# M I N E  A N D  T U N N E L L I N G  V E N T I L A T I O N

## GRAPHICAL INTERPRETATION AND ANALYSIS

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# Foreword

There can be no teacher of mine ventilation, at any level, who would attempt to explain what is meant by the operating point of a mine fan without sketching the fan characteristic and the resistance curve of the mine. It is equally certain that no student would deduce the effect of a change in mine resistance on the operating point without physically, or at the very least mentally, sketching the curves.

One intention in this book is to show how graphical or diagrammatic representation of this kind can be used much more widely, as an aid to understanding and anticipating the consequences of planned or accidental actions in a mine network, or in ducted ventilation in tunnel excavations. Any action which changes the resistance of part of a network affects the air distribution in all other parts, and for safe operation it is important that responsible personnel are alert to possible adverse effects elsewhere.

The other principal aim is to demonstrate, by a series of exercises, the feasibility of qualitative analysis by graphical construction and representation, and its application to planning, monitoring and control; to a limited degree for networks, where computers are long established for major planning, but extensively for tunnel and heading ventilation. Whether or not the techniques are applied to these problems, they are based on coherent ventilation principles and as such are a useful learning vehicle.

The book is in three parts, the first of which includes an introduction to the relevant theory and terminology. This is followed by chapters on qualitative deduction of flow distribution in networks, and on fan combinations and the factors affecting selection.

The second part deals entirely with quantitative analysis of network flows by graphical construction. The easier exercises are carried out on the same network as that chosen for qualitative deduction in the first part, whereby the reader gains familiarity with the network and can confirm the validity of the deduction processes.

The final part is concerned with ducted ventilation in tunnelling. Here, the method of analysis is mathematical and only the presentation of the results is graphical. In a number of exercises the use of the graphs for planning, monitoring and control is illustrated. The concluding chapter deals with the theory of recirculatory ventilation arrangements and the analysis of dust concentrations with these systems.

Representative student exercises, with answers and solution hints as necessary, are appended.

Mathematically, there is nothing more complex than the flow equations and their transposition. Other than that, the requirement of the reader is an ability to interpret graphs and to reason logically. Most of the content was used for several years by the author in the teaching of mature technician, diploma and first degree students. Since the work is concerned with the application of principles to practice, technicians are able to relate it to their field experience, and so are at no serious disadvantage relative to those who may be better equipped intellectually to deduce from principles.

It is hoped that teachers and students at these levels will find the text of interest, and that it may have worth as a reference manual for mining and civil engineers or advanced technicians engaged in planning, monitoring and control of ventilation in mining and tunnelling.

# PART ONE

GENERAL: Deduction of flow in networks and the principles of fan combinations.

# INTRODUCTORY THEORY

## The development and application of mining air flow equations

Although it has been assumed that readers will have a fundamental knowledge of the principles of air flow in passages, those which are relevant to the text are to be briefly treated in this introduction. For civil engineers in particular, whose main interest will be in tunnelling ventilation, the forms of flow equation adopted in mine ventilation engineering need some explanation.

Those who are conversant with the expressions and their application can proceed directly to the first chapter, but may care to glance at the comments on terminology before doing so.

### The flow equations.

It is perhaps worth beginning with the origins of the equations as they were developed in Britain.

In the second half of the nineteenth century, J. J. Atkinson pioneered the formalising of the study of air flow in mines. He is best remembered for the Atkinson equation, which he introduced, relating the frictional pressure loss in mine roadways to the physical conditions and the flow rate of air.

$$P = \frac{KSV^2}{A}$$

where: P is the frictional pressure loss

K a friction factor related to surface roughness

S the product of the roadway perimeter and length, termed the rubbing surface by Atkinson

V the air velocity

A the cross-sectional area.

The expression can be compared with the Darcy equation for the turbulent flow of incompressible fluids in pipes.

$$p = \frac{4\rho f l v^2}{2d}$$

When d is converted to the equivalent diameter 4A/C for non-circular ducts, this becomes

$$p = \frac{\rho f}{2} \times Cl \times \frac{v^2}{A}$$

Since Cl is Atkinson's rubbing surface, his K is $\rho f/2$, where $\rho$ is the air density and f a dimensionless friction factor.

The more useful form of the Atkinson equation is

$$P = \frac{KSQ^2}{A^3} \qquad (V = Q/A)$$

Although K has the units of density and strictly speaking varies with it, the normal approach for planning purposes is to treat it purely as a physical roughness factor at a specified air density, then apply a multiplier if necessary for other densities, for example at great depth. Tables of K values have long since been compiled.

In the 1920's, one of the Penman brothers claimed in their mine ventilation text book to have introduced what he called the modified Atkinson equation, $P = RQ^2$, with R replacing $KS/A^3$. He named his unit of resistance the Atkinson.

The resistance concept was a leap forward for the purpose of planning. The resistances of individual roadways in a proposed design could be calculated using Atkinson's original expression, then the series/parallel configuration of the network combined mathematically to give the overall resistance of the design. Having also estimated the air flow required, the fan pressure necessary was obtained.

For existing mines, measurements of pressure differences and flow rates between junctions provide the resistances of the parts. These pressure/quantity surveys enable plans of resistance networks to be prepared, which can be modified by the addition or elimination of branch resistances to assess future effects and actions necessary.

The simplified examples above form the basis of mine ventilation analysis today, It was not until the development of more sophisticated analytical techniques, culminating in the digital computer, that full exploitation was possible.

With the adoption of the Standard International system, the numerical values of resistance changed and to avoid confusion the name of Atkinson could not be retained for the unit. When pressure difference is in newtons per square metre ($N/m^2$) and air flow in cubic metres per second ($m^3/s$), the dimensions of R are $Ns^2/m^8$.

For reasons unknown to the writer the Atkinson replacement in Britain was termed the "gaul", and for convenience that term is used in the book in preference to writing the dimensions.

Combination of resistances.

If three airways $R_1$, $R_2$ and $R_3$ are in series and air flows through them at a rate Q, the total frictional pressure loss P is the sum of the losses in each. Let $R_t$ be the total resistance.

$$P = P_1 + P_2 + P_3$$

$$\therefore \quad R_tQ^2 = R_1Q^2 + R_2Q^2 + R_3Q^2$$

$$\text{and} \quad R_t = R_1 + R_2 + R_3$$

With airways $R_4$ and $R_5$ in parallel, pressure difference P across them is common and the total flow $Q_t$ divides as $Q_4$ and $Q_5$. Let $R_c$ be the combined resistance.

$$Q_t = Q_4 + Q_5$$

$$\therefore \quad \sqrt{\frac{P}{R_c}} = \sqrt{\frac{P}{R_4}} + \sqrt{\frac{P}{R_5}}$$

$$\frac{1}{\sqrt{R_c}} = \frac{1}{\sqrt{R_4}} + \frac{1}{\sqrt{R_5}}$$

$$\text{and} \quad R_c = \frac{R_4 R_5}{(\sqrt{R_4}+\sqrt{R_5})^2}$$

When the parallel group is in series with the series group, the overall resistance is R.

$$R = R_1 + R_2 + R_3 + \frac{R_4 R_5}{(\sqrt{R_4}+\sqrt{R_5})^2}$$

$$= R_t + R_c$$

The overall resistance of any network consisting of resistances is series and parallel, no matter how extensive, can be computed by progressive combination of the branches in the manner outlined.

Distribution of flow.

When airways are in parallel, the division of flow must bear some relationship to their resistances.

For a parallel group of three airway $R_1$, $R_2$ and $R_3$, the total flow Q divides as $Q_1$, $Q_2$ and $Q_3$. The pressure loss P against friction is common to the airways, singly and as a group. If the combined resistance is R,

$$P = RQ^2 = R_1Q_1{}^2 = R_2Q_2{}^2 = R_3Q_3{}^2$$

$$\text{and} \qquad \frac{Q}{Q_1} = \sqrt{\frac{R_1}{R}} \qquad \text{etc.}$$

Thus the division of flow is inversely proportional to the square roots of the resistances, so that

$$Q \propto \frac{1}{\sqrt{R}}, \quad Q_1 \propto \frac{1}{\sqrt{R_1}}, \; Q_2 \propto \frac{1}{\sqrt{R_2}} \;\text{ and } Q_3 \propto \frac{1}{\sqrt{R_3}}$$

## Resistance of Regulators

Those unfamiliar with the term will find regulators defined overleaf.

Any restriction in a roadway is a resistance in series with it. The introduction of a regulator in a branch increases the resistance and the total resistance is the sum of branch and regulator. The purpose of the regulator is to fix the flow at some predetermined level, in which case the flow is the known quantity and the resistance is unknown. When the network is analysed the value of the total resistance is obtained, and that of the regulator is got by deducting that of the branch.

The cross-sectional area of the regulator can be calculated approximately from its resistance. There is no need for precision because construction incorporates means of varying the aperture when installed, to produce the desired flow rate.

By ignoring the velocity in the airway and applying orifice plate theory, the relationship between the pressure drop across the regulator and the velocity in the aperture is

$$p = \rho v^2/2$$
$$v = \sqrt{\frac{2p}{\rho}}$$

Assuming a discharge coefficient of 0.65, the flow rate Q through an aperture A is Av, and

$$Q = 0.65A\sqrt{\frac{2p}{\rho}}$$
$$\text{and} \quad \frac{Q}{\sqrt{p}} = 0.65A\sqrt{\frac{2}{\rho}}$$

Taking $\rho$ as 1.25 kg/m$^3$ and substituting $\frac{1}{\sqrt{R}}$ for $\frac{Q}{\sqrt{p}}$, where R is the resistance of the regulator

$$A = \frac{1.2}{\sqrt{R}}$$

The constant of 1.2 applies only to SI units, with A in square metres and R in gaul.

Resistance of leakage paths.

Separation doors and air locks are always imperfect seals and are branches, differing only from planned branches in being of high resistance. In sum, leakage flows constitute a substantial proportion of total flow and must be taken into account in planning.

The resistances used for planning are average values derived from many recorded measurements of pressure difference and leakage rates in working mines. The potential for leakage through and around doors in zones still subject to strata movement from mineral extraction is greater than in stable ground, and lower resistances are usually allocated to the former.

Terminology.

Mining terminology across the English-speaking world is far from standard, and because this book deals with applications some mining terms have to be used.

An attempt has been made to use general expressions for clarity. For example, tunnelling is understood by all and in the context of ventilation there is no need for any other; the purpose of the excavation, and hence its special name, is not relevant.

It is hoped that most of the named features or techniques are self-explantory. Some which may not be are defined below.

Downcast and upcast refer to vertical mine shafts. The former is the air inlet shaft and the latter the outlet or return.

Fandrifts are the short connecting passages between the surface fan and the mine shaft.

Booster fans are underground fans to increase flow in parts inadequately served by the surface fan.

Auxiliary fans, or auxiliary ventilation, refer to ducted ventilation in tunnelling.

Regulators are restricting aper^tures constructed in branches to reduce flow in these parts.

In the writer's experience, quite competent students can be confused by the variety of expressions for the pressure loss against friction between two points. All have the same meaning and the reason for selecting one rather than another is either customary usage by the individual or relates to what exists between the points.

The many combinations of pressure <u>loss</u>, <u>drop</u>, <u>difference</u>, <u>absorbed</u>, and <u>in</u>, <u>across</u>, <u>along</u>, <u>at</u>,<u>around</u> are synonymous.

# CHAPTER 1

## The effects on air flow of changes in mine networks

### Frictional resistance to air flow

In mine ventilation, the relationship between air flow and the pressure drop or loss to overcome friction in producing it, is taken as $P = RQ^2$, where P is the frictional pressure loss in the airway or network of airways, and Q the rate of air flow. R is a composite resistance constant based on air density and the dimensions, configuration and surface roughness of the roadways in the network.

There are assumptions of incompressible and fully turbulent flow in the expression, which seem justified by the fact that a mine is not a neat arrangement of pipes, so that dimensions and roughness in themselves are nothing better than fair estimates. There is also the further complication of static and moving obstructions in a mine. However, perhaps the only justification necessary for the simplified expression is that system design based on it gives acceptable standards of accuracy in practice.

For a particular mine resistance, say $R_m$, the rate of air flow produced for a range of pressure drops can be calculated, and plotting the corresponding values on PQ co-ordinates gives a resistance characteristic curve for that mine. To demonstrate the effect on curve form of a change in mine resistance, the process can be repeated for higher and lower values, $R_h$ and $R_l$. The curves are shown in figure 1.1.

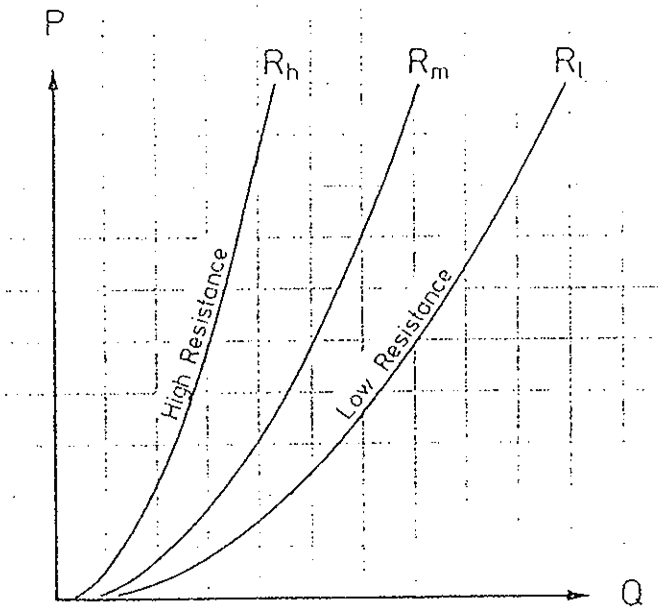



Figure 1.1 Resistance Characteristics

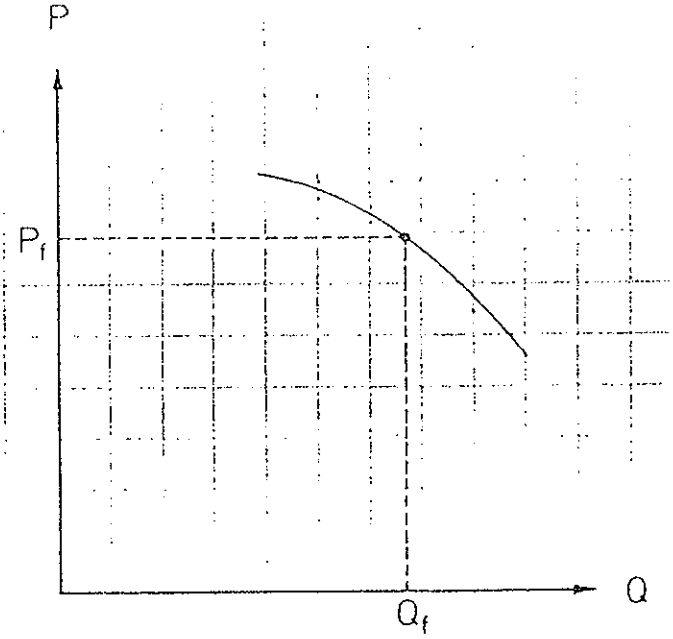



Figure 1.2 Fan Operating Point

## Fan characteristic and operating point

If a fan is run under test conditions at its designed speed against a range of discharge apertures, the pressure developed and the flow rate can be recorded for each aperture. Plotting the results on PQ co-ordinates gives that fan's pressure/quantity characteristic curve. Assuming that the fan is properly installed, maintained and run at its designed speed at a mine, and that the air density under test conditions and at the mine are similar, the curve can be applied to the installation. (If the fan is to be used at altitude its characteristic may have to be pressure modified to allow for the lower density at the installation.)

Should a gauge at the mine record a pressure $P_f$ developed by the fan, the flow rate will be $Q_f$ as indicated on the curve in figure 1.2. The point $P_f$, $Q_f$ is the operating point of the fan. $P_f$ is also the pressure difference or drop across the mine, but $Q_f$ includes surface airlock leakage and flow into the mine is $Q_f$ minus leakage. This aspect will be commented on later.

Using $P_f$ and $Q_f$, the resistance of the mine (which includes the airlock resistance), can be calculated from $P_f = R_m Q_f^2$. For the derived value of $R_m$ it is obvious that a plot of its resistance characteristic will pass through the point $P_f$, $Q_f$ on the fan curve. It follows that by superimposing the characteristic of any fan on any mine resistance curve, the operating point of that fan will be determined by its intersection with the resistance curve, as in figure 1.3.

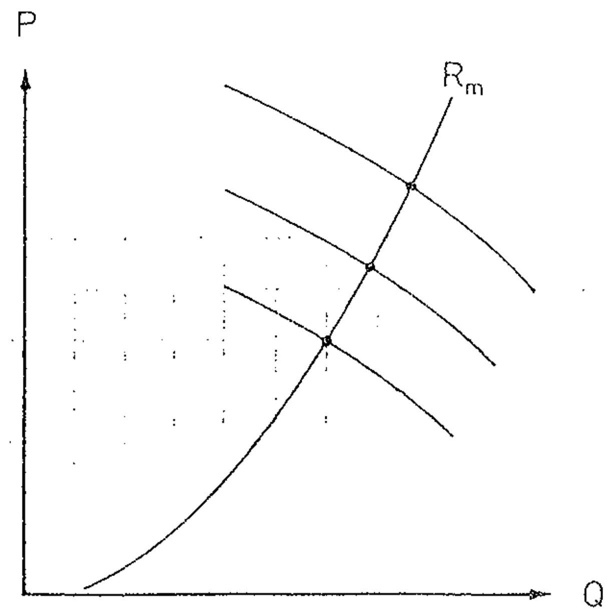



Figure 1.3 Fan Operating Points

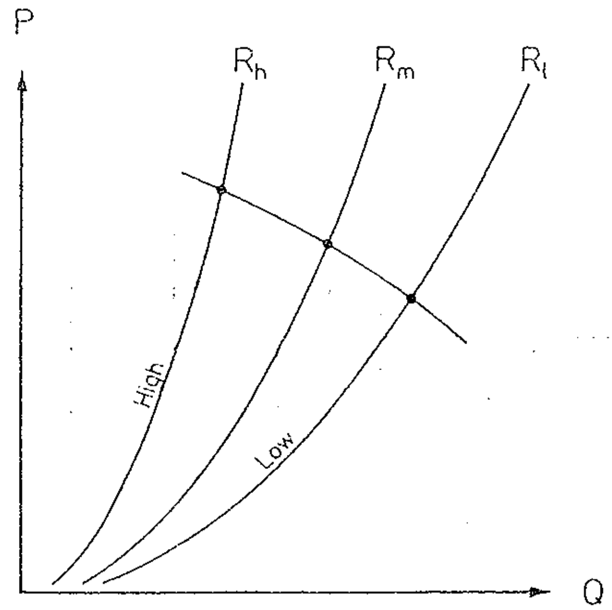



Figure 1.4 Fan Operating Points

It should also be evident that if the resistance of a mine changes, the installed fan's operating point will change (figure 1.4). At higher resistance, such as $R_h$, the pressure developed increases and the flow decreases, with the opposite effect at a lower resistance $R_L$.

Pressure diagrams

In the present context, pressure diagrams are essentially graphs showing the frictional pressure loss in the trunk airways of a mine network. They also indicate pressure differences across parts of the network which are not included in the diagram.

If sufficient information is available, scaled diagrams can be drawn. Since the only purpose here is to demonstrate how the diagrams can be used to facilitate a qualitative analysis of changes in flow patterns when resistance in part of a mine changes, precise scaling is unnecessary and neat sketch graphs suffice.

In these graphs, the gradient or slope depends on airway resistance and the rate of air flow. If air flow is constant, the pressure drop, and hence the gradient, increases with increase in resistance. If resistance is constant, the pressure drop, and hence the gradient, increases when air flow increases.

Figure 1.5 illustrates a mine network and sketch pressure diagram for the trunk airways and circuit $C_3$. There are two other circuits, $C_1$ and $C_2$. The fan develops a pressure $P_f$, which is the pressure drop in the network or the pressure difference across it. The surface

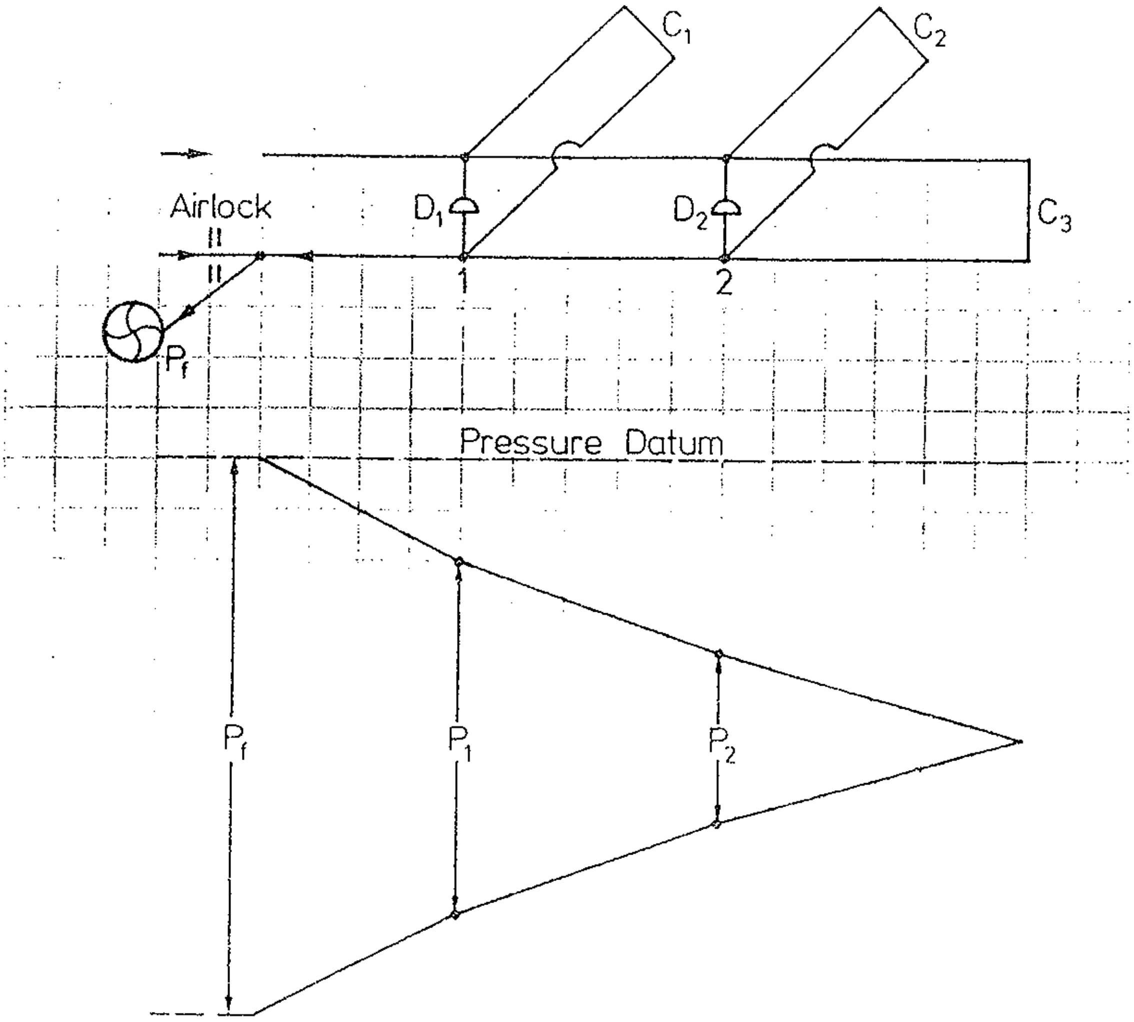



Figure 1.5 Pressure Diagram for Trunk Airways and Circuit $C_3$

airlock is a high resistance flow path in parallel with the mine network and is an integral part of the system supplied by the fan. The pressure difference across the airlock is $P_f$, the fan pressure.

Further information provided by the diagram is that the pressure differences across circuits $C_1$ and $C_2$ are $P_1$ and $P_2$ respectively. If the pressure differences increased or decreased, flow in the circuits would be affected accordingly.

In order to determine the effect of a change in resistance in part of the mine on flow distribution in this network, a modified diagram, which is constructed step by step as deductions allow, is superimposed on the original. Although each deduced change in air flow is elementary, it is difficult to carry the logical consequences to the next deduction stage without a diagram extended to that stage.

The technique, and its merit in helping to create a general understanding of the effects of a change in resistance, should become clear in the examples which follow.

Increase in resistance

It is proposed to deduce the effects in the network figure 1.5, of restricting circuit $C_3$ by the installation of a regulator.

The first step is to sketch the network and diagram of figure 1.5 in figure 1.6 to show the original condition. The modified diagram is to be superimposed as deductions are made, and although it is shown completed in figure 1.6, the reader should try to imagine that it is

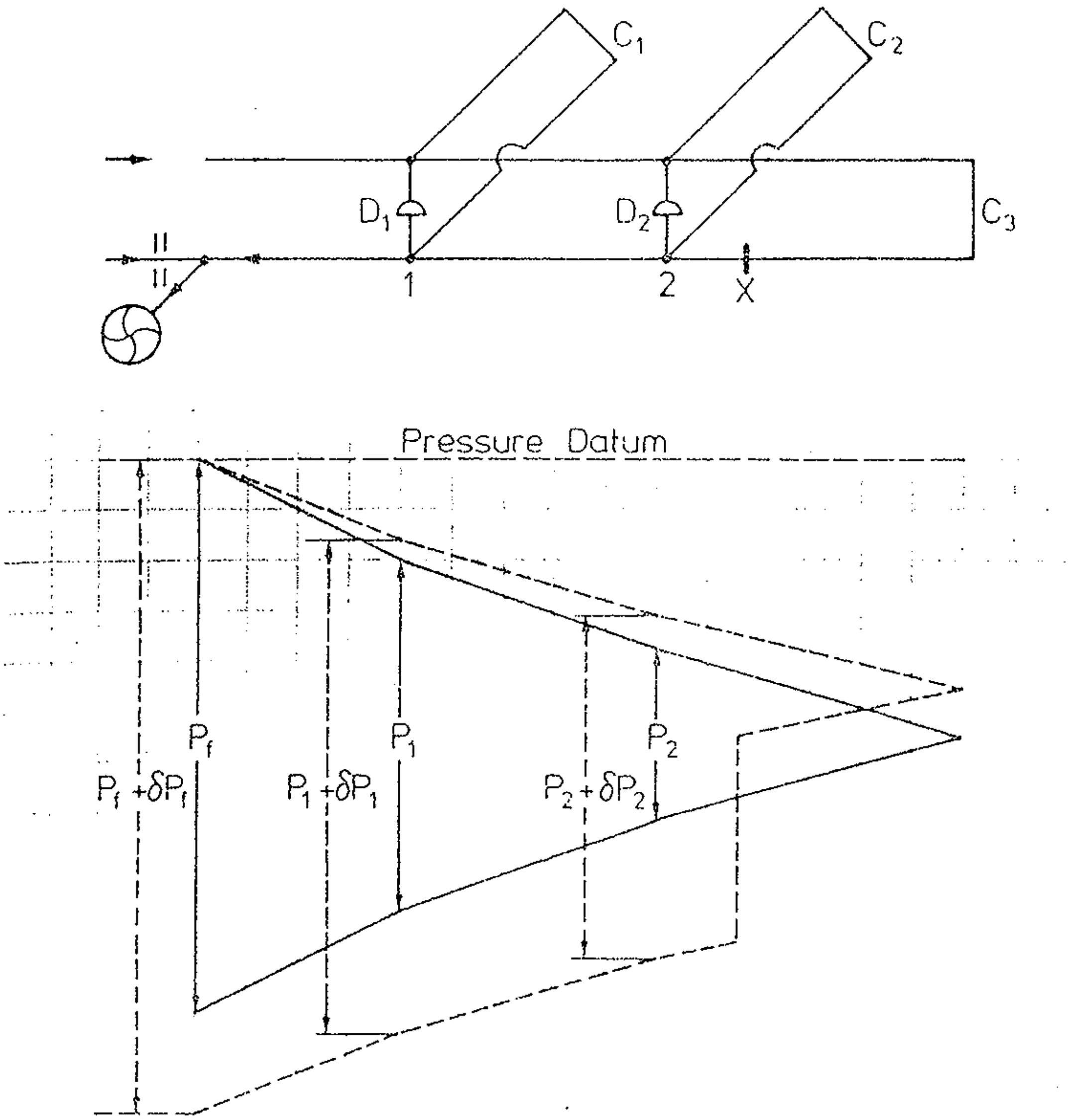



Figure 1.6 Original Diagram and a Diagram Modified by a Regulator at X

not, and that it will be constructed as the argument develops. The regulator is at X, and the deduction and construction stages are as follows:

An increase in resistance anywhere increases the resistance of the mine as a whole, resulting in a fall in fan flow to $Q_f - \delta Q_f$ and a rise in pressure developed to $P_f + \delta P_f$. The end point of the modified diagram is therefore $P_f + \delta P_f$.

The increase in fan pressure increases airlock leakage, hence flow into the mine is reduced by that amount and $\delta Q_f$. Resulting from reduced flow, the pressure drop and so the slope to point 1 is less, and the diagram can be started in both intake and return at lesser slope than the original up to point 1.

It will be observed that the pressure difference at this position has increased to $P_1 + \delta P_1$, thus there is more flow in $C_1$ and more leakage through the separation doors. This further reduction of airflow towards $C_2$ and $C_3$ decreases the pressure drop between points 1 and 2, and the diagram can be extended to the latter position at a reduced slope, indicating that the pressure difference there has risen to $P_2 + \delta P_2$.

Because the resistance of circuit $C_2$ is unchanged, flow into it increases. The same applies to the separation doors. Consequently, there is a final reduction of airflow into circuit $C_3$, which was to be expected.

The diagram is completed by its extension at reduced slope on both sides into $C_3$ and closed by a vertical pressure drop at X, the location of the regulator.

The general conclusion is that restriction of flow in part of a mine will increase it in all other parts, but the increases will be less than the saving because of higher leakage everywhere and lower fan flow. Since wasted air (leakage) may be up to half of total flow, half of the flow diverted from a regulator circuit can be lost to leakage and the gain in other parts may be much less than anticipated.

Study of the completed diagram and comparison with the original yields additional information. The increase in pressure difference is proportionately greater at $C_2$ than at $C_1$, so that the airflow gain is proportionately greater in $C_2$.

Again, within the restricted circuit the pressure difference between intake and return from point 2 to the regulator is now much higher, but not much lower beyond the regulator. Should there be substantial leakage paths within $C_3$, greater leakage may result, and taken from a reduced total flow. The closer the regulator is to position 2, the lower the risk of this adverse effect.

Finally, it should be recognised that the scale of the changes deduced will depend on the degree of increase in resistance, but no matter how small the latter, there will be some change, which is always in the direction described.

Decrease in resistance

If the reasoning with regard to the effects of an increase is valid, there is no need to cover the same ground to prove that the reverse would be true for a decrease in resistance. Had the regulator in circuit $C_3$ been the original condition, its removal must produce changes in the opposite direction.

To illustrate the slight difference in approach when the resistance of another circuit is altered, the case of decreasing the resistance of circuit $C_1$ by enlarging its roadways will be examined. The original situation is again taken as that of the previous example. Figure 1.7 refers, but as before the modified diagram does not exist and is to be drawn.

> Reduction of resistance in $C_1$ causes a drop in mine resistance and fan pressure falls to $P_f - \delta P_f$, which becomes the end point of the modified pressure diagram.
>
> Fan flow rises to $Q_f + \delta Q_f$, and because of the lower fan pressure there is a reduction in airlock leakage. For both reasons there is increased flow into the mine. The diagram can now be started in intake and return up to point 1 at greater slope because of greater airflow and hence an increased pressure drop.

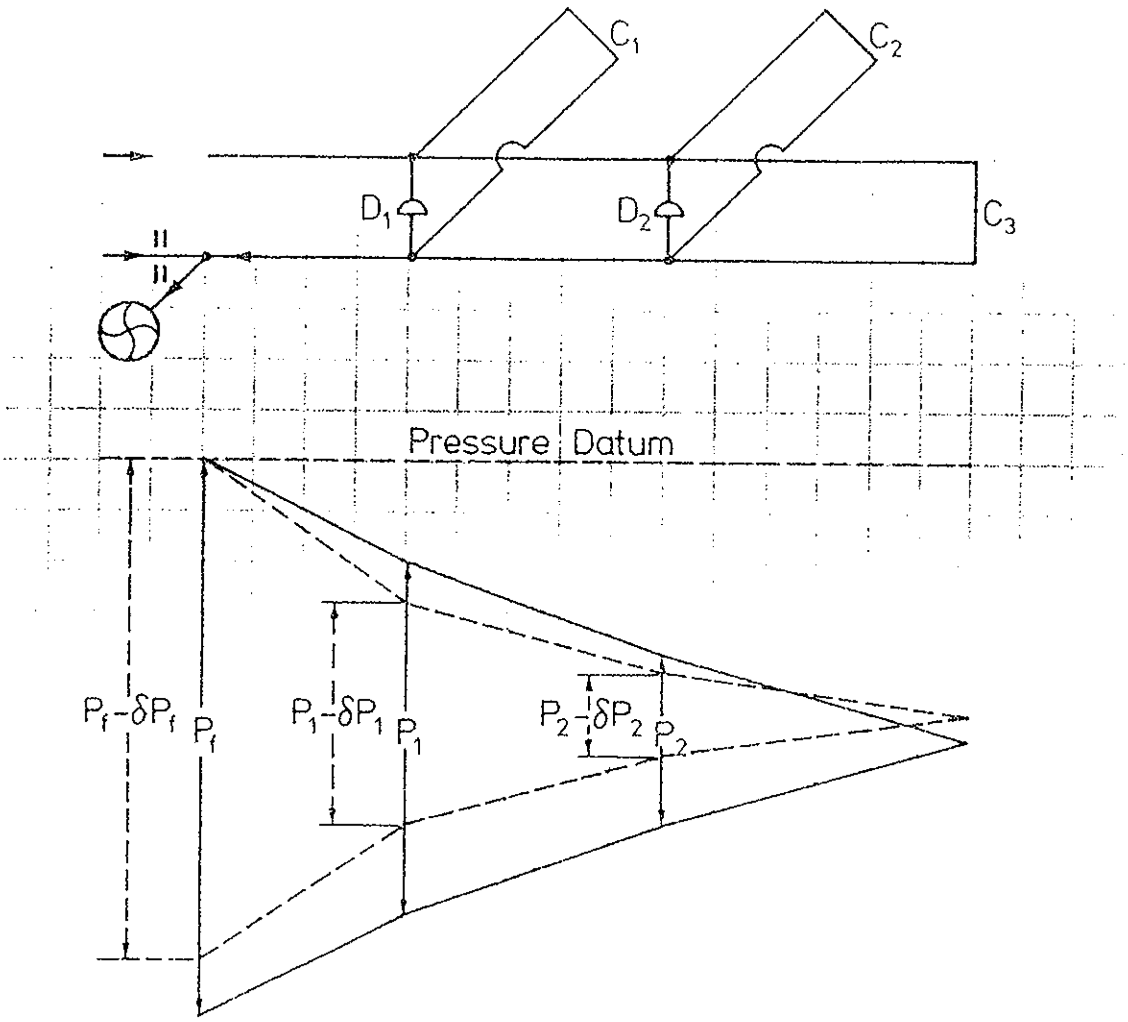



Figure 1.7 Original Diagram and a Diagram Modified by Reduced Resistance in $C_1$

Inspection at point 1 reveals that pressure difference has fallen from $P_1$ to $P_1 - \delta P_1$ and consequently a reduction in airflow into $C_2$ and $C_3$, because resistances there are unchanged. For the same reasons there is reduced leakage at both separation doors. The total effect on $C_1$ is to increase flow by the rise in fan flow, the reductions in leakage everywhere and in flow into $C_2$ and $C_3$. The diagram can be extended to position 2 at reduced slope because of the reduced flow deduced, and completed into $C_3$ in the same way.

As in the case of an increase in resistance, the degree to which the pattern of air distribution is affected will depend on the scale of change of resistance, but it will always be in the direction deduced above.

Summarising, the effect of reducing the resistance in any part of a mine is to increase flow in that part and reduce it in all other parts, including leakage paths. There is an added benefit by virtue of the increased flow from the fan.

The effect of booster fans

Booster fans are underground fans installed in a circuit for the purpose of increasing flow in that part . The effect is equivalent to reducing circuit resistance and so the resistance of the network, save in one important respect. Whereas reduction in a circuit's resistance decreases flow in other circuits, the booster fan can decrease it to the extent of reversal in some circuits.

Figure 1.8 shows a network and diagram of the original system, together with a diagram modified by a booster fan at X. The reasoning in the construction of the diagram is as in the previous examples and is only briefly outlined here.

Reduction of mine resistance lowers fan pressure and raises fan flow.

Airlock leakage decreases and flow into the mine is greater by the sum of the decrease and the increase in fan flow.

The increased pressure gradient to point 1 reduces pressure difference between intake and return at that point, so there is reduced flow into $C_1$ and through the doors, leading to a further increase in flow towards point 2.

The steeper gradient from point 1 to point 2 again reduces pressure difference at the latter. Since the resistances of $C_2$ and the doors are unchanged there is reduced flow into $C_2$ and through the doors, and a consequent increase in flow into the boosted circuit.

