine a value for the acceleration due to gravity. (1959)

59. Suspend a simple pendulum *CD* of length about 15 cm. from the *mid-point* C of approximately 80 cm. of thread ACB, the ends A and B of which are attached to a horizontal metre rule. (The metre rule is to be clamped with its graduated face vertical and towards the observer. The ends A and B of the thread are to be tied to two wire loops which can just slide along the metre rule.) Measure the angle ACB, 2θ, and find the period, T sec., of small oscillations of the pendulum in the vertical plane normal to ACB. Repeat using FOUR other values of 2θ ranging from about 80° to 160°.

Plot a graph of T^2 against $\cos\theta$ and, assuming that $T^2 = a\cos\theta + b$, use the graph to determine a and b. Hence evaluate a/b.

Measure the length, l_1, of the thread ACB, and the length, l_2, of the simple pendulum CD. Evaluate $l_1/2l_2$. (1952)

60. Hang a weight W on the spiral spring and determine (i) the extension y in cm., (ii) the time period T, in sec., of small oscillations in a vertical plane. Repeat for FOUR other values of W.

Plot a graph with y as ordinate and T^2 as abscissa. Show that the relation between y and T is $y = AT^2 + B$ where A and B are constants. Determine the value of A from the graph. (1955)

61. Set up a sonometer using the given wire and load it with a weight of 2 kgm. Find the length (l cm.) of the sonometer wire which is in tune with one of the forks (frequency n cycles per second). Find the corresponding length for each of the other four forks.

Plot a graph with l as ordinate and $\frac{1}{n}$ as abscissa.

From the slope of the graph find a value for the mass per unit length of the wire. $n = \frac{1}{2l}\sqrt{\frac{T}{m}}$, usual symbols.

Assume a reasonable value for the density of the material of the wire (steel) and calculate an approximate value for the diameter of the wire. Is your answer reasonable? (1958)

62. Attach to the unknown weight which is hanging on the sonometer wire one end of the piece of wire provided; this wire has loops at its ends for easy attachment. Connect the other end of this piece of wire to the hook of the spring balance whose position should be adjusted so that the wire pulls vertically upwards on the unknown weight. The tension in this piece of wire (T gm.-wt.) is to be adjusted by raising or lowering the point of support of the spring balance. Determine the shortest length (l cm.) of the sonometer wire which is in tune with the given fork for SIX different values of T.

Plot a graph with l^2 as ordinate and T as abscissa and deduce the magnitude of the unknown weight.

[Unknown weight of approximately 2 kgm. Spring balance to read up to 1,000 gm.-wt. Tuning fork 256 c.p.s.] (1956)

63. Find the shortest length (l_1 cm.) of an air column closed at one end which will vibrate in tune with one of the forks. Determine l_1 for each of the other four forks. (The length of the air column is to include the restricted portion.) Repeat, but this time find l_2, the next length for resonance.

Plot a graph with $(l_2 - l_1)$ as ordinate and $1/n$ as abscissa, n being the corresponding frequency of the fork in cycles per second.

Using your graph determine the velocity of sound in air at 0°C. (1958)

64. By adjusting the amount of water in the bottle, find the volume (V ml.) of air in the bottle which will resonate with one of the tuning forks (frequency n c/s) supplied. The volume V should be measured up to but excluding the neck. Repeat with each of the other four forks.

Plot a graph with $\log V$ as ordinate and $\log n$ as abscissa and use your graph to determine the value of x in the relation $V = kn^x$.

In your account of the experiment state clearly how you measured the volume V.

[300 ml. reagent bottle; 500 ml. measuring cylinder.] (1956)

65. Apply the method of mixtures to determine the specific heat of paraffin by cooling it with ice.

Use a fall of temperature of between 5°C. and 8°C. Take the temperature of the calorimeter and its contents at regular intervals throughout the experiment and plot a graph having temperature as ordinate and time as abscissa. Use this graph to make some allowance for heat exchange between the calorimeter and its surroundings. Assume that the latent heat of fusion of ice is 80 cal. gm.$^{-1}$. The specific heat of the material of the calorimeter will be supplied. (1959)

66. Apply the method of mixtures to determine the heat absorbed per unit mass of solid dissolved in forming an aqueous solution.

Dissolve a mass of the solid in five times its mass of water. Take the temperature of the calorimeter and its contents at regular intervals throughout the experiment and plot a graph with temperature as ordinate and time as abscissa. Use this graph to make some allowance for heat exchange between the calorimeter and its surroundings.

The solid and water having stood side by side overnight are to be assumed to be at the same temperature. The specific heat of the solution is to be taken as 0·91 cal. gm. $^{-1}$ deg. $^{-1}$ C. The specific heat of the material of the calorimeter will be supplied.

[Use well-powdered 'hypo', $Na_2S_2O_3 . 5H_2O$, which should have stood overnight near a beaker of the water, so that the materials to be mixed are initially at the same temperature.] (1959)

67. Apply the method of mixtures to determine the specific heat of liquid paraffin. Make some allowance for heat exchange between the calorimeter and its surroundings, preferably by using the graph referred to below.

Use the 50 gm. weight as the hot body and about 100 gm. of the paraffin in the calorimeter. Take the temperature of the calorimeter and its contents at regular intervals throughout the experiment and plot a graph with temperature as ordinate and time as abscissa. Assume that the specific heat of brass is 0·090 cal./gm./°C. The specific heat of the material of the calorimeter will be supplied. (1957)

68. Plot cooling curves for hot water in a calorimeter with the calorimeter (*a*) about half full of water, (*b*) about two-thirds full.

Half fill a weighed calorimeter with water so that the temperature immediately after this operation is about 65°C. Observe the temperature of the contents at intervals as it cools over the range 60°C. to 45°C. Weigh the calorimeter and water after the experiment. Repeat with the calorimeter about two-thirds full of water. Plot both cooling curves on the same frame of axes and obtain from them the ratio of the times taken to cool over the same temperature interval, when the temperature interval concerned is (i) 60°C. to 50°C., (ii) 60°C. to 45°C., and (iii) 55°C. to 45°C. Calculate also the ratio of the total thermal capacities in the two experiments.

The specific heat of the calorimeter material will be given.

[Use a calorimeter of volume not more than 150 c.c.] (1955)

69. Find the specific heat of brass assuming that the time taken by the calorimeter and its contents to cool between two fixed temperatures is, in the experiment described below, directly proportional to the total thermal capacity.

Place a 100 gm. brass weight inside a weighed calorimeter and then half fill the calorimeter with hot water so that the temperature immediately after this operation is about 65°C. Observe the temperature of the contents at intervals as it cools over the range 60°C. to 45°C. Weigh the calorimeter and its contents after the experiment. Repeat the experiment with the weight removed and the calorimeter about two-thirds full of water. Plot cooling curves for both experiments on the same frame of axes. From the graphs determine the ratio of the times taken in cooling over the same temperature interval, and hence deduce the specific heat of brass.

