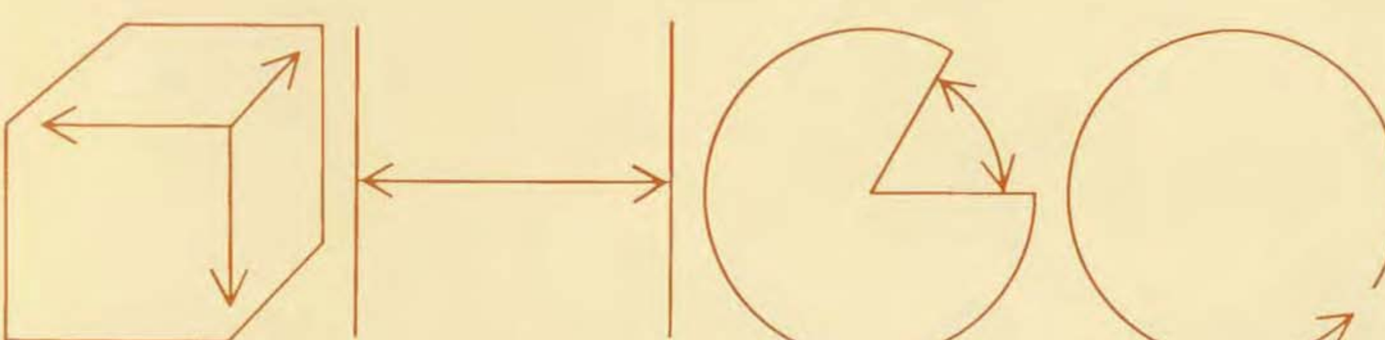
FOUNDATIONS OF MECHANICAL ACCURACY

WAYNE R. MOORE



This is the third book by Moore Special Tool Co.

Moore Special Tool Company, Inc., of Bridgeport, Conn., U.S.A., has built a world-wide reputation since 1924, both as a manufacturer of special tooling to extremely close accuracies and of machine tools which make possible a very high degree of precision. In the latter category, its jig borers, jig grinders, measuring machines, and the accessories related to this equipment are considered to be among the best of its kind produced in the industrial world.

A simultaneous characteristic of the company is its desire—and rare ability—to communicate the intimate knowledge it has acquired of these specialties to a wide audience. "The Moore Literature Library" is well-known within the industries it serves. Besides a wide array of brochures and case-history material, Moore in 1946 published a 448-page book, *Precision Hole Location*, by J. Robert Moore, and, in 1954, *Holes, Contours and Surfaces*, by F. C. Victory and Richard F. Moore. These two books, devoted to jig boring and jig grinding, have sold over 40,000 copies. The latter book is still in print.

In this third book, Wayne R. Moore has assembled in the 350 pages of *Foundations of Mechanical Accuracy* the company's intimate knowledge of and experience with mechanical accuracy, and how to achieve it. He has illustrated his text with over 500 original photographs and drawings. This book tells how to attain precision in manufacturing to millionths of an inch and how to control such precision by appropriate measuring techniques.

The book is divided into four main sections: geometry, standards of length, dividing the circle, and roundness. A fifth section covers "Universal Measuring Machine Techniques and Applications."

Introductory by M.I.T.'s Dean-Emeritus of Science

The introduction is by Dr. George R. Harrison, Dean-Emeritus, School of Science, Massachusetts Institute of Technology, a world-renowned spectroscopist whose accurate diffraction gratings are used for measuring the lengths of light waves in the laboratory and in astronomy. Here are excerpts:

"Basic to man's behavior is his ability to determine, modify, and adapt to his environment. This he has been able to do in proportion to his skill at making measurements, and fundamental to all other measuring operations is his ability to determine locations in the material world. Thus the science of mechanical measurements is a fundamental one. It is this science, and the art which accompanies and informs it, with which this book is concerned."

After recounting his experience in working with the Moore Special Tool Company since 1959 to develop more accurate ruling engines for producing diffraction gratings, Dr. Harrison writes:

"It is easy to see why the scientist who is primarily occupied with obtaining 100,000 straight grooves in a single operation, each a narrow mirror properly inclined to the beam of light which is to be reflected from them, welcomes most gratefully the development of fine mechanical machines which can, in an almost literal sense, be 'bought off the shelves'. The amount of painstaking labor, skill in design, and the heritage of fine workmanship required before machines can be brought to such a stage of perfection, will be appreciated most of all by readers of this excellent book."

Photo by William Vandivert

WAYNE R. MOORE literally grew up with a passion for precision, which he inherited from his father, Richard F. Moore. In 1924, Dick Moore, a toolmaker, had opened a two-man shop in Bridgeport to make special tooling for watch, clock and typewriter plants. It has grown to worldwide eminence.

Wayne joined the company in 1953 after earning a degree in economics at Yale, and then completed his apprenticeship as a tool and diemaker. While at Yale, he captained, in 1952-53, what has been called the greatest swimming team of Bob Kiphuth, famous Eli coach. He won gold medals in both intercollegiate championship races and in the 1952 Olympics at Helsinki.

The research and writing of this book, as well as the time he devoted to supervising the extensive illustrations, were sandwiched in over a period of 7 years while he has been active in helping the Moore Company develop its advanced metrology and machine tool products.

He resides with his wife, Janice, and five children in Nichols, Connecticut, where he is a dedicated organic gardener.

FOUNDATIONS OF MECHANICAL ACCURACY

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FOUNDATIONS OF MECHANICAL ACCURACY

WAYNE R. MOORE

With an Introductory by Dr. George R. Harrison,
Dean-Emeritus of Science, Massachusetts Institute of Technology

THE MOORE SPECIAL TOOL COMPANY · BRIDGEPORT, CONNECTICUT

Preface

A TECHNICAL BOOK devoted to a little-explored subject originates long before it is actually written. Many people contribute to its content through their guidance and assistance. This book is no exception.

I consider myself fortunate to be associated with a company whose policy has always been to share both its processes and its techniques. To make available the resources of Moore Special Tool Company for the improvement of industry, science, and society in general has been the philosophy of my father, Richard F. Moore, who founded the company in 1924. The policy has been rewarding to the company in many ways. I am grateful that I have the opportunity of continuing in what has become a Moore tradition.

In 1946, Moore published its first full-length book, *Precision Hole Location for Interchangeability in Toolmaking and Production*, by J. Robert Moore. In 1954, *Holes, Contours and Surfaces*, by Richard F. Moore and Frederick C. Victory, followed.

This volume was planned to explain in graphic detail the significant course which mechanical technology has taken since *Holes, Contours and Surfaces* appeared. This course is directed inexorably *towards greater accuracy*. I undertook the task largely because of Richard F. Moore's encouragement, guidance and support. Most of the mechanical principles described herein can be traced to him.

The significance of the World's Bureaus in establishing and maintaining standards is described in a special section, Pages 95–97, written especially for this book by an outstanding metrologist of each Bureau: P. Carre, of the Bureau International des Poids et Mesures, France; L. W. Nickols, of the National Physical Laboratory, England; E. Engelhard, of the Physikalisch Technische Bundensanstalt, West Germany; A. G. Strang, of the National Bureau of Standards, U.S.A. They made possible a description of the functions of their sections of each Bureau, met with the author personally for helpful discussions, and also contributed valuable additional material. Their colleagues—Stanley P. Poole, of NPL; Rudolf Noch, of PTB, and T. R. Young, of NBS—also provided useful information.

I warmly thank T. R. J. Oakley, of NPL, who not only reviewed the entire manuscript and illustrations meticulously, and gave innumerable suggestions and comments. It was my good fortune to enlist for this important role a man who soon confirmed that I could have selected no one with a greater depth of knowledge and experience in the subject.

Richard L. Parnoff, the Chief Inspector at Moore, also reviewed the manuscript and the illustrations. He brought to the project the same thoroughness and valuable suggestions that aided the authors of *Holes, Contours and Surfaces*.

The Moore Company and I are singularly honored to have Dr. George R. Harrison, Dean Emeritus of Science of the Massachusetts Institute of Technology, write the Introductory. His encouraging words and advice, including the refining of the book's title, were also in a personal sense very important to me.

Robin Gosling, of the Science Museum, London, and Bernard Bothmer, Curator of Ancient Art, Brooklyn Museum, led me to many historical works. I was able to find items of historical interest with the help of Gilbert L. Dannehower, of High Precision Products Company; George Schaffer and Rupert LeGrand, of *American Machinist*, and Mrs. Nettie Wright Adams, editor and publisher, *The Lure of Litchfield Hills*.

Many firms, institutions and individuals, whose names are credited throughout the pages, contributed to the content of the book.

Years of exposure of the Moore staff to world-renowned metrologists, who came to Bridgeport in their pursuit of accuracy, greatly enhanced the scope of the book. I single out particularly James Bryan, of the Lawrence Radiation Laboratory, University of California, with whom many informative discussions were held.

Alfred Sturzenegger, of the Precima Company, West Germany; Robert Mundy, of the Catmur Corporation, England; Claude Pardessus, of Stokvis et Fils, France; Walter Zindel, of the Moore Office in Switzerland, and Arvid Arvidsson, of Sweden, all provided helpful liaisons within their countries.

So many of my colleagues at Moore Special Tool Company assisted in bringing this project to a successful conclusion that space doesn't permit listing all by name. Albert Johnson, chief engineer of special products, and Anto Lindberg, chief engineer of standard products, and their staffs; Richard Kuba, advertising coordinator, gave much time and interest to it. Mrs. Justine Haydu not only typed and retyped the manuscript with unfailing good humor, but managed to organize a mountain of source material, pursue the bibliography and maintain the paperwork so efficiently as to permit a book of this size and scope to be researched in an office concerned with the engineering and sale of machine tools.

My deep thanks go to numerous Moore employees, some of whom appear in illustrations throughout the book and others behind the scenes, for their cheerful cooperation in so many ways.

The writing itself took place in the quiet confines of the company's legal offices, the chambers of Charles Brody and Seth Brody, old friends and advisors. To the Brodys, their partners and staff, my grateful thanks for the splendid retreat they provided.

Since the Moore Company itself is publishing this book, we also required all the disciplines associated with publishing. For this, I was fortunate to have the services of the company's long-time marketing and communications counsellors, The Fred Wittner Company, which had guided both previous books to successful completion. Fred Wittner helped to shape the direction of the book and to edit it for publication; he also contributed sound advice, based on his great breadth of experience. Sel Torby designed it and supervised its production with understanding, good taste, and consummate skill and patience.

All of the color and black and white photography taken at Moore is the work of William Vandivert, a resourceful journalist-photographer, who was a Life Magazine "great" for many years, and who also proved to be a discerning critic and counsellor. The engineering drawings are the product of F. R. Gruger, Jr., outstanding technical illustrator, who did the same work for *Precision Hole Location* and *Holes, Contours and Surfaces*.

WAYNE R. MOORE
Bridgeport, Connecticut, U.S.A.
July 22, 1970

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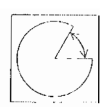

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Introductory

BASIC to man's behavior is his ability to determine, modify, and adapt to his environment. This he has been able to do increasingly as his skill at making measurements improved, and fundamental to all measuring operation is his ability to determine locations in the material world. Thus the science of mechanical measurements is a basic one. It is this science, and the art which accompanies and informs it, with which this book is concerned.

I am particularly happy to be invited to write these introductory words because it gives me an opportunity to testify to the tremendous importance of the availability of machines which make precise and accurate mechanical measurements possible. My acquaintance with the Moore Special Tool Company ended a quest for instruments of the utmost mechanical refinement, which could then be refined still further by the application of optical and electronic controls in ways not previously attempted, because the technologies needed for such attempts had not previously been available.

As a spectroscopist interested in measuring to seven significant figures the lengths of light waves, themselves only 10 to 20 millionths of an inch long, I was seeking ways of ruling bigger and better diffraction gratings. With these the light waves from atoms and molecules, whether in the laboratory or in the stars, could be more adequately studied.

The problem is simple to outline. On a glass or fused quartz mirror blank coated with a thin layer of aluminum deposited in vacuum, one desires to engrave 100,000 long grooves, each straight to a millionth of an inch, parallel to its neighbors to within that tolerance, and equally spaced, so that every groove is within a millionth of an inch of its proper location. Furthermore, any repeated or periodic errors in groove location should be held to less than one-tenth of a millionth of an inch.

Up until 1947 these specifications had been fairly well met for gratings up to 6 inches in width by purely mechanical ruling engines, built in scientific laboratories, usually in a cooperative effort between a physical scientist and a superbly skilled instrument maker. But many experts had spent long years in futile attempts at ruling wider gratings with longer grooves. Some had felt that the way to solve this problem was by making light waves themselves correct the errors of the engraving machine during the ruling process, but the proper technologies for carrying this out were not yet available.

After having taken a solemn oath to myself never to get entangled with the unending problems of grating ruling, I decided in 1947 that the newly available mercury isotope lamps might furnish light of a sufficient singularity of color to guide such an engine. When the University of Chicago offered M.I.T. an old, warped, partially rebuilt engine whose base castings had been machined under the direction of A. A. Michelson back in 1900, I felt that if interferometric control could make this device work, it could make any engine work.

The next ten years were spent in developing optical control methods and servomechanisms which did, indeed, reduce the errors of positioning of the engine ruling tool to 1/600th of their previous magnitude. With this so-called "A" engine, described in the last section of this book, my colleagues and I were able to rule many gratings of 10-inch width and of a quality never previously attained.

In 1959 we were ready to build a second, larger engine, and I began a search for producers of very accurate screws. It seemed of great importance to demonstrate that a commercially built machine, placed under interferometric control, could be made to function as a ruling engine. The Moore Special Tool Company had available drive screws which were nine times more accurate than that used in our A engine, and after testing two or three of these we ordered a Moore Universal Measuring Machine of 18-inch capacity, without the superstructure. When placed under interferometric control this proved much more accurate than the "A" engine, and with it many outstanding gratings up to 16 inches in width, with grooves up to 8 inches long, have been ruled.

As recounted later, when this engine was successful we ordered a No. 4 measuring machine from Moore, have now put this under interferometric control, and have ruled a number of gratings in sizes up to 12 x 15 inches. We hope eventually to produce 18 x 24 inch gratings with it.

From this story it is easy to see why the scientist who is primarily occupied with obtaining 100,000 straight grooves in a single operation, each a narrow mirror properly inclined to a beam of light which is to be reflected from them, welcomes most gratefully the development of fine mechanical machines which can, in an almost literal sense, be "bought off the shelves."

The amount of painstaking labor and skill in design, and the heritage of fine workmanship required before machines can be brought to such a stage of perfection, will be appreciated most of all by readers of this excellent book. That it will be welcomed by a wide range of readers goes without saying.

GEORGE R. HARRISON
Dean Emeritus, School of Science
Massachusetts Institute of Technology

". . . . . the architect in his work ought to be practiced in all accomplishments. Yet reason, in view of the scope of matters, does not permit us, as need demands, to have a complete, but only a moderate knowledge of the various subjects involved. Hence I beg your Highness and other readers of these volumes to pardon any explanation that too little agrees with the rules of literary art. For it is not as a lofty thinker, nor as an eloquent speaker, nor as a scholar practiced in the best methods of literary criticism, but as an architect who has a mere tinge of these things, that I have striven to write the present treatise. But in respect to the meaning of my craft and the principles which it involves, I hope and undertake to expound them with assured authority, not only to persons engaged in building, but also to the learned world."

—Vitruvius, "De Architectura"

FIG. 1—*The attainment of a "cubic concept" of accuracy in the Universal Measuring Machine requires the individual mastery of four mechanical arts—geometry, length, dividing the circle and roundness.*

Throughout the text, an attempt will be made, where relevant, to immediately accompany each given dimension with the equivalent figure in metric or English units, whichever the case may be.

The converted figure will not always be exact, but will be rounded off to what seems to be the nearest significant figure.

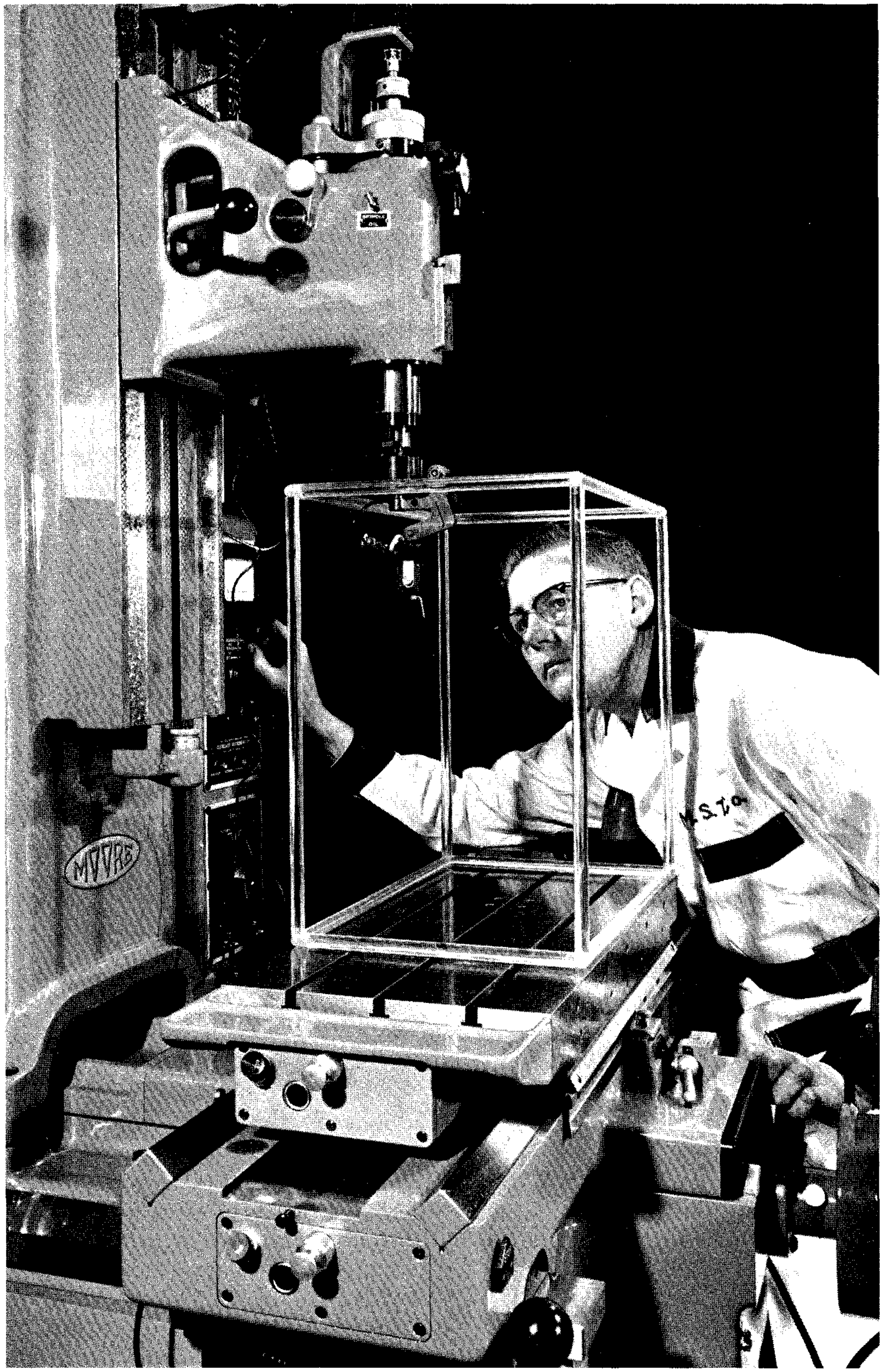
This will be done with a special bracket used only for this purpose.

For example:

10 millionths of an inch [0.00025 mm]
100 mm [3.937 inches]
20°C. [68°F.]

It is hoped that this will provide greater ease of reading to those who might be more familiar with one or the other system.

However, in those cases where the converted figure detracts from clarity, or does not aid in understanding, it will be omitted.



We are confronted today with a bewildering array of measurement hardware and measurement techniques. However necessary, they tend to obscure the beautiful and fundamentally simple nature of the measurement process itself.

As did Vitruvius, we recognize our incomplete knowledge of the total subject involved, and certainly a lack of eloquence. Yet, as builders of tools, we find ourselves uniquely qualified to "undertake to expound with assured authority" the meaning and significance of measurement . . . both to show it reduced to its simplest elements and to explain how these, in turn, relate not only to advanced mechanisms, but to the very frontiers of measurement.

The frontiers of measurement are critically related to the progress of civilization itself, notably in interchangeability of manufacture. When brought to their highest level, the concepts described here contribute to extending the frontiers of scientific knowledge to the outermost limits of the universe. As an example, these principles have been applied to the manufacture of ruling engines used to produce the most accurate gratings now available—gratings that are mated with giant astronomical telescopes to analyze light from the most distant stars.

The concept of measurement which unfolds derives largely from our own experience. Because of this approach we may dwell too lightly or even neglect certain aspects which others may think more significant; yet it is hoped that the gain to the reader will be greater continuity and a fuller comprehension of the total concept of measurement.

At Moore, a goal had been set to build a machine tool to a cubic concept of accuracy.* It would measure by coordinates to a much closer tolerance than had previously been achieved. The cube would have a tolerance of approximately 25 millionths of an inch in an 11 by 18 by 17 inch travel [0.0006 mm in 279 by 457 by 432 mm].

The reader may appreciate the difficulty of this task when reminded that the tolerance of a single gage block of the highest laboratory quality is ± 0.000001 (1 millionth of an inch) per inch of length [0.000025 mm per 25 mm] or approximately 18 millionths of an inch over 18 inches [0.00046 mm over 457 mm] (if indeed a gage block could be built to such a tolerance in larger sizes).

Besides, this was not to be just a "static" cube, but rather a "live" cube, within which the ordinates must provide this positional accuracy of 25 millionths of an inch, [0.0006 mm] including straightness and squareness over an infinite number of intervals within the cube, Fig. 1.

Existing in-shop standards and masters were not capable of attaining the desired accuracies. A complete re-evaluation led to one conclusion: We had to go back to our fundamental standards and build from there.

This process forms the basis of our story.

To achieve this new generation of accuracy and to incorporate it to the maximum in a Universal Measuring Machine required the individual mastery of four mechanical "arts."

1. Geometry
2. Standards of Length
3. Dividing the Circle
4. Roundness

1. GEOMETRY: The total geometry of the machine tool has its foundation in the flat plane. The familiar surface plate is its embodiment. From the surface plate evolves straightedges, squares, scraping masters and machine ways.

2. STANDARDS OF LENGTH: Here the emphasis is on where the measuring element of a machine tool—in Moore's case the lead screw—derives its accuracy. In the process of arriving at the lead screw system, all possible forms of length-measuring standards come under consideration, such as: gage blocks, end standards, precision scales and lightwave measuring interferometers.

3. DIVIDING THE CIRCLE: Accurate circle division is a requirement of all laboratories and machine shops. It is also closely related to the cubic concept of accuracy since a machine tool of the jig borer family must measure by coordinates as well as have the facility to make angular measurements.

4. ROUNDNESS: Precision machine tools must achieve roundness of many mechanical parts and especially with their spindles. The focal point of roundness here is the Universal Measuring Machine spindle. Its performance, in turn, is dependent on the overall accuracy of holes, shafts, balls and other components which comprise its construction.

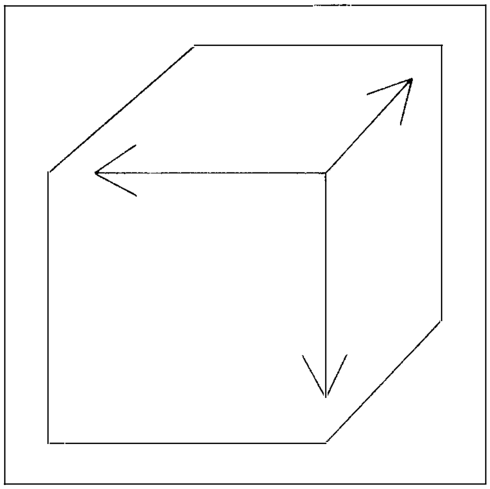
These four mechanical arts are truly the "Foundations of Mechanical Accuracy," since all forms of measurement can be resolved into only these four fundamentals.

Geometry, dividing the circle and roundness need no reference to an outside authority; the degree of accuracy depends only on the technique, facilities and skill of the maker. Standards of length, on the other hand, are arbitrary, so are ultimately derived from some authoritative source, such as the National Bureau of Standards of the United States, the National Physical Laboratory of England, the German Standards Bureau, or the International Bureau.

*Richard F. Moore & Frederick C. Victory, *Holes, Contours and Surfaces*, Moore Special Tool Company, 1955, p. 56.

GEOMETRY

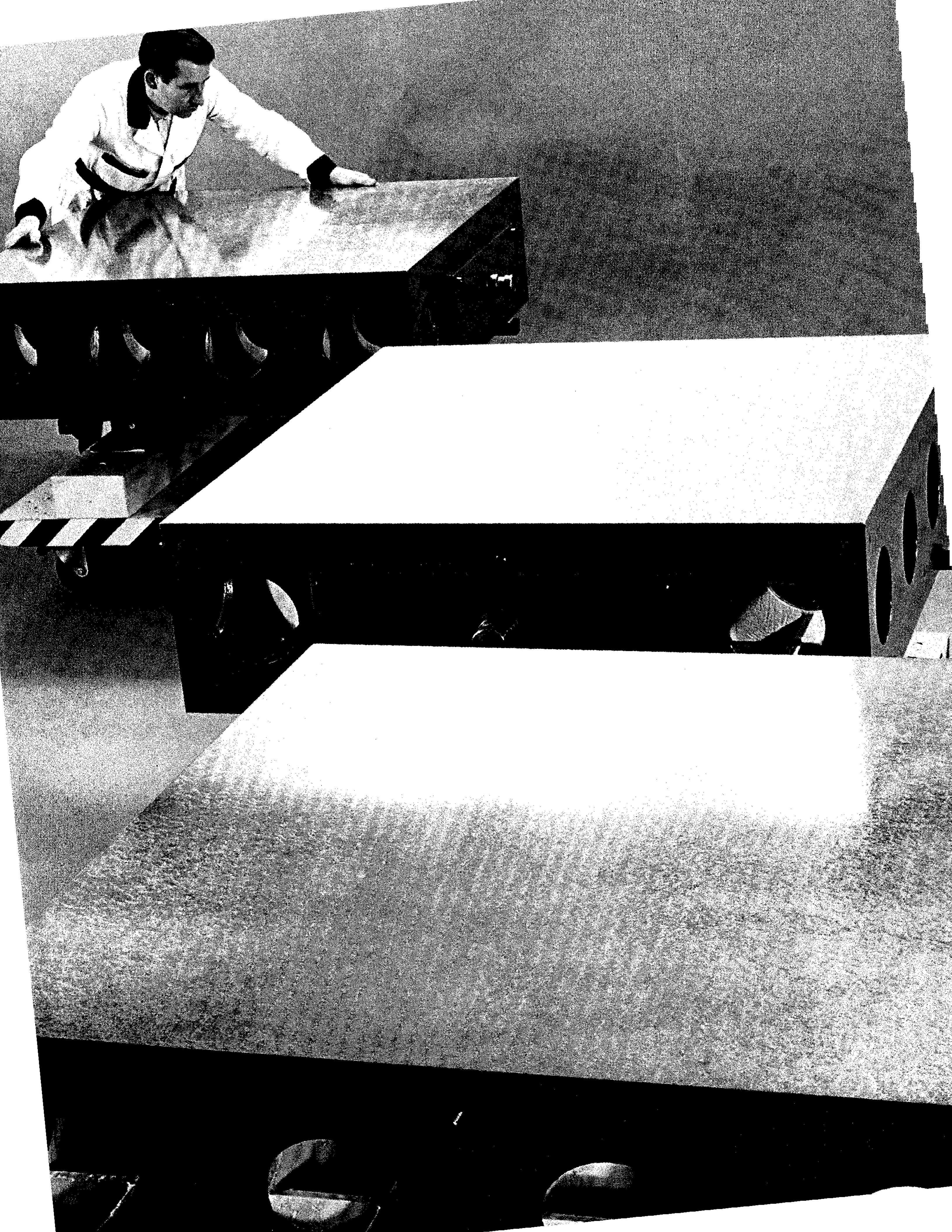
1



The foundation of the mechanical art of geometry is the flat plane. Evolving from the flat plane are master straight-edges and squares, scraping masters, laps, and finally the geometric accuracy of the machine-members themselves.

FIG. 5—*The foundation of all geometric accuracy and indeed of all dimensional measurement is the flat plane.*

Flatness is inherently attained by the cross matching of three surface plates. These master 48-inch [1219 mm] surface plates are made of stabilized iron, are square and extremely rigid because of their box-type construction.



Preliminary to discussing the mechanical art of geometry, some common misconceptions about cast iron, a prime material component of most of the elements of geometry, must be dispelled.

Also analyzed here are the principles of recommended inspection procedure. In the discussion of geometry that follows, frequent references will be made to these principles.

ENVIRONMENTAL EFFECTS ON CAST IRON

It is not uncommon for a cast iron part, whether straightedge, surface plate, or machine tool, to seem to lose its straightness, flatness, squareness, or to change in some other manner over a period of time. The stability of the iron is often blamed when, in fact, this is rarely the case.

This section has a threefold purpose:

1. To show that cast iron is inherently stable;
2. To differentiate between real and apparent sources of instability;
3. To point out those environmental conditions essential to geometrical accuracy.

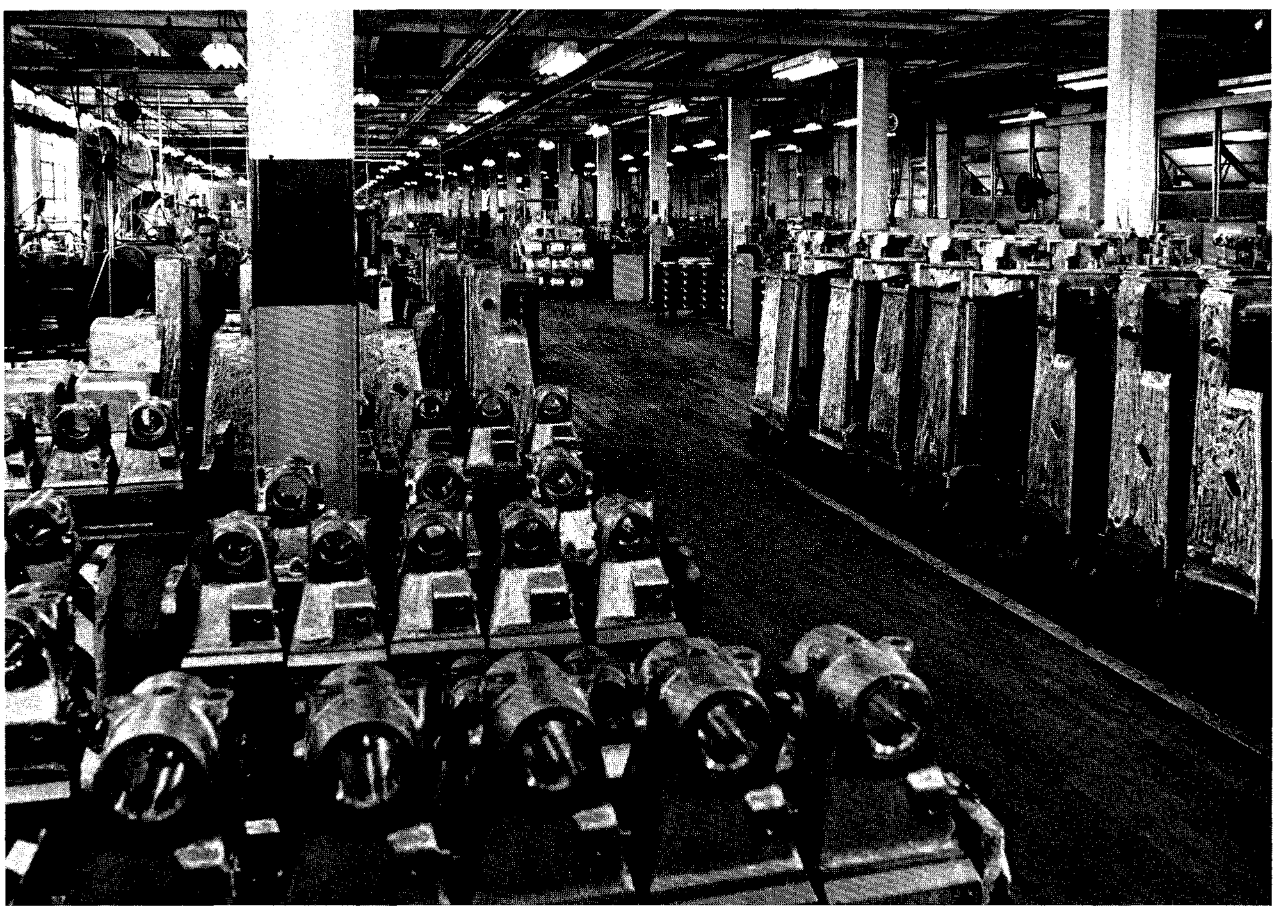


FIG. 2—*The conclusion that cast iron is inherently stable is based partly on strong statistical evidence—that of thousands of castings machined and scraped to a higher order of accuracy as well as careful records kept over many decades.*

1. Foundry Technique

Foundry technique is a factor in stability and hence in final accuracy.

A. *Proper composition* of the iron improves machinability, wear qualities, and the quality of the scraped surface (it is physically difficult to accurately scrape a bad casting or one with blow-holes).

B. *Stability of the iron depends mostly on slow, uniform cooling in the mold after casting.* This, in turn, depends on molds of the proper design, and on allowing sufficient time for complete cooling before the casting is exposed to air. There is possibly no other metal more stable than cast iron that meets the preceding two specifications.

Our faith in the stability of iron derives from strong statistical evidence: the experience of thirty years of precision machine tool manufacture, involving, at the time of writing, over 7,000 machines, Fig. 2. It also derives from the study of a jig grinder which had been returned for repairs after having been in a severe fire in an automotive plant. Completely scorched, its paint had been burned off and it was caked in tar and soot. The temperature was high enough to melt the aluminum guards into a puddle on the table.

The component cast iron parts were first immersed in a pit of solvent for cleaning, then inspected. There was virtually no deviation from the original factory calibration. Any lingering doubts we might have had about the stability of cast iron were dispelled.

The inherent stability of cast iron was also confirmed by Nickols of the N.P.L., who made tests on its stability over a period of seven years.*

*L.W. Nickols, "Investigations into the Stability of Castings (with particular reference to Meehanite castings)," NPL Technical Bulletin S.S.193, May, 1940.

For the bases, columns, tables and cross slides of the machine tools it builds, as well as for surface plates, straightedges and scraping masters, Moore uses only a Meehanite cast iron, close-grained, of closely controlled analysis and cooled slowly in the mold.

II. Machining of Cast Iron

Despite its stability, cast iron does not differ from many other metals in that the removal of a substantial amount of material by machining, especially the outer skin, will alter its equilibrium. Before the finish cut, the piece is first allowed to relax by release of the clamps; it is then properly supported and re-clamped without bending, Fig. 3.

The piece may or may not be free of stresses, depending on the method by which it was machined.

The preferred method of machining is to single-point plane important functional cast iron surfaces, Fig. 4. The reasoning behind this procedure may be seen in a controlled experiment conducted to determine the effects of machining on cast iron. Using cast iron gibs as test pieces, it was found that with single-point planing, the gibs would spring the least from machining and would be absolutely stable henceforth. Milling the gibs caused more machining distortion and a somewhat permanent instability until the gibs were stress-relieved. In other words, it is possible to *machine-in* instability.

III. Elastic Deflection

A large cast iron section will easily bend when a load is applied, or when weight is added, or may even bend under its own weight. So often and in so many ways does elastic deflection occur, that it is easily mistaken for instability of the iron itself. Deflection may be minimized through design and support, but never completely eliminated. In some instances, as the reader will observe with the two-footed gage (page 26),

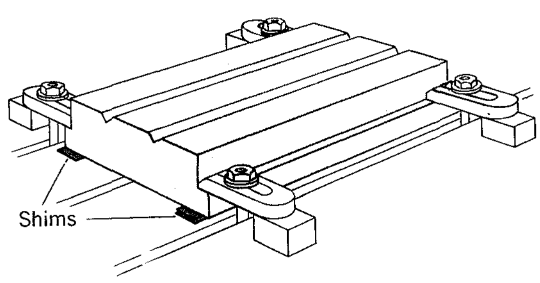
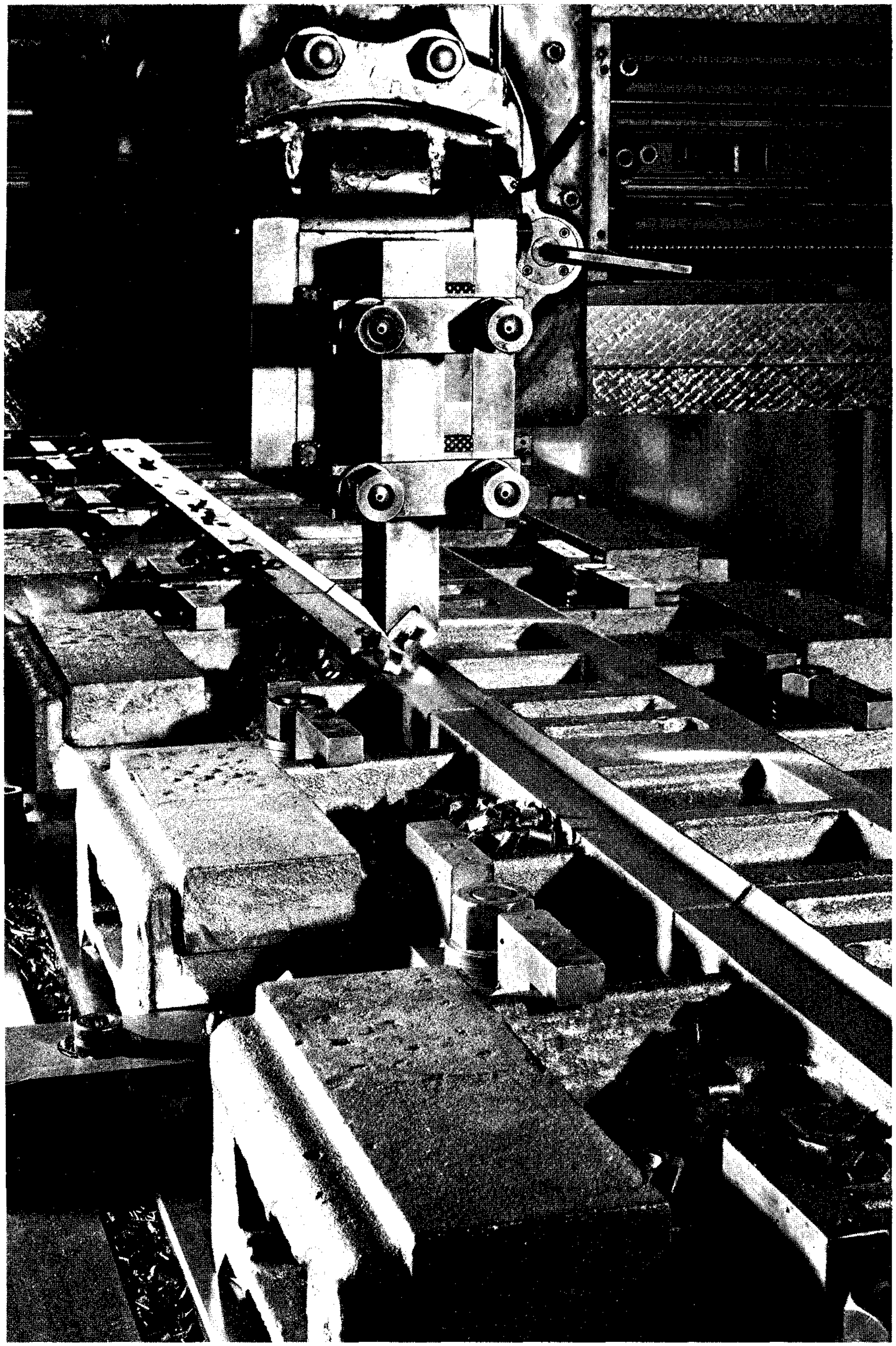


FIG. 3—*For maximum accuracy when machining surfaces, irregularities in the supporting surface are balanced out through the use of shims. Most of the heat and stress of machining is removed in a first rough-cut.*

The workpiece is unclamped, permitting it to relax. It is supported evenly once again, clamped less tightly and finished with a light skim cut.

FIG. 4—*Stability of the casting is assured initially by slow cooling in the mold. However, the method of machining may also introduce stresses. Major functional surfaces of machine members, such as the ways, should be single-point planed.*



deflection is not necessarily detrimental to accuracy, since the amount of deflection is almost perfectly constant, given like conditions. In the case of the extremely rigid 48 inch [1219 mm] master surface plate, a small amount of deflection still occurs, and will be a temporary limiting factor in the attainable accuracy of the plate.

It is important to recognize that, with every step in the attainment of accuracy, the problem of elastic deflection is always present. This fact will continually be emphasized throughout the book.

IV. Temperature and Instability

A. *Geometric relationships are not effected by the value of ambient temperature, providing it is steady.* For example, a surface plate, flat at a temperature of 70°F. [21.1°C.], will be flat at a temperature of 90°F. [32.2°C.]. A test square, in error by .2 seconds of arc at 90°F., will be in error by .2 seconds of arc at 70°F. [21.1°C.]. In a machine tool, two female V's of one member that match two male V's of another member where both are the *same* temperature, will also match each other when both are some *other* temperature. The distance between the V's in each will change, but by the same amount.

B. *Temperature Differentials*—If, however, the piece or pieces are subject to localized heat or cold, not only does growth or shrinkage occur, but the piece may be subject to unpredictable distortion. It returns to its normal geometric relationship only when the temperature throughout is again made uniform. The distortion which occurs as a result of uneven temperature is the source of a great deal of misunderstanding and confusion. The result so resembles that which one would expect from "unstable" iron that it is not surprising the iron is blamed. Imagine a situation in which a piece had been scraped, inspected and, unknowingly, proved accurate in a condition of non-uniform temperature. When the piece returns to uniform temperature, attempts to repeat the previous accuracy check are in vain.

Some persistent, recurring sources of temperature differentials are worth mentioning:

—Proximity to radiators, doors, windows or drafts;

—Heat from handling;

—Changes in room temperature. This may particularly effect larger pieces, because the time required to "soak out" may be several hours.

—Stratification—It is extremely difficult to control the temperature of a room accurately from floor to ceiling. Even in advanced metrology laboratories, where temperature can be controlled to $\pm \frac{1}{4}$°F. [$\frac{9}{64}$°C. approx.] within a height of two or three feet [0.6 to 0.9 meter] there will usually be a difference of 2°F. [1.1°C.] from floor to ceiling. This is satisfactory for small work, but the average machine tool stands at least six feet [1.8 meters] so will be subjected to temperature gradients of the room. (This effect on linear measurements will be dealt with on pages 118, 119 and 171, 172). Temperature control is, of course, the best answer but will be of little value unless certain correct procedures are also followed.

Conclusion

The theory that a cast iron part must be exposed to the weather to rust and "age" in order to stabilize it is a carry-over from the past. In the absence of closer measuring facilities or adequate temperature control, the stability of the iron was blamed. Supposed cases of instability might have been traced to machining practices, deflection or, most often, to temperature variations.

Cast iron is an ideal material. It is readily available, can be easily cast to shape, and is relatively uninfluenced by humidity. It has nearly the same coefficient of expansion as steel and will give a bearing to which a piece may be scraped. Above all, it is one of the most stable of materials. These advantages are not present in all steels, granite, or other materials which might be considered as a substitute.

Requirements of an Inspection Tool

The requirements of an ideal inspection tool are five-fold. They are analyzed here in advance of the discussion of geometry because they all pertain to the inspection principles Moore espouses:

It is accurate;
It requires a minimum of operator skill;
It inspects a specific type of error;
It is fast to use;
It is self-checking.

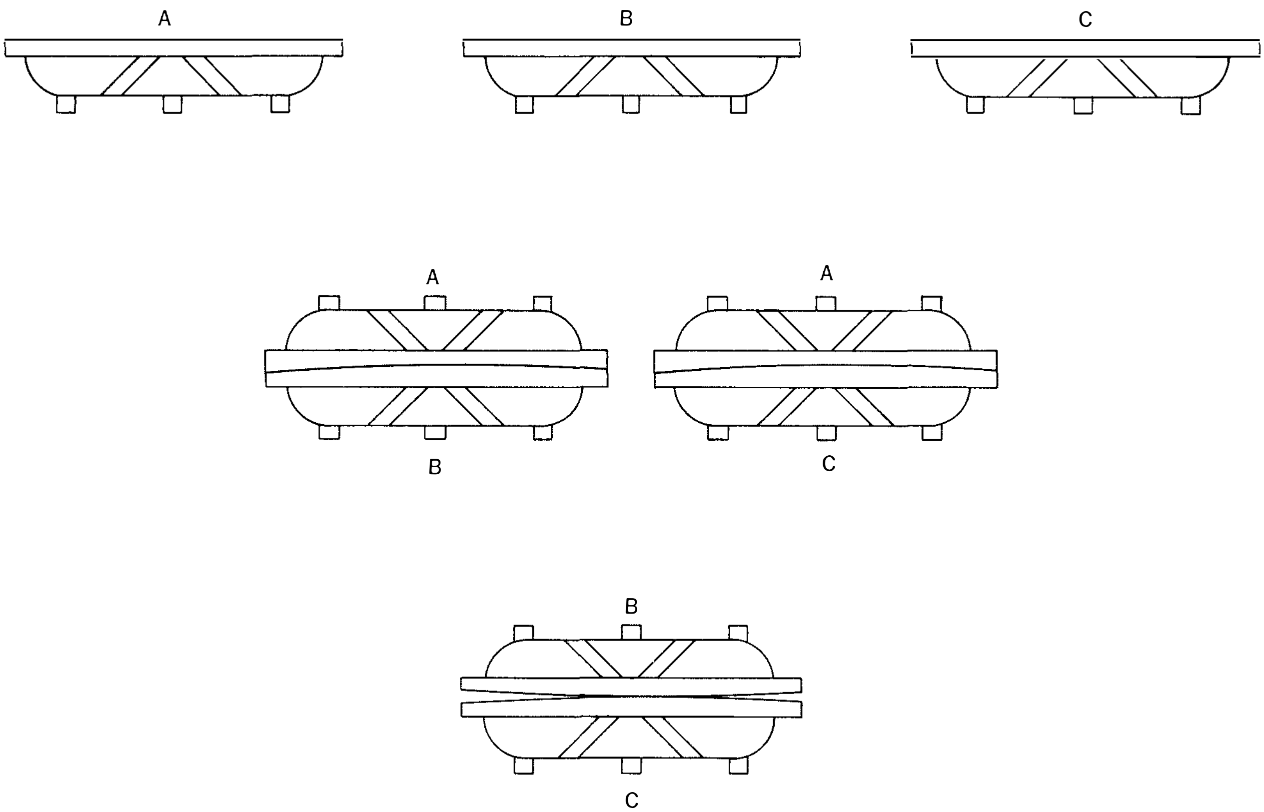
The first two requirements are readily understood: the degree of accuracy of calibration depends on the accuracy of the inspecting instruments; devices which reduce dependence on operator skill contribute to both efficiency and accuracy.

Inspection should not just show that "something's wrong." This only leads to costly checking, misunderstandings, and greater chance for error. It is sounder to inspect for specific error; e.g., deviation from a horizontal straight line travel of a machine's ways. Nothing should be assumed to be correct and left uninspected. For example, if the deviation from a horizontal straight line travel of a machine's ways has been inspected, it does not follow that the vertical straight line travel has also been inspected.

The requirement of *speed* in inspection is not generally appreciated. Inspection must be performed fast for more than just economical reasons. Where inspections become "involved," where there is a time lapse between start and finish of a check, the more assuredly will errors creep in from temperature change—change in the datum of the calibration instrument, "re-picking up," or from the necessity of lengthy calculations. Even under the best of temperature-controlled conditions, body heat alone can still make metal bend, twist, or grow. This can cause confusion if not understood.

Finally, a good inspection tool should be capable of being checked against itself. Ideally, in exploring for a specific type of error, a method should be used which each time simultaneously re-checks the gage. If this is possible, the inspection method gains much in reliability.