The diagram is extended from both ends into $C_3$ at increased gradient and closed by a pressure <u>rise</u> at

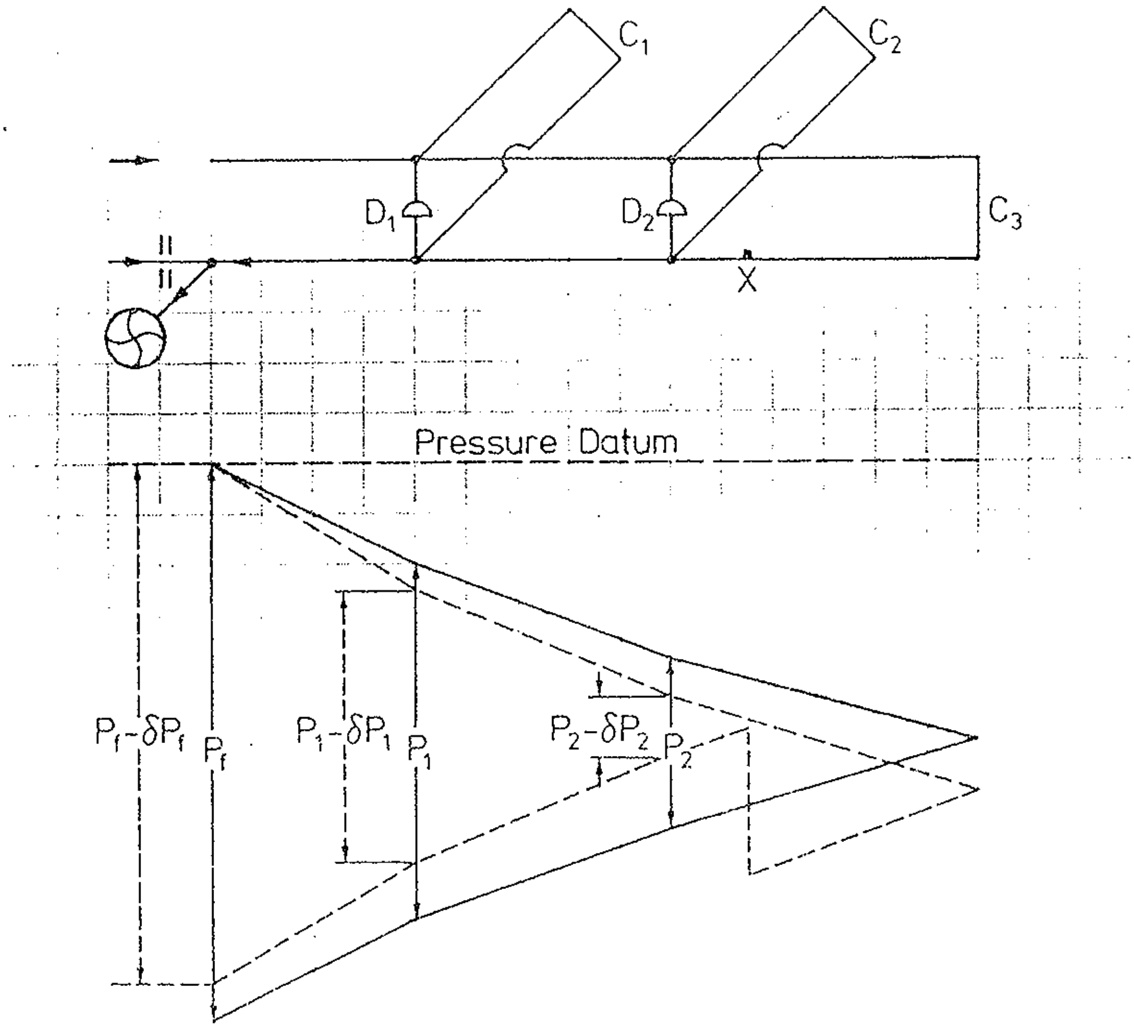



Figure 1.8 Original Diagram and a Diagram Modified by a Booster Fan at X

the booster fan. The pressure rise is the pressure developed by that fan.

In this diagram the pressure differences at points 1 and 2 have been reduced, but not reversed, so there is no reversal of air flow.

In a well-planned installation reversal conditions would only be created by accident, perhaps stoppage of the main fan or a heavy fall of ground which significantly changed the mine resistance.

In normal circumstances an over-powered booster fan could cause reversal. A similar situation might be created where there was an installation of parallel surface fans, with one stopped for inspection or maintenance and the booster fan continuing to run.

Referring to figure 1.9, the main fan develops a relatively low pressure, with the result that pressure differences across the circuits in the original system are correspondingly low. Construction of the modified diagram with a booster fan at X is by the same reasoning as before, but in this case pressures are higher in the return airway than in the intake in the hatched zone, which includes $C_2$. Reversal will take place in $C_2$ and through the separation doors, the circuit receiving return air from $C_3$, with this air recycled into $C_3$. Flow is in the normal direction in $C_1$ and through the separation doors there.

Within a boosted circuit, recirculatory conditions can be created through leakage paths, even if there is no reversal in other

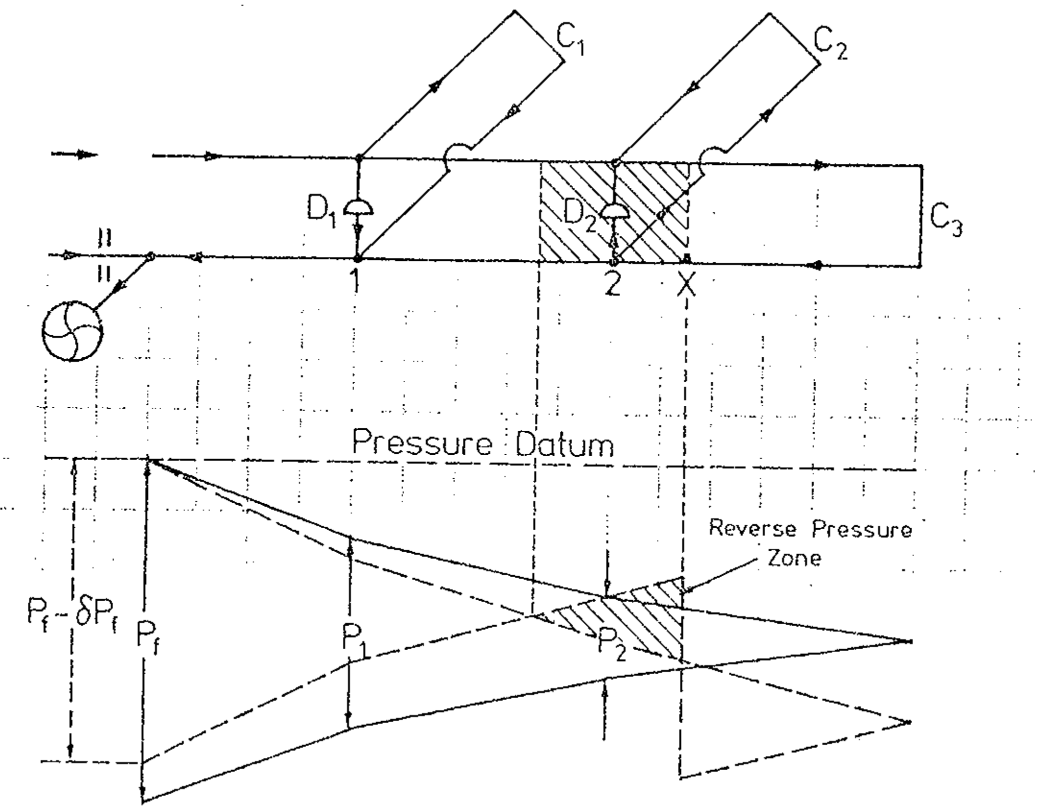



Figure 1.9 Showing Reversal of Air Flow in Circuit $C_2$ by a Booster Fan at X

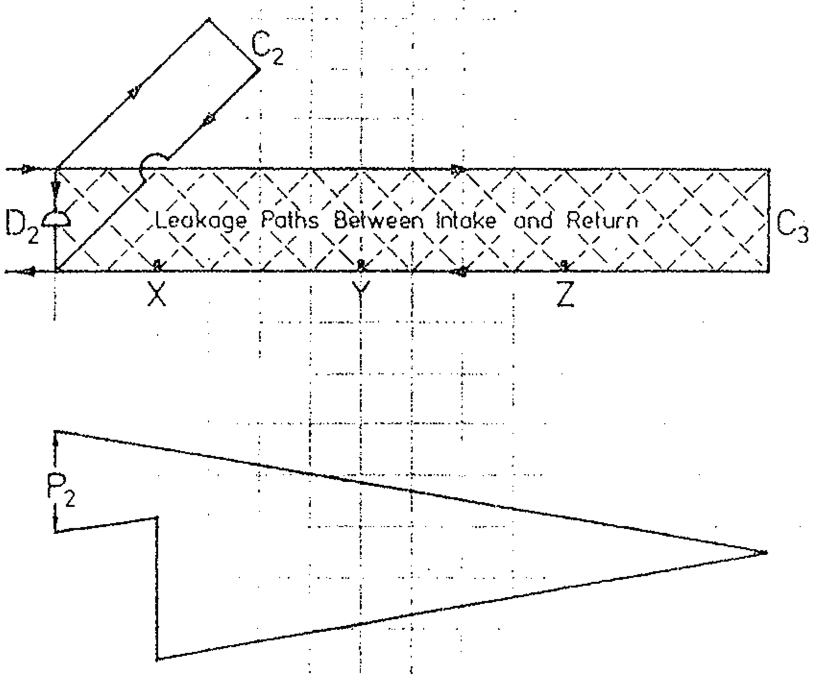
circuits. The reason is that the fan has been sited beyond what is sometimes termed the "neutral point".

In figure 1.10, circuits $C_2$ and $C_3$ are shown, with the booster fan at the alternative locations X, Y and Z in $C_3$. The pressure diagrams indicate that the pressure difference $P_2$ across the circuits is positive, meaning that air flow in $C_2$ is in the normal direction, wherever the fan is located.

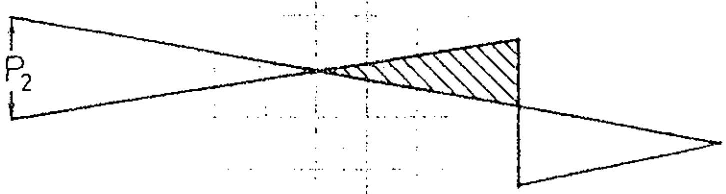
With the booster fan at X, pressure difference everywhere in circuit $C_3$ is positive and any leakage will be from intake to return. By locating the fan at Z, the zone between Y and Z is under a reversed pressure difference and leakage will take place from return to intake, contaminating the fresh air.

At location Y, the fan would raise pressure in the return to that in the intake opposite - the neutral point. This is considered to be the ideal site, because leakage in the normal direction will be at a minimum and there is no recirculation.

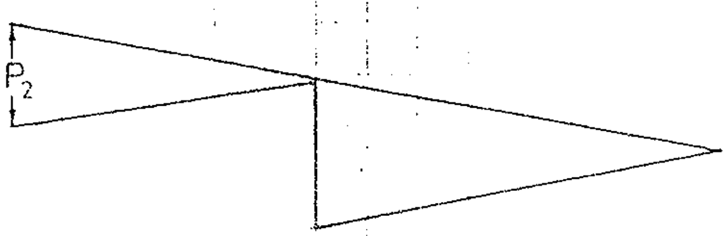
It should be remembered that the extraction of minerals is an operation involving the advancing of access tunnels, or retreating and abandoning them progressively. The changes created in the circuit by mining methods gradually change the position of the neutral point. In particular, in retreating extraction techniques a fan, originally sited suitably, may pass into the reverse leakage zone as extraction proceeds.




Booster Fan at X. Leakage in the Normal Direction but Potentially High.




Booster Fan at Z. Leakage in the Reverse Direction Between Y and Z.




Booster Fan at Y. Minimum Leakage in Normal Direction. No Reversal.

Figure 1.10 Effect of Booster Fan Location on Leakage Within Circuit $C_3$

Assessment

The usual reason for installing a regulator is to divert some of the air flowing in one circuit into another, but it has been shown that this is a negative solution because it reduces flow into the mine and increases the leakage. The chief advantages of regulators are that they are fairly easy and relatively cheap to install, and that adjustment of sliding doors provides flexibility instantly and at no additional cost. The facility of adjustment also means that final decision on the degree of control required can be left until the effects can be measured.

Set against these advantages are the losses in useful flow, through leakage paths, which may take time and labour to rectify by locating and sealing. Another problem is that the air diverted elsewhere by the regulator is distributed in varying degrees to all other circuits, but may be needed in one in particular.

Reduction of resistance is a positive solution to increasing flow in a selected circuit. Not only does it confine the benefit to that circuit; it increases total flow and reduces leakage, so that the proportion taken from other circuits is minimised.

Although it may be impractical to engage in a major programme of repair, enlargement or driving an additional airway, inspection of the circuit could identify localised restrictions and remedies; bulky plant badly sited; a congested junction requiring a short by-pass; excessive material stocks or mine car standage.

Where there are long trunk airways causing high pressure drop, the pressure differences across remote circuits is frequently inadequate. In such circumstances, regulators elsewhere or reduction of resistance in the remote circuits would be insufficient and the only solution is a booster fan.

# CHAPTER 2

## Fan combinations

The combination of fans in series, parallel and series/parallel groups is an indispensable feature of mine and tunnel ventilation practice.

The main reason for this is that a wide range of requirements can be met by a limited range of fans. In tunnelling and other developmnent drivages the duty is constantly changing, making it impractical to install a single fan for the life of the operation, or to replace the unit at frequent intervals. Combinations also give flexibility to booster installations and, by the inclusion of standbye groups, rotational repair and maintenance can be carried out with minimal disruption of the ventilation.

If the best arrangement is to be made it is essential to understand the characteristics of combinations, and the intention in this chapter is to examine them by graphical construction and interpretation. As in the previous chapter, the assessment is mainly qualitative rather than quantitative.

To simplify construction and clarify the argument, the fan characteristics in most examples are drawn as smooth curves without their unstable regions. Instability is taken into account where it is relevant, but the use of smooth curves in other cases does not detract from the validity of the general deductions and the conclusions drawn from them.

The reader should use dividers on the figures if he wishes to check that he understands their construction. This is strongly recommended for the examples on unstable operation of parallel fans, where there is a quantitative element.

Pairs of similar fans

The most common installation is of two indentical fans in series or in parallel. The construction of the series combined fan curve from the single curve is shown in figure 2.1.

Assuming that the combination when applied to a resistance $R_1$ produces flow $Q_1$, the flow through both fans is $Q_1$. Reading from the single fan curve, the pressure developed by one fan at flow $Q_1$ is $P_1$, so the combination develops $2P_1$, giving a point on the characteristic $2P_1, Q_1$. At resistances $R_2$, $R_3$ etc the points are $2P_2$, $Q_2$ and $2P_3$, $Q_3$ etc, from which the combination curve can be drawn. For any fan the combined characteristic can be constructed by doubling the pressure ordinates on the single curve at the corresponding flow rates.

To explain the limits of benefit to be expected from two fans in series compared with one fan, the curves are sketched in figure 2.2 with high and low resistance characteristics $R_h$ and $R_l$.

At low resistance, the fan curves are converging and the operating points are very close together, indicating that there is an insignificant increase in flow when two fans are in series at low resistance.

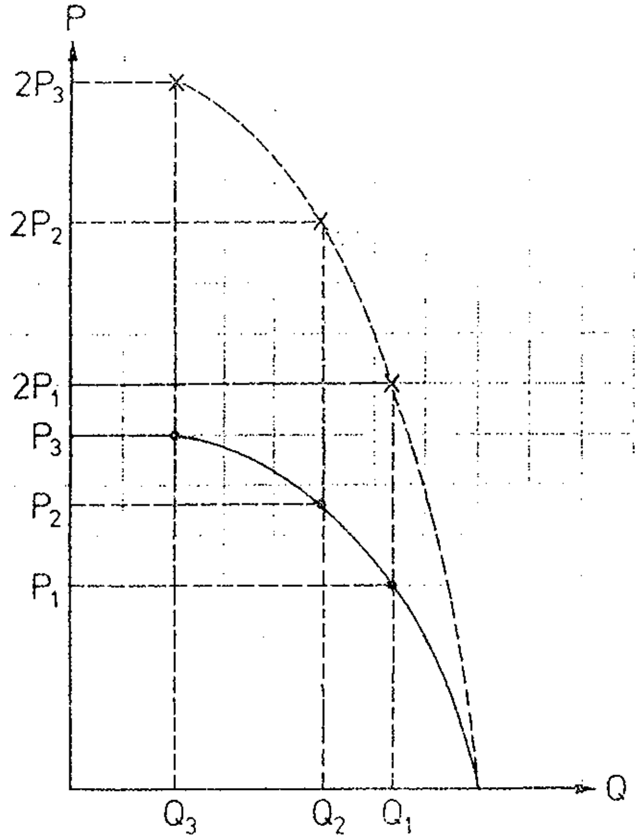



Figure 2.1 Construction of Curve for Two Fans in Series.

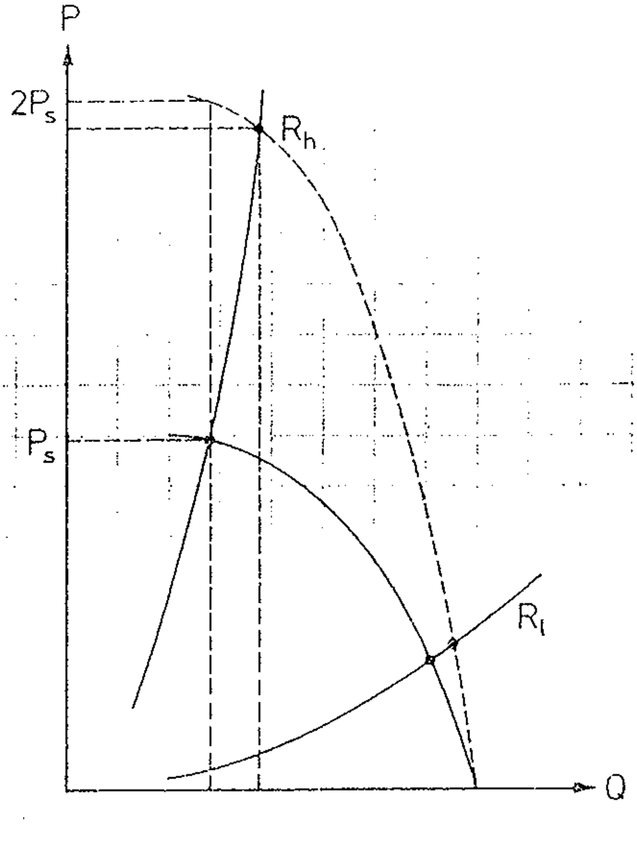



Figure 2.2 Operating Points for Single and Series Fans at High and Low Resistan

For the high resistance $R_h$, the pressure at the operating point of the combination approaches $2P_2$, which is twice that of the single fan. With constant resistance, in this case $R_h$, flow produced is proportional to the square root of pressure difference ($P = RQ^2$, hence $Q \propto \sqrt{P}$ when R is constant), from which it is deduced that at high resistance the air flow with the combination approaches $\sqrt{2}$ times that of the single fan.

The general conclusion is that a series arrangement of two similar fans will result in a gain, over one fan, ranging from nil at low resistance to a maximum of $\sqrt{2}$ times at high. The latter represents an increase of approximately forty percent at very high resistance.

For parallel fans, the reasoning in the construction of the combined curve is along the same lines as for series, but on the basis of doubling air flow instead of pressure.

When two similar fans are in parallel, they develop the same pressure and each creates flow at the same rate. At resistance $R_1$ the pressure developed by the combination is $P_1$. Reading from the single fan curve in figure 2.3, the flow from each is $Q_1$, and from the combination $2Q_1$, to give a point on the combination curve $P_1$, $2Q_1$. It follows that points on the characteristic are obtained by doubling the flow indicated at a range of pressures on the single curve, as in figure 2.3.

In figure 2.4, the fan characteristics and high and low resistance characteristics $R_h$ and $R_l$ are drawn. At high resistance, the operating points are close together, indicating no advantage from the

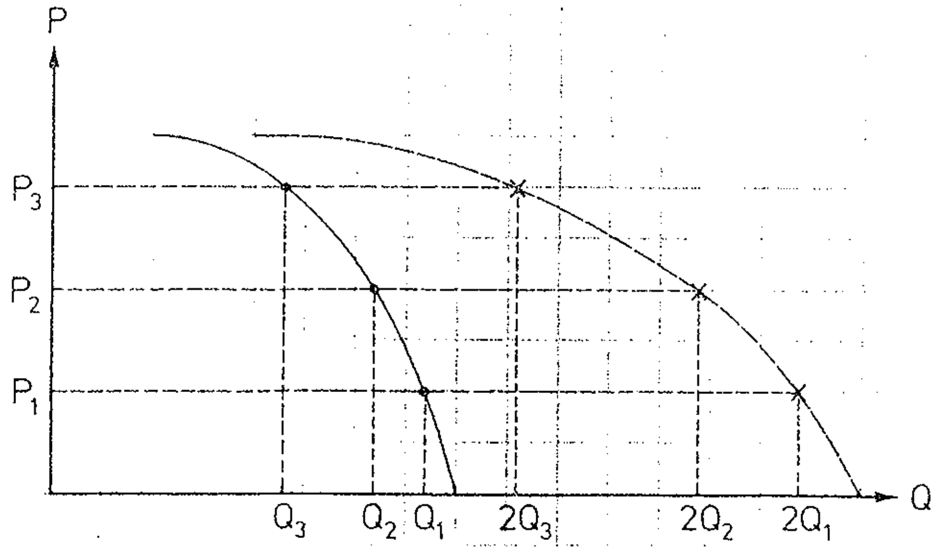



Figure 2.3 Construction of Curve for Two Fans in Parallel.

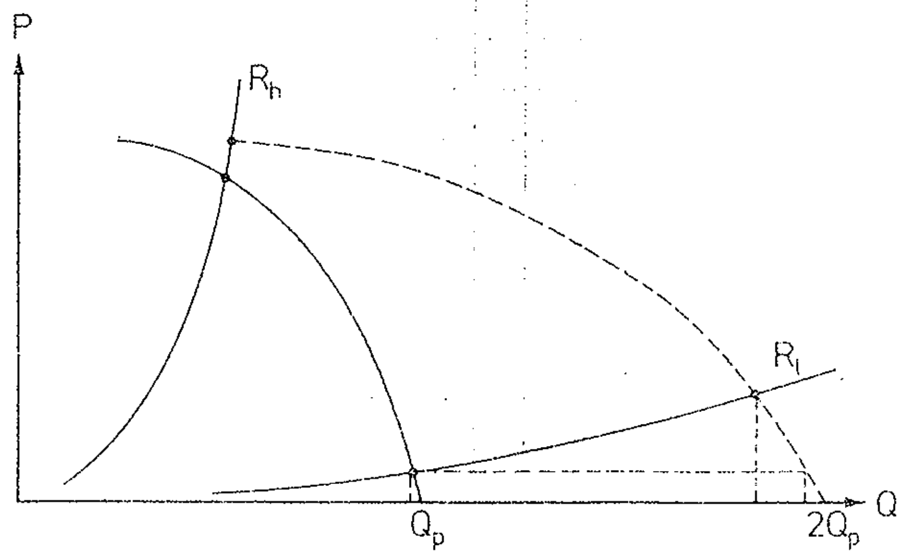



Figure 2.4 Operating Points for Single and Parallel Fans at High and Low Resistance.

combination. At low resistance, observation of the operating points shows that the flow produced by the two fans is almost $2Q_p$, twice that of the single fan.

The general conclusion is that for two similar fans in parallel, the advantage over one fan ranges from nil at high resistance to a flow approaching double at low.

Comparison between series and parallel

If the series arrangement is better at high resistance and the parallel at low, there must be some critical resistance, say $R_C$, at which the advantage switches.

Figure 2.5 shows single, series and parallel curves. The point of intersection of the combinations is an operating point which they have in common, and the resistance characteristic which passes through it is what has been referred to as the critical resistance, $R_C$. For $R_C$, both combinations develop pressure $P_C$ and create flow $Q_C$.

The resistance $R_C$ is the divide between the zones of advantage, with a series pair of fans having an advantage at higher resistance and a parallel pair at lower. The term "high resistance" can now be defined as any resistance greater than the critical resistance, whilst "low resistance" is one which is less than $R_C$. The actual value of $R_C$ naturally depends on the characteristic of the fan.

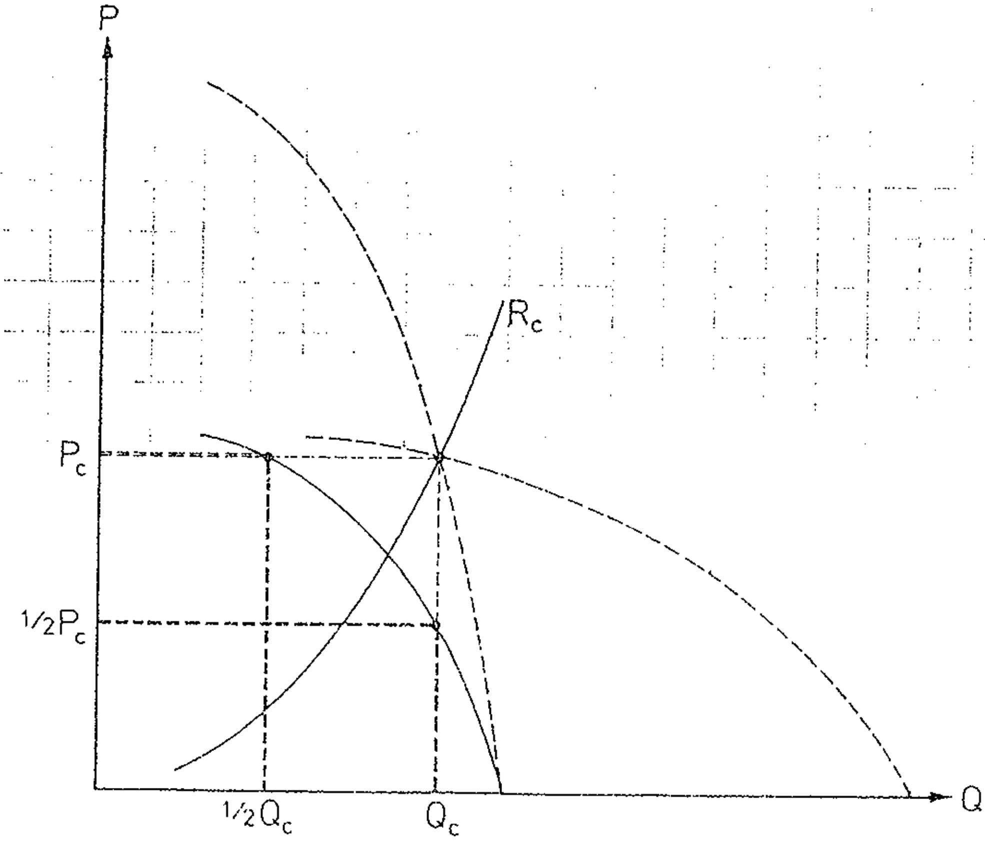



Figure 2.5 Critical Resistance and Single Fan Operating Points for Series and Parallel.

Suppose that in practice an auxiliary fan is in use in a tunnel and an increase in flow is required. If the fan characteristic is available, measurement of either pressure developed or flow produced by the single fan enables its operating point to be established, then the duct resistance calculated. If the combination curves and the resistance curve are plotted, the advantage zone in which the latter lies can be identified and action taken accordingly.

It should be noted that although the combination performances at the critical resistance are the same, those of the individual fans are not. In figure 2.5 the operating point for either combination is $P_C$, $Q_C$, but for each series fan it is $\frac{1}{2}P_C$, $Q_C$ and for each parallel fan it is $P_C$, $\frac{1}{2}Q_C$.

In a network where the resistance is critical and likely to remain so, other factors affect choice. In a parallel arrangement the facility exists to carry out maintenance on one fan while the other continues to supply air at a reduced rate. There are also considerations of space for installation and comparative costs. In major installations, the power cost may be a factor if the fans operating at $\frac{1}{2}P_C$, $Q_C$ have a greater or lesser mechanical efficiency than at $P_C$, $\frac{1}{2}Q_C$.

Pairs of dissimilar fans

The combination of dissimilar fans is not common and is probably the result of lack of availability. Not all mining or tunnelling undertakings have immediate access to central stores from which the plant best suited to the task can be requisitioned. For many small private operators the only equipment they have is what is on site and the need to improvise is frequent.

Fans of different capacities can be used to advantage in combination, but the potential exists for adverse effects, including mechanical damage. Although such occurrences are unlikely, they can happen. Expert advice is not always at hand and when it is, it is not always requested or taken.

In order to examine the circumstances in which dissimilar combinations are disadvantageous, it is necessary to consider the extension of a fan's characteristic into negative flow and negative pressure quadrants.

Figure 2.6 shows the characteristics of two fans which for convenience are referred to as large and small and designated $F_l$ and $F_S$. The extensions of $F_S$ are to be explained.

Suppose that the fans are coupled in parallel to a large chamber which is otherwise sealed. Initially the vessel is at atmospheric pressure and when the fans are started air passes into it at the fans' maximum capacities $Q_l$ and $Q_S$. As the pressure in the chamber rises, flow continues at a reducing rate corresponding to the fan

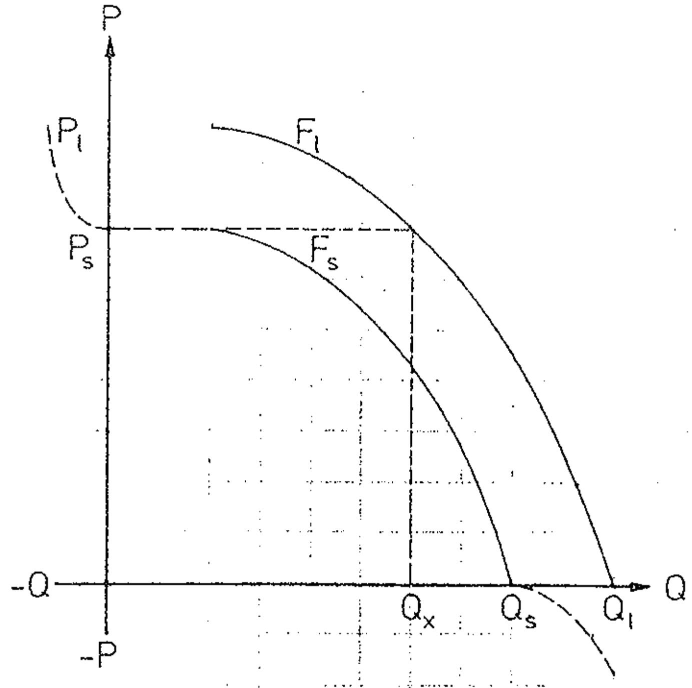



Figure 2.6 Extended Characteristic

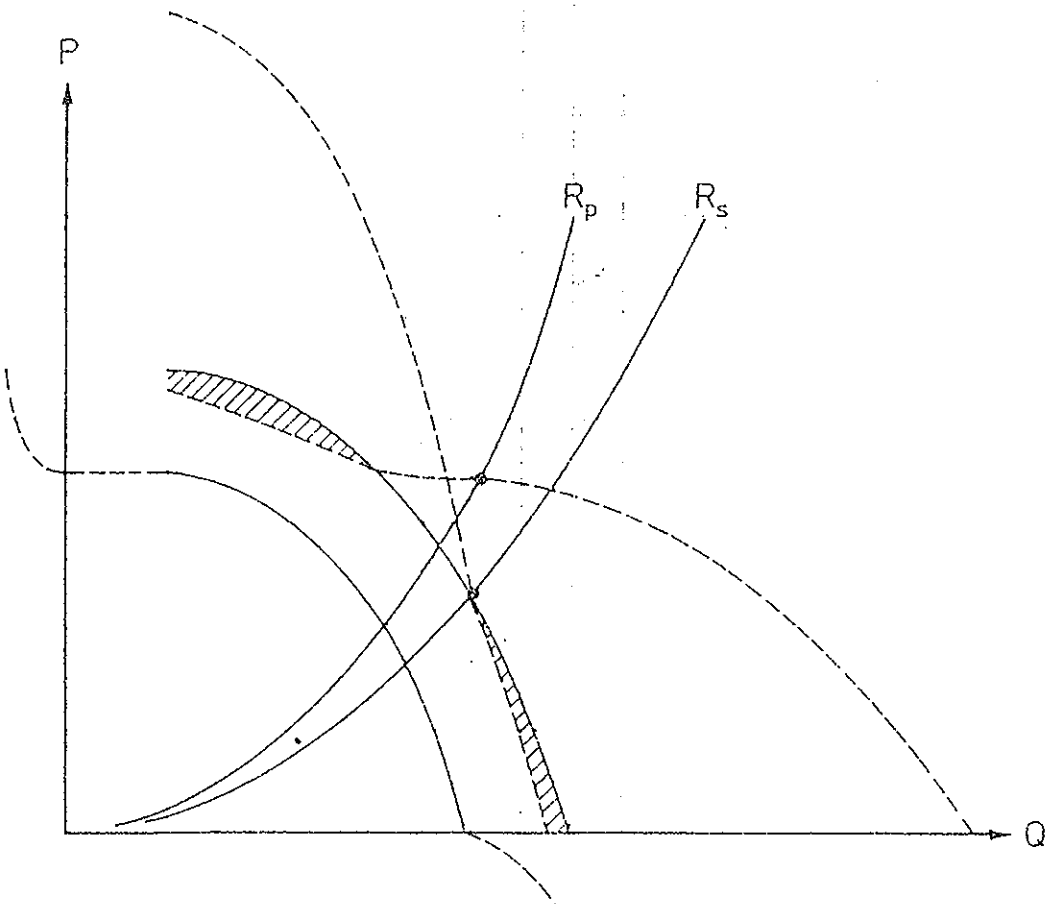



Figure 2.7 Dissimilar Fans in Series and Parallel.

curves. When pressure reaches $P_S$, the smaller fan, although continuing to run, delivers no air to the chamber. At that pressure, inspection of the curve of fan $F_L$ shows that it is still delivering at the rate $Q_X$, which decreases as the pressure in the chamber approaches $P_L$, the fan's maximum. The consequence is that although $F_S$ is running "normally", air flows through it in the wrong direction and at an increasing rate as the chamber pressure rises. Balance is achieved somewhere between the pressure $P_S$ and $P_L$, when air is being discharged from the vessel through fan $F_S$ at the rate at which $F_L$ is passing it in.

Figure 2.6 shows the curve of $F_S$ extended, quite legitimately, into negative flow. Because fans under test are not subjected to this treatment, the shape of the curve is uncertain, but that is not relevant to the discussion.

In the case of negative pressure, consider that the larger fan is operating alone against a low resistance system and passing air at a rate greater than $Q_S$, which is the maximum of the smaller fan. If the latter is then coupled to the system in series it is incapable of delivering at this rate and acts as an additional resistance, with a pressure <u>drop</u> across it. For that reason the curve can be extended from $Q_S$ at negative pressure, again of uncertain form.

The series and parallel combination curves are in figure 2.7. Construction is done on the same principle as for similar fans, with addition of indicated pressures for series and of quantities for parallel. The negative pressure and flow conditions result in the combined curves falling inside the curve of the larger fan over parts of their lengths, which are hatched in the figure. Should the fans be in parallel at resistances greater than $R_p$ in figure 2.7, the smaller fan becomes a resistance in parallel with the system resistance and air passes through it in a reverse direction back to atmosphere, despite the fact that it is running. With the fans in series at a resistance less than $R_s$, the smaller is a resistance in series and air is forced through it by the larger.

In both cases the larger fan alone would deliver more air than the combination, quite apart from the risk of damage to the second fan by its operation in conditions for which it was not designed.

Multiple series combinations

Multiple combinations are widely used for duct ventilation of access tunnels and for booster installations. The writer once visited a tunnel being driven for water supply in which six fans were in series. In British coal mines there are blocks of twelve fans in series/parallel combinations as boosters.

The construction of multiple curves is a logical extension of what has been described for pairs of similar fans. If there are n fans in series and P,Q is a point on the charactertisic of one fan, then nP,Q is a point on the combination curve. With n fans in parallel the point is P,nQ. For a series/parallel block of n x m fans it is nP, mQ.

The history of the six series fans referred to above is of interest. The tunnel was of small cross-section and at the time of the visit

1.5 km in length. Because of the confined space the ventilation duct diameter was small and at this length its resistance was excessive. Presumably fans had been added one by one to an original installation of a single fan.

Excavation was by highly efficient drilling and blasting, with a cycle being completed in two hours. Air discharged at the tunnel face by a forcing method of ventilation took more than two hours to return to the outlet, which meant that there were two plugs of blasting fumes if work was continuous. It had been made a condition of the tunnelling method that operations had to be suspended when there was more than one plug of fumes, with the result that time was being lost awaiting discharge of a plug.

The contractor's solution had been to turn the fans round and exhaust ventilate, but the spiral-wire flexible ducting collapsed under the high pressure difference created by the six fans. The problem was solved by putting the fans at intervals in the duct along its length, the arrangement seen by the writer.

The adding of fans in series in order to maintain an adequate air supply as resistance increases would seem to be straightforward and is illustrated in figure 2.8.

With one fan and a resistance $R_1$, the fan develops pressure $P_1$ and delivers air at the rate $Q_1$. When the resistance has increased to $2R_1$ and a second fan is added, the pressure developed is $2P_1$ and the flow rate of $Q_1$ is maintained. This rate is held constant by more fans and finally when six are installed the resistance is 6R and pressure developed 6P .

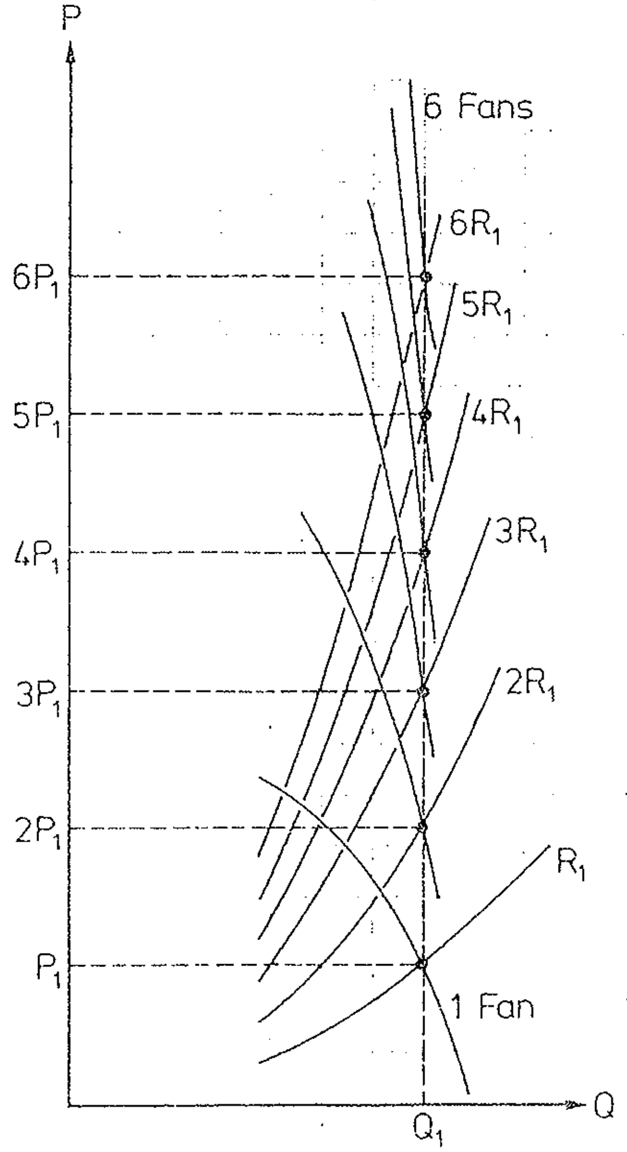



Figure 2.8 Maintaining Constant Flow with Increasing Resistance.

Unfortunately, even the best duct installations leak and not all of the air passed by the fans reaches the face of the tunnel, where it is usually required. As the duct is extended, more leakage paths are created and the pressure drop across them rises with each additional fan. This twofold effect creates rapidly increasing leakage, and an adequate supply at the tunnel face requires something more than just keeping delivery at the fan constant. In the case of the water tunnel it must be assumed that initially the supply was more than adequate.

Resistance and leakage in auxiliary ventilation systems are dealt with in chapter 6.

## Multiple parallel combinations

When three or four axial flow fans are in parallel, as in some booster combinations, it is necessary to examine the effect of the unstable region of the fan characteristic near to the pressure axis. If a fan operates in this region, slight changes in resistance can cause sudden fluctuations in pressure and the risk of mechanical damage. With several fans in parallel, one or more may operate in the unstable mode although the others are stable. Why this is so is explained below.