The specific heat of the calorimeter material will be given.

[The calorimeter should be of about 5 cm. diameter and of volume about 150 cm.^{3}.] (1955)

70. Place the glass block on a page of your answer-book with one of its largest faces uppermost. Mark its outline with a pencil and draw a line *AB* which cuts its two longest sides normally at *A* and *B*. Place a pin vertically into the paper at *A* and trace the path of a ray of light from the pin which leaves the opposite face of the block at a point *C* (say) in the direction *CD*. Measure the angle ($i°$) which the ray *CD* makes with the normal to the block at *C* and also the distance of *C* from *B* (a cm.). Repeat for **four** different values of a. The values of a chosen should extend from one-third of the breadth *AB* of the block up to the maximum possible.

    Plot a graph with $\dfrac{1}{\sin^2 i}$ as ordinate and $\dfrac{1}{a^2}$ as abscissa. Find the gradient of the graph and hence determine a value for the refractive index (n) of the material of the glass block, given that the gradient is equal to b^2/n^2 where $AB = b$ cm. (1959)

71. On a page of your answer book place a rectangular glass block with its smallest dimension vertical. By means of pins trace the path of a ray of light through the block, the ray entering and leaving by the longer sides. Measure the angle of incidence (i) and the length (l cm.) of the ray within the block. Repeat for FOUR more rays.

    Plot a graph having $1/l^2$ as ordinate and $\sin^2 i$ as abscissa. Find the gradient G of the graph and the intercept I on the $1/l^2$ axis. Evaluate I/G. (1958)

72. On a page of your answer book place a rectangular glass block with its smallest dimension vertical. By means of pins trace the path of a ray of light through the block, the ray entering and leaving by the longer sides. Measure the angle of incidence (i) in air, the angle of refraction (r) in glass, and the lateral displacement (d cm.) of the ray. Repeat for FOUR more rays.

    Plot a graph having $d \cos r$ as ordinate and $\sin (i - r)$ as abscissa. Find the gradient of the graph. (1956)

73. Place the triangular glass prism on a page of your answer-book and with the help of pins trace the path of a ray of light through the prism. Measure the angle of incidence i_1 and the angle of emergence i_2 and repeat for **four** more rays.

    Using the same axes plot two graphs, one with $(i_1 + i_2)$ as ordinate and the other with $2i_1$ as ordinate, both against i_2 as abscissa. Note the point of intersection, measure the refracting angle of the prism with a protractor and hence deduce a value for the refractive index of the material of the prism. (1959)

74. Place a triangular glass prism on a page of your answer-book. By means of pins trace the path of a ray of light which passes through the prism. Measure the angle of incidence (i), the angle of emergence (e), and the angle of deviation (d) of the ray. Repeat for **five** more rays.

    Plot, preferably on the same frame of axes, (i) $(d - e)$ as ordinate and i as abscissa, (ii) e as ordinate and i as abscissa. From the graphs determine the refracting angle of the prism and the value of i (or e) corresponding to minimum deviation. Hence calculate the refractive index of the glass of the prism. (1956)

75. By means of a pin locate the centre of curvature of a concave mirror and hence deduce the position of its principal focus F. Now place this pin at right angles to the axis of the mirror at a point beyond F and by means of a second pin locate the real image of the first formed by the mirror. Determine the distances **from** F of the object and image pins (x_1 and x_2 cm. respectively). Repeat for four more corresponding values of x_1 and x_2.

    Plot a graph having log x_2 as ordinate and log x_1 as abscissa. Find the gradient of the graph. Find the intercept on the log x_2 axis and from it deduce the focal length of the mirror. (1958)

76. Place the concave mirror face upwards on the floor or bench and determine its radius of curvature R cm. by arranging an object pin above it so that it coincides in position with its reflected image.

    Now place the concave mirror face upwards on the bottom of the glass vessel and cover it with a depth of d cm. of water (where d is not *less* than 1 cm.). Again arrange the object pin on the axis of the mirror above the vessel so that it coincides in position with its image formed by reflection at the surface of the mirror. Find the height h cm. of the pin above the water surface. Repeat for **four** more values of d. Plot a graph with d as ordinate and h as abscissa.

    Given that these distances are related by the expression

    $$d = a - bh$$

    find from the graph values for the constants a and b.

    [Use mirror of radius of curvature 20–30 cm. The depth of the glass vessel must certainly be less than two-thirds of the mirror radius, but should not be less than about half the radius.] (1955)

77. Arrange the lens on the bench with its axis horizontal and, using the pins provided, find two points A and B on the lens axis distant a and b from the lens respectively such that the real image of a pin at A appears at B. Repeat for **five** more values of a and arrange that neither a nor b is ever greater than about four times the focal length of the lens.

    Plot a graph with the product $(a \times b)$ as ordinate and $(a + b)$ as abscissa. Find the gradient of the graph and hence a value for the focal length of the lens. (1959)

78. Provided the distance of separation (d cm.) of the object and image screen is sufficient, two positions of the lens can be found for each of which an image is focused on the screen. For a given value of d measure the size of the image formed in each position (l_1 cm. and l_2 cm.). Repeat for **four** other well spaced values of d.

    Plot a graph with $(l_1 + l_2)$ as ordinate and d as abscissa. Read from your graph the value of d when $(l_1 + l_2)$ is zero, and the value of $(l_1 + l_2)$ when d is zero. (1957)

79. Find by a direct method, using a pin and an auxiliary plane mirror, the position, relative to the nearer face, of one of the focal points F of the converging lens provided.

    Place the given illuminated object so that its centre is on the lens axis on the opposite side from F, and focus the real image on the graduated screen. Find the distance b cm. between the image and the point F, and also m the transverse linear magnification of the image. Repeat for **four** more object positions. Plot a graph with b as ordinate and m as abscissa, and find the slope of this graph. Comment on the result. The size of the object will be given. (1954)

80. Fix a converging lens in a holder with its principal axis horizontal. Use a pin method, with a plane mirror, to determine the focal length (f) of the lens. Also locate five **virtual** images formed by the lens when a vertical pin is placed on the principal axis of the lens at five suitable distances from it. Calling the distances from the lens of object and image u and v respectively, and considering u, v and f all as positive magnitudes, plot a graph of log $(f - u)$ and log $(f + v)$. Deduce a relation between u, v and f from the graph. (No credit will be given for a theoretical treatment of the problem.) (1949)

81. Investigate the relation between the distances of the image and the object from a converging lens backed by a plane mirror.

Place the plane mirror horizontally on the floor or bench, and lay the converging lens upon it. Arrange an object pin on the axis of the lens so that it coincides in position with its image and so find the focal length f cm. of the lens. Then place the object pin on the axis at a distance u cm. above the lens, u being at least $f/2$. Locate the image of this pin using a second pin and measure its height v cm. above the lens. Repeat for **four** more values of u.