FIG. 6—*The classical method of creating a flat plane is based on the cross matching of three plates, such as "A," "B" and "C" (top). The technique is unrelated to the initial accuracy of the plates. "A" is scraped to match "B" (middle left) and also to match "C" (middle right). At this point, only conformity has been achieved. When "B" is compared to "C" (lower), error is revealed.*



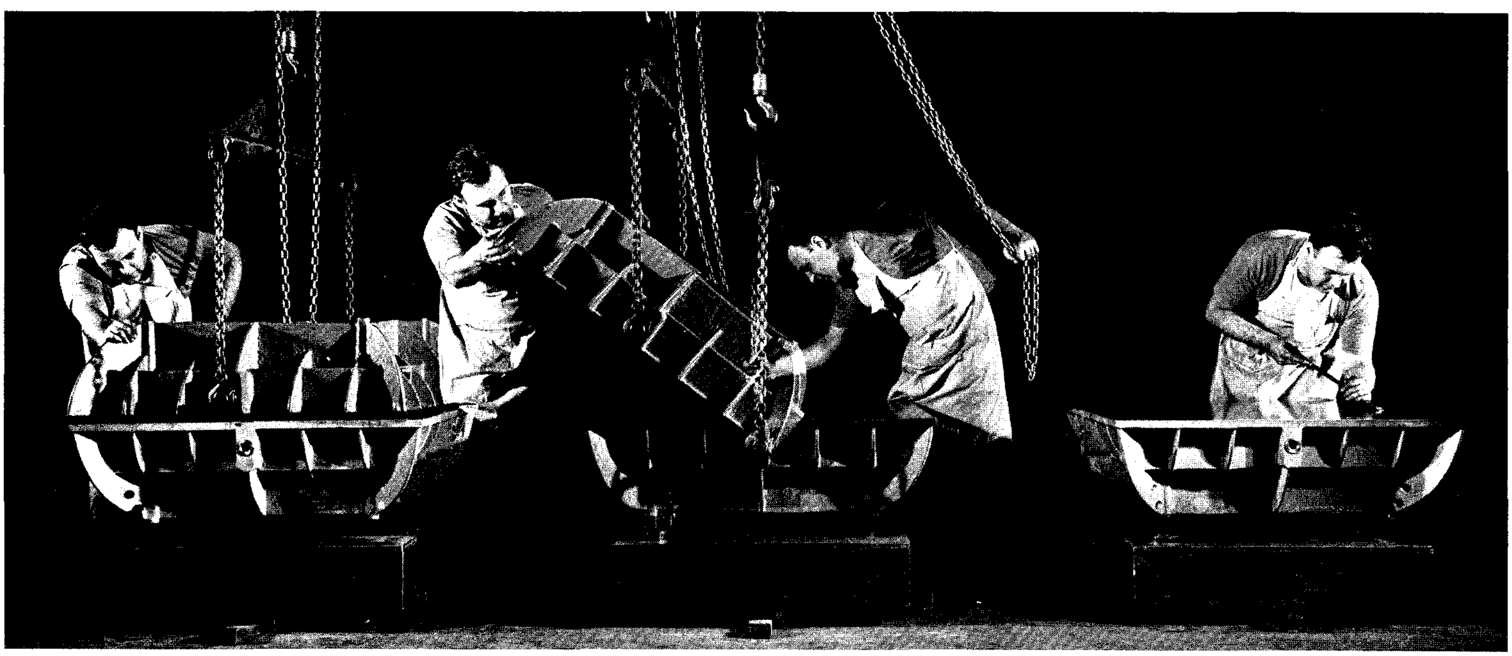


FIG. 7—*By systematically matching three surface plates and scraping the high points of their contact, three flat planes are created, regardless of initial flatness of the plates.*

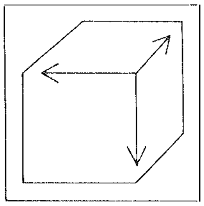
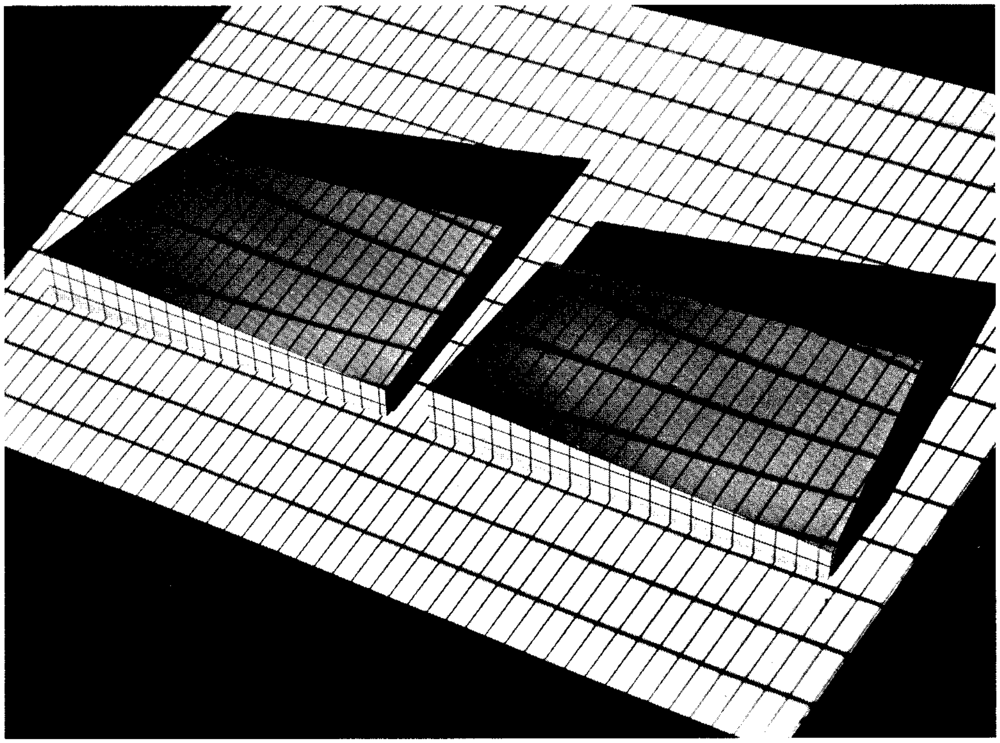


FIG. 8—*Fig. 6 is only partially true. The classical three-plate method does not apply when the plates are rectangular. Two rectangular plates are shown with an identical exaggerated "twist" (opposite diagonals are high and low). Although the plates are not flat, they will match perfectly, even if turned end-for-end. This is obviously also true if a third plate of identical shape is introduced.*



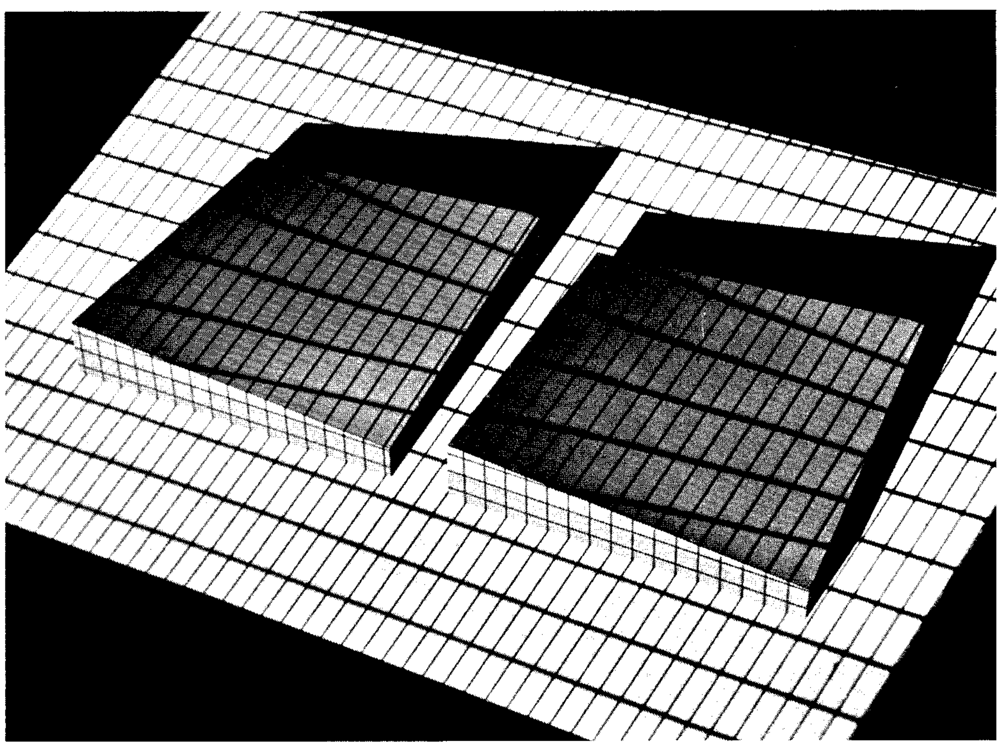


FIG. 9—*A square plate will reveal a twist, since it may be turned through 90° and applied once again.*

1. THE FLAT PLANE

The classical method of creating a flat plane is based on the use of three plates. The procedure is simple:

When two plates are not flat but still match, one will not match the third. By continually lapping or scraping the high points of their contact until all three show perfect bearing when intercompared, three flat planes are created, Fig. 6 and Fig. 7.

Rectangular plates may have a "twist," Fig. 8, and still match each other to show a perfect bearing even if turned end-for-end, yet none of the plates may be flat. A square plate turned 90° on its mate would reveal a twist, Fig. 9, but it is not practical to do this with a rectangular plate since the overhang would introduce as much error as it was intended to discover.

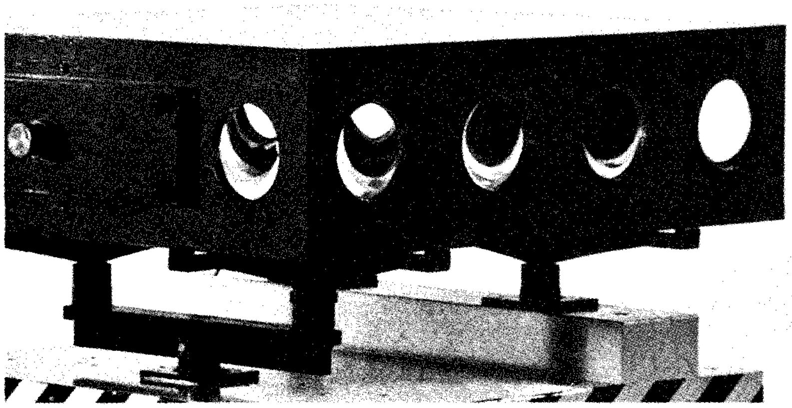
The master flat planes illustrated in Fig. 5, consist of 48 inch [1219 mm] surface plates of stabilized cast iron. They are of box-like, or sandwich, construction with strong internal ribbing, Fig. 10. This makes them many times more rigid than conventionally-designed surface plates, Fig. 11.

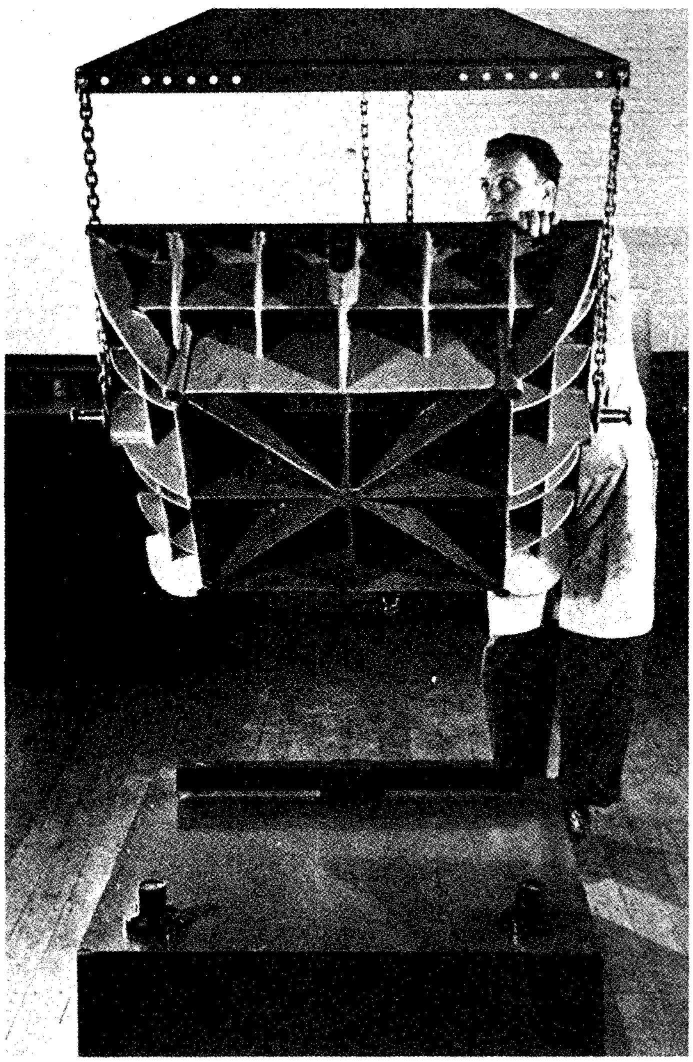
Awareness of the potential rigidity in this design came from a technical report* on the rigidity of a welded steel surface plate, fabricated of two steel plates with internal steel ribbing of an overall thickness to resist bending. This design is much more rigid than conventional surface plate construction. The reader may prove this to his own satisfaction by a practical experiment. Simply take a flat piece of wood and add only ribbing and four sides to it. Try bending this "conventional" design. Next, attach a second flat piece to form a sandwich, and try to bend the assembly. Rigidity is increased many-fold.

However much rigidity is desirable, the possible instability of a weldment rules against having this design as a master. Not

*Adolph Kleinsorge, "Welded Surface Plates," Bulletin 60-WA-241, American Society of Mechanical Engineers, New York.

FIG. 10—*2600 lbs. [1180 kg.], box-type surface plate, with internal ribbing, is many times more rigid than conventional surface plates. Flatness that can be achieved by the three-plate method is for the most part, dependent on rigidity.*





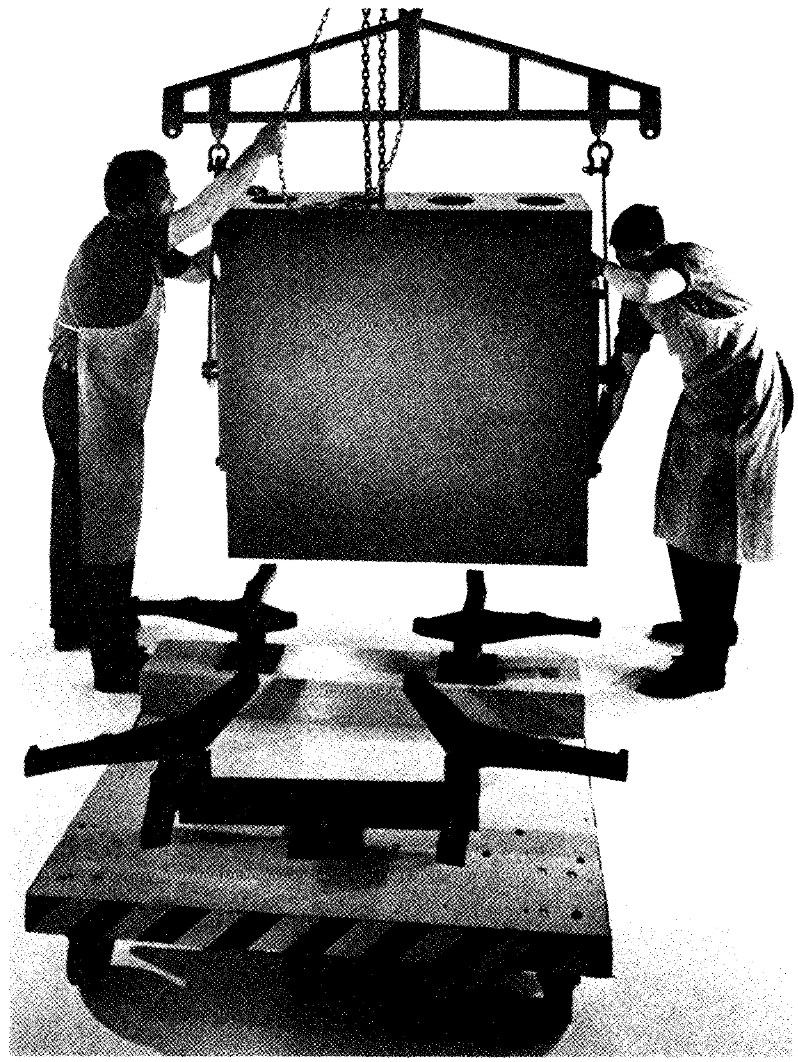


FIG. 11—*42-inch [1067 mm] square surface plates, designed with deep external ribbing, and supported on three points, one of which is a balance beam—were first adopted as the master flat plane.*

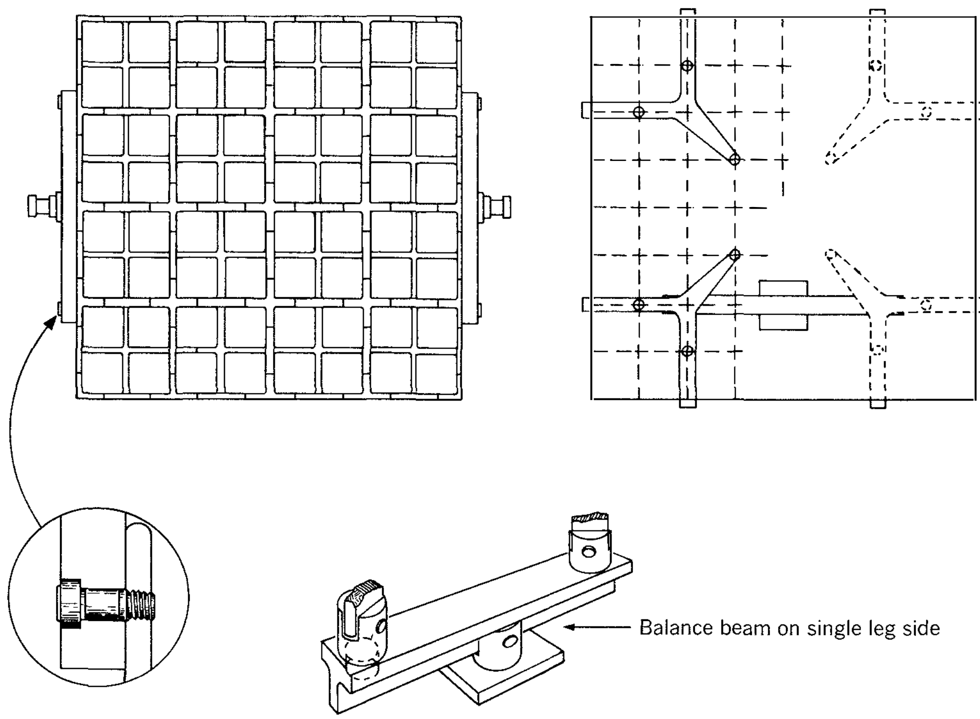
The superiority of the box construction later became apparent.

FIG. 12—*The degree of flatness which can be attained with the master 48-inch [1219 mm] surface plate, and also its accuracy in use, depends on the type of support it receives.*

Three-point support is used for geometric stability. The single-leg side uses a balance beam, taking the weight from the corners of that side. To further distribute the weight and to minimize bending, each of the four support points in the corners is itself a three-pad contact. This provides a total of 12 support points, each placed under the corner of a rib.

FIG. 13—*To prevent stress, each of the four support points of the master, box-type surface plate is free to pivot. Arrangement of the 12 contact points, each under the corner of a rib, is shown.*

Side lifting plate is attached through use of shoulder bolts, which provide clearance to the side plate all around, minimizing both bolting and lifting stresses.



until a similar construction of cast iron was seen at the Dixi company (Le Locle, Switzerland), was it realized that such a construction was feasible as a solid casting. Complexity of the pattern and difficulty in casting both proved to be much less hindrance than first anticipated. Accordingly, six 48-inch [1219 mm] surface plates were designed and cast. All the rigidity that could be desired, plus the stability inherent in cast iron, was found in this design.

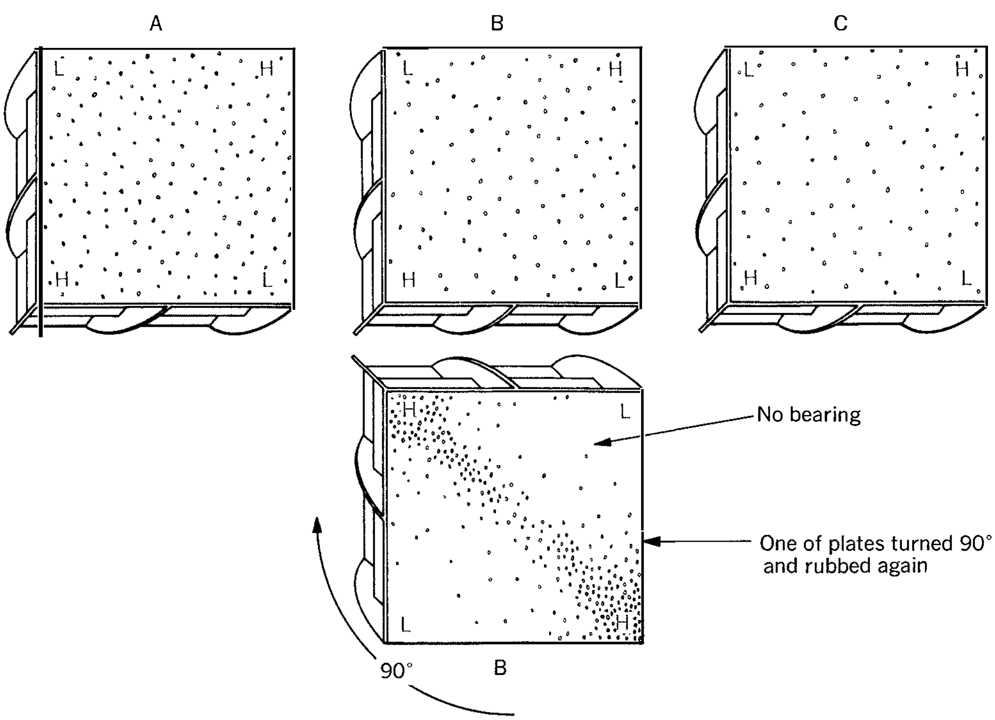
The basic design underwent further evolution. The plate was supported on its underside at three points for geometric stability. A "two-legged equalizer" on the single-point support takes the weight from the corners of one side. To further distribute the weight and to minimize bending, each of the four support points in the corners serves as a three-pad contact. Each pad is, in turn, located directly under a corner of a symmetrically-placed ribbing arranged in squares, Fig. 12.

While this construction has the advantage of the geometric stability of three-point support, note also, Fig. 13, that the weight of the surface plate is distributed on twelve points to minimize local bending—especially important when carrying the weight of large workpieces, machine members, or scraping masters. Resistance to bending is also necessary in achieving its initial accuracy, since it must support its mate in the process of cross-matching and scraping.

The 48-inch [1219 mm] surface plates have ½ inch [12.7 mm] thick internal ribbing and ¾ inch [19 mm] side thickness. Top and bottom surfaces are of one-inch [25.4 mm] thickness. Each surface plate weighs 2600 pounds [1180 kg.].

FIG. 14—*The round shape of the granite surface plate is also geometrically correct for establishing flatness. Granite surface plates are the most familiar form of the flat plane and are convenient for many classes of inspection. The surface plate shown is flat to 50 millionths of an inch [0.0013 mm].*

FIG. 15—*Surface plates "A," "B" and "C" are twisted, having opposite diagonals high, "H," and low, "L." When matched as shown (top), the bearing appears uniform. When any one of the plates is rotated and applied once again (bottom), the bearing pattern then appears as illustrated.*



Creating a Master Flat Plane

The 48 inch [1219 mm] surface plates are square. Most surface plates in use today are rectangular, having something like a 4:3 relationship (which is the usual longitudinal to cross-travel relationship in machine travel). Square or round plates are geometrically most correct for creating a flat plane by the three-plate method, Fig. 14.

To create a Master Flat Plane, the procedure is to systematically cross-match three 48 inch [1219 mm] cast iron surface plates as well as to successively turn them 90° one to another to reveal "twist," Fig. 15. Red rouge is commonly used on the plate which, though in error, is periodically chosen as the master, and a lighter orange rouge used on the plate to be scraped. The result is a pleasant, visible contrast of dark, high spots on a soft, non-glare background.

Initial deviations from flatness are usually considerable. The hills and valleys, Fig. 16, are kept low and wide while roughing by using a wide, flat scraper blade and long, deep cuts until some uniformity is achieved, Fig. 17.

A liberal use of rouge is found to be desirable at first, but the difference between smears, or "false bearing," is noted, and emphasis is placed on cutting the areas of dark, glossy spots. The rouge actually has size, so it is wiped thinner and drier as the bearing closes in to insure almost direct contact of plate to plate without any false bearing. As the bearing is closed in, it begins to have a "salt-and-pepper" appearance. As the spots become progressively more uniform and evenly spaced, a narrower blade is used, the angle of cut is raised gradually from the horizontal, and the stroke is shortened.

The type of scraping stroke found most satisfactory is the "half moon," Fig. 18. The advantage is that the stroke starts from the valley, reaches its greatest intensity directly on the spot (plateau), and

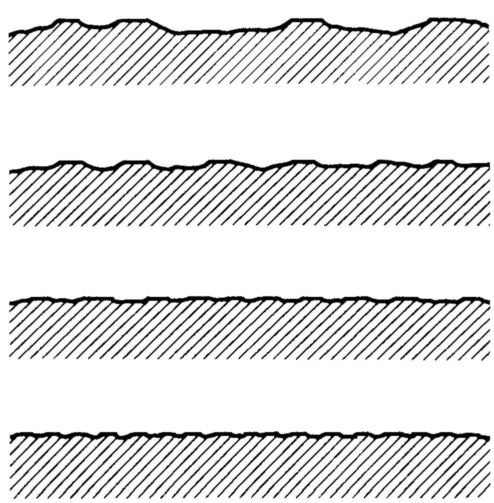
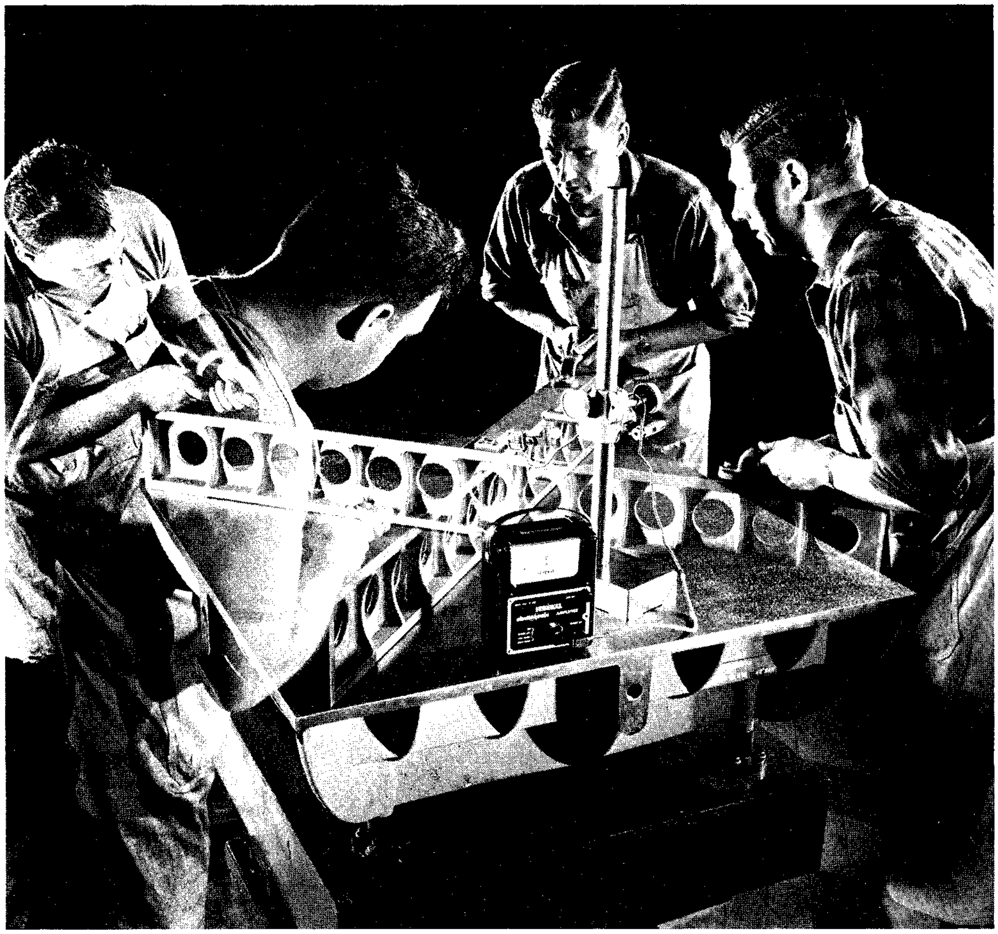


FIG. 16—*The "bearing" of a scraped surface is a series of uniformly high plateaus, which are wide apart when scraping begins. After repeated scrapings, the bearing comes closer and closer together (top to bottom).*

FIG. 17—*A skilled, patient scraping hand can achieve almost unbelievably accurate surfaces purely by scraping to the bearing imparted, and without the use of auxiliary inspection equipment.*

FIG. 18—*Dark areas are plateaus of bearing, the lighter areas the valleys in between. The "half-moon" stroke starts from the valley, reaches its greatest intensity directly on the plateau and again fades to nothing as it passes to the other side.*

FIG. 19—*Two-footed twist gage, sensitive to a few millionths of an inch [one-tenth μm] is used for inspection of overall twist. The method is foolproof and completed in a matter of minutes.*



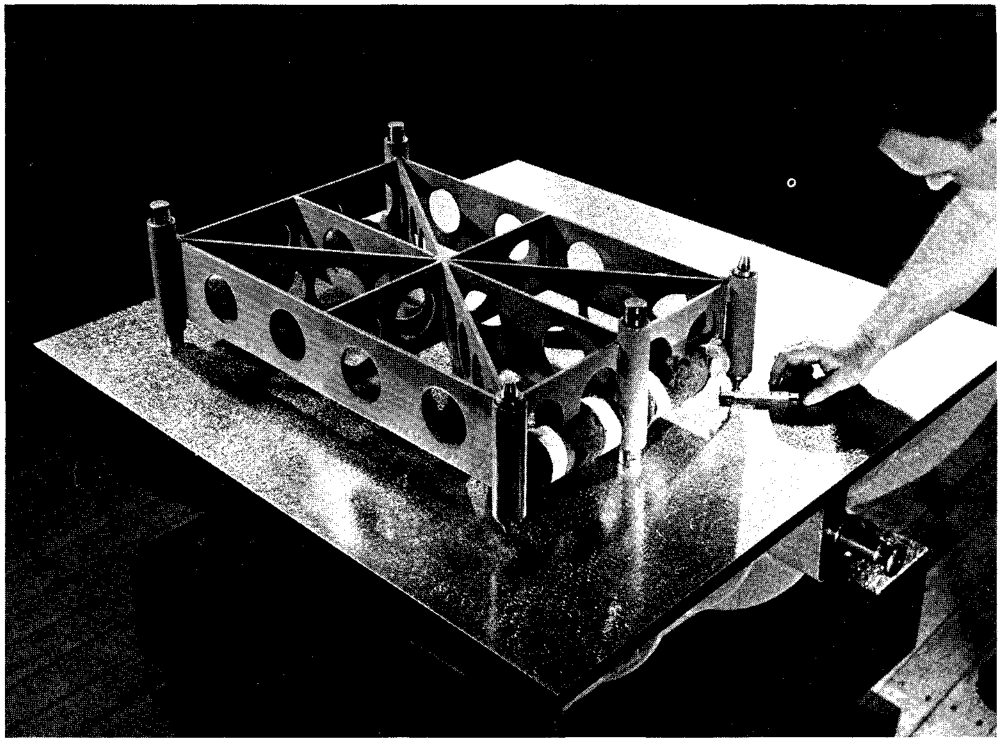
again fades to nothing as it passes to the other side. The type of cut used also depends on the purpose for which the surface is to be used. For instance, a surface to be used as a master for bearing should be cut deep for longer life, whereas the cut should be shallow on the ways of a machine where rollers are to be used for smoother rolling action.

The scraping procedure takes considerable skill and the experienced scraping hand is a precious resource. A novice can easily "break up" the bearing into small spots too soon, creating a "salt-and-pepper" effect, but with wide gaps between the spots. A poorly done job will sometimes reveal either the remnants of spots in a straight row, which can only mean they are retained from the original planing, or telltale hard spots on the edge of the plate where the spots are harder to hit. A requirement of a certain number of spots to the inch does not mean as much as would be supposed. For instance, a surface plate worn evenly may have wide spots and still be flat. Of much more importance is the uniformity of bearing.

The procedure just outlined will result in three plates flat to 50-75 millionths of an inch [one or two μm]. They are not yet truly flat due to their own elasticity, despite adequate ribbing and support. The bearing may appear perfect, but the plates continually bend to conform one to the other.

To achieve the sought-after 25 millionths of an inch [0.0006 mm] requires inspection at this point. A two-footed twist gage, Fig. 19, is employed. An electronic indicator, with its base resting on the plate, is set so that its measuring probe registers zero or datum on a small central lapped pad on the gage, when the end feet rest on the diagonal corners of the plate. Leaving the zero set, the twist gage is quickly swung 90° to the opposite diagonal corners. The relative difference in heights, or "twist," is registered as a plus-or-minus reading against

FIG. 20—*Three-footed twist gage has two gaging pads at the corners of one side. A small gage having a slight taper of 0.000050 inch per one-half inch [approximately one μm per 10 mm] of length is applied at the two gaging pads. The twist gage is self-proved upon being turned 90° on the surface plate and tested once again.*



the lapped pad. Even though the twist gage is known to sag appreciably, this sag is a constant, as evidenced by extremely good repeatability of the zero.

More local errors may be detected by exploration with the three-footed twist gage, Fig. 20. The gaging points with this instrument are two lapped flats, fixed on the bottom corners of the single-foot side, and facing the plate. A wedge-shaped gage, tapered accurately 0.0003 inch over 3 inches [0.0076 over 76 mm] or 0.000050 inch for every inch of length [0.00254 mm for every 25.4 mm] of length, is pushed under the lapped flats to calibrate change in height of the two lapped flats.

A third method uses a surface gage with a protruding arm to which an electronic indicator probe is fixed. The plate may be searched for even more local errors in this manner, Fig. 21.

It is important to note, however, that if the correct scraping procedure is followed, errors will not be of a local nature, but only those of overall bow or twist.

In a fourth method, overall "bow" is inspected with a "straddle" surface gage, and a special straightedge having two support feet .554L apart* and three indicating pads, Fig. 22. The straightedge can be reversed for self-check, Fig. 23.

There will be a large area in the center of the plate which is perfectly flat. The explanation for this will be seen in a test for rigidity:

The two-footed twist gage is positioned on diagonal corners and the indicator zeroed on the central pad. Two hundred and fifty pounds [113 kg] can be added to the center of the table with a deflection of no more than 5 millionths of an inch [0.000127 mm]. Two hundred and fifty pounds [113 kg] added to the corners will

*When a straightedge is supported on two points equidistant from its ends and separated by the factor .554L (*where L is the length of the straightedge*), it will deflect the least from elastic flexure.

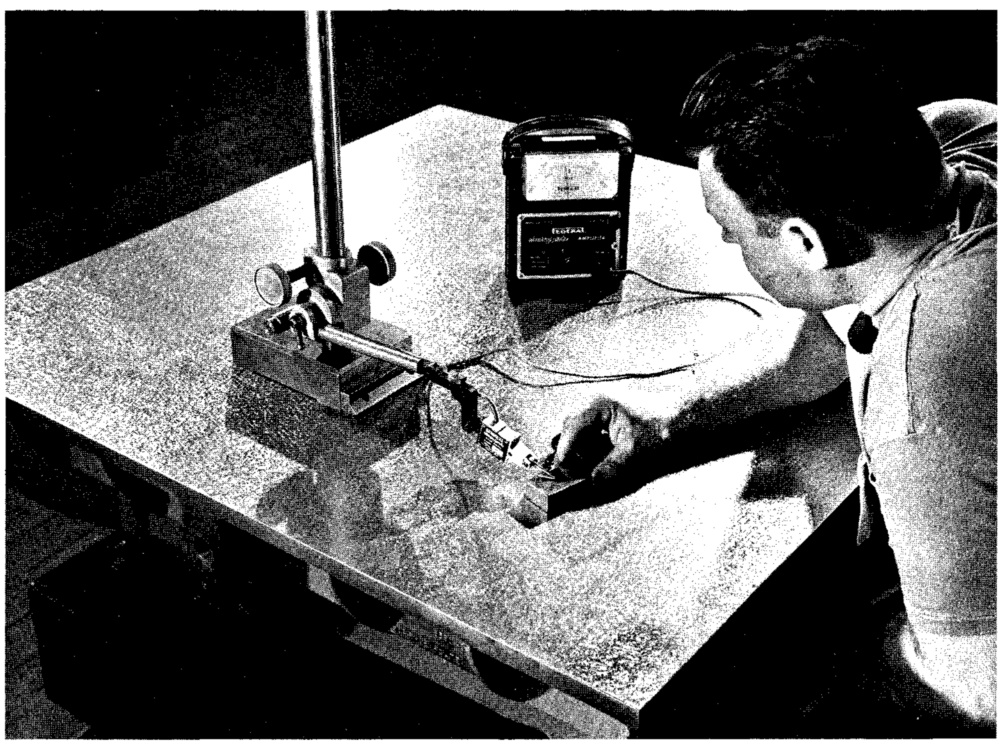
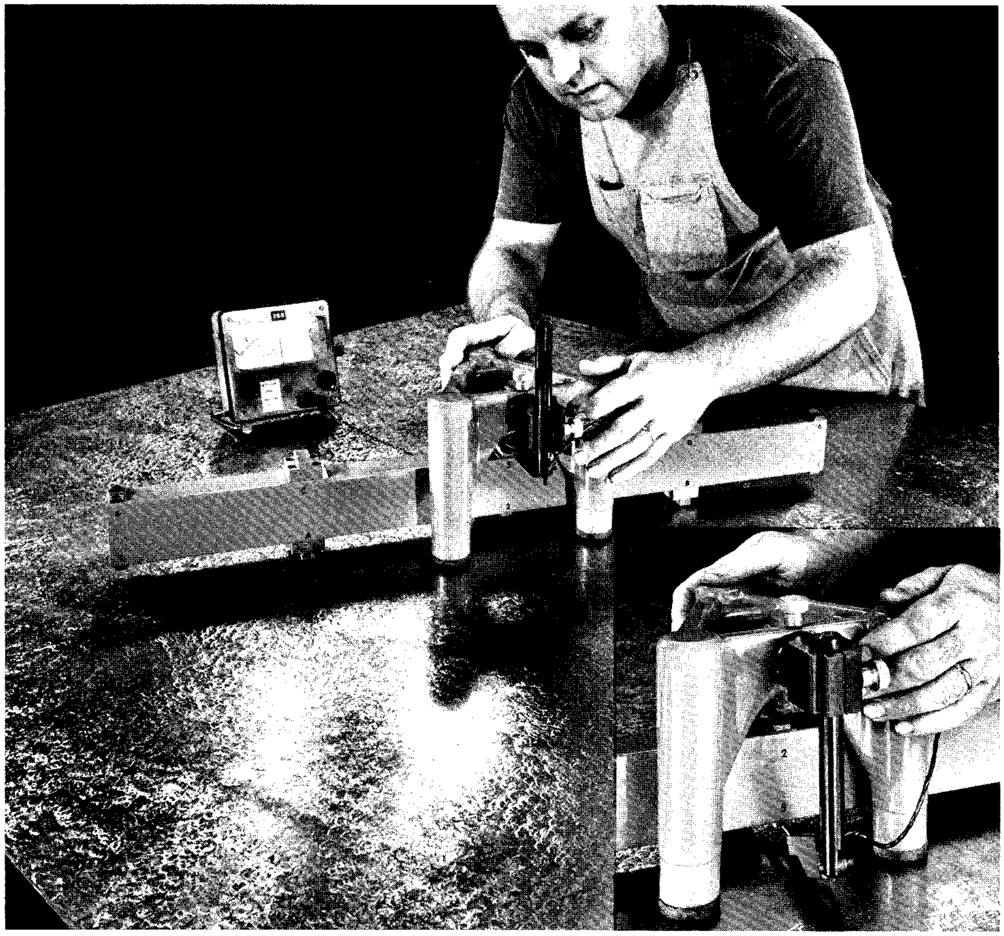


FIG. 21—*In searching for local errors, an electronic indicator and stand and a small lapped block are employed.*

FIG. 22—*Overall curvature of the plate is inspected with a "straddle" surface gage and a straightedge having support feet .554L apart, and three indicating pads.*

FIG. 23—*(insert) The special straightedge is self-checked by reversal.*



cause a deflection of 15 millionths of an inch [0.0004 mm].

The plates must now be scraped not only to the bearing, but to the errors found from inspection. There is no doubt that the rouge is slightly abrasive and to a certain extent also laps the plates flat, but the practice of stoning to remove local errors is of dubious value. The temporary accuracy achieved is at the expense of uneven wear as the plate is used. Stoning may be used sparingly and evenly over the whole plate but only for the purpose of removing the slight burr resulting from scraping.

An autocollimator may be used to calibrate a master plate, using the method shown diagrammatically, Fig. 24. While it is an extremely sensitive instrument, one disadvantage is greater time consumption (during which temperature fluctuations may change the datum). Cumulative errors may result from moving the reflecting target mirror and changing the span of the target mirror feet. The necessity of making charts and analyzing the results can contribute to error. Accuracy of determination is not much better than the 50-75 millionths of an inch [one or two μm] achieved without an inspection.

15-Minute Check for Flatness

This dramatic test was made on three 42 inch [1067 mm] master plates—

Three plates were matched one against the other for bearing. Bearing was close and uniform.

The two-footed twist gage was set on diagonal corners on the first plate and a datum zero set. Moving the twist gage to the opposite corner, then actually repeating this on the other two plates without changing the datum (this involves carefully moving the electronic indicator and stand), revealed no more than 15 millionths of an inch [0.0004 mm] spread of indicator readings for all 6 diagonals. Total time elapsed: 15 minutes.

A guest metrologist who was present at this time conceded that autocollimating a surface plate completely, as illustrated in Fig. 24, would take about three hours per plate, or a total of nine hours.

If the scraping were not of the highest order, so that the "bearing" could be relied upon to prove the absence of local error, the 15-minute check for flatness would be neither adequate nor valid.

Cast iron is of fairly porous texture. Can such a surface, which is, moreover, flat only on "plateaus" spaced apart with depressions, be called flat to 15 millionths of an inch [0.0004 mm]?

Such tolerances are stated with the realization that they begin to conflict with the controversial subject of "surface texture" and all its inherent uncertainties and discrepancies (see pages 125-129). On the other hand, such readings are entirely reliable when a square inch [25 mm square] or so of the scraped surface can be spanned, Fig. 25, Fig. 26. Further clarification is difficult since "surface texture" definitions are not adequately descriptive.

Granite Surface Plate

Granite, for use as a surface plate, is acknowledged to be a very satisfactory material for all types of shop, inspection and laboratory work. It is by far the most widely used.

On the other hand, the claim that the

FIG. 24—*The calibration of a master surface plate (as shown with an autocollimator) requires about three hours and involves cumulative errors.*

FIG. 25 (*center*)—*A scraped surface is made up of a series of plateaus. To indicate directly over this surface is incorrect procedure. Instead, a sufficient area should be spanned with a hardened steel block, which has been lapped flat and parallel.*

cast iron surface plate is headed for extinction is not borne out in actual practice. Many machine-tool manufacturers, for example, still use and prefer cast iron surface plates.

The granite surface plate does not provide as acceptable a "bearing" as does cast iron to which one can scrape masters and machine members. For this reason, it does not have a place here in the "evolution" which will be followed to machine geometry.

See outline of the most important criteria to apply in closer evaluations of the advantages and disadvantages of cast iron compared to granite for use as a surface plate. One point in the outline calls for further clarification:

GRANITE AND MOISTURE—The claim that the flatness of a granite surface plate is effected by moisture has not been proved conclusively.

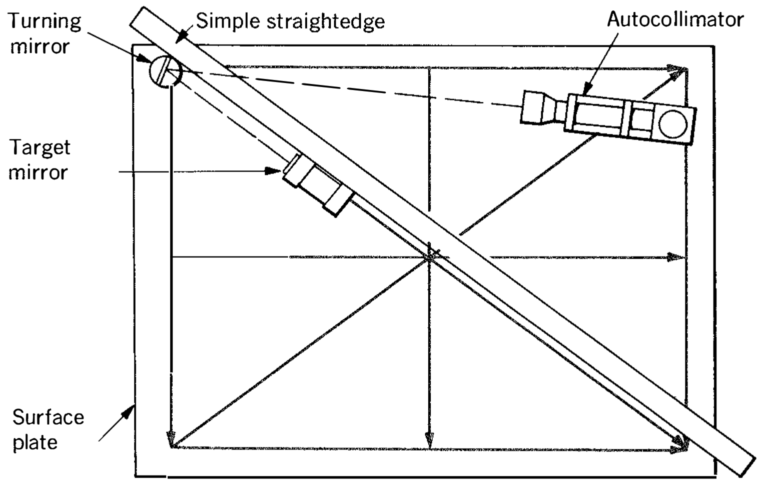
In a controlled test by Oakley*, two black granite plates were copiously wetted with water for some 70 hours. Measurements made at intervals after the surfaces of the plates had been dried showed only a small change in flatness, but revealed that the plates took about 10 days to regain their original flatness. This would seem to argue against the practice of wetting to clean.

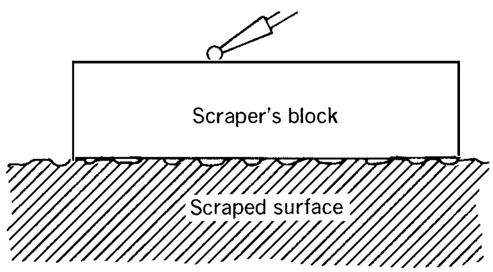
Oakley cautions, however, that the effect of a high-humidity atmosphere has not been tested. This raises the possibility that some loss of flatness may result from high humidity.**

The results should also alert manufacturers of granite surface plates to the potential danger involved in lapping with a liquid solvent. The prevalent practice of lapping followed by immediate autocollimation should be avoided.

*T. R. J. Oakley, "The effect of moisture on the flatness of black granite surface plates," "NPL Technical Bulletin GGG-P-463b, August 3, 1961.

**Unpublished letter from T. R. J. Oakley, February 21, 1968.





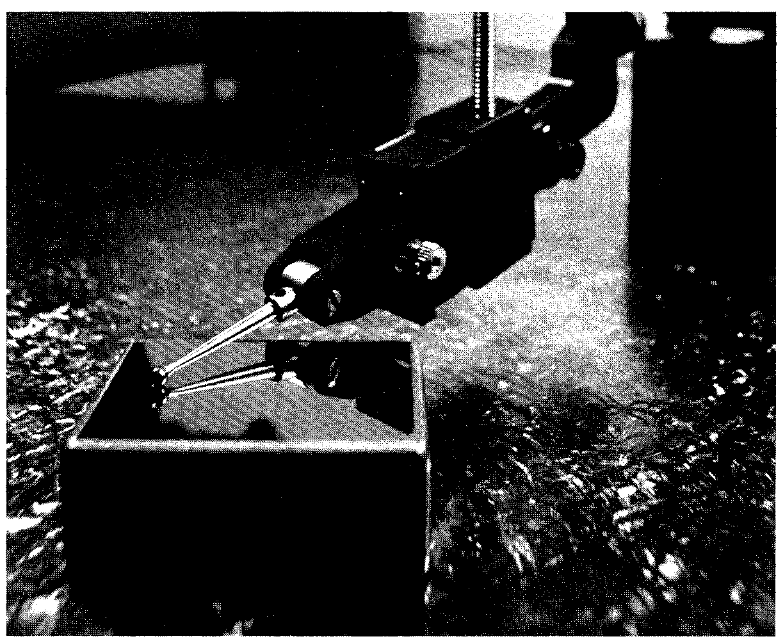


FIG. 26—*"Scraper's block" of hardened nitralloy steel, lapped flat and parallel to .000005 inch [0.000127 mm], is used as a gaging point when inspecting scraped surfaces.*

A Comparison Between Cast Iron and Granite for Use As Surface Plates

CHARACTERISTIC	CAST IRON	GRANITE
Wear	Good	Good
Stability	Excellent	Excellent
Rigidity	Excellent	Excellent
Relative Weight for Comparable Strength	High strength for given weight (ribbing easily cast integral to plate)	Strong, but less for given weight (impractical to apply ribbing)
Moisture	Rusts, but will not distort	Won't rust, but may distort
Fabrication, reconditioning	Lapped or scraped	Must be lapped
Bearing	Will give up a bearing (advantage)	Will not easily give up a bearing (disadvantage in use, may also limit attainable accuracy)
Accuracy	Depends on manufacturer	Depends on manufacturer
Burr	Raises up (disadvantage)	Makes a hole (advantage)
Available shapes and sizes	Limited, often needs special pattern	Almost unlimited, can be sawed or shaped.
Versatility in use	Excellent—can be machined, drilled and tapped	Good, but needs inserts and fasteners.
Temperature effect (absorption)	Fast to absorb heat, slow to dissipate (can be advantage or disadvantage)	Slow to absorb heat, slow to dissipate (can be advantage or disadvantage)
Temperature effect (radiation)	Reflects radiant heat (advantage)	Absorbs radiant heat, especially black granite (disadvantage)
Temperature effect (coefficient)	The same coefficient of expansion as most steels (usually an advantage but can be a disadvantage)	Coefficient unlike steel (usually a disadvantage but can be an advantage)
Cost	Fairly expensive	Relatively inexpensive

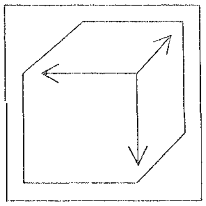
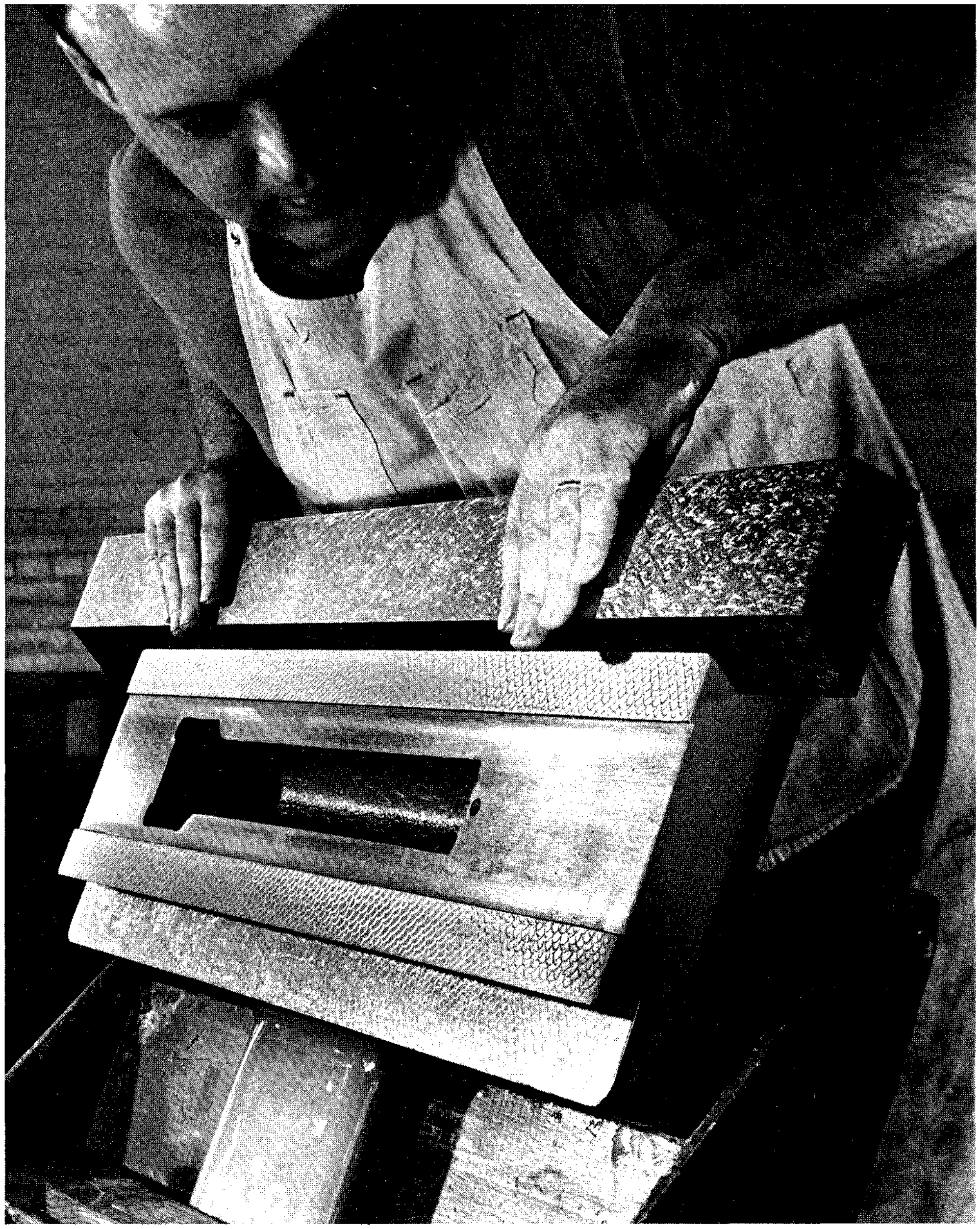


FIG. 27—A straightedge of the form shown was used to scrape the dovetail ways of No. 1 and No. 2 Model Jig Borers. Its accuracy was limited due to lack of rigidity and because its 45° form was not self-proving.