The fan characteristic in figure 2.9 includes the unstable region. At any pressure between the trough and peak of the curve, there are three operating points, one of which is stable and two unstable. If the system resistance is too high the fan runs in the unstable mode.

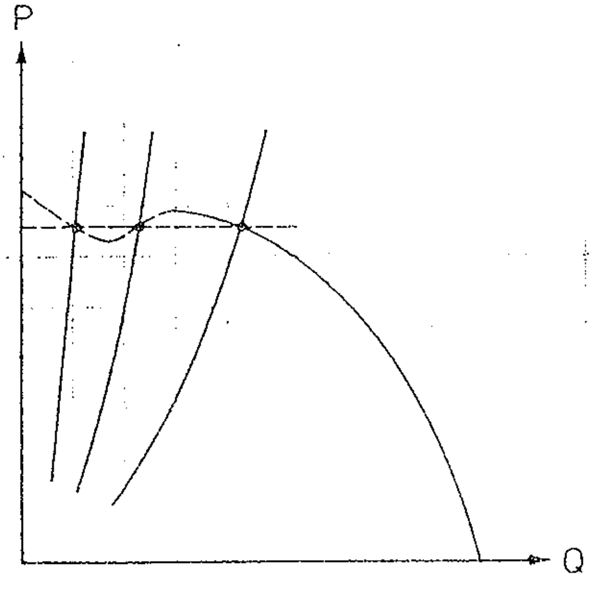



Figure 2.9 3 Operating Points.

Two or more similar or dissimilar fans in parallel all develop the same pressure, but otherwise operate as if they were quite separate from each other against parallel resistances which are equivalent to the resistance of the system in which they are combined. If the fans are dissimilar the load is shared unequally according to the fans' characteristics.

At an unsuitable combined resistance, whereby the pressure developed is in the critical region, one or more of a parallel group of similar fans could have an unstable operating point, with the others on the stable part of the curve. Were that to happen, the fans would function as if they were dissimilar.

In figure 2.10 the single fan curve is labelled WXYZ, where WX and XY are unstable and YZ is stable. The combined curves for three and for four fans in the stable mode are constructed on the P, 3Q and P,4Q principle and shown as the solid lines Y'Z'.

Assuming one of the fans to be unstable, short "shadow" curves for that combination can be drawn by adding the Q values indicated on WX and XY to the stable curve for three fans. These are the broken lines W'X' and Y'X'. The only purpose of the curve for three fans is to facilitate this construction.

An unsuitable resistance $R_u$ intersects all three curves and illustrates three possible operating modes: all fans stable; one unstable on WX; one unstable on XY. Detail is shown for the last of these, taking the combination operating point as being on Y'X'. One

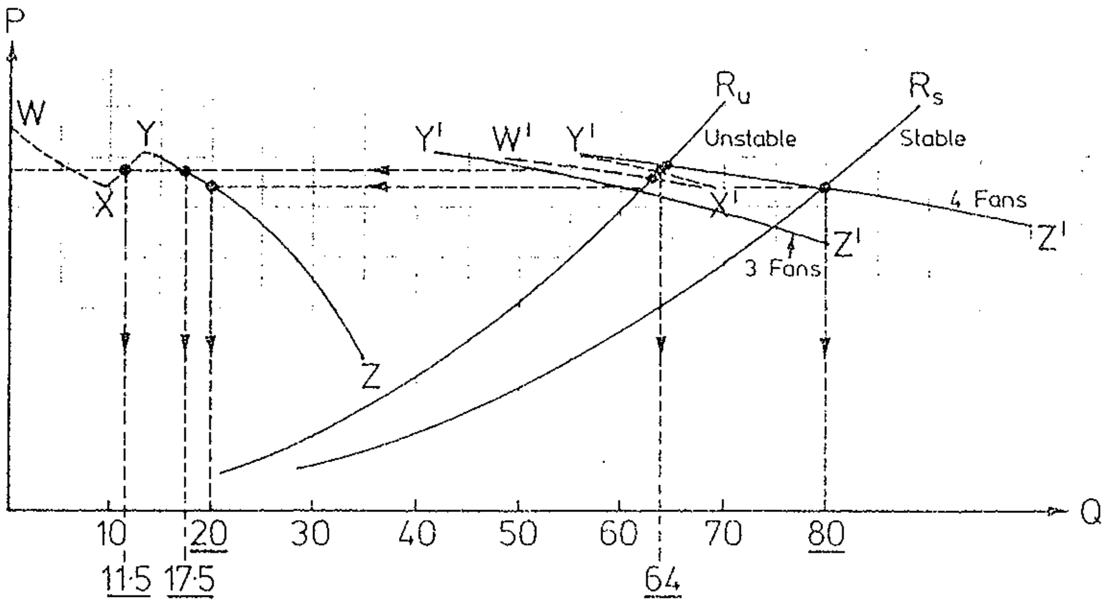



Figure 2.10 4 Parallel Fans. Stable and Unstable Operation.

fan operates on the curve XY, passing 11.5 units of flow, and three fans are stable on YZ, each delivering 17.5 units. The total flow is 64 units. With all fans stable the total is almost the same, but each delivers 16 units.

To avoid the risk of unstable operation, the resistance characteristic for the combination should intersect the stable curve Y'Z' at a pressure not greater than the pressure at the trough of the single curve. The resistance $R_s$ in the figure is in the stable condition. The total flow is 80 units, with each fan passing 20 units.

In installations where the circuit resistance exceeds $R_s$, a leakage path to recirculate air through the fans is sometimes introduced to lower resistance and create stability.

The analysis above has concentrated on one fan exhibiting instability. Using the same technique it could have been demonstrated that two fans might be in that state. The only reason for not doing so is that detail would have been obscured by too many shadow curves.

Instability in parallel groups applies equally to series/parallel because of the parallel element. Figure 2.11 shows the combination curve for a grouping of twelve fans, four in parallel and three in series, including the unstable shadows. The same fan characteristic as in the previous example has been used, with stable and unstable resistances three times greater ($3R_s$ and $3R_u$), so that the fan operating points should be the same as for the parallel arrangement in figure 2.10, which they are.

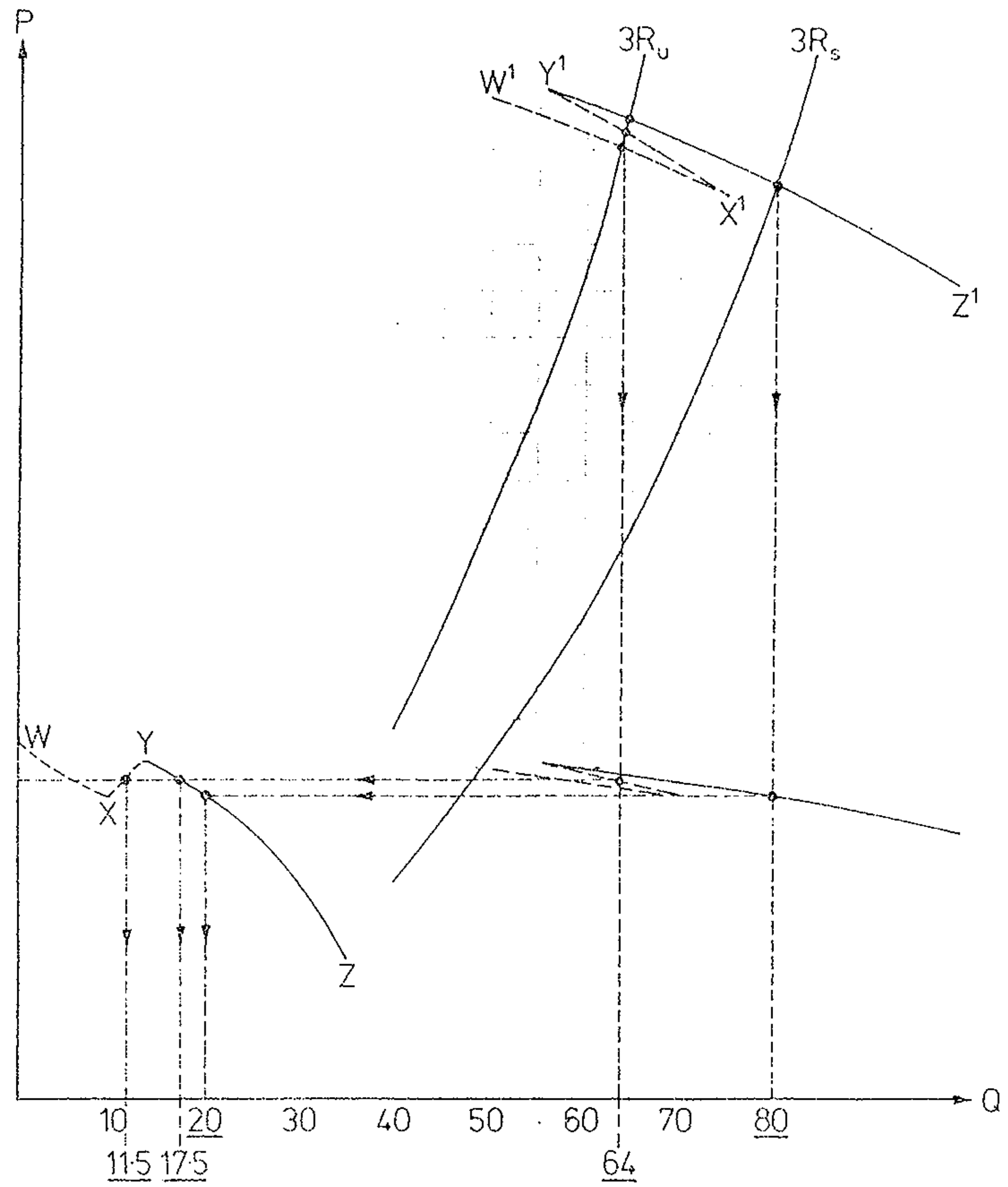



Figure 2.11 Series / Parallel (3×4) Fans. Stable and Unstable Operation.

# PART TWO

MINING: Graphical analysis of networks and the effects of changes.

# CHAPTER 3

## Introduction to graphical analysis of networks

Some years ago, the writer considered the possibility of analysing networks graphically, on the grounds that resistance characteristics can be combined in a similar way to fan curves. After some preliminary work, the graphical solution to an extensive network problem, which included a booster fan, was successfully tested against the computer solution.

The method is not an approximation technique. It is mathematically coherent but requires very little in the way of mathematical expertise and can be applied to many planning exercises by a competent technician. A further advantage is that it leads to a much better understanding of ventilation principles and practice. It also gives the technician greater satisfaction than does the collection and tabulation of data to feed to a computer.

In this short chapter it is proposed to outline the basis of construction and presentation, then construct and analyse graphically the network used previously for pressure diagrams. In the next chapter the changes in flow patterns brought about by resistance changes, which were qualitatively deduced with the aid of diagrams, will be examined. In that way, the dual purpose of confirmation of the deductions and the explanation of graphical representation and analysis is served.

Instruments and method

Although the logic of representation is not difficult to understand, poor draughtsmanship will produce unsatisfactory results.

Graphical analysis is a two-stage process. The first stage is to represent the network graphically and the second is to analyse it. Even gross errors in the first stage are unlikely to be identified until inconsistencies are revealed in the analysis and the exercise has to be done again.

Inaccuracies of construction also only become evident after completion of the second stage, when it is discovered that the summed air distribution does not correspond with the indicated fan flow. With care, a fair draughtsman should achieve an accuracy of about one percent, provided he is given the proper equipment.

The first essential for accuracy is presentation on the largest practicable scale. As a guide, if a careful practitioner is more than one percent inaccurate when comparing the summed distribution with total flow, the scale is suspect.

Since the starting point for every exercise on a particular network is the plotting of the resistance curves of all branches, a good master copy of the curves shoud be prepared on a suitable scale and prints taken from it. The risk of constructional error or inaccuracy is thus minimised and much time is saved. The master is the graphical equivalent of the stored program for a network regularly examined by computer analysis.

The equipment required is simple but essential: a good working surface; good lighting; straight edge; french and flexible curves; dividers and compasses; fine-point retractable pencil and a rubber.

When plotting curves, a sufficient number of points should be located to ensure accuracy over the whole length. Even on a short curve the number should never be less than four. Accuracy is most important for characteristics which are close to the vertical or horizontal. French curves are preferable to flexible except when the characteristic being plotted is nearly straight.

Dividers are preferable to compasses when locating points requiring more than a one step addition. A scaled rule must never be used for locating. It is tedious, slow, inaccurate and liable to reading and transfer errors. Because of the tedium and the concentration required when using a rule, there is also the tendency to locate an insufficient number of points.

A line diagram of the network is needed and is worth including on the master copy of the curves. A logical identification code must be adopted for ease of initial analysis and to make the completed exercise intelligible to competent personnel who did not construct it. These aspects will be dealt with in the exercises.

Starting with a sheet showing a line diagram, identification code and the basic curves, a complex network can be analysed by an able draughtsman in under an hour.

In the analyses in this and the following chapters, it is advisable to apply dividers to the figures to ensure that the constructions are understood, rather than just accepted.

Graphical representation

A ventilation network can be represented graphically if the resistances of its parts are known or estimated.

Just as fan curves can be combined, so can resistance curves. The network is a group of airways in a series/parallel configuration and its composite characteristic is derived by combination in the same way as a multiple fan characteristic.

If two or more resistances are in series, the air flow through them is common and the total pressure drop is the sum of the pressure drops in each. When they are in parallel it is the pressure drop, or pressure difference across them, which is common, and the total flow is the sum of the individual flows.

Figure 3.1 shows a simple arrangement of three airways $R_1$, $R_2$ and $R_3$ in parallel, and in series with airways $R_4$ and $R_5$. The curves of the resistances are drawn and the objective is to construct the composite characteristic $R_c$ for the arrangement.

The first step is to plot the combination curve $R_p$ for the parallel group. At about six positions on the pressure axis, dividers are used to locate points by addition of the corresponding flows. For example, at pressure $P_p$ the flows are $Q_1$, $Q_2$ and $Q_3$ and the total is $Q_t$. This curve is now is series with $R_4$ and $R_5$, so that points on the total resistance characteristic $R_c$ are located by the addition of pressures for about six flows. For $Q_t$ the pressures are $P_4$, $P_5$ and $P_p$ and the total is $P_t$, giving a point $P_t$, $Q_t$.

The original curves are drawn as continuous lines and the derived curves are broken. This practice is adopted in all exercises.

Closed networks

A closed network is one in which a fan is included.

Figure 3.2 shows a line diagram of a closed network and the resistance characteristics of all its parts. The airlock L and separation doors $D_1$ and $D_2$ are taken to have the same resistance and a single curve represents all three. This also applies to the trunk airways $R_1$ and $R_2$, as well as to $R_3$ and $R_4$. The fan characteristic is included.

The resistance curves in the figure are the starting point of any exercise in which changes to the existing network are to be investigated. They constitute the master copy referred to earlier.

Before considering the effects of change, in the next chapter, it is proposed to analyse the original network.

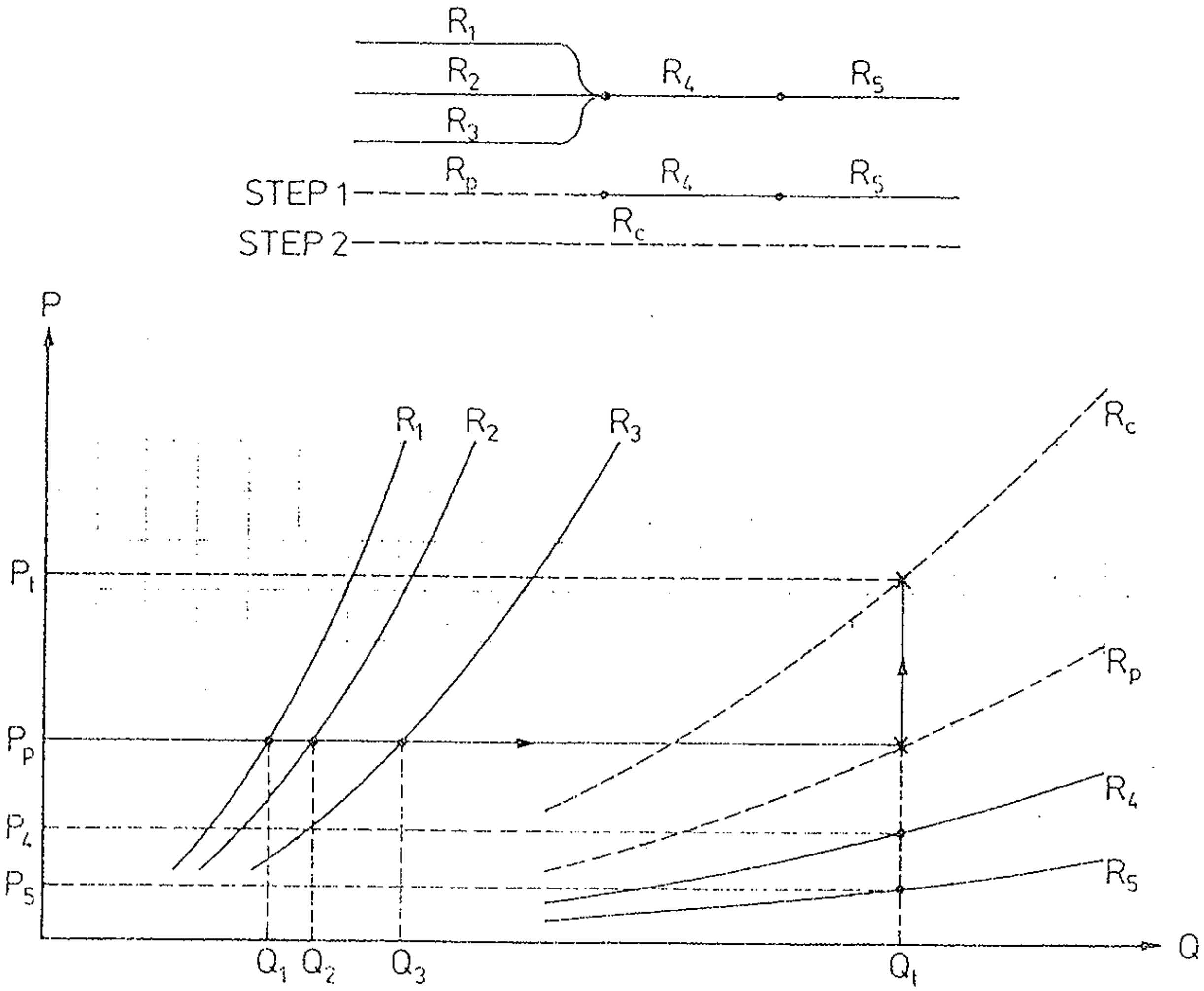



Figure 3.1 Series/Parallel Combination Characteristic.

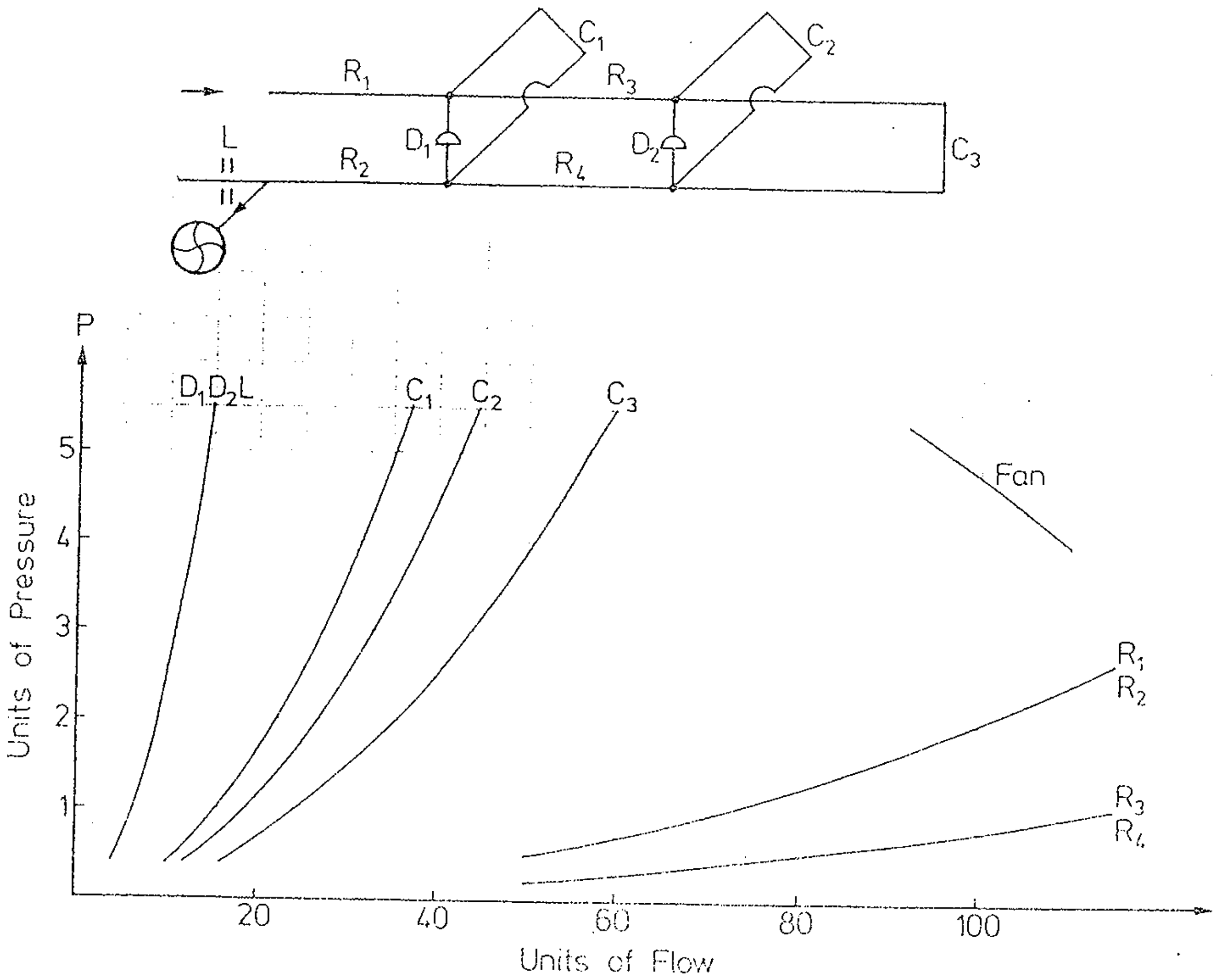



Figure 3.2 Line Diagram and Resistance Characteristics.

In the line diagram in figure 3.3 a series of numbers or symbols are shown at various locations. The combining of characteristics always begins at the most remote circuits, in this case the parallel group $C_2$, $C_3$ and $D_2$. The symbol 1 represents the combination characteristic of the group and the derived curve is given that designation.

Similarly, the symbol 2 indicated the combination of $R_3$ and $R_4$ in series with the parallel group 1. Symbol 3 is the parallel arrangement of 2, circuit $C_1$ and doors $D_1$.

The entire underground network, consisting of $R_1$ and $R_2$ in series with 3, is 4. Finally, 5 is the whole system, consisting of the airlock in parallel with the underground network, against which the fan operates.

As stated, construction commences with the parallel group $C_2$, $C_3$ and $D_2$.

> By the addition of flows, points on the derived curve are located and the characteristic given the designation 1 in the graphical presentation in figure 3.3.
>
> The combination is in series with $R_3$ and $R_4$, and the addition of pressures for these three produces the curve 2, which is then in parallel with $C_1$ and $D_1$, leading to the characteristic 3.

Curve 4 is the underground network and is derived by the series combination of $R_1$, $R_2$ and 3, whilst 5 is the parallel arrangement of the airlock L and 4.

The graphical stage of the exercise is now complete.

The intersection of the final curve 5 with the fan characteristic is the fan operating point. For ease of comparison with later exercises the fan curve has been deliberately drawn to operate at 100 flow units, and the pressure developed is read from the graph as 4.8 units.

The analysis proceeds by retracing the construction through the derived curves from 5 to 4 to 3 to 2 to 1.

On the pressure line from 5 to 4 and extended to the airlock characteristic L, flow into the mine is 86 units and airlock leakage 14 units.

From 4 to 3 is the pressure drop in the shafts and/or trunk airways $R_1$ and $R_2$.

At the intersection with 3 it is seen that the pressure difference is 1.8 units. Tracing across on that line to 2 and beyond, the flow into $C_1$ is 21 units, leakage through the doors $D_1$ is 8.5 units and 56.5 units flow towards the remote circuits.

From 2 to 1 is the pressure drop in the airways $R_3$ and $R_4$.

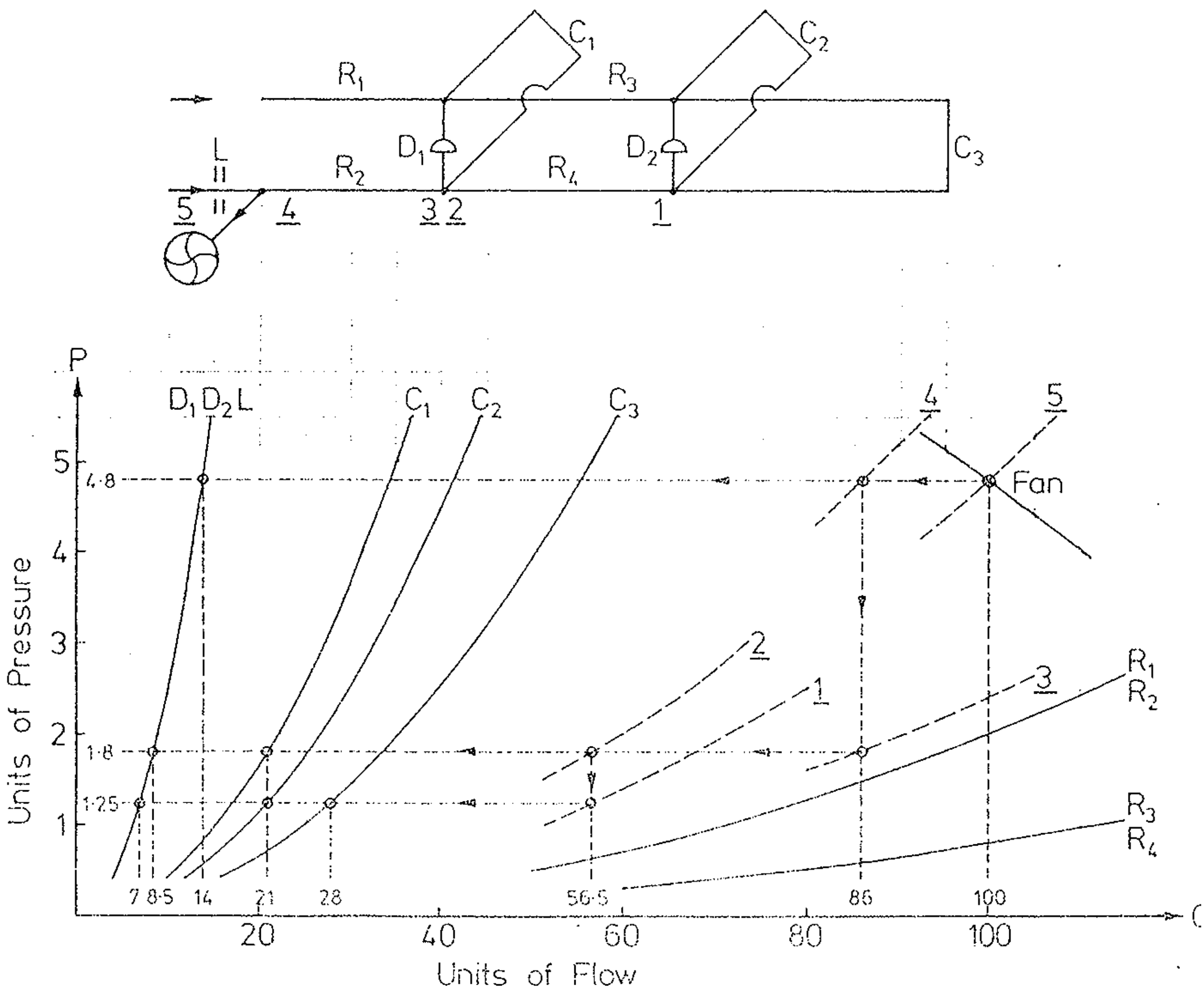



Figure 3.3 Analysis of Basic Network.

Reading at the intersection on 1, the pressure difference across the remote circuits is 1.25. The flows into $C_2$, $C_3$ and through the doors $D_2$ are 21, 28 and 7 units respectively.

The details of the analysis are assembled in the table.

| | L | $C_1$ | $D_1$ | $C_2$ | $C_3$ | $D_2$ | TOTAL | FAN |
|---|---|---|---|---|---|---|---|---|
| Flow | 14 | 21 | 8.5 | 21 | 28 | 7 | 99.5 | 100 |
| Pressure Difference | 4.8 | 1.8 | 1.8 | 1.25 | 1.25 | 1.25 | - | 4.8 |

The graphical construction in the example consisted of plotting five derived characteristics, and it may have been noticed that they are only short lengths. It is never necessary to construct the complete curves.

Pressure difference across the circuits in a network decreases with distance from the surface of the mine. Because the construction of the derived curves begins at the most remote circuits, where pressure difference is lowest, the first curve need not be extended beyond low pressure limits. The length of that curve then governs the lengths of all succeeding derived curves. If the first curve is long enough to contain the flow analysed (in this exercise 56.5 units) all others will be long enough.

It is usually possible to make a rough estimate of the flow to be expected in a remote circuit, so that the length of the characteristic can be limited to the region of the estimate.

# CHAPTER 4

## Graphical analysis of changes in network resistance

In a working mine, the flow distribution is known, and what is required of the ventilation specialist is an assessment of the action necessary to alter the distribution, or the effect on it of future mine development.

The analysis of the network in the previous chapter has shown the flow distribution. That can now be taken to represent the current position in a mine in which the consequences of changes in network resistance are to be investigated.

The situations which are to be examined have already been the subject of qualitative assessment with the aid of pressure diagrams. These were:

restriction by a regulator;
reduction of resistance in a circuit;
introduction of a booster fan.

### Restriction by a regulator

In the network with which the reader should now be familiar, a regulator is to be placed in circuit $C_3$ to reduce the air flow from 28 to 14 units, in order to increase flow in circuit $C_2$.

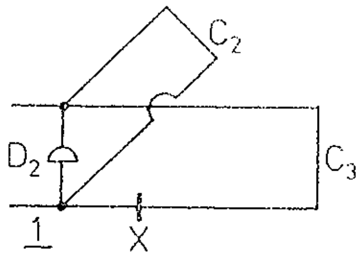
Because networks can only be analysed when all resistances are known, it is first necessary to determine a resistance for the modified $C_3$ circuit. It was shown by pressure diagrams that the pressure difference across circuits changes when the network resistance increases or decreases, and for that reason it is not possible to establish a real modified resistance in advance of the construction. What is known is that, regardless of the pressure difference, the flow in the circuit will be 14 units. The only resistance characteristic which can satisfy that condition is a vertical through 14 flow units. Such a characteristic is unreal, but it is a legitimate device for the graphical construction and its analysis.

Figure 4.1 is a line diagram of the parallel group $C_2$, $C_3$ and $D_2$, and their resistance characteristics. The vertical through 14 units is $C_{3m}$, the modified characteristic of $C_3$. In the graphical construction the curve $C_{3m}$ is used and $C_3$ is ignored.

The parallel combination curve of $C_2$, $C_{3m}$ and $D_2$ is derived in the usual way and shown in the figure.

The line diagram and the graphical construction and analysis for the whole network is illustrated in figure 4.2. With the knowledge of the distribution in the original network, it is estimated that the flow in the remote circuits will be between 45 and 60 units, hence the first derived characteristic can be limited to that region.

Construction of all derived characteristics is exactly as before.



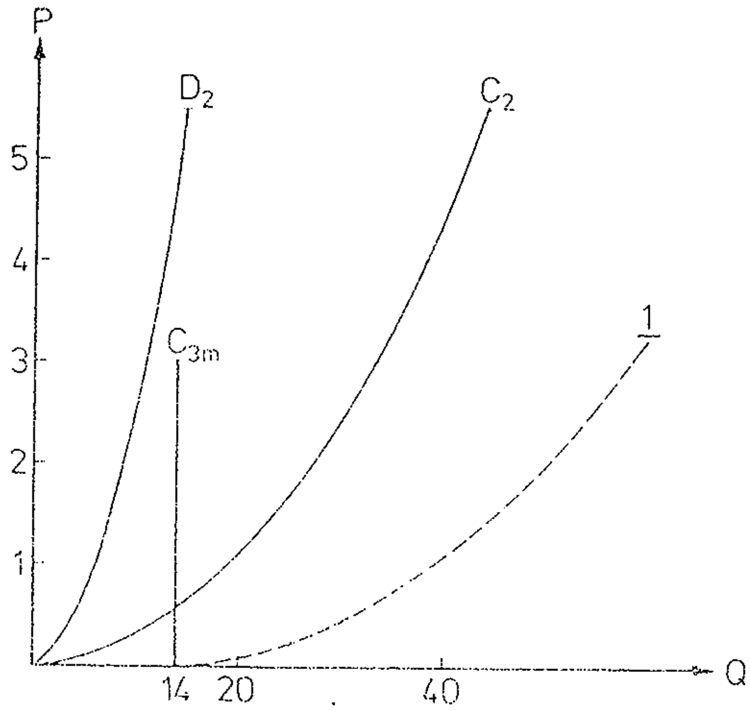




Figure 4.1 Combination Characteristic with Regulator at X.

Curve 1 is the parallel group $C_2$, $C_{3m}$ and $D_2$.

Curve 2 is the series group 1, $R_3$ and $R_4$.

Curve 3 is the parallel group 2, $C_1$ and $D_2$.

Curve 4 is the series group 3, $R_1$ and $R_2$.

Curve 5 is the parallel group 4 and L.

The fan operating point is 97.5 flow units at 5 pressure units.

By retracing through the construction, still ignoring the original circuit $C_3$, the air distribution and pressure differences are as in the table below, with the same information for the original network included for comparison.

| | | L | $C_1$ | $D_1$ | $C_2$ | $C_3$ | $D_2$ | TOTAL | FAN |
|---|---|---|---|---|---|---|---|---|---|
| Flow | Original | 14 | 21 | 8.5 | 21 | 28 | 7 | 99.5 | 100 |
| | Modified | 14.5 | 23.6 | 9.7 | 26.5 | 14 | 8.9 | 97.2 | 97.5 |
| Press | Original | 4.8 | 1.8 | 1.8 | 1.25 | 1.25 | 1.25 | - | 4.8 |
| diff | Modified | 5.0 | 2.28 | 2.28 | 1.93 | 1.93 | 1.93 | - | 5.0 |

The difference between the sum of the distributed flow and the fan is an acceptable construction error.

The deductions in chapter 1, using pressure diagrams were as follows:

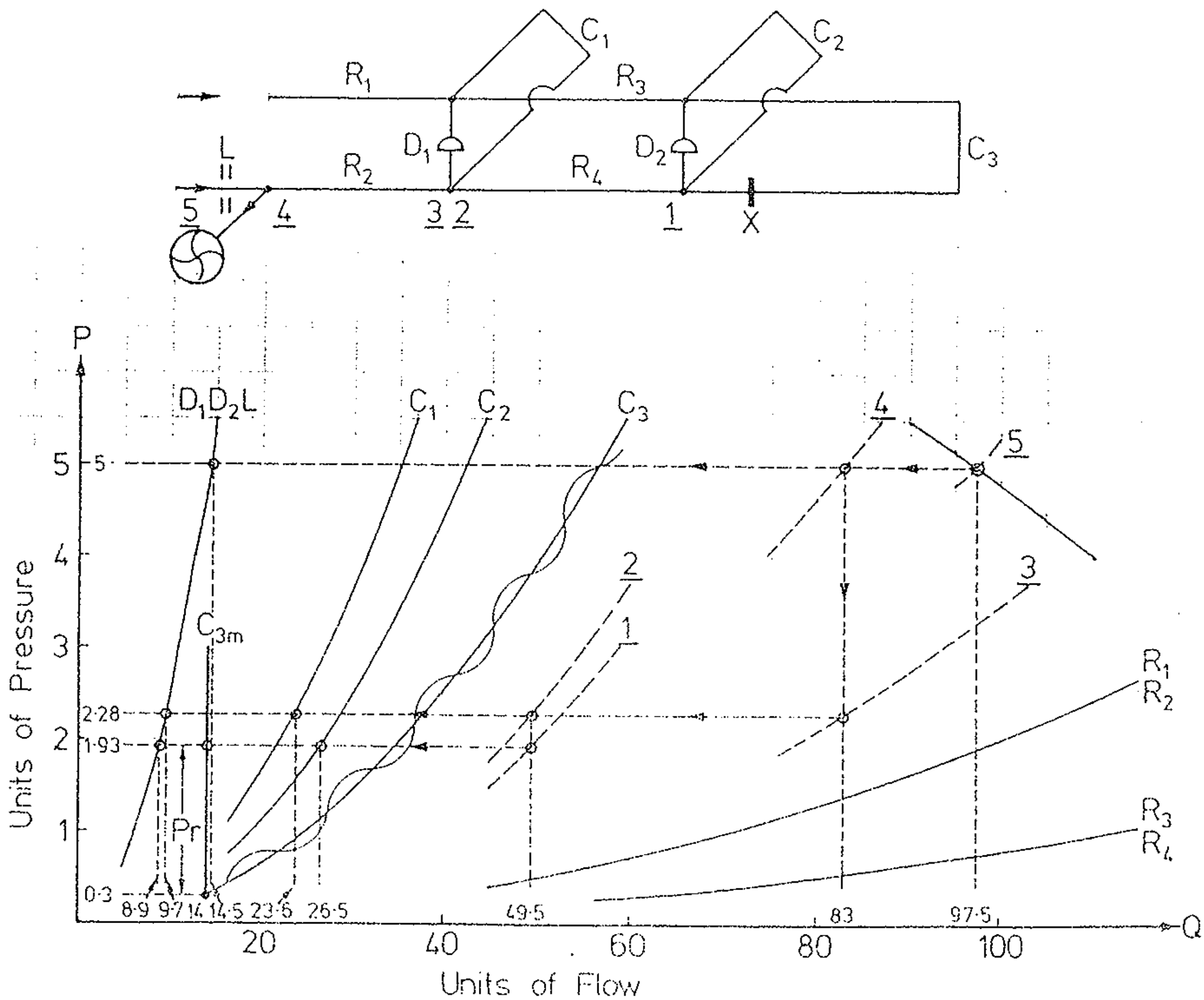



Figure 4.2 Regulator at X to Reduce Flow to 14 Units.

When the resistance of a circuit increases, the resistance of the network increases and the fan pressure rises and the air flow falls.

There is increased flow in all other parts, including leakage paths, but the increases in the circuits is less than the reduction in the regulated circuit because of the higher leakage and lower fan flow.

The gain is greater in $C_2$ than in $C_1$.