Plot a graph having $1/v$ as ordinate and $1/u$ as abscissa, and find the gradient of the graph and the intercepts on each of the axes. Find also the reciprocal of the mean of these two intercepts. (1955)

82. Connect the resistance R, the torch bulb, the rheostat and the accumulator in series. Measure the potential drop across R (v_1 volts) and across the bulb (v_2 volts) for about ten different values of current over as large a range as possible.

Plot a graph with v_2 as ordinate and v_1 as abscissa.

Find the potential drop across the lamp when its resistance is equal to R. Calculate the corresponding current, the value of R being known.

[Use an Osram torch bulb OS75, 6·5v, 0·3A; 5 ohm fixed resistance labelled R and with value marked; rheostat 0–50 ohms; voltmeter 0–1·5V; one accumulator; connecting wire.] (1958)

83. Set up the metre bridge circuit to compare two resistances A and B. Resistance B is to consist of the one ohm 'standard', while resistance A is a length (x cm.) of the given specimen of resistance wire. Find the balance point and measure its distance (l cm.) from the end of the bridge nearer resistance A. Repeat for **six** different values of x.

Plot a graph with $1/l$ as ordinate and $1/x$ as abscissa and deduce the resistance per cm. length of the given specimen. Using this value find the resistivity of the material of this wire. (The supervisor will supply a screw-gauge on request.)

[Use bare Eureka wire of S.W.G.24.] (1956)

84. The resistance provided consists of a length of uniform wire, part of which has been permanently wound on to a reel. Determine with the metre bridge the resistance (R ohms) of the wire between a point l cm. along the wire measured from the reel and the end of the wire which just protrudes from the reel. Repeat for **six** different values of l.

Plot a graph with R as ordinate and l as abscissa. From the graph deduce (a) the resistance of the wire per cm. length, (b) the length of wire wound permanently on to the reel.

[Details of special coil: Take 101 cm. of bare 24 S.W.G. Eureka wire. Wind 39 cm. of this wire on to a small reel such that there is a short lead of about 2 cm. and a long lead of 60 cm. See that the turns are insulated from each other and bind over with insulating tape so that the turns cannot be seen.] (1956)

85 Measure the resistance (R) between two points l cm. apart on the given

loop of wire (take l as the length of that part of the loop between the two points which does not have the join in it). Vary the length l from 10 to 90 cm. in approximately 10 cm. steps and determine the corresponding values of R.

Plot a graph with R as ordinate and l as abscissa. Read off the maximum value of R (R_{max}) and find the value of l for which $R = 4/5\ R_{max}$.

[Details of the loop: this consists of 102 cm. of bare (i.e. no covering whatsoever) resistance wire of 2·5 to 3 ohms per metre (e.g. 26 S.W.G. Eureka), the last cm. at each end of this piece of wire to be bent at right angles and twisted together to form the loop, of net length 1 metre.] (1959)

86. Connect the unknown resistance P and length l (approximately 100 cm.) of the bare resistance wire in parallel, and place in one arm of a metre bridge. Using the standard resistance Q, whose value will be given to you, find a balance point on the bridge wire. Let x be the distance in cm. of the distance of the balance point from the end of the bridge wire adjacent to the compound resistance. Determine the value of $\frac{L - x}{x}$, where L is the total length of the bridge wire in cm. Repeat these observations for **four** further values of l and plot a graph with $\frac{L - x}{x}$, as ordinate and $\frac{1}{l}$ as abscissa. *From the graph* find the resistance per cm. of the resistance wire and the resistance of P.

Measure the diameter of the resistance wire and hence find the resistivity of the material of the wire.

[P should be of magnitude 2·95–3·05 ohms. Q should be a 1·00 ohm standard. The bare resistance wire should have resistance of about 3 ohms per metre; Eureka 26 S.W.G. will be suitable.] (1954)

87. Determine the resistance of the given wire at different temperatures using a metre bridge.

Connect up the metre bridge in the usual way and measure the resistance of the specimen of wire (R ohms) at about 20°C. intervals between room temperature and the boiling point of water.

Plot a graph with R as ordinate and the corresponding temperature as abscissa. Using the graph determine the resistance R_0 of the wire at 0°C. Find the gradient G of the graph and evaluate G/R_0.

[The 'given wire' should be 150 cm. of 26 S.W.G. Nickel wound into a coil, provided with terminals and arranged so that no short circuiting occurs on immersion in the water bath. A 1·00 ohm standard resistance will be a suitable match.] (1958)

88. The value of an unknown resistance is to be determined using a potentiometer.

Connect up a circuit consisting of the unknown resistance X in series with the 100 ohm fixed resistance, an accumulator and a rheostat R (R may be a resistance box or one arm of a Post Office box, in which case values of R between 0 and 500 ohms should be used).

Find the lengths of wire l_1 and l_2 on the potentiometer which have the same potential drop across them as exists between the ends of the unknown resistance X and the 100-ohm resistance respectively when R is a minimum. Without altering the potentiometer circuit repeat when R is a maximum and also for **four** intermediate settings of R.

Plot a graph with l_1 as ordinate and l_2 as abscissa. Find the gradient of the graph and hence a value for X.

[X should be about 68 ohms and can conveniently be of radio-type mounted between terminals. A rheostat for inclusion in series with the potentiometer wire, which has a maximum setting about equal to the resistance of the potentiometer wire, should be used to vary the sensitivity of the potentiometer.] (1959)

89. The potential difference between the ends of a resistance is to be determined using a potentiometer.

First connect an accumulator in series with the resistance marked 'A' and the resistance box (R ohms). Then connect up the potentiometer circuit in the usual way. For each of **five** increasing values of R between 50 and 500 ohms, find the length of wire (l cm.) on the potentiometer which has the same potential drop across it as exists between the ends of resistance 'A'.

Plot a graph with $1/l$ as ordinate and R as abscissa. Read from your graph the value of R when $1/l$ is zero.

['A' should be about 100 ohms and can conveniently be a radio-type resistor mounted between terminals.] (1957)

90. The magnetic field on the axis of a coil of wire carrying an electric current is to be investigated in the following manner.

Place the coil of wire of radius a so that its plane lies in the magnetic meridian and place the magnetometer needle on the axis of the coil. Connect up a circuit to pass a current of 1 ampere through the coil, this current to be maintained constant throughout the experiment. For **six** values of the distance x from the centre of the coil to the magnetometer needle determine the deflection θ of the magnetometer needle. Choose values of x so that θ varies between 15° and 55° approximately.

Plot a graph with $\log(10 \tan \theta)$ as ordinate and $\log(a^2 + x^2)$ as abscissa. Find the gradient of the graph.

[The coil should consist of 10 turns of diameter 14 to 15 cm.] (1959)

91. The field at the centre of a coil of wire passing a current is to be balanced against the field due to a bar magnet.

Connect the tangent galvanometer coil with reversing key in series with the accumulator and variable resistance. Set the coil vertically in the magnetic meridian. Pass a current through the coil and adjust its value so that the magnetic needle at the centre of the coil is deflected about 55°. Note the value of the deflection (θ_0°). Bring up the magnet, supported on the wooden block and in the 'end on' position along the axis of the coil in such a way as to reduce the deflection to zero. Note the distance of the centre of the magnet from the centre of the coil (d cm.). Remove the magnet. Repeat the observations for **four** smaller values of θ.