2. STRAIGHTEDGES

All straightedges are derived from the flat plane, but design will vary with different applications.

A straightedge, Fig. 27, was used as a master for scraping the dovetail ways of the Moore Model No. 1 and No. 2 machines. Its uniform structure minimized distortion from heat, but it was not sufficiently rigid to prevent bending, either from its own weight or from the application of pressure to produce a bearing. A further disadvantage was that its 45° form, unlike a 90° form, was not selfproving.

In the quest for a straightedge capable of producing closer accuracies, other designs evolved, Fig. 28. It was observed that while each would resist bending in one direction, none possessed sufficient cross-section rigidity to resist bending in all directions. Also, being of non-uniform construction, they easily distorted from uneven temperature distribution.

Case History No. 1

A straightedge of a type shown at left in Fig. 28 was matched to a master surface plate. The bearing pattern continually shifted, yet tests indicated that the shift was not caused by deflection. A chance remark revealed that the surface plate had recently been transferred from another area.

The suspicion that temperature was the culprit was easily confirmed by deliberately holding the top of the straightedge for a short period of time. The heat of the hand made the bearing pattern shift even more drastically. What had taken place was that the temperature of the air differed from the temperature of the surface plate. The top of the straightedge was influenced by air temperature, and the base was influenced by the temperature of the surface plate upon which it rested, with uncertain gradients of temperature in between. The result was a changing and unpredictable dis-

FIG. 28—*The straightedges shown were at various times used as masters for machine ways, but were not self-proving, not sufficiently rigid, and unduly sensitive to temperature variations.*

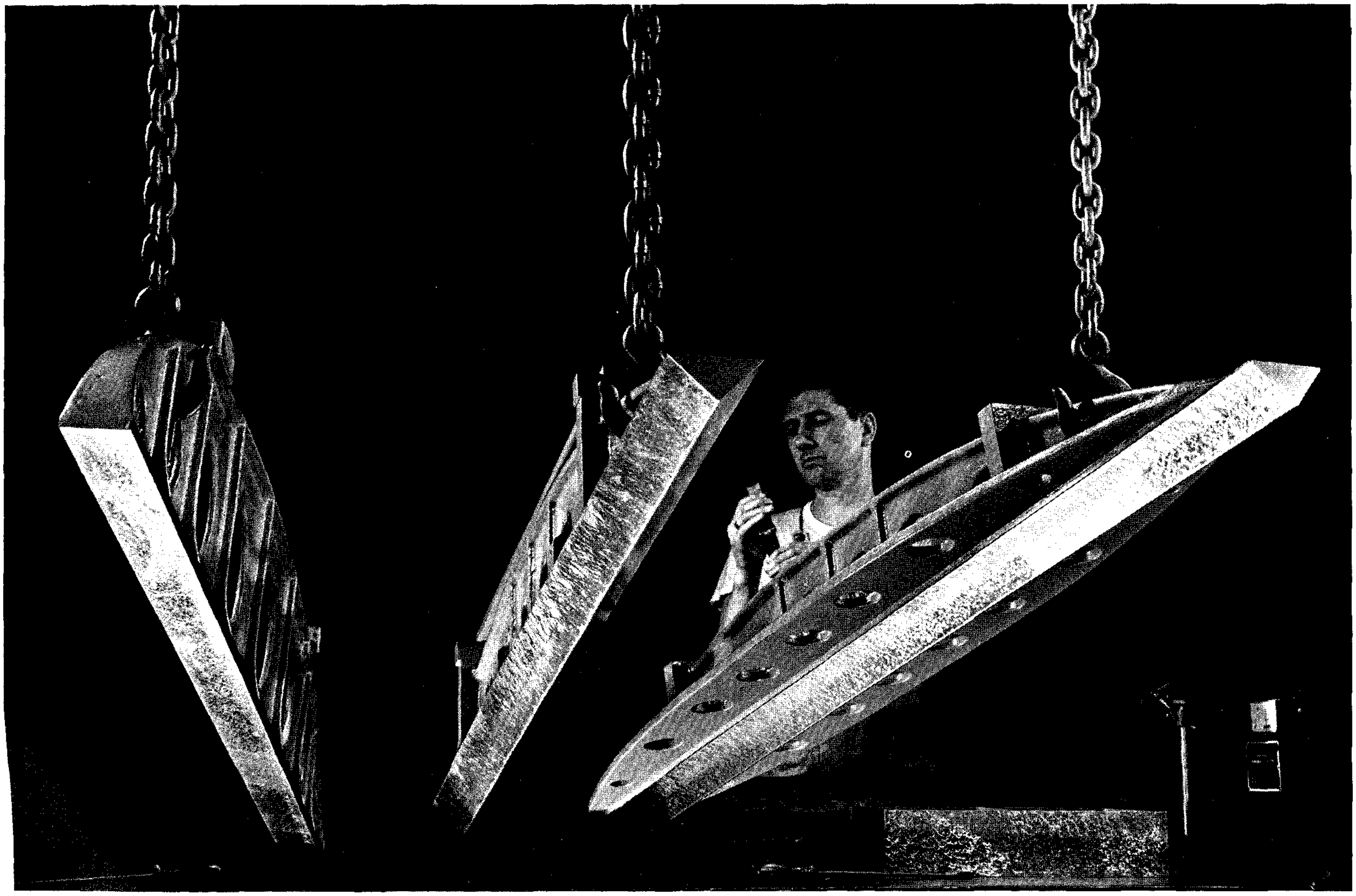
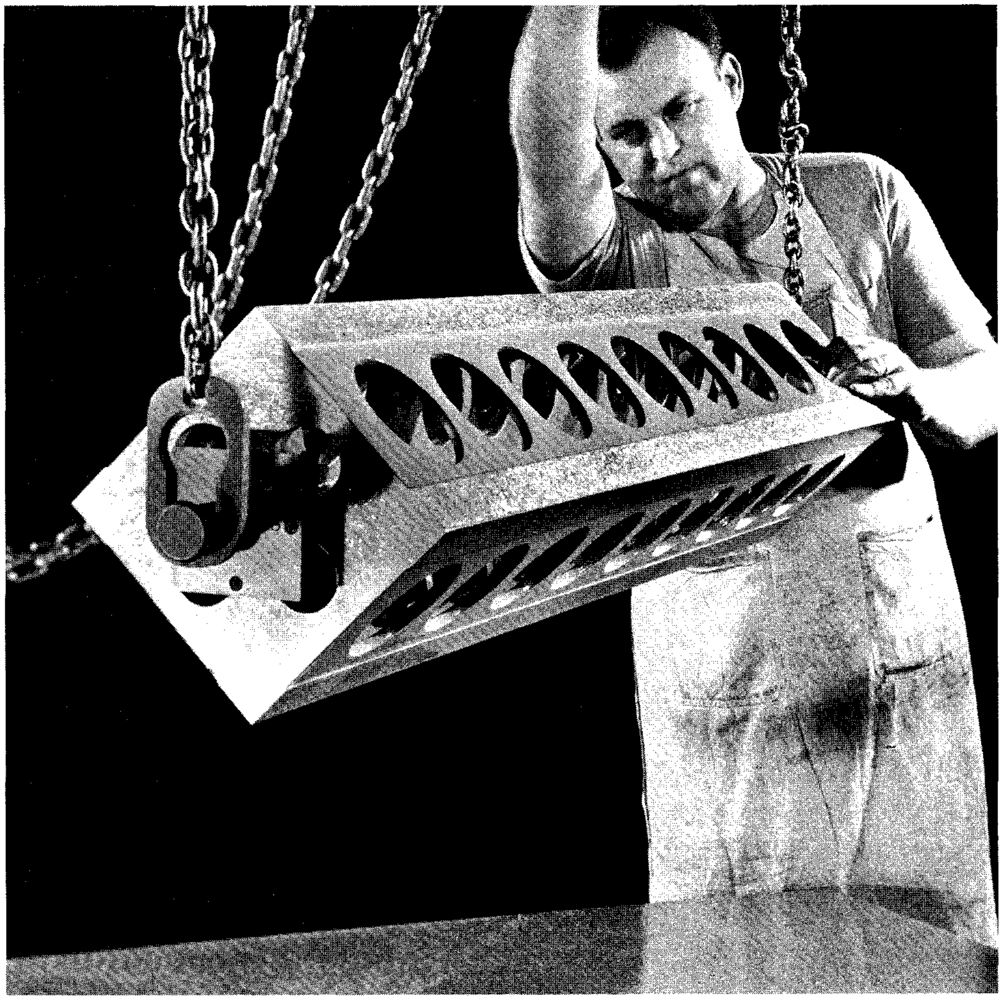


FIG. 29—*The box straightedge is the best design. It is extremely rigid, its 90° form is self-proving and it is relatively insensitive to temperature change.*



tortion of the straightedge due to its own non-uniform temperature.

CONCLUSION—This type of straightedge was judged too susceptible to distortion under slight temperature differentials, making it impractical to use where close tolerances are required.

Case History No. 2

A machine V-way was scraped, using the middle straightedge of Fig. 28 as a master, until the bearing was uniform. To self-prove the straightedge it was turned end-for-end in the V-way. The bearing was still uniform. Yet subsequent autocollimation revealed that machine "V" had considerable horizontal deviation from a straight line.

CONCLUSION—This straightedge was bending to conform to the machine "V," and had insufficient rigidity to be used as a master.

Bearing in mind the limitations which were apparent with conventional straightedges, a master straightedge was designed, Fig. 29, with the following features:

1. Rigid cross section to minimize deflection in *all directions;*
2. A symmetry and uniformity which minimize distortion when the straightedge is subjected to uneven temperature distribution;
3. A 90° form to be used as a master to construct a master "V";
4. A 90° form and straightness which are self-proving both in fabrication and in use.

Creating a Master Straightedge

Fig. 30 shows the approach taken to scrape the master straightedge. Side 1 of the straightedge is matched to the master sur-

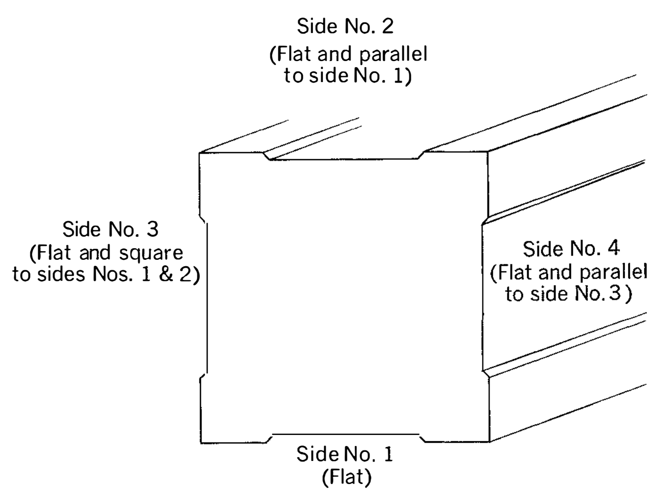


FIG. 30—*The sides of the box straightedge are scraped in the order of the numbers listed.*

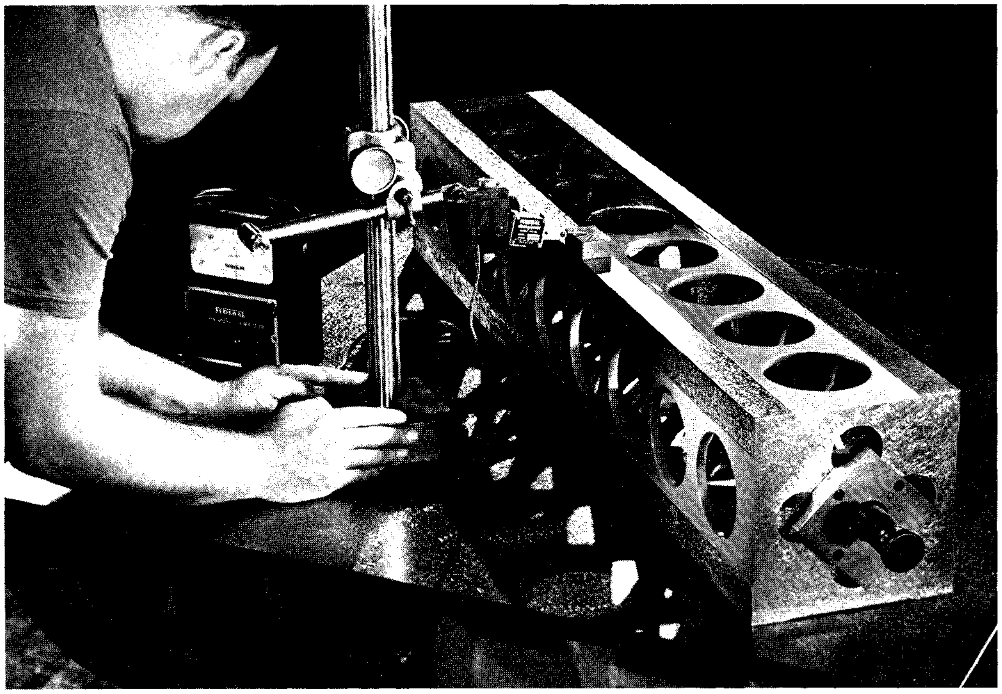


FIG. 31—*After side 1 is scraped flat, side 2 is scraped parallel to it. Inspection uses the master surface plate as a flat datum.*

face plate. Side 2 is also matched and, by means of a thickness check, Fig. 31, also is scraped parallel to side 1. Side 3 is scraped square to sides 1 and 2. Inspection is by a common method, Fig. 32. With the straightedge supported on side 1, a knife edge on the indicator stand is pressed against side 3, and a zero set. The straightedge is turned 180° to side 2, the indicator and edge again pressed into contact with side 3.

Any out-of-squareness is revealed as half the difference between the two indicator readings and gives the direction in which side 3 must be adjusted for squareness while still maintaining flatness. For highest accuracy and in order to avoid local flatness errors in the master surface plate, the straightedge should be turned end-for-end, as well as through 180°, so that the position of the indicator stand on the surface plate is not altered.

Once 3 is completed, side 4 is scraped parallel to it, which means that side 4 is automatically square to sides 1 and 2.

The resulting straightness can be no better than the 25 millionths of an inch [0.0006 mm] flatness of the master surface plate, since the straightedge will bend this amount and, in fact, may have as much as 40 millionths of an inch [0.001 mm] bow. This is not revealed in a check either for bearing or for thickness. Any improvement upon the 40 millionths of an inch [0.001 mm] straightness can only be achieved by proving the straightedge against a Measuring Machine. Squareness and parallelism, however, are obtained to 10 millionths of an inch [0.00025 mm], since the overall bending does not effect local cross-sections.

It is important to note that both straightness and squareness have been developed from the surface plate. Other designs of straightedges and squares are created similarly.

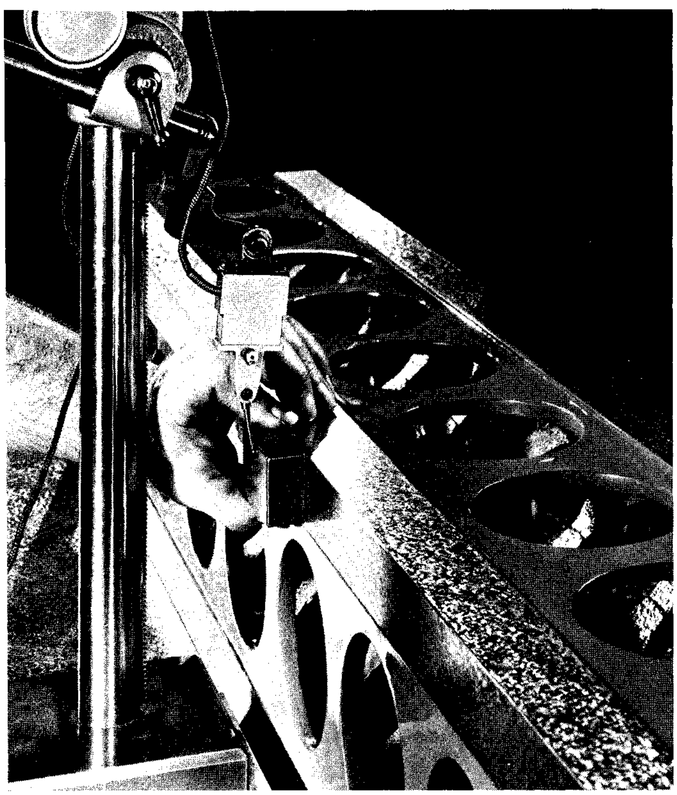


FIG. 32—*Side 3 is scraped flat and square to sides 1 and 2. The knife edge on the indicator stand is pressed against the lower area of side 3. Any out-of-squareness is revealed as half the difference of the indicator readings when the straightedge is turned over (180°), to side 2 and compared again as shown.*

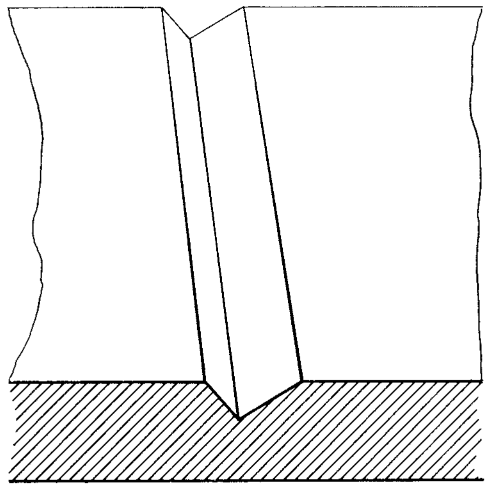


FIG. 33—*A single, female V can be made extremely accurate simply by scraping to the bearing imparted when rubbed to the master straightedge.*

The function of the master straightedge will be to produce the straightness and 90° form of a master "V."

3. THE FEMALE DOUBLE V MASTER

An accurate female V master, Fig. 33, is created by matching a machined V to the right-angle corner of the master straightedge. Purely by scraping to the bearing imparted, and without the use of auxiliary inspection devices, the 90° form of the V will be in error less than 10 millionths of an inch over its 1½ inch depth of flank [0.00025 mm over 38 mm] and its straightness will be close to 0.0001 inch [0.0025 mm] accuracy over its length, for these reasons:

1. The straightedge is highly resistant to deflection across its diagonal section;
2. Since the squareness error of the straightedge over 8 inches [203 mm] was less than 10 millionths of an inch [0.00025 mm], the 1½ inches [38 mm] of corner being used will be proportionately less in error.
3. The straightedge can be self-checked by reversal;
4. Each of the four corners of the straightedge provides another cross-check and long wear-life.

The ability to achieve straightness to 25 millionths of an inch [0.0006 mm] depends on the support given the female master. If supported only on a rough-cast surface when being rubbed for bearing, it will bend. Even the precaution of supporting the female master on its points of least deflection will not prevent bending when the weight of the straightedge is added, Fig. 34. The proper method is to scrape the underside of the female master flat, and when being

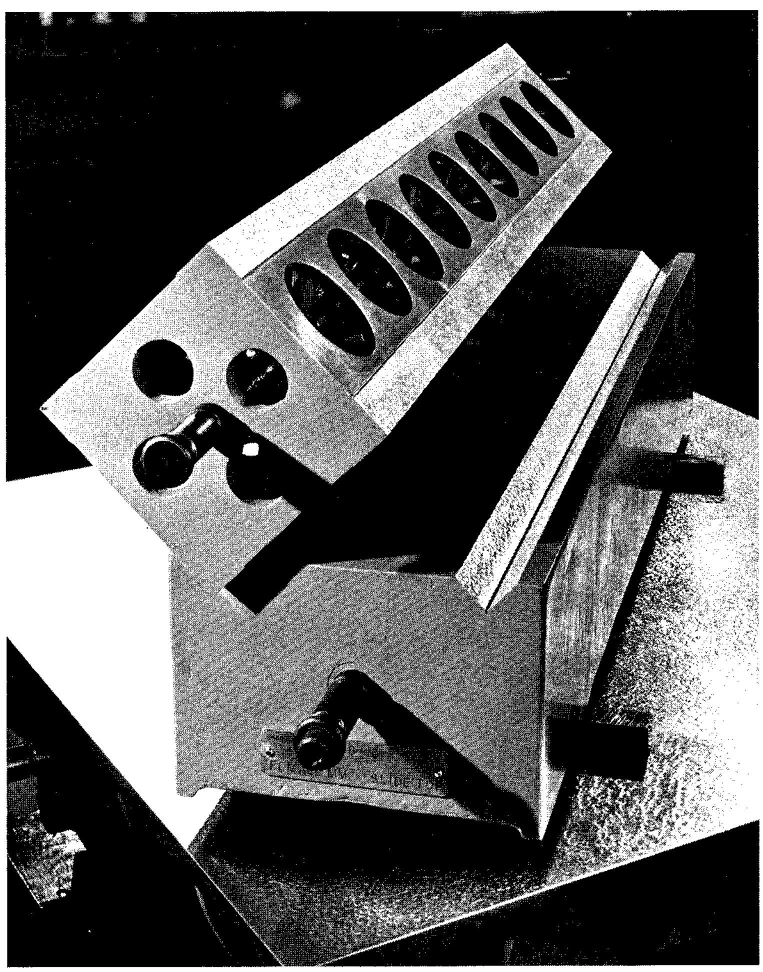


FIG. 34—*The female double V master will easily bend if supported on a rough-cast surface, or even if supported on the points of least deflection, as shown.*

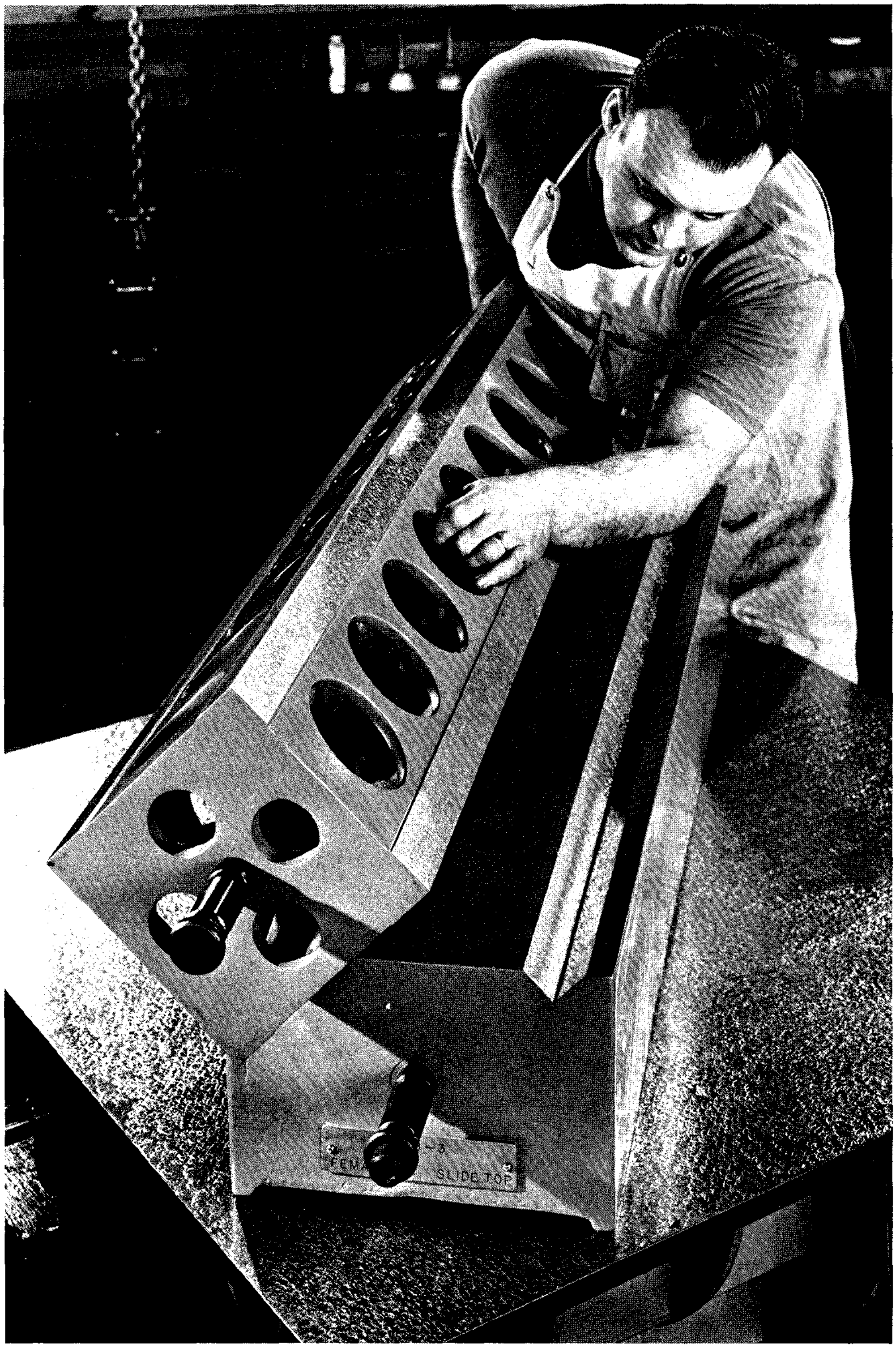


FIG. 35—*The proper method of support for a master is to scrape its underside flat and to rest it on a perfectly flat surface.*

rubbed for a bearing, to support it on the master surface plate, directly over the triangle of the three-point support, Fig. 35.

The single V must be straight and of 90° form. The double V presents, in addition, more complex problems of geometry: lean, center-distance, horizontal parallelism and vertical parallelism ("twist"), Fig. 36. For reasons of machine design, which will be fully explained in a later section, Moore uses double V-ways of 6½ inch [165 mm] and 8½ inch [216 mm] center-distance on the base construction of its No. 1½ and No. 3 machines. The female double V master will be the authority for these double V's.

Scraping each V to the straightedge only results in two straight 90° forms, but random in space. To bring the V's into a prescribed geometric relationship to each other, there must be a systematic inspection and correction of each type of error mentioned in Fig. 36.

The now-flat underside of the female master not only provides a deflection-free support, but in conjunction with the straightedge and the 48-inch [1219 mm] plate on which it is supported, provides a reference datum in many of the following inspection procedures.

1. *Form—Fig. 37.*—The 90° V is chosen mostly because of its unique relationship to the flat plane, so it is easily duplicated and proved. An *exact* 90° is not a prerequisite to the ultimate accuracy of the machine V provided the mate to the female V is of an identical angle.

It has been seen that the right angle is precisely achieved through use of the straightedge. One method of proof of the 90° angle sometimes suggested in treatises on measurement is by means of two round pins, such as 2¼ inches [57.15 mm] and ½

FIG. 36—*Form, lean, center-distance, vertical and horizontal straightness, horizontal and vertical parallelism—all must be established and inspected in the double V design way system.*

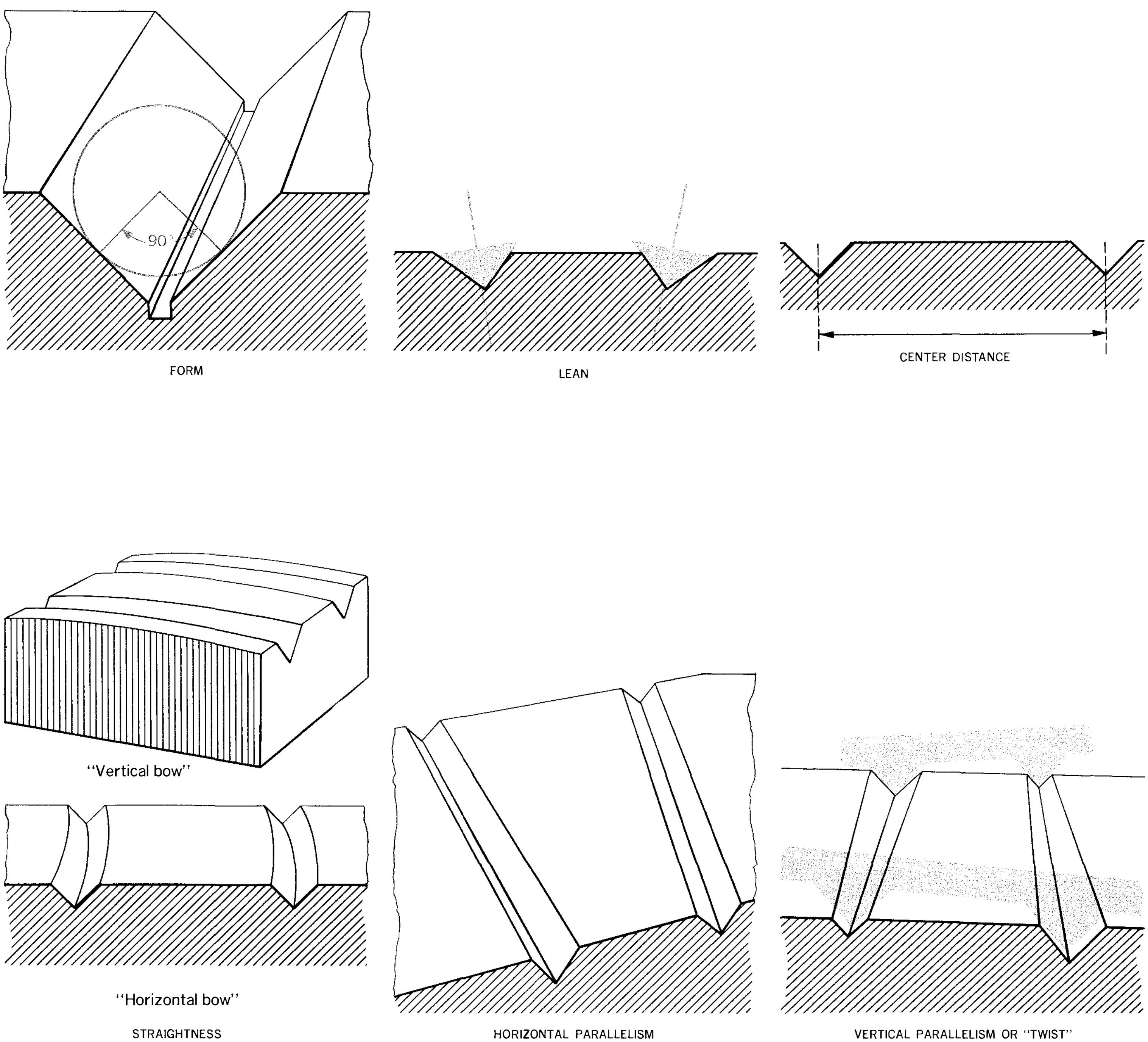
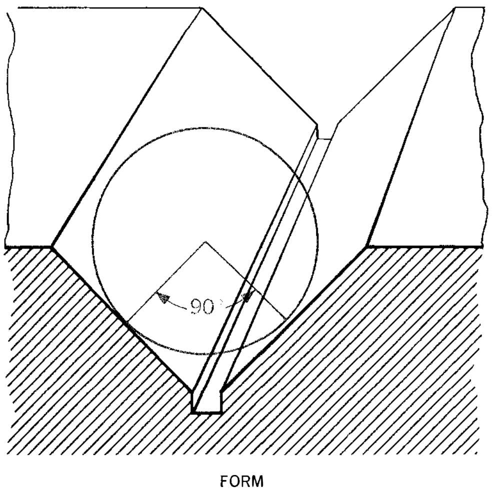
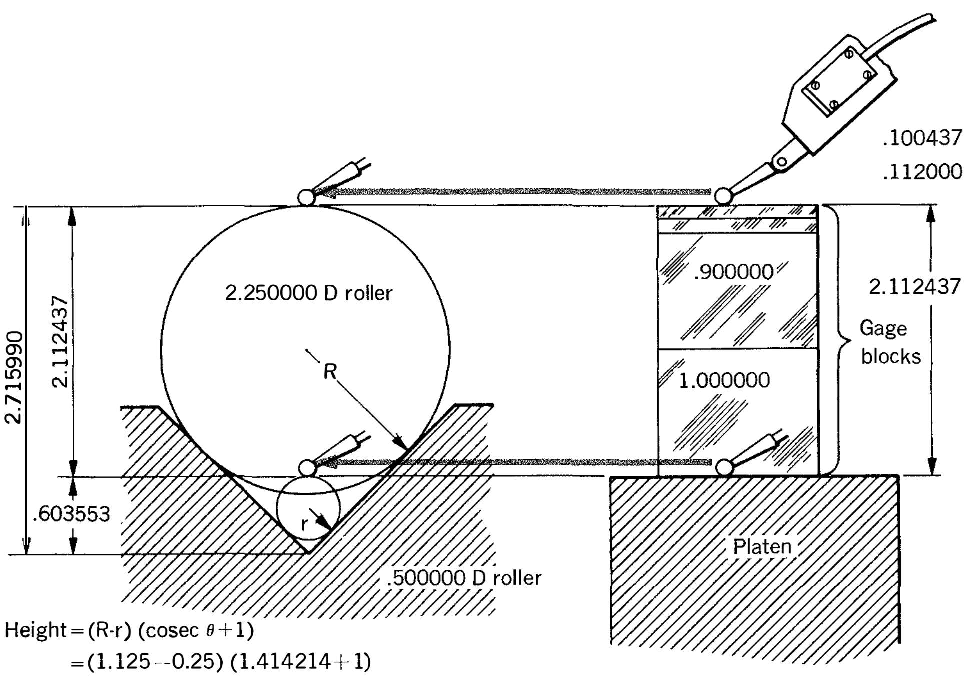


FIG. 37—*The 90° V-form is established by the master straightedge and can be made very accurately because of its unique relationship to the flat plane.*





Height = (R-r) (cosec θ + 1)
= (1.125 − 0.25) (1.414214 + 1)
= 0.875 x 2.414214
= 2.112437

All dimensions shown are in inches.

FIG. 38—*One method of proof of the 90° form which is sometimes advocated does not result in accuracy in practice.*

inch [12.7 mm] whose sizes are accurately known, Fig. 38.

Measuring their relative differences in height in the V by comparison with gage blocks will reveal the correctness of the 90° angle. This method, however, involves many cumulative errors (size and roundness of the pins, picking up their high point in the V, the line-contact of the pins in the V, the error in the gage blocks, etc.). A better method would be to use a master cylinder square in the V and view a light gap against one flank of the V while set against the other.

Neither method would match the accuracy already achieved by matching the V to the straightedge.

2. *Lean—Fig. 39.*—In two methods of inspecting for "lean," the V's are compared to a common datum, the flat underside of the female master. In the first method, a 4 inch x 4 inch [100 mm x 100 mm] square gage, fixed to the end of the straightedge which rests in one of the V's, is inspected for parallelism to the surface plate, Fig. 40.

Lean of the V relative to the base of the female master shows as an out-of-parallelism of the gage. Lean of the V's relative to each other shows as an out-of-parallelism of the gage when the straightedge is placed in the second V. This set-up is self-proving. If the straightedge is truly square, parallelism of the gage will be identical as each of the four corners of the straightedge are placed in the same V. The straightedge may be turned end-for-end to inspect the square gage.

In another method, a small V-gage, which has two sides at 90° to each other, is used. The third side, at 45° to the other two, is indicated across, Fig. 41, to discover any localized lean. Repeat readings made when the gage is reversed in the V-way self-checks the gage.

FIG. 39—*Lean.*

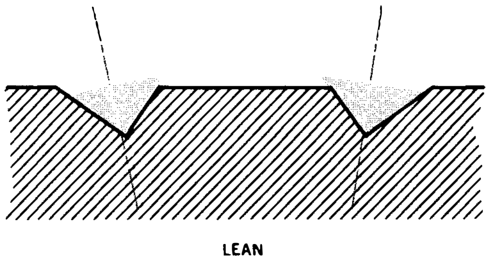
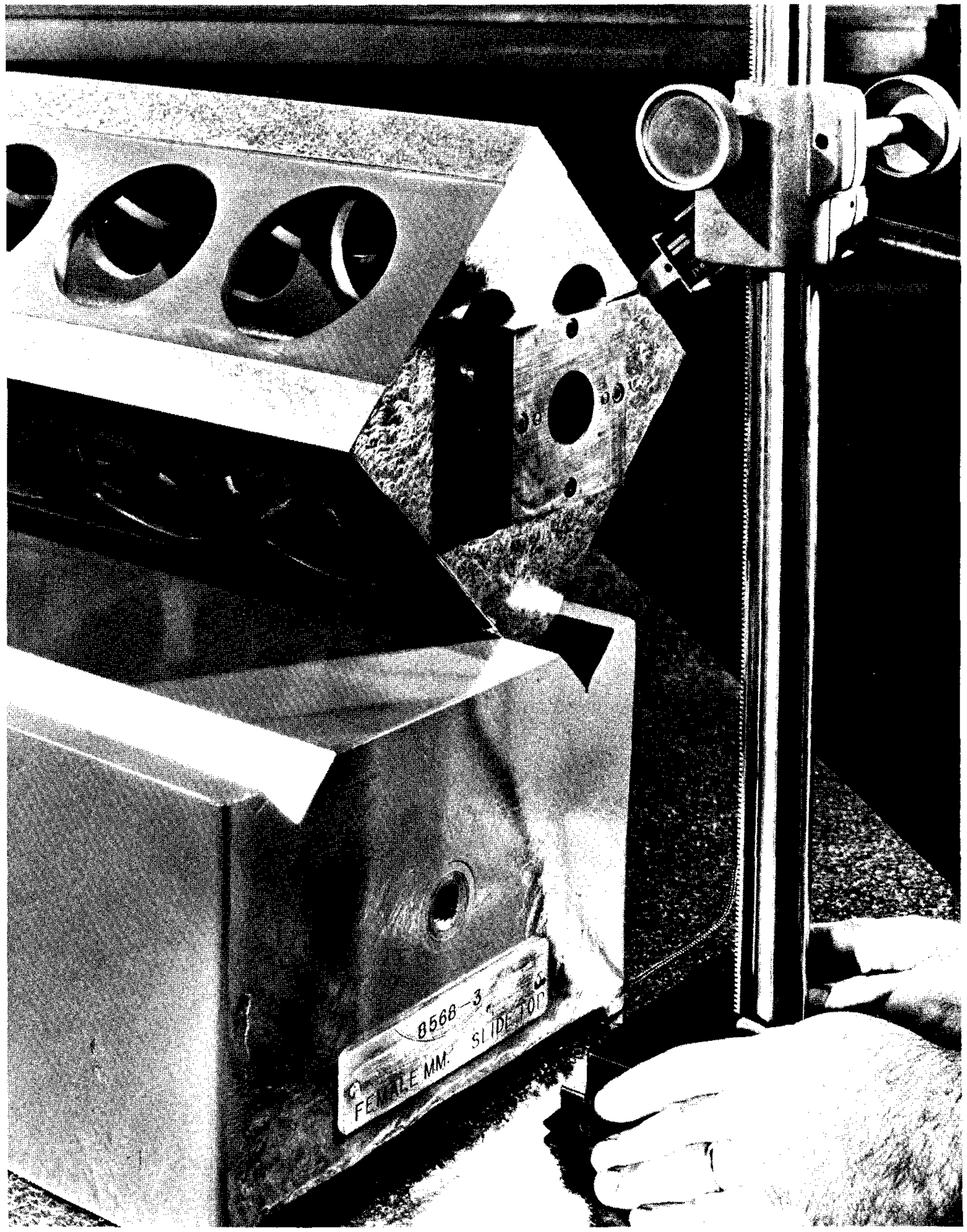


FIG. 40—*Lean of the V is inspected as shown. The straightedge is self-proved by being turned end-for-end as well as by placing each of its corners in the V and repeating the check.*



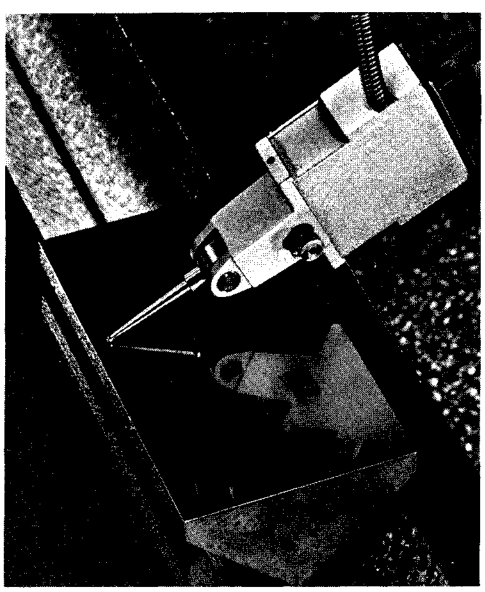


FIG. 41—*Another method of inspecting lean, but more locally, employs a small V-gage.*

FIG. 42—*Center-distance of the V's. Standardized center-distances of 6.5000 inches [165.100 mm] and 8.5000 inches [215.900 mm] are used for convenience of interchangeability of machine-members. An exact center-distance is not a prerequisite to accurate performance, providing mating members are the same center-distance.*

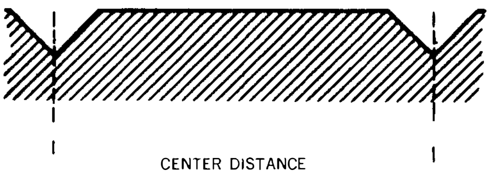
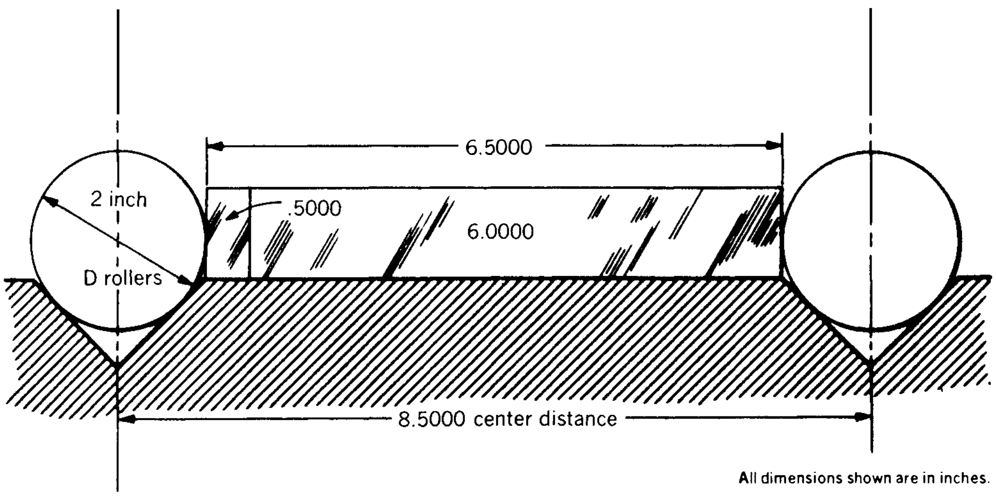


FIG. 43—*(center) Measurement of center-distance of the V's by means of gage pins is not sufficiently reliable.*



3. *Center-Distance. Fig. 42.*—It might be debated that the center-distance of two V's is not a derivative of the flat plane but a linear function, hence more properly treated under "standards of length." However, as with the 90° angle, a known, measured center-distance is not a prerequisite to an accurate system. Mating V's must only be compared by inspection to verify that they are of the *same* center-distance.

Standardized center-distances of 6.5000 inches [165.100 mm] and 8.5000 inches [215.900 mm] are used on No. 3 and No. 1½ machine V-ways for convenience and interchangeability.*

In one method of establishing distance, the correct stack of gage blocks must fit between two pins in the V's, Fig. 43. Since this method relies too much on "feel," a better method is to check the center-distance of the V's on the Moore Universal Measuring Machine, Fig. 44.

Once the center-distance is established, it is transferred to other "working" masters by means of a special double-V gage. One V of this gage is reed-hinged to allow setting against an electronic indicator, Fig. 45. Once a datum or "zero" is set, the scraping master may be compared to the double-V gage, Fig. 46. The female master is never again used in production, but only periodically as the ultimate arbiter of center-distance.

4. *Vertical and Horizontal Straightness, Fig. 47* (left and right respectively). It has been seen that 0.0001 inch [0.0025 mm] straightness can be achieved through use of the straightedge alone, but straightness in the horizontal plane is more easily achieved than that of the vertical. The reason is that the straightedge, when rest-

*Due to historical circumstances, the standardized center distances are not actually nominal as implied, but are known precisely.

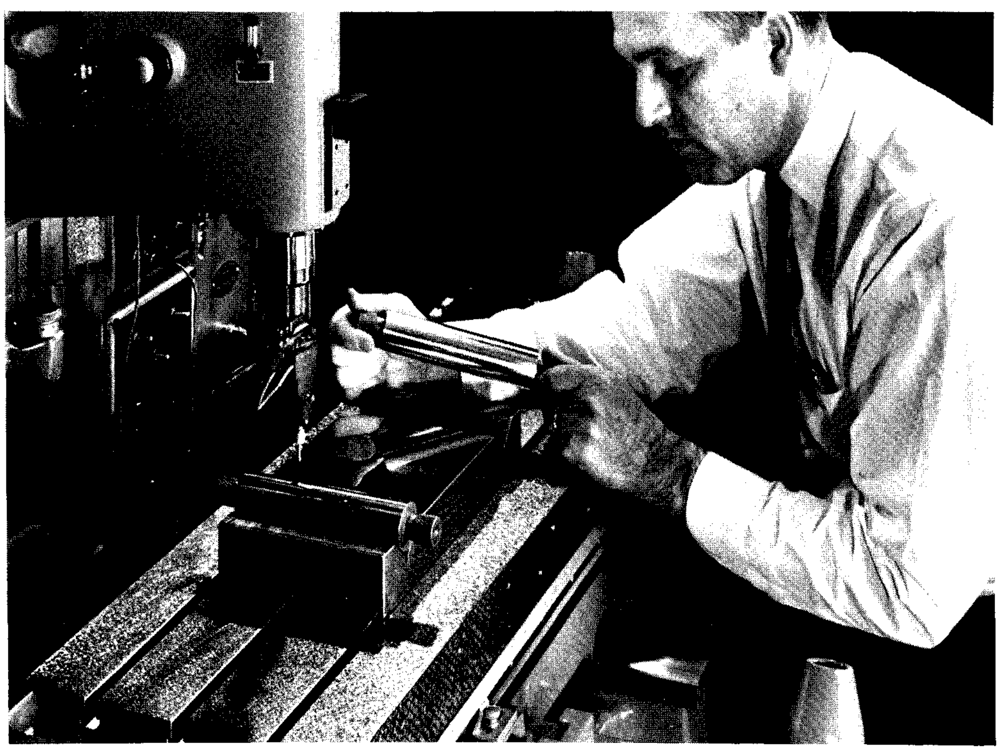
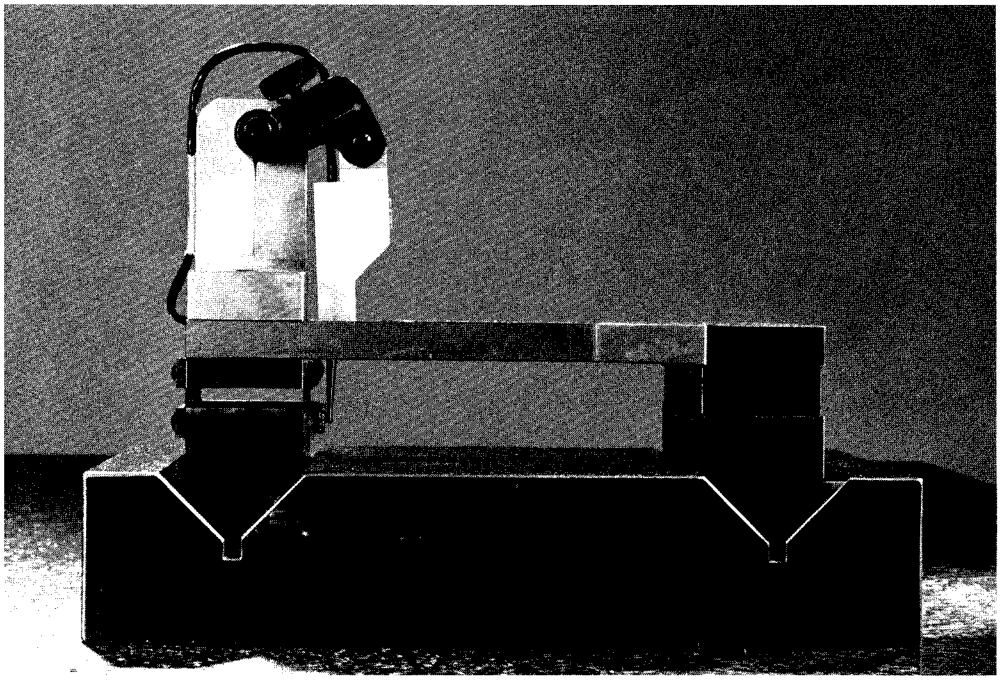


FIG. 44—*The Universal Measuring Machine is the most accurate method for establishing center-distance of double V masters.*

Chief Inspector here establishes center-distance of the ultimate master, which is a hardened, ground and lapped double V gage.