All of these deductions are confirmed by the analysis. Flow at the fan has fallen by 2.5 units and leakage has increased by 3 units. Although flow in $C_3$ is reduced by 14 units, the gain is only 2.6 units in $C_1$ and 5.5 units in $C_2$.

Referring to the figure, the pressure difference across circuit $C_3$, which includes the regulator, is 1.93 pressure units. The pressure drop in the circuit proper is seen to be 0.3 units, and so the pressure drop across the regulator is 1.63 units. From this and the flow of 14 units the resistance and cross-sectional area of the regulator can be calculated.

Reduction of circuit resistance

In chapter 1 the resistance of circuit $C_1$ was reduced and the effect on distribution in the network was deduced. This condition is to be analysed graphically on the assumption that physical alterations are proposed, within the circuit, which will reduce its resistance to half of the original.

Figure 4.3 shows the line diagram and the reduced resistance characteristic $C_{1r}$.

Graphical construction is done in the same way as in the previous examples. From the analysis of the original network it is estimated that flow in the remote circuits will be of the order of 50 units and the first derived characteristic, <u>1</u>, is limited accordingly.

From the intersection of the final derived curve with the fan characteristic the fan operating point is 4.65 pressure units and flow 102 units. Details of the analysis are tabulated.

| | | L | $C_1$ | $D_1$ | $C_2$ | $C_3$ | $D_2$ | TOTAL | FAN |
|---|---|---|---|---|---|---|---|---|---|
| Flow | Original | 14 | 21 | 8.5 | 21 | 28 | 7 | 99.5 | 100 |
| | Modified | 13.8 | 27.5 | 7.8 | 19.4 | 26 | 6.5 | 101 | 102 |
| Press | Original | 4.8 | 1.8 | 1.8 | 1.25 | 1.25 | 1.25 | - | 4.8 |
| diff | Modified | 4.65 | 1.5 | 1.5 | 1.05 | 1.05 | 1.05 | - | 4.65 |

The deductions with pressure diagrams are again confirmed:

> There is an increase in flow from the fan and reduced leakage.

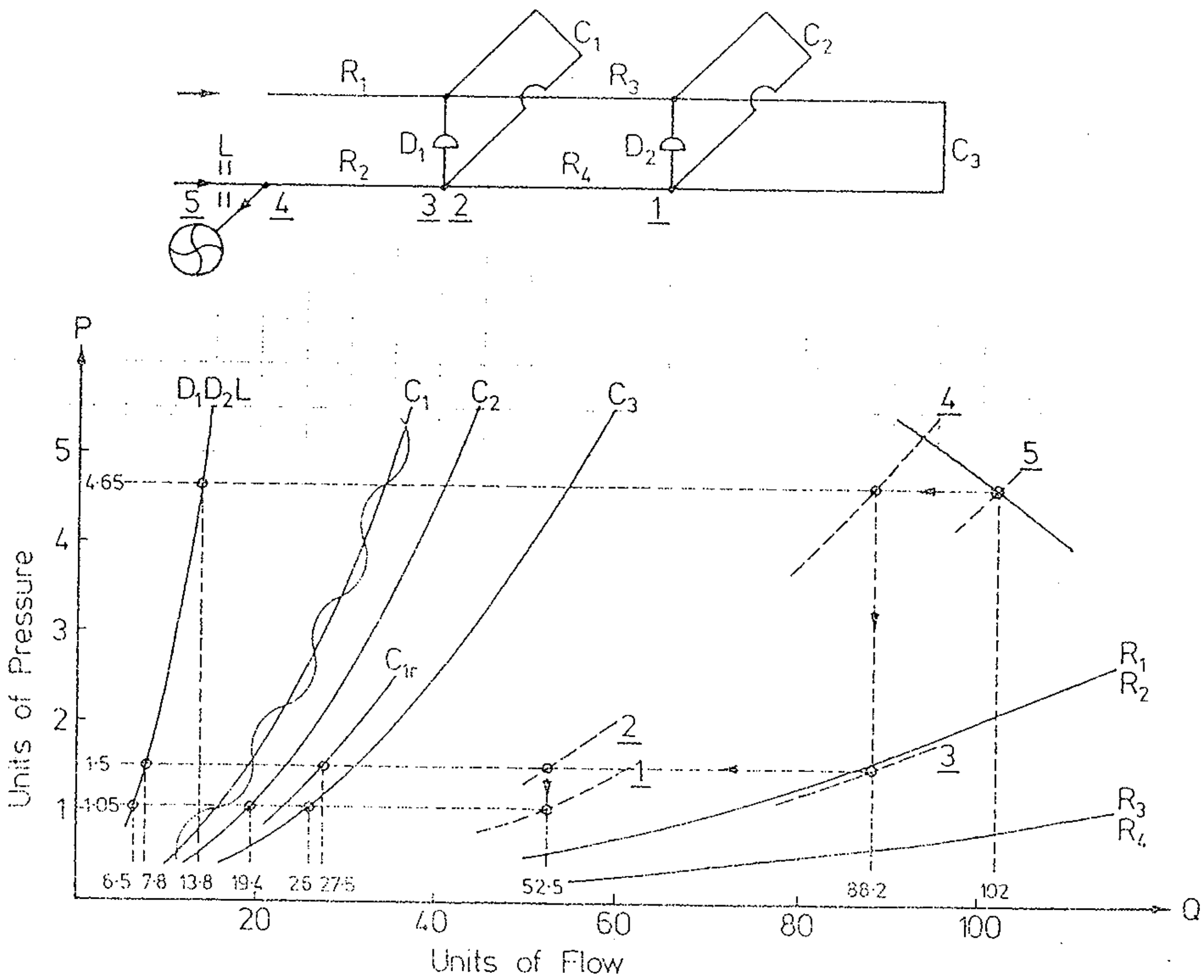



Figure 4.3 Reduction of Resistance in $C_1$

Although flow into circuits $C_2$ and $C_3$ is reduced it is not significant.

Flow into $C_1$ is increased by 6.5 units of which 3.6 units are from $C_2$ and $C_3$ and the rest are from the higher fan flow and lower leakage.

It should be evident that reducing the resistance of a circuit is a positive means of increasing flow in it, whereas restriction by a regulator in another circuit is a negative approach.

With the regulator, the fan flow is less than the original and the leakage is more. The air which is usefully diverted is distributed between circuits indiscriminately and cannot be directed to a selected circuit (unless another regulator is installed).

In this example, the circuit resistance was reduced by half and the effect investigated. An alternative would have been to fix the flow required in the circuit and determine by analysis the extent to which the resistance would have to be altered to achieve that flow.

The next example, which is concerned with booster fans, is also of use to demonstrate the alternative technique.

Introduction of a booster fan (1)

When a booster fan is proposed, the planning exercise usually consists of deciding what flow is needed and then analysing the system to find the fan duty and the effects on flow elsewhere.

Suppose that the flow in circuit $C_3$ is to be increased to 40 units by a booster fan at X, as in figure 4.4. The fan is the equivalent of reducing the circuit resistance to the extent that the flow rate will be 40 units whatever the pressure difference across the circuit. As with the installation of a regulator, the device of an unreal $C_{3m}$ is constructed as a pressure ordinate through 40 flow units, and the $C_3$ characteristic is ignored in the construction and analysis.

Starting with an estimation that the rate of flow towards the remote circuits will be about 60 units, the first curve is constructed. The intersection of the final curve and the fan charateristic gives the fan operating point as 4.58 pressure units and 103 units of flow.

The table shows the distribution and pressure differences, with the original for comparison.

| | | L | $C_1$ | $D_1$ | $C_2$ | $C_3$ | $D_2$ | TOTAL | FAN |
|---|---|---|---|---|---|---|---|---|---|
| Flow | Original | 14 | 21 | 8.5 | 21 | 28 | 7 | 99.5 | 100 |
| | Modified | 13.8 | 19 | 7.5 | 16.7 | 40 | 5.8 | 102.8 | 103 |
| Press | Original | 4.8 | 1.8 | 1.8 | 1.25 | 1.25 | 1.25 | - | 4.8 |
| diff | Modified | 4.58 | 1.42 | 1.42 | 0.75 | 0.75 | 0.75 | - | 4.58 |

These results again confirm the qualitative deductions, which were that flow at the fan would increase and that all leakages would decrease, as would the flows in $C_1$ and $C_2$.

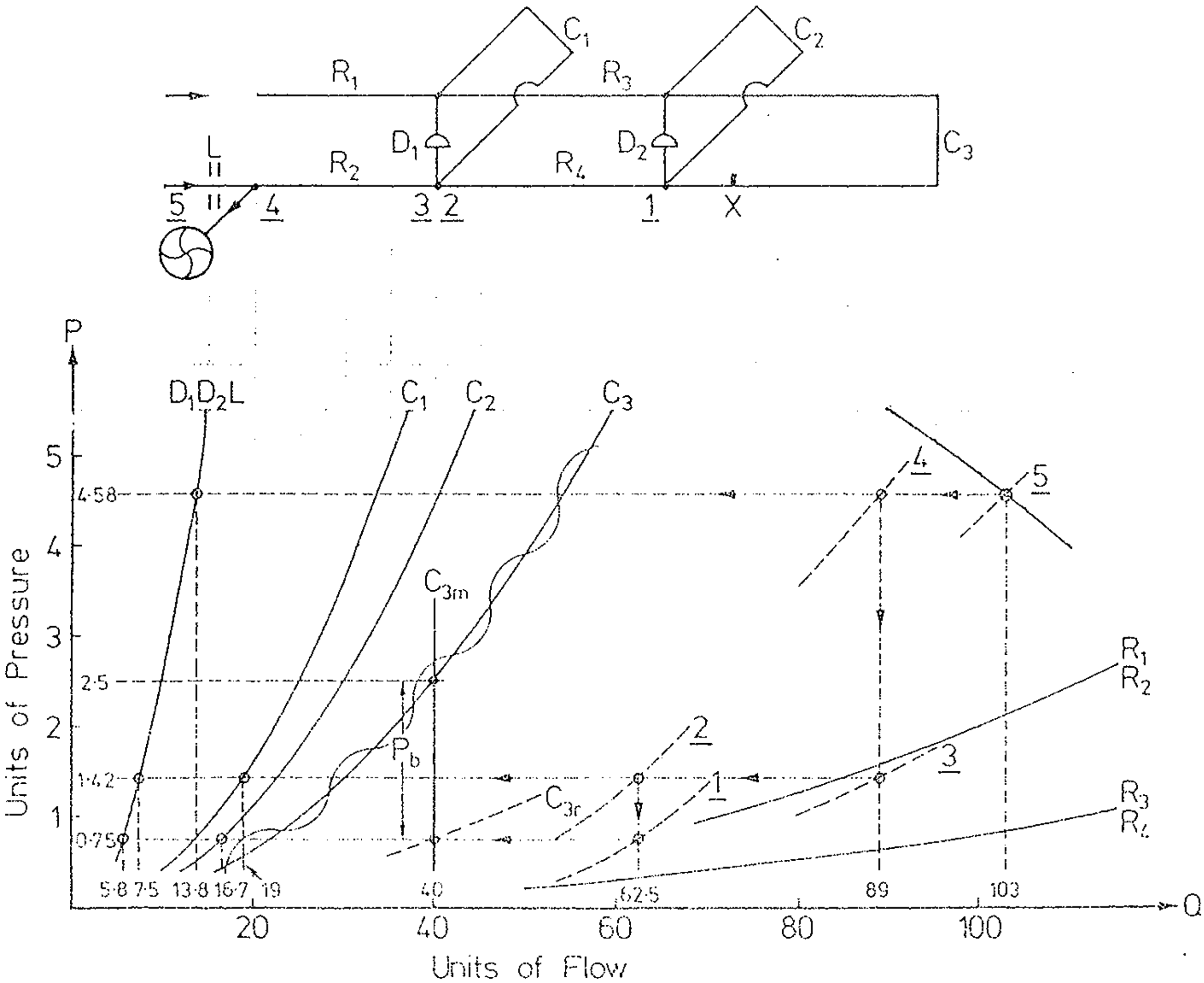



Figure 4.4 Booster Fan at X to Increase Flow to 40 Units (1).

Although the additional air flow in $C_3$ is 12 units, only 6.3 units of this is the shared loss from circuits $C_1$ and $C_2$. The greatest loss is from $C_2$, which was predicted by the pressure diagram analysis.

Referring to the figure, at a flow of 40 units the pressure drop around circuit $C_3$ is 2.5 units, and the pressure difference across it is only 0.75 units. The booster fan must provide for the deficiency and a fan is required to develop 1.75 pressure units at a flow rate of 40 units.

The effect of reducing the resistance of a circuit was illustrated by reducing the resistance of $C_2$ to half of its original value. The alternative method of analysis would have been to fix the flow required in $C_2$ and find the reduction in resistance which would be necessary to achieve that flow.

If the flow of 40 units in $C_3$ had been planned by reducing the circuit resistance instead of by booster fan, the construction would be the same as for the fan, and the distribution analysed would be identical. Referring to figure 4.4, the point 0.75 pressure units and 40 units of flow is a point on the reduced resistance curve $C_{3r}$ which is shown in the figure. This is the resistance required.

Had that curve been used instead of the ordinate through 40 units it also would have indicated the same distribution throughout the network.

Introduction of a booster fan (2)

The analysis above showed that to produce a flow of 40 units the fan pressure would have to be 1.75 units, so that any fan with that point on its characteristic would have the desired effect. It is intended to demonstrate this in the next example, but first the combination of a fan characteristic and a resistance characteristic must be considered.

When a booster fan is installed in a circuit it operates against the whole network and not just the circuit. This is obvious from the fact that, if the main fan were stopped, some degree of air flow would continue in all parts of the network because of the underground fan. For that reason, the intersection of the fan curve with the circuit resistance curve is not the fan operating point.

In figure 4.5, a fan curve and a circuit curve C are shown, together with a line diagram of the system.

When the air flow in the circuit is $Q_2$, the pressure drop in it as read from the curve C is $P_c$, and the fan develops a pressure of $P_b$.

A pressure gauge across the separation doors would record a pressure difference $P_2$, which is the difference between $P_c$ and $P_b$. An observer who was unaware of the booster fan would measure $P_2$ across the doors and a flow rate of $Q_2$ and assume that the point $P_2$, $Q_2$ was a point on the resistance characteristic of the circuit.

The points $P_1$, $Q_1$; $P_2$, $Q_2$ and $P_3$, $Q_3$ are in fact points on the

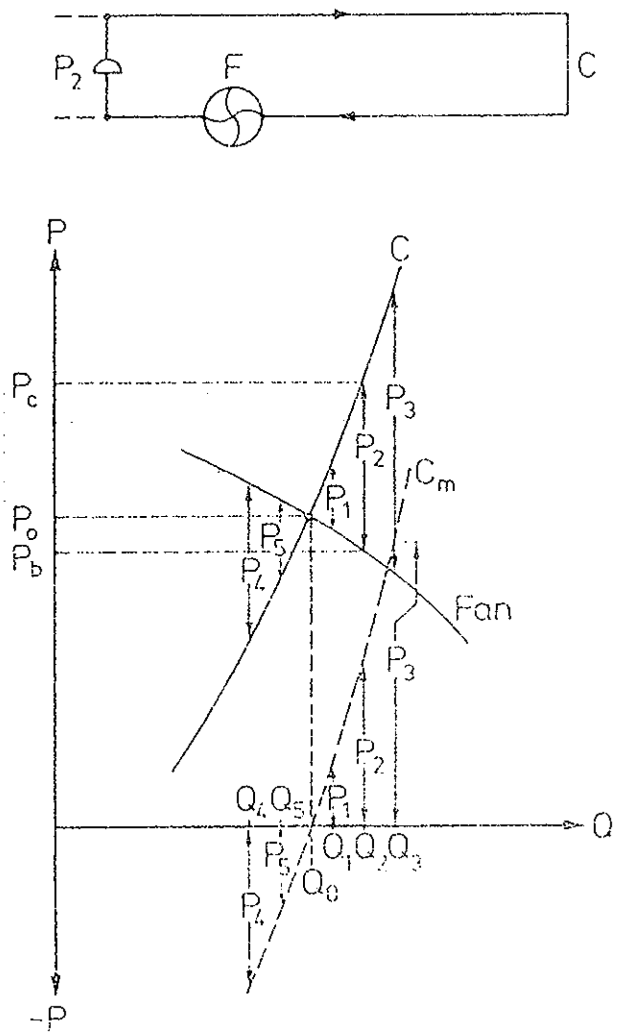



Figure 4.5 Modified Resistance Characteristic.

modified characteristic $C_m$, which has been drawn through them. At a flow rate $Q_o$, the fan develops a pressure $P_o$ and the pressure drop in the circuit is $P_o$, so that there is no pressure difference across the separation doors.

At flow rates less than $P_o$, such as $Q_4$ and $Q_5$, the pressure differences $P_4$ and $P_5$ are negative and the curve $C_m$ extends into the negative pressure zone. Flow in the circuit would be in the normal direction but leakage through the doors would be reversed.

In the graphical construction for a complete network, the modified curve $C_m$ replaces both the fan curve and the true resistance curve for the circuit.

Figure 4.6 illustrates the analysis for the network, including a booster fan with the point 1.75, 40 on its characteristic. In an actual exercise it would not be known in advance that this is the operating point, because the object of the analysis is to determine that point and the effects of the fan on the distribution in other parts of the network.

The reason for choosing this particular fan characteristic is to confirm by the analysis, which should provide the same answers as the previous example, that the theory of combining the fan curve and resistance curve is sound.

The construction and analysis are done as before, but the modified

$C_{3m}$ curve $C_{3m}$ must first be constructed and the curve $C_3$ and the fan curve are thereafter ignored. Neglecting the minor differences from the

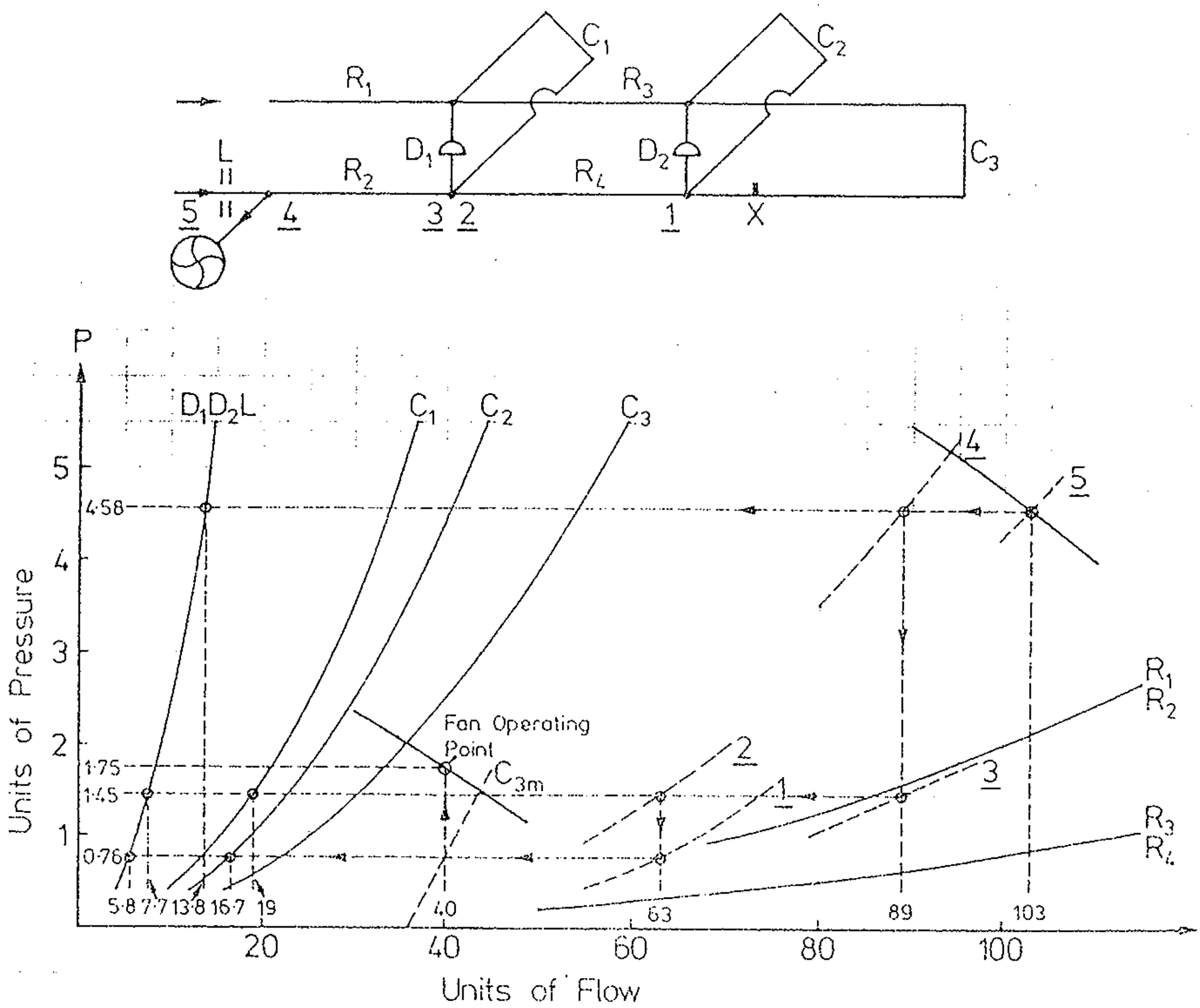



Figure 4.6 Booster Fan at X (2).

previous solution, the theory of the modified resistance characteristic is confirmed.

Referring again to figure 4.6, the final stage of the exercise is to locate the operating point of the fan. This is done by moving from the 0.76 pressure line intersecting the modified curve, to the fan characteristic, indicating that the fan operates at 1.75 units of pressure and a flow rate of 40 units.

## Natural ventilating pressure and air expansion

The effect of heat addition to the air in its passage through the mine is to lower its density. In a deep mine, the density difference between the air in the downcast and upcast shafts creates a pressure difference which is equivalent to introducing a booster fan in the return (upcast) shaft.

If this natural ventilating pressure is assumed to be constant, it can be introduced as a fan with a flat characteristic, as shown in figure 4.7, where the NVP is taken to be 0.3 pressure units. The fan then modifies characteristic 4 to 4n by dropping 0.3 units from 4.

A further influence in deep mines is air expansion. An approximate compression/expansion rate is one percent per hundred metres of depth. If the shafts are a thousand metres deep, the rate of flow at the fan is ten percent greater than in the mine.

In the example figure 4.7 the shafts are assumed to be at that depth, and the curve 4n shifts because of expansion by ten percent of the flow rate to 4e, to which the airlock resistance is added in parallel to produce characteristic 5, against which the fan operates.

The reason for the curve shift is, in effect, a recalculation of the mine resistance at the surface air density. The fan passes air at that density and so it is to that resistance curve that the fan characteristic is properly applied.

If the effect of NVP is ignored there is slight underestimation of the flow which the fan will create, but if expansion is ignored there will be overestimation.

In this particular example the effect of an increase because of the NVP is more than offset by compression. In the example figure 3.3, in which neither NVP nor expansion were allowed for, the fan passed 100 units, of which 86 units flowed in the underground workings. In figure 4.7 the fan passes 106.5 units, but the flow of 93 units into the downcast shaft is compressed to 84.5 units at the shaft bottom.

In general, where underground mines are of high resistance and require high fan pressures, the effect of NVP is small relative to the fan pressure and can be ignored. If the mine is deep, expansion must be allowed for to ensure that the fan duty is not seriously underestimated.

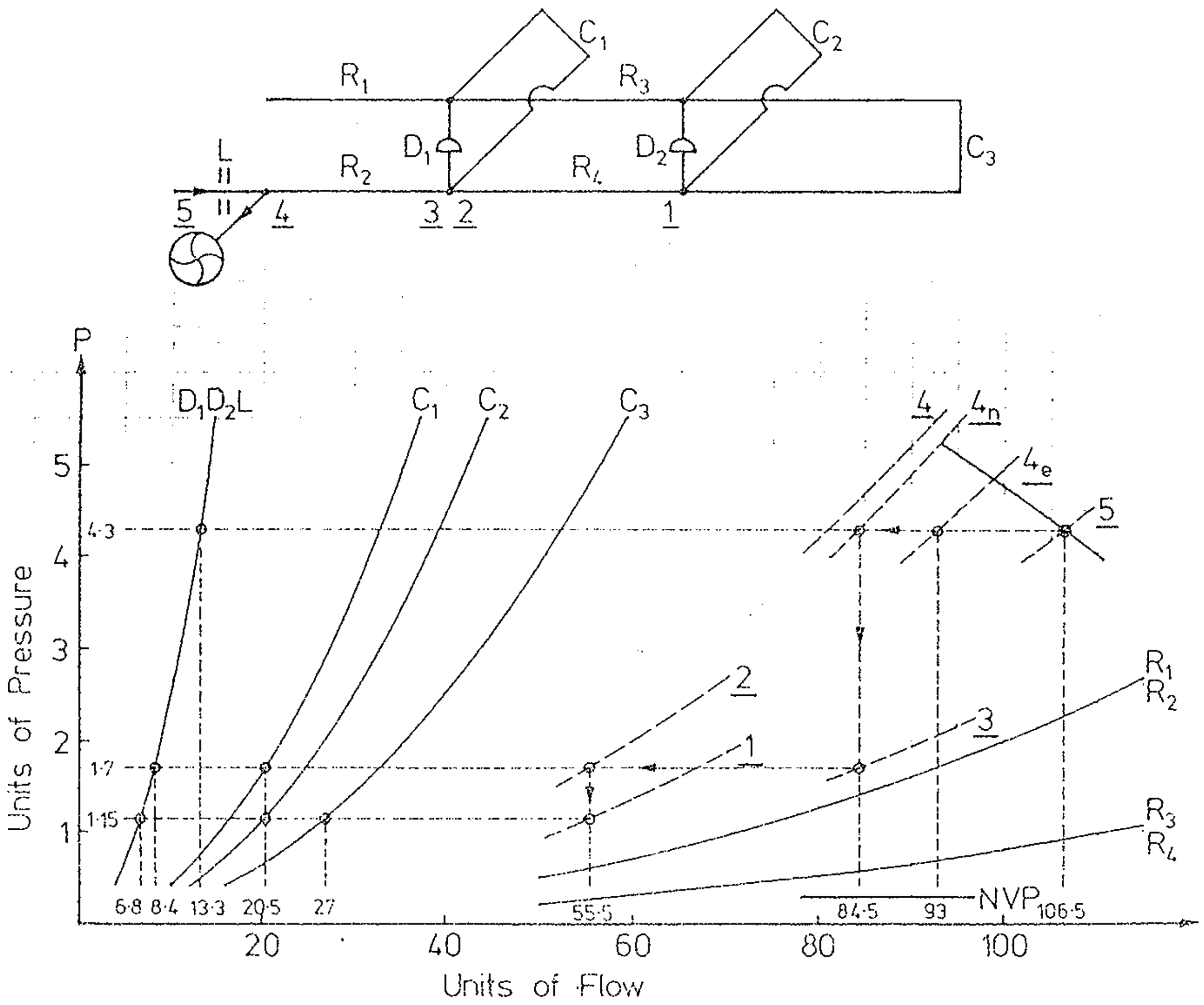



Figure 4.7 Effect of Natural Ventilating Pressure and Expansion.

# CHAPTER 5

## Further graphical analysis

### Actual mine network

The line diagram in figure 5.1 is of a working coal mine in which the remaining reserves are remote from the shafts. On cessation of production in circuits $C_1$ and $C_2$, a new production unit $W_2$ was to be developed and the air flow in $C_1$ and $C_2$ restricted.

By estimating resistances for $W_2$ and the restricted circuits, analysis by digital computer indicated that the total air flow into $W_1$ and $W_2$ would be about 50 $m^3/s$.

Using the same basic information on resistances and the fan characteristic as is required for computer analysis, the network was analysed graphically.

Referring to the diagram, the airlock resistances $L_1$ and $L_2$ are shown in a slightly different manner from that in the networks in the preceding chapter. The resistance $R_1$ is the fan drift at the surface, $L_1$ is the leakage resistance of the fan drift access and $L_2$ the resistance of the mine shaft airlock. Both $L_1$ and $L_2$ are in parallel with the underground network. The resistance $R_2$ is the combined resistance of the shafts, whilst $R_3$, $R_4$ and $R_5$ are the combined resistances of the adjacent lengths of intake and return airways between junctions.

The graphical construction is no different from that of earlier examples. The first step is to label the diagram to indicate the sequence and to provide a ready means of identifying the derived curves. There will be ten of the latter:

1. The parallel group $D_4$, $D_5$, $W_1$ and $W_2$

2. The airways $R_5$ in series with 1

3. $D_2$, $D_3$ and $C_2$in parallel with 2

4. The airways $R_4$ in series with 3

5. $C_1$ in parallel with 4

6. The airways $R_3$ in series with 5

7. Doors $D_1$ in parallel with 6

8. The mine shafts $R_2$ in series with 7, representing the resistance of the underground network.

9. The airlocks $L_1$ and $L_2$ in parallel with 8

10. The fan drift $R_1$ in series with 9, to give the resistance characteristic of the system.

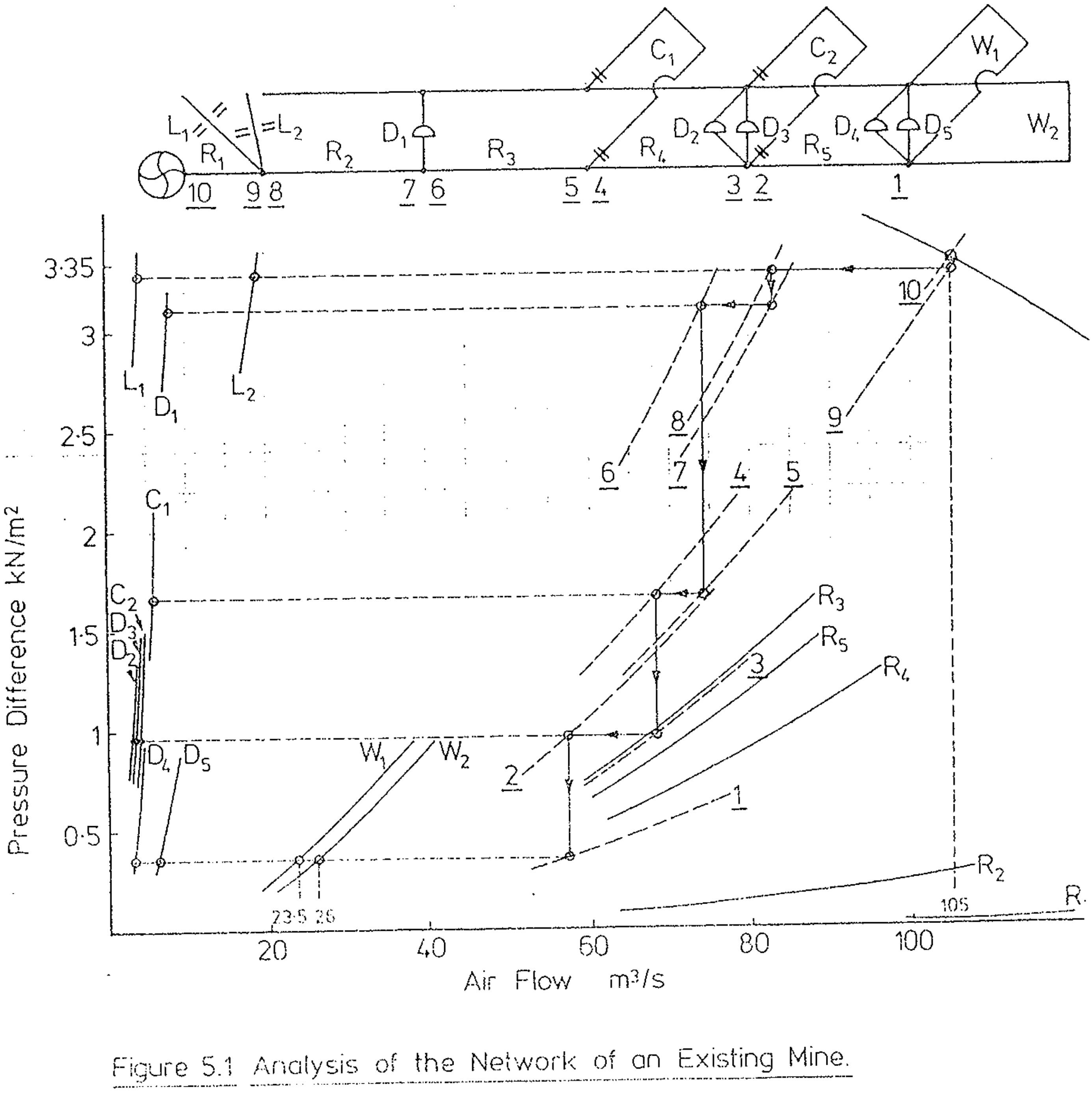



Figure 5.1 Analysis of the Network of an Existing Mine.

Following this sequence of construction, the operating point of the fan is determined as 3.35 $kN/m^2$ and 105 $m^3/s$. Tracing back through the derived curves illustrates that the air flows in $W_1$ and $W_2$ would be 23.5 $m^3/s$ and 26 $m^3/s$ respectively.

The results agree with those calculated by the computer.

Network with booster fan

An air flow of 50 $m^3/s$ did not approach the planned requirement of 70 $m^3/s$, and since the exercise had already included restriction in circuits $C_1$ and $C_2$, further modification had to be made.

A proposal for a booster fan installation was tested by computer analysis and found capable of meeting requirements. The arrangement is shown in the line diagram in figure 5.2, with the fan combination located in a short length of trunk airway of negligible resistance beyond the doors $D_2$.

For graphical analysis, introduction of the booster fan necessitates twelve derived curves instead of ten. Referring to the diagram, curve 3 is that of the parallel arrangement of 2, $D_3$ and $C_2$, and curve 4 is the combination of 3 and the booster fan. The principles of construction of the combination have already been described in detail and need not be repeated.

A new feature of the present exercise is that it identifies reversal of air flow through the doors $D_2$. Before commencing construction of the derived curves, an experienced technician, after plotting the booster fan characteristic, would notice that it would be likely to develop a high pressure.

Because the fan is to be installed in a remote part of the mine, where pressure differences are low, this would lead him to suspect the possibility of reversal by the booster fan, especially through the adjacent doors in $D_2$. For that reason, he would extend the basic curve of $D_2$ into the negative pressure and flow quadrant of the graph.

When the derived curve 4 is constructed, it is also extended into negative pressure and curve 5, which is the parallel combination of 4 and $D_2$, is similarly treated.

It is important to recognise that curves are derived by algebraic addition. For $D_2$ in the negative flow quadrant, the indicated flows are deducted from 4, so that 5 falls to the left of 4 here and crosses over the axis. The same applies to the derivation of 6 in relation to the addition of pressures of $R_4$ and the negative element of 5.

Continuation of construction to the intersection of the total system characteristic with the fan characteristic indicates that the operating point would be 2.9 $kN/m^2$ and 123.7 $m^3/s$, which is an increase of 18.7 $m^3/s$ over the system without the booster fan.

Analysis of flow is as before, by retracing the construction sequence. From 6 to 5, which represents the pressure drop in the

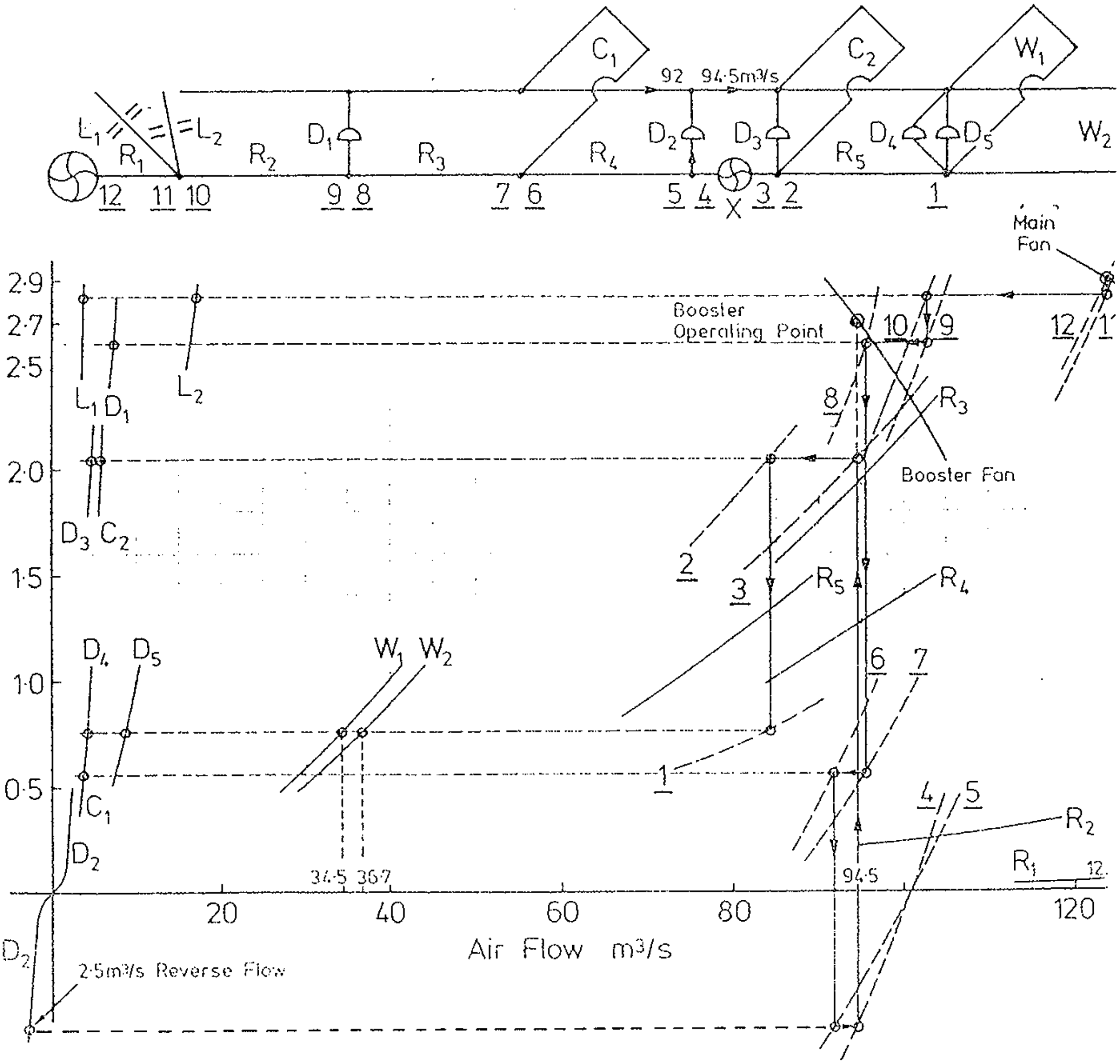



Figure 5.2 Analysis of a Network with a Booster Fan at X.

trunk airways $R_4$, the pressure difference becomes negative, illustrating that reversal of flow would take place across connections between intake and return. The doors $D_2$ are a connection and there would be recirculation of 2.5 $m^3/s$. The flow pattern is shown on the line diagram, with 92 $m^3/s$ in the $R_4$ intake flowing towards the $D_2$ junction and 94.5 $m^3/s$ away from it.