Plot a graph with $\log(10 \tan \theta)$ as ordinate and $\log d$ as abscissa. Find the slope of the graph.

Describe fully in your account how the apparatus was set up.

[A tangent galvanometer which will provide deflections between 10° and 60° is the simplest apparatus readily available. The number of turns used is immaterial provided this range of deflections is obtained. The magnet should be 5 cm., or less, in length and of magnetic moment about 450 c.g.s. units. (1957)

92. Set up the deflection magnetometer in the 'broadside on' position with respect to a suitably placed bar magnet whose centre is a distance d from the magnetometer. Determine the deflection θ of the magnetometer needle, and hence the value of the magnetic field F, due to the magnet at the magnetometer using the value of the horizontal component of the earth's magnetic field H, which will be given to you. Repeat this procedure for **four** other values of d.

Plot a graph with F as ordinate and d as abscissa and find from it the value of d when $F = H$. Hence determine the magnetic moment of the magnet assuming that its magnetic length is 0·8 of its geometrical length. (1955)

Theoretical considerations relevant to problems 51–92 given on pages 480–90.

(In each discussion the symbols used are only defined when they refer to quantities which are not already given a symbol in the question.)

51. Let d cm. be the distance of the centre of mass of the loaded rule from the zero end.

Then, taking moments about the knife-edge we have

$$100(y - x) = M(d - y).$$

Hence
$$y = \frac{100}{(100 + M)} \cdot x + \frac{M \cdot d}{(100 + M)}.$$

Thus the gradient of the graph is $\frac{100}{100 + M}$, from which M is deduced, and, knowing this, the intercept leads to the determination of d.

52. For this suspension $T = \frac{2\pi}{d}\sqrt{\frac{I_0 l}{Mg}}$

where l is the length of the equal vertical strings,
and I_0 is the moment of inertia about the vertical axis through the centre of gravity.

Hence in this case $T = \frac{\text{constant}}{d}$

i.e. $$T = kd^{-1}.$$

Thus the gradient of the graph plotted is -1 (see p. 36).

53. Let I_0 be the moment of inertia about the vertical axis through the centre of gravity,
l be the length of the vertical strings,
M be the mass of the metre rule,
m be the mass of each weight put on at a distance x cm. from the centre of gravity.

The equation which applies is then

$$T = \frac{2\pi}{d}\sqrt{\frac{(I_0 + 2mx^2)l}{(M + 2m)g}}.$$

In this case

$$T = \frac{2\pi}{10}\sqrt{\frac{(I_0 + 100x^2)50}{(M + 100)g}}.$$

$$\therefore \qquad T^2 = \frac{4\pi^2 \times 50}{100(M + 100)g} \cdot (I_0 + 100x^2)$$

$$= \frac{2\pi^2}{(M + 100)g}(I_0 + 100x^2).$$

$$\therefore \qquad T^2 = \frac{200\pi^2}{(M+100)g} \cdot x^2 + \frac{2\pi^2}{(M+100)g} \cdot I_0.$$

Thus
$$\frac{A}{G} = \frac{I_0}{100}\left[\frac{gm\,.\,cm^2}{gm}, \text{i.e. in cm}^2\right].$$

For most metre rules (of mass about 100 gm.) I_0 is about 8×10^4 c.g.s. units.

$$\therefore \qquad \frac{A}{G} \simeq 800 \text{ cm}^2.$$

Note also that if the mass is 100 gm.

$$\frac{A}{G} = (\text{radius of gyration about C.G.})^2.$$

54. Refer to page 71.

55. The equation given can be written

$$L^2 = \frac{2ab^3.E}{3Mg}\left(\frac{h}{p}\right).$$

Hence the gradient of the graph required is $\frac{2ab^3.E}{3Mg}$. Thus if values of M, a, b are determined, E is calculable from the gradient.

56. The equation which applies here is $d = \frac{Mg}{4bc^3E} \cdot a^3$

where b is the breadth of the ruler,
c is the thickness,
E is Young's modulus,
and M is the mass in grams used as a load at the centre.

Thus
$$d = ka^3.$$
$$\therefore \qquad \log d = 3 \log a + \log k$$

and the gradient of the graph required should therefore be 3.
The information deducible from the graph is that $d \propto a^3$.

57. If we assume the centre of gravity of the metre rule to be at the 50·0 cm. mark we obtain, by taking moments

$$G(y-d) = M\frac{(x-y)}{2}$$

where G is the weight of the glass stopper
and M is the weight of the metre rule.

Hence
$$x - y = \frac{2G}{M}(y-d).$$

The gradient, m, of the graph of $(x-y)$ against $(y-d)$ is thus $\frac{2G}{M}$, and hence from m and M, a value of G can be found.

If G' is the apparent weight of the stopper in water, for the second part of the experiment

$$x - y = \frac{2G'}{M}(y - d).$$

If the gradient of this graph is m', it is clear that G' could be found in the same way as G, using the second graph. From this the specific gravity of glass is found from $\frac{G}{G - G'}$.

In fact G' need not be evaluated, for it follows from the above equations that the specific gravity is $\frac{m}{m - m'}$.

58. If d cm. is the distance of the knot above the C.G. of the weight,

$$T = 2\pi\sqrt{\frac{l + d}{g}}.$$

$$\therefore \qquad T^2 = \frac{4\pi^2}{g}\cdot l + \frac{4\pi^2}{g}\cdot d.$$

The gradient of the graph is thus $\frac{4\pi^2}{g}$.

59. The arrangement is shown in Fig. 269.

From this it is evident that

$$T = 2\pi\sqrt{\frac{\frac{l_1}{2}\cdot\cos\theta + l_2}{g}}$$

hence

$$T^2 = \frac{2\pi^2 l_1}{g}\cos\theta + \frac{4\pi^2 l_2}{g}.$$

Thus

$$a = \frac{2\pi^2 l_1}{g} \text{ and } b = \frac{4\pi^2 l_2}{g}.$$

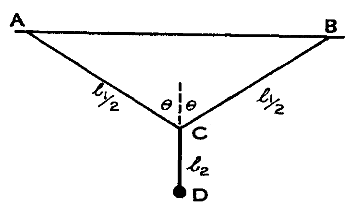


FIG. 269

Now $\qquad l_1 \simeq 80$ cm. $\qquad \therefore a \simeq 1{\cdot}6$

and $\qquad l_2 \simeq 15$ cm. $\qquad \therefore b \simeq 0{\cdot}6$

If the instructions are followed carefully the values obtained for a and b should be near to these figures.