FIG. 45—*To transfer center-distance from the ultimate master, a double V male gage is used. One V of the gage is reed-hinged to allow setting a datum with an electronic indicator.*

FIG. 46—*Once the datum is set, the center-distance of the female double V master can be compared to the hardened master and scraped to agreement.*



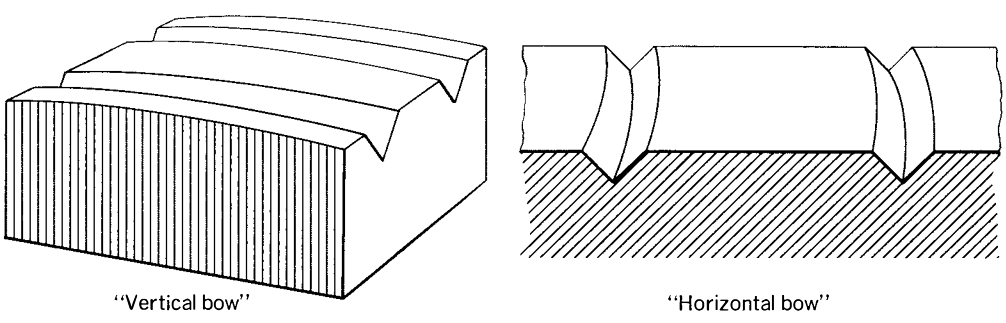
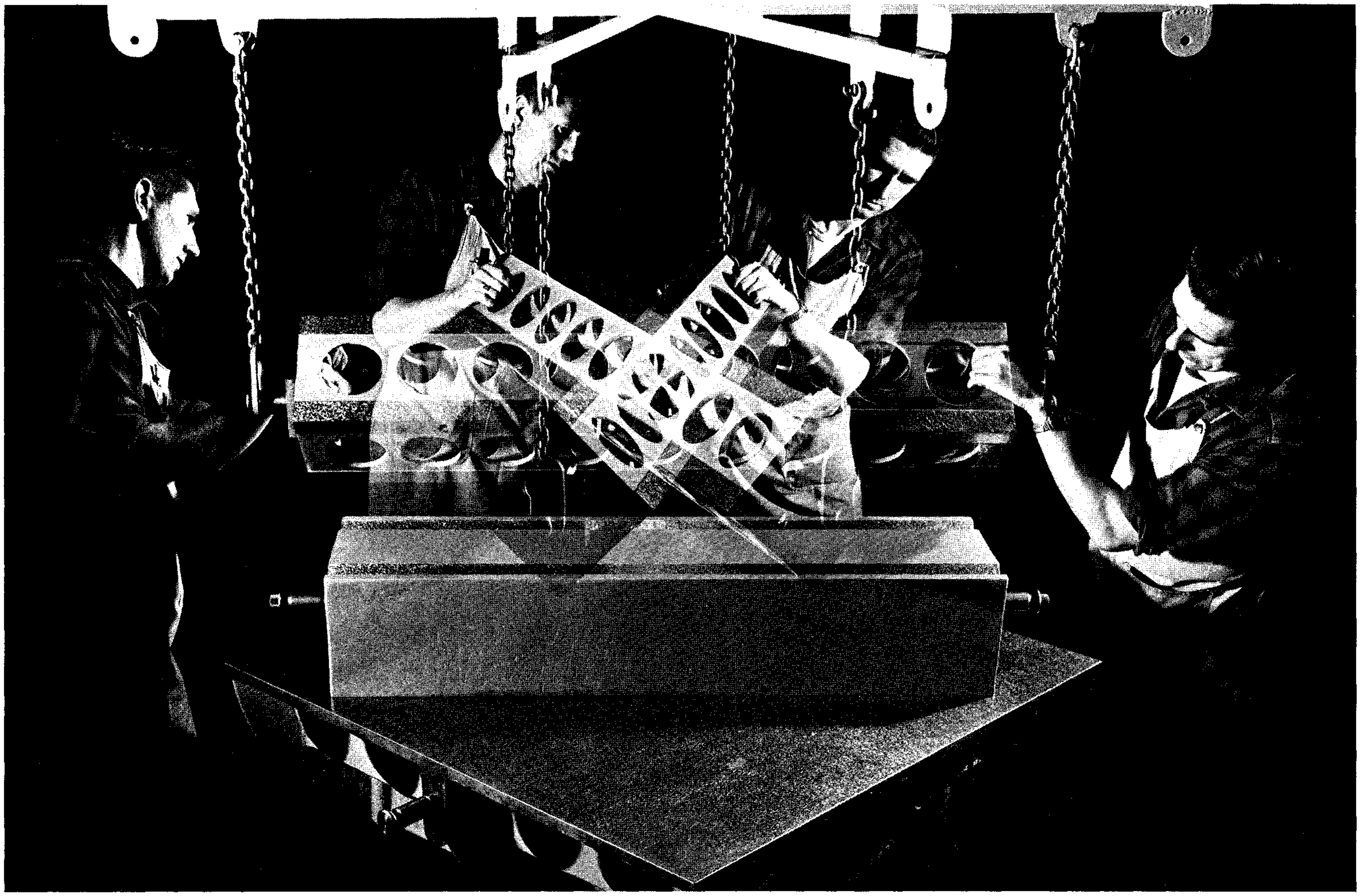


FIG. 47—*Vertical (left) and horizontal (right) curvatures in V-ways are shown. Straightness in both planes is established through use of the straightedge and master surface plate by self-proving methods.*

FIG. 48—*The straightedge imparts its straightness to the female V. The straightedge is self-proved upon being reversed 180° and examining the bearing. The method is sensitive, since any errors are opposed upon reversal.*



ing in the V-way, has greater force down through its vertical diagonal due to its own weight than across its horizontal diagonal. The straightedge thus bends more to conform to errors of curvature of the female master in the vertical plane.

Self-proving the horizontal by reversing the straightedge end-for-end reveals, through bearing change, even the slightest bow of the straightedge itself, Fig. 48. Self-proving the vertical direction by turning the straightedge upside down, Fig. 49, self-proves the vertical straightness, but to some extent repeats the vertical deflection. Fortunately, the vertical straightness deviation can be given two good inspections. In the first, change in height of a 1⅛ inch x 1⅛ inch [28.6 mm x 28.6 mm] square section gage with a small indicating pad is recorded over the length of each V. In a second method, each V is autocollimated for vertical straightness, Fig. 50.

The most convenient method of inspecting horizontal straightness of each V is by autocollimation.

5. *Horizontal Parallelism, Fig. 51.* Since all double-V's at Moore have standard center-distances, ultimately derived from the 6½ inch [165 mm] and 8½ inch [216 mm] female double-V masters, the actual *center-distance* need no longer be measured. The problem is now only that of *matching* of the V's in terms of horizontal parallelism, without the connotation of any actual distance.

Horizontal parallelism is inspected with a fixture, shown in Fig. 52 (or the gaging setup of Fig. 45 may be used). An indicator and arm are fixed to a cylinder resting in one of the V's. Rotating the cylinder slowly in the V (against a spring helper) registers a zero of the indicator against the high point of a cylinder in the adjacent V. Parallelism is charted by comparing sub-

FIG. 49—*Vertical straightness is self-proved by turning the straightedge upside down. The indicator shown at the left is used to verify the straightedge, as in Fig. 40.*

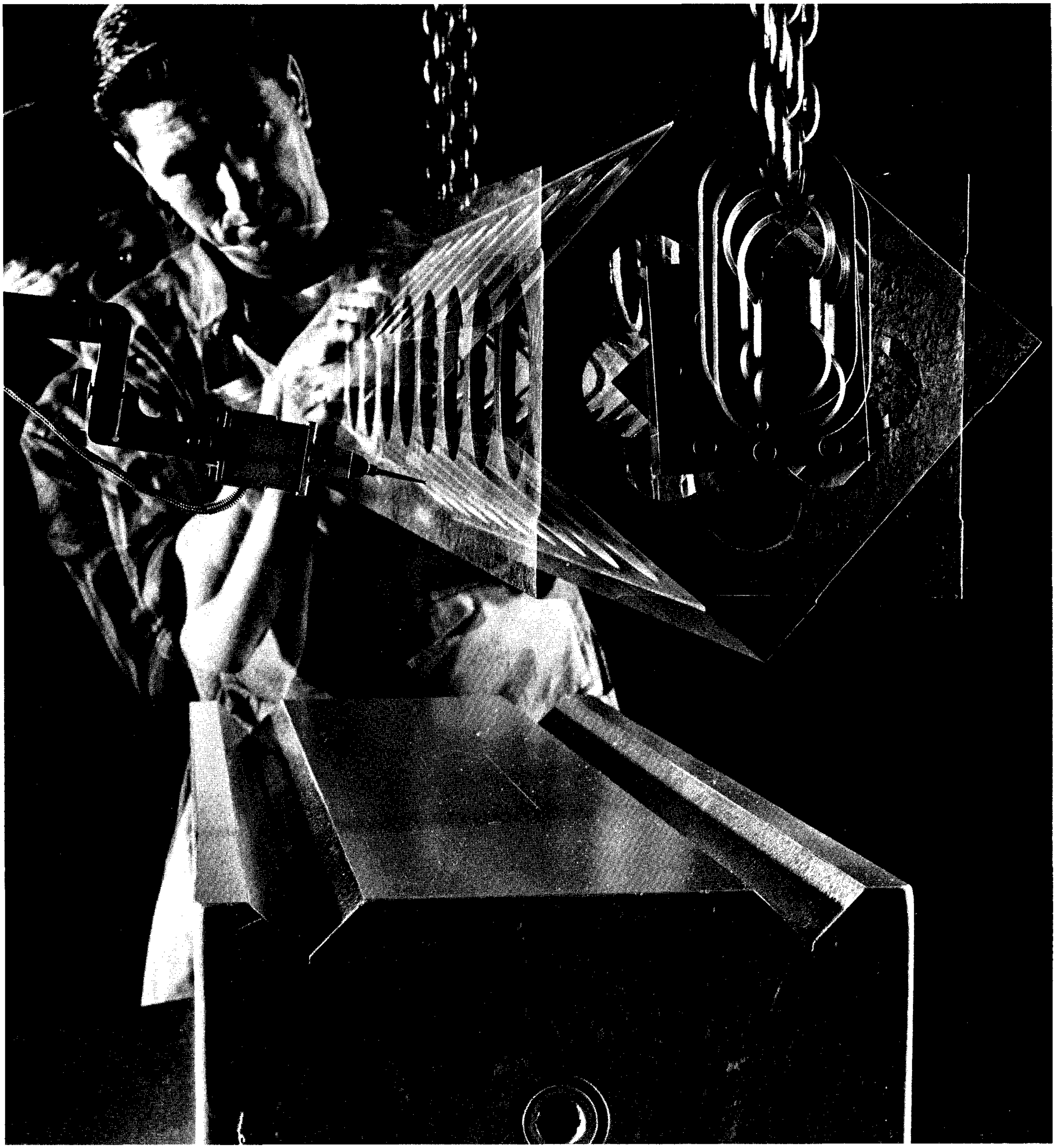


FIG. 50—*The most convenient inspection for straightness in both planes is by autocollimation.*

sequent readings taken over the length of the V's to this zero. The latter inspection, while it may reveal certain errors of straightness, should not be the basis of correction for straightness. (Attention is called to "Requirements of an Inspection Instrument," page 19). This inspection does not reveal which V deviates, or how much. Similarly, an inspection for horizontal parallelism would discover no error in two V's which were parallel but not straight.

6. *Vertical Parallelism—known also as "twist", Fig. 53.* "Twist" of the V's is inspected in the same manner as the indicator method under "vertical straightness," Fig. 54, using a precision plug gage, except that the V's are now presumed to be straight, and are inspected for parallelism.

Autocollimation will only reveal deviation from a straight line, and thus does not inspect either horizontal parallelism or twist.

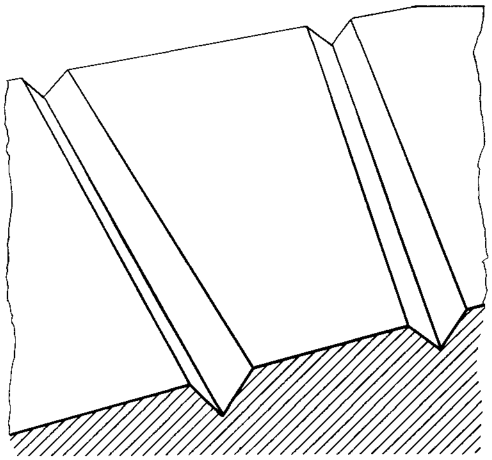
For simplicity, the procedure outlined was confined to the female master. In practice, a mating male double-V master was developed simultaneously by matching it to the female master. By reversing, both the male and the female masters are self-checked for center-distance and straightness, Fig. 55. Although accurate, the straightedge is not as sensitive and reliable as is the final check where mating double-V masters are reversed. It is a definite advantage to have masters that *encompass both rails.*

Of all the various way-designs in common usage, such as the V and flat, or the gib-type, only the double-V can be reversed as a self-check, if a master is to be used that gives bearing on both rails at once.

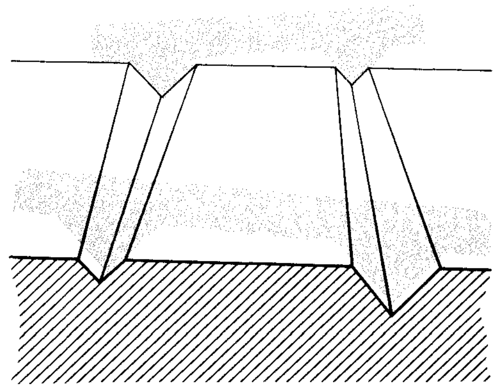
The inherent value of the double-V construction was apparent as early as 1931 when it was used between the column and housing of the No. 1 machines, Fig. 56. The double-V design was repeated in the column of the No. 2 machines. This ex-

FIG. 51—*Horizontal parallelism of the V's must be generated and inspected when a double V-way design is employed.*

FIG. 53—*Vertical parallelism or "twist" is one of the most difficult and troublesome errors to eliminate in machine slide-ways. Many machine-tools have a twist in their ways because the masters used are developed from surface plates having a "twist."*



HORIZONTAL PARALLELISM



VERTICAL PARALLELISM OR "TWIST"

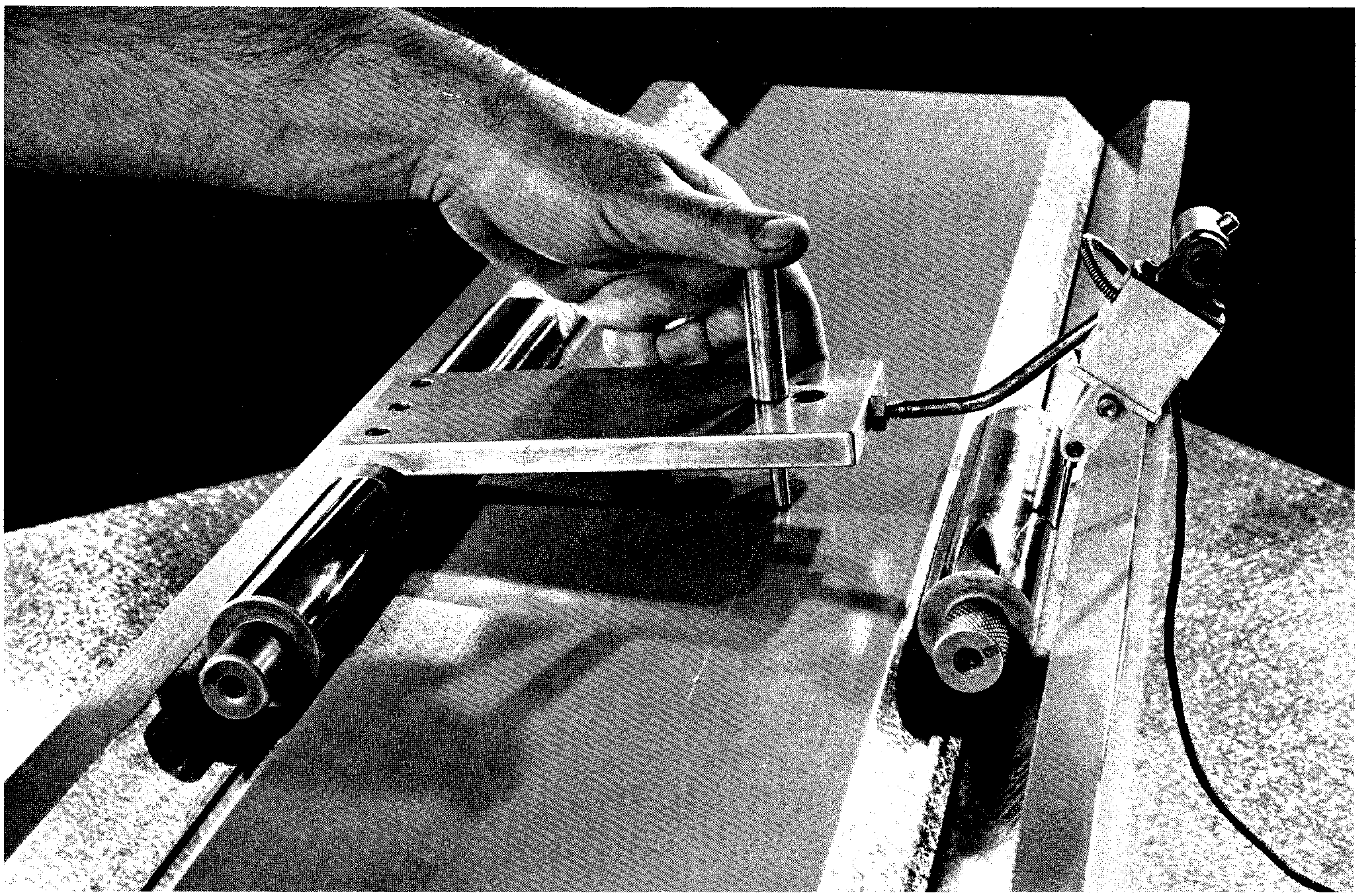


FIG. 52—*Horizontal parallelism is inspected with this gaging set-up, or by the reed-hinged gage shown in Fig. 46.*

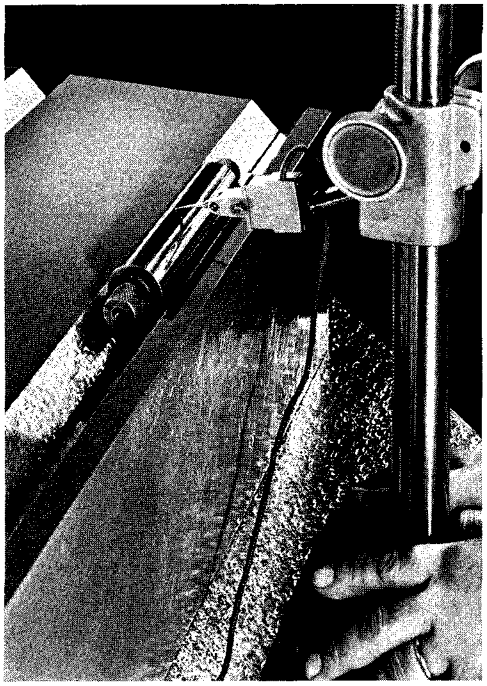


FIG. 54—*To inspect for twist, the height of both V's is compared over full length, using the master surface plate as the datum.*

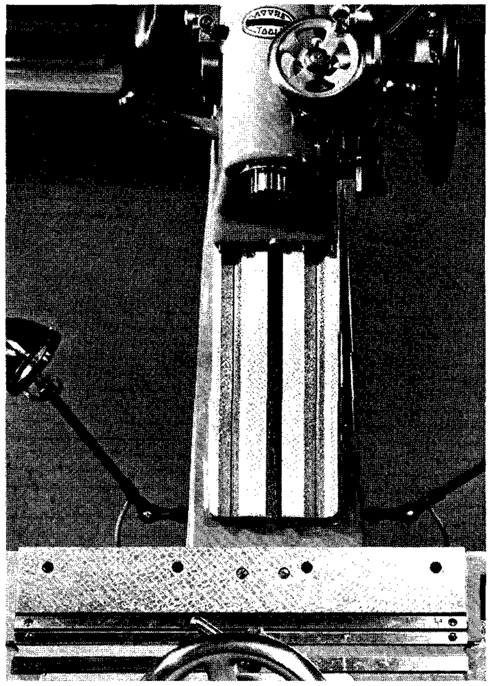
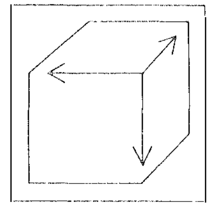


FIG. 56—*The advantage of the double V was recognized early and was used in the column of the No. 1 Jig Borer.*



perience formed a basis for the evolution of skills and techniques necessary in working to a double-V.

In singling out the specific types of errors, the writer recognizes that it is one thing to discover them and quite another to translate analysis into correction. Scraping the double-V, involving many combinations of errors, will put a good scraper to his mettle. He must thoroughly understand the "geometry" involved, for he may be scraping for several types of errors simultaneously. An unnecessary amount of time may be expended if he fails to put a proper value on each.

Usually, several years of training are required before a man is given the task of scraping a double-V. It is readily admitted that when badly done, a double-V can be the worst type of machine construction. An accurate double-V, on the other hand, besides being a "natural" standard, will be seen to be the most advantageous in terms of actual machine performance.

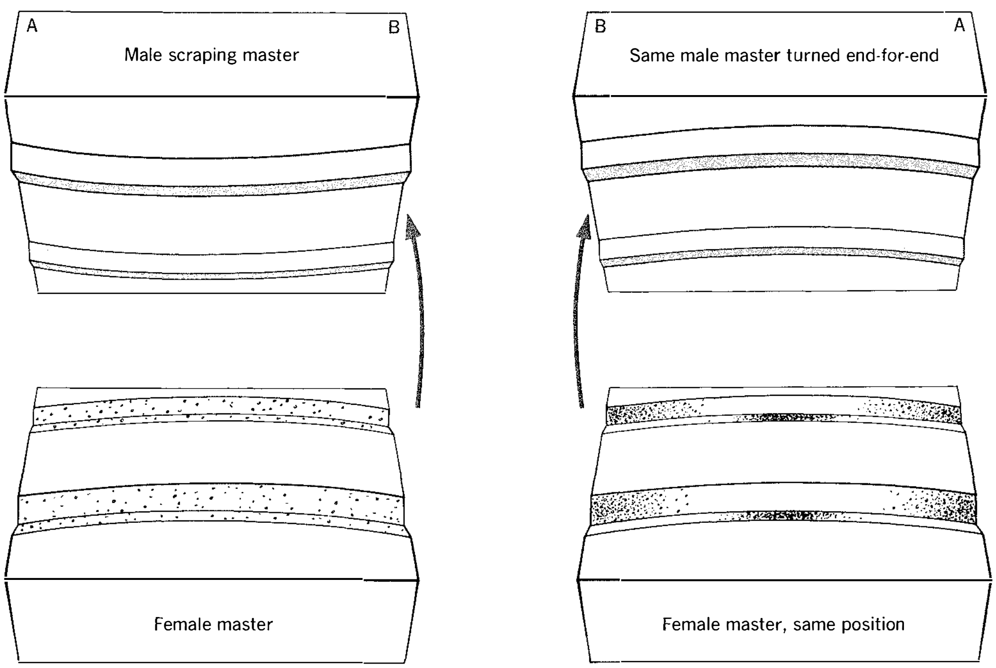


FIG. 55—*The advantage of the double V is best illustrated here. If male and female conform, but are not straight (left), then upon reversal (right), the errors are opposed. The bearing is non-uniform (lower right). The ability of double V masters, or machine-members to be reversed provides a quick, sensitive check which is always available.*

4. MACHINE DESIGN

Coordinate Location

A machine tool with two movable axes, "X" and "Y," each with its measuring element, can position to any point in a plane, Fig. 57. X and Y axes may both carry the piece to position it relative to the spindle, or the X axis may alone carry the piece and the Y axis carry the spindle. Coordinate location may be in a vertical as well as a horizontal plane.

With a third axis, "Z," perpendicular to X and Y, the location is to any point in a cube bounded by these three travels. A full measuring element is not always necessary in the Z axis (a machine may work mainly on through holes), but auxiliary means are usually included to establish distance.

FIG. 57—*The theory of coordinate-location to establish any point in a plane is shown here. The principle is the same with all coordinate-locating machine-tools, even though the type of machine construction, way design and measuring element may vary.*

Geometry as a Function of Machine Accuracy

Straightline Travel: A Factor in Locational Accuracy

Relatively slight errors of straightness in a machine's ways may result in very sizable errors in location when machining or measuring holes and surfaces in an actual workpiece.

The nature of this error can be pictured as spokes in a wheel, Fig. 58. For example, a horizontal curvature of only 0.0001 inch in 10 inches of travel [0.0025 mm in 250 mm] will introduce a locational error of 0.0008 inch at 10 inches out [0.02 mm at 254 mm] from the machine's lead screw (or other measuring element). The actual travel is greater or less than nominal depending on whether the interval that is set is on the side of the lead screw axis farther from or nearer to the center of curvature of the ways.

The same magnification of error also occurs in the vertical plane. In the case of a concave arc, Fig. 59, travel is foreshortened, the axes of the holes are out of parallel, and point at one another at some distance above the table.

In the case of a convex arc, Fig. 60, travel is lengthened, the axes of the holes are out of parallel, and point at each other at some distance below the table.

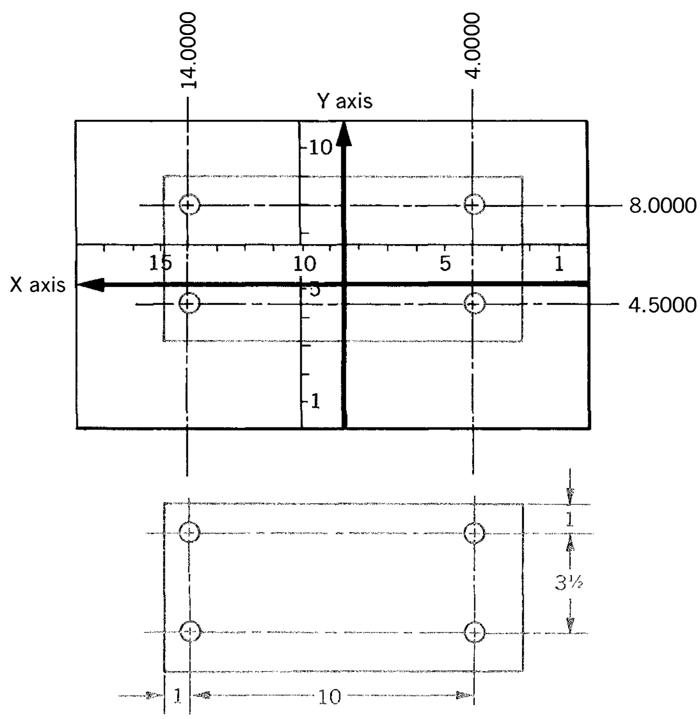
The principles involved here have to do with what is often referred to in metrology as the "Abbe effect."

Causes of an Arc in Travel

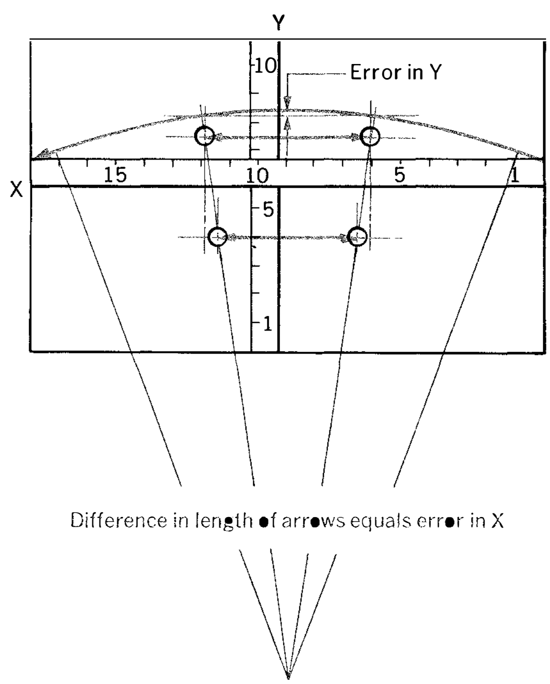
The causes of an arc in travel are:

1. Original error of straightness scraped or machined into the ways.
2. Deflection of machine members.

To prevent deflection, each axis must be supported in its full travel. The designer is often tempted to increase the travel of the



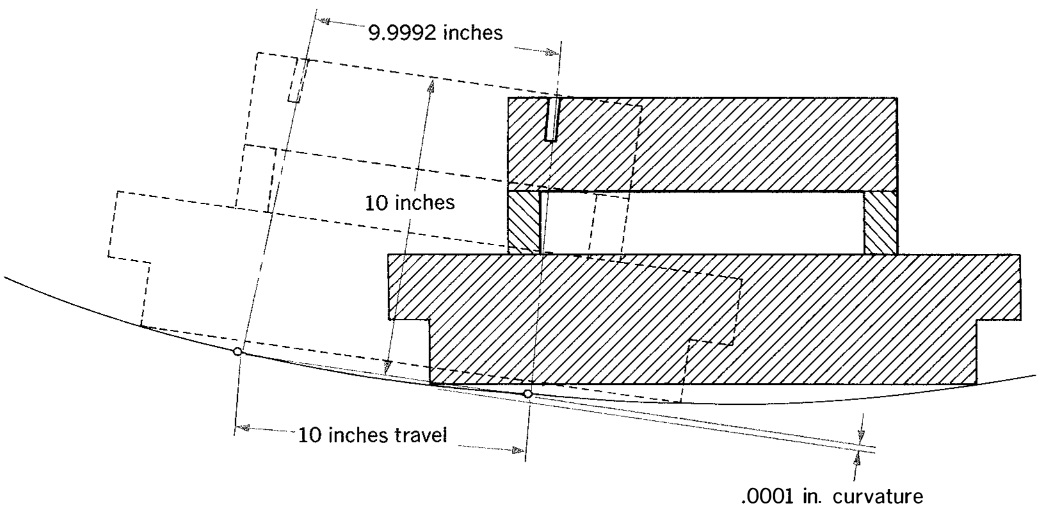
All dimensions shown are in inches.



All dimensions shown are in inches.

FIG. 58—*Curvature of travel is best visualized as spokes in a wheel. The measuring element remains unaltered, but the actual distance the part moves varies along the spoke. This error is very severe and occurs regardless of the type of measuring element in use (lead screw, precision scale, laser interferometer, etc.).*

FIG. 59—*A concave travel in the vertical plane is shown. 0.0001 inch curvature in 10 inches of travel [0.0025 mm per 250 mm] will cause a shortening of travel of .0008 inches [0.02 mm] at a distance 10 inches [250 mm] above the ways.*



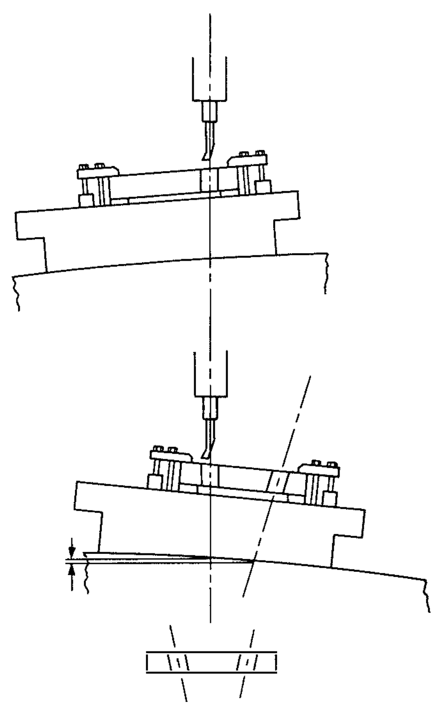


FIG. 60—*A convex arc in the vertical plane is illustrated. Error is magnified as in Fig. 59, but the center-distance of holes is now established too far apart, and out of parallel as shown.*

axes without support, since it is less expensive. The tolerances required of vertical millers and similar machines will permit this, but it is an unfortunate compromise in high-accuracy machines. The resulting "overhang" causes a sag as the table passes beyond its support, Fig. 61. Deflection from weight can have a constant value, but the conditions of deflection must be ***identically repeated*** for this to be so. For example, in Fig. 62, the ways can be scraped concave to compensate for the deflection caused by the table, but not for the variety of weights of workpieces that may be mounted on it.

Wear of Machine Ways

The ways in a machine tool tend to wear concave, because the center of the travels is most used. Wear can be minimized in design by:

1. An overall machine configuration or way design that tends to minimize wear;
2. Having the two guideways on each axis subject to uniform load, uniform friction;
3. Preventing excessive wear on one short portion of the travel.

The machine's measuring element is usually blamed for loss of positioning accuracy when more often the cause is wear in the machine's ways.

Deliberately putting an error into the measuring element to compensate for wear is a poor practice. Accuracy is still attained at one distance and only one distance from the ways, Fig. 63. At all other distances along the "spoke," that axis will be in error. Instead, every possible design precaution should be taken to discourage wear, especially uneven wear, since even a relatively small arc can produce serious errors.

Another poor substitute for geometric accuracy is shifting a machine tool's precision scale to compensate for curvature of travel.

Squareness of Travel Is a Factor in Locational Accuracy

Coordinate location demands a 90° relationship of the X-Y travels. Out-of-squareness causes a locational error, Fig. 64. Out-of-squareness most often has a constant value with each machine, but there are circumstances under which this is not so. Squareness may be altered by deflection, shift of the travels (due to poor guide ways), or heat. If the axes do not travel straight, squareness calibration can only have a mean value, Fig. 65.

When used in one relative position, the Z axis is usually not a function of coordinate location accuracy. However, loca-

FIG. 61—*If the axes are not supported over full travel, movement of machine members causes a sag, resulting in errors as shown in Figs. 59 and 60.*

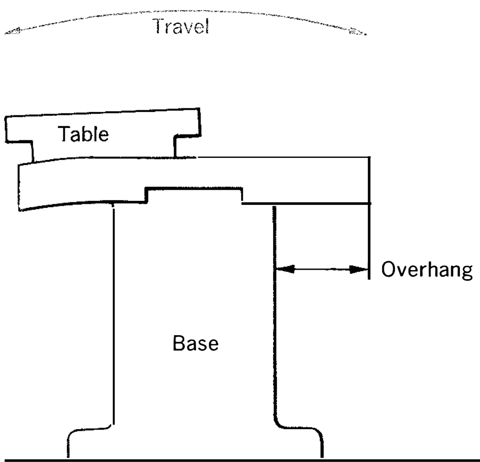
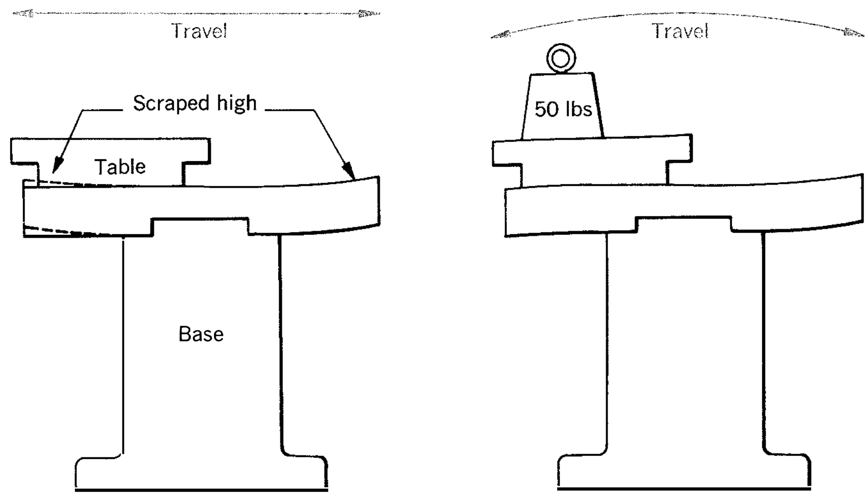


FIG. 62—*Attempts to compensate for "overhang" by scraping the ends of the travels high (left) is inadequate, since the deflecting force is not always the same (right).*



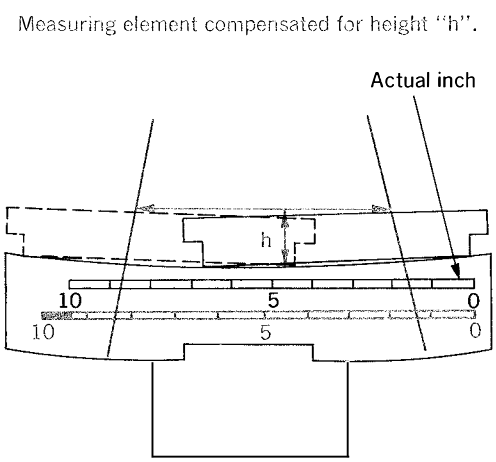


FIG. 63—*Compensation for curvature of travel by lengthening the measuring element, or shifting it while the axis moves, is also a poor substitute for geometric accuracy. The actual travel is only correct at one point along the "spoke."*

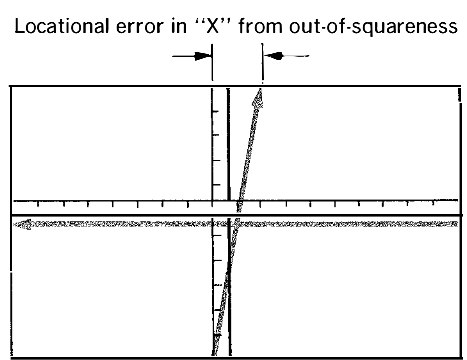


FIG. 64—*Out-of-squareness of X and Y axes causes a locational error.*

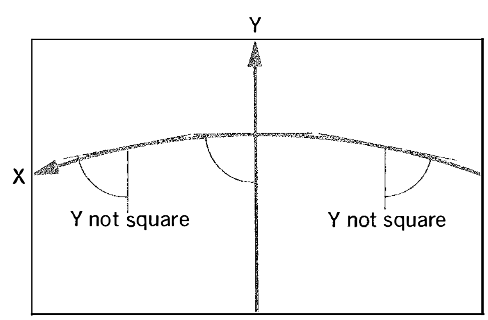
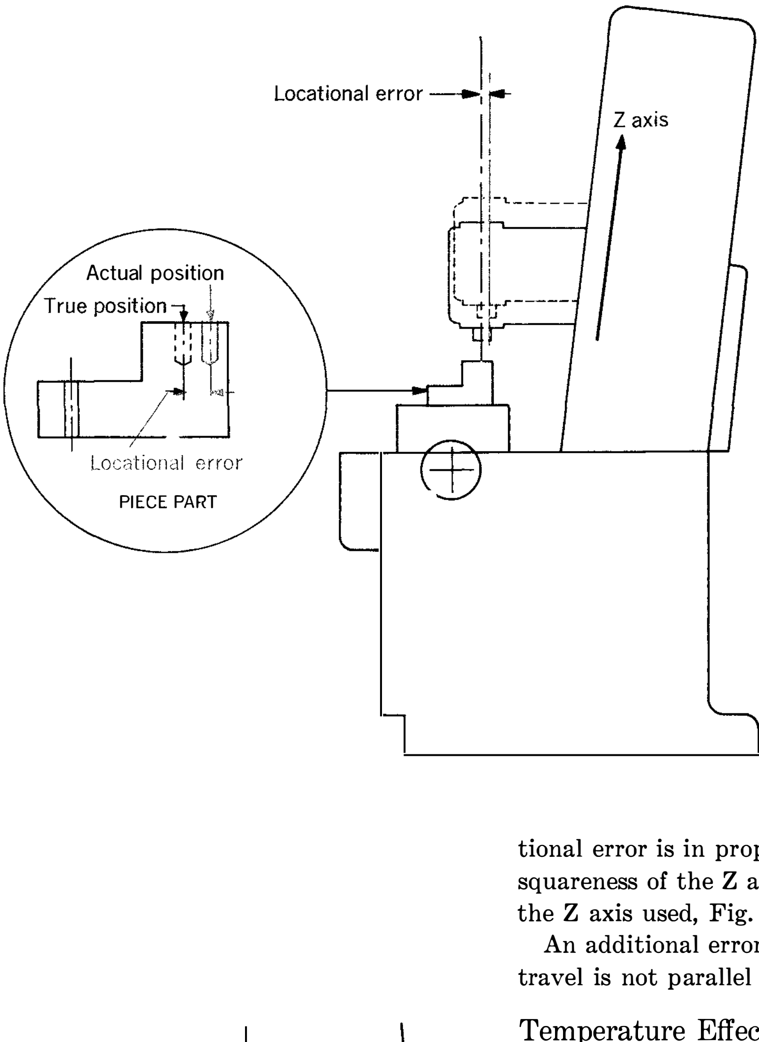


FIG. 65—*If the axes do not travel straight, squareness can only have a mean value.*

FIG. 66—*Locational error may be caused by the out-of-squareness of the Z axis, when boring holes at different heights.*



tional error is in proportion to the out-of-squareness of the Z axis, and the extent of the Z axis used, Fig. 66.

An additional error is caused when quill travel is not parallel to the Z axis, Fig. 67.

Temperature Effects on Geometry of the Machine

Sources of uneven temperature distribution from the environment have already been mentioned in regard to scraping masters. Consequences of temperature variation are even more detrimental to the accuracy of a machine tool.

Most subtle and most difficult to combat is "stratification" of room temperature, which usually takes the form of a cold floor and warm ceiling. A machine tool also has its own heat-producers—motors, spindle bearings, gear and belt drives, lights, heat from cutting.

It is impossible to completely eliminate uneven temperature distribution in a machine. It *is* possible to minimize the loss of accuracy due to "temperature" through observance of the following design considerations:

1. Sources of heat should be removed or insulated from the main body of the machine;
2. Spindle bearing heat should be isolated from the coordinate (X-Y) axes.
3. If X and Y axes are at the same room level, the measuring element of each will be more nearly the same temperature;
4. Where possible, the coordinate axes, the measuring element and the workpiece should all be in the same "heat sink."

MACHINE CONFIGURATION

Accurate hole-location machine tools are best represented by those in the "jig borer family" where the most sophisticated construction is employed. Despite individual characteristics, jig borers can be classified under three basic designs:

1. Planer-type
2. Horizontal spindle
3. Compound-type

While there is overlapping of function, each design has a certain realm of work for which it is best suited. It will be observed that none of the designs is perfect. A feature of one may be an advantage only by compromising elsewhere. The user must analyze the design with a view to what fits his own type of work. It is instructive to do so with these considerations in mind:

1. Deflection
   a. Of the machine's members from movement
   b. From cutting pressure
2. Temperature
3. Type of workpiece
4. Operator convenience
5. Wear

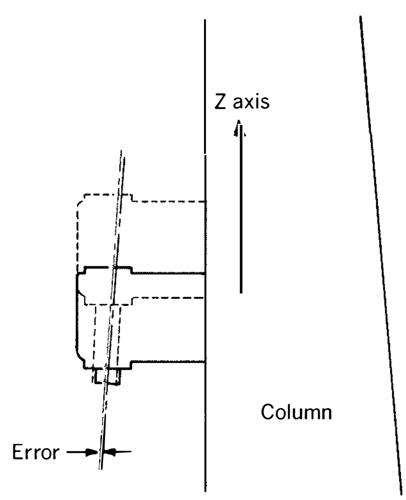
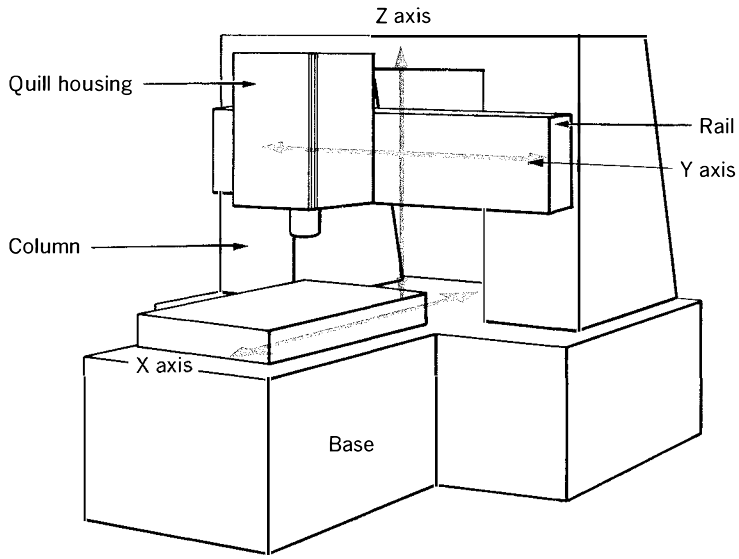


FIG. 67—*Misalignment of the quill may also cause a locational error.*

FIG. 68—The planer-type jig borer achieves large capacity in one plane without becoming unduly massive, and is best suited for flat work.



The Planer-Type Jig Borer

The design of the planer-type jig borer, Fig. 68, includes a long base which supports the table, or X axis, in its full travel. Two upright columns, straddling the base, are joined at the top for rigidity. The two columns guide and support a cross rail, which, in turn, carries the spindle housing containing the spindle, quill, spindle gears, feed gears, etc. The spindle housing, guided by ways in the rail, travels as the Y axis.

The cross rail is positioned vertically by two lead screws, one at each end, which must be of identical leads to maintain parallelism of the rail to the table at all heights.

There are two primary advantages of the planer-type design. Foremost is the fact that X and Y axes can each be given separate support. This is of benefit especially in larger machines to limit deflection in the base (contrast this with the compound-type). Secondly, it achieves large capacity without becoming unduly massive.

To establish parallelism of the spindle housing travel to that of the table, the column mounts are scraped. Squaring the X and Y travels is accomplished by shifting the columns and then taper-doweling in place.

The rail guide-way is scraped convex to compensate for the deflection of the rail which results from the weight of the spindle housing. The amount of deflection can be a constant factor, but only if the conditions of deflection are repeated.

For this reason, it is necessary in order to achieve maximum accuracy that the spindle housing be returned to a central position before the rail is clamped to the columns, or is elevated or lowered. This procedure is required in terms of the rail-elevating screws as well. They must be of an identical lead to maintain parallelism of rail to table. This is possible only when the load shared by each is constant.

The precaution of coming to center can effectively reduce the variance of deflection which would otherwise occur, but adds to the time required for setting.

The top way of the rail also is scraped convex for reasons of wear. The center of travel is subject to more than normal wear, since most of the load is carried by the upper way in the rail. An arc in this rail results in a locational error, magnified with the distance of the cutting tool or indicator from the ways, Fig. 69. With better conditions of support in the base, there should be no undue wear in the base ways. If the table travels in an arc in the vertical plane, positional error will be magnified with the height above the bed ways.