The booster fan would develop a pressure of 2.7 $kN/m^2$ and pass 94.5 $m^3/s$. Finally, the air flows into $W_1$ and $W_2$ would be 34.5 $m^3/s$ and 36.7 $m^3/s$.

The entire analysis again agreed with that of the computer.

An exercise of this type need not be confined to a single variation. For example, if it had been wished to restrict flow in $W_1$ to 30 $m^3/s$ by a regulator, a pressure ordinate would have been drawn through that value to replace the curve of $W_1$ for the purposes of analysis. The analysis itself would have shown an increase in flow in $W_2$ and the pressure drop across the regulator, the area of which could then have been calculated.

Pressure diagrams

Graphical analysis can be used to produce scaled pressure diagrams as quantitative confirmation of the qualitative deduction of diagrams in chapter one.

The diagrams in figure 5.3 are drawn from the information provided by the analyses in figures 5.1 and 5.2.

For the original network (figure 5.1), the end point of the diagram is 3.35 kN/m$^2$, which is the fan pressure.

From 12 to 11 on the graph is the pressure drop in the shafts. Half of this is taken to be in the downcast and half in the upcast. The diagram can be started from both ends at slopes representing half of the pressure drop. The process is repeated for 10 to 9, which is the pressure drop in $R_3$, and so on, until the slopes meet at zero pressure differences at he extreme of $W_2$.

The same exercise is carried out on the booster fan graphs (figure 5.2), for which the end point is 2.9 kN/m$^2$. After stage 6 to 5, which is the drop in $R_4$, there is a vertical drop of 2.7 kN/m$^2$ representing the booster fan pressure, before closure in $W_2$.

Interpretation of the effect of the booster fan is by inspection of the slopes and the pressure differences between intake and return. The increase in slope throughout is indicative of increased flow in the trunk airways and in $W_2$; the lower pressure differences between intake and return up to the booster fan position are interpreted as reduced leakages in the fan drift and through doors, and reduced flow in circuit $C_1$; the higher differences beyond it indicate increased leakage at the doors and greater flow into $C_2$ and $W_1$; the reversed difference illustrates that recirculation takes place through the doors at $D_2$.

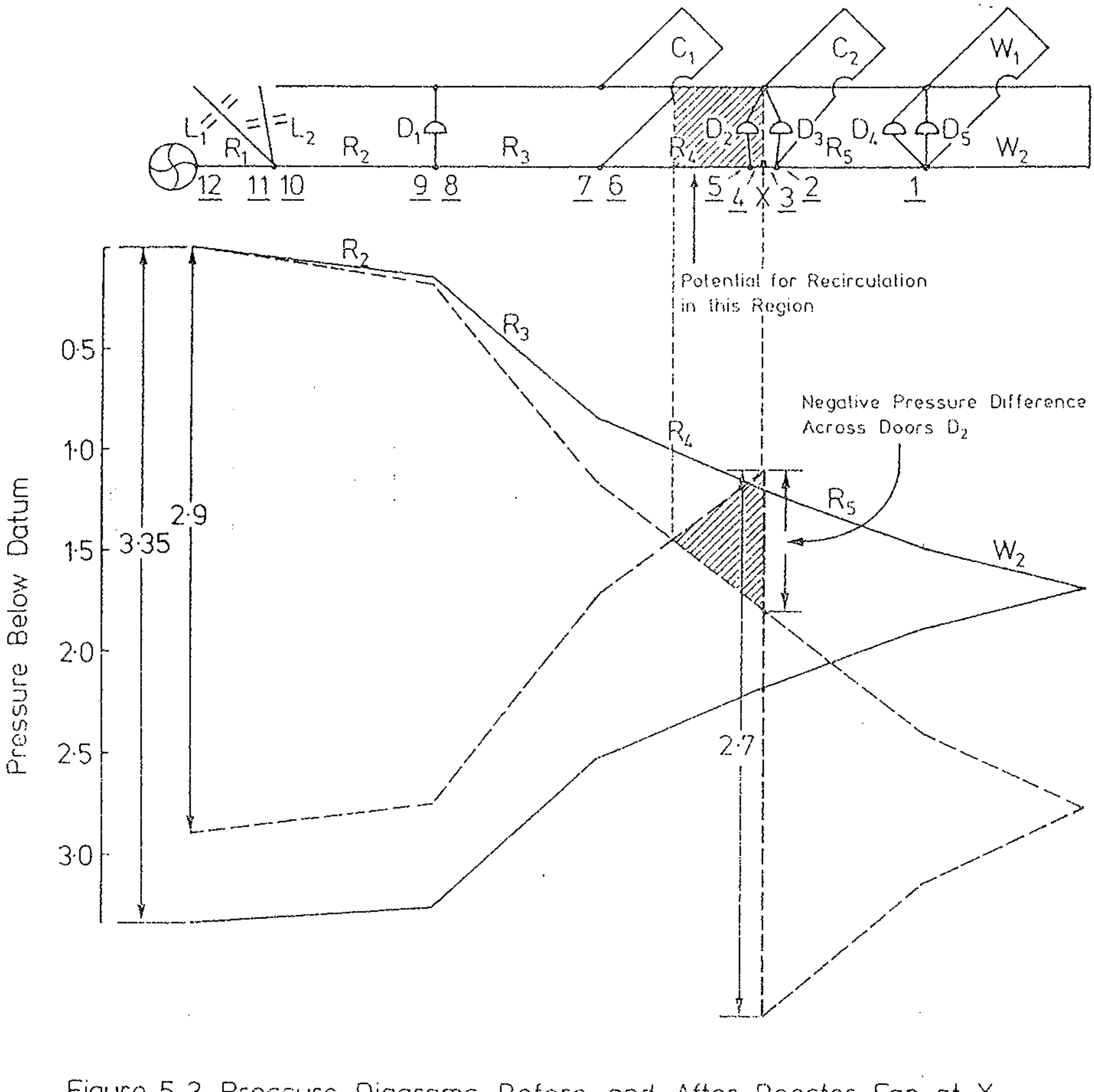



Figure 5.3 Pressure Diagrams Before and After Booster Fan at X.

Another aspect of the diagram is that it reveals the zone in the airways $R_4$ where recirculation would take place through unidentified leakage paths. This information is not obtainable directly from the graphical analysis, but can be deduced by inspection of the pressure drop in $R_4$.

Referring back to figure 5.2, the pressure drop in $R_4$ is from the derived curve 6 to 5 and passes into the negative difference region roughly half way on the ordinate. Assuming a uniform pressure drop, the interpretation is that approximately half the length of $R_4$ would be in the reversed pressure zone.

Planned recirculation (1)

In the case under consideration, provision of a forty percent increase in airflow, from 50 $m^3/s$ to 70 $m^3/s$, requires a multiple series/parallel fan combination almost as powerful as the surface fan.

If the reason for augmenting the supply of air is excessive heat, moisture, or dust, rather than contamination by gas emission or blasting fumes, an alternative solution is to recycle a proportion of the air through air conditioning or dust extraction plant.

The technique is illustrated and analysed in figure 5.4. The recycling fan and ancillary plant are sited in the connection $D_2$. With the doors removed, the roadway has an estimated resistance of $R_f$. A fan used in this way acts in opposition to the main fan and would reduce air flow into the mine. For that reason, if an increase of

20 $m^3/s$ is required in the working districts it is necessary to recycle a greater amount, say 30 $m^3/s$.

The exercise begins with the erection of the ordinate B at 30 $m^3/s$ in the negative flow quadrant. The ordinate is the unreal modified combination characteristic of a booster fan, as yet of unknown duty, and the roadway resistance $R_f$. An unreal characteristic as an enabling device for graphical construction was explained in chapter four.

Other than to comment on the derivation of curve 3, it is unnecessary to describe the construction. The curve is the parallel grouping of 2, the modified characteristic B, doors $D_3$ and circuit $C_2$. It falls to the left of 2 because of the constant negative contribution of B.

Intersection of the total system characteristic with that of the fan is at 3.48 $kN/m^2$ and 98 $m^3/s$. Comparing that operating point with 3.35 $kN/m^2$ and 105 $m^3/s$ of the original network (figure 5.1) demonstrates that the recycling fan is opposing the main fan and equivalent to increasing the resistance of the mine.

From the analysis, the fresh air flow in the $R_4$ intake airway is 59 $m^3/s$, which is supplemented by 30 $m^3/s$ of recycled and conditioned air. Of the mixed flow, 10 $m^3/s$ flows through doors and circuit $C_2$ in the normal direction and 79 $m^3/s$ towards $W_1$ and $W_2$. With leakage of 12.5 $m^3/s$ through $D_4$ and $D_5$, 66.5 $m^3/s$ flows into the production districts.

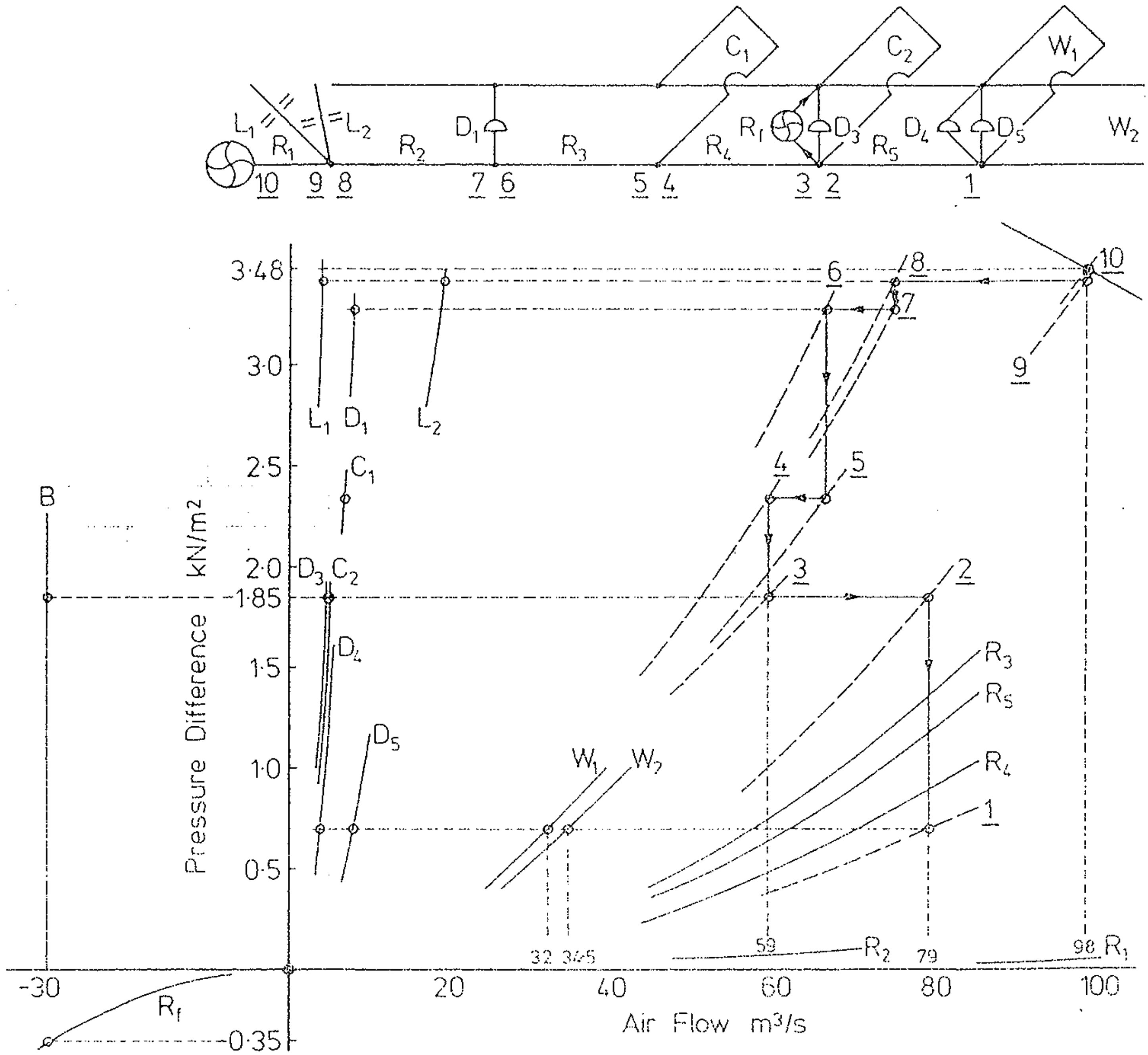



Figure 5.4 Analysis of a Network with Recirculatory Fan in $R_f$ (1)

Still considering the analysis in figure 5.3, the pressure difference across the junction at 3 is 1.85 kN/m$^2$ and is positive. At 30 m$^3$/s, the pressure drop in the recycling airway $R_f$ is 0.35 m$^3$/s, so that the recirculating fan must operate at 2.2 kN/m$^2$ and 30 m$^3$/s. If that fan has also to overcome the resistance offered by conditioning or dust extraction plant it would need to develop greater pressure.

It is obvious that the fan combination is much simpler and less powerful than the booster fan complex. For the latter, bypass arrangements, possibly involving the excavation of a roadway around the fan, may be necessary to maintain a sufficient supply of air when the fan is stopped. With the recycling fan stopped, flow would revert to normal without special arrangements.

Planned recirculation (2)

Recycling can be investigated graphically for a fan of known characteristics, rather than on the basis of a predetermined reciculation rate.

In figure 5.5, the characteristic of a recirculatory fan is shown in the negative pressure/flow quadrant of the graph, as is the characteristic $R_f$ of the roadway in which it operates. Combining these produces the derived characteristic $R_b$, which is required for the construction. The principles of combination have been described elsewhere. Analysis shows that the main fan operates at 3.5 kN/m$^2$ and 97 m$^3$/s, with flows into $W_1$ and $W_2$ of 32.5 m$^3$/s and 35 m$^3$/s. The recycling fan operating point is 2.35 kN/m$^2$ and 32.5 m$^3$/s.

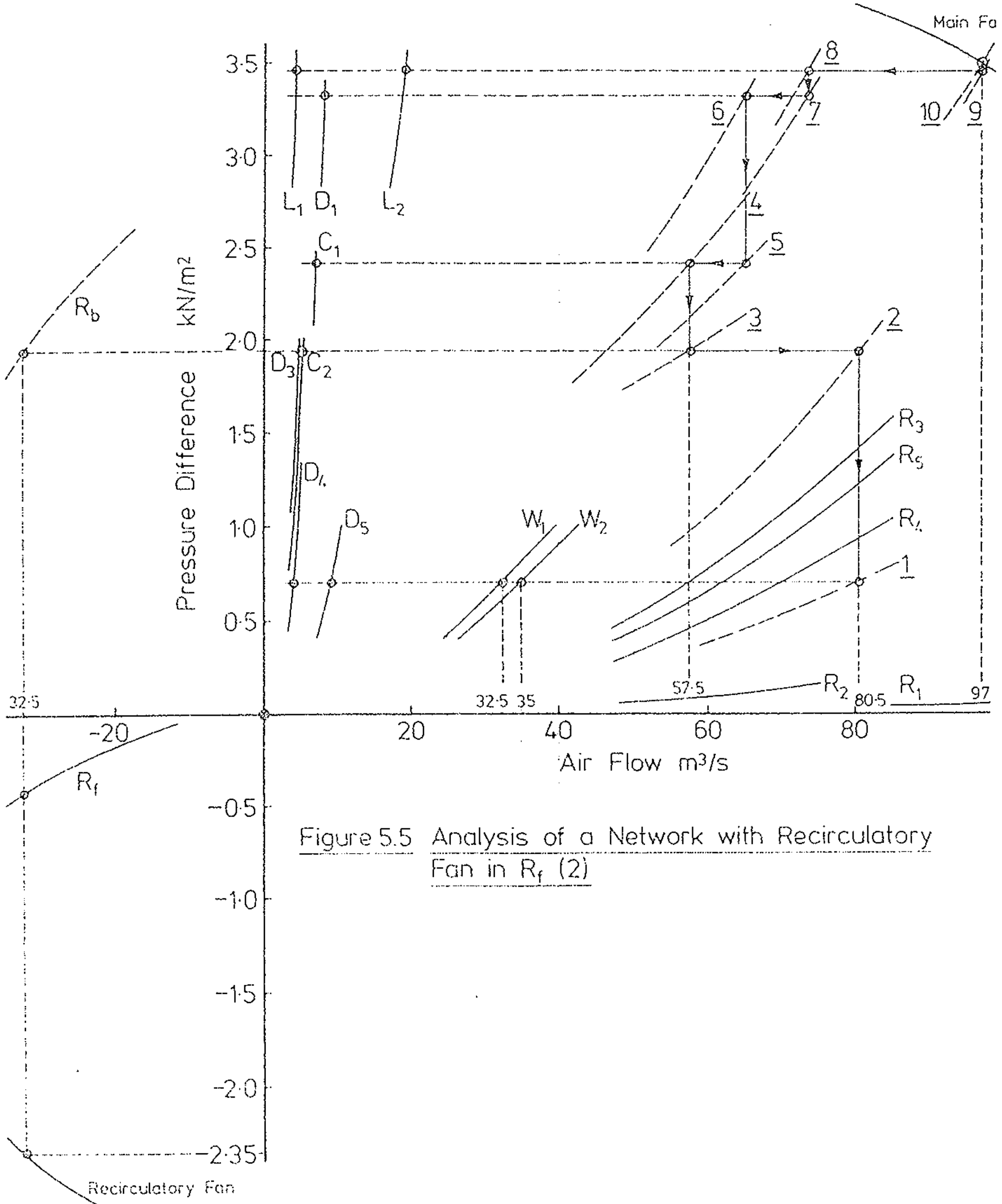



Figure 5.5 Analysis of a Network with Recirculatory Fan in $R_f$ (2)

## Extensive networks

For extensive networks, construction and analysis can be greatly simplified by limiting the detail to the part in which changes are to be made.

Figure 5.6 is a line diagram of a network in which modifications are proposed in part C, but not in A or B.

Before the change, or changes, the pressure differences across each part, and the air flows in them, are known. From that information, single characteristics for both A and B can be drawn without the need to complicate the graph with the detail within them. Construction is then on a scale similar to the earlier exercises in this chapter, and requiring ten derived curves.

Suppose that a proposed modification in C would result in a decrease in airflow into A from 60 $m^3/s$ to 40 $m^3/s$. Because no physical alterations have taken place within A, distribution in its circuits is affected proportionately and can be calculated easily if required. This applies equally to part B.

Nor is it always necessary to include detail in the modified part. If, as is shown in figure 5.6, the change proposed is a booster fan at X in part C, all circuits within it would be proportionately affected and so C could also be represented by a single characteristic, leading to even fewer derived curves.

An essential condition for detailed graphical construction is that airways must be wholly in series or wholly in parallel with each other. If they are not, graphical combination is impossible. In figure 5.6, the broken double line between circuits in part A is an airway illustrating an arrangement which has no graphical solution. In such circumstances, part A cannot be analysed in detail and must be treated as a unit represented by the single curve already referred to.

## Applying the method

Provided the principles outlined have been understood, there is no reason why the ventilation technician should not take tentative steps towards putting the method into practice at a mine with which he is familiar. Ideally, the initial exercises should be on problems to which the answers are known.

The first stage is to prepare a line diagram, its key feature being simplicity. It need not bear any physical resemblance to the network other than as a true representation of its paths in rectangular pattern, suitably labelled for identification. Preparation of the diagram is a useful exercise in itself.

From the known pressure differences and airflows, or from measurements to obtain them, the resistances of the airways and circuits can be calculated and the basic characteristics plotted on a master graph sheet, together with the characteristic of the main fan. It has already been said that the scale should be as large as possible.

With regard to separation doors, it is normally sufficient to have a single resistance characteristic for all which are in settled ground. In the examples in this chapter the errors in the analyses would have been small if one characteristic had been used for the doors $D_1$, $D_2$, $D_3$ and $D_4$.

Where doors are in unsettled localities, they are frequently less effective seals than those in stable zones and would require a different resistance curve.

A prerequisite of successful and satisfying execution is accurate and rapid construction. The intending practitioner is strongly advised to spend time acquiring skill, with dividers and rigid or flexible curves, in producing derived characteristics. Until he has done so the construction is laborious and the results imperfect and frustrating.

# PART THREE

TUNNELLING: Graphical presentation and the design and monitoring of ducted air flow systems.

# CHAPTER 6

## The Analysis of air flow in leaky ducts

The one thing which all auxiliary ventilation duct installations in mines have in common is that they leak.

In the worst cases, less than ten percent of the air passed by the fan reaches the face of the tunnel or heading; in the best, fifty percent may leak.

For effective planning of installations, leakage is the prime consideration, and it must be quantified in an operation in which it changes from week to week as the duct is extended.

The problem is quite different from that of mine networks. By comparison, these have a permanence affected only by infrequent and deliberate actions planned months in advance.

Many years ago, the National Coal Board in Britain (now British Coal Corporation) introduced the concept of a "leakage coefficient" for the design of auxiliary ventilation systems. The coefficient was defined as the leakage which takes place from one hundred feet of ducting at a uniform pressure difference of one inch of water gauge across the duct wall.

To plan an installation, a value for the coefficient was estimated, based on the quality and type of ducting and from experience of the installation standard which might be achieved. The coefficient selected was then used with graphs, in an exercise to assess the fan duty for the desired flow rate at the face of the excavation.

The technique was limited to low leakage rates, and did little to assist the technician in his understanding of auxiliary systems.

About 1980, the writer realised that a rigorous mathematical analysis was possible if leakage is seen to be from discrete flow paths, in parallel with an otherwise leakless duct. The treatment simulates an installation in which the leakage is from the duct joints.

In this chapter the general mathematical analysis is given and presented in graphical form for a particular case. The purpose of the graphs is to show and interpret the trends of change in resistance and leakage as the duct extends. Fan requirements are examined and the effects of spacing the fans in the duct are considered.

General analysis

A duct which leaks at its joints is a true series/parallel network. The stages of analysis to determine the resistance of the network are illustrated in figure 6.1 and explained below.

The same ducting is used throughout and each section has a leakless resistance $R_d$. All joints are equally effective or ineffective and have a leakage resistance $R_l$. The overall resistance of the leaky duct is to be computed.

At the free end of the duct, the first leakless section is in parallel with the first leakage path. Their combined resistance $R_1$ is given by

$$\frac{1}{\sqrt{R_1}} = \frac{1}{\sqrt{R_d}} + \frac{1}{\sqrt{R_l}} \quad \text{and } R_1 = \frac{R_d R_l}{(\sqrt{R_d}+\sqrt{R_l})^2}$$

As can be seen in the figure, $R_1$ is in series with the second leakless section and the combined resistance is $(R_d+R_1)$. which is in parallel with the second leakage path. That combination has a resistance $R_2$, where

$$\frac{1}{\sqrt{R_2}} = \frac{1}{\sqrt{(R_d+R_1)}} + \frac{1}{\sqrt{R_l}} \quad \text{and } R_2 = \frac{(R_d+R_1)\ R_l}{\left[\sqrt{(R_d+R_1)}+\sqrt{R_l}\right]^2}$$

The procedure is repeated for successive sections. Where there are n sections the overall resistance against which the fan acts is $R_n$, and

$$R_n = \frac{(R_d+R_{n-1})R_l}{\left[\sqrt{(R_d+R_{n-1})}+\sqrt{R_l}\right]^2}$$

Figure 6.2 indicates the stages of the analysis of airflow. The rate at which air is discharged (or enters in the case of an exhaust

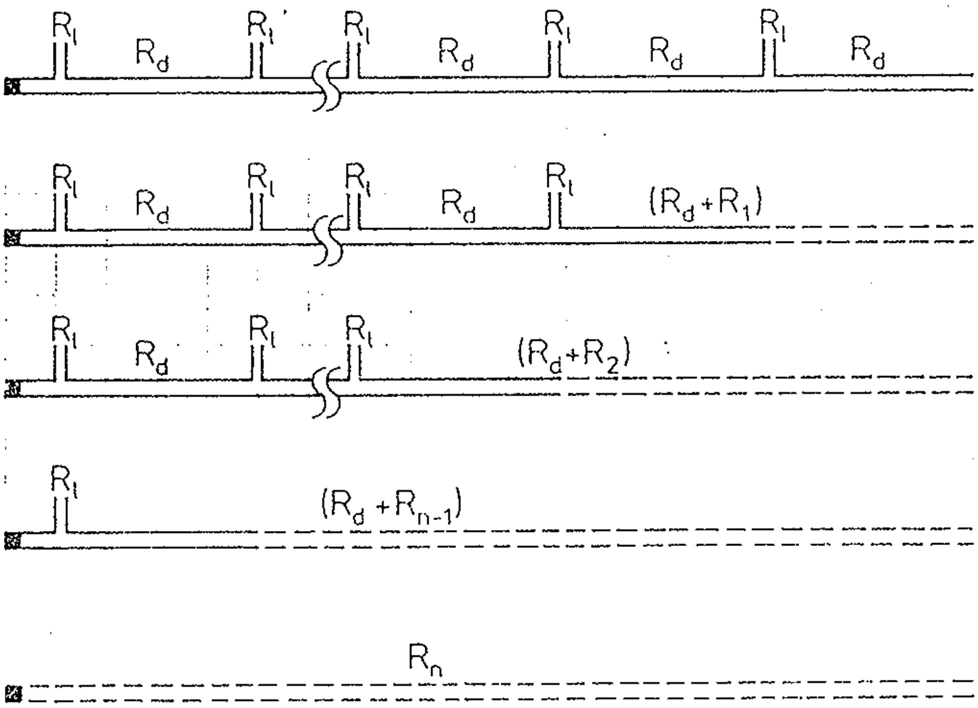



Figure 6.1 Analysis of Resistance of a Leaky Duct

system) from the free end of the duct is $Q_o$.

Air flows in parallel airways are inversely proportional to the square roots of the relevant resistances. At the open end the resistances are $R_d$ and $R_l$. The flow in $R_d$ is $Q_o$ and the leakage flow can be expressed in terms of $Q_o$, $R_d$ and $R_l$. If the combined flow is $Q_1$ then

$$Q_1 = Q_o + Q_o\sqrt{\frac{R_d}{R_l}} \qquad = Q_o\left(1+\sqrt{\frac{R_d}{R_l}}\right)$$

The second leakage path, also of resistance $R_l$, is in parallel with the resistance $(R_d+R_1)$, and the combined flow $Q_2$ is

$$Q_2 = Q_1\left(1+\sqrt{\frac{R_d+R_1}{R_l}}\right)$$

Continuing through the system, total flow $Q_n$ at the fan is

$$Q_n = Q_{n-1}\left(1+\sqrt{\frac{R_d+R_{n-1}}{R_l}}\right)$$

The assumption in the above is that the pressure drop in the tunnel is not significant. For example, $R_{n-1}$ and $R_l$ are considered to discharge to the same pressure.

// Finally, the fan pressure $P_f$ necessary to deliver air at the rate $Q_o$ from the end of the duct is

$$P_f = R_n Q_n^2$$

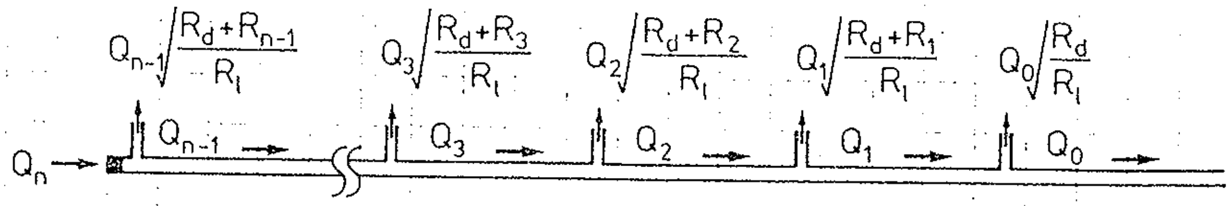



Figure 6.2 Analysis of Flow in a Leaky Duct.

Calculations of $R_n$ and $Q_n$ for a particular installation are easily done by programmable calculator or, with a little patience, on one of a simpler type.

Particular analysis

For a long duct and graphical presentation of the results, it is not necessary to break the system down into short lengths. By considering an installation of several long leakless sections and the same number of leakage paths, the application of the method can be demonstrated.

National Coal Board leakage coefficients are useful indicators of the broad limits of good and bad standards, and are suitable for establishing realistic leakage resistances. By pure coincidence, they also convert from Imperial to almost the same numerical value in SI units, when expressed as leakage in litres per second from one hundred metres of duct under a uniform pressure difference of one hundred newtons per square metre across the duct wall.

The numerical values which have been used for planning range from about 50 for an installation of a high standard to 250 for poor, when applied to a 600 mm diameter duct (coefficient selection is influenced by duct diameter. For a very small diameter a coefficient of 50 would not be a good standard).

Coefficients can easily be converted to resistances. Taking the value 100, 0.1 $m^3/s$ leaks from 100 metres of duct at a pressure of 100 $N/m^2$. If the leakage is from a single path, its resistance $R_l$ is obtained from

$$100 \ (N/m^2) = R_L \times 0.1^2$$

and $$R_L = 10\ 000 \text{ gaul.}$$

The term "gaul" has been adopted for the SI unit of resistance in British mining.

The installation to be examined is of a system of length 600 metres and a leakless resistance of 16 gaul per 100 metres. The resistances of leakage paths at 100 metre intervals are 10 000 gaul and the fan duty for a delivery flow of 3 $m^3/s$ is to be calculated.

Referring to the general analysis and figure 6.1, the stages in determination of the overall resistance of the system are

$$\frac{1}{\sqrt{R_1}} = \frac{1}{\sqrt{16}} + \frac{1}{\sqrt{10\ 000}} \qquad R_1 = 14.79$$

$$\frac{1}{\sqrt{R_2}} = \frac{1}{\sqrt{(16+14.79)}} + \frac{1}{\sqrt{10\ 000}} \qquad R_2 = 27.64$$

$$\frac{1}{\sqrt{R_3}} = \frac{1}{\sqrt{(16+27.64)}} + \frac{1}{\sqrt{10\ 000}} \qquad R_3 = 38.40$$

$$\frac{1}{\sqrt{R_4}} = \frac{1}{\sqrt{(16+38.4)}} + \frac{1}{\sqrt{10\ 000}} \qquad R_4 = 47.18$$

$$\frac{1}{\sqrt{R_5}} = \frac{1}{\sqrt{(16+47.18)}} + \frac{1}{\sqrt{10\ 000}} \qquad R_5 = 54.22$$

$$\frac{1}{\sqrt{R_6}} = \frac{1}{\sqrt{(16+54.22)}} + \frac{1}{\sqrt{10\ 000}} \qquad R_6 = 59.78$$

A reader continuing the exercise to 1000 metres should find that the stage resistances are

64.13 67.50 70.10 72.10

The flow calculations are also as in the general analysis to which figure 6.2 refers.

$$Q_1 = 3\left(1+\sqrt{\frac{16}{10\ 000}}\right) = 3.12 \qquad (1.04)$$

$$Q_2 = 3.12\left(1+\sqrt{\frac{16+14.79}{10\ 000}}\right) = 3.29 \qquad (1.10)$$

$$Q_3 = 3.29\left(1 + \sqrt{\frac{16+27.64}{10\ 000}}\right) = 3.51 \qquad (1.17)$$

$$Q_4 = 3.51\left(1 + \sqrt{\frac{16+38.40}{10\ 000}}\right) = 3.77 \qquad (1.26)$$

$$Q_5 = 3.77\left(1 + \sqrt{\frac{16+47.18}{10\ 000}}\right) = 4.07 \qquad (1.38)$$

$$Q_6 = 4.07\left(1 + \sqrt{\frac{16+54.22}{10\ 000}}\right) = 4.41 \qquad (1.47)$$

If the exercise is continued to 1000 metres the stage values are

4.80 (1.60) 5.24 (1.75) 5.73 (1.91) 6.27 (2.09)

Figures in parenthesis are the ratio of flow in the duct at that point to the delivered flow of $3m^3/s$.

From the calculations, the overall resistance of 600 metres is almost 60 gaul and air flow at the fan is 4.4 $m^3/s$, from which the fan pressure is

$$P_f = 60 \times 4.4^2 = 1162\ N/m^2$$

It should be recognised that the system against which the fan operates includes the tunnel, but the latter's resistance is normally so small relative to that of the duct that it can be ignored. However, within the tunnel there are many surfaces in addition to that of the perimeter (for example, the duct surface) which increase resistance disproportionately, and where the duct is of large diameter relative to tunnel cross-section an allowance in fan pressure may be advisable.

Graphical interpretation

A glance at the numerical values of resistance reveals a dramatic reduction in the rate at which it increases at each stage. With a leakless duct, resistance would increase by regular 16 gaul increments, whereas it is only 2 gaul between 900 and 1000 metres in the leaky installation.

The results are graphed against distance in figure 6.3, and extrapolated to 1300 metres. Inspection of the trend indicates that the overall resistance tends towards an upper limit of about 75 gaul, regardless of length. This deduction is correct and could be confirmed by further calculation.

A direct consequence is that beyond a certain distance, in the example at around 1000 metres, there is no material increase in resistance, and the installed fan will pass air at a constant rate from that point. It will be shown later that the leakier the duct, the shorter is the length at which that happens.

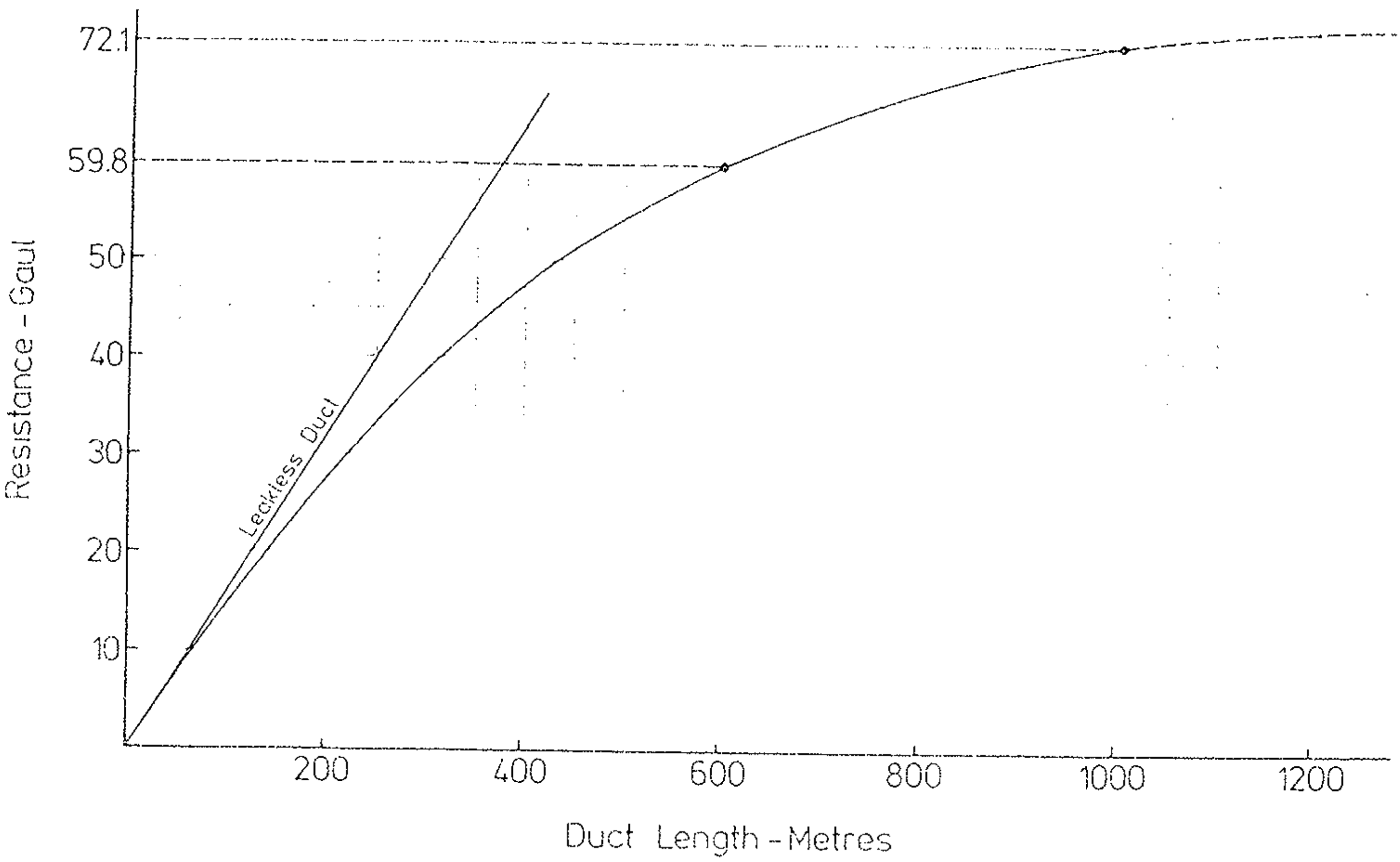



Figure 6.3 Leaky Duct Resistance.

In contrast, the rate of increase in leakage accelerates with length. From the flow calculations, it is 0.12 $m^3/s$ at the first point and 0.54 $m^3/s$ at 1000 metres. The graph in figure 6.4 plots the flow required at the fan to supply 3 $m^3/s$, and on a second scale the ratio of the flow at the fan to the delivered flow.

At 600 metres the ratio is 1.47, so that the fan flow required is 4.4 $m^3/s$, but at 1000 metres it is 2.09 and the fan must pass 6.27 $m^3/s$. By extrapolation to 1300 metres it can be seen that 8.2 $m^3/s$ would be required, the flow ratio being 2.73.

The problem of accelerated leakage rates is compounded by the fact that the installed fan passes air at a reducing rate as resistance increases, until 1000 metres in this case.

From the calculations, a fan developing 1162 $N/m^2$ would pass 4.4 $m^3/s$ at 600 metres, to discharge the planned flow of 3 $m^3/s$. In figure 6.5 the appropriate fan characteristic is drawn, together with the resistance curves for 600 metres (60 gaul) and 1000 metres (72 gaul).

At 1000 metres the flow from the fan has dropped from 4.4 $m^3/s$ to 4.13 $m^3/s$, and the flow ratio is then 2.09 so that delivery is at a rate of 2 $m^3/s$.

To maintain the planned rate, a fan or combination of fans must produce 6.27 $m^3/s$ at 1000 metres. The point is indicated at X on the resistance characteristic.