Also $\frac{a}{b} = \frac{l_1}{2l_2}$ so that the final measurements serve as a further check on the care and accuracy with which the main part of the experiment has been performed.

60. Let the spring constant be k gm.-wt./cm.

$$\therefore \qquad W = ky$$

and $$T = 2\pi\sqrt{\frac{W + s/3}{kg}}$$ (see p. 68).

Hence $$y = \frac{g}{4\pi^2} \cdot T^2 - \frac{s}{3k}.$$

$$\therefore \qquad A = \frac{g}{4\pi^2},$$ i.e. about 25 cm./sec.^{2}

61.
$$n = \frac{1}{2l}\sqrt{\frac{T}{m}}.$$

In this case $T = 2{,}000$ gm.wt. and m is in gm./cm.

$$\therefore \qquad l = \sqrt{\frac{2{,}000g}{4m}} \cdot \frac{1}{n} = \sqrt{\frac{500g}{m}} \cdot \frac{1}{n}.$$

The gradient of the graph is thus $\sqrt{\frac{500g}{m}}$. The density of steel is about $7{\cdot}7$ gm./cm^3.

62. Let the unknown weight be W dynes.

Then $$n = \frac{1}{2l}\sqrt{\frac{W - T}{m}}$$

where n = the frequency of the fork

and m = the mass per unit length of the wire in gm./cm.

$$\therefore \qquad 4n^2l^2m = W - T$$

i.e. $$l^2 = \frac{W}{4n^2m} - \frac{T}{4n^2m}.$$

This is the equation for the graph. It follows that the (negative) intercept on the T-axis is W (put $l = 0$ in the equation).

63. If V = the velocity of sound at t°C, $\quad l_2 - l_1 = \frac{V}{2n}$.

Thus the gradient of the graph is $\frac{V}{2}$.

If V_0 is the velocity of sound at 0°C

$$\frac{V_0}{V} = \sqrt{\frac{273}{273 + t}}.$$

64. The equation for a resonating cavity is

$$n = \frac{v}{2\pi}\sqrt{\frac{C}{V}}$$

where C is a constant,

v is the velocity of sound in air at the appropriate temperature.

Hence $$V = \frac{Cv^2}{4\pi^2} \cdot n^{-2}.$$

$$\therefore \qquad \log V = -2 \log n + \log\left(\frac{Cv^2}{4\pi^2}\right).$$

This is the equation for the graph plotted and x should be equal to (-2).

65. If the paraffin is initially at room temperature the graph of temperature against time will be ABC in the Fig. 270. BC represents the period after all the ice has melted when the calorimeter and its contents are warming due to the heat received from the surroundings. Heat was of course also being received whilst the ice was melting (AB) and with perfect thermal insulation the graph would have been ADE.

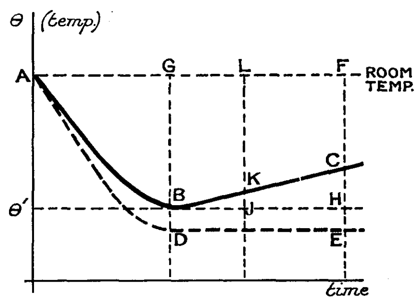


FIG. 270

If the rate of gain of heat may be assumed to be proportional to the difference in temperature between the calorimeter and the surroundings then by applying reasoning similar to that for the conventional cooling correction we can obtain a 'heating' correction. The area ratio method can be applied to give the correction to be subtracted from θ' as

$$\frac{\text{Area of AGB}}{\text{Area of GFCB}} \times \text{temperature interval CH.}$$

If time is short the 'equal area' method may be used by selecting ordinate LKJ such that the time interval GL is half that of AG. The correction is then temperature interval KJ.

66 and 67. Cooling corrections in accordance with the 'area ratio' method or the 'equal area' method (see pp. 113–18).

68. The ratio of the thermal capacities is the ratio of the times taken for falls in temperature through the same interval.

69. If the second experiment is performed using just enough extra water to restore the level to that which was reached with the brass weight present, the conditions of the two experiments are nearly identical and the law of cooling may be applied with more confidence.

70. In Fig. 271 since $\dfrac{\sin i}{\sin r} = n$

$$\frac{1}{\sin^2 i} = \frac{1}{n^2} \cdot \frac{1}{\sin^2 r}.$$

$$\therefore \quad \frac{1}{\sin^2 i} = \frac{1}{n^2} \operatorname{cosec}^2 r.$$

$$\therefore \quad \frac{1}{\sin^2 i} = \frac{1}{n^2} \cot^2 r + \frac{1}{n^2}.$$

In Fig. 271, $\cot r = \dfrac{b}{a}$.

$$\therefore \quad \frac{1}{\sin^2 i} = \frac{1}{n^2} \cdot \frac{b^2}{a^2} + \frac{1}{n^2}.$$

Thus the gradient is, as stated, $\dfrac{b^2}{n^2}$.

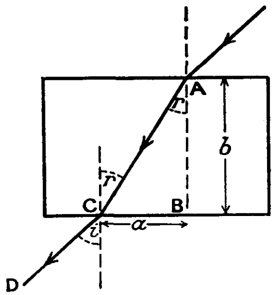


FIG. 271

71. Let t be the breadth of the block and n the refractive index.

Then, in Fig. 272,

$$\sin^2 r = \frac{l^2 - t^2}{l^2} = 1 - \frac{t^2}{l^2}.$$

But $\quad \sin^2 i = n^2 \sin^2 r.$

$$\therefore \quad \sin^2 i = n^2 - \frac{n^2 t^2}{l^2}.$$

$$\therefore \quad \frac{1}{l^2} = -\frac{1}{n^2 t^2} \cdot \sin^2 i + \frac{1}{t^2}.$$

Hence $I = \dfrac{1}{t^2}$ and $G = -\dfrac{1}{n^2 t^2}$.

$$\therefore \quad \frac{I}{G} = -n^2.$$

The value of n is usually about 1·5,

$\therefore \quad \dfrac{I}{G}$ should be about $-2{\cdot}25$.

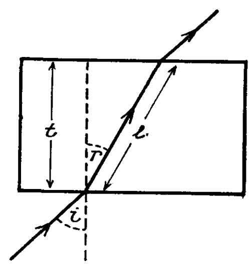


FIG. 272

72. Let t be the breadth of the block.

In Fig. 273, $\widehat{BCE} = (i - r)$.

$\therefore$ BC $\sin (i - r) = d$.

Also $\dfrac{t}{BC} = \cos r$.

Eliminating BC between these two equations we have

$$t \sin (i - r) = d \cos r.$$

Thus the gradient of the graph plotted is t.

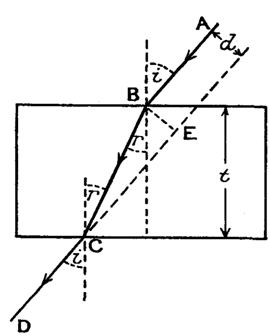


FIG. 273

73. For minimum deviation $i_1 = i_2$.

Therefore where $i_1 + i_2 = 2i_1$ we have the values coinciding with minimum deviation.