Worksize limitations are determined by the configuration of the machine. The piece must fit under the spindle and be-

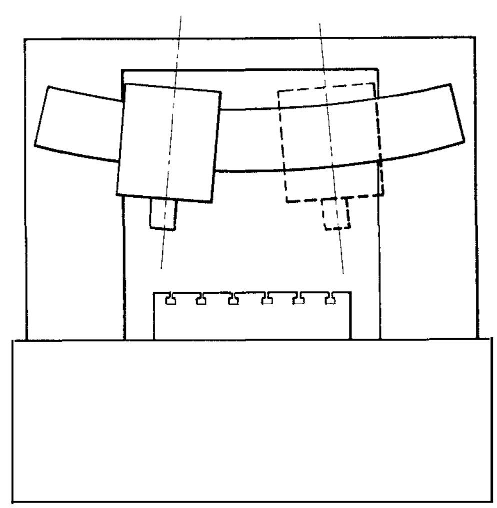
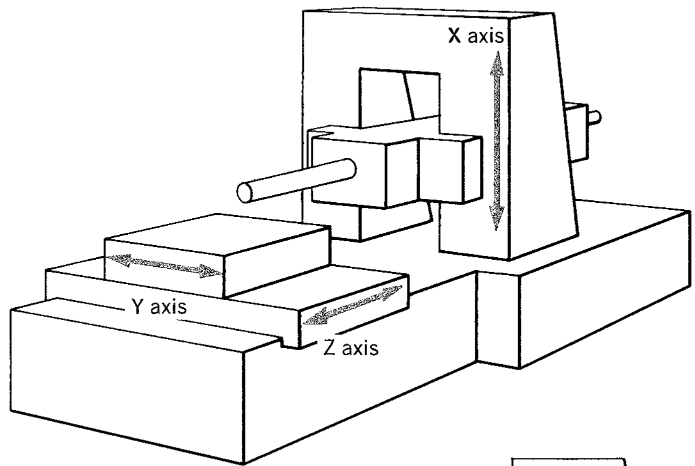
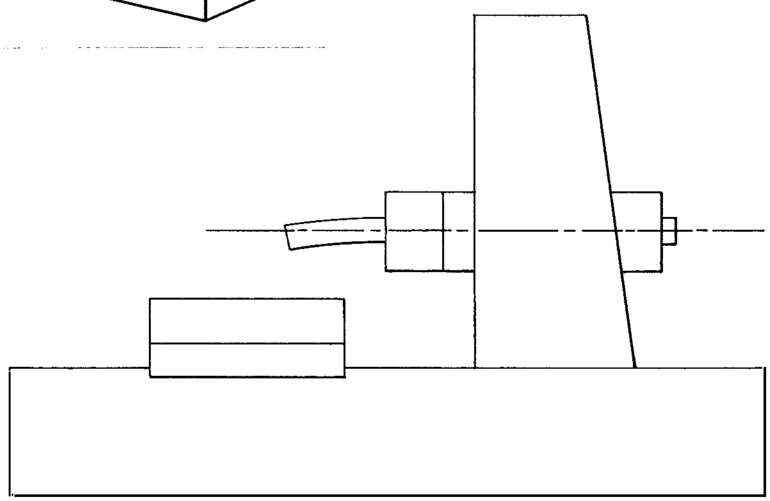


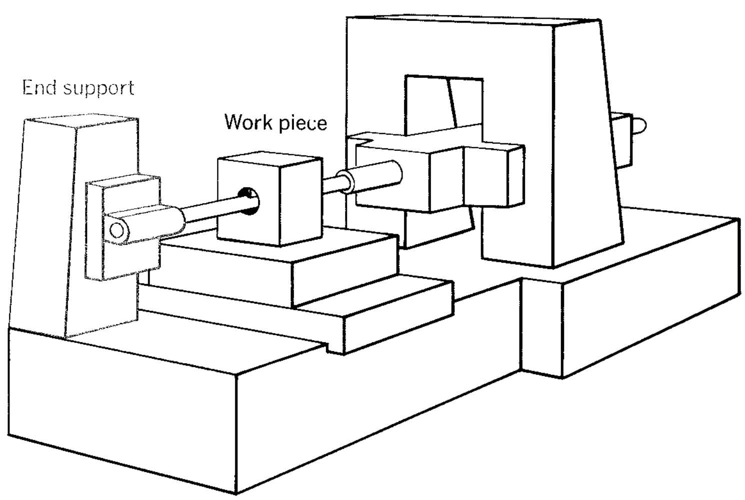
FIG. 69—An arc in the rail of the planer-type jig borer will result in a locational error magnified with the distance of the cutting tool or indicator from the ways.

FIG. 70—*The horizontal spindle jig borer is a rigid design, well-suited for heavy machining and box-type workpieces.*

FIG. 71—*(center) The quill of the horizontal spindle jig borer sags of its own weight as it is extended from the housing.*







tween the columns. For this reason, the planer-type is more suited to flat work.

Besides the necessity of returning to center of balance before elevating the rail (which includes the weight of dials, gears, etc.), setting time is increased by two other factors:

1. Since the spindle housing moves as one of the axes, it is at times difficult to reach by the operator for tool changing, operating spindle controls, or indicating the workpiece;
2. Separation of X and Y axes places positioning indexes and handles farther apart on the machine.

With the indirect relationship of the travels—the spindle housing travels on the rail, the rail on the columns, the column fastened to the base—temperature becomes more critical. Any localized heat, such as from spindle-bearing warmup or heat on one of the columns, can more easily alter parallelism and squareness of the travels. Stratifications of room temperature may cause the measuring element in the rail to be warmer than the measuring element in the base.

The Horizontal Spindle Jig Borer

As with the planer-type, the horizontal spindle jig borer, Fig. 70, gives separate support to X and Y axes. The bed supports the table, or Y axis, in its full travel. However, the spindle is horizontal, and its housing travels as a vertical Y axis. Coordinate locations are then in a vertical plane.

The spindle housing is usually elevated by a lead screw and guided by the ways in a single or sometimes double column.

In addition, there is a Z axis in a horizontal plane on the base, parallel to the axis of the spindle, to accommodate different size workpieces, or to control depth of cut; this axis is equivalent to the rail-height adjustment in the planer-type machine.

A horizontal spindle can sag of its own weight as it is extended, Fig. 71, or can

FIG. 72—*Use of end supports as shown will prevent loss of accuracy of the horizontal quill only with a great deal of time and care.*

Use of the Z axis to feed the workpiece with the quill fixed is another method whereby error due to quill sag is avoided.

The most satisfactory method is to use an accurate indexing table and to in-line bore the piece half-way from each side.

settle as its weight squeezes out the oil film between the quill and its bearing.

An early method of minimizing spindle sag in horizontal spindles by means of end supports, Fig. 72, is still widely used today. This procedure achieves accuracy only with care and time. Another way to cope with spindle sag is to use the Z axis to feed the workpiece into the spindle. This, in turn, introduces location problems, because the table rises on an oil film as it moves. Use of roller ways will minimize the problem of oil film, but introduces the even more serious problem of shielding the rollers against dirt and chips.

Actually, the problem of spindle sag has been satisfactorily solved with the advent of accurate indexing tables. To avoid long quill extensions, the piece is indexed 180° and "in-line" bored from the opposite side.

Where use of the horizontal spindle presents problems of sag, there is an advantage in being able to take a heavy cut without deflection: the spindle is backed by the full rigidity of the column.

Extremely heavy workpieces, such as box jigs, gear boxes, and housings, can be machined most productively on this machine. They are easily indexed to all four sides, a good cut may be taken, and they can be accommodated on the table with no obstructions. However, flat pieces are more awkward to handle because they must be mounted on an angle iron to be presented to the spindle.

Operator accessibility to controls is difficult to achieve in a large machine, and is probably best met by the horizontal spindle design. The spindle and positioning controls can be reached by the operator from one position.

There should be no inherent wear problem due to the horizontal design, but an arc in the travel would, as in the planer-type, magnify positional error the greater the distance of the spindle from the column ways or from the bed ways.

With this type of column construction, localized heat would cause no undue distortion, but the squareness relationship of the travels is not as direct as with the compound-type machine. Spindle warmup can be a source of positional error, because the spindle housing moves as one of the coordinates in location. With the box-type work for which the horizontal machine is best suited, the Z axis may be just as important as X and Y axes, in which case having a spindle in one of the axes is unavoidable. Since the spindle housing is at the work level, stratification of room temperature is not as serious a problem as in the planer-type.

The Compound-Type Jig Borer

The base of the compound-type machine, Fig. 73, supports both travels. The compound slide itself, being guided and supported by the ways in the base, moves as the Y axis. The upper ways of the compound slide, guide and support the table travel, or X axis. *The squareness relationship of the travels (X and Y axes) is thus embodied in one member, the compound slide.*

A single column mounted on the back of the base carries the spindle housing in its vertical adjustment, or Z axis. This adjustment is used for depths beyond the range of the quill travel, or to accommodate larger workpieces, and must be perpendicular to the X and Y axes.

As with the planer-type jig borer, the spindle is vertical and coordinates are in the horizontal plane.

Loss of accuracy from temperature is minimized in the compound-type machine for the following reasons:

1. The single column design minimizes distortion from localized heat;
2. Table, compound slide, both linear standards and workpiece are all in the same equalizing "heat sink."
3. The linear standards of X and Y axes will be the same temperature despite stratification of room temperature;

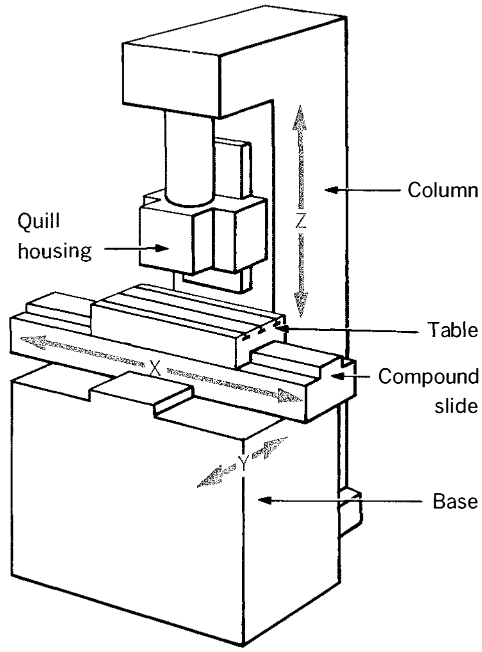


FIG. 73—*The compound-type jig borer is preferred in the smaller machines. In the larger size, it becomes very massive, considering its capacity, but is sometimes a desirable compromise when the class of work falls in between the requirements of the planer-type and horizontal spindle jig borer.*

4. Squareness of the travels, being maintained in one member, the compound slide, is not likely to be altered by temperature conditions;
5. Spindle bearing heat is isolated from the positional axes (although the spindle axis will still shift due to heat).

There should be no undue wear due to the compound-type design. The most common error resulting from wear is a concave arc. The workpiece limit is defined by the throat distance (column to spindle), and by the working height under the spindle nose. However, with this design, riser blocks (spacers) are easily installed between column and base to increase working height. Large, box-type pieces are not machined as efficiently as on the horizontal spindle machine.

In the smaller compound-type machines,

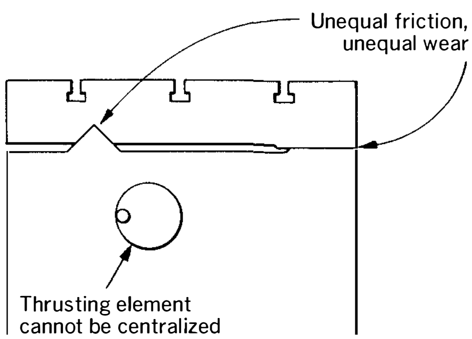


FIG. 74—The V and flat way design, though often considered the ideal, has many disadvantages, notably in unequal friction of the ways and inability to centralize the thrust.

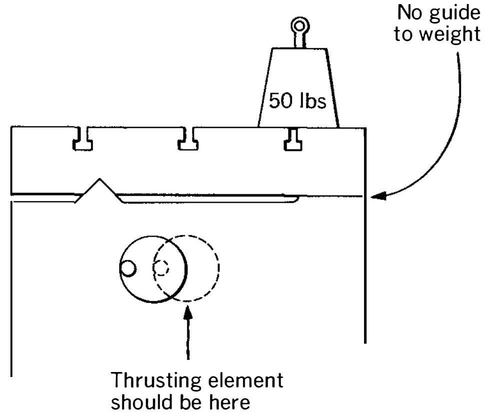


FIG. 75—When a weight is placed over the flat way of the V and flat design, the ability of the V to guide is diminished. The thrusting element is now not balanced.

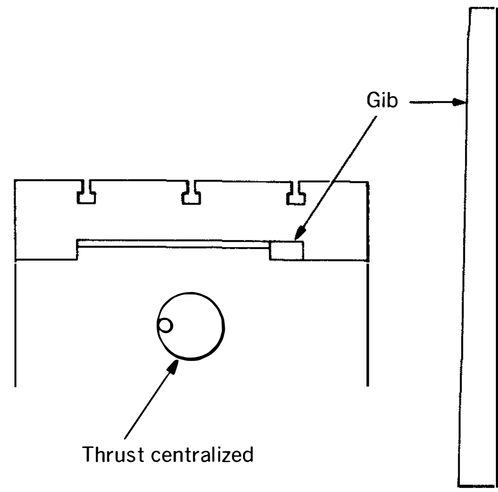


FIG. 76—Square-type gibbed way. Fundamentally correct, symmetrical. Thrust can be centralized, but once gib is adjusted for wear, initial alignment is lost.

positioning handles and spindle controls can be reached by the operator from a standing, or even sitting, position. Rapid adjustment for work height is possible with a counter-balanced housing and a simple clamping arrangement. The larger the compound-type machine becomes, the less convenient it is to operate.

Because of the small overhang of the spindle housing, the advantage of a vertical spindle is gained without sacrificing cutting rigidity, although relatively speaking, not as rigid a cut is possible as in the horizontal-spindle machine.

Both table and compound slide must be supported in their full travels which means that, for additional capacity, the machine gains in size virtually as its cube. The compound slide, in moving, has the additional weight of the table to support. If the table is at the extremes of its travel, or if a large workpiece is not centered, the compound slide must move an off-center weight. For these reasons, deflection in the base and a deflection or shift in travel in the compound slide are difficult to prevent in the larger compound-type machines. Because of lesser workloads involved, this is not as much of a problem in the smaller compound-type machine.

In the smaller size machine, the compound-type is to be preferred. The design of the larger-size machine depends on the type of work it is to do. It is, therefore, much more difficult to select a design.

In the larger machine category, it would seem that there is much in favor of the horizontal spindle machine where there is to be heavy metal-cutting, especially of box-type pieces; the planer-type is preferred where capacity is needed for large, flat pieces, especially measuring-type work; and the compound-type as a compromise for all-around work.

Machine Way Design

So far, it has been shown only how the double-V scraping master evolves from the flat plane and how its design lends itself to being made quite accurately.

The reason the double-V design is preferred in a coordinate machine is best understood by a consideration of the *alternatives* to it.

Three classifications, the V and flat, the gibbed way, and the central V would generally include all those designs most commonly used for accurate locational machines.*

Each type should be analyzed in the context of five important criteria:

1. How good a guide does it provide for straightline travel?
2. What will be the wear conditions?
3. What type of scraping master can be used?
4. Can the ways be self-checked?
5. Is a gib necessary?

1. The V and Flat, Fig. 74

Despite widespread acceptance and use of the V and flat in machine design, it has many disadvantages.

Friction, or "drag" is greater on the V than on the flat.

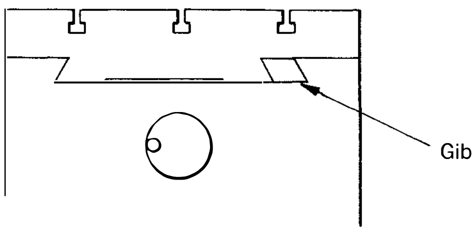
The single V, placed to one side, is not a sufficient guide for horizontal straightness when there is side pressure. Thus, the thrusting element (lead screw, rack and pinion, or other), is not centered between V and flat, but is usually placed directly

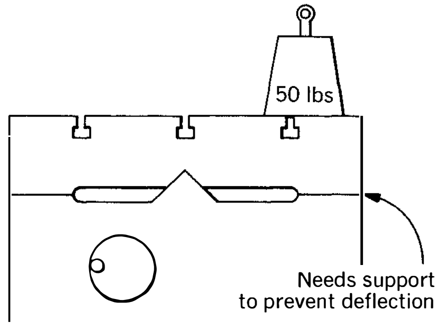
*Cylindrical guide-ways have been suggested as one other alternative for a jig borer type of machine. The shortcomings of this design become evident with this question: "How are the cylinders to be made and fixed to the machine in such a manner that accuracy is achieved, and yet be rigid enough to eliminate deflection, either from the sag of the cylinders themselves, or from the weight of a heavy moving carriage?"

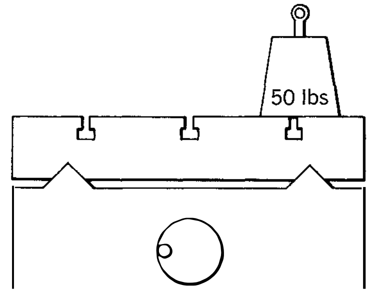
FIG. 77—*Dovetail-type gibbed way. Resists lifting pressures, side shift.*

FIG. 78—*The central V-way design. Weight given more guide than with V and flat, however the thrust cannot be centralized unless the V is cut away or spread, then must be more massive.*

FIG. 79—*The double V-way design with off-center weight.*







under the V, or at least favoring the V, in an attempt to balance the thrust, Fig. 74. This can only be a compromise, for the same conditions of thrust do not apply when the workpiece weight is added. More seriously, if the workpiece is mounted off-center on the flat-way side, Fig. 75, there will be a twisting effect, or a "shift" when the direction of travel is reversed. This results because a V-way depends on weight to work; if weight is *removed*, its ability to guide is diminished.

Since there are different conditions of friction on each rail, it would not be expected that this design would wear well or uniformly.

It would be impractical to use a scraping master that encompasses both rails since the relative height of V and flat would have to be maintained so exactly that there would be virtually no wear-life to the master. If such a master were used, it would not be capable of reversal for a self-check, nor could the table be reversed on its bed as a self-check when scraping. No gib is necessary with the V and flat design.

2. THE GIBBED-WAY, Fig. 76 and Fig. 77

The gib-type way, two forms of which are shown, actually has much in its favor. Wear in the machine's ways can be adjusted for, prolonging useful life.

Both the square-type and the dovetail gibbed way provide a good guide against "shift" in travel. The thrusting element can be symmetrically placed. An off-center weight is well-guided.

The dovetail is a practical design to resist heavy lifting or side pressures which result from "overhang," or from large, overhanging workpieces, or from heavy machining cuts.

The square-type gib is geometrically more correct for producing accuracy. However, neither gibbed design is capable of the ultimate in accuracy. When the gib is adjusted for wear, there is not an identical repeat of fit or alignment.

Commonly, a machine's ways wear in the middle of the travel. Adjusting the gib for wear can thus only be a compromise between a good fit in the center and a good fit on the ends of the travel.

The square-type gibbed way can use a master that encompasses both rails; the dovetail-type cannot. Neither design is truly self-checking by reversal.

3. THE CENTRAL V, Fig. 78

Although less frequently used in machine design, the central-V would be thought a more desirable alternative to the V and flat. The thrusting element can be centralized under the V. An off-center workpiece would be more adequately guided.

Its infrequent use may be explained by the fact that it is often impractical to mount the thrusting element directly under the V (in which case the central V loses much of its value), or because the central V requires two outer flats for support.

As with the V and flat design, it would not be practical to use a master which encompasses all rails.

However, the table can be reversed on the bed as a self-check. No gib is necessary with the central-V design.

4. THE DOUBLE V, Fig. 79

The double-V provides the best guide for straightline travel. The thrusting element is symmetrical between the V's. Each rail is subject to uniform friction.

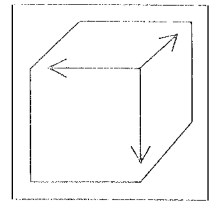
From Fig. 79, it is seen that no matter where the workpiece is placed, there is always weight on a V to enable it to guide.

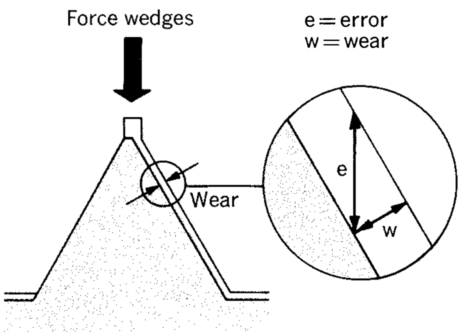
The symmetrical way construction results in the most uniform wear, and the longest wear-life.

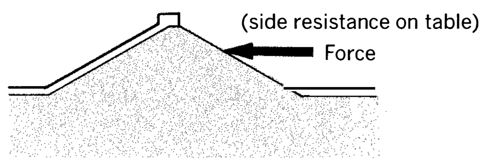
The double-V master, it will be remem-

FIG. 80—*When a way-form less than 90° is employed, there is greater friction of movement and wear rapidly diminishes accuracy.*

FIG. 81 —*A way-form more than 90° does not provide adequate horizontal straight-line guide.*







bered, encompasses both rails and can be reversed as a self-check (see page 44). The bearing of the machine ways may also be self-checked by reversal. No gib is necessary with the double-V design.

The 90° Form V-way

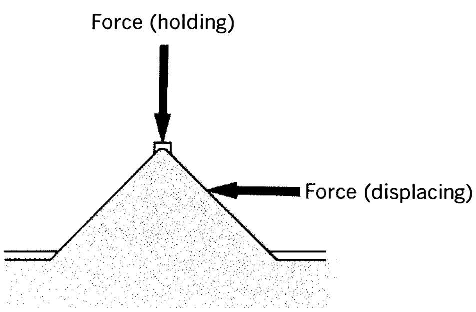
Similarly, the advantage of the 90° form is best understood by examining the *alternatives* to it.

With a form *less* than 90°, Fig. 80:

1. There is a weaker cross section;
2. Difficulty is encountered in accurately scraping to a bearing;
3. There is a wedging action as the table slides on its mate, causing greater resistance;
4. A small amount of wear rapidly diminishes accuracy.

With a form of *more* than 90°, Fig. 81, there is less guide against "side shift." In fact, it would act as an inclined plane.

It has already been shown that the 90° form has the most direct relationship to the flat plane. If some angle slightly more or less than 90° represents the ideal way-form, certainly the 90° form is close enough to that ideal to be the best *practical* choice, Fig. 82.



5. THE MOORE NO. 3 DESIGN

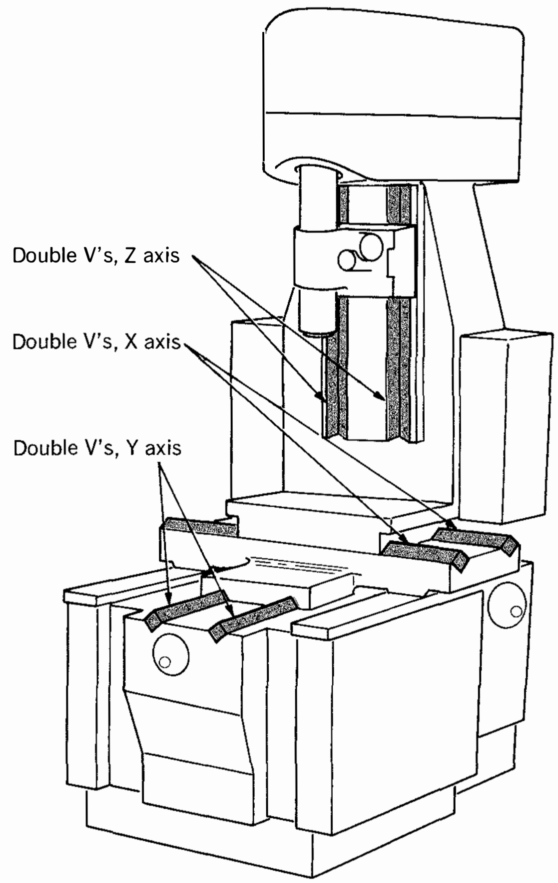
Based on the analyses already presented, it was concluded that the ideal design for a coordinate machine of 11 inches x 18 inches [279 mm x 457 mm] travel* should incorporate the following, Fig. 83:

1. 90° V-ways;
2. A compound-type configuration;
3. Double V construction on all three axes.

*It will be seen that in the larger model Measuring Machine, something more akin to the planer-type machine was selected.

FIG. 82—*The 90° form V-way is the best guide for straight-line travel and has the most direct relationship to the flat plane.*

FIG. 83—*The Moore No. 3 design employs double V-ways on all three axes, (jig borer shown).*



The base of the machine supports cross-slide and table in their full travels. Double V-ways in the base guide the cross-slide and fully resist any side shift. In addition, two outer flats prevent deflection of the cross-slide member, either from table or workpiece weight.

Double V's in the cross-slide guide and support the table in its full travel.

From Fig. 84, it is seen that with the double V design, even when the table is at the extremes of its travel with weight added, deflection is prevented and the cross-slide is still guided for straight-line travel. Thrust of lead screws in both axes is centralized between the V's.

In contrast, if this same example is applied to some form of V and flat design, Fig. 85, so often considered the ideal, it is evident that one V is not a sufficient guide against "side shift."

Fig. 86 shows the machine members that make up the Moore design—base, cross-slide, table, column, housing. The hardened and ground ways are bolted to accurately scraped surfaces and lapped in place to final accuracy. Mating cast iron way surfaces are scraped to match the lapped ways.

Two closely related reasons dictated the decision to use hardened, ground and lapped ways: 1) The attainment of accuracy. 2) The prevention of wear.

1. Attainment of accuracy:
   a. Finer corrections are possible in the lapping operation.
   b. Coordinate movements must be as friction-free as possible to assure that accuracy of positioning is commensurate with the potential accuracy of the lead screw.
2. Prevention of wear:
   a. The wear-life of the hardened, ground and lapped way construction is estimated to be at least 10 to 1 over that of the conventional cast-iron to cast-iron way design.
   b. The consequent reduction and

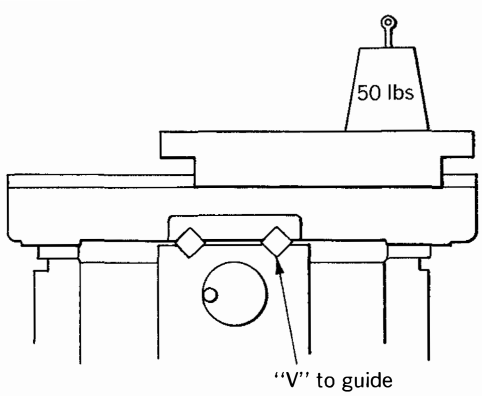


FIG. 84—*The Moore No. 3 design double V-way provides a good guide for straight-line travel since the weight is always over one of the V's.*

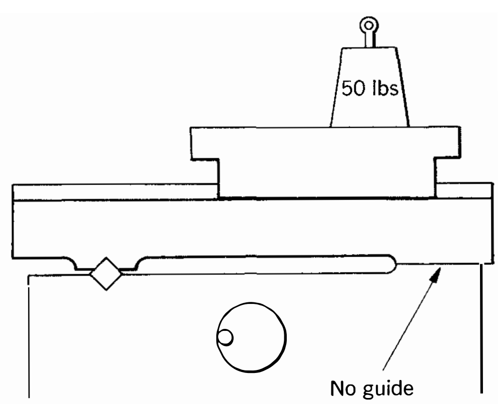
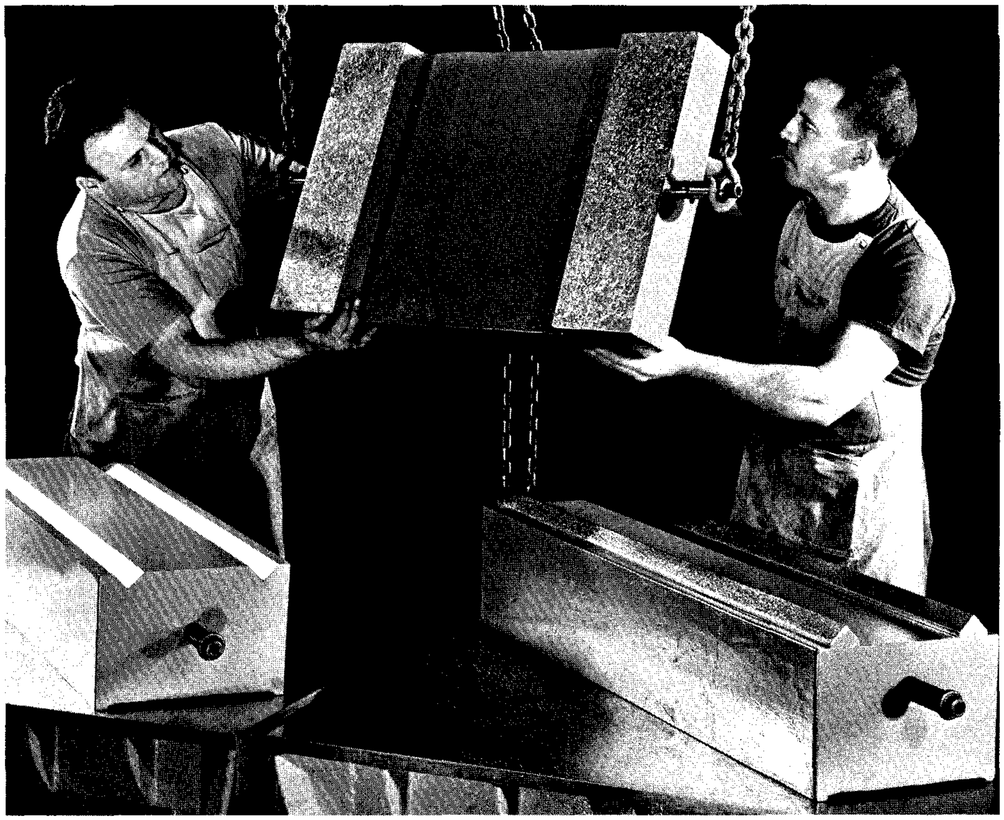


FIG. 85—*When the table and weight are off-center, the V and flat have lost much of their ability to guide.*

FIG. 86—*Machine members that make up the No. 3 design—starting from bottom right, clockwise—base, cross-slide, table, quill housing and column.*

FIG. 87—*The three forms of scraping masters used for machine slide ways are: 1) flat masters, 2) female double V masters and 3) male double V masters.*



almost complete elimination of wear insures retention of the initial accuracy of straightness and squareness of the movements.

SCRAPING MASTERS

Absolute interchangeability of the machine members is not feasible when working to millionths of an inch [tenths of a μm]. There are economies to be realized by attaining a degree of interchangeability up to the point of final mating. This is accomplished through the use of highly accurate "scraping masters" of three forms, Fig. 87: 1. Flat masters, 2. Female double-V masters, and 3. Male double-V masters. The origin of these masters and their contribution to accuracy have already been described.

At each operation, such as the scraping of the female V's in the base, two masters are provided, one for roughing and one for finishing. After approximately eight operations, the finishing master is worn too much to be relied upon and is now used as the roughing master. It in turn is replaced by a freshly scraped master. The roughing master is completely re-scraped. To follow such a schedule on a production basis, an adequate inventory is kept of all the various types of masters needed.

1. Base, Fig. 88

The female V's and the flat ways in the base are not used as way surfaces, but are to receive the hardened way inserts. They are nevertheless scraped to 0.0001 inch [0.0025 mm] accuracy in order to achieve a good mounting surface for the hardened ways, and to minimize the subsequent amount of lapping on the hardened ways.

The master used on the flat ways is sufficiently rigid for the tolerance at this stage to transfer its straightness to the flats, but not enough to prevent twist. Inspection for twist is by means of a two-footed twist gage.

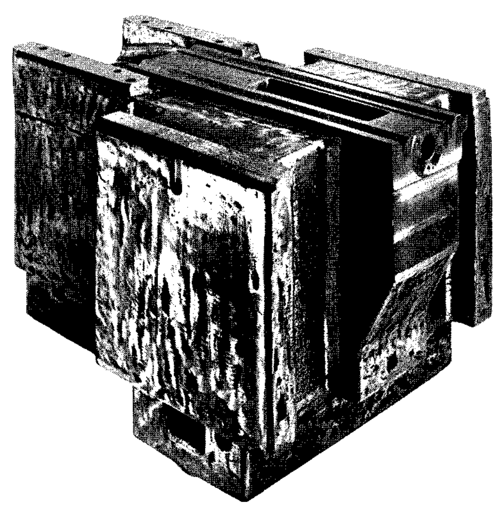
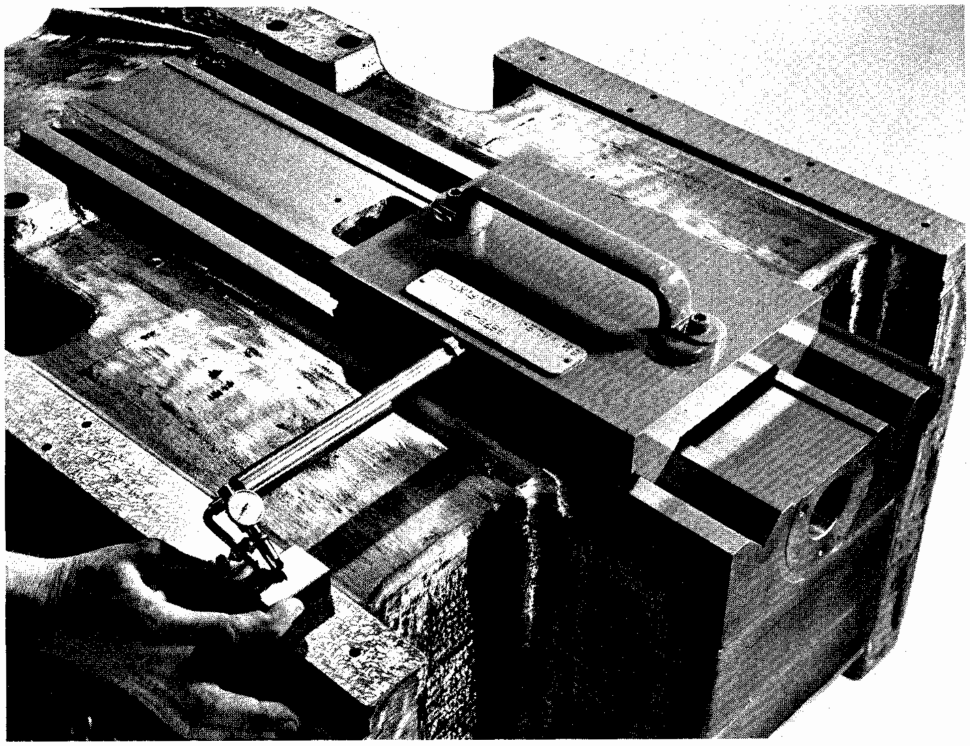


FIG. 88—*No. 3 Base—rough-scraped.*

FIG. 89—*No. 3 base, inspection of parallelism of V's to flats.*



The female V's in the base are scraped to a male double-V master. Inspection for vertical straightness and parallelism, as well as parallelism to the now-finished flats is accomplished by means of a "bridge" fixture (see "Geometry," page 77). The V-master is also continually reversed.

A special table, to which is fixed an indicator, Fig. 89, is used to cross-check parallelism of the flats to the V's. The masters are depended upon to produce uniform center distance of the V's.

2. Cross-Slide, Fig. 90

The fixture shown in Fig. 91 has hardened, ground and lapped V's of 8.5000 inch [215.900 mm] center distance. These V's are parallel to the scraped top surface of the fixture and also square to two scraped end posts.

The top V's of the cross-slides are first scraped to a male double-V master so that they may be used to rest the slide on the fixture without deflection.

While mounted on the fixture, the following geometry, Fig. 92, is scraped into the cross-slide:

1. Vertical straightness of the V's and flats;
2. Vertical parallelism of the V's to each other and to the flats;
3. Uniform thickness of top to bottom ways;
4. Squareness of top to bottom V's. It is important to note that the squareness of the coordinate axes is embodied in only one machine member, and has to do with the relationship of top to bottom V's of the cross-slide.

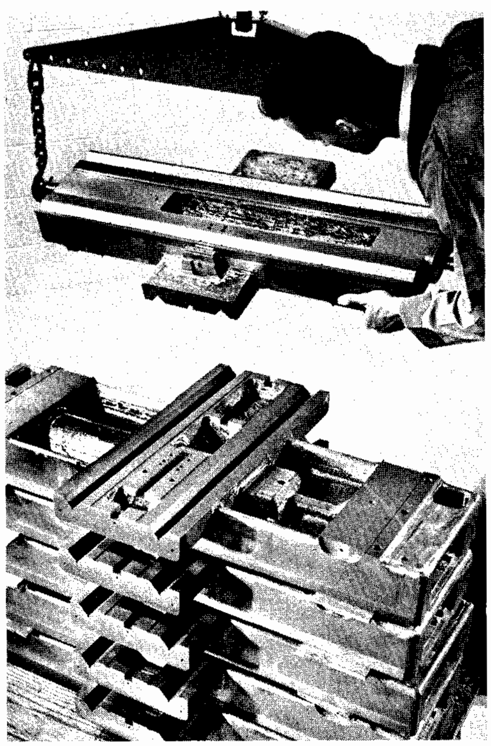
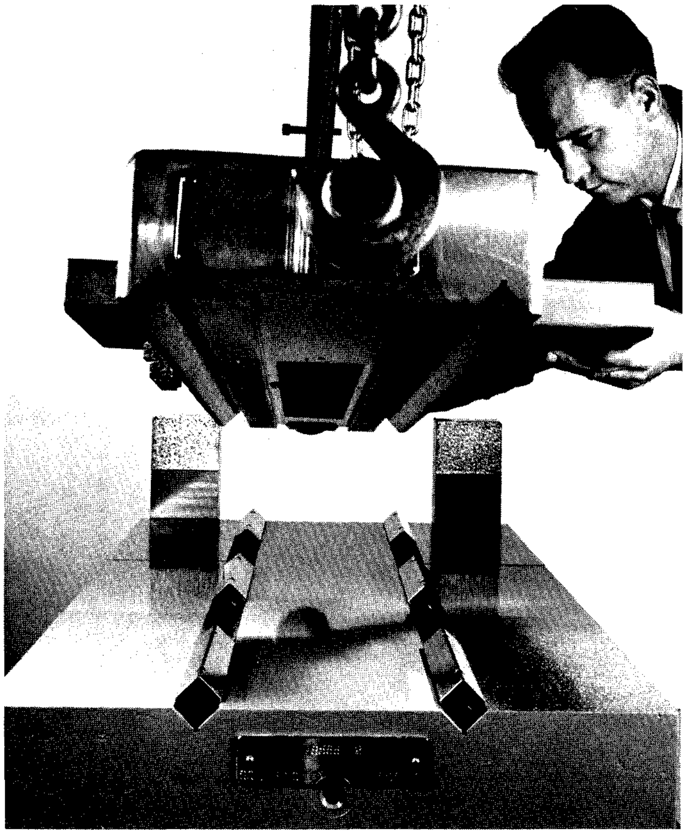


FIG. 90—*No. 3 cross-slide, rough-scraped.*

FIG. 91—*Squaring fixture for cross-slide.*



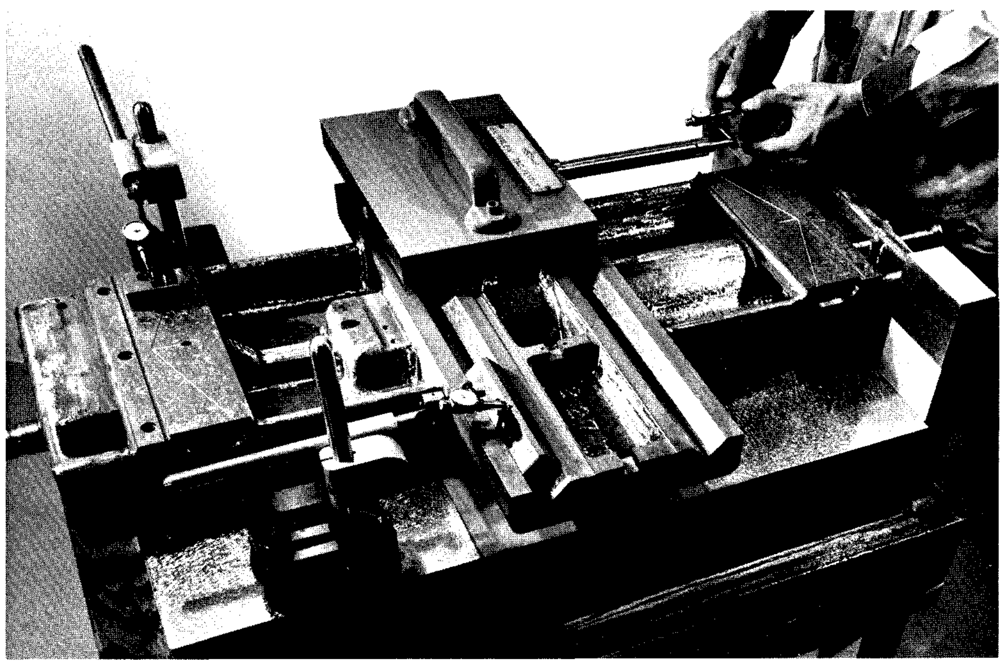
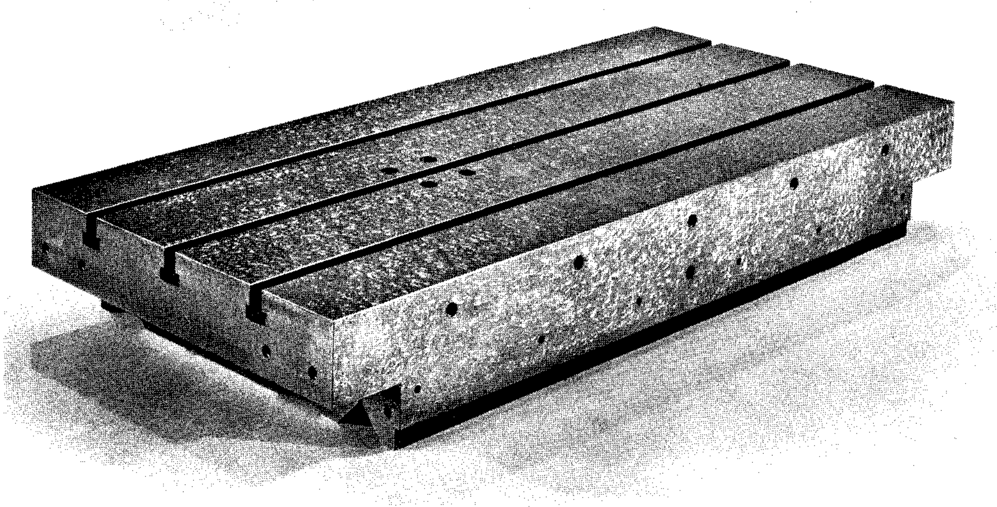


FIG. 92—*Squareness of the compound-slide V's is established by traversing a table holding an indicator past end posts. The end posts have been scraped square to the hardened V's of the fixture on which the cross-slide is now mounted. Other features which may be inspected are shown by the two other indicators on stands.*

FIG. 93—*No. 3 table.*



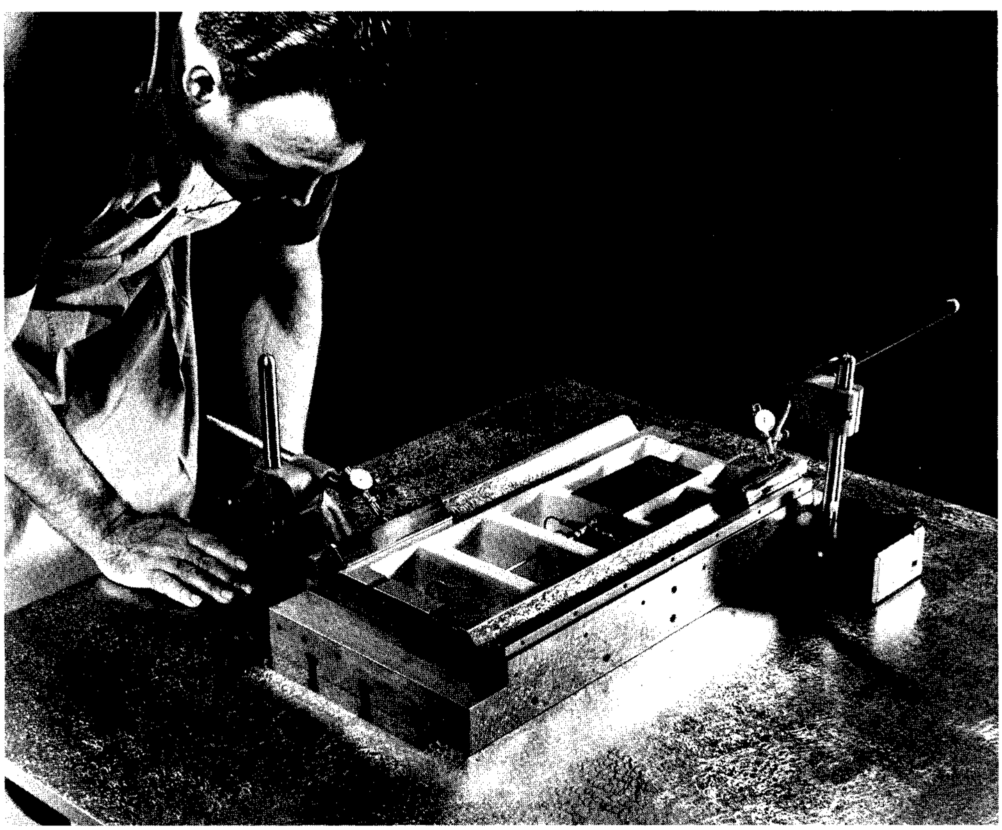


FIG. 94—*While the table is resting on the surface plate, the parallelism of its V's to its top is inspected, as is the parallelism of the V's to its sides using an indicator and stand with a knife edge (far right).*

3. TABLE, Fig. 93

The V's in the table are scraped to a male double-V master. The table-top is inspected for parallelism to the V's while resting on the master surface plate, Fig. 94. Inspection for parallelism of the V's to table top is performed by indicating with an indicator and stand across a gage held in the V's (performed by operator, Fig. 94). The sides of the table are lastly scraped parallel to one another, parallel to the V's, and square to the table top. The indicator and stand setup to inspect parallelism of sides to V's is shown at the far end of the table, Fig. 94.

4. COLUMN, Fig. 95

A double-V master is used to scrape the column ways. The surface used to mount the column to the base is scraped flat and roughly square to its V's, Fig. 96. Since adding any appreciable weight to the column will alter its relationship to the base, final squaring of the column is done after all parts are assembled to it.

5. QUILL HOUSING, Fig. 97

An abbreviated study of the "operations" on the quill housing affords an interesting example of the painstaking procedures required for the attainment of accuracy, Fig. 99. Operation 12, jig grinding the bushings is shown in Fig. 98.

FIG. 95—*No. 3 Measuring Machine column—rough-scraped.*

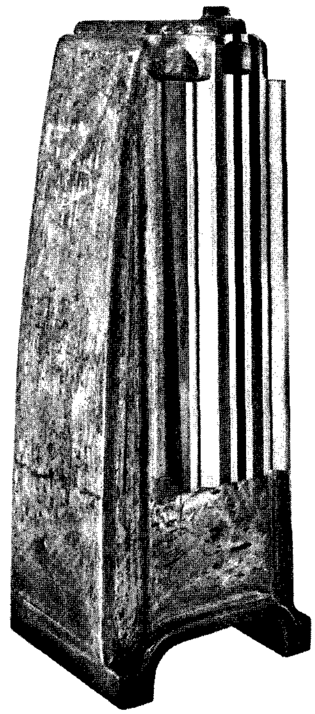
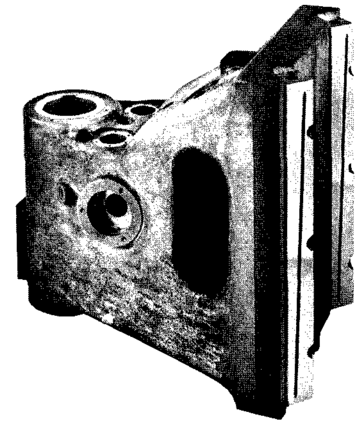


FIG. 97—*No. 3 Measuring Machine quill-housing rough-scraped.*



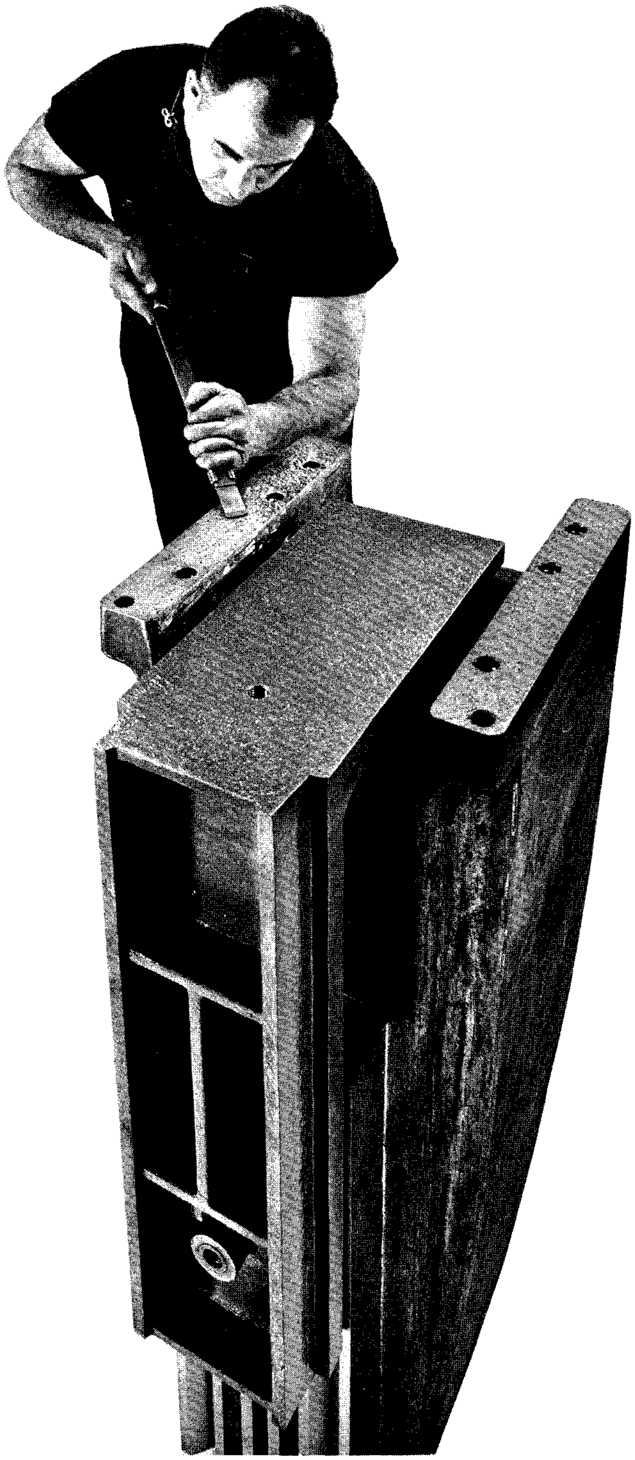


FIG. 96—*The column is inverted and its mounting surface to the base is scraped roughly flat and square to its own V's. A special squaring master is fastened to the column V's and used as a datum from which to measure.*

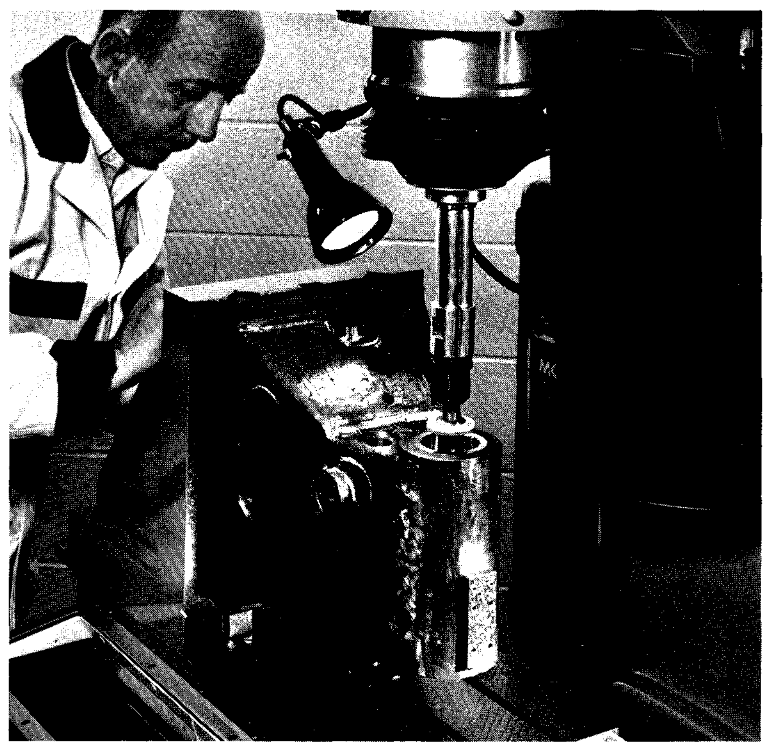


FIG. 98—*To establish alignment of the quill to the housing ways, the hardened bushings in the quill housing are jig ground while the quill housing is mounted on a sturdy angle iron.*

FIG. 99—*An abbreviated "methods sheet" affords an interesting example of the procedures required for the attainment of accuracy.*

Note that there are four separate scrapings, plus a lapping operation on the V's of the quill housing.