With two of the original fans in series the operating point is Y, and

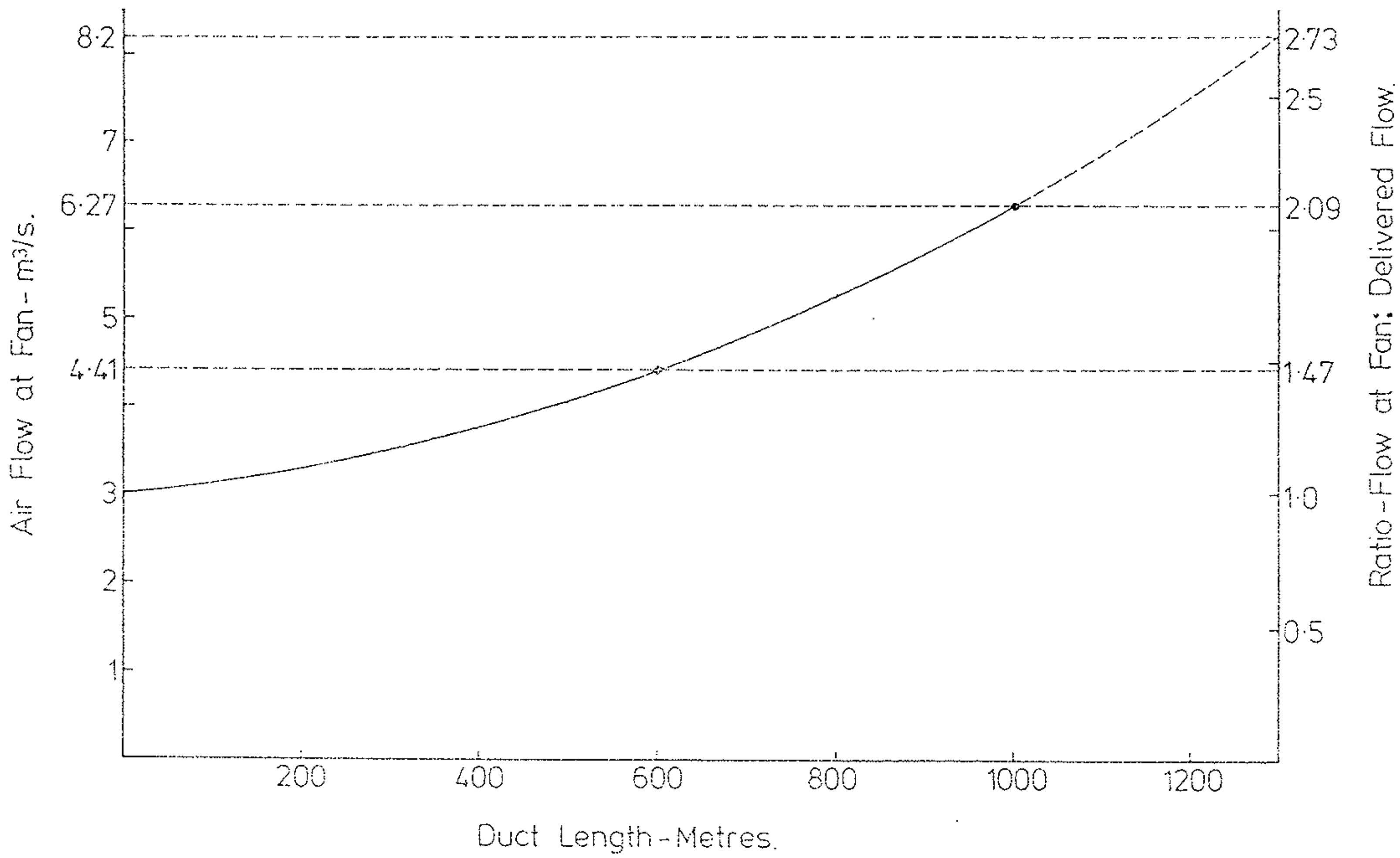



Figure 6.4 Leaky Duct: Fan Flow for $3m^3/s$ Delivered.

the fans would pass 5.25 $m^3/s$ to discharge 2.5 $m^3/s$ at the tunnel face. A combination of four fans in a series/parallel arrangement would operate at Z, close enough to the requirement to be satisfactory.

By an increase in duct diameter the solution is less drastic. It can be shown that the resistance of ducting is, theoretically, inversely proportional to the fifth power of diameter, and this is approximately true in practice. If a 760 mm duct is installed instead of 610 mm there is a threefold reduction of resistance.

The low resistance curve at 1000 metres is shown in figure 6.5 and intersects the single fan curve at 5.85 $m^3/s$, of which 2.8 $m^3/s$ would be delivered at the end of the duct. This seems sufficiently close to be acceptable.

When two fans are in parallel the operating point is 7.25 $m^3/s$, of which 3.47 $m^3/s$ is delivered, exceeding the requirements. Also, since there is no substantial change in resistance after 1000 metres, the fans would operate at a constant 7.25 $m^3/s$. Up to a flow ratio of 2.4 at 1200 metres the combination would deliver 3 $m^3/s$ or more.

The best practice in long tunnels is to install the largest diameter duct that can be reasonably accommodated and conveniently erected. The disadvantage of small diameter is evident from the experience of those concerned with the water supply tunnel cited in chapter one. There, six fans in series were needed for what must ultimately have been a less than satisfactory result, although the contractor had probably no alternative in view of the small diameter of the tunnel.

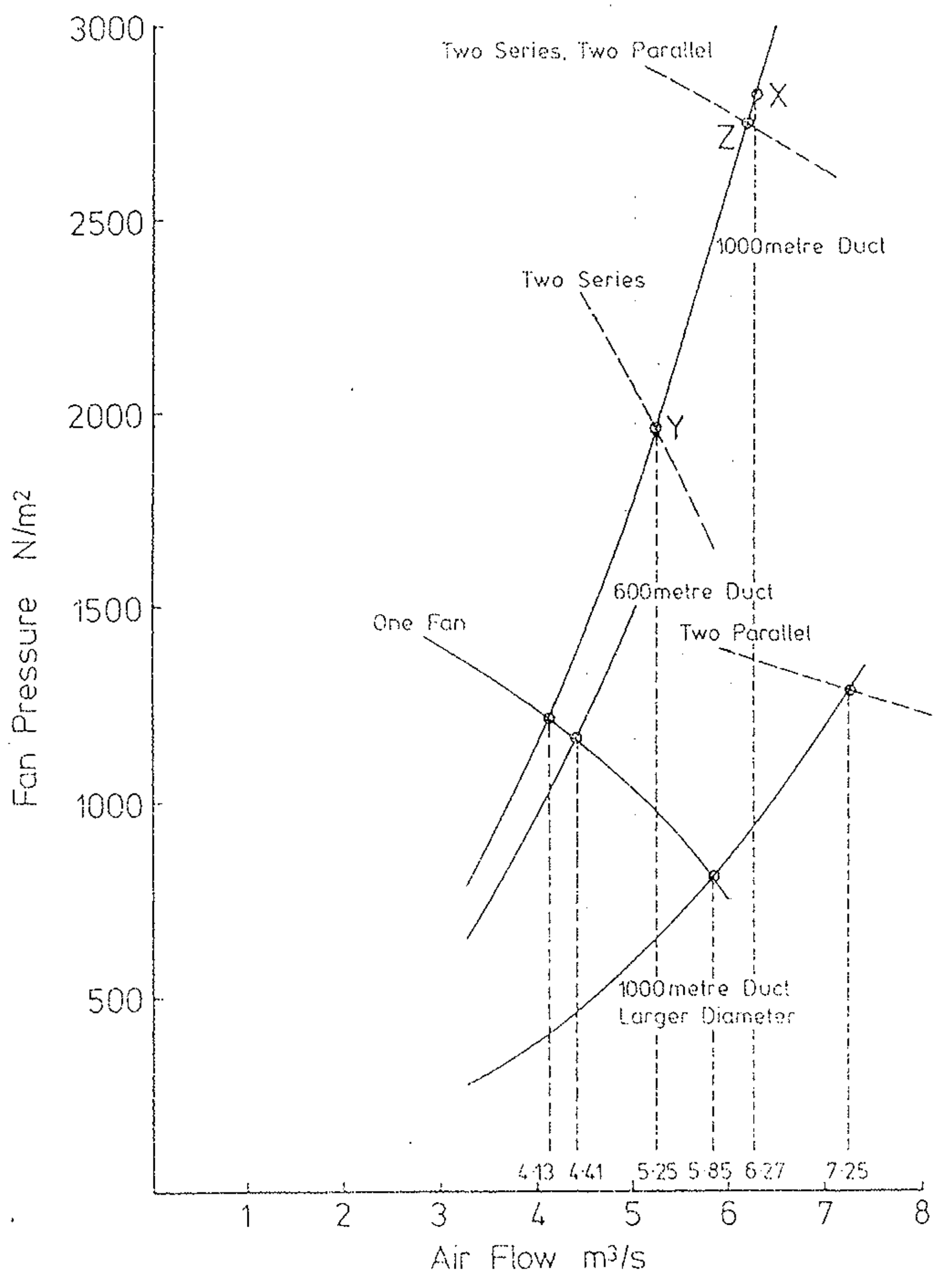



Figure 6.5 Required Fan Duty (X) at 1000metres.

It was only eight feet!

The spacing of fans in series

To minimise leakage, series fans can be located at intervals in the duct instead of grouped. In this way the mean pressure difference across the duct wall is reduced, with a consequent reduction in leakage.

The correct siting of the fans is a complex question and the principles are best explained by first considering pressure diagrams for flow in a leakless duct.

In leakless ducts the flow is constant, with all fans developing the same pressure regardless of position, and the pressure gradient is constant throughout.

Figure 6.6 shows the diagrams for three fans in different locations. All fans develop a pressure P.

In diagram (a) the fans are grouped and the pressure rise on entry is 3P. In (b) they are regularly spaced, with the second and third dividing the duct into equal lengths.

Diagram (c) is for the two fans located irregularly and closer to the first, and in (d) they are nearer to the open end.

Considering (d), the pressure falls below datum, which is the external atmosphere pressure, and in a leaky duct recirculatory

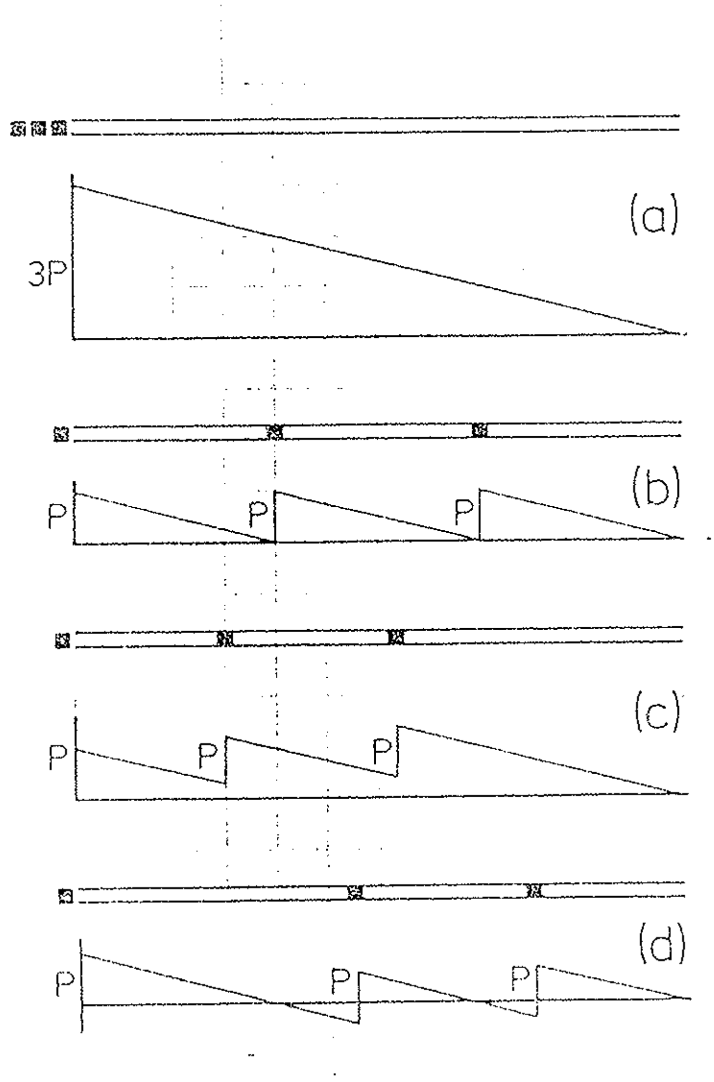



Figure 6.6 Pressure Diagrams for 3 Fans in a Leakless Duct.

leakage would take place.

Comparing (b) and (c), the recirculatory condition is avoided but the mean pressure difference is greater in the latter and so (b), where the spacing is regular, is preferable and is the optimum arrangement.

The criterion for optimum siting is that from the first fan the pressure has fallen to atmospheric at entry to the second, and again to atmospheric at entry to the third (and the fourth etc if there are more than three). The fans are operating as if they were quite independent of each other.

Unfortunately, the optimum siting for fans in leaky ducts is extremely complex and is at an irregular spacing, depending on the characteristics of the fan and the leakiness of the installation. Nor is the spacing a constant ratio for different lengths of installation at the same standard.

In figure 6.7, a fan characteristic is shown with the hypothetical operating points of three fans $F_1$, $F_2$ and $F_3$ which are in the optimum positions in the duct.

The first fan delivers air at the rate $Q_1$, but because of leakage this is reduced to $Q_2$ at entry to the second and to $Q_3$ on entry to the third. Consequently, the second fan develops a higher pressure than the first, and the third a higher pressure still.

Figure 6.8 is of an imaginary pressure diagram which satisfies these conditions. With succeeding fans operating at higher pressure and

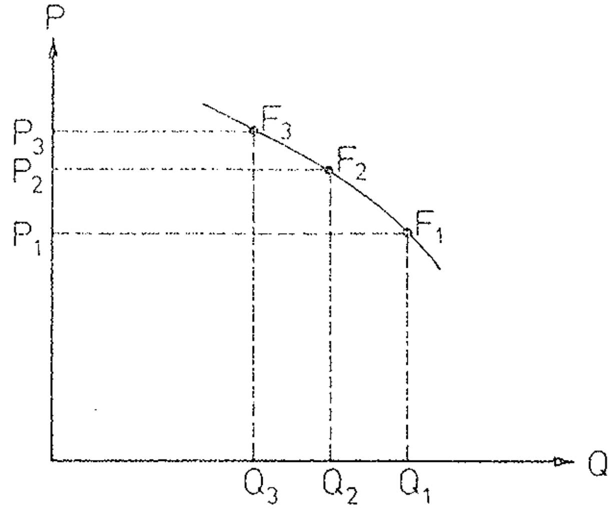



Figure 6.7 Operating Points of Fans in a Leaky Duct at the Optimum Locations.

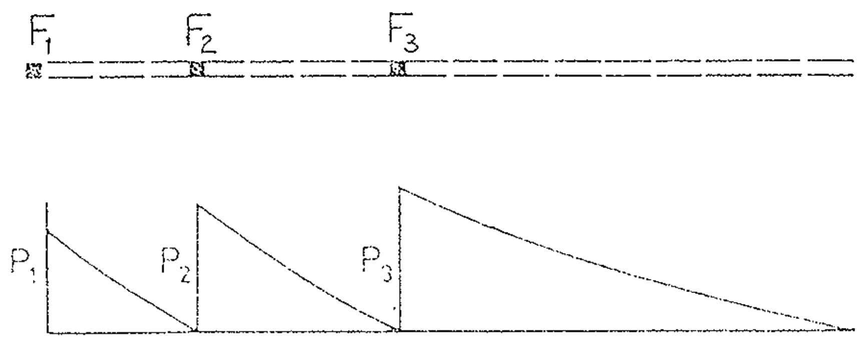



Figure 6.8 Pressure Diagram for Fans in a Leaky Duct at the Optimum Locations.

lower flow, they must be operating against increasing resistances, hence increasing lengths of duct, and this would apply to any number of fans.

Analysis of optimum spacing

Determination of the ideal spacing can be accomplished using the previous example and the graphs produced in that connection. It is assumed that the installation is to extend beyond a thousand metres and it is proposed that three fans should be spaced.

Although the following analysis is logically sound, it suffers the disadvantage of requiring the location of the second fan to be estimated in order to fix the position of the third, and hence the length of the installation for which these positions are optimum. Ideally, the length should be selected and the positions for that length determined. If the estimated position does not give the spacing for the planned length, further attempts are necessary.

The estimated position of the second fan is 200 metres from the first, so that the latter will operate on the 200 metre length as if it were independent.

The procedure is as follows:-

1. Reading from figure 6.3, resistance at 200 metres is 27.4 gaul.

2. Plotting the 27.4 gaul curve on the fan curve in figure 6.9, the fan operating point of $F_1$ is 5.65 $m^3/s$.

3. From figure 6.4, the flow ratio at 200 metres is 1.1, and so 5.14 $m^3/s$ is delivered to fan $F_2$.

4. Reading from the fan curve in figure 6.9, the operating pressure of $F_2$ at 5.14 $m^3/s$ is 1000 $N/m^2$.

5. From the above values, the resistance of the length against which $F_2$ operates is 37.9 gaul.

6. From figure 6.3, the length of duct of resistance 37.9 gaul is 295 metres.

7. From figure 6.4, the flow ratio at 295 metres is 1.17, from which it is calculated that of 5.14 $m^3/s$ from $F_2$, 4.4 $m^3/s$ is delivered to $F_3$.

8. Plotting 4.4 $m^3/s$ on the fan curve in figure 6.9, the fan pressure is 1160 $N/m^2$ and the duct resistance against which $F_3$ operates is 60 gaul.

9. From figure 6.3, the duct length at 60 gaul is 600 metres.

10. From figure 6.4, the flow ratio at 600 metres is 1.47, and of 4.4 $m^3/s$ from $F_3$ delivery from the open end of the duct is exactly 3 $m^3/s$.

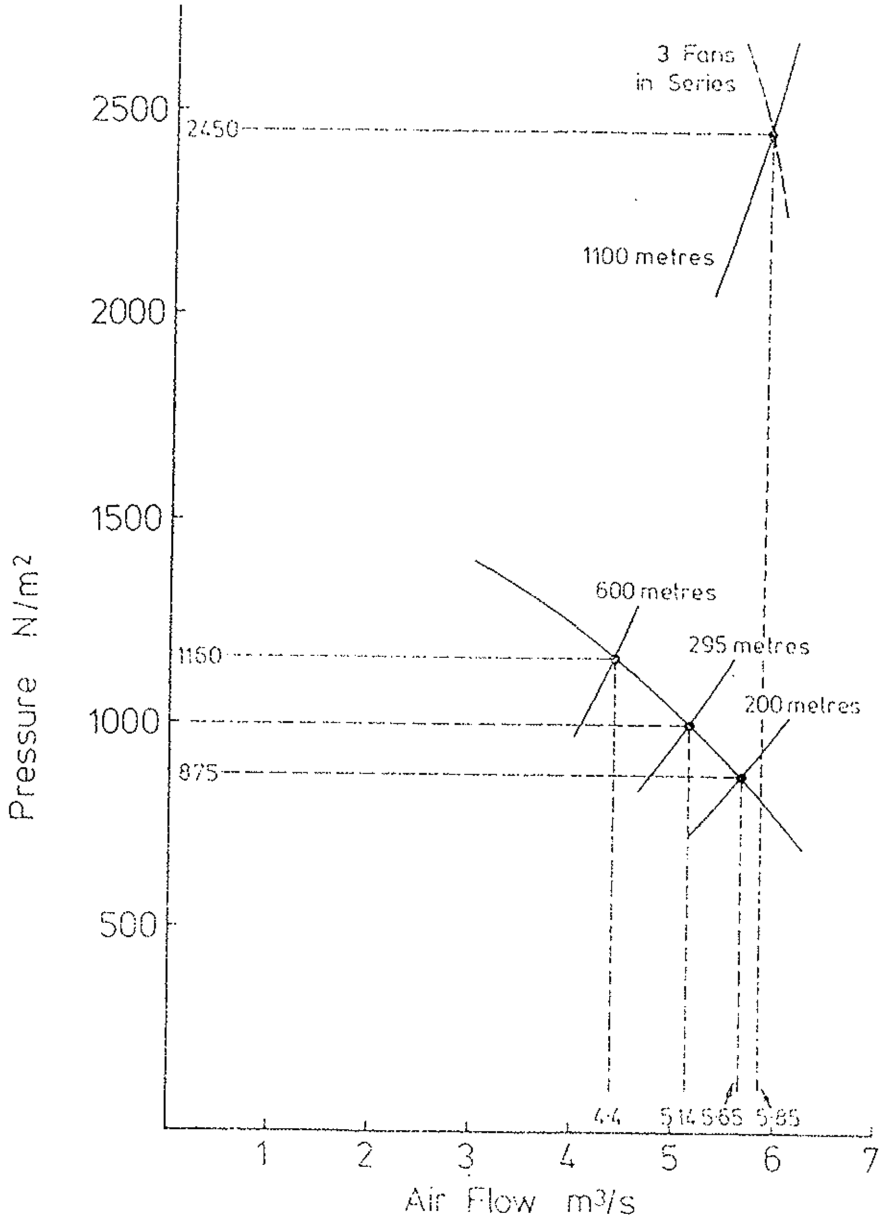



Figure 6.9 Operating Points for Optimum Spacing and for Grouped Fans.

11. The locations of $F_2$ and $F_3$ are 200 metres and 495 metres respectively from $F_1$, and the total length of the installation is 1095 metres, say 1100 metres.

The fact that the last fan operates against exactly 600 metres, as in the previous example, and so delivers 3 $m^3/s$, surprised the writer and is pure chance. Selection of 200 metres as the location for the second fan determined the position of the third, and that selection was random. Had another choice been made the answer would have been different.

In order to compare the delivered flow with that which would be got with the fans as a group, the 1100 metres duct, which from figure 6.3 has a resistance of 73 gaul, is plotted in figure 6.9 with the curve for three fans in series. The operating point is 5.85 $m^3/s$ at a pressure of 2450 $N/m^2$.

From figure 6.4 the flow ratio is 2.28 and the delivered flow rate is thus 2.56 $m^3/s$.

For the spaced system, the first fan passes 5.65 $m^3/s$, of which 3 $m^3/s$ is ultimately delivered at the end of the duct. Here, the overall flow ratio is 1.88, compared with 2.28 for the grouped fans, indicating the effectiveness of spacing in reducing leakage.

Figure 6.10 shows the pressure diagrams for the grouped and spaced systems, which illustrate that leakage is reduced in the first two lengths by spacing, but

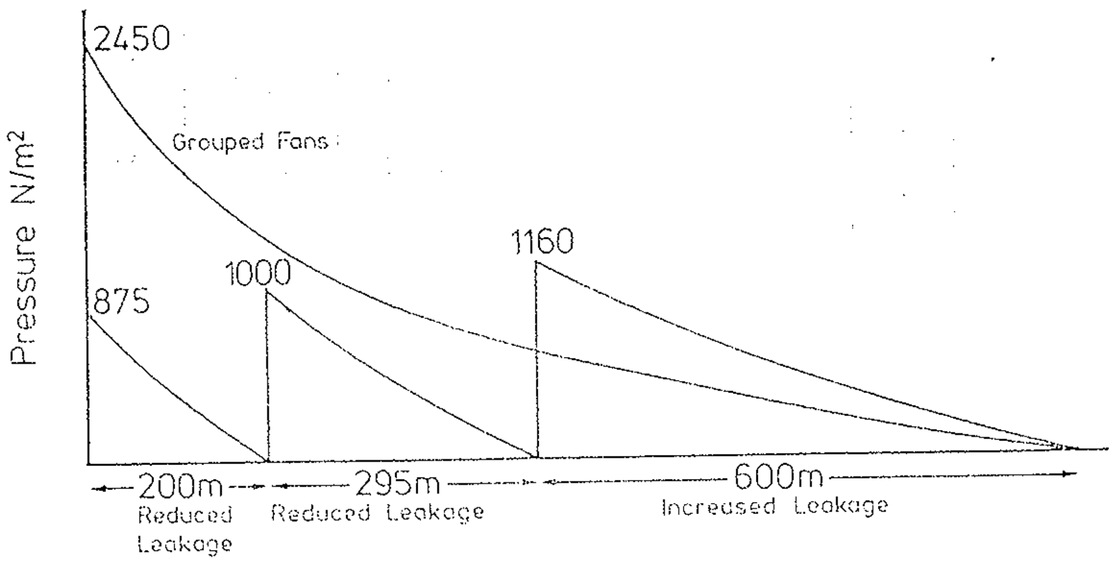



Figure 6.10 Pressure Diagrams for Grouped and Spaced Fans.

increased in the last.

The gain in delivered flow is somewhat less than might have been expected. Because the fans in an optimum system operate as if independent of each other, the effective resistance is the sum of the parts, which is 125 gaul. By comparison, the resistance of the duct as a single unit is 73 gaul, and the advantage of spacing is partially offset by reduced initial flow and higher fan pressures, leading to higher leakage.

The leakier the system, the more pronounced is this adverse effect and it becomes questionable whether spacing is warranted. There is also a limit to the number of fans which can be located and that aspect is dealt with in the next chapter.

In practice, if spacing creates a dramatic increase in delivered flow, a high degree of recirculation should be suspected.

# CHAPTER 7

## Planning and monitoring tunnel installations

The techniques described in the previous chapter can be applied to the design and monitoring of any installation with the aid of a composite set of resistance and flow curves. In this chapter, the principles of construction of the set are explained, the curves are produced and their application illustrated by a variety of exercises. The chapter is concluded with further deductions on the spacing of fans.

### Principles of curve construction

To construct a suitable range of curves, limits have to be put on what are considered to be good and bad leakage standards. From experience of leakage coefficients, the best standard has been taken as that of the coefficient 50 applied to a leakless duct of resistance 8 gaul per 100 metres, and the worst with the coefficient 250. The sole purpose of the coefficients, as they are to be used here, is to derive realistic leakage resistances consistent with the leakage rates experienced in practice.

Derivation of resistances from coefficients has already been shown. For the coefficient 50, the leakage resistance is 40 000 gaul. In a duct of leakless resistance 8 gaul per 100 metres, the ratio of the resistances is 5000.

It is by the adoption of ratios as the basis of construction that the application of the curves is broadened. All installations having a resistance ratio of 5000 are of the same leakage standard, and equivalent to one in which there are leakage paths of resistance 5000 gaul at 100 metre intervals in a leakless duct of unit resistance per 100 metres. Such an installation has been termed a unit system by the writer.

Resistance analysis of a unit system is exactly as described in the general analysis and the example in chapter six, and the results differ from those of real systems of the same ratio in scale only. The actual resistance of any installation is the product of the leakless resistance of the duct and the unit system resistance.

From the resistances at each stage of the analysis, the air flows are determined as before, assuming a delivered air flow of 1 $m^3/s$, or unit delivery. By selecting unit delivery, the numerical values of the flow rates in the duct are also the flow ratios. For any installation, the actual flow rate at any point in the duct is the product of the ratio and the delivered flow required.

The unit system resistance and flow ratio curves in figure 7.1 cover a range for the coefficients 50, 75, 100, 150, 200 and 250. Placed on a qualitative scale of leakage standards, they are defined as:

Excellent; high; good; fair; low; very low.

A qualitative definition is thought to be better than one expressed in technical terms which are often meaningless to anyone other than the definer.

In chapter six, the analysis was of a system with leakage at intervals of 100 metres, which does not conform to practice and leads to slight underestimation of the system resistance. The purpose of taking long intervals was to illustrate the principles of analysis for every stage of a full installation, and to make it easy for the reader to confirm the results and check the construction of the curves. The range of curves in figure 7.1 has been prepared from data provided by computer analysis for leakage paths at 5 metres intervals.

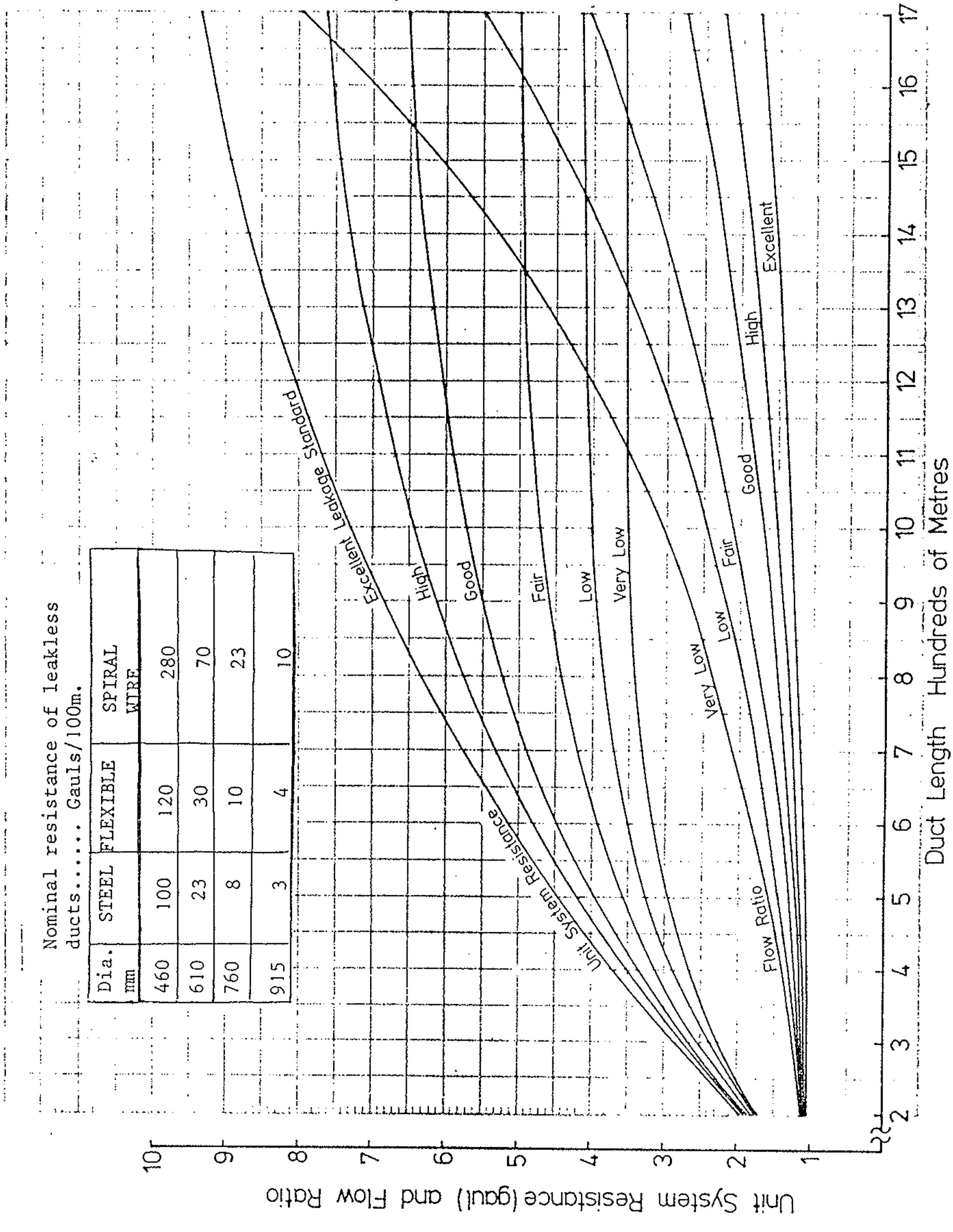
Interpretation of the curves

By presenting the curves as a composite set, the comparative trends in resistance and in leakage rates at the various standards become apparent. The most significant features are seen at the extremes of standard, with respect to the overall resistance, the rate of increase in resistance and the rate of increase in leakage.

Regarding the overall resistance, by 900 metres at the highest standard it is double that of the lowest, and at 1800 metres it is almost treble. What this means is that a fan would pass air at a very much higher rate in the system of poorest standard.

Although the bulk of the air at a low standard leaks, it may serve a useful purpose in the dilution of contaminants produced along the

*Figure 7.1 is required frequently, and is repeated inside the back cover, where it folds out*




Nominal resistance of leakless ducts...... Gauls/100m.

| Dia. mm | STEEL | FLEXIBLE | SPIRAL WIRE |
|---|---|---|---|
| 460 | 100 | 120 | 280 |
| 610 | 23 | 30 | 70 |
| 760 | 8 | 10 | 23 |
| 915 | 3 | 4 | 10 |

Figure 7.1 Resistance and Flow Ratios for Leaky Ducts.

length of the tunnel. Provided an adequate supply reaches the tunnel face, an installation of lower rather than higher standard may be the more effective in particular circumstances. This does not require selection of new ducting and planning to install it badly, but the deliberate choice of old and still serviceable stock, which often has imperfect joints.

The rate of increase in resistance falls off much more rapidly at lower standards. For installations of "fair" quality or less, there is no real increase beyond 800 metres, and fans would then pass air at a constant rate regardless of length.

There is another consequence of unchanging resistance, concerning the spacing of series fans, which will be examined later.

The importance of good standards in minimising leakage in long tunnels is revealed by inspection of the flow ratio curves. For a delivery of 1 $m^3/s$ at the extremes of standard, 9 $m^3/s$ from the fan is needed at 1800 metres for the poorest standard, and less than 2 $m^3/s$ for the best. It is obvious that good ducting, properly installed, is essential in long tunnels.

The differences between the resistances and flow ratios of the different qualities of installation mean that fan requirements to provide a particular delivery rate vary greatly, depending on the standard aimed for or achieved. This is shown by the planning exercises.

Planning exercises

Procedures in the exercises involve identification of points on the curves. To prevent too much confusing detail in the figure, the points have not been marked, and the reader must check for himself to ensure that the process is understood.

Essential for design purposes are the fan characteristics and leakless duct resistances, with the former provided by manufacturers. The exercises do not extend to fan selection, but some leakless resistances are given in the table below. They should be treated with caution in planning. It is best to use values obtained from monitoring actual installations and this will be explained later.

Nominal resistance of leakless ducts in gaul per 100 metres.

| Dia'r mm | Steel | Fully flexible | Spiral wire |
|---|---|---|---|
| 460 | 100 | 120 | 280 |
| 610 | 23 | 30 | 70 |
| 760 | 8 | 10 | 23 |
| 915 | 3 | 4 | 10 |
| 1060 | 1.5 | 2 | 4 |
| 1200 | 0.5 | 0.7 | 2.5 |

Before considering comprehensive design exercises, a few examples of the process are outlined, using figure 7.1.

a) For an installation of 800 metres of "good" leakage standard, the unit system resistance is 5.2 gaul. If the duct leakless resistance is 30 gaul per 100 metres, the total system resistance is 156 gaul.

The flow ratio is 1.5, and for a required flow at discharge of 2 $m^3/s$, a flow rate of 3 $m^3/s$ is necessary at the fan.

At a resistance of 156 gaul and a flow rate of 3 $m^3/s$, the fan would require to develop a pressure of 1400 $N/m^2$ ($P = RQ^2$).

An alternative route to the fan pressure is by calculating the unit system pressure from the unit resistance and the flow. At 5.2 gaul and 3 $m^3/s$ it is 46.8 $N/m^2$, from which the fan pressure is 1400 $N/m^2$ for the 30 gaul resistance. This is probably the better approach because the unit system pressure can be used to derive the fan pressure for a range of leakless resistances.

(b) With a "low" standard at 1450 metres, the resistance and flow ratio curves intersect, both having the value 4.2. A leakless duct of 50 gaul per 100 metre gives the installation a resistance of 210 gaul, and if the fan passes 6.3 $m^3/s$ the delivered flow rate is 1.5 $m^3/s$.

(c) In underground mines, the quantity of air which can be taken from the fresh air flow passing the tunnel entrance is sometimes restricted.

Assume that 5 $m^3/s$ is the maximum that can be taken to supply a tunnel of ultimate length 1400 metres, and a delivered rate of 2.5 $m^3/s$ is required. The planner wishes to estimate the leakage standard which must be achieved.

The flow ratio must be 2. At 1400 metres the ratio does not lie on a curve, but is close to "high", which is the standard on which the design should be based.

It is hoped that the above illustrations are an adequate introduction to the exercises.

Exercise 1 A tunnel is to be driven to 1600 metres with a delivered flow rate of 2.5 $m^3/s$. Serviceable flexible ducting at 610 mm and 760 mm is available.

Because the ducting is not new it is considered that the best standard that can be achieved is "good". The first step is to examine the feasibility of using the 610 mm duct.

From the curves at 1600 metres,

| | |
|---|---|
| Unit system resistance | 6.5 gaul |
| Flow ratio | 2.55 |
| Flow at the fan | 6.4 $m^3/s$ |

Unit system pressure 264 $N/m^2$

From the resistance table, 610 mm flexible duct has a leakless resistance of 30 gaul, from which

Required fan pressure = 30 x 264 = 7920 $N/m^2$

The pressure is excessive and 760 mm duct, with a leakless resistance of 10 gaul, is tested.

Required fan pressure = 10 x 264 = 2640 $N/m^2$

This is taken to be acceptable and the fan pressures and flows at intermediate stages, say 500 and 1000 metres, are determined.

| | 500 m | 1000 m |
|---|---|---|
| Unit system resistances | 4 | 5.75 gaul |
| Flow ratio | 1.25 | 1.7 |
| Flow at the fan | 3.1 | 4.3 $m^3/s$ |
| Fan pressure | 384 | 1063 $N/m^2$ |

The fan operating points at the stages are

| | 500 m | 1000 m | 1600 m |
|---|---|---|---|
| Pressure $N/m^2$ | 384 | 1063 | 2640 |
| Flow $m^3/s$ | 3.1 | 4.3 | 6.4 |

Fan and fan combination characteristics are then examined in order to make the appropriate selection. Fan changes will be made at intermediate distances and the installation can be monitored and the planned changes modified if necessary.

Monitoring procedures are described later.

Exercise 2 In an underground mine, a tunnel 800 metres long is to be ventilated by the available pressure difference across the separation doors between intake and return airways. The pressure difference is 800 $N/m^2$.

The tunnel is from the intake airway and the delivery rate required is 1.5 $m^3/s$.

Since development is in the intake airway, an exhausting system must be used, which precludes flexible duct.

With pressure fixed, the exercise consists of determining an acceptable leakless resistance for the duct, and hence its type and diameter. The standard is expected to be "good".

| | |
|---|---|
| Unit system resistance | 5.2 gaul |
| Flow ratio | 1.5 |
| Flow into tunnel | 2.25 $m^3/s$ |
| Unit system pressure | 26.3 $N/m^2$ |
| Pressure available | 800 $N/m^2$ |
| Leakless duct resistance | 30.4 gaul/100 m |

Consulting the resistance table, 610 mm steel or 760 mm spiral wire would be satisfactory, both giving a margin for error in the design.

Exercise 3   A tunnel of very small cross-section and ultimate length 1500 metres is to be supplied by 460 mm ducting, with a delivery flow of 1.25 $m^3/s$.

For the conditions stated it will be found that low standards require excessive fan pressures, so that a very high standard is necessary. Flexible ducting is excluded because of the possibility of damage. Installation standards for steel and spiral wire are taken as "excellent" and "high" respectively.

| | Excellent | High |
|---|---|---|
| Unit system resistance | 8.95 | 7.4 gaul |
| Flow ratio | 1.6 | 2 |
| Flow required at fan | 2 | 2.5 $m^3/s$ |
| Unit system pressure | 36 | 46.3 $N/m^2$ |

The leakless resistances of steel and spiral at 460 mm are 100 and 280 gaul respectively.

Fan pressure for steel duct      3600 $N/m^2$

Fan pressure for spiral duct      12950 $N/m^2$

The spiral installation is unacceptable on the grounds of excessive fan pressure.