Now $$D_{min} = 2i_1 - (r_1 + r_2) = 2i_1 - A.$$
$2i_1$ is read from the graph, A is measured, hence D_{min} is known.

Substituting in $n = \dfrac{\sin\left(\dfrac{D_{min} + A}{2}\right)}{\sin \dfrac{A}{2}}$ yields a value for n.

74. From the geometry of Fig. 274(A)

$$i + e = A + d.$$
$$\therefore \quad d - e = i - A.$$

Hence the graph of $(d - e)$ against i is linear and has intercepts each equal to A, so the second graph will be as shown in Fig. 274(C).

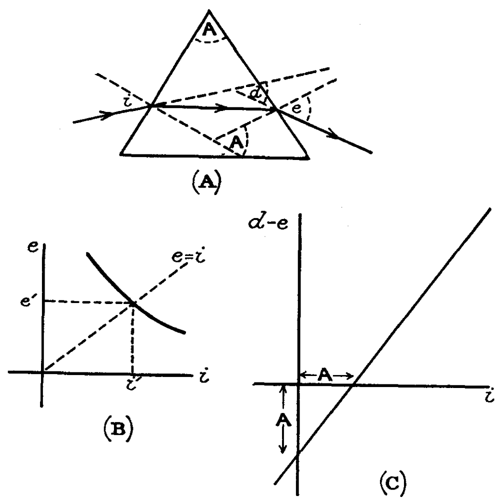


FIG. 274

At minimum deviation $e = i$, so if the line $e = i$ is drawn to intersect the curve, the values obtained, e' and i', should be equal and are the angles of incidence and emergence corresponding to minimum deviation (d_{min}).

The value of d_{min} can be found, using i' from Fig. 274(B), and hence the refractive index calculated from the usual equation.

75. From Newton's Equation (see p. 179) $x_1x_2 = f^2$.

$$\therefore \quad \log x_2 = -\log x_1 + 2 \log f.$$

Thus the gradient of the graph should be -1 and the intercept on the $\log x_2$ axis (and incidentally also on the $\log x_1$ axis) is $2 \log f$.

It is necessary to estimate the value of $2 \log f$ before plotting the graph as otherwise the intercept will be well off the graph paper.

76. In Fig. 275, ray OAB must be travelling normal to the mirror along AB in order to form an image at O after reflection at B and emergence at A. If C is the centre of curvature, BAC must be a straight line.

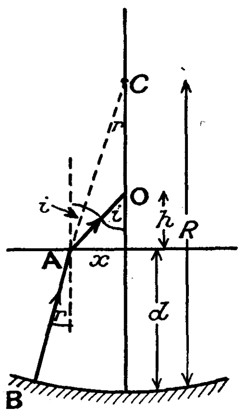


FIG. 275

From the geometry of the figure, and applying the approximation $\frac{\sin i}{\sin r} = \frac{\tan i}{\tan r}$ for small values of i and r, we obtain

$$n = \frac{x}{h} \div \frac{x}{(R-d)}.$$

$$\therefore \qquad d = R - nh.$$

Comparing this with $d = a - bh$, we see that $a = R$ and $b = n$.

77.
$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}.$$

$$\therefore \qquad \frac{b+a}{ab} = \frac{1}{f}.$$

$$\therefore \qquad ab = f(a+b)$$

Thus the gradient of the graph is f.

78. Let the size of the object be a cm.

Then $\qquad \frac{l_1}{a} = \frac{v}{u}$ and $\frac{l_2}{a} = \frac{u}{v}$.

$$\therefore \qquad l_1 + l_2 = a\left(\frac{v}{u} + \frac{u}{v}\right) = a\frac{(v_2 + u^2)}{uv} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

But $$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} \qquad \text{i.e.} \frac{u + v}{uv} = \frac{1}{f}.$$

$$\therefore \qquad uv = fd \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and $$d = u + v \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Eliminating u and v between (1), (2), (3) we obtain,

$$l_1 + l_2 = a\left(\frac{d^2 - 2df}{fd}\right) = \frac{a}{f}.d - 2a.$$

Therefore when $l_1 + l_2 = 0, \quad d = 2f.$
and when $d = 0, \quad l_1 + l_2 = -2a.$

79. $$m = \frac{v}{f} - 1 \text{ (with usual symbols).}$$

$$\therefore \qquad m = \frac{b + f}{f} - 1 = \frac{b}{f}.$$

$\therefore \qquad b = fm$ and the gradient of the graph is f.

80. The relationships can be seen by examining Fig. 276.

Applying Newton's equation we obtain,

$$(v + f)(f - u) = f^2.$$

$$\therefore \qquad \log (f - u) = -\log (v + f) + 2 \log f$$

i.e., the gradient is -1.

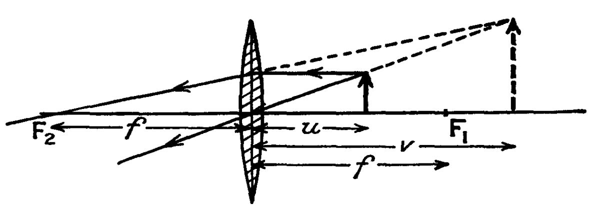


FIG. 276

In the question set, when the graph yields this gradient, the equation $\log (f - u) = -\log (v + f) + K$ can be written down, from which the relationship

$$(v + f)(f - u) = \text{constant}$$

can be deduced.

81. A convex lens of focal length f, backed by a plane mirror, behaves as a concave mirror of focal length $f/2$.

82. The graph should be as shown in Fig. 277. The resistances will be equal when $v_2 = v_1$, since the same current flows through them. Drawing the line $v_2 = v_1$ as shown is the best method of locating the point on the curve for which this condition holds.

Dividing this p.d. by the value of R gives the required current.

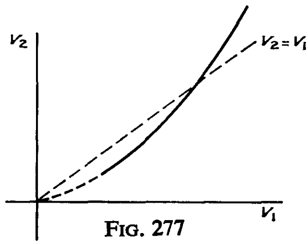


FIG. 277

83. Let A have resistance of r ohms/cm.

Then $$\frac{xr}{1{\cdot}00} = \frac{l}{100 - l}.$$

$$\therefore \quad \frac{1}{xr} = \frac{100 - l}{l} = \frac{100}{l} - 1.$$

$$\therefore \quad \frac{1}{l} = \frac{1}{100r} \cdot \frac{1}{x} + \frac{1}{100}.$$

Hence the gradient is $\frac{1}{100r}$ and the (negative) intercept on the $\frac{1}{x}$ axis is r.

84. Let the resistance of the wire be r ohms/cm., and let the length of wire wound on the reel be x cm.

Then $$R = lr + xr.$$

Thus the gradient is r and the (negative) intercept on the l axis is x.