METHODS

Date— | **Order No.** | **No. Pcs. This Lot**

First Load Center— Planer - O.S.

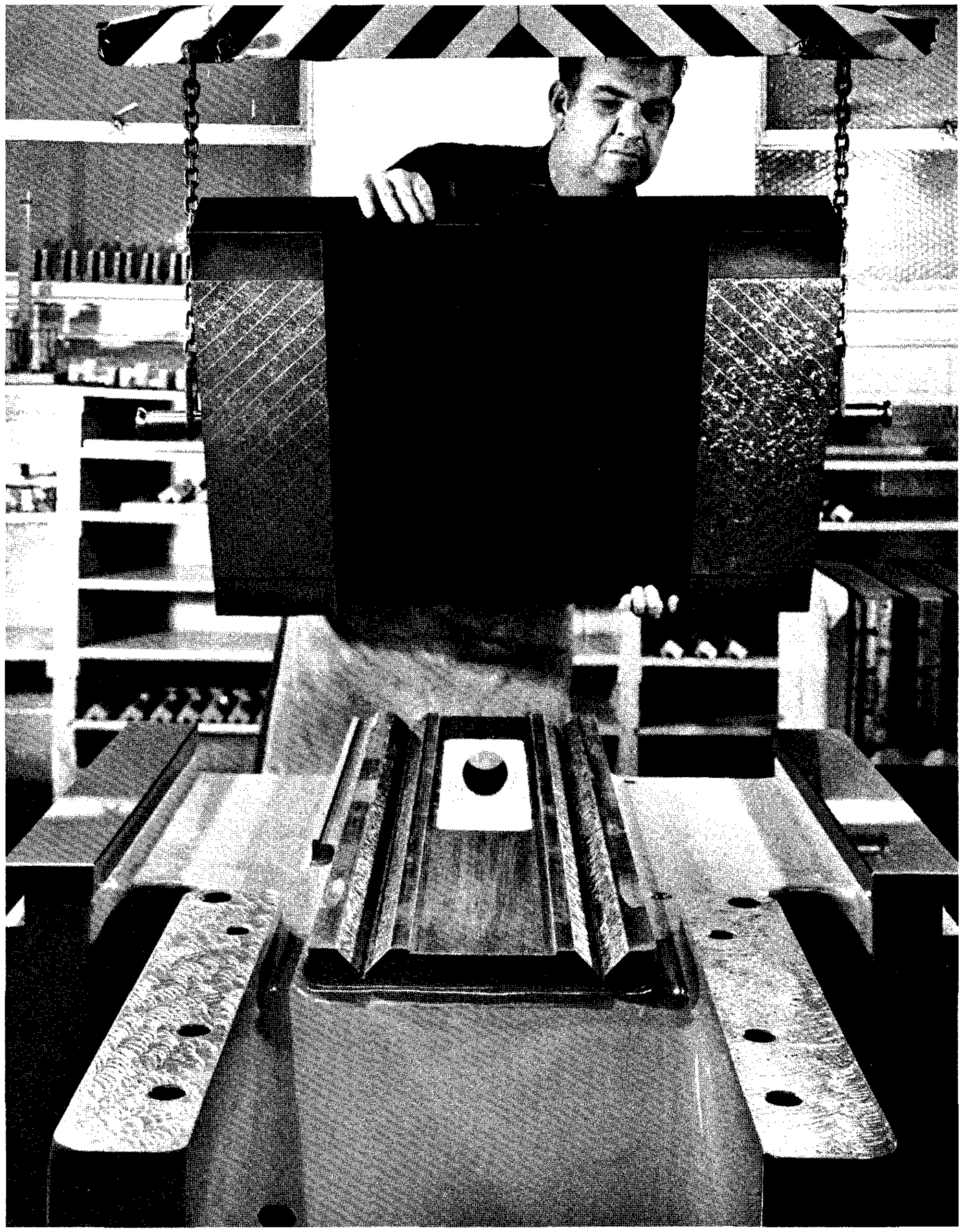
Material— G.D. Meehanite | **Part No.—** 4870 | **Class—** #3MM #1-1/2MM

Size— To Pattern | **Part Name—** Quill Housing - 2nd Half

Form— Casting | **Std. Lot—** | **Req Per Mach.—**

NO.	OPERATION	TOOLS REQUIRED
1	Check casting for mis-match. Plane back section & v's to B/P gage. Plane to 9" dia.	
3	Rough scrape V's. Assemble hardened ways (no. 5064 2 req'd.)	
10	Season.	
11	Re-scrape V's and scrape pad.	
12	Grind bushings to size leaving .0006" - .0007" for lapping.	
13	Lap quill housing bushing to plug gage. After rescrape finish lap bushings and do necessary bench work to #4870 (Quill Housing) before painting. After painting clean up for assembly.	
15	Remove harden ways (quill housing), check bearing with master. Re-scrape using plug in bushing hole to check alignment. Final check after ways are reinstalled - Master #8552.	
17	Rescrape column Vee's to new master. Match quill hsg. to master. Assemble and lap harden ways to match column ways. Scrape for alignment. Lap quill hsg. ways with 38-1200 compound to column ways.	
21	Alignment of quill with column upright .000025 T.I.R.	

FIG. 100—*The master flat lap is scraped accurately, then impregnated uniformly with diamond lapping compound. It is used to relate the two outer hardened flat ways.*



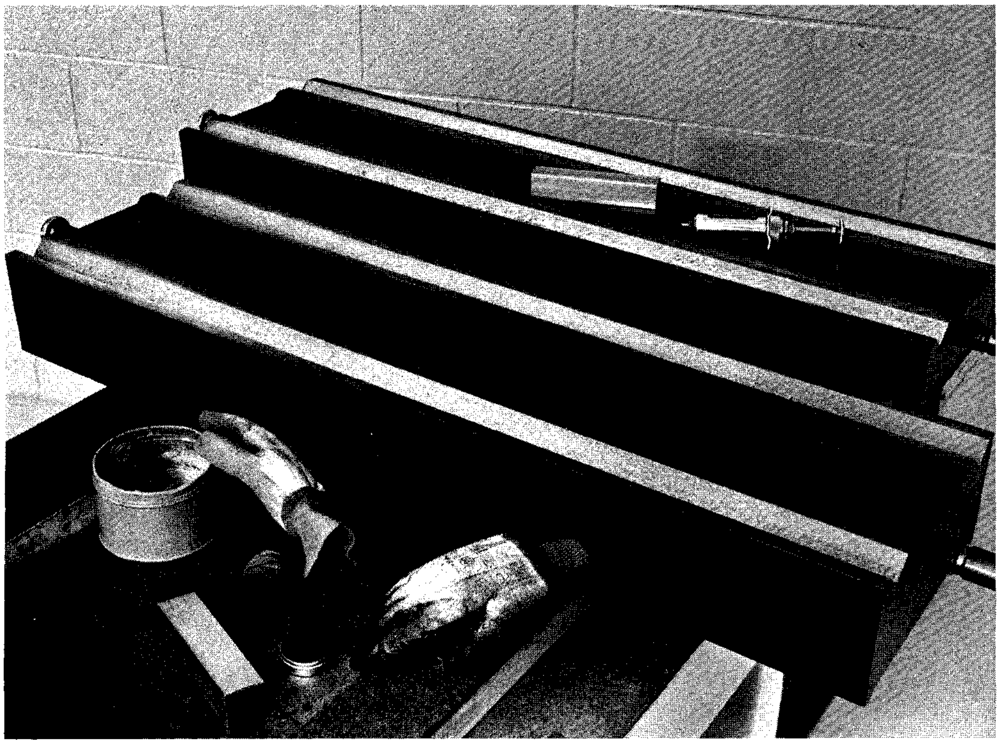
FINAL GEOMETRY

The procedures, techniques and masters described here are common to the No. 3 Jig Borer, No. 3 Jig Grinder and No. 3 Universal Measuring Machine, which are the same in their basic designs. The only essential difference is that the No. 3 Universal Measuring Machine is carried to a higher order of accuracy. In regard to geometric accuracy, the higher level of accuracy of the Universal Measuring Machine takes place in "final geometry." For consistency, all operations and tolerances in this section will be referring to the Measuring Machine.

Trueness of geometric relationships—straightness, parallelism, center-distance, and the fit between matched, sliding surfaces—is achieved through use of a combination of precise fixtures and gages, autocollimators, electronic indicators, various sizes of master laps and checking masters—all used in temperature-controlled environments.

The Master Laps

The master laps, both flat (shown in Fig. 100) and double V type, can be compared to the scraping masters in that they are both scraped to final accuracy by identical means (pages 35–45). The master laps differ, however, in that they are lastly impregnated uniformly with diamond lapping compound. Thus, the scraping master *imparts a bearing* to which the ways are *master for the hardened ways is in the foreground. Behind it is the master lap, on which is a diamond paste applicator and charging block. Bearing rouge and bluing are used to check bearings, and gloves to minimize the conduction of body heat into masters.*



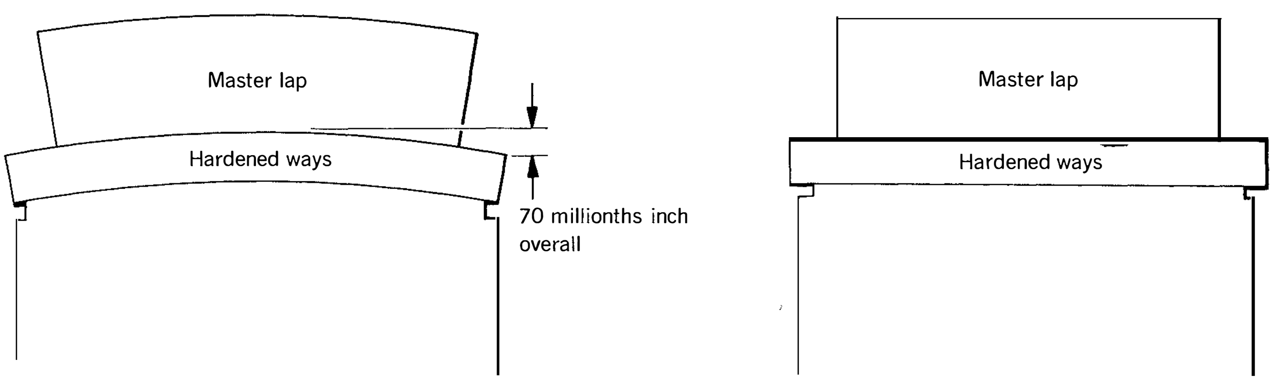


FIG. 102—*The master lap is too rigid to bend locally, right, but may deflect as much as 70 millionths of an inch [0.0018 mm] overall, left.*

FIG. 103—*Because the master laps will bend overall, small hand laps are also necessary.*

cut, while the *master lap itself cuts* the ways. In Fig. 101, a scraping master is in the foreground and the lapping master behind it.

There is a difference in the type of surface which results. The scraping operation is used to produce a series of uniformly high spots in an unhardened material, such as cast iron. The master laps are used to produce a very high micro-finish in the hardened steel ways.

The master lap, although accurately scraped, does not automatically lap out the slight errors remaining in the hardened ways after being fixed to the machine. It will be recalled (see page 26) that elastic deflection takes place. Small, local errors are eliminated, but not those of overall bow and twist, Fig. 102.

The operation of lapping requires that a load be applied so that, in the process, the lap wears as well as the machine ways. If used too long, the lap rapidly loses its accuracy.

The master laps thus will not correct geometry strictly by themselves. For this reason, the lapping operation involves all four of the following steps:

1. Use of small hand laps, Fig. 103, allows the ways to be lapped locally, Fig. 104;
2. Use of scraping masters, in this application more properly termed "checking masters," which aid in the hand-lapping by indicating areas of bearing, Fig. 105;
3. Frequent inspection (again the emphasis is on quick, accurate, foolproof checks);
4. A more discriminate use of the master laps.

Wear of the master lap is evidenced by its failure to agree with the checking

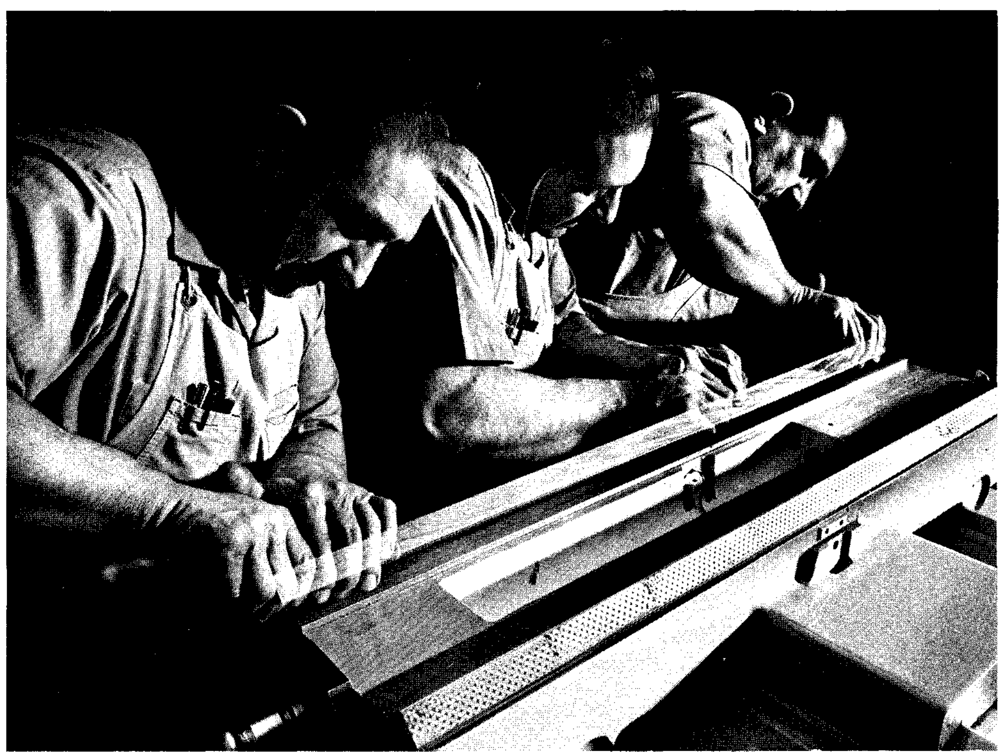


FIG. 104—*Hand-lapping of the hardened double V requires an experienced hand and a thorough understanding of the geometry involved. If the surface is lapped too deep locally, many additional hours may be spent bringing the total surface down to this low point.*

FIG. 105—*The use of highly accurate checking masters greatly facilitates the lapping of the double V-way. A careful study of the bearing reveals where and how the V's must be lapped next.*

master when both are rubbed on the ways for a bearing.

The reader might ask, "Why not correct the hardened ways first, then fix them to the machine?" The answer is that bolting causes distortion, Fig. 106. Also, the ways do not seat exactly. They must be *corrected in place* to assure correct geometry. This is the reason behind the master laps. The ways to which the hardened ways are fixed have been scraped very accurately in order to provide good mounting surfaces and also to minimize the amount of lapping necessary.

THE ELECTRONIC INDICATOR AND THE AUTOCOLLIMATOR

Two measuring instruments—the electronic indicator and the photo-electric autocollimator—have become virtually "standard equipment" for the precise operations required in final geometry. It is appropriate here to include a brief description of these instruments and their use.

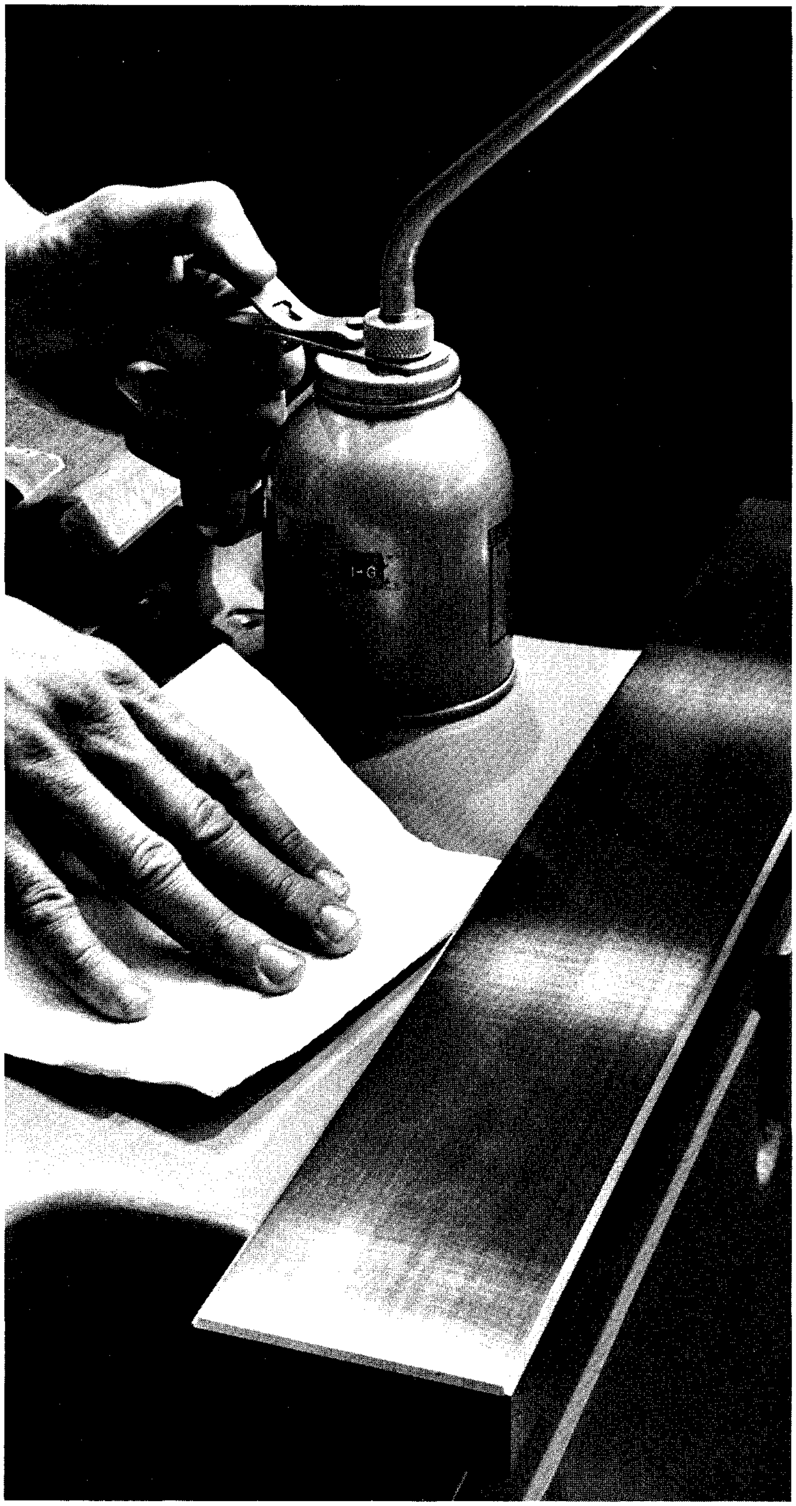
The introduction of the electronic indicator, in particular, has contributed substantially to a whole new plane of accuracy.

Yet, the potential level of accuracy in which these instruments permit one to work is only achieved in fact by creating the proper environment, taking precautions against the errors which may be introduced by the instruments themselves (or through their use), and by the development of specialized supporting equipment.

The Electronic Indicator

The mechanical dial indicator has long been the workhorse of the workshop. With modern designs, Fig. 107, one can be fairly certain of readings within 25 millionths of an inch [0.0006 mm]. Sometimes, it is necessary to gently tap its mount with some small rigid object to overcome any friction,

FIG. 106—*The three variations in surface appearance are very shallow depressions (local errors) in the flat ways revealed after the application of the master flat lap—in this case caused by bolting the ways to the base. This example illustrates how sensitively local errors are revealed by the master laps and also why the hardened ways must be corrected in place.*



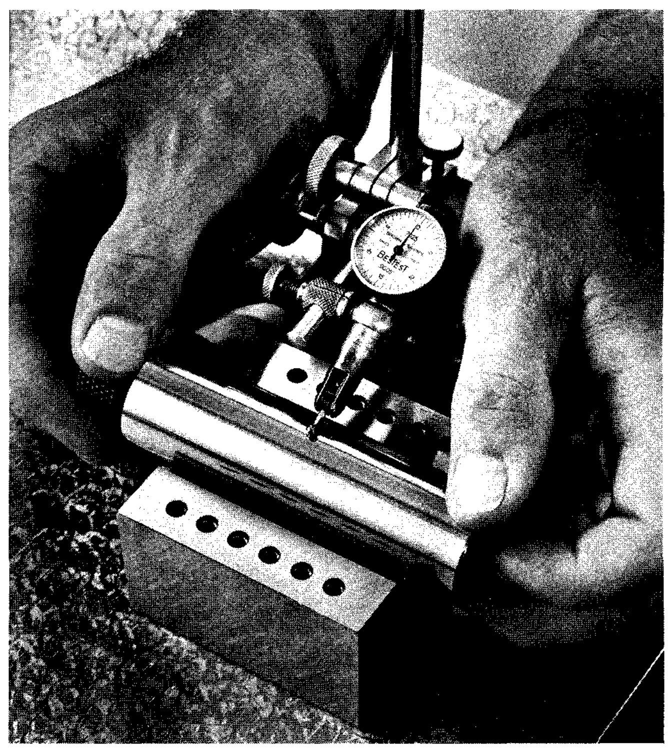
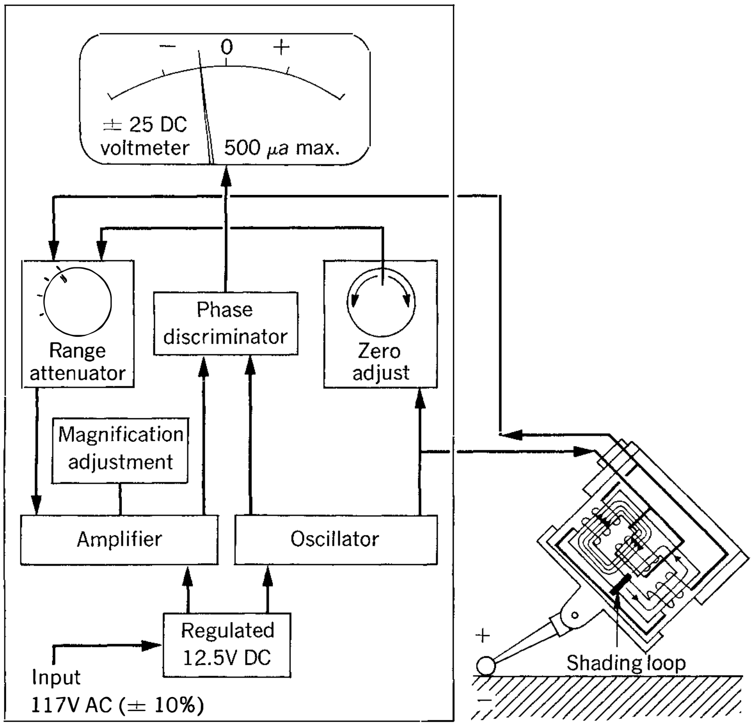
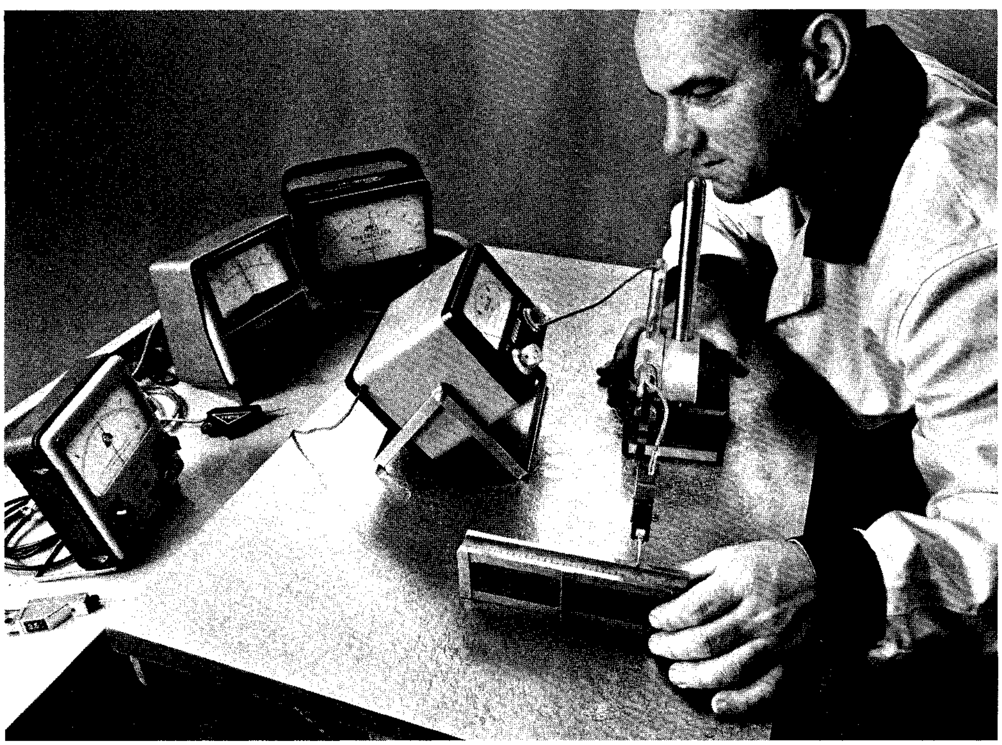


FIG. 107—*The mechanical indicator is a very necessary shop measuring tool. However, in those applications where an indicator is required, but in tolerances to millionths of an inch [one or two μm or less], the electronic indicator is generally preferred.*

FIG. 108—*Schematic diagram of a typical electronic indicator*
Courtesy of Federal Products Corporation, Providence, Rhode Island.





or "lag," of the internal mechanism when making readings. Such a precaution, together with the relatively high gaging force, lends some uncertainty to measurements below the 25 millionths of an inch [0.0006 mm] figure.*

The practical limit reached on magnification by mechanical means was overcome with the introduction of the electronic indicator. This instrument is made up of a gaging head and an amplifier.

The gage head may consist of one of several kinds of transducers to which is brought a continuous alternating voltage.

In a typical system, Fig. 108, mechanical movement of the contact probe alters the output or voltage of the gage head, proportional to displacement. The small alteration in voltage is amplified by means of a sensitive meter (except in the case of the capacitive-type head), to be read in terms of units of length.

Switching selection enables a convenient range of magnifications in one instrument. Magnifications are available of up to 100,000 to 1, where 1 millionth of an inch [0.000025 mm] is easily discernible.

A more detailed analysis of the circuitry is not included here since this information is well covered by suppliers and other sources.**

The electronic indicator has many functional advantages:

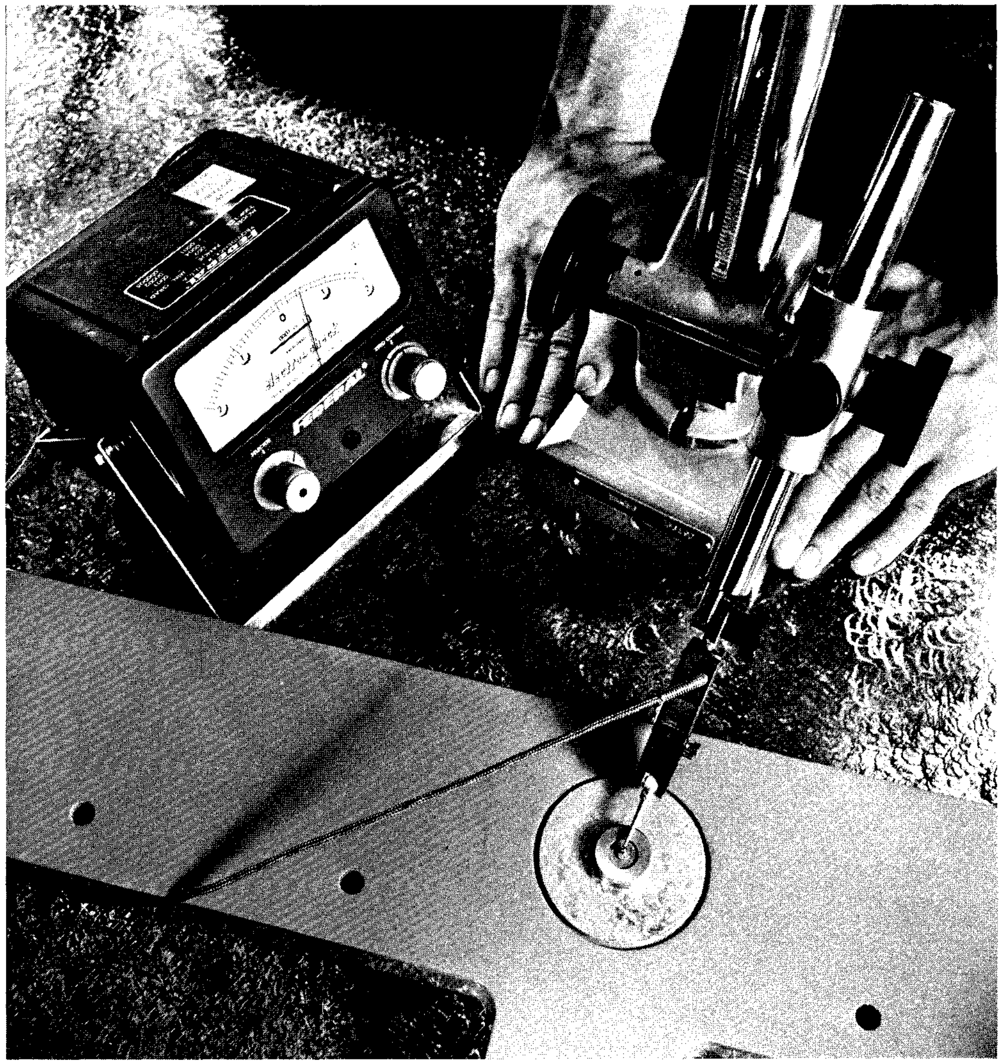
1. High magnification—ranges extend up to 100,000 to 1;
2. A *range* of magnifications in one in-

*Mechanical indicators to "millionths" magnification do exist, but are more vulnerable to damage, harder to read and to use, and not as universal. They are more suitable for use in a fixed position, being too awkward, for example, in general surface gage use.

**See "Air and Electronic Gaging," *American Machinist*, October 12, 1964; L. O. Heinold, Jr., "Electric and Electronic Gages" in *Handbook of Industrial Metrology* (ASTME Publication, 1967), pp. 232–245; Ted Busch, *Fundamentals of Dimensional Metrology*, pp. 225–227.

FIG. 109—*Electronic indicators may suffer a loss of linearity over a period of time, so they should be re-calibrated on a regular calendar basis. Even with this precaution, the best measuring practice is to avoid large ranges of meter readings and to use the indicator as much as possible as a "nulling" device.*

FIG. 110—*Careless handling detracts from the accuracy of the instrument. The operator has allowed the cord leading to the gaging head to rub against the working area, causing erroneous readings.*



strument—which adds greatly to convenience in line-up, initial referencing, choosing the right magnification for the job, etc.;

3. Light gaging force—1.5 oz. [43 grams] and even less;
4. Ruggedness—since amplification is by electronics rather than by delicate mechanical parts;
5. Immediate response—due to use of electronics;
6. Flexibility—with the proper supporting tools, the electronic indicator has an almost unlimited applicability to inspection procedures.

The following may be considered possible sources of error from the instrument itself and may have a bearing on working accuracy:

REPEATABILITY—or a short run ability to repeat readings.

DRIFT—The indicator may be relied upon for a datum but wanders over a period of time.

TEMPERATURE—The effect of temperature change, apart from the temperature of the workpiece, may alter the calibration of the instrument.

MAGNETISM—Some makes of electronic indicators may be influenced by even the slightest residual magnetism.

VOLTAGE FLUCTUATION—An indicator that works from ordinary line current may be subject to short-run wandering due to voltage fluctuation (especially noticeable in the higher magnification range of 50,000 and 100,000 to 1).

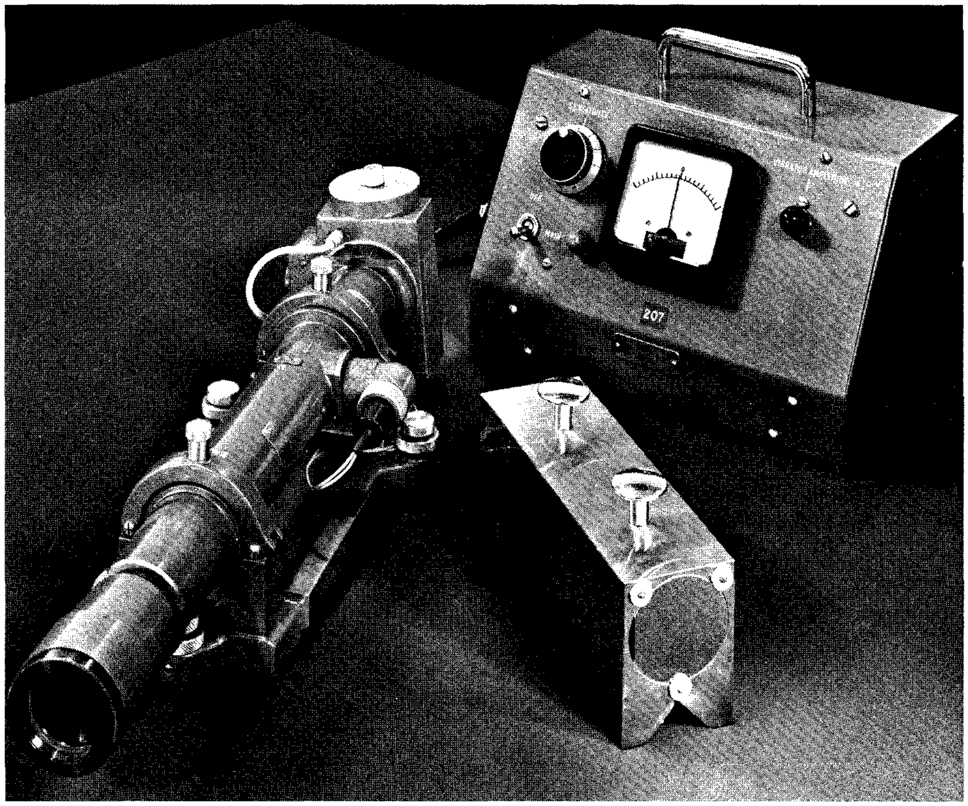
BATTERY DETERIORATION—While a battery-operated indicator may be more sensitive and stable over the short run (not being subject to voltage fluctuations), it may be prone to a more sudden loss of calibration as the cells lose their charge.

LOSS OF LINEARITY—Periodic adjustments for linearity are expected, but short-run changes stemming from unstable components can be dangerous in the inspection procedure.

DEGREE OF LINEARITY—It should be continually borne in mind that the electronic indicator is a comparator, with its own linearity tolerances; if habitually relied upon for wide ranges, the greater the error from non-linearity.

The essential point is that the foregoing potential sources of error can impair the accuracy of determination unless proper precautions are taken. One device for maintaining the calibration of electronic indicators, Fig. 109, is a hardened, ground and lapped wedge, tapered accurately 0.0003 inch over 7 inches [0.0076 mm over 178 mm] or 0.000010 inch [0.00025 mm] per line interval. Another is a voltage stabilizer which gives consistent voltage to the 0.000001

FIG. 111—*The photo-electric autocollimator, with a suitable target mirror, such as that shown in the foreground, will inspect straightness of a machine's ways in both the horizontal and vertical plane.*



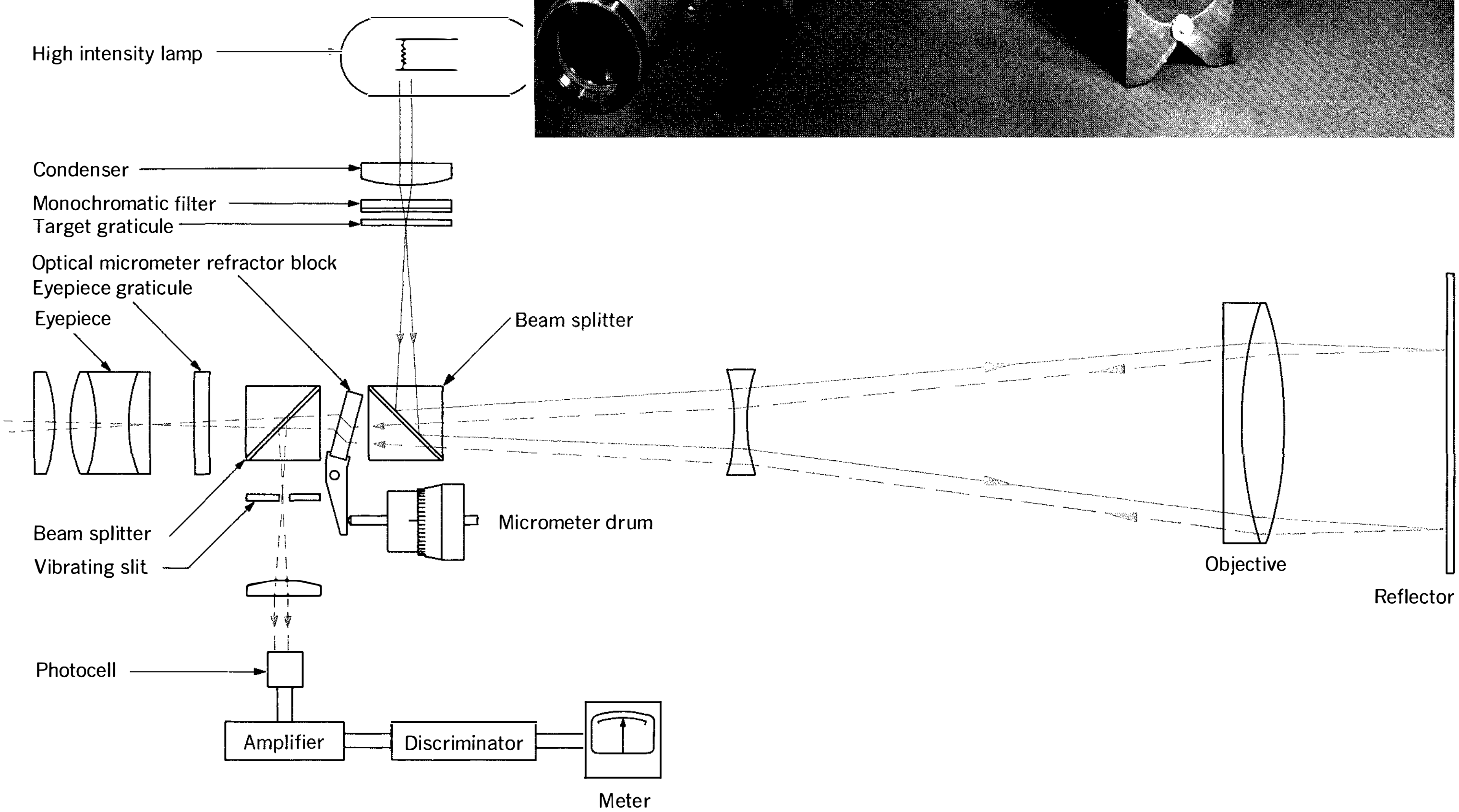


FIG. 112—*Photo-electric autocollimator schematic diagram. Model TA-5 (monochromatic) is shown.*
Courtesy of the Rank Organization, Hilger-Watts Division, London, England.

inch [0.000025 mm] indicators used in calibrating step gages (see page 182).

There are, in addition, sources of error in the environment, such as dirt, oil, air film, stability of the setup, finish and geometry of the workpiece, deflection, angle of the probe tip to the work, vibration, "temperature," parallax, etc., not related to the instrument itself. Again, these and other potential sources of error are well described by suppliers. These can only be eliminated through the education, experience and *awareness* of the user. A common operator error is to allow the cord leading to the gage head to rub against nearby surfaces, causing invalid readings, Fig. 110. The proper method to avoid this is shown in Fig. 109.

Autocollimator

The autocollimator is an optical instrument used in conjunction with a reflecting mirror to accurately measure very slight deviations from a datum angle. Briefly, a target line, placed at the principal focus of an objective lens, is illuminated. The emergent collimated (parallel) rays carrying the image are reflected back into the instrument by a suitable target mirror. When this mirror is tilted through an angle θ, the reflected image rays are tilted through 2θ and the displacement of the image in the instrument is measured by a micrometer-microscope in the instrument. By turning the dial of the micrometer screw, the image is re-zeroed at each reading between two parallel setting lines viewed through the eye-piece. The angle of tilt can be measured in the horizontal or the vertical plane and is read directly on the micrometer dial.

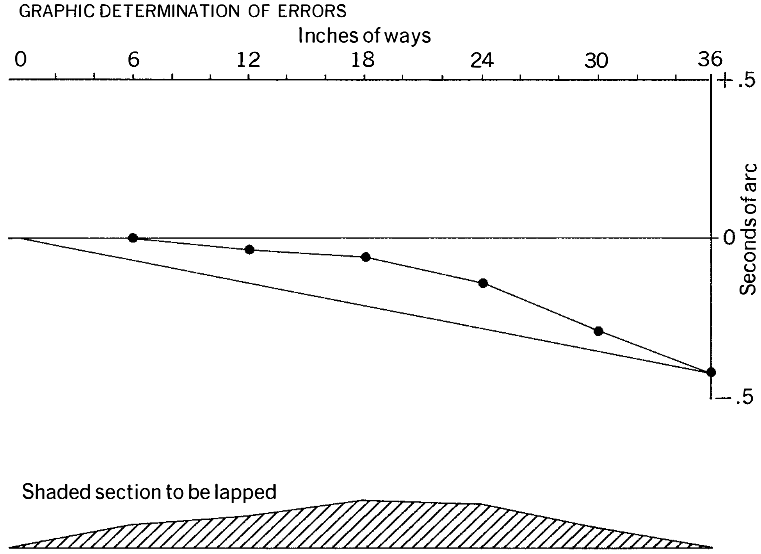
Operator fatigue and possible error in setting have in recent years been overcome with the development of the photo-electric autocollimator. The instrument is shown in Fig. 111 and a schematic of its operation in Fig. 112. The idea for this system originated in England with the National Phys-

FIG. 113—*A typical series of autocollimator readings is recorded. Actual error may be determined algebraically as shown. A graphic representation of actual error is easiest to visualize for the purpose of corrective lapping.*

ALGEBRAIC DETERMINATION OF ERRORS

Length of ways (inches)	Reading seconds of arc	Accumulated seconds of arc	Correction seconds of arc	Actual error seconds of arc
0				
6	0.0	0.0	+0.7	+0.7
12	−0.4	−0.4	+1.4	+1.0
18	−0.2	−0.6	+2.1	+1.5
24	−0.8	−1.4	+2.8	+1.4
30	−1.5	−2.9	+3.5	+0.6
36	−1.3	−4.2	+4.2	0.0

GRAPHIC DETERMINATION OF ERRORS



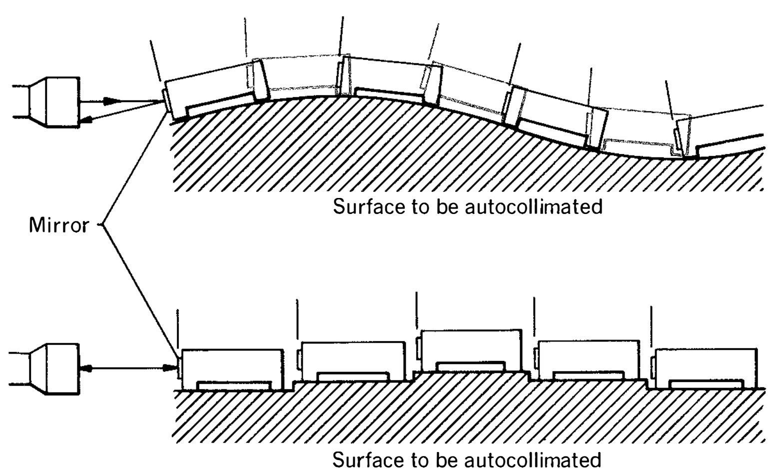
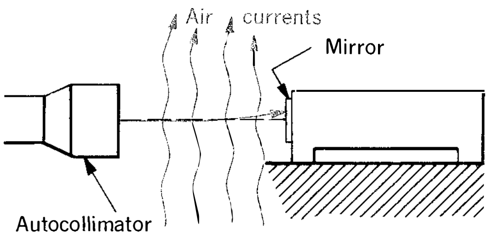


FIG. 114—*When "stepping-off" the target mirror, the requirement that the steps be related must be carefully adhered to (above) if the readings obtained are to be valid. Failure to do so (lower) may lead to error in calibration.*

FIG. 115—*Air currents in the optical path between the autocollimator and the target mirror cause fluctuations in the readings obtained. This effect becomes progressively more damaging to accuracy as the distance from autocollimator to target mirror increases.*



ical Laboratory. It consists of a vibrating slit, a photoelectric detector, and an electronic amplifier for magnified viewing on a meter.

The autocollimator, with suitable reflecting surfaces or optical gages, is thus capable of calibrating straightness, flatness, squareness, or the division of the circle.

Checking Straightness with the Autocollimator

Checking straightness with the autocollimator requires a simple setup—a rigid mounting surface for the autocollimator, and a two-footed mount to which the mirror is fixed.

Three elements are involved in the determination of straightness by "stepping-off" the mirror:

1. The angle of each step;
2. The length of each step;
3. The relation of the steps to one another.

The autocollimator measures the first element, the angle. The second element, the length of each step, is established simply by using mirror-mount feet with some nominal center-distance length, (if element No. 2 is absent, the test cannot be made). The third element—relating the steps—is accomplished by positioning the forward foot of the mirror-mount at that point where the rear foot previously rested, for the full length of the surface to be inspected.

In this manner, the autocollimator readings are translated into a total calibration of the straightness of the bed, Fig. 113.

Generally, the choice of center-distance of the feet is a compromise: if too short, the greater number of readings required may accumulate errors in calibration; if too long, then local errors are not shown.

If element 3 (inter-relationship of each step) is not strictly enforced, the results of the inspection are invalid. Using Fig. 114 as an exaggerated example, if the steps are not related, no error is shown, although the actual error may be many seconds.

Many of the sources of error already attributed to the electronic indicator apply as well to the autocollimator, in addition to which should be added, fluctuations from air currents, Fig. 115. Errors can be introduced through use of the instrument: the flatness and reflectivity of the target mirror should be of high quality.