Analysis to determine the fan duty at intermediate distances will lead to selection of suitable fans.

Exercise 4  At its full extent, a tunnelling development will consist of a main tunnel 1000 metres in length, with a 300 metre subsidiary branch of limited cross-section at the mid point. The delivered flow rate in the main tunnel is to be 2.5 $m^3/s$, and 1 $m^3/s$ in the subsidiary, with planned standards of "good" and "fair" respectively.

| | |
|---|---|
| 500 m flow ratio in main line | 1.25 |
| Flow at 500 m | 3.1 $m^3/s$ |
| Flow ratio in subsidiary | 1.2 |
| Flow in subsidiary | 1.2 $m^3/s$ |
| Total flow at junction | 4.3 $m^3/s$ |

The overall resistance of the branched system will not be much less than that of an installation of the main line. To simplify the design exercise, an assumption is made that the branch does not exist and that the total flow of 4.3 $m^3/s$ at 500 metres is from the main line alone. The slightly greater overall resistance by the assumption errs on the side of greater flow in the real system from the fan(s) eventually selected.

For the imagined system,

| | |
|---|---|
| Delivered rate (4.3/1.25) | 3.5 $m^3/s$ |
| Flow ratio at 1000 m | 1.7 |
| Flow required at fan | 6 $m^3/s$ |
| Unit system resistance | 5.75 gaul |
| Unit system pressure | 207 $N/m^2$ |

Taking a 760 mm flexible duct, with a leakless resistance of 10 gaul

| | |
|---|---|
| Required fan pressure | 2070 $N/m^2$ |

Returning to the branched system, the main and subsidiary branches are in parallel. For the main branch,

| | |
|---|---|
| Unit system resistance | 3.9 gaul |
| Overall resistance | 39 gaul |

The resistance of 39 gaul is in parallel with that of the subsidiary branch. Since resistances are inversely proportional to the squares of the air flows, which are 3.1 $m^3/s$ and 1.2 $m^3/s$, the subsidiary resistance can be calculated.

| | |
|---|---|
| Subsidiary overall resistance | 260 gaul |
| Unit system resistance | 2.5 |
| Leakless duct resistance | 104 gaul |

From the resistance table, a 460 mm steel duct meets the requirement, and a flexible duct of the same diameter approximates to it. The latter is selected for compatibility with the main line.

The selected system is 760 mm and 460 mm flexible ducting, with a minimum fan duty of 2070 $N/m^2$ and 6 $m^3/s$.

Monitoring

The routine recording of air flow, without some means of measuring deviation from normal, does little more than confirm what is already known; that the rate of air flow is reducing and that at some time action will have to be taken. If the timing of that action has been planned in advance, undetected abnormality in the rate of leakage will inevitably upset the plan.

Any installation, whether or not designed by the method which has been described, can be monitored for abnormality by applying the routine recordings of air flows to the design curves for flow ratios.

The curves are based on the relationship between the resistances of leakage paths and duct. If the relationsip remains constant and the flow ratios for a routine series of measurements are plotted on the graph, they will follow the same trend as the ratio curves, although it is unlikely that they will lie on any one of them.

Should the relationship change, the trend of the plot will be towards a curve of a high or lower leakage standard. If the former, the quality of the installation is improving; if the latter, it is deteriorating and the rate of leakage is abnormal.

In the table below are weekly recorded flow rates for a particular installation which is advancing rapidly. The flow ratios calculated from the measurements are included.

| | | | | | | |
|---|---|---|---|---|---|---|
| Length in metres | 700 | 740 | 780 | 830 | 870 | 910 |
| Flow at fan - $m^3/s$ | 6 | 5.9 | 5.8 | 5.8 | 5.7 | 5.6 |
| Delivery - $m^3/s$ | 4.4 | 3.9 | 3.7 | 3.4 | 3.3 | 2.9 |
| Flow ratio | 1.35 | 1.5 | 1.55 | 1.7 | 1.75 | 1.9 |

Inspection of the table yields no information other than that the trend seems to be as expected; with increasing length the resistance increases and flow at the fan decreases; with increasing length leakage increases and the delivery rate is reduced.

The flow ratios in the table are plotted on the ratio curves in figure 7.2, and the trend of the plot illustrates that what appears

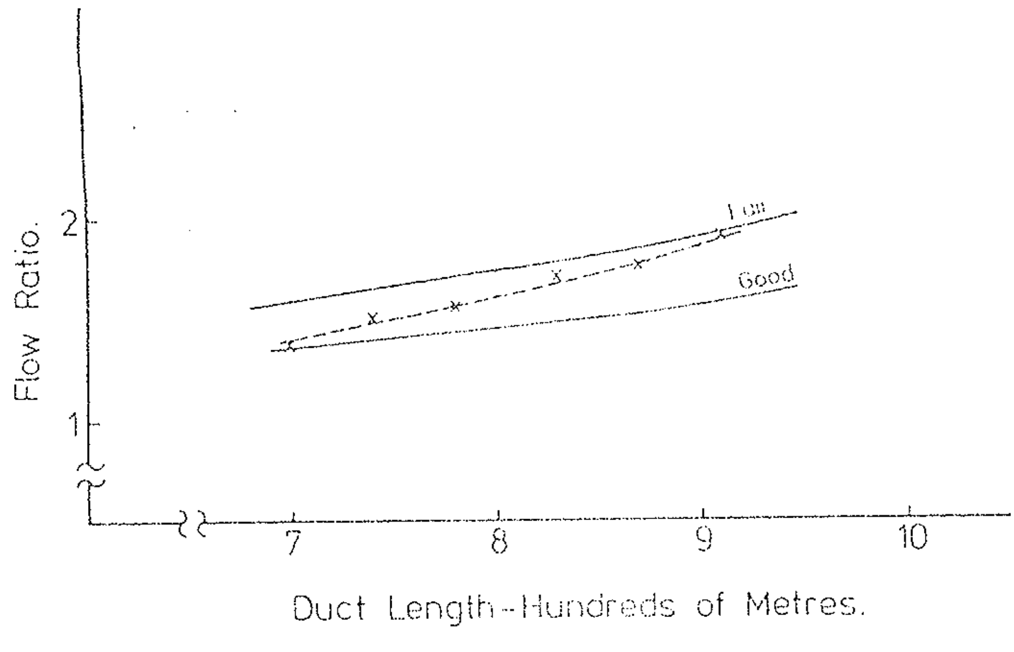



Figure 7.2 Plot of Measured Flow Ratios.

from the table to be a normal trend is abnormal. For some reason the standard of the installation is deteriorating and needs attention.

When a system has been designed using the curves, a plot of the ratios of routine measurements may follow the normal trend, but not at the design standard. If that standard was "high" and the plot is at or near "good", the quality of the installation has been over-estimated and the planned delivery rate will not be achieved with the fan selected.

It is not necessary to have a full plot for this deduction to be made. One or two measured ratios, plotted on the figure and distant from the design curve, allow the same conclusion to be reached. In addition to its control function, the information is useful as a guide in future planning.

Duct resistance can be determined if fan pressure is measured as well as air flow, or read from the fan characteristic at the recorded flow at the fan. The resistance is a further check on conformity with the plan, and again can be of assistance in future planning. The method is illustrated in the exercise below.

> At a length of 1200 metres, fan performance is recorded as 4600 $N/m^2$ and 4.5 $m^3/s$, with a delivered flow rate of 2 $m^3/s$. The leakless resistance of the duct has to be calculated.

The flow ratio is 2.25, and from figure 7.1 at 1200 metres the standard indicated by that ratio is midway between "good" and "fair".

At this position in relation to the resistance curves, the unit system resistance is 5.5 gaul.

From the fan performance, the overall resistance of the installation is 227 gaul. Dividing by the unit resistance, the leakless resistance per 100 metres of duct is 41 gaul.

The result can be compared with that which was used in the design. If the leakless resistance has been underestimated in planning, the delivery rate will fall short of plan. Resistances specified by manufacturers are obviously for new duct, but there is no information on old to assist the planner, unless it is provided by field measurement.

Spacing of series fans

Before continuing, reference should be made to the planning exercise in chapter six on the location of fans in a duct. There, it was shown that three fans were ideally placed when they operated against lengths of 200, 300 and 600 metres in an installation of 1100 metres.

As the installation extends from 1100 metres and a fourth fan is considered, the exercise can be continued. The fan will be at 1100 metres, but it cannot be installed until the duct length from that point has a resistance which corresponds with that calculated from the fan duty, otherwise recirculatory conditions are created.

At 1100 metres, flow in the duct is 3 $m^3/s$, and the fan in figure 6.9 would operate at 3 $m^3/s$ and about 1300 $N/m^2$, from which the resistance is 144 gaul. When the resistance curve in figure 6.3 is consulted, it is seen that this is far beyond the limit resistance of the installation, which would have to be of infinite length before a fourth fan could be added. In other words, another fan can never be installed without causing recirculation.

The reason for the effect is the levelling-off of resistance in long installations. Referring to figure 7.1, for any standard less than "good" there is no real increase in resistance beyond 1000 metres, and it is at these standards that spacing would be contemplated to minimise leakage.

Were the installation which has been analysed to extend to 2500 metres, or any distance, all three fans would remain in fixed positions within 500 metres of inlet, with no prospect of adding another without recycling occurring. At 1500 metres (when the third fan operates on 1000 metres), conditions become constant, and all fans have fixed operating points regardless of installation length. The installation is shown in figure 7.3.

Up to the third fan at 500 metres from inlet, leakage is also constant, but it continues to increase in the last length and the delivered flow reduces steadily. One method of increasing the latter is to install another fan or fans at inlet, but then the fans in the

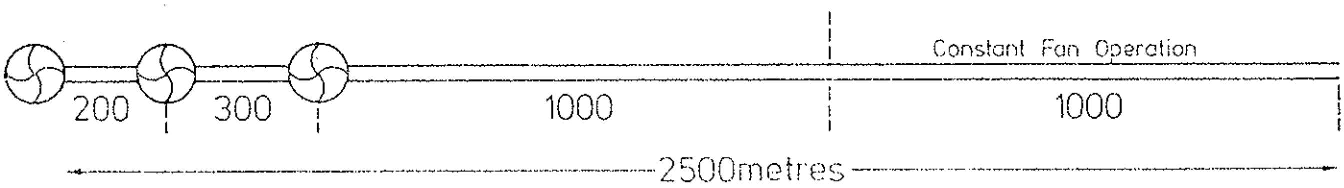



Figure 7.3 Location of Spaced Fans in a Leaky Duct to Minimise Leakage.

duct are no longer at the ideal positions.

It is theoretically possible to regularise the distances between the fans by having succeeding units of different characteristics, which develop a lower pressure for the flow rate at each stage, but this solution is not practical and would require more fans, all different.

Perhaps it is worth mentioning that spacing could also be regularised by locating restricting orifices in the duct beside each fan. However, in the previous chapter it was shown that the advantage of spacing was partially offset by the fact that the sum of the resistances of the parts is greater than the resistance of the whole. With orifices in the duct the resistances of the parts are further increased and there may even be a reduction in the delivered flow compared to that of grouped fans. One of the appended exercises demonstrates the principles and the fact.

// The conclusion must be that the spacing of fans is of uncertain efficacy and of sufficient complexity as to be avoided.

If it is proposed to examine the spacing of fans, measurements of fan pressure, flow and delivered flow can be made on the installation as it exists. From these values, the standard of installation and the leakless resistance of the duct can be got from the curves in figure 7.1.

With this information and the fan characteristic, the spacing exercise can be carried out as described in the previous chapter.

# CHAPTER 8

## Overlap and recirculatory tunnel systems

The basic choice in tunnel ventilation is of a forcing or an exhausting system, and the advantages of forcing are the disadvantages of exhausting. These advantages include the following:

Flexible ducting, which is cheapest and most easily transported, can be used.

Fresh air is delivered to the tunnel face.

Gas emitted (eg in coal mines), dust produced and blasting fumes are effectively and rapidly flushed out.

Gas emitted and dust raised or produced along the length of the tunnel are carried away from the face, and not towards it as with exhausting systems.

Explosive gas and dust do not pass through the fan.

The main disadvantages of the forcing method are that any dust produced passes over the workmen, and that the entire length of the tunnel is contaminated by respirable dust and blasting fumes.

There are several methods of installation design which are intended to embrace the best features of both systems. These mainly involve simulation of the characteristics of the exhaust system in installations which are fundamentally forcing, and vice versa.

In this final chapter some of the methods are described and, where appropriate, mathematically analysed. The techniques are neither presented nor analysed graphically, and on these grounds have no place in the book. They are, however, more easily understood if the descriptions and analyses are accompanied by diagrammatic representation, and for that reason it is felt that the topic merits inclusion.

Simple overlap installations

An overlap system is shown in figure 8.1, and consists of a main installation, which in this case is forcing, and a secondary unit operating in the opposite mode. The secondary unit passes approximately half of the air delivered or exhausted by the main.

Although there is more plant in the tunnel, the fan and switchgear of the secondary unit are remote from the face, and because of the short length and lower flow, ducting of lesser diameter than that of the main installation can be used. This is attractive in a zone in which there is intense activity and bulky plant.

If the ducting for the secondary unit is steel, the installation can be of fixed length and monorail mounted, to be advanced or retracted

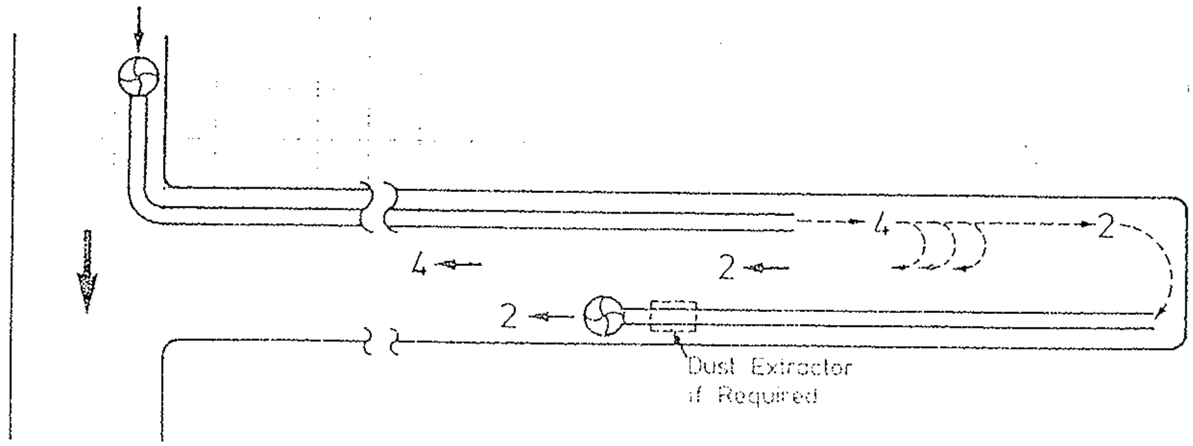



Figure 8.1 Overlap System with Main Fan Forcing.

as required, avoiding the necessity for extension. It also operates at constant duty. The frequency of extension of the main line depends on the length of overlap and the rate at which the excavation advances, but it does not interrupt or disrupt tunnelling operations unduly.

A reasonable rate of flow is necessary in the overlap zone to ensure that it too is adequately ventilated. In the figure, the main fan delivers 4 $m^3/s$ and this splits equally between the secondary unit and the overlap. If the unit is of fixed length the flow rate in it is constant, and it is less difficult to maintain balance than with an extending duct. Some advantages of the method are that:

The exhausting secondary fan ensures that dust which is produced does not pass over the workmen, and with filters in the duct, discharge of respirable dust into the tunnel is reduced.

Whereas the air delivered by a conventional exhaust system could be contaminated, the forcing fan provides a fresh supply.

In conventional exhaust installations, the air tends to drift to the inlet rather than sweep the face, but with the influence of forcing a degree of streaming and scouring is introduced.

Although streaming is desirable, the forcing duct must not be too close, or more than 2 $m^3/s$ would reach the face. Should that happen, as in figure 8.2, 2 $m^3/s$ of dust laden air flows into the exhaust inlet and the excess of 0.5 $m^3/s$, equally dusty, passes back over the workmen.

The concentration is also higher than it would be without overlap, when 4 $m^3/s$ would reach the face and produce a lower concentration than 2.5 $m^3/s$.

The method has an application in long tunnels where the pick-up of heat, moisture and repirable dust is excessive, and where the operation is dust-producing.

An installation in which the main fan exhausts has the same physical layout, with the position of the duct exhaust end being less critical. It has several advantages over the simple exhaust method.

> The forcing unit scours the face and prevents the accumulation of gas in pockets.
>
> In drill/blast excavations, fumes are rapidly flushed out by the forcing system, and the tunnel is kept clear by exhausting. These features create a better working environment and reduce the delay in long tunnels following blasting.

The method is unsuitable if dust is an additional problem.

Overlap installations require a good main line supply of air. If the delivery rate is low, the divided flows may be inadequate, and

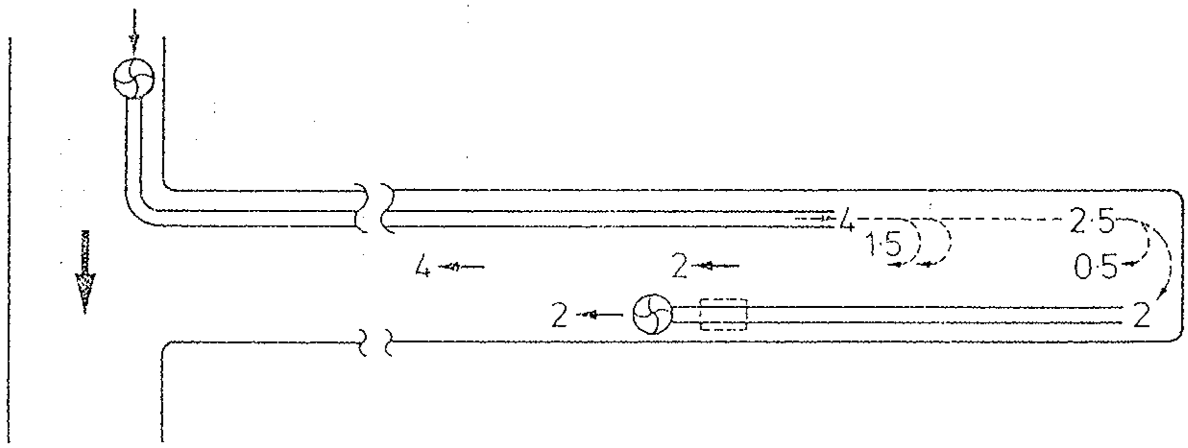



Figure 8.2 Overlap with Excessive Delivery at Tunnel Face.

difficult to keep in balance.

## Controlled recirculation

In the early 1960's, staff at the British Safety in Mines Research Establishment carried out investigations into the nature of recirculation in tunnel ventilation, showing that it deserved consideration in providing a safer and healthier environment.

To mining engineers conditioned to associating recirculation in any form with danger, the concept was not easy to accept. That, together with the need to seek permission from the inspectorate for a system which contravened mining regulations, probably delayed its introduction.

Much later, and mainly to alleviate the problem of respirable dust in mechanised headings, some recirculatory systems were introduced.

## Principles of recirculation

In the tunnel in figure 8.3a, gas is being emitted at a rate of $q$ $m^3/s$. Fresh air flow at the entrance is $Q$ $m^3/s$, of which $nQ$ $m^3/s$ is passed by the fan into the tunnel, $n$ being less than unity. The gas concentrations in the tunnel and in the airway beyond it are respectively

$$q/nQ \quad \text{and} \quad q/Q$$

Figure 8.3b shows the same arrangement, but in this case the fan passes (Q+nQ), where Q is the fresh air component and nQ a recycled fraction of contaminated air. The concentration in the tunnel is to be determined, and this can be done by logical deduction.

Because the fresh air rate approaching the tunnel is Q, and the emission rate is q, the concentration in the airway on the return side of the entrance must always be q/Q, recirculation having no influence.

Referring to the figure, the air leaving the tunnel splits, with Q flowing out of the system and nQ recycling. The same mixture flows at all three locations, and so the concentrations in the tunnel and in the recycled fraction are also q/Q.

Comparing the result with the non-recirculatory, where the concentration in the tunnel is q/nQ, which is greater than q/Q, the recirculatory method causes a reduction. The reason is not that air is being recycled, but that all of the fresh air is taken into the tunnel.

If the argument is not accepted, suppose that recycling does cause a build-up in concentration in the system, to some higher value than q/Q. As a consequence, the concentration in the return airway will also be higher, because it is the same mixture as in the tunnel. In that event, gas is being carried away at a greater rate than it is emitted, which is clearly ridiculous.

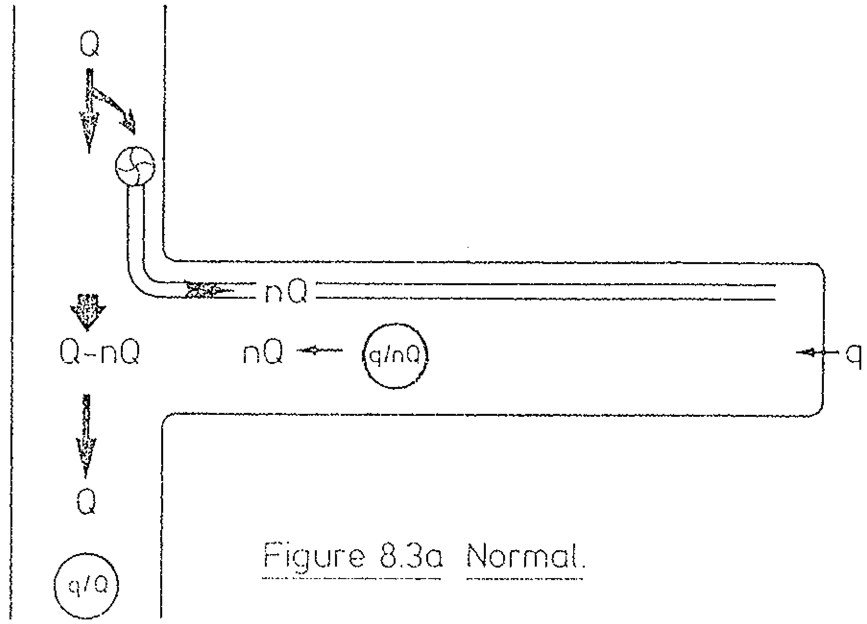



Figure 8.3a Normal.

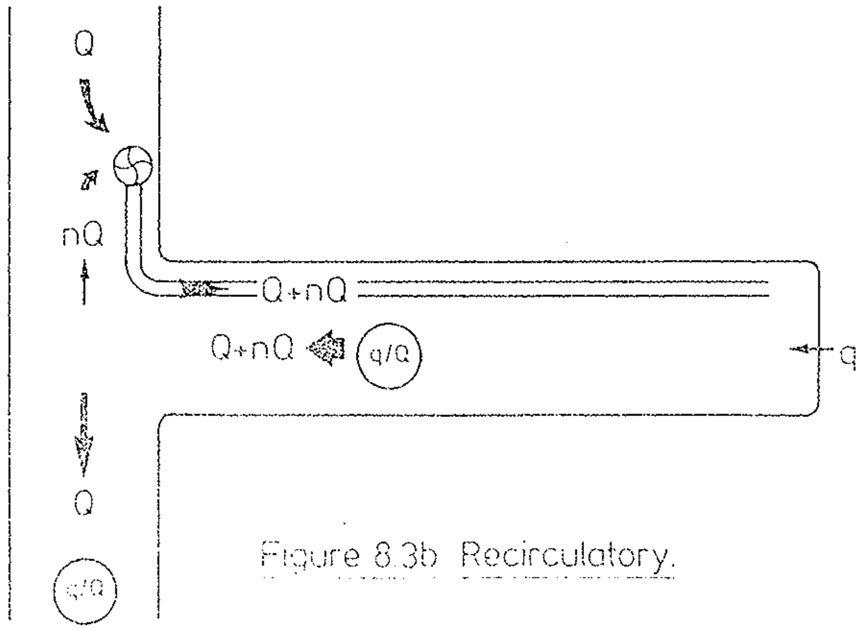



Figure 8.3b Recirculatory.

Figure 8.3 Gas Concentrations for Normal and Recirculatory Systems.

As formal proof, let the unknown concentration in the tunnel be C, so that the recycled fraction nQ is at that concentration, and carries gas back into the tunnel at the rate nQC. The conditions at the tunnel face on discharge from the duct are then

| | |
|---|---|
| Gas flow | $nQC + q$ |
| Air flow discharge | $Q + nQ$ |

$$\text{Concentration} \quad \frac{nQC + q}{Q + nQ}$$

By definition, the concentration is C, which when equated to the expression and resolving gives q/Q, as deduced.

Taking a simple numerical example, fresh air flow at the tunnel entrance is 5 $m^3/s$ and emission 0.05 $m^3/s$. The concentrations when 2 $m^3/s$ and 7 $m^3/s$ are passed by the fan are to be compared.

At 2 $m^3/s$:

| | |
|---|---|
| Concentration in tunnel | $0.05/2 = \underline{0.025}$ |
| Concentration in return | $0.05/5 = \underline{0.01}$ |

In the recirculatory case, 2 $m^3/s$ are recycled at a concentration C, and 7 $m^3/s$ flows in the duct.

At 7 $m^3/s$:

$$\text{Gas flow} \qquad 2C + 0.05$$

$$\text{Air discharge} \qquad 7$$

$$\text{Concentration } C = \frac{2C + 0.05}{7}$$

$$\text{Hence, } C = \underline{0.01}$$

This is the concentration in the tunnel, the return airway and in the recycled air.

Although the same result would be obtained by passing 5 $m^3/s$ into the tunnel, with no recirculation, an element of recycling is essential in practice, otherwise there would be no flow in the zone between the fan and the tunnel entrance.

<u>Recirculatory overlap systems</u>

A recirculatory overlap system differs only from simple overlap in the fact that the secondary fan circulates air at a greater rate than the main installation delivers it. It is proposed to explain the system and analyse its effect by means of an imaginary case study of a force ventilated tunnel with a dust problem to be solved. A general analysis will be given later.

The situation envisaged is of a long mechanised tunnel in which the shift average dust concentration has reached an excessive level at

15 mg/$m^3$. Air flow delivery is at 2 $m^3$/s from a forcing system and it is not thought that to increase the flow would be a practical solution.

Exhaust ventilation is ruled out for various reasons, as is a simple overlap on the grounds of low flow rates after splitting. The conclusion is to investigate the effect of a recirculatory installation on the dust concentration.

The assumption is that the excessive level is caused by the face operations, in which case the shift average concentration can be converted to an average rate of production of respirable dust. With an air flow rate of 2 $m^3$/s and a concentration of 15 mg/$m^3$, the rate of dust production is 30 mg/s.

Figure 8.4 shows the installation. The forcing fan delivers 2 $m^3$/s and the exhaust overlap circulates 4 $m^3$/s though an extractor considered to be 70% efficient on respirable dust. The dust concentration is to be determined near the exhaust fan discharge, and between the forcing delivery and the tunnel face, marked X and Y on the figure.

The flow pattern is also shown on the figure. The discharge from the exhaust fan divides, 2 $m^3$/s flowing out of the tunnel and 2 $m^3$/s recycled to the face, both flows at the same dust concentration. Recycled air meets fresh air, also 2 $m^3$/s, and the mixture flows to the face, where it picks up dust at 30 mg/s before entering the exhaust duct.

Analysis starts by stating that the concentration at X is C $mg/m^3$, then following the route of the recycled air at that concentration.

| | | |
|---|---|---|
| Air recycled | 2 | $m^3/s$ |
| Dust recycled | 2C | mg/s |
| Dust produced | 30 | mg/s |
| Dust into duct | 2C + 30 | mg/s |

The extractor leaves the fraction 0.3 of the dust entering it in the discharged air.

| | | |
|---|---|---|
| Dust from duct | 0.3 (2C+30) mg/s | |
| Air flow in duct | 4 | $m^3/s$ |
| Dust concentration leaving duct | $\frac{0.6C+9}{4}$ | $mg/m^3$ |

This is the concentration at X, which is C by definition.

$$C = \frac{0.6C+9}{4}$$

from which the concentration is $\underline{2.6\ mg/m^3}$.

2 $m^3/s$ of recycled air at this concentration mixes with 2 $m^3/s$ of fresh air, so that:

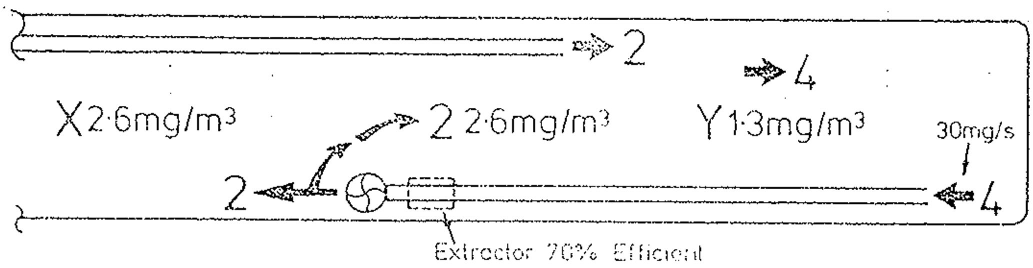



Figure 8.4 Recirculatory Overlap System.

$$\text{concentration at Y} = \frac{2 \times 2.6}{4} = \underline{1.3 \text{ mg/m}^3}$$

The concentration of 2.6 mg/m$^3$, when compared with 15 mg/m$^3$ for the forcing fan alone, indicates that the efficiency of the system as a dust extraction process is greater than the efficiency of the extractor. Why this should be so is shown in the general analysis which follows.

Although an assumption was made that all of the dust was produced at the tunnel face, this was merely a device to provide a convenient collecting point for the purpose of analysis. That some dust would be in the forcing discharge, or raised between the exhaust discharge and the tunnel face, does not affect the result at X, although it does at Y.

For example, if the forcing delivery carried 2 mg/m$^3$, the concentration at Y would be 2.3 mg/m$^3$, instead of 1.3 mg/m$^3$.

General analysis of recirculatory overlap

It is usual for a general analysis to precede a particular, but by reversing the order and giving a numerical example, the reasoning in the general case is sometimes easier to grasp.

The analysis below is valid for gas emission and dust production, and units are omitted from the expressions: an emission rate of q m$^3$/s and a dust rate of q mg/s are both q; an air flow rate of Q m$^3$/s is **Q**.

What is intended is to derive a general expression for the gas or dust concentration in a tunnel with a recirculatory overlap system. That expression is to be presented in a form which allows comparison with a force ventilated tunnel, at the same delivery and emission rates. These are respectively Q and q.

For the force ventilated system, the concentration is q/Q.

Referring to figure 8.5, which represents the recirculatory installation:

The delivered flow rate is Q

The gas emission or dust production rate is q

The flow rate in the exhaust installation is RQ, where R is the ratio of exhaust to delivered flow.

The recycled flow rate is (R -1) Q

The concentration at C is to be determined.

Dust extractors are not equally efficient on fresh and recycled dust, and this is taken into account. The efficiency on fresh dust is $E_1$ expressed as a fraction, and $(1-E_1)$ is the dust remaining after the extractor. For recycled dust the efficiency is $E_2$ and the fraction remaining is $(1-E_2)$.

Analysis begins by following the recycled flow $(R-1)Q$, and the concentration is C:

| | |
|---|---|
| Rate of contaminant return | $(R-1)\,QC$ |
| Rate of contaminant emission | $q$ |
| Rate into exhaust duct | $q + (R-1)\,QC$ |
| Rate out of duct | $(1-E_1)q + (1-E_2)(R-1)\,QC$ |
| Air flow in duct | $RQ$ |
| Concentration C | $\dfrac{(1-E_1)q + (1-E_2)(R-1)\,QC}{RQ}$ |

$$\text{Rearranging, } C = \frac{1-E_1}{1+E_2\,(R-1)}\; q/Q$$

$$= K.\; q/Q$$

It can be concluded from inspection of the expression that;

With regard to gas emission, the extractor efficiencies $E_1$ and $E_2$ are nil, from which K is unity and the gas concentration is $q/Q$, indicating no change from the forcing system. Nor would there be a change in dust without the extractor.

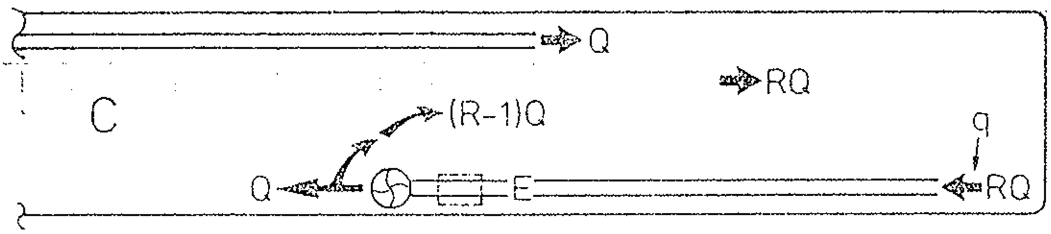



Figure 8.5 Recirculatory Overlap System. General Case.

Efficiencies $E_1$ and $E_2$ are positive, and cursory inspection shows that the numerator of K is always less than the denominator, whatever the efficiencies. Consequently $K\ q/Q$ is always less than $q/Q$.

The higher the efficiencies, the smaller the numerator and the greater the denominator, hence the lower the concentration. This is to be expected.

If the efficiency $E_2$ is nil on recycled dust, K becomes $(1-E_1)$, showing that the minimum reduction in $q/Q$ is directly related to the efficiency of the extractor. For example, if $E_1$ is 0.8, the dust concentration is $0.2\ q/Q$, or one fifth of that for conventional forcing.

If the efficiency is not nil on recycled dust, K is less than $(1-E_1)$, and the efficiency of the system is greater than the efficiency of the extractor, because the latter has the opportunity to draw more dust from the same parcel on recycling.

A high value of R represents a high rate of flow in the exhaust installation and a further reduction in concentration, because the volume recycled is increased.

If the design is based on nil efficiency on recycling and the result indicates that an acceptable dust level would be achieved, any efficiency on recycled dust can be regarded as a bonus. It is almost impossible to put a figure on an efficiency for multiple recycling.

A rapid assessment of any installation can be made by substituting actual values in the expression. Suppose that in a tunnel ventilated by a forcing fan passing 2.5 $m^3/s$, the shift average dust concentration is 16 $mg/m^3$.

Ventilation by the recirculatory method is proposed, the exhaust fan to pass 4 $m^3/s$ with a dust extractor 80% efficient. The probable dust concentration is to be assessed for

a) 80% efficiency on all dust

b) 40% efficiency on recycled dust

c) nil efficiency on recycled dust

From the original forcing system, the rate of dust produced is 40 mg/s (2.5 x 16).

a) $$\frac{1 - 0.8}{1 + 0.8\,(1.6-1)} \times \frac{40}{2.5} = 2.2 \text{ mg/m}^3$$

b) $$\frac{1 - 0.8}{1 + 0.4\,(1.6-1)} \times \frac{40}{2.5} = 2.6 \text{ mg/m}^3$$

c) $$(1-0.8) \times \frac{40}{2.5} = 3.2 \text{ mg/m}^3$$

In a real system, and assuming normal operation, the only variable in the equation is the fresh air delivery, which will reduce as the tunnel extends.

Suppose that it falls to 1.5 $m^3/s$, the ratio R becomes 2.7 instead of 1.6.

a) $$\frac{1 - 0.8}{1+0.8\ (2.7-1)} \times \frac{40}{1.5} = 2.3 \quad mg/m^3$$

b) $$\frac{1 - 0.8}{1+0.4\ (2.7-1)} \times \frac{40}{1.5} = 3.2 \quad mg/m^3$$

c) $$(1-0.8) \times \frac{40}{1.5} = 5.3 \quad mg/m^3$$

By assuming 80% efficiency on all dust, there is no deterioration despite the decrease in fresh air flow. This is improbable in practice and the safest assumption is that efficiency on recycling is nil, in which case the dust concentration is in inverse proportion to the rate of fresh air delivery. This is more in line with reason.

Recirculation in advance headings

In British coal mining, coal development drivage is sometimes done in advance of a longwall face. When the drivage is at the air intake end of the face, the dust production in it is carried into the coal face by the forcing system of ventilation in the heading, to add to the dust problems in the former.

A heading which is force ventilated is shown in figure 8.6a. The rate of flow in the airway is 10 $m^3/s$ and this air has already a dust load of 2 $mg/m^3$. The heading is supplied with 3 $m^3/s$ and the return flow dust concentration is 8 $mg/m^3$. The dust concentration entering the coal face is calculated as follows:

Dust flow from airway = 7 x 2 = 14 mg/s

Dust flow from heading = 3 x 8 = 24 mg/s

Total dust flow = 38 $mg/m^3$

Concentration entering face = 38/10 = 3.8 $mg/m^3$.

With conditions otherwise unchanged, the fan is turned round to exhaust at the same rate through a dust extractor 70% efficient on all dust. Figure 8.6b shows the arrangement.

The reader may wish to analyse the system and determine the dust concentrations in the heading and entering the coal face. The answers are shown in the figure.

In this case, an assumption of constant efficiency on all dust has no effect of significance, because the recycled fraction is small.

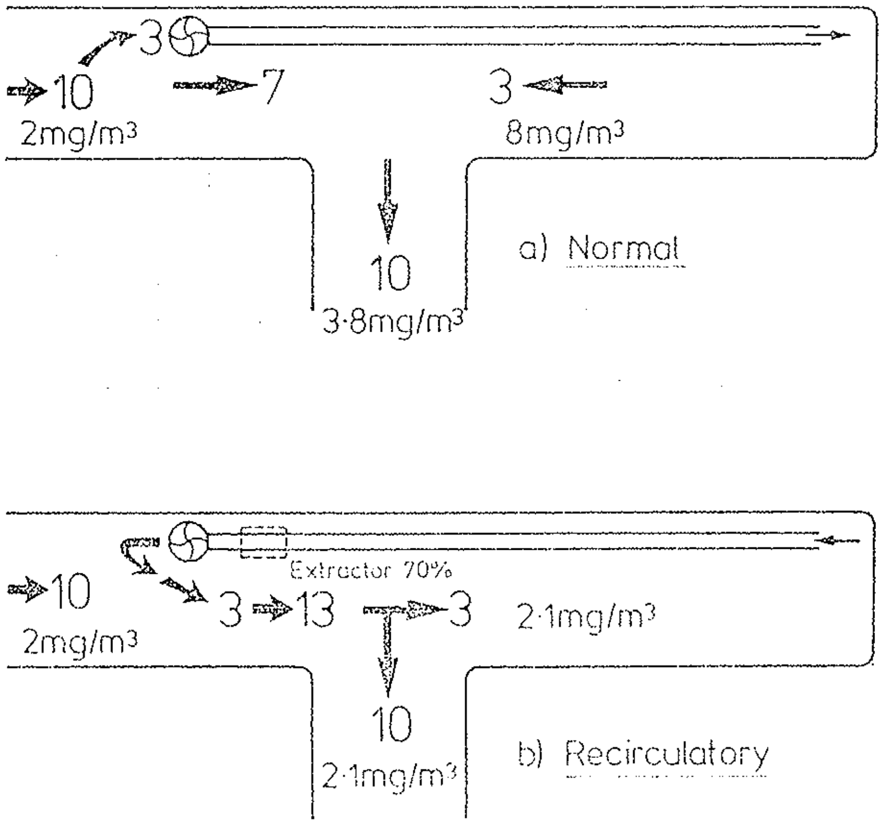



Figure 8.6 Advance Heading Ventilation.