85. Let the resistance per cm. of the wire of which the loop is made be r ohms.

Then $\frac{1}{R} = \frac{1}{lr} + \frac{1}{(100 - l)r}$ (applying the formula for resistances in parallel and remembering that the loop is 100 cm. long).

$$\therefore \quad R = -\frac{r}{100} \cdot l^2 + rl \quad . \quad . \quad . \quad . \quad . \quad (1)$$

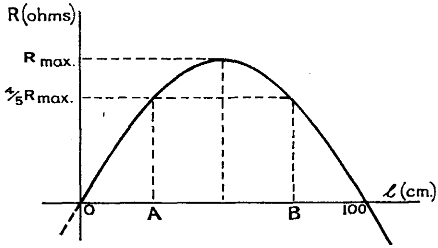


FIG. 278

The graph should therefore be as shown in Fig. 278.

The maximum value is for $l = 50$ cm., i.e. when $R = 25r$. For eureka S.W.G. 26 (resistance 2·95 ohms/metre) this will be 0·72 ohm.

If $R = \frac{4}{5} \cdot R_{max} = \frac{4}{5} \times 25r$,

then $R = 20r$.

Substituting $R = 20r$ in equation (1) above we obtain

$$l^2 - 100l + 2{,}000 = 0$$

which solves to give $l = 72{\cdot}4$ or $27{\cdot}6$ cm., which are the values you should obtain from your graph at B and A respectively.

86. Let R be the resistance of the compound resistor,
R' be the resistance of the standard resistor,
and r be the resistance per cm. of the bare resistance wire.

Then
$$\frac{L - x}{x} = \frac{R'}{R}$$

and
$$\frac{1}{R} = \frac{1}{lr} + \frac{1}{P}.$$

Eliminating R between these two equations we obtain

$$\frac{L - x}{x} = \frac{R'}{r} \cdot \frac{1}{l} + \frac{R'}{P}.$$

Thus the gradient of the graph is $\frac{R'}{r}$ and the intercept is $\frac{R'}{P}$.

87. $\frac{G}{R_0}$ is the temperature coefficient of resistance for the material of the wire.

88. $\frac{l_1}{l_2} = \frac{X}{100}$. Hence the gradient of the graph is $\frac{X}{100}$.

89. Let the potential drop per cm. along the potentiometer wire be k volts.

Then the current in the circuit BAR is given by $\frac{kl}{A}$ and also by $\frac{E}{A + R}$ where E is the e.m.f. of accumulator B.

$$\therefore \quad \frac{kl}{A} = \frac{E}{A + R}.$$

$$\therefore \quad \frac{1}{l} = \frac{k}{EA} \cdot R + \frac{k}{E}.$$

Thus when $\frac{1}{l} = 0$, $R = -A$.

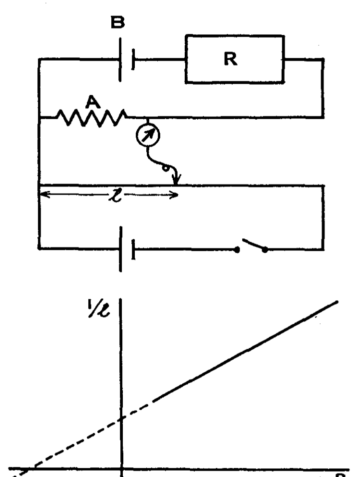


FIG. 279

90. The field strength due to n turns carrying current of i e.m.u. is

$$\frac{2\pi a^2 ni}{(a^2 + x^2)^{3/2}}$$

In this experiment $i = \frac{1}{10}$ e.m.u. (1 amp.)

$$\therefore \qquad \frac{2\pi a^2 n}{(a^2 + x^2)^{3/2}} = 10 \cdot H_e \tan\theta,$$

where H_e is the horizontal component of the earth's magnetic field.

$$\text{Thus} \qquad \log\left(\frac{2\pi a^2 n}{H_e}\right) - \log(a^2 + x^2)^{3/2} = \log(10\tan\theta).$$

$$\therefore \qquad \log(10\tan\theta) = -\frac{3}{2}\log(a^2 + x^2) + K.$$

Thus the gradient of the graph should be $-1{\cdot}5$.
[If the current is not 1 amp. the gradient of the graph required is still $-1{\cdot}5$ because $\log(\tan\theta) = \log(10\tan\theta) - \log 10$ and the log 10 merely alters the position of the intercept.]

91. As the field due to the coil and due to the magnet are equal and opposite

$$\frac{2M}{d^3} = H_e \tan\theta$$

where M is the moment of the magnet.

$$\therefore \qquad \tan\theta = \frac{2M}{H_e} \cdot \frac{1}{d^3}.$$

$$\therefore \qquad \log(10\tan\theta) - \log 10 = \log\left(\frac{2M}{H_e}\right) - 3\log d.$$

$$\therefore \qquad \log(10\tan\theta) = -3\log d + K.$$

The gradient of the graph is thus -3.

92. The graph of F against d should be as shown in Fig. 280.
H is given, hence the dotted lines can be drawn to find x, the value of d for $F = H$.
Now in general

$$F = \frac{M}{(d^2 + l^2)^{3/2}}$$

and thus for x,

$$H = \frac{M}{(x^2 + l^2)^{3/2}}.$$

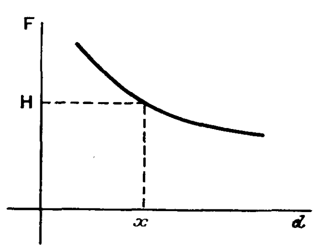


FIG. 280

Thus if $2y$ is the geometrical length of the magnet,

$$M = H[x^2 + (0{\cdot}8y)^2]^{3/2}$$

and everything on the R.H.S. is known.

CHAPTER LX

ADVANCED PROBLEMS

The problems given in this Chapter are different from those given in Chapter LIX in that they are much more difficult and require much more time—in some cases perhaps several weeks. They are intended to introduce the student to the peculiar difficulties which are encountered in research. On this subject there is much ignorance. Research does not consist of one glamorous discovery after another but is essentially a patient attack on the difficulties encountered. It is usually only after years of hard, and often tedious, work that a result is obtained and even then it may not be a startling discovery. It may be a further confirmation of a theory or a slightly more accurate determination of a constant. The problems presented here are not, of course, of such magnitude, but they should give the student who has the good fortune to devote time to some of them the opportunity to show his patience and ingenuity.