Where both the autocollimator and the target mirror gage can remain fixed, extremely close readings may be taken and repeatability is excellent. Conversely, when mirror or instrument must be moved often, great care is required. For example, inspecting a surface plate by autocollimation involves an accumulation of readings, a time lag, perhaps a temperature change. Much depends on how accurately the target mirror can be moved. Errors are also easily introduced when the autocollimator itself must be moved to a tie-down point. The autocollimator should be used to show overall deviations. Where possible, local deviations are more truthfully shown by rubbing for a bearing. The fabrication of the 48-inch [1219 mm] master surface plates already described is a good example of this point.

While the autocollimator is an indispensable instrument, it will be seen that certain inspection procedures are faster and more directly interpretable by using the electronic indicator in conjunction with accurate gages.

Base Flat Ways

The hardened, flat ways, which have been ground in pairs flat and parallel to .000125 inch [0.003 mm] are bolted to the base on the scraped, outer flats.

Two types of error may be inspected for:

1. Straightness of each way; 0.3 seconds of arc—equivalent to a convexity or concavity of 5 to 10 millionths of an inch [0.1 to 0.2 μm] over the length of the ways.

FIG. 116—*One technique for measuring parallelism of the flat ways utilizes the three-footed twist gage—and simultaneously provides another working-check of straightness of each flat way. This method requires the use of a master surface plate as a datum and is self-checking.*

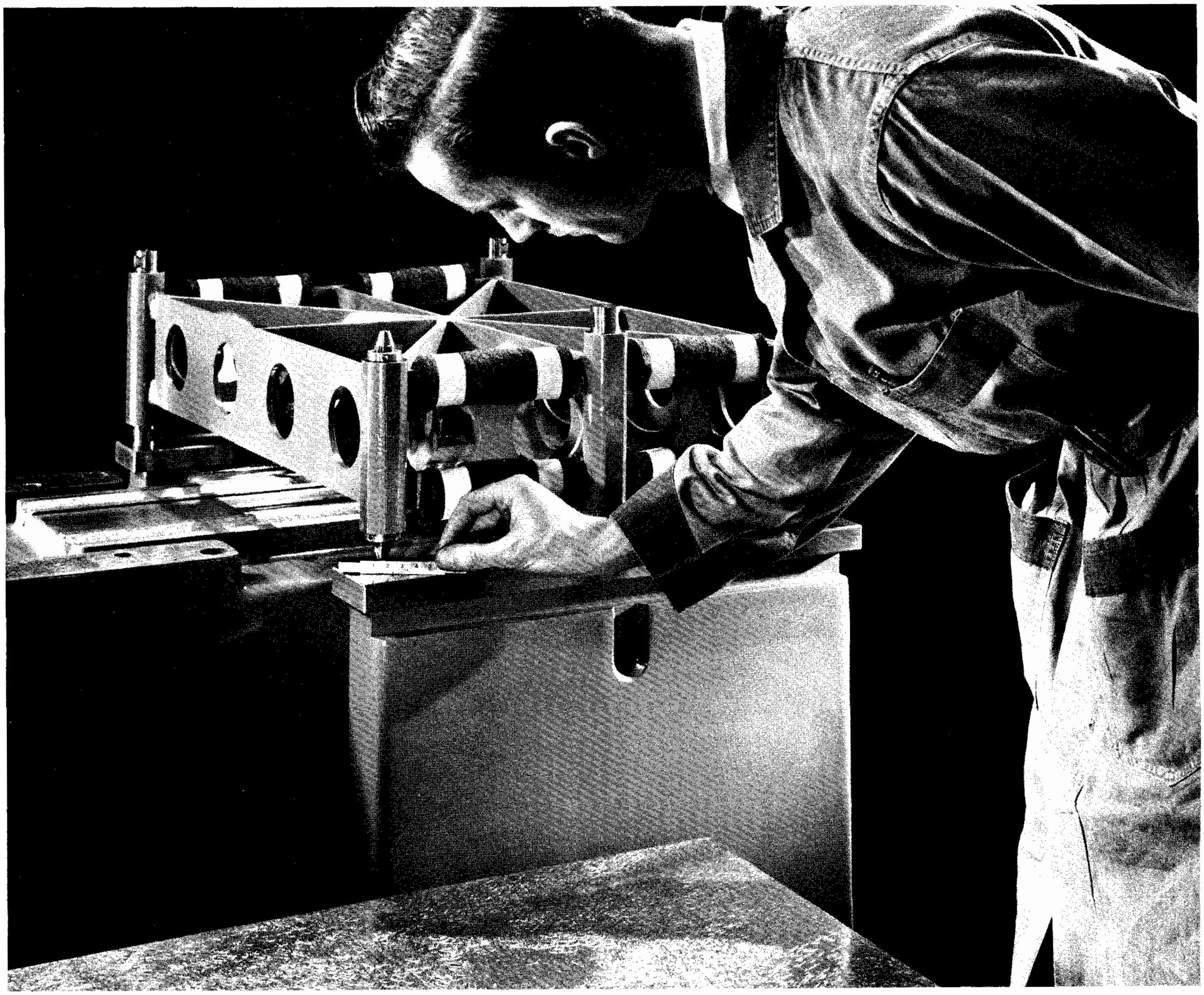
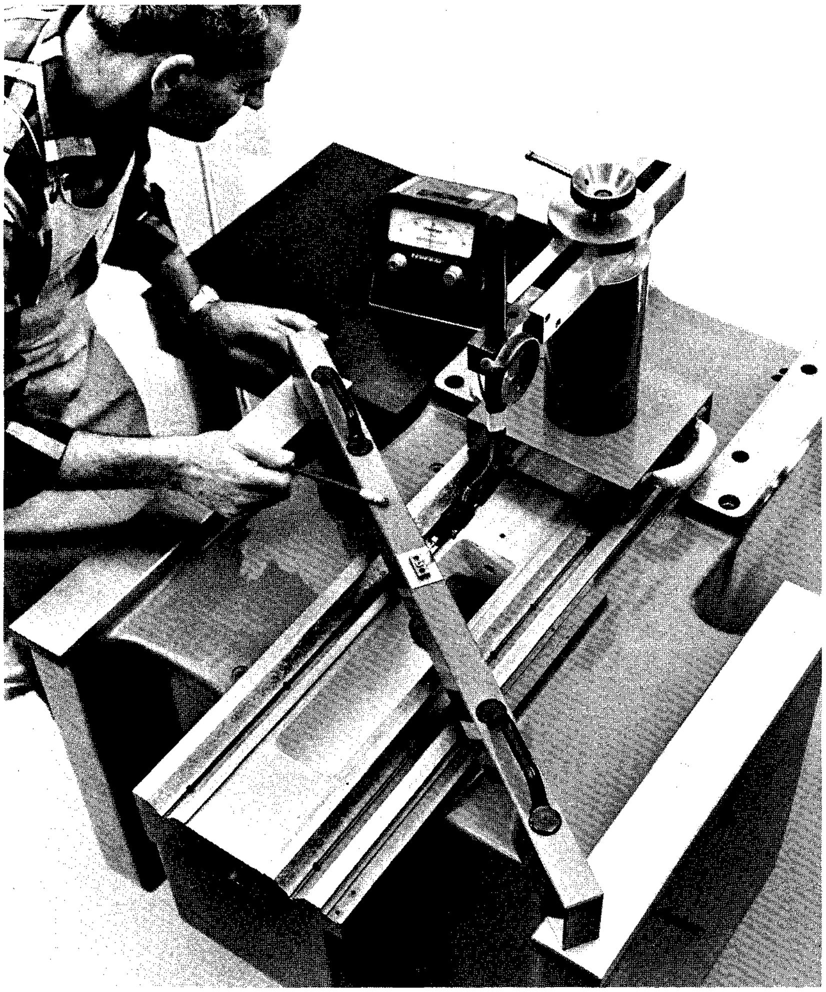


FIG. 117—*Use of the two-footed twist gage is the most reliable method for determining pure twist. A self-check only requires that the original setting be repeated. The operator is settling out the hysteresis effects in the twist gage by tapping it with a pencil.*



2. Twist, (parallelism of outer flats over their full lengths): 10 millionths of an inch [0.00025 mm].

Straightness of each flat way is inspected by a photo-electric autocollimator.

Twist is inspected by two methods. In the first, the three-footed twist gage uses a master surface plate as a reference. To be correct, the flat ways must have the same reading as the master plate. The master plate itself is proved when the same readings are obtained upon turning the twist gage 90° on the plate. The three-footed twist gage also provides another working-check on straightness of the flats, Fig. 116.

In a second method to check "twist," the two-footed twist gage is used. In this case a self-check only demands a repeat of the "zero," Fig. 117.

Correction of the ways is accomplished by a small hand lap and also a master flat lap.

By way of example, a "twist" in the flats is corrected by lapping the high ends, tapering gradually to the middle with the small hand lap, Fig. 118. This is followed by the large lap which blends over small local deviations and also relates the two ways.

The tolerance of straightness and parallelism of the flats is 10 millionths of an inch [0.00025 mm]. The flats could be said to represent a master surface plate built into the base; they become a reference for all subsequent measurements of geometry.

Base V-Ways

The hardened V-way inserts are next fixed to the scraped female V's in the base. Lapping the V-ways is a similar procedure to that employed in correcting the flats. A small hand lap and a large female double-V master lap are used.

Potential errors in the V include all those encountered in constructing the female double-V master, such as lean, center-distance, form, twist, straightness, except that errors are removed by lapping rather than by scraping.

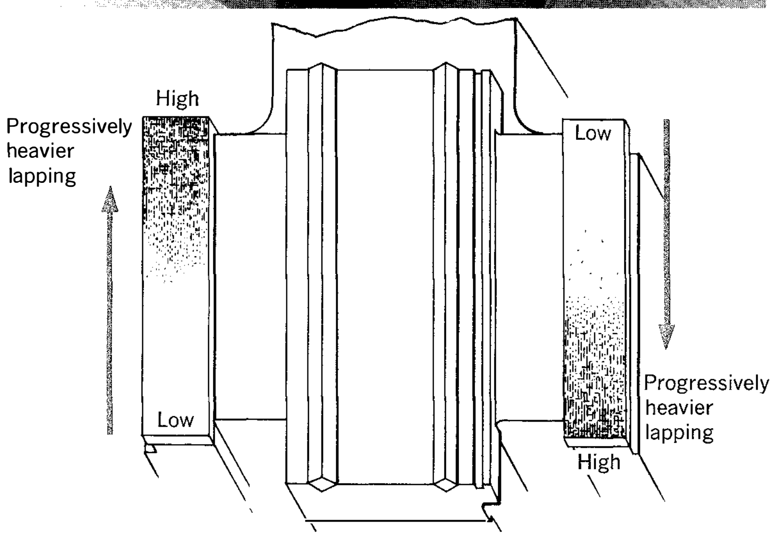


FIG. 118—*The method of hand-lapping to remove a twist in the flat ways is illustrated here.*

FIG. 119—*The "bridge" fixture relies on the now-finished flat ways as a datum and inspects straightness and parallelism of the V-ways.*
Two indicators are used in order that the full 31 inches [787 mm] of V-way may be inspected from the 20 inches [508 mm] of flat ways.

FIG. 120—*Once the base flat ways and V-ways are lapped to geometric accuracy, the base becomes the "master," and the cross-slide is scraped to match it by means of a bearing check.*

Straightness of each V, both in the vertical and horizontal plane, is inspected by autocollimation, using a special V-gage with mounted mirror. Tolerance of straightness is 0.5 seconds.

Twist of the V's is inspected with a bridge fixture, Fig. 119, using the plane created by the flat ways as a datum. A lapped V-gage having a small indicating pad is used as the indicating point. By fixing two indicators on the bridge, the full 31 inches [787 mm] of V-way may be inspected from the 20 inches [508 mm] of flat way. It is only necessary that the V's be parallel and not of identical height, since the cross-slide will be scraped to match the base. Tolerance of parallelism of the V's to one another and to the flats is 10 millionths of an inch [0.00025 mm].

Cross-Slide

Three steps in the manufacturing process insure that the cross-slide now very nearly matches the completed base:

1. The cross-slide has been scraped accurately to a fixture;
2. The flat ways are ground alike in pairs to a thickness that matches a particular base assembly;
3. All double-V masters in use are of identical center-distance.

In final fitting, the base is used as the master and the cross-slide is scraped to match. Bluing must in this case be used, since the hardened and lapped ways will not give up a bearing using rouge.

Matching the cross-slide to the base involves the following procedures:

1. Check of the bearing, Fig. 120, must be uniform;
2. Check for sideways movement, Fig. 121, maximum 5 millionths of an inch [0.000127 mm];
3. Check for "squash," Fig. 122, maximum 5 millionths of an inch [0.000127 mm].

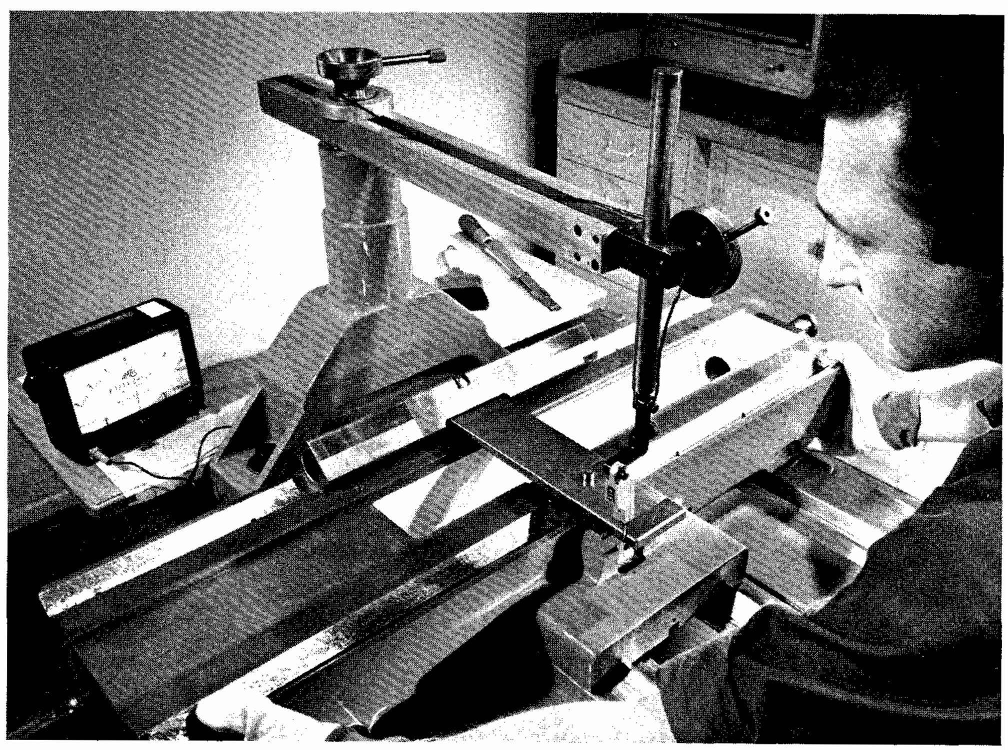


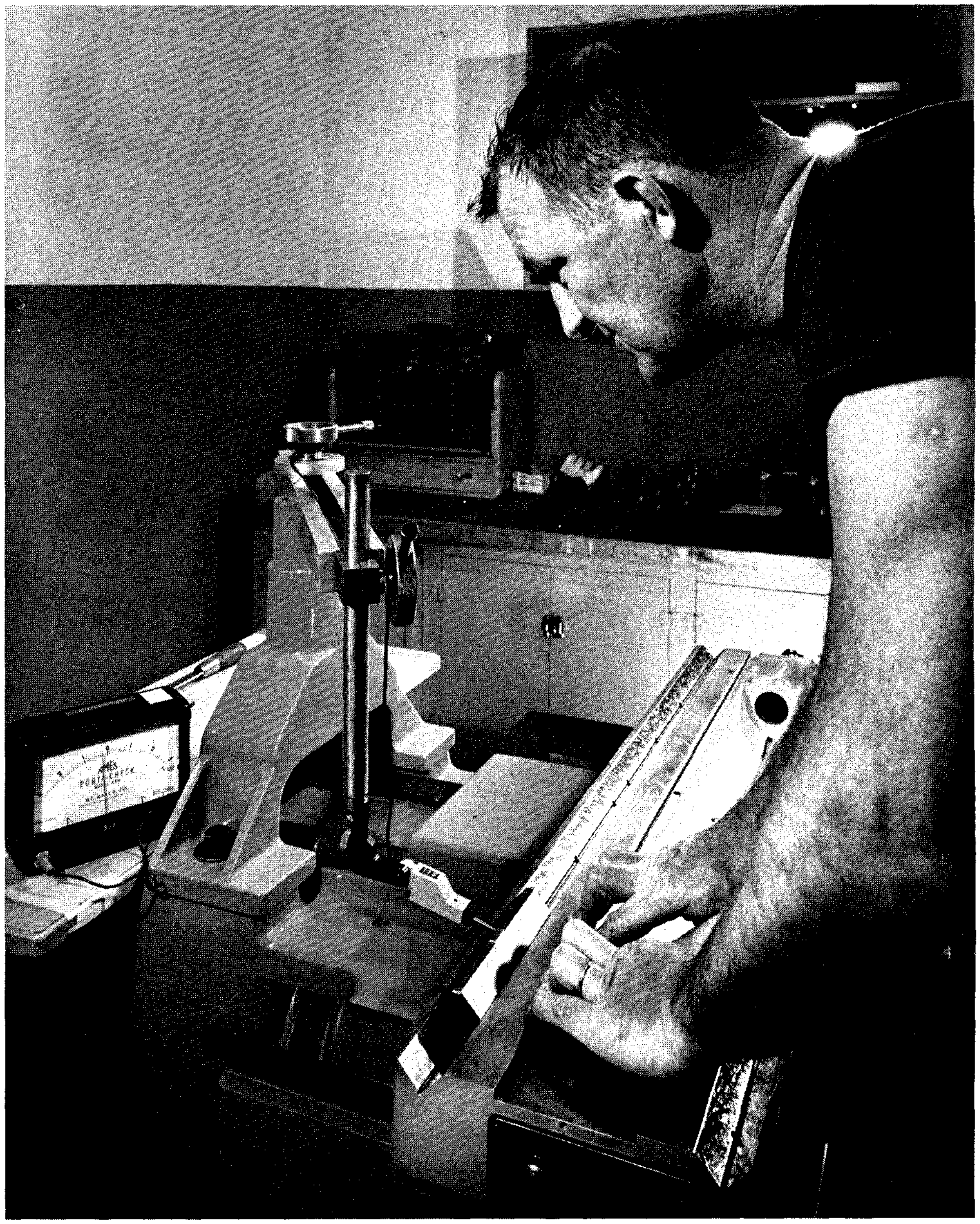
FIG. 121—*The cross-slide has been scraped to match the base. The operator must not see more than 5 millionths of an inch [0.000127 mm] sideways movement when pushing and pulling the ends of the cross-slide.*

FIG. 122—*In another check for the match of cross-slide to base, "squash" should not exceed 5 millionths of an inch [0.000127 mm].*

Once fully matched to the base, the cross-slide is perfectly supported for corrective scraping on its upper V's with a fresh double-V male master. Most important, *it is corrected and inspected under the conditions in which it will be used.*

Squareness may have been altered when matching the cross-slide to the base, so it is re-inspected, using the V-square of Fig. 123, which is straight and square within 10 millionths of an inch [0.00025 mm]. Note that this square is theoretically not self-checked by reversal since a mismatch of its base to the V-way may misrepresent true squareness.* However, the V-square is not used as a final check, but is a convenient tool to discover errors of squareness when they may be more easily scraped out. The effort spent in establishing squareness at this stage proves profitable since mounting the hardened ways in the upper V's does not usually alter squareness.

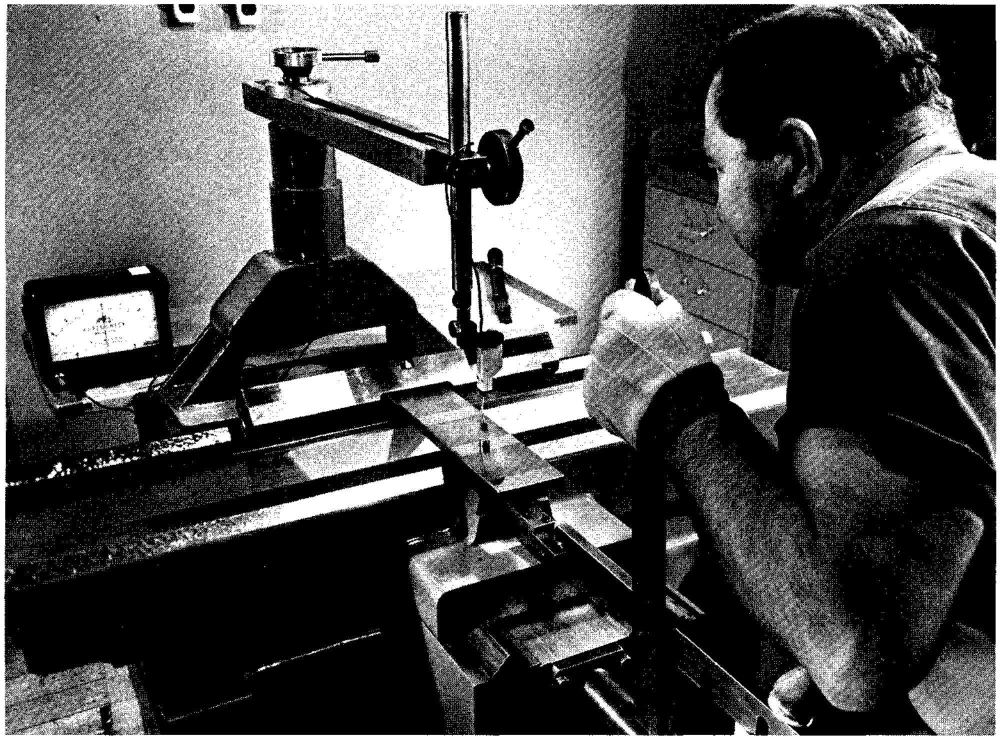
Twist is inspected by comparing adjacent points in the V's against a fixed indicator. This latter inspection relies on the good geometry of the baseways, and demonstrates again the necessity for the close tolerance specified initially on the flat ways.



*A cylindrical-bodied square for seating in the V is also used and is self-checking. However, in various stages of scraping, the readings are more misleading because they only allow for line-contact of the cylinder in the V.

FIG. 123—*Prior to mounting of the hardened ways in the cross-slide, an inspection is made for squareness using a square with a V base.*

Although the upper scraped female V's in the cross-slide are not functional surfaces, the technique of establishing geometry requires that they be made very accurately.



Straightness of each V is inspected by autocollimation. Corrective scraping involves a consideration of vertical and horizontal straightness, twist and thickness, while maintaining squareness, form and horizontal parallelism.

Hardened Ways Fixed to Cross-Slide

Once fixed to the cross-slide, Fig. 124, inspection of the hardened V-ways is the same as previously followed with the scraped V's except that gages must match male V's. Correction is by small hand laps and female double V-laps. Inspection for bearing requires female double-V checking masters.

Tolerance of straightness of each V by autocollimation is 0.4 seconds as obtained in Fig. 113.

Tolerance of parallelism of each V: 5 millionths of an inch [0.000127 mm]. In Fig. 125 twist is inspected by comparing adjacent points of the hardened V-ways.

FINAL INSPECTION

Table

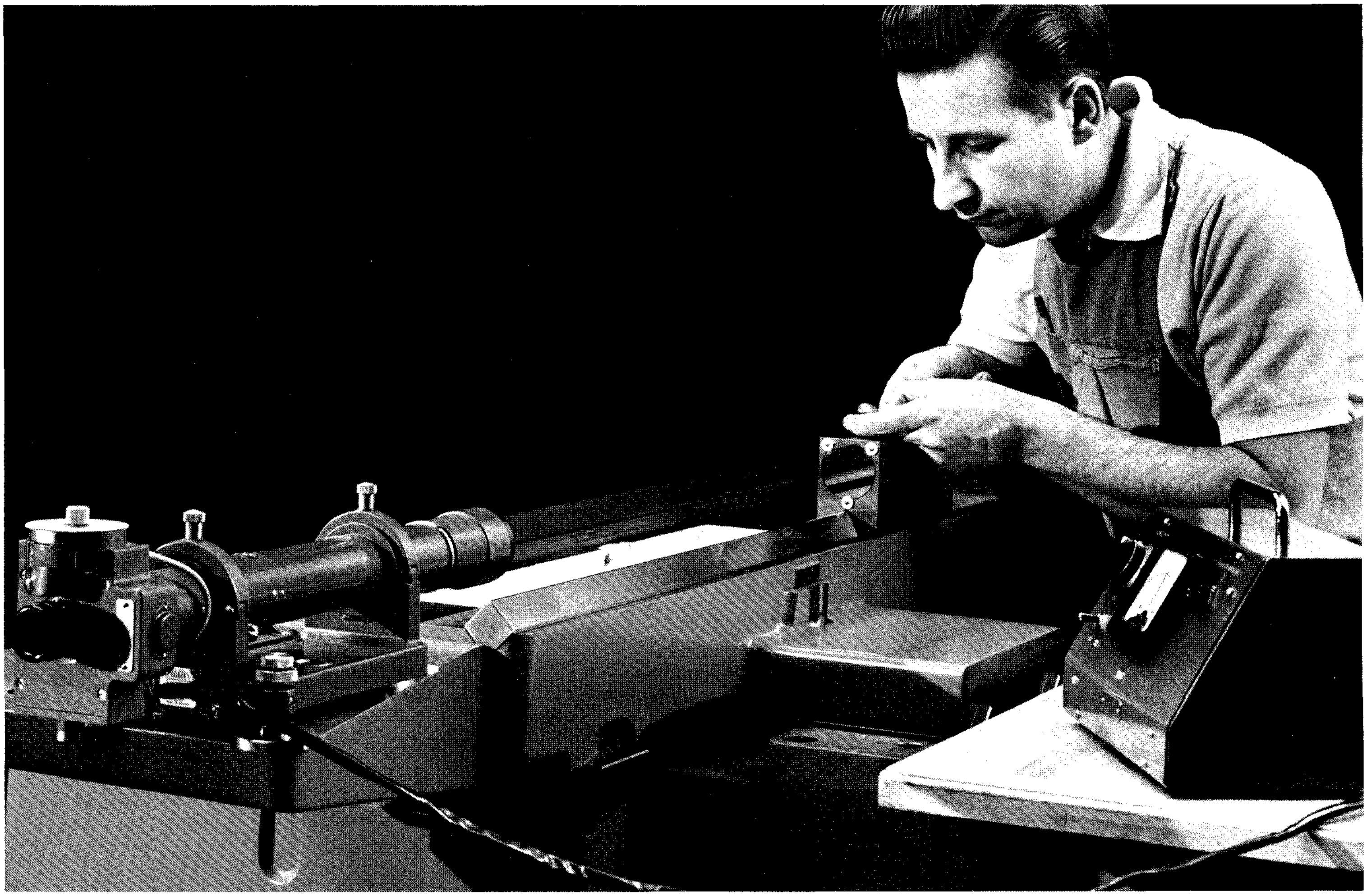
The table ways are scraped to fit the upper rails of the cross-slide. The separate checks made on all the rails do not guarantee that the axes will perform exactly as inspected, so the base is now final-inspected for straight-line travel and squareness under the influence of all the combinations of twist, horizontal parallelism, bow, etc., of each rail fitted to the table.

Final Autocollimator Inspection

A much more accurate determination of straightness is possible with the autocollimator once the table has been fitted to the cross-slide, for the following reasons:

1. Only the table must now be moved, and the mirror-mount need not be touched or handled;
2. The inspector must now only look

FIG. 124—*The hardened and ground V-ways have now been fastened to the upper scraped female V-ways. Each V is inspected for straightness using the photo-electric autocollimator. Correction is by means of small hand laps and female double V laps.*



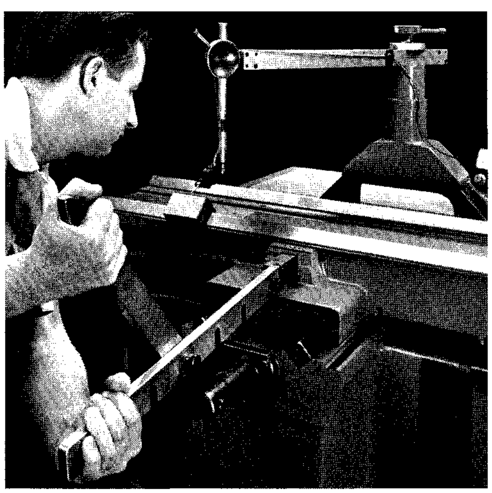
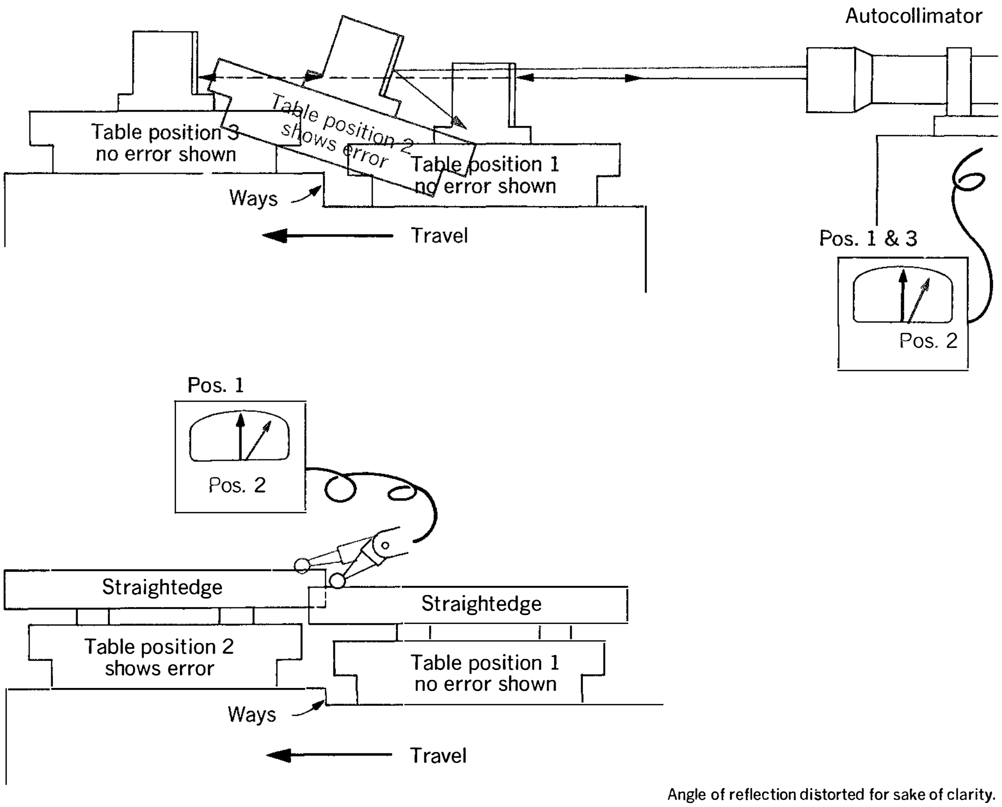


FIG. 125—*Vertical parallelism is measured by comparing adjacent points of the rails, using the cross-slide movement on the base as a datum. The necessity of high accuracy of the base slideways is here apparent; any initial errors would be transferred to each subsequent operation, such as the one shown.*

FIG. 126—*This diagram analyzes one particular type of error in the ways—first, as it would be shown with the autocollimator and target mirror (top), and second, as it would appear when using the straightedge and electronic indicator (bottom).*



carefully to record any angular deviation over full travel.

There are several precautions in the use of the autocollimator which may be worth mentioning at this point:

1. It is conceivable that the inspector may miss or misinterpret the nature of the error, Fig. 126;
2. The autocollimator, while stable at short ranges, fluctuates increasingly the greater the distance of the reflecting mirror from it, as a result of air currents;
3. The autocollimator should be properly mounted on the machine in such a manner that any deflection caused by moving the cross-slide or table does not deflect the machine member to which the autocollimator is mounted. The practice of providing separate support for the autocollimator, such as mounting on a surface plate, is an undesirable alternative, since the orientation of that support to the machine may unknowingly shift during the inspection process. This shift can be caused simply by walking in the environs of the machine;
4. If the error in the ways causes the table to bend rather than to change its angle, part of the error may not be shown, Fig. 127. However, the stiffness of the table minimizes the problem in this case. Where the table is a thinner section, the center-distance of the feet of the mirror-holding gage should be lengthened so as to include bending.

It was felt desirable to develop a completely different method which would supplement the autocollimator in inspecting straight-line travel.

Many methods were tried and discarded. They included:

A "high-low" check where two indicators were zeroed on two fixed pairs of parallel-lapped flats at each end of the

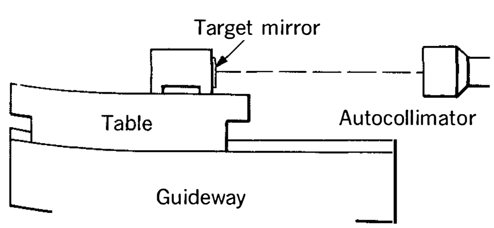
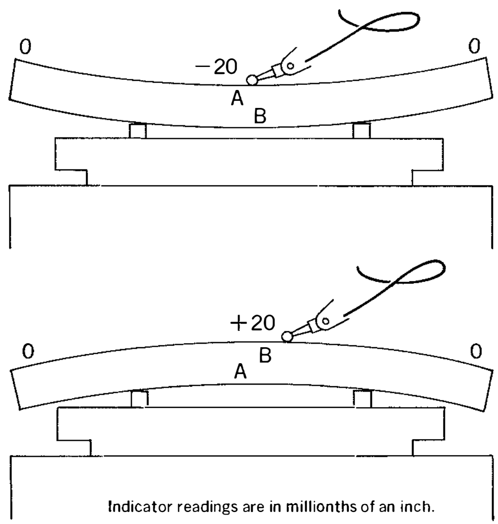


FIG. 127—*When the target-mirror feet are too short a span, full error from bending of the table does not register.*

FIG. 128—*Each time the straightedge is used, it is specified that it be turned over and the inspection repeated. Duplicate readings should be obtained for the check to be valid.*



gage and at different heights was employed but did not show local error.

A technique where the Step Gage (see pages 180–185) was calibrated at the front and back of the table and also at different heights above the table (very sensitive, since errors of straightness are tremendously magnified, but not convenient for "production").

A precision level measures deviations sensitively, but only errors in the vertical plane are shown. Also, with this method, two levels reading differentially would have to be used. One would be mounted on the moving element to measure straightness, and the other on the machine base, to separate out effects which alter the *whole* machine with respect to gravity (caused by the nature of the floor support, or deflection from movement of the machine carriage, or walking in the environs of the machine).

The conclusion was reached that the straightedge had many fundamental advantages when used to inspect straightline travel:

1. The inspection is directly interpretable to the operator;
2. The straightedge is fast to use;
3. The inspection can be self-contained on the machine. The indicator can usually be placed in a position where the movement of the slideway does not introduce misleading readings due to deflection:
4. The straightedge is directly related to the flat plane;
5. The straightedge can be self-checked by reversal, Fig. 128.

But it was also recognized that the straightedge method itself had limitations which had to be overcome:

1. *Necessity for absolute perfection in the straightedge.* The design of the straightedge which fulfills this requirement is shown in Fig. 129. These nitralloy straightedges are 26 inches

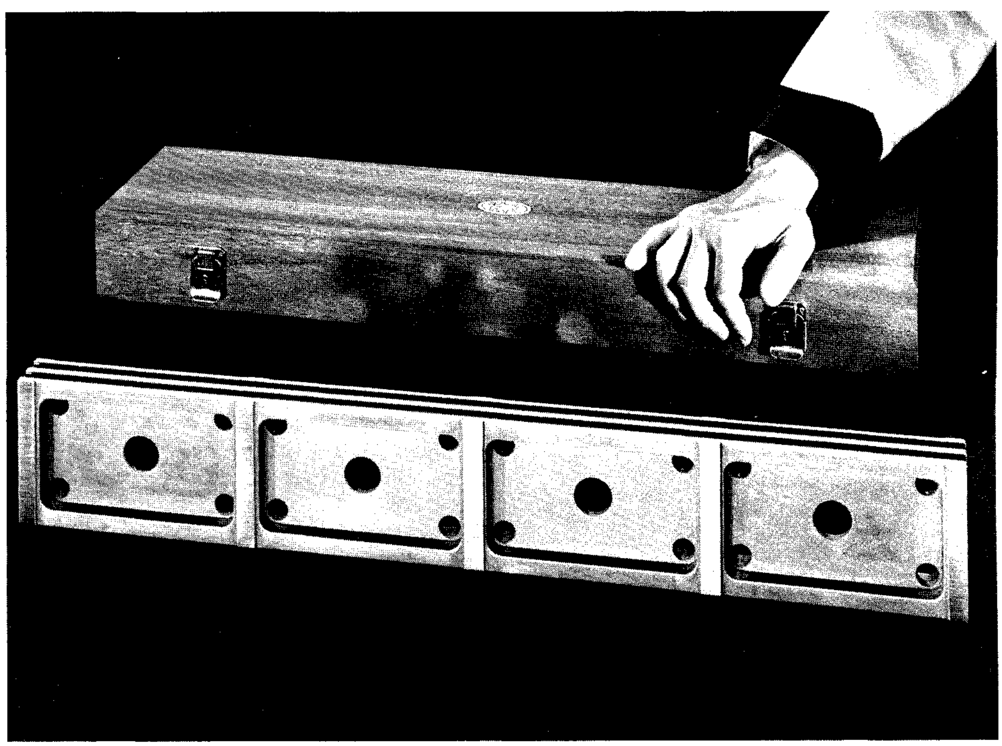


FIG. 129—*Nitralloy straightedges used in final calibration of straightness are 26 inches [660 mm] in length. These gages are extremely hard, stable, and lapped to a final accuracy of 5 millionths of an inch [0.000127 mm] as to straightness and parallelism of their sides.*

FIG. 130—*When using a single, fixed indicator, and a straightedge travelling past it, full error of way curvature may not be apparent.*

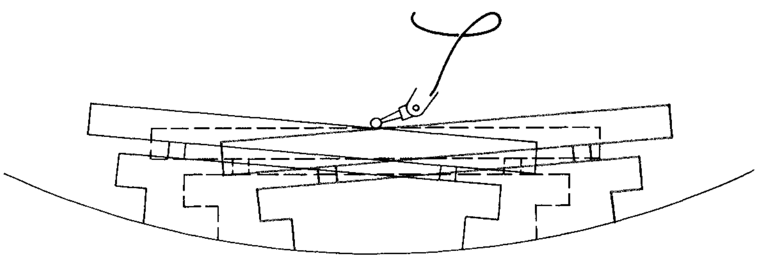
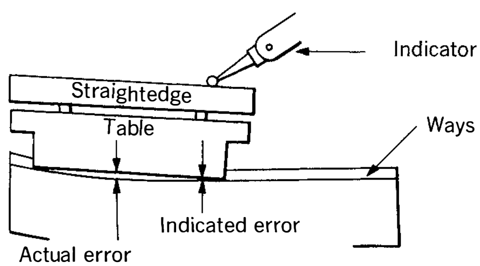


FIG. 131 (Center)—*A sudden error, especially at the extremes of travel, may not be apparent if the indicator is left in only one fixed position.*



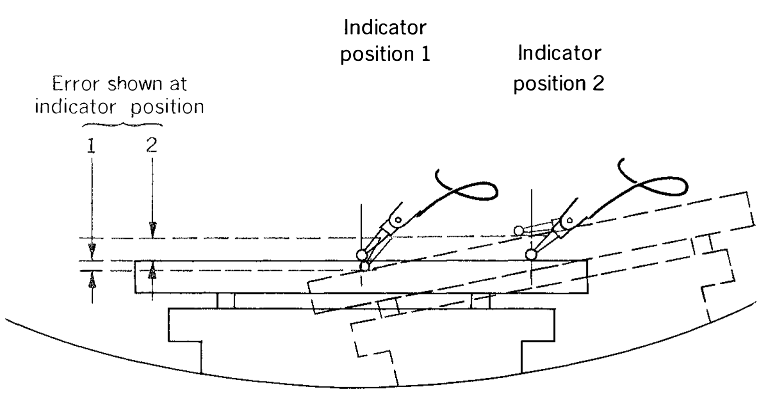


FIG. 132—*When only one indicator is used, the indicator probe must be repositioned along the straightedge and the slide moved once again.*

in length [660 mm]—extremely hard, stable and lapped to a final accuracy of 5 millionths of an inch [0.000127 mm] as to straightness and parallelism of their sides;

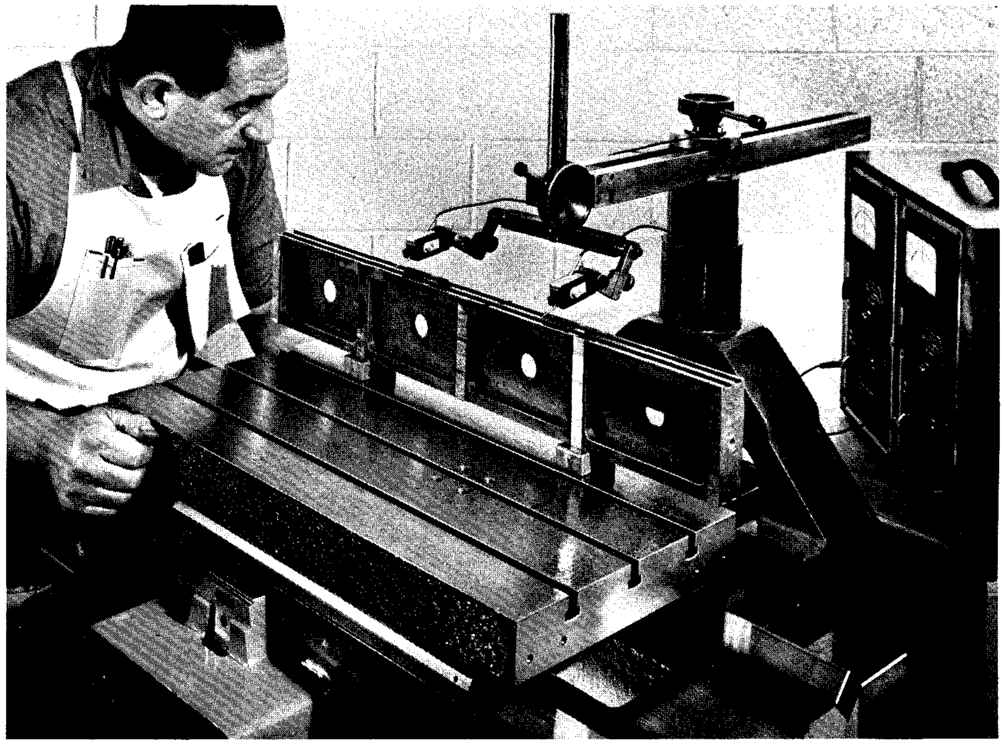
2. *Distortion of straightedge due to temperature—* Precautions must be taken to prevent distortion from handling by the use of insulating blocks or gloves and care in handling. Furthermore, standard inspection procedure specifies that at each check, the straightedge is reversed, so that any temporary distortion would be immediately apparent;
3. *The straightedge cannot be used until the table is matched to the cross-slide—* It was decided that the straightedge would be used as a final, double-check following inspection by the autocollimator. The requirement that the machine straightness had to pass *two* completely different methods of inspection was felt to be an advantage;
4. *When the error in the machine's ways is in the form of an arc of relatively large radius, and a single fixed indicator is read against a straightedge moving past it, the error may not be shown, Fig. 130.* This is even more apparent in the case of a sudden error at the extremes of travel, Fig. 131.

The limitation of a single fixed indicator can be overcome by repositioning the indicator along the length of the straightedge and moving the slide once again as in Fig. 132. The major objection to the use of a single indicator is that it must be physically repositioned as shown in order to insure that error is registered. Once moved, however, the original datum is lost and the error in the travel is not related from end-to-end.

Another procedure, theoretically more correct, is to attach the indicator to the machine table and read it

FIG. 133—*To inspect straightness of travel in both planes, a double indicator is used. To inspect straightness in the vertical plane, the straightedge is mounted on its points of least deflection, (.554L).*

Straightness in the horizontal plane is inspected with the straightedge resting on its side. In both cases, the straightedge is self-checked by reversal.



against a straightedge mounted somewhere on the base. If a mount *could* be secured somewhere on the base, this would still be awkward because of practical difficulties, such as in mounting and aligning the straightedge, turning the straightedge over for a self-check, and in being able to differentiate between curvature of the ways and "twist" of the ways.

In order to make the straightedge most sensitive to errors of curvature and yet remain convenient in use, the following procedure is adopted as standard: two indicators are used, both attached to a common bar, but spread apart 9 inches [229 mm] and fixed to an adjustable arm. The adjustable arm projects from a sturdy mount fixed to the rear of the base, Fig. 133.

The "double" indicator does not actually discover any error that would not be shown by re-positioning a single indicator, but does provide the following operational advantages:

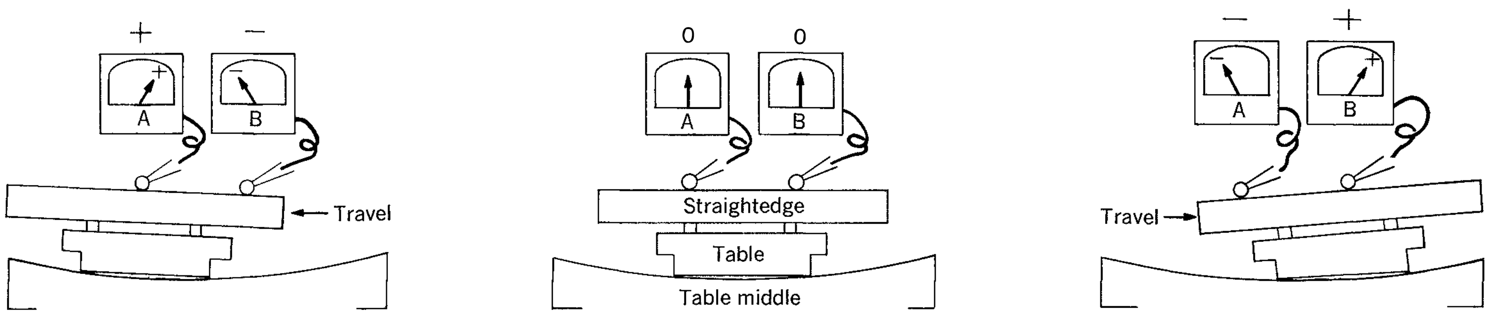
a. The error in the ways is related over full travel

b. By using two indicators spread apart as a permanent part of the set-up, any error of curvature is at all times visible to the operator on at least one of the indicators.

c. It allows the full 26 inches [660 mm] of straightedge to be used although machine travel in the "Y" axis is only 18 inches [457 mm] giving slightly greater magnification of error at the extremes of the travel.

d. The most typical error in the machine's slide way is what might be called a "uniform arc," which may

FIG. 134—*When checking straightness of travel of a machine's ways with the straightedge resting on its table, a "double indicator" is much preferred over a single indicator.*



be either concave or convex. Referring to Fig. 134, showing a machine with a concave arc, if both indicators are set to "zero" in the middle of the travel, movement to the left will cause a "plus" reading on indicator "A" and a minus on indicator "B." Movement to the right will cause the opposite, a "minus" on indicator "A" and a "plus" on indicator "B"—thus giving a doubling effect to the error. The tolerance of straightness in both planes of both axes is 20 millionths of an inch [.000508 mm]. The straightedge is mounted firstly on edge on its points of least deflection to inspect for vertical straightness, and secondly rested on its side to inspect horizontal straightness.

In final inspection, when using the double indicator method, the deviation of readings of both planes of both axes must not exceed 20 millionths of an inch [.000508 mm]. Each time, the straightedge is reversed for a self-check.

Squareness

For final inspection of squareness of the X-Y axes, a T-square accurate to 10 millionths of an inch [.000254 mm] is used, Fig. 135. The base rail of the square is aligned with the X axis using an indicator. Leaving the square in the same position, the indicator is swung to indicate the blade by sliding the Y axis.

Both the square and the machine are simultaneously checked by comparing the readings obtained when the square is reversed, Fig. 136. Shop tolerance of squareness is 20 millionths of an inch [0.5 μm].

Table Top

Using a flat master for bearing, the tabletop is lastly scraped for "thickness" (parallelism to the ways) and for flatness. The inspection procedure consists of positioning nine points of the table under a fixed indicator by moving cross-slide and table. The tolerance specification of 20 millionths of an inch [0.5 μm] TIR by this method is a severe one, for it necessitates near-perfect geometry of the whole base construction, Fig. 137.

Column

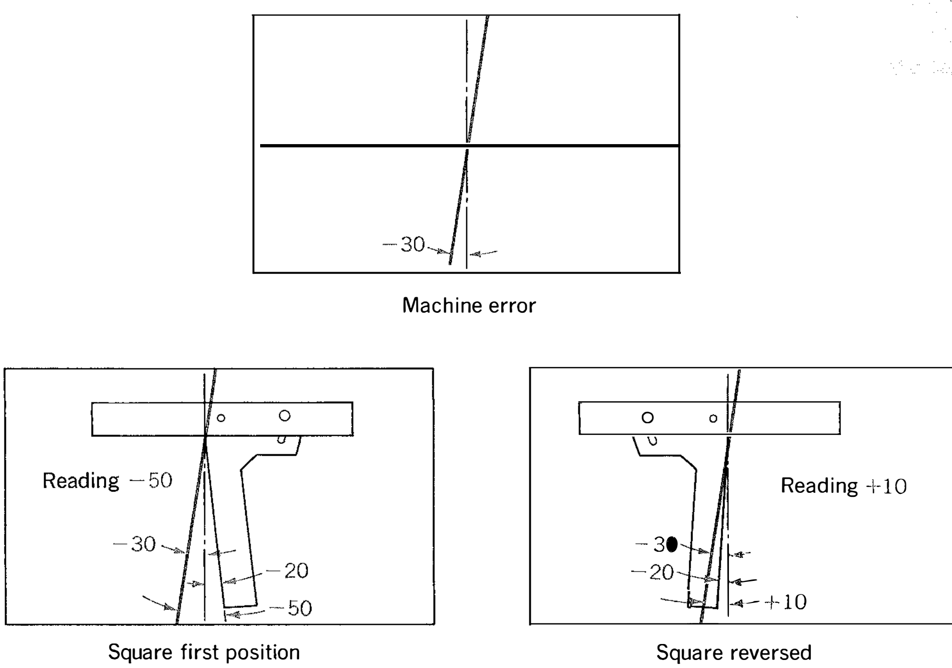
The column is scraped to a male double-V master and autocollimated for straightness of the ways.