## Exercises

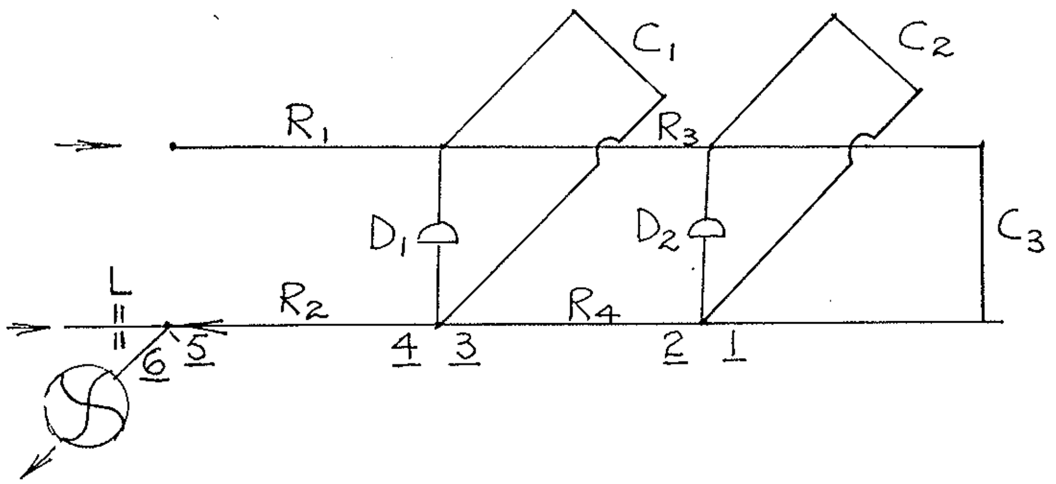
The exercises are for those who wish to do more than simply follow the reasoning in the text.

In extensive deep mines it is unlikely that graphical analysis will find favour where there is computer access, although it is quite feasible to solve most problems by graphical construction. The main advantage claimed for the method, and for the exercises here, is that they help personnel in the field to understand and hence anticipate the indirect consequences of deliberate and accidental acts from day to day.

With regard to duct ventilation in tunnelling, there is no doubt that the method of analysis is useful for both learning and planning, as well as for monitoring and control. This also applies to dust analysis in recirculatory systems.

Exercises - Chapters 3 and 4

The exercises are based on the network analysed in chapters 3 and 4.




Resistances of all parts of the network, and points on the fan characteristic, are shown below.

| Resistances | $C_1$ | $C_2$ | $C_3$ | $R_1+R_2$ | $R_3+R_4$ | $D_1D_2L$ |
|---|---|---|---|---|---|---|
| gaul | 2 | 1.25 | 0.8 | 0.1 | 0.05 | 10 (each) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Fan: $N/m^2$ | 2450 | 2280 | 2100 | 1900 | 1680 | 1440 |
| $m^3/s$ | 95 | 100 | 105 | 110 | 115 | 120 |

A master graph sheet from which copies can be taken must be prepared (blue graph paper does not usually photocopy). On A4 paper, suitable scales are 200 $N/m^2$ and 5 $m^3/s$ per centimetre, with the flow scale on the long edge. A line diagram of the network should be included for easy reference.

After the first exercise has been done, the others should not be started before an attempt is made to deduce the effect of the change in conditions defined in the relevant exercise. The process of deduction was demonstrated in the first chapter. On completion of the graphical solution, the deduced and analysed results can be compared.

If the process of deduction followed by analysis followed by comparison is adhered to, a general understanding of the effects of changes develops.

Exercise 1

Determine the total airflow, its distribution and the fan operating point.

| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|---|
| | 22 | 24.5 | 31 | 10 | 9 | 13.5 | 110 $m^3/s$ |

The fan operating point is 1900 $N/m^2$, 110 $m^3/s$.

Note: From the fan operating point, the system resistance is 0.157 gaul ($P=RQ^2$).

Because the network is simple series/parallel, without regulators or booster fans, the network resistance can be calculated and compared with the result from the graphical solution.

Exercise 2

A regulator in $C_3$ restricts flow to $20m^3/s$. Determine all flows, the fan operating point, the pressure drop across the regulator and its cross-sectional area.

| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|---|
| | 24.5 | 28 | 20 | 10.5 | 10 | 14 | 107 $m^3/s$ |

The fan operating point is 2040 $N/m^2$, 107 $m^3/s$.

The pressure drop across the regulator is 700 $N/m^2$ and the cross-sectional area $0.9m^2$.

Exercise 3

Repeat the above exercise for a regulator in $C_1$ to restrict flow to $15m^3/s$.

| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|---|
| | 15 | 26.5 | 32.5 | 10.5 | 9.5 | 14 | 108 $m^3/s$ |

The fan operating point is 1980 $N/m^2$, 108 $m^3/s$.

Pressure drop across the regulator is 650 $N/m^2$, with cross-sectional area $0.7m^2$.

Exercise 4

A booster fan in $C_3$ produces $40m^3/s$. Determine all flows and the operating points of both fans.

| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|---|
| | 20.5 | 21 | 40 | 9.5 | 7.5 | 13.5 | 112 $m^3/s$ |

The main fan operating point is 1820 $N/m^2$, 112 $m^3/s$.
The required booster fan duty is 720 $N/m^2$, 40 $m^3/s$.

Exercise 5

Repeat the previous exercise when the booster fan in $C_3$ has the following points on its characteristic.

| | | | | | |
|---|---|---|---|---|---|
| $N/m^2$ | 1140 | 1000 | 840 | 680 | 500 |
| $m^3/s$ | 35 | 37.5 | 40 | 42.5 | 45 |

| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|---|
| | 20.5 | 21 | 41 | 9 | 7.5 | 13.5 | 112.5 $m^3/s$ |

The main fan operating point is 1780 $N/m^2$, 112.5 $m^3/s$.
The booster fan operating point is 780 $N/m^2$, 41 $m^3/s$.

Exercise 6

A booster fan in $R_4$ produces 80 $m^3/s$. Determine all flows and fan duties.

(An ordinate through 80 $m^3/s$ replaces the derived characteristic 2 and is in parallel with $D_1$ and $C_1$).

| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|---|
| | 16.5 | 30.5 | 38.5 | 7.5 | 11 | 12.5 | 116.5 $m^3/s$ |

The main fan operating point is 1620 $N/m^2$, 116.5 $m^3/s$.
The required booster fan duty is 950 $N/m^2$, 80 $m^3/s$.

Exercise 7

Flow of 80 $m^3/s$ in $R_4$ is proposed by a new main fan, without a booster fan and with a regulator in $C_1$ to reduce flow there to 15 $m^3/s$.

Determine the distribution, the required fan duty and the cross-sectional area of the regulator.

(There is no need to construct any derived characteristics except the first, curve 1. The only significant point on that curve is at 80 $m^3/s$, and it is projected to locate the significant point on 2, 3 etc).

Answer:

| $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|
| 15 | 30.5 | 38.5 | 12 | 11 | 16 | 123 $m^3/s$ |

The required fan duty is 2640 $N/m^2$, 123 $m^3/s$.

The pressure drop across the regulator is 1050 $N/m^2$ and its cross-sectional area is 0.56 $m^2$.

Exercise 8

Determine the distribution and the main fan operating point (the original fan) if circuit $C_1$ is sealed.

Answer:

| $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | L | Total |
|---|---|---|---|---|---|---|
| nil | 29.5 | 37 | 12 | 10.5 | 14.5 | 103.5 $m^3/s$ |

The fan operating point is 2170 $N/m^2$, 103.5 $m^3/s$.

In this exercise it is interesting to note that a "saving" of 22 $m^3/s$ by sealing $C_1$ results in a gain in $C_2$ and $C_3$ totalling only 11 $m^3/s$.

Exercise 9

Assume a natural ventilating pressure of 200 $N/m^2$ and 10% compression/expansion in the shafts $R_1$ and $R_2$, and determine the effects in the original system.

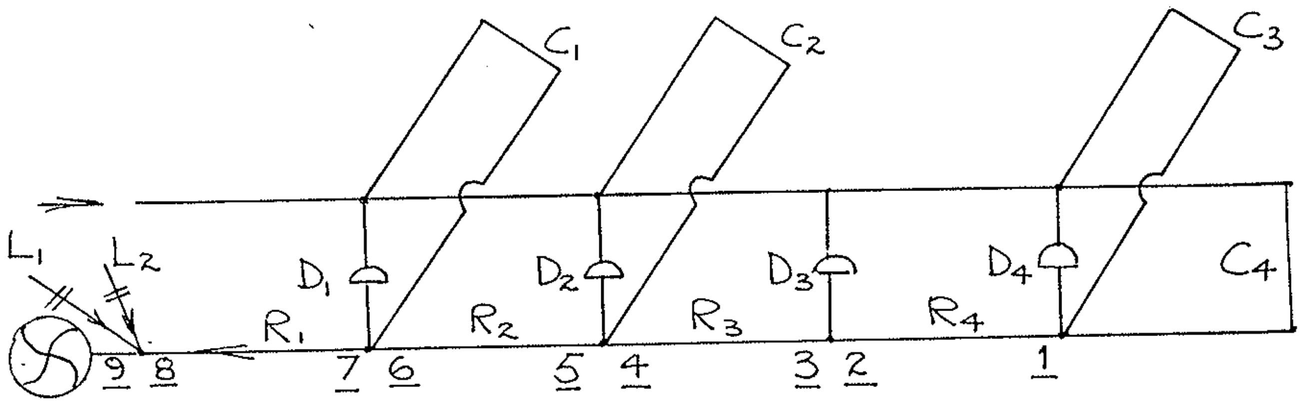
| Answer: | $C_1$ | $C_2$ | $C_3$ | $D_1$ | $D_2$ | Total |
|---|---|---|---|---|---|---|
| underground | 21.5 | 24 | 30.5 | 10 | 9 | 95 $m^3/s$ |

| surface | from mine | L | Total |
|---|---|---|---|
| | 104.5 | 12.5 | 117 $m^3/s$. |

The fan operating point is 1600 $N/m^2$, 117 $m^3/s$.

Exercises - Chapter 5

All of the exercises are based on a network similar to that in chapter 5.




Resistances of the parts of the network and points on the fan characteristic are shown below. The resistances $R_1$, $R_2$, $R_3$ and $R_4$ are the combined resistances of the intake and adjacent return airway.

| Resistances | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $R_1$ | $R_2$ |
|---|---|---|---|---|---|---|
| gaul | 1.5 | 0.75 | 0.525 | 0.375 | 0.045 | 0.0375 |

| $R_3$ | $R_4$ | $D_1, D_2, L_1$ | $D_3, D_4, L_2$ |
|---|---|---|---|
| 0.045 | 0.015 | 15 (each) | 6 (each) |

| Fan | | | | | | |
|---|---|---|---|---|---|---|
| $N/m^2$ | 3450 | 3150 | 2850 | 2700 | 2500 | 2300 |
| $m^3/s$ | 186 | 196 | 205 | 209 | 215 | 220 |

On A4 graph paper, suitable scales for the master are 250 $N/m^2$ and 10 $m^3/s$ per centimetre, the latter on the long edge. Because some exercises involve negative pressure and flow, the graph origin should be 5 centimetres in and up from the bottom left corner of the grid.

Exercise 1

Determine the total air flow, its distribution and the fan operating point.

| Answer: | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|
| | 31.5 | 35 | 31 | 36.5 | 14 | 21.5 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 10 | 8 | 10 | 8.5 | 206 $m^3/s$ |

The fan operating point is 2830 $N/m^2$, 206 $m^3/s$.

Note: Because the network is simple series/parallel the system resistance can be calculated and compared with the answer obtained from the graphical solution.

Exercise 2

Determine the effect of sealing circuit $C_1$.

| Answer: | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|
| | nil | 40.5 | 35.5 | 42 | 14.5 | 22.5 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 11.5 | 9 | 11.5 | 10 | 197 $m^3/s$ |

The fan operating point is 3120 $N/m^2$, 197 $m^3/s$.

Note: Although 31.5 $m^3/s$ is "saved", the total gain in the other circuits is only 15.5 $m^3/s$.

Exercise 3

Determine the effect of reducing flow in $C_1$ and $C_2$ to 20 $m^3/s$ each by means of regulators, and calculate the cross-sectional area of the regulators.

(An ordinate through 20 $m^3/s$ represents the modified resistance characteristic of both $C_1$ and $C_2$).

Answer:

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|
| 20 | 20 | 36.5 | 43 | 14.5 | 22.5 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 11.5 | 9 | 12 | 11 | 200 $m^3/s$ |

The fan operating point is 3000 $N/m^2$, 200 $m^3/s$.

The pressure drops across the regulators: $C_1$ 1240 $N/m^2$
$C_2$ 1050 $N/m^2$

Cross-sectional areas of the regulators: $C_1$ 0.68 $m^2$
$C_2$ 0.74 $m^2$

Exercise 4

With circuit $C_1$ sealed and a booster fan in $R_4$ passing 110 $m^3/s$, determine the distribution and fan operating points.

(The derived curve <u>2</u> is replaced by an ordinate through 110 $m^3/s$, which is then in parallel with $D_3$).

Answer:

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ | |
|---|---|---|---|---|---|---|
| nil | 34.5 | 44.5 | 52.5 | 14 | 21.5 | $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 11 | 8 | 5 | 13 | 204 $m^3/s$ |

The main fan operates at 2900 $N/m^2$, 204 $m^3/s$.
The required booster fan duty is 930 $N/m^2$, 110 $m^3/s$.

Exercise 5

With circuit $C_1$ sealed and a booster fan in $R_4$ having the points below on its characteristic, determine the distribution and fan operating points.

| Booster fan: | | | | |
|---|---|---|---|---|
| | $N/m^2$ | 1800 | 1500 | 1100 |
| | $m^3/s$ | 110 | 120 | 130 |

(The booster fan characteristic is drawn. The derived curve <u>2</u> is modified by the fan characteristic as shown in figure 4.5 in chapter 4.

Construction proceeds using the modified curve.

Assuming the possibility of reverse flow through the doors $D_3$, the curve of $D_3$ is extended into the negative pressure and flow quadrant, as in the exercise in figure 5.2 in chapter 5).

Answer:

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|
| nil | 29 | 51 | 60 | 14 | 21.5 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 10.5 | 7 | -2 | 15 | 206 $m^3/s$ |

The main fan operates at 2830 $N/m^2$, 206 $m^3/s$.

The booster fan operates at 1350 $N/m^2$, 124 $m^3/s$.

There is reverse flow of 2 $m^3/s$ through doors $D_3$.

Exercise 6

A booster fan is installed in $C_1$ to create flow at 45 $m^3/s$. Determine the distribution and the fan operating points.

(The curve of $C_1$ is replaced by an ordinate through 45 $m^3/s$).

Answer:

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|
| 45 | 32.5 | 29 | 34 | 13.5 | 21 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 10 | 7.5 | 9.5 | 8 | 210 $m^3/s$ |

The main fan operates at 2680 $N/m^2$, 210 $m^3/s$.

The required booster fan duty is 1725 $N/m^2$, 45 $m^3/s$.

Exercise 7

In order to increase air flow in $C_3$ and $C_4$, the separation doors $D_4$ are removed and a fan installed in that roadway to recycle 30 $m^3/s$ of conditioned air. The resistance of the roadway is 0.375 gaul.

Determine all flows and fan duties.

(An ordinate at a negative flow of 30$m^3/s$ is the imaginary resistance characteristic of the fan and roadway. This ordinate is in parallel with $C_3$ and $C_4$ to give the first derived curve, 1. This is shown in figure 5.4 in chapter 5. The 0.375 gaul curve is drawn in the negative pressure and flow quadrant).

| Answer: | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|
| | 34 | 39.5 | 42 | 49 | 14 | 22 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 11 | 9 | 12.5 | -30 | 203 $m^3/s$ |

The main fan operating point is 2925 $N/m^2$, 203 $m^3/s$.

The recycling fan must operate at 1240 $N/m^2$, 30 $m^3/s$.

Exercise 8

A recirculatory fan with points on its characteristic as shown is located in roadway $D_4$, which has a resistance of 0.375 gaul when the doors are removed.

Determine all flows and the operating points of the fans.

| Recycling fan: | $N/m^2$ | 1350 | 1250 | 1100 | 900 |
|---|---|---|---|---|---|
| | $m^3/s$ | 25 | 30 | 35 | 40 |

(The fan characteristic and resistance characteristic are drawn in the negative pressure and flow quadrant, then combined in the derived curve which is in parallel with $C_3$ and $C_4$, as in the example figure 5.5 in chapter 5).

Answer: The recycling fan characteristic has been chosen to give the same answers as in the previous exercise.

Exercise 9

Ignoring the existing main fan, determine the operating point of a new fan to provide $50m^3/s$ in $C_4$, when $C_1$, $C_2$ and $C_3$ are each restricted to $25m^3/s$ by regulators.

(An ordinate through $25m^3/s$ represents the modified resistance curves of $C_1$, $C_2$ and $C_3$. In this exercise it is not necessary to construct any curves. The only significant point on curve $C_4$ is at $50 m^3/s$. The parallel combination of $C_4$, $C_3$ and $D_4$ at that point gives the significant point on the first derived curve, which is used to locate the significant point on each subsequent curve).

| Answer: | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $L_1$ | $L_2$ |
|---|---|---|---|---|---|---|
| | 25 | 25 | 25 | 50 | 16 | 25 $m^3/s$ |

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | Total |
|---|---|---|---|---|
| 12 | 10 | 14.5 | 12.5 | 215 $m^3/s$ |

The new fan must operate at 3600 $N/m^2$, 215 $m^3/s$.

The pressure drops across the regulators in $C_1$, $C_2$ and $C_3$ are 1275, 1050 and 630 $N/m^2$ respectively, with cross-sectional areas 0.84, 0.93 and 1.2 $m^2$.

## Exercises - Chapter 6

In this group of exercises the resistances and flow ratios of leaky ducts have to be calculated. In some cases resistance and fan combination curves have to be plotted.

By assuming leakage paths at 100 metre intervals in an otherwise leakless duct, the number of calculations is minimised and the exercises can be done using a simple pocket calculator. Although a little tedious, the exercises help towards a better understanding of the curves in chapter 7.

### Exercise 1

A duct of leakless resistance 20 gaul per 100 metres, with 100 000 gaul leakage paths at these intervals, is to extend to 1200 metres.

Points on the characteristic of the fan to be used are shown below. Determine the fan operating points and delivered flows at

a) 600 metres with one fan

b) 1200 metres with two fans in 'series'.

| Fan: | | | | | |
|---|---|---|---|---|---|
| $N/m^2$ | 1800 | 1500 | 1250 | 1000 | 750 |
| $m^3/s$ | 2.2 | 2.95 | 3.45 | 3.9 | 4.3 |

(Resistances and flow ratios are calculated for 600 and 1200 metres. The resistance curves and fan curves are plotted to find the flows at the fans, then the flow ratios are applied to determine the delivered flows.

| Answers: | 600m | 1200m |
|---|---|---|
| Resistance - gaul | 99 | 156 |
| Flow ratio | 1.16 | 1.45 |
| Fan pressure $N/m^2$ | 1225 | 2200 |
| Fan flow $m^3/s$ | 3.5 | 3.75 |
| Delivered flow $m^3/s$ | 3.0 | 2.6 |

Exercise 2

If the duct and leakage path resistances in the previous exercise are halved, determine the delivered flows with the same fans.

| Answers: | 600m | 1200m |
|---|---|---|
| Delivered flow $m^3/s$ | 3.6 | 3 |

(The system resistance must also be halved. At this lower resistance, the fans would have been better in parallel).

Exercise 3

An installation of leakless resistance 50 gaul per 100 metres and leakage resistances 40 000 gaul at that interval, has three fans in series at the optimum spacing, with the second fan 200 metres from the first, which is at the inlet.

Points on the fan characteristic are

| | | | | | | |
|---|---|---|---|---|---|---|
| Pressure | $N/m^2$ | 3600 | 3050 | 2500 | 2000 | 1000 |
| Flow | $m^3/s$ | 3 | 3.5 | 4 | 4.4 | 5 |

Determine the length of the installation and the delivered flow, and compare it with the delivered flow with the fans as a group.

Answers: Installation length 1750m

Delivered flow with spaced fans $1.5 m^3/s$

Delivered flow with grouped fans $1.25 m^3/s$

Details of the stages of analysis are

Resistance at 200 metres is 88 gaul.

First fan operates at 1800 $N/m^2$, 4.5 $m^3/s$.

Flow ratio is 1.085.

Second fan operates at 2300 $N/m^2$, 4.15 $m^3/s$.

Resistance against second fan is 134 gaul.

Duct length at this resistance is about 350 metres.

Flow ratio at 350 metres is 1.2.

Third fan operates at 3050 $N/m^2$, 3.5 $m^3/s$.

Resistance against third fan is 250 gaul.

Duct length at 250 gaul is about 1200 metres.

The flow ratio at 1200 metres is 2.28.

The delivered flow is 1.5 $m^3/s$.

At 1750 metres resistance is 265 gaul, flow ratio 3.6.

Grouped fans operate at 5400 $N/m^2$, 4.5 $m^3/s$.

Exercise 4

An installation is to consist of 800 metres of main duct with 600 metre and 400 metre parallel branches. The leakless resistance per 100 metres of duct and the leakage resistances are shown below.

| | Resistances in gaul | |
|---|---|---|
| Duct | Duct | Leakage |
| 800m | 20 | 16 000 |
| 600m | 30 | 24 000 |
| 400m | 100 | 80 000 |

If the delivered flow from the 600 metre branch is to be 2 $m^3/s$, determine the flow from the other and the fan duty required.

Answers: Delivered flow from 400m is 1.4 $m^3/s$.

Fan duty required is 6750 $N/m^2$, 8.3 $m^3/s$.

Stages in the analysis are

For 600m duct resistance is 118 gaul, flow ratio 1.41.

Flow into 600m duct is 2.8 $m^3/s$.

For 400m duct resistance is 304 gaul, flow ratio 1.23.

Flow into 400m duct is 1.8 $m^3/s$ ($Q \propto 1/\sqrt{R}$).

Delivered flow from 400m is 1.4 $m^3/s$.

Total flow at the junction is 4.6 $m^3/s$.

Combined resistance at the junction is 45 gaul.

Overall system resistance is 98 gaul.

Fan flow required is 8.3 $m^3/s$.

Fan pressure required is 6750 $N/m^2$

Exercise 5

In the planning exercise in chapter 6 on spaced fans, $3m^3/s$ were delivered compared with $2.56\ m^3/s$ when the fans are grouped.

Assuming that spacing in the 1100m duct is regularised by having the second and third fans at 370m intervals from the first, the former fans with restricting orifices in the duct, determine the delivered flow and the orifice cross-sectional areas. Figures 6.3, 6.4 and 6.9 apply.

Answers: $2.5m^3/s$ $0.2m^2$ $1.2m^2$

(From figures 6.3 and 6.4, the resistance and flow ratio at 370m are 45 gaul and 1.24. From figure 6.9, at 45 gaul the fan passes $4.8m^3/s$ and delivers $3.87m^3/s$ to the second fan, which operates at $1250\ N/m^2$, so that resistance is 83 gaul. An orifice of resistance 38 gaul is required, its area approximately $0.2\ m^2$. The third fan passes $3.12\ m^3/s$ and delivers $2.5\ m^3/s$. The orifice area can be found as above. Note that the flow ratio 1.24 applies to all three lengths)

The answer indicates that to introduce resistance to regularise the fan intervals defeats the purpose of spacing, which is to increase the delivered flow compared with that of the fans as a group.

Exercises - Chapter 7

In this group the exercises are all based on the composite curves in figure 7.1, with some requiring the plotting of fan and resistance characteristics.

Exercise 1

A 1000 metre installation of 760mm flexible duct is planned to deliver 3 $m^3/s$ at an installation standard of "good". Determine the fan duty required.

Answer: 1500 $N/m^2$, 5.1 $m^3/s$.

Exercise 2

What is the minimum delivered flow with the fan which would deliver 3 $m^3/s$ in the previous exercise, if the standard is only "fair"?

Answer: 2.4 $m^3/s$

Exercise 3

A heading 800 metres long is to be ventilated by a pressure difference of 900 $N/m^2$ across separation doors between intake and return, with the heading in the intake airway. If the delivered flow is to be 2 $m^3/s$ when the leakage standard is "high", select suitable ducting.

Answer: 610mm steel or 760mm spiral.

Exercise 4

When a duct installation is 850 metres the delivered flow rate is 2 $m^3/s$ and the fan operating point 1200 $N/m^2$, 3.2 $m^3/s$.

Determine the standard of the installation and the leakless resistance per 100 metres of duct. If the installation extends to 1700 metres, find the fan duty necessary to maintain a delivered flow of 2 $m^3/s$, assuming that the same standard is maintained.

Answer: The standard is "good".
Leakless resistance per 100 metres is 22 gaul.
Fan duty at 1700 metres is 4300 $N/m^2$, 5.5 $m^3/s$.

Exercise 5

In an installation of 700 metres the delivered flow rate is 2.2 $m^3/s$ and the fan operating point 1100 $N/m^2$, 3.3 $m^3/s$.

An installation of ducting in similar condition is to extend to 1000 metres and deliver 3 $m^3/s$. Determine the fan duty required.

If the installation then extends to 1400 metres without additional fan power, what is the flow rate at that distance?

Answer: Fan duty required 4300 $N/m^2$, 6.2 $m^3/s$.
Delivered at 1400 metres 2 $m^3/s$.

(It is assumed that the standard is the same as that of the 700 metre installation. Calculation of the delivered flow at 1400 metres is on the basis of no significant increase in resistance beyond 1000 metres, with the fan continuing to pass 6.2 $m^3/s$).

Exercise 6

The following are routine airflow measurements taken as a duct extends.

| Length metres | Fan arrangement | Air flow at inlet | $m^3/s$ delivered |
|---|---|---|---|
| 800 | single fan | 2.6 | 2 |
| 1000 | single fan | 2.4 | 1.5 |
| 1200 | two parallel | 3.8 | 2 |
| 1400 | two parallel | 3.6 | 1.6 |

With the aid of figure 7.1, what conclusion can be drawn regarding the standard.

Answer: There is a deterioration in standard from "high" to "good".

(The fact that two measurements are for a single fan and two for parallel fans, is not relevant. The flow ratios indicate the trend. In this case the rate of increase in the flow ratio is abnormal.

Field measurements frequently indicate deterioration which is not necessarily associated with declining standards of installation, or damage. As length increases the fan pressure rises, and even more with the addition of fans, with the result that existing leakage paths may be enlarged. The resistances of the leakage paths are consequently reduced, whilst the resistance of the leakless duct remains constant).

Exercise 7

An installation of final length 1550 metres requires a minimum delivered flow of 2.5 $m^3/s$. The ducting has a leakless resistance estimated at 20 gaul per 100 metres and the planned leakage standard is "high". The fan(s) to be used have a characteristic as in the table below.

Determine the final arrangement and the intermediate change points, if any.

| | | | | | |
|---|---|---|---|---|---|
| Fan: | $N/m^2$ | 1750 | 1600 | 1450 | 1250 |
| | $m^3/s$ | 2 | 3 | 4 | 5 |

Answer: One fan to 800 metres.

Two series to 1200 metres.

Three series to 1550 metres.

(In chapter 2 it was shown that there are resistance zones of advantage for series and parallel arrangements, with the limits depending on the fan characterisic. In this exercise the advantage lies with series, and it will be found that whilst the ultimate requirement is met using three fans in series, it is not met with a series/parallel block of four fans).

Exercise 8

In an installation of "good" standard and a duct of leakless resistance 30 gaul per 100 metres, two fans having the characteristic of the previous exercise are to be spaced, with the first at inlet and the second 400 metres from it.

Determine the length of the optimum installation, the operating points of the fans and the delivered flow. Compare this flow with that for the two fans located at inlet.

| | | |
|---|---|---|
| Answer: | Optimum length | 1200 metres |
| | First fan | 1480 $N/m^2$, 3.8 $m^3/s$ |
| | Second fan | 1580 $N/m^2$, 3.2 $m^3/s$ |
| | Delivered flow | 2.1 $m^3/s$ |

For the two fans located at inlet on 1200 metres.

| | |
|---|---|
| Operating point | 2900 $N/m^2$, 4 $m^3/s$ |
| Flow ratio | 2 |
| Delivered flow | 2 $m^3/s$ |

Exercise 9

At a mine where 760mm spiral wire ducting is frequently used, planning is based on a leakless resistance of 23 gaul per 100 metres and a leakage standard of "high".

The measurements below are from four different installations. Use them to check the validity of the resistance and standard adopted for planning.

| | Fan | | delivered | Length |
|---|---|---|---|---|
| | $N/m^2$ | $m^3/s$ | $m^3/s$ | metres |
| a) | 2000 | 3.4 | 2 | 1000 |
| b) | 900 | 2.5 | 1.8 | 750 |
| c) | 2950 | 4.1 | 2.3 | 1200 |
| d) | 4700 | 5 | 2.5 | 1400 |

Answer: a) 31 gaul per 100 metres at "good" standard.

b) 28 gaul per 100 metres at "good" standard.

c) 27 gaul per 100 metres between "good" and "high".

d) 27 gaul per 100 metres nearer "high" than "good".

The resistance and standard are consistently under-estimated and over-estimated respectively.

Exercise 10

In a duct 2200 metres long, pressure and air flow 500 metres from the fan are 3600 $N/m^2$ and 6 $m^3/s$. The flow rate at discharge is 2.75 $m^3/s$.

Estimate the standard of the installation and the leakless resistance of the duct.

Answer: The standard is "good".

Leakless resistance is 15.4 gaul per 100 metres.

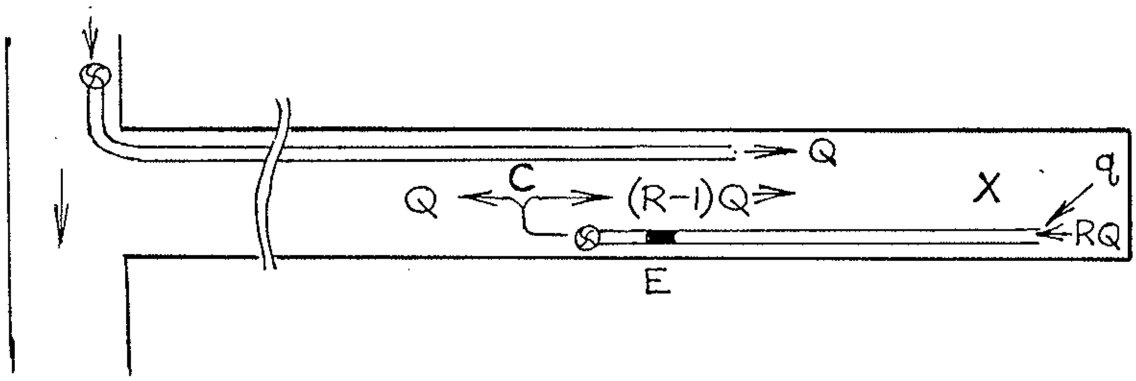
Strictly, the answer only applies to 1700 metres of the installation, and the assumption is that the first 500 metres are of the same standard and resistance. The shorter the latter distance the more valid is the assumption.

The method can be adopted when it is not convenient to measure close to the fan.

Exercises - Chapter 8

The exercises are concerned with respirable dust concentrations in recirculatory systems. The intention is that the problems should be solved from first principles, then checked using the general expression which was developed.

The diagram relates to all of the exercises.




$Qm^3/s$ is the delivery rate of fresh air.

$RQm^3/s$ is the flow rate in the exhaust duct.

R is the ratio of the exhaust flow rate to the delivery rate.

q mg/s is the rate at which fresh dust enters the exhaust duct.

E is the efficiency of the dust extractor.

C $mg/m^3$ is the dust concentration in the discharged and recycled air.

X $mg/m^3$ is the dust concentration approaching the tunnel face.

Exercise 1

In the tunnel which is force ventilated with a fresh air delivery rate of 2.5 $m^3/s$, the shift average respirable dust concentration is 10 $mg/m^3$.

If an exhaust recirculatory fan passing 4 $m^3/s$ is installed, with a dust extractor 75% efficient on fresh dust, determine the dust concentrations C and X when

a) efficiency on recycled dust is 75%.
b) efficiency on recycled dust is 40%.
c) efficiency on recycled dust is nil.

| Answer: | | C $mg/m^3$ | X $mg/m^3$ |
|---|---|---|---|
| | a) | 1.7 | 0.64 |
| | b) | 2.0 | 0.75 |
| | c) | 2.5 | 0.94 |

Exercise 2

In a tunnel which is force ventilated with air at a delivery rate of 2.5 $m^3/s$ and a dust concentration of 2 $mg/m^3$, the shift average concentration is 10 $mg/m^3$.

If an exhaust recirculatory fan passing 4 $m^3/s$ is installed, with a dust extractor 75% efficient on fresh dust, determine the dust concentrations C and X when;

a) efficiency on recycled dust is 75%

b) efficiency on recycled dust is 40%

c) efficiency on recycled dust is nil

| Answer: | C $mg/m^3$ | X $mg/m^3$ |
|---|---|---|
| a) | 1.7 | 1.9 |
| b) | 2.0 | 2.0 |
| c) | 2.5 | 2.2 |

(It is assumed that the dust in the delivered air has not previously passed through an extractor).

Exercise 3

In a recirculatory system the air delivered to the tunnel face carries respirable dust at a concentration of 1.5 $mg/m^3$. The flow rate is 2.5 $m^3/s$. The exhaust fan passes 4 $m^3/s$ and incorporates a dust extractor which is 80% efficient on the first pass and 40% on recycling. The tunnelling machine produces respirable dust which is raised into the air at a rate of 40 mg/s.

Determine the concentrations C and X.

Answer: C $2.8\ mg/m^3$

X $2.0\ mg/m^3$

Exercise 4

What is the effect in the above installation of the delivery rate falling to $1.5\ m^3/s$.

Answer: C $3.4\ mg/m^3$

X $2.7\ mg/m^3$

Exercise 5

In a recirculatory system the delivered air flow is at a rate of $2\ m^3/s$ and has a respirable dust concentration of $2.5\ mg/m^3$. At the tunnel face respirable dust is produced at a rate of 50 mg/s, and the recirculatory fan passes $3.5\ m^3/s$.

If the dust extractor is half as efficient on recycled dust as it is on the first pass, determine the efficiency necessary for a concentration at X of $2.5\ mg/m^3$.

Answer: 88%

Nominal resistance of leakless ducts...... Gauls/100m.

| Dia. mm | STEEL | FLEXIBLE | SPIRAL WIRE | |
|---|---|---|---|---|
| 460 | 100 | 120 | 280 | 280 |
| 610 | 23 | 30 | [illegible]0 | 70 |
| 760 | 8 | 10 | 23 | 23 |
| 915 | 3 | 4 | [illegible]0 | 10 |

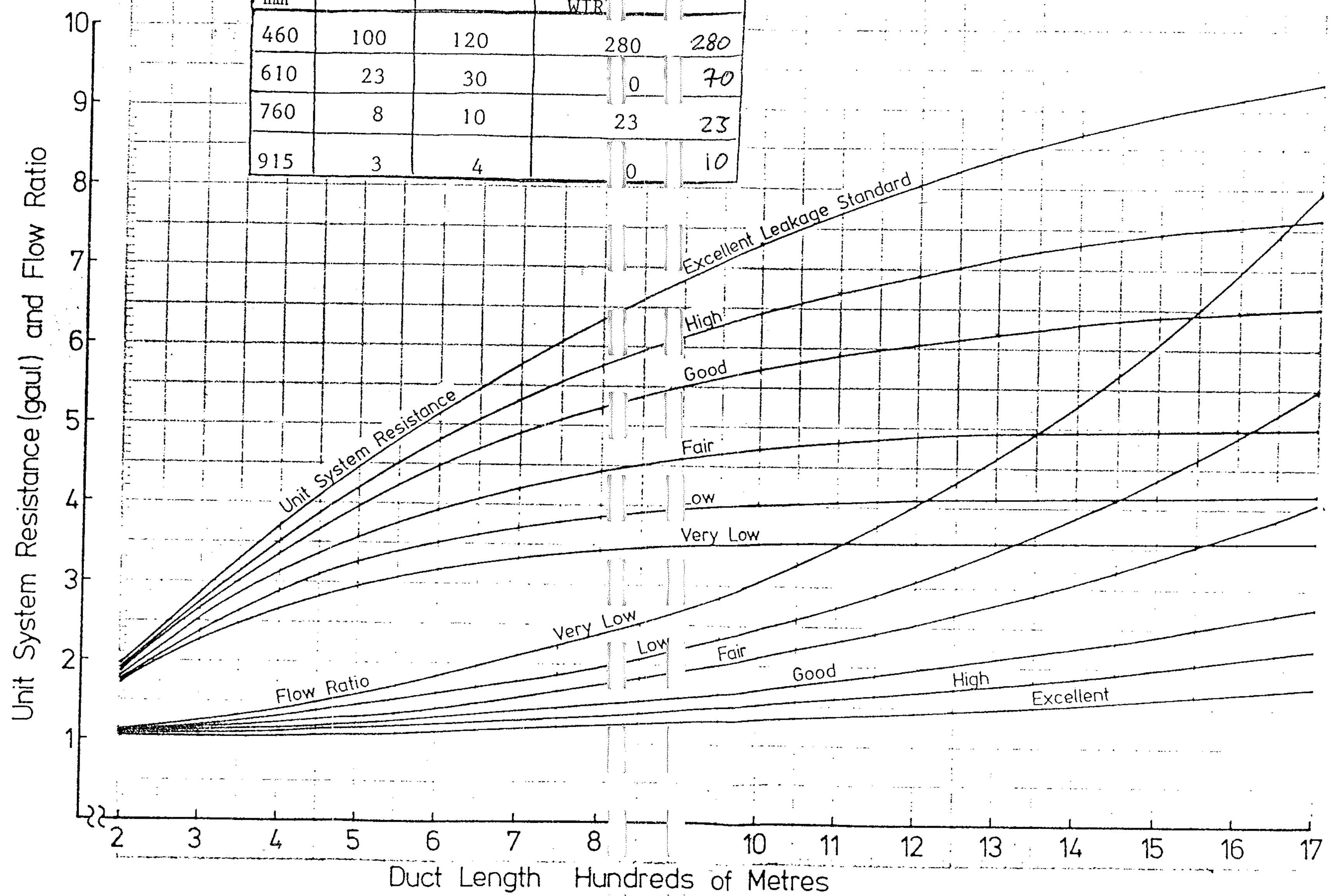



Figure 7.1 Resistance and Flow Ratios for Leaky Ducts.