1. Using a Fletcher's trolley with an uncalibrated vibrator, determine the acceleration due to gravity.
2. Determine Young's modulus for the material of a three-inch rubber band.
3. Determine the diameter of eureka wire of S.W.G. 47.
4. Determine the acceleration due to gravity by a method depending on the simple harmonic motion of mercury in a U-tube.
5. Investigate the variation with temperature of the viscosity of engine oil.
6. Determine the specific heat of cork dust.
7. Determine the coefficients of expansion of wood (i) in the direction of the grain, and (ii) across the grain.
8. Determine the specific heat of mercury.
9. Find the ratio of the specific heats for a dry gas, using a dust tube method.
10. Verify Wiedemann and Franz's Law for copper, iron and brass.
11. Determine the melting point of phenol, using a thermocouple.
12. Determine the boiling point of liquid air.
13. The inconsistent results obtained in Experiment 61, p. 154, on emissivity, are mainly due to the fact that some heat is *convected* from the vicinity of the wire. Eliminate this error and improve on the method as fully as possible to obtain more consistent results.
14. Investigate how the note emitted by a violin string depends on the relative humidity of the atmosphere.
15. Determine the fraction of the incident light which is transmitted by a red filter.
16. Set up the apparatus for producing Newton's Rings. Use this to determine the refractive index of glycerine without assuming the wave-length of the monochromatic light used.
17. Determine the more important wave-lengths of the bright lines in the flame spectra of lithium, calcium and strontium.
18. Make a polarimeter and calibrate it.

19. Determine the resistivity of mercury.
20. Investigate the maximum current which can be carried by copper wire of S.W.G. 32 (i) when one long straight piece is used, (ii) when a solenoid consisting of a single layer is used, and (iii) when a solenoid consisting of several layers is used.
21. Obtain a graph showing the relationship between the resistance of carbon and the temperature.
22. Verify the formula for the magnetic field at a point on the axis of a solenoid caused by a current flowing in it.
23. Determine what percentage of the power consumed by a 100-watt, 240-volt electric lamp is converted into heat.
24. Compare the e.m.f.'s produced by (*a*) a thermocouple of iron and copper and (*b*) a thermocouple of copper and constantan (eureka), when the cold junctions are both maintained at 0°C and the hot junctions are given various temperatures between 0°C and 360°C.
25. Convert a given microammeter into a universal instrument.

APPARATUS

List of apparatus assumed to be readily available and which is not therefore included in the lists given of apparatus needed for the experiments.

Metre rules.
Vernier callipers.
Chemical balances (0–250 gm.).
Boxes of weights (0–200 gm.).
Scales for weighing, to accuracy of 1 gm., loads up to 2 kg.
Weights for the latter.
Stands and clamps.
Tripods.
Bunsen burners.
Gauzes.
Flasks.
Beakers.
Measuring cylinders.
Test tubes.
Corks.
Thread.
Pins (small and optical).
Knitting needles.
Plotting compasses.
Wires for electrical connections, D.C.C. copper of at least three diameters, say S.W.G. 14, 24, 32 and P.V.C. of various colours.
Flex (5 amp.).
240-volt A.C. Mains.

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SOLUTIONS TO EXERCISES

Exercises on limits of error given on pp. 28–9.

1. 10·0 (± 0·9) gm./cm^3.
2. 8·0 (± 0·34) gm./cm^3.
3. 10·7. [% errors in the four quantities used to calculate the modulus are as follows: Force 1%; Area of cross-section 5%; Extension 4·5%; Length of wire 0·2(3)%.]
4. 67 (± 5) dynes/cm. [Perimeter of slide = 20·4 (± ·084) cm.]
5. 0·645 (± 0·005) mm. [Errors as follows: mass of mercury 1·43%; length of column 0·07%; Therefore error in (diameter)^2 is 1·6%. Therefore error in diameter is 0·8%.]
6. 2·01(± 0·01) [As $T \propto \sqrt{l}$, the percentage variation in T will be $\frac{1}{2}$ of that in l, see p. 24.]
7. ± 0·4 cm. [Variation in T is 0·2%. Therefore variation in l is 0·4%. Value of l is nearly 100 cm.]
8. 1·83 (± 0·06) × 10^{-5}/°C. [Notice that most of the inaccuracy is contributed by the observations using the screw-gauge. Note too the correct way to express the result.]
9. 13·3 (± 0·1) cm.
10. 10%. [This seems incredible but the zero readings of the instrument must be allowed for so that the actual errors in voltage and amperage are (± 0·1). This gives % error in voltage of 3$\frac{1}{3}$ and amperage 6$\frac{2}{3}$. The most important other factor is that the current recorded includes that passing through the voltmeter so that 6$\frac{2}{3}$% is optimistic, i.e. this method does not yield a result known to 10% accuracy.]

Exercises on graphs given on pp. 40–44

1. 22 ohms.
2. 0·0036 per °C.
3. 14·6 gm.-wt./cm
4. 3·15 ohms.
5. 10 cm.
6. 0·9.
7. Plot D against x^3; gradient is $kw/4zy^3$, hence, k can be evaluated after w, z and y have been determined experimentally.
8. Plot h^2 against T^2h; gradient is $\frac{g}{4\pi^2}$ and negative intercept is k^2.
9. If $y = \frac{1}{v}$ and $x = \frac{1}{u}$ then $y = -x + \frac{1}{f}$; hence gradient is -1 and intercept on each axis is $\frac{1}{f}$.
10. Two possible graphs can be used:
    (i) Plot y against $\frac{x^2}{y}$ when intercept is $4f$.
    (ii) Plot $y^2 - x^2$ against y when gradient is $4f$.
11. Plot l against $\frac{1}{f}$; gradient is $\frac{V}{4}$, intercept is $-C$.
12. Transform equation to $d^2 = \frac{m}{H_c}. \cot \theta$. Hence a graph of d^2 against $\cot \theta$ should be linear if inverse square law is true. [Plotting $\frac{1}{d^2}$ against $\tan \theta$ will serve but involves more work.]
13. Plot $\frac{1}{V}$ against $\frac{1}{R}$; intercept is $\frac{-1}{r}$.
14. $g = 987$ cm./sec². Intercept on axis of M is $\frac{S}{3}$.
    Gradient is ratio of two quantities each determined to a good order of accuracy. $\frac{S}{3}$ is very small and a very small variation in the gradient of the line drawn will cause a comparatively large variation in $\frac{S}{3}$.
15. 34 cm.
16. $a = 2{\cdot}5$; $n = 4$.
17. This example requires plotting logarithms involving negative characteristics (see p. 37). Plot $\log_{10} h$ as ordinates against $\log_{10} l$ as abscissa. The $\log_{10} h$ range need only be from $\bar{1}{\cdot}000$ to $\bar{3}{\cdot}0000$. Answers: $k = 0{\cdot}01$, $p = 0{\cdot}5$.
18. This is a case where the intercept cannot conveniently be shown but is better deduced. Plot $\log_{10} T$ as ordinates against $\log_{10} l$, using the ranges 0 to 0·3 and 1·3 to 2·0 respectively. Intercept on $\log_{10} T$ axis can then be calculated using a rough sketch and similar triangle theorems. Answer: $T = 0{\cdot}2\sqrt{l}$.
19. Intercepts, which should be made equal, are $\log f^2$, i.e. $\log f^2 = 2{\cdot}17$. Therefore $\log f = 1{\cdot}085$. Hence $f = 12$ cm.
20. The theoretical aspects of problems 51–92 are given on pp. 490–501.

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