The column is squared to the base, Fig. 138, after final assembly to the actual conditions under which the machine will operate—with housing and all components in place.

The close tolerance specified above on the table top now assures a reliable squareness check. The cylinder square shown is self-checked by reversal.

Tolerance on squareness is 50 millionths of an inch [1.3 μm].

FIG. 135—*Final inspection of squareness employs a nitralloy T-square, accurate to 10 millionths of an inch [0.00025 mm]. The square is self-checked by reversal. Tolerance of squareness of the machine axes is 20 millionths of an inch [0.0005 mm].*



To find out-of-squareness of machine:

(I) Machine + square = −50
(II) Machine − square = −10†
2 x Machine = −60 (I) + (II)
Machine = −30
(−30) + square = −50 (sub in I)
square = −20

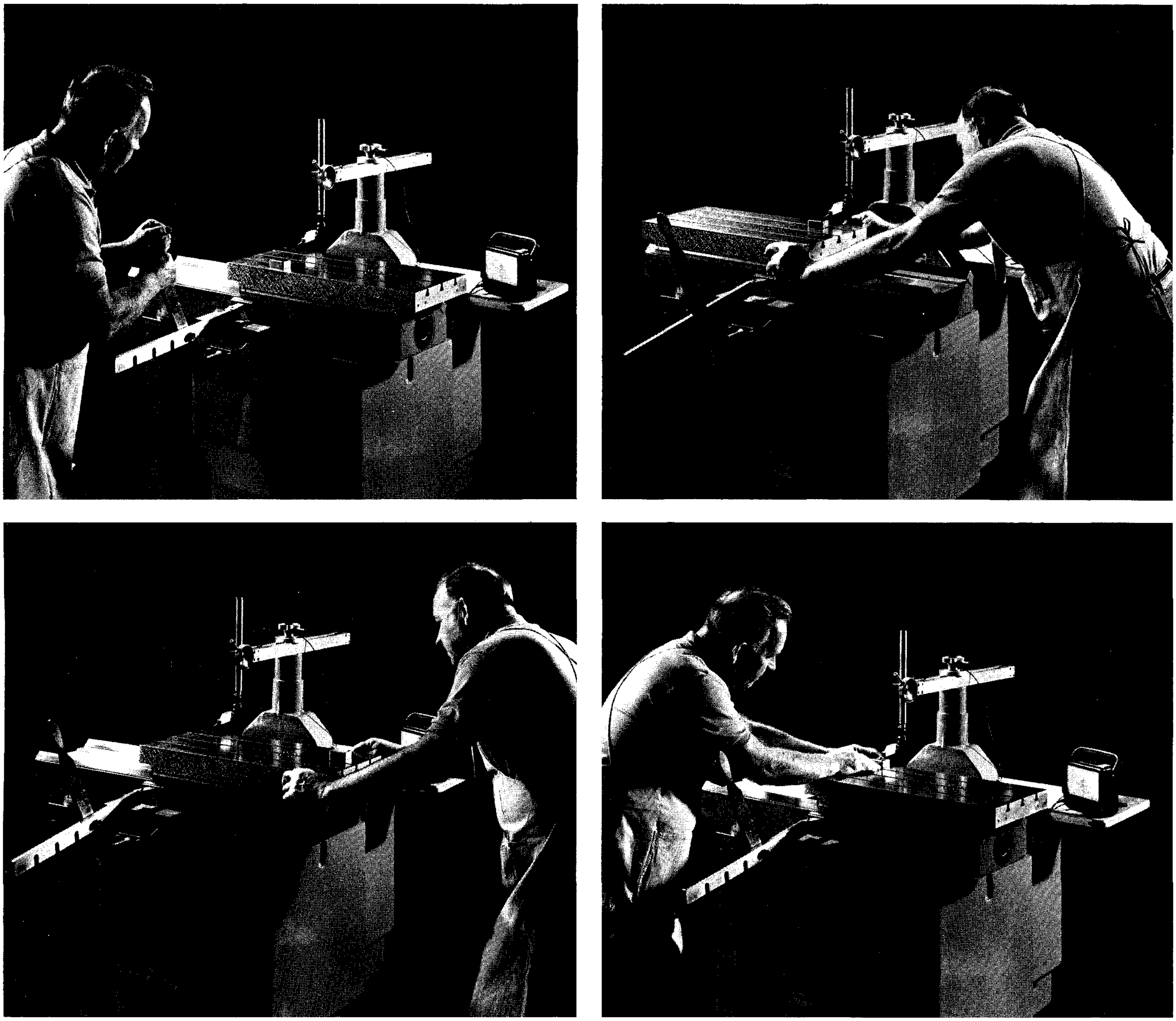
†Actual reading was + 10 but the sign changes due to indicating from opposite side

Readings are in millionths of an inch

FIG. 136—*Actual squareness error of both the machine axes and the T-square is determined upon reversal of the T-square.*

FIG. 137—*"Thickness" of the machine table and flatness of its top are lastly established by positioning nine points of the table under a fixed indicator. This is done by moving the machine axes.*

A tolerance of 20 millionths of an inch [0.0005 mm] by this method is severe, since it requires near-perfect geometry of the whole base construction.



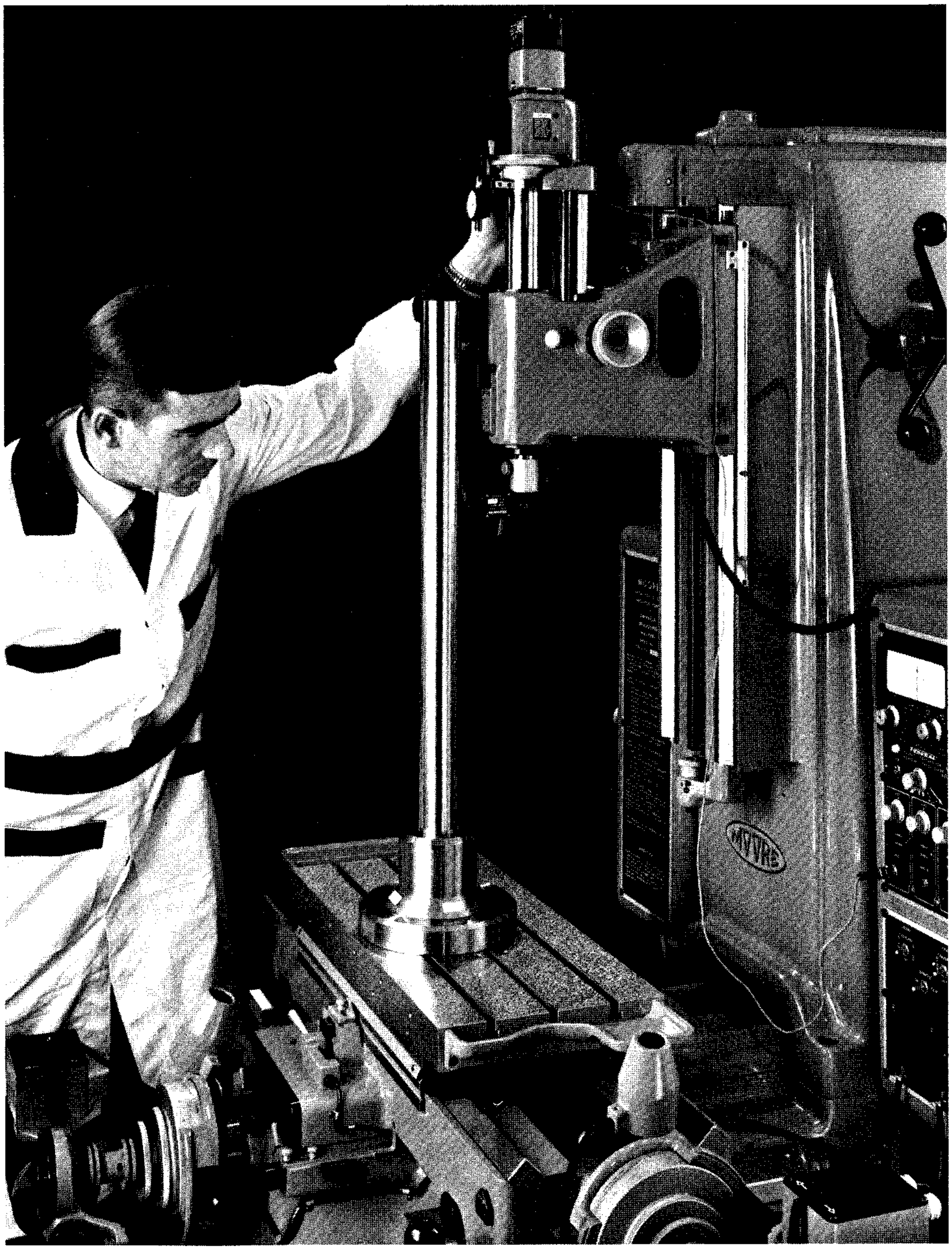
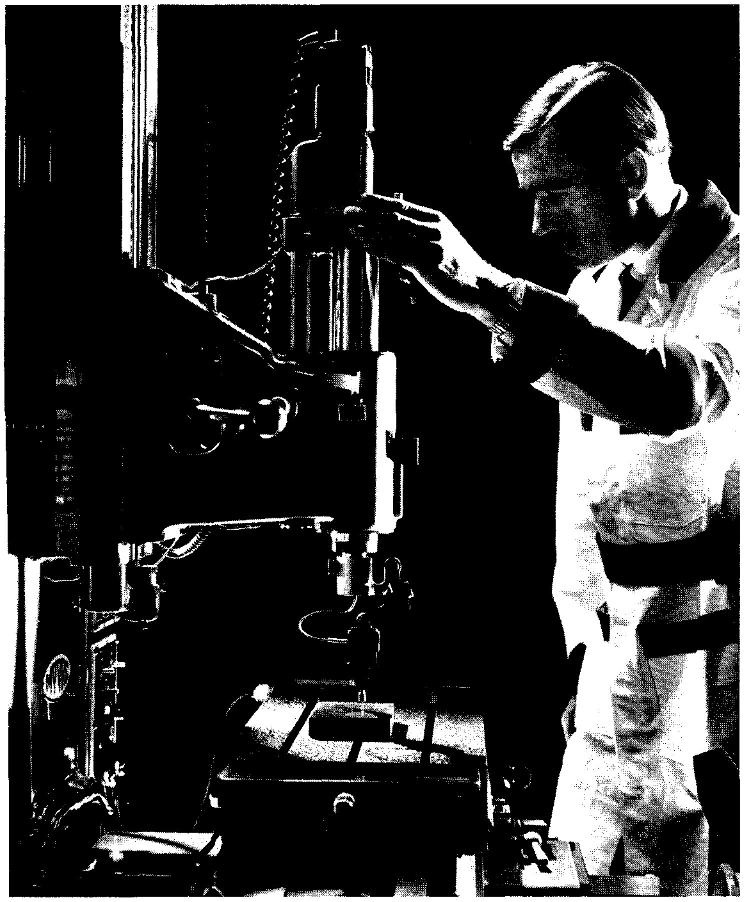
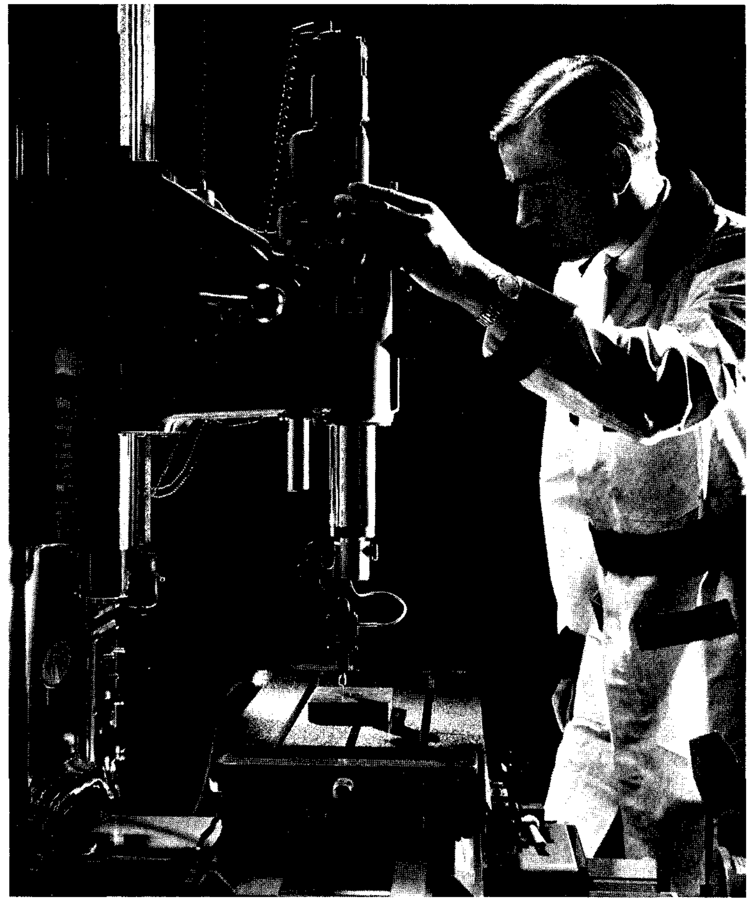


FIG. 138—*The column is squared to the plane of travel of the base by using a cylinder-square master. The close tolerance previously specified on the table top allows this to be done with great accuracy. The cylinder square is self-checked by reversal.*

FIG. 139—*Alignment of the quill to the housing travel is inspected in two directions by using a lapped round hole.*

The hole is picked up with the housing lowered and quill retracted (left). Error in both directions registers when the housing is raised and the quill extended (right). The doubling effect makes this inspection highly sensitive.





Alignment

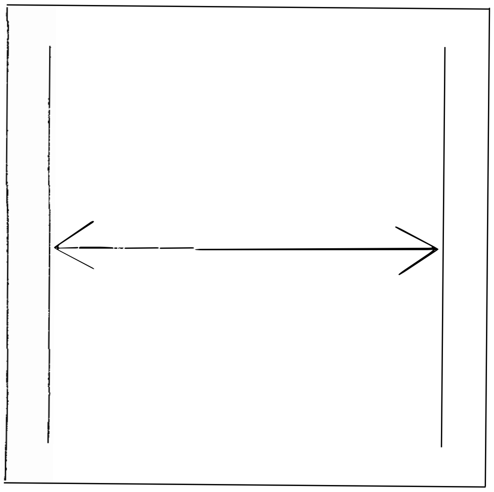
Alignment of the quill travel is also lastly inspected in its final, vertical position, Fig. 139.

Readings taken when revolving an indicator fixed to the spindle, first with the housing lowered and quill retracted (left), and next with the housing raised and quill extended (right), show quill misalignment in both directions. The doubling effect by using a hole makes this method very sensitive. The holes used are lapped round within 5 millionths of an inch [0.000127 mm] and of high micro-finish.

Tolerance of alignment is 30 millionths of an inch [0.00076 mm].

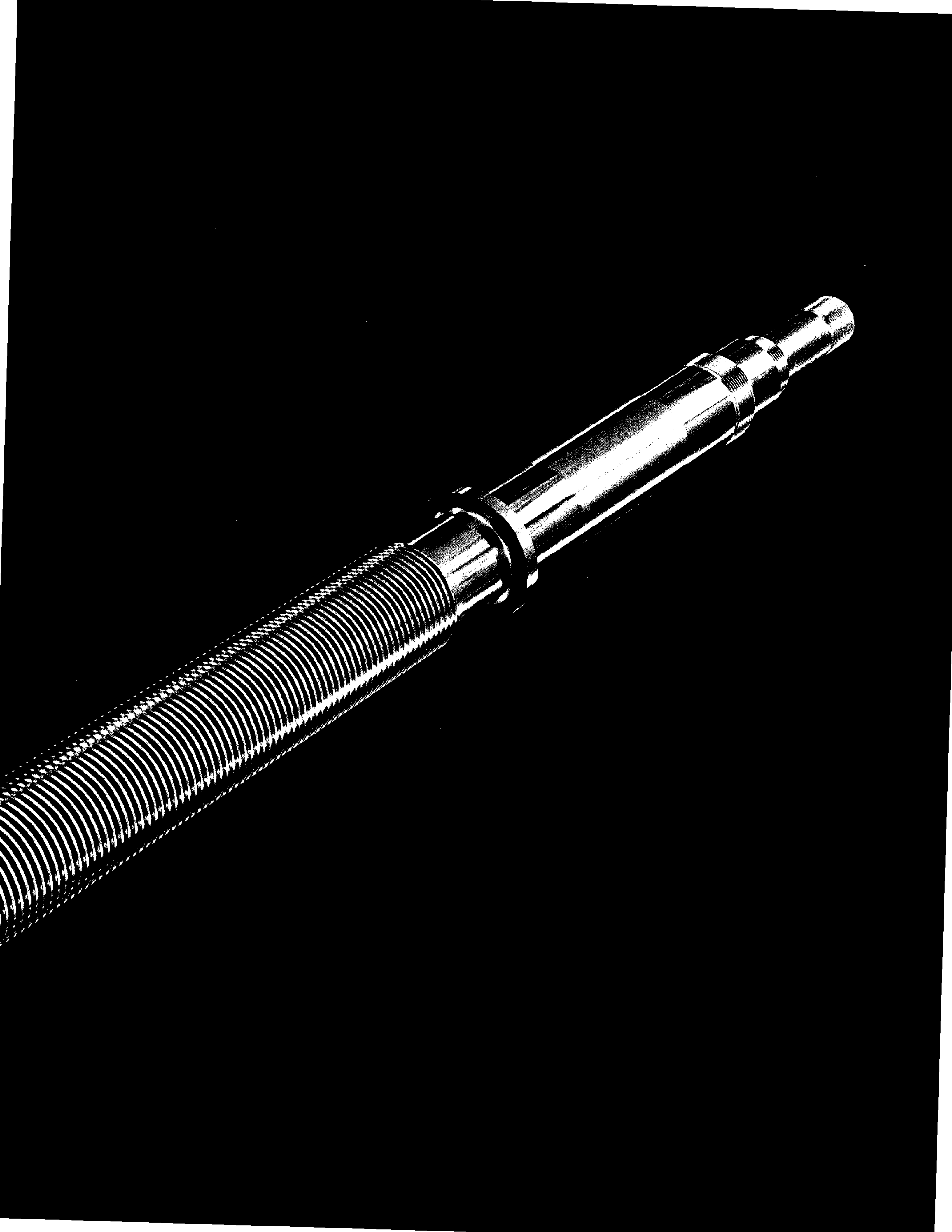
STANDARDS OF LENGTH

2



The responsibility for the establishment and maintenance of the ultimate standard of length, which is at present a specified number of wavelengths of the krypton 86 isotope, rests with the international and national bureaus of standards. The accuracy of derived length-standards such as gage blocks, precision scales, Step Gages, lead screws, and laser interferometers depends in large measure on how truthfully they represent the ultimate length standard.

FIG. 140—*The master lead screw is the measuring element in all Moore machines. Its accuracy is the culmination of efforts in establishing accurate and "traceable" standards of length.*



THE STANDARDS BUREAUS

Modern manufacturing technology is based on precise, reliable dimensional measurements. Ultimately, all of these measurements are comparisons with standards developed and maintained by bureaus of standards throughout the world.

Most bureaus are research centers as well, where the science of precision measurement is continuously refined. The bureaus direct much of their research toward the solution of industry's measurement problems and serve as forums and clearing-houses for information on measurement. Mass production, automation, advanced products—these are some of the benefits directly conferred on mankind by the work of the bureaus. The indispensable relationship of the bureaus to the total scheme of technology will be continually emphasized throughout this section; for it is particularly in the matter of length standards that the need for national and international agreement becomes most apparent. By way of emphasizing their vital role, on the following pages appear unique contributions by an official of each of four leading bureaus, describing the scope of their work.*

*A good source of additional information: Arnold W. Young, *The Bases of Measurement Calibration Facilities in National Foreign Laboratories,* Paper presented at AOA Standards & Metrology Meeting, Philadelphia, April, 1970.

BUREAU INTERNATIONAL
DES
POIDS & MESURES

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F92- SEVRES FRANCE
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TELEPHONE: 037 00-51

Functions, Activities and Goals of
the Bureau International
des Poids et Mesures

The International Bureau of Weights and Measures was founded on May 20, 1875, by the Conference of the Metre in which seventeen different countries were participating. At the present time forty countries are members of the Conference and take an active part in the management of the International Bureau, the facilities of which they are joint owners.

The International Bureau is a scientific center and metrological laboratory in its own right, with the main purpose of creating a unified worldwide system of physical measures.

Its duties as such are:

-to establish basic standards as well as reference systems for the principal physical measurements and to preserve national and international masters;

-to ensure international coordination between measurements of corresponding purposes;

-to determine physical constants and to coordinate worldwide research in the field of basic metrology.

In the years following its creation, the International Bureau, being mainly concerned with lengths and masses, concentrated on the preparation of the standards which were distributed to the participating governments. Later on, the work on the gas thermometer led to the determination of the standard hydrogen thermometric scale, and the investigation into the dilatation of nickel alloyed steel enabled C. E. GUILLAUME to discover the invar alloy. The accurate determination of the mass-volume-relationship of water, the dilatation factors of the standard platinum-iridium alloy and the use of invar wires in connection with geodesic length measurements go back to this same period.

As early as the nineties, the International Bureau found a new field of activities with the determination by MICHELSON and BENOIT and later on by BENOIT, FABRY and PEROT of the red spectrum line of cadmium.

Even though it entered the new fields of electrical (1927) and photoelectrical (1933) standards and of ionizating radiations (1960), the Bureau did not fail to keep developing its initial activities.

On October 14, 1960, the Eleventh General Conference on Weights and Measures meeting in Paris availed itself of the work done as early as 1954 to redefine the meter in terms of the wavelength of the orange red spectrum line of the isotope of krypton having a mass number of 86.

Interferometry is successfully used for measuring material length standards and for the determination of gravitational acceleration, with unprecedented accuracy.

Even though the orange red spectrum of krypton is still the primary length etalon, laser radiations are now being actively investigated.

Progress in the fields of electronics and quantum physics seem to open up new possibilities towards ever more accurate metrological standards. To live up to its vocation, the Bureau shall leave no avenue of progress unexplored.

P. Carre
For the Director J. Terrien
10 March 1969

NATIONAL PHYSICAL LABORATORY
TEDDINGTON,
MIDDLESEX.

The work of the National Physical Laboratory,
Teddington, England

The main objectives of the National Physical Laboratory are summarised in the following quotation from the formal opening of the Laboratory in 1902: "To bring scientific knowledge to bear practically on our everyday industrial and commercial life, to break down the barriers between theory and practice, to effect a union between science and commerce."

To attain these objectives, a large part of the work of the Laboratory is concerned with the establishment and maintenance of basic standards of measurement and the furtherance of their use by industry. An important contribution to this task is made by research carried out to develop new and improved standards and better and more accurate methods of calibrating them. Intercomparisons are made between the NPL standards and the national standards of other countries and those maintained by the International Bureau of Weights and Measures at Sèvres. Industrial reference standards in certain fields of measurement are calibrated at the Laboratory in terms of the NPL standards and by this means industry is enabled to establish a uniform basis of measurement throughout the country in conformity with similar measurements made abroad. The latter objective has been facilitated by the establishment of the British Calibration Service (BCS) of the Ministry of Technology, and all the laboratories approved by BCS in the field of engineering metrology have reference standards traceable to NPL.

In addition to the work on basic standards, the NPL also assists industry in the United Kingdom by advising on problems of measurement and where appropriate by developing suitable measuring instruments to solve these problems.

L. W. Nickols
Head, Metrology Centre
1 May 1969

Physikalisch-Technische Bundesanstalt

Abteilung I

Braunschweig,
Bundesallee 100

Fernsprecher: 5921, Durchwahl Ober 592
Fernschreiber: 9-52822 (ptb b5wg)
Telegramme: Bundesphysik Braunschweig
Frachtgut: Braunschweig—Lehndorf
Expressgut: Braunschweig—Hbf

Dimensional Metrology at PTB

The PTB (Physico-Technical Institute of the Federal Republic of Germany), formerly named PTR (Physico-Technical Institute of the German Reich) was founded in 1887 and hence is the oldest national physical laboratory of the world. Its original objectives were:

1) to carry out research in all fields of physics and engineering, thus assuring maximum application of the physical and engineering sciences to the advancement of industry;

2) to be in charge of testing materials, mechanisms, structures and measuring instruments or tools.

Today, one of its chief concerns is the maintenance of our measuring system, particularly the maintenance of the fundamental physical and technical standards as well as the invention or development of new methods of definition and their control. This, of course, has to be done in close collaboration with the other national laboratories.

In 1969, nearly 1300 people, among the approx. 300 scientists, were working at PTB, which is subdivided into the six classical divisions: mechanics, electricity, heat, optics, acoustics and atomic physics.

Dimensional metrology is the prevailing objective of the mechanics division which includes, besides others, three length measurement laboratories: length unit, end measures and line measures.

The length unit laboratory played a leading role at the recent redefinition of the meter in terms of the wavelength of the orange red krypton 86 line. The krypton 86 lamp and useful instruments enabling end gages to be measured with light waves, for instance the well-known Koesters interference comparator for the measurement of end gages up to 100 mm (4 in.) and the big Koesters end gage interferometer for the measurement of longer gages up to 1000 mm (40 in.) have been designed and important research on the application of light waves to length measurement has been carried out in this laboratory. Using the Koesters end gage, interferometer gages are measured in terms of a light wavelength *in vacuo*, thus eliminating the uncertainty of the refraction of air.

The precision is the highest attainable at the present time and is limited mainly by the imperfections of today's end gages and by the difficulty in measuring the temperature more accurately than to 10^{-3} degrees. Actually the uncertainty of determining end gages up to 1000 mm is of the order of 10^{-8} m. Aiming at the creation of an eventual future length standard in terms of the wavelength of a laser radiation research on the application of lasers to length metrology was started years ago. A xenon-ion laser as a rather promising light source for establishing a more suitable wavelength standard has been developed.

Shorter end gages up to 100 mm (4 in.) are calibrated in the end gage laboratory using the Koesters interference comparator. The lowest attainable uncertainty is $\pm$ 0.02/μm (approx. $\pm$ 1/μm). Longer end measures are measured in this laboratory either by interferential comparison or by the use of various mechanical measuring equipment.

In the line measures laboratory a 1 m-comparator with photoelectric microscopes is used for comparing line meters by a displacement method. Line scales in general can be calibrated either in relation to end gages using a Koesters type interferometer or fundamentally using a helium-neon laser and a fringe counting technique. Measuring tapes and wires up to 50 m are measured in the same laboratory using a tape bench or a geodetic tape comparator furnished by the SIP Company.

In addition to the aforementioned basic length measurement laboratories, another group of length metrology laboratories, concerned particularly with industrial measuring problems, is working at PTB. There are enough facilities for the measurement of all kinds of gap gages, balls, cylindrical plug or ring gages and tapered plugs or rings. An interferential method and new types of feelers have been developed for these measurements. The characteristics of thread gages, particularly of the various forms of tapered threads according to the requirements of the API-standards, also of gears or worm gears can be determined by means of equipment designed for the greatest part at PTB. A high precision method is used for the calibration of rotary tables, angular index tables, angle dividers, circle graduations in general and for checking autocollimators. Conventional equipment is available for investigations on surfaces.

Prof. Dr. E. Engelhard
Leitender Direktor, PTB
August 9, 1969

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

Functions, Activities, and Goals
of the
National Bureau of Standards
Washington, D.C. 20234

The National Bureau of Standards is organized into the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Radiation Research and the Center for Computer Science and Technology.

The Institute for Basic Standards provides the central basis within the United States for a complete and consistent system of physical measurement, coordinates that system with the measurement system of other nations, and furnishes essential services, including measurement and dissemination of fundamental properties of matter, leading to accurate and uniform physical measurements throughout the Nation's scientific, industrial, and commercial communities.

This Institute serves classical subject matter areas such as: Applied Mathematics, Electricity, Metrology, Mechanics, Heat, Atomic and Molecular Physics, Radio Standards Physics, and Engineering, Time and Frequency, Astrophysics, and Cryogenics.

The Institute for Material Research assists and stimulates industry through research to improve understanding of the basic properties of materials, develop data on the bulk properties of materials, and devise measurement techniques for determining these properties.

This Institute's efforts are in technical fields such as Standard Reference Materials, Analytical Chemistry, Polymers, Metallurgy, Inorganic Materials and Physical Chemistry.

The Institute of Applied Technology develops criteria for the evaluation of the performance of technological products and services, provides specialized information services to meet the needs of the Nation's industrial community, and provides a variety of specialized technical services for other Federal Agencies.

This Institute deals with Engineering Standards, Weights and Measures, Invention and Innovation, Vehicle Systems Research, Product Evaluation, Building Research, Electronic Technology, Technical Analysis, and Measurement Engineering.

The Center for Radiation Research conducts programs important to the Nation in basic standards, materials research, and applied technology utilizing radiation and nuclear scientific techniques.

The Center for Computer Science and Technology provides technical services to Government agencies and conducts research in the field of automatic data processing, computer language, and systems design.

The Office for Information Programs promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal government and promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System.

2

The National Bureau of Standards is continually working on means to define standards of length, mass, time and temperature in terms of natural constants which can be reproduced anywhere with high fidelity by anyone with access to specified technical facilities. NBS cooperates with the National Standards Laboratories of many nations and the International Bureau of Weights and Measures through committee activities.

A. G. Strang
Chief Engineering Metrology Section
Metrology Division NBS
August 4, 1969

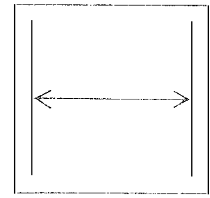
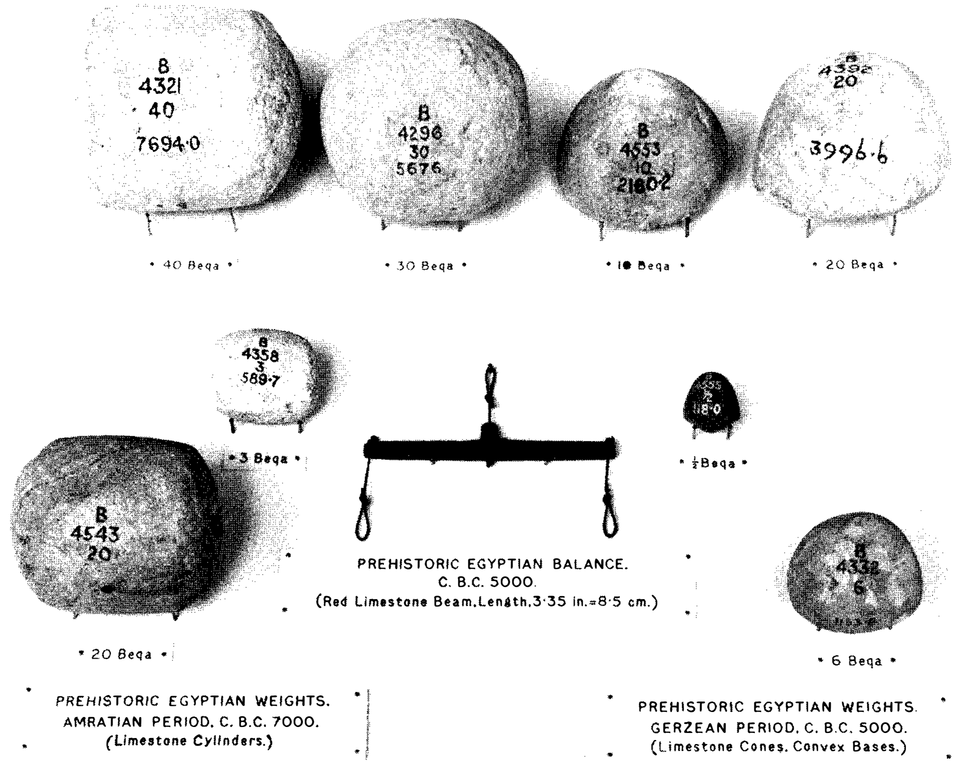


FIG. 141—*Standards of length and weight became necessary as civilizations emerged. The oldest of these prehistoric Egyptian weight-measures dates to 7000 B.C.*
Courtesy of Science Museum, London.
British Crown Copyright.



1. History of Official Length Standards

Most measurements in the broad realm of *dimensional metrology* are self-proving or "natural"; they require no reference to outside authority. By way of example, a block of granite can be made flat, or the divisions of a sundial placed as accurately as tools, skills, and the ability to measure allow. While measuring devices may become more sophisticated, principles of measurement remain the same.

With the measurement of length, however, such is not the case. Some authority must determine what constitutes an inch or a millimeter. Since the length of an object varies with its temperature, the same authority must further decide at what temperature it is to be measured. A standard of length, in other words, is arbitrarily derived.

The origin of the present standards of length and weight dates back thousands of years, Fig. 141. It was not until 1960, when light waves were chosen as the fundamental standard, that the unit of length was finally related to some unchanging phenomenon in nature. This standard of measurement realizes a long sought-after goal of metrologists—the agreement on an immutable standard.

To understand the complexity of the length-measuring problem, it is valuable to re-trace how standards evolved.

IN THE BEGINNING

In his earliest attempts to relate the sizes of various objects about him, man compared them to the limbs of his body. Such a comparison was logical because these "units" could be easily understood by a fellow-human. Moreover, they provided an adequate and readily available means of measurement.

Not until civilization progressed in technology and men became more interdependent did it become apparent that such

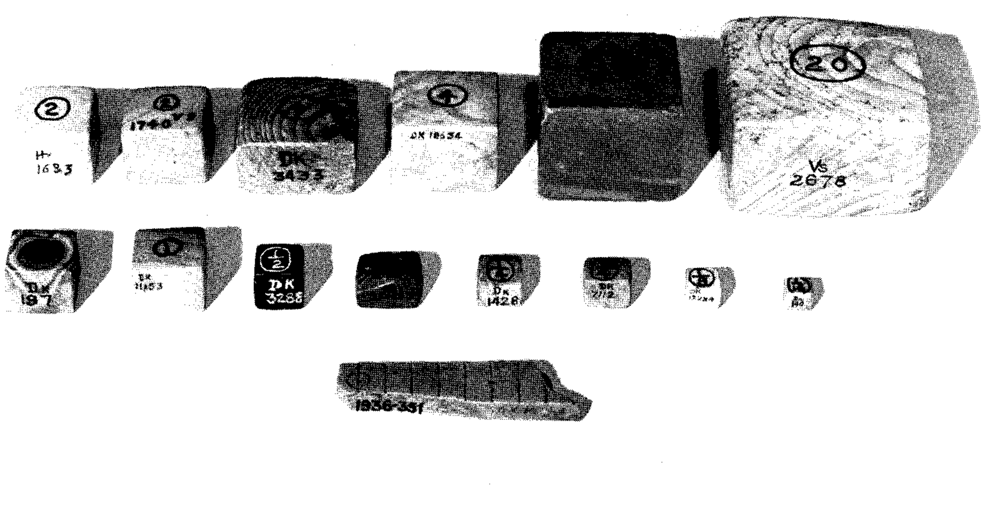


FIG. 142—*Mohenjodaro stone weights and fragments which have been preserved are several thousand years old. The Indus civilization, while highly developed, was completely destroyed and apparently had little influence on subsequent cultures.*
Courtesy of Science Museum, London.
British Crown Copyright.

FIG. 143—*Sacred importance was attached to standards of length and weight. Shown is a decapitated sculpture of Gudea, Governor of Lagash, circa 2175 B.C. On his lap is a tablet with the graduated rule.*
Courtesy of the Louvre, Cliché des Musées Nationaux.

"units" were inadequate. In their place, physical duplicates were made which were multiples and sub-multiples of these units. These standards of measurement were often stored in a temple or other safe place, where official copies originated.

Early cultures felt the need for standardization of measurements of length, weight, and volume. Although measuring systems most often developed independently, there were also many cultural cross-influences. A striking example is the agreement between the ancient Hebraic cubit, 17.60 inches [447 mm] and the Egyptian short cubit, 17.64 inches [448.05 mm].

Sarton observes in *A History of Science*: "The outstanding cultural patterns coalesced in the valleys of great rivers in northern subtropical regions . . . . Those rivers are the Nile, the Euphrates and the Tigris, the Indus and the Ganges, the Hwang Ho and the Yangtze, and perhaps also the Menam and the Mekong."*

Actually, the ancient Chinese and Indus cultures seem to have had little influence on our own.

Professor Harkness lists the Babylonian or Chaldean system of weights and measures as the most ancient. He believes it is from this culture that the Egyptians derived their system of weights and measures.** Perry states that the earliest Egyptian weight was taken from the prehistoric Indus civilization.*** Early Indus stone weights are shown in Fig. 142.

It is impossible to trace with any degree of certainty the origin of standards of weights and measures, or for that matter the exact beginnings of civilizations. It is certain, though, that each civilization at an early date developed systems of weights and measures to which almost sacred importance was attached, Fig. 143.

Historians may disagree as to which is the earliest, but it appears Egypt passed on the strongest heritage to western culture.

*George A. Sarton, *A History of Science*, p. 19.

**William Harkness, "The Progress of Science as Exemplified in the Art of Weighing and Measuring." *Smithsonian Institution Report*, July 1888, p. 616.

***John Perry, *The Story of Standards*, p. 24.

FIG. 144—*In Egypt, land survey for purposes of taxation and administration led to measuring and counting.*

Courtesy Metropolitan Museum of Art, New York. Photograph used with the permission of Mr. William Vandivert.

THE EGYPTIAN HERITAGE

Egypt was most favored geographically in that it had a long, navigable waterway—the Nile. This great river's periodic overflowing fertilized the Nile Valley enabling the establishment in Egypt of a stable agrarian-based culture. The shifting bed of the Nile stimulated advanced technology in land survey, enabling rulers to better administer and tax their domain. This advancement, in turn, led to measuring and counting, which together form the keystone of engineering, Fig. 144.

The high level of Egyptian accomplishment was made possible by a continuous culture of several thousand years. Unfortunately most of Egypt's treasures and monuments were lost, having been plundered by a succession of conquerors—the Greeks, Romans, Arabs, French, British, and the ancient Egyptians themselves. Enough remains, however, to make the assessment that it was a highly developed civilization.

Of the remaining few, the most commanding monument to Egyptian ingenuity is the Great Pyramid built for Khufu (Cheops) of the fourth dynasty. It measured about 775 feet [236.22 meters] on one side alone, and stood nearly 480 feet [146.30 meters] high. The mean error in the length of its sides was only 0.6 inch [15 mm]; in its angle it fell short of being a perfect square by only 12 seconds, Fig. 145.

Egyptian architectural prowess is equally evidenced by the obelisk. Though many of the great granite obelisks were transported to other countries of the world, one at Aswan remains because it developed a fissure and was never fully quarried. If extraction and removal were possible, it would measure 137 feet [41.75 meters] in height and weigh 1,168 short tons [1059.6 metric tons]. The harnessing of upwards of 30,000 men at a time to fashion and erect such monuments was surely one

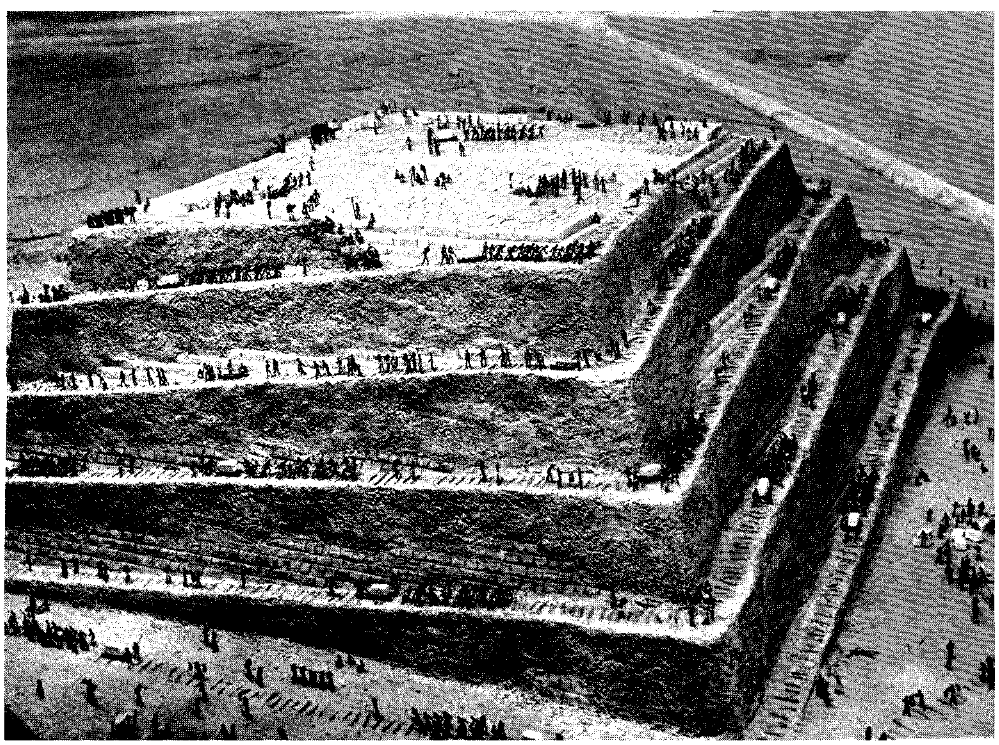
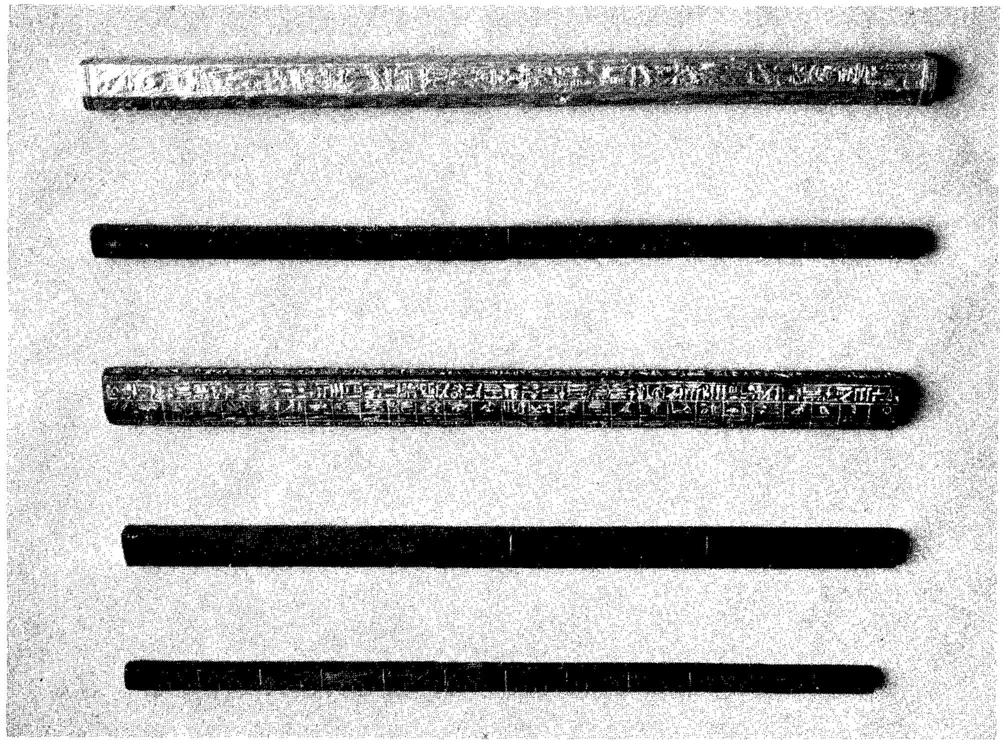


FIG. 145—*Construction of huge structures, such as pyramids 480 feet high [146.3 meters], presented immense problems in logistics which could not have been surmounted without well-established standards.*

Courtesy of the Museum of Science, Boston, Mass.

FIG. 146—*The cubit was an important unit of measure in the ancient world. Official physical representatives of the cubit were made and stored in places of safe-keeping. The five Egyptian cubits shown are of different materials.*
Courtesy *La Rivista (RIV)*, May, 1961.



of immense logistics, requiring organization, engineering and well-established standards of measurement.

Bothmer* emphasizes the influence of Egypt on Greece and Rome. He states that much as "imported" goods are highly prized today, so too whatever came from Egypt was especially valued. The Egyptians had an undeniable sense of the order of things, a sense assimilated and in turn disseminated by the Greeks. The Romans, in turn, acquired this faculty and passed it on to the civilized world. The lasting influence of Egyptian thinking is very apparent in the matter of standards. To cite an example, the length of the ancient Egyptian foot, 11.78 inches [299.2 mm] does not differ appreciably from that of the present foot [304.8 mm].

Authorities disagree as to which unit of length was the most commonly used. Assuredly, the "cubit" (tip of finger to bent elbow) was a basic unit of measurement. Others maintain that the fathom (length of outstretched arms) was more important. Recent comparisons of 5 Egyptian cubits, using modern techniques, lead Professor Scamuzzi of Turin to conclude that the most basic unit was that of the *digit* (much as the inch is to the English system and the millimeter is to the metric). He feels that all other units of measurement, such as the cubit, were convenient multiples of the digit.**

The more ancient Short Cubit was composed of 24 digits, approximately .736 inch [18.7 mm] each. The number 24 was apparently chosen because it could be conveniently divided. Later, the Royal Cubit came into use, probably by adding 4 digits. The Royal Cubit, composed of 28 digits, was no longer mathematically convenient. Later dynasties wished to preserve its length, however, so that the Royal Cubit was restored to its 24 digit subdivision, making a new long digit of .858 inch [21.8 mm].

Of the five cubits in the Turin Museum, Fig. 146, two are of wood (their lengths, it should be noted, are suspect since they undoubtedly underwent considerable shrinkage); one is wood-core and gold-covered, and another is of basalt. Still another is bronze.

Most interesting of the 5 cubits is specimen No. 3. Inscribed on this cubit is the digit, its multiples and sub-multiples, and both the Short and Royal Cubit, showing the transition. A close-up of this specimen is shown in Fig. 147.

BABYLONIAN CONTRIBUTION

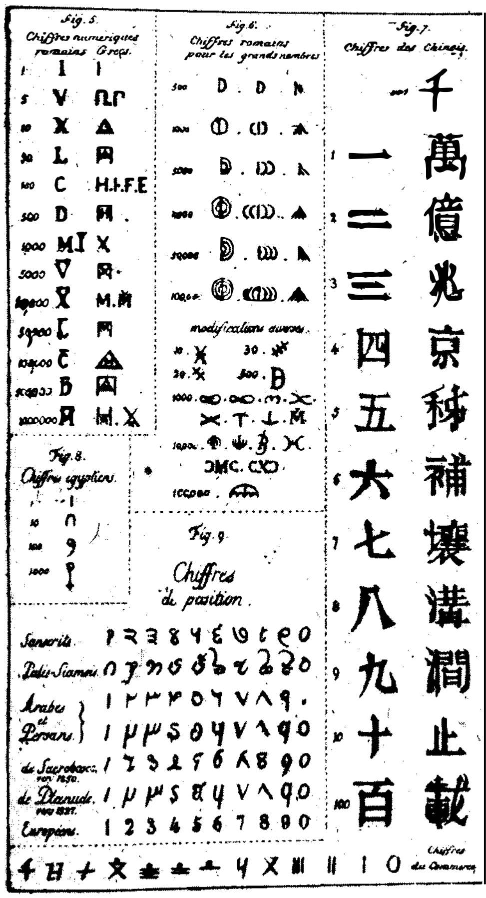
The Babylonians, successors to the Egyptians, were primarily mathematicians and men of reflection. Contrary to popular

*Author's conversation with Bernard Bothmer, Egyptologist, Brooklyn Museum, Brooklyn, New York, May 28, 1968.

**Ernesto Scamuzzi, "Historical Comments about Some Cubits Preserved in the Egyptian Museum of Turin," *Technical Journal of RIV* (Turin), May, 1961, p. 20.

FIG. 147—*A close-up of an inscribed cubit. The space between each line represents a "digit." The digit was a convenient unit of length, much as the millimeter is in the metric system and the inch is in the English system.*
Courtesy *La Rivista (RIV)*, May, 1961.

FIG. 148—*Marks for weights and measures of various civilizations.*
Courtesy of Science Museum, London.



opinion, they were not such dedicated observers and recorders of natural phenomenon. Consequently, they were less adept at the art of astronomy than is often supposed. Their prime contribution was the addition of numerical foundations to the existing store of knowledge. Attributed to them is the sexagesimal system of numbers which has survived to this day. The system is still used for navigation and the recording of time.

The number 6 and its multiples were also found to have special mathematical relationships, especially with regard to angles. Our present system (see "Dividing the Circle," page 205) is largely of Babylonian derivation.

THE ANCIENTS AND PROPORTION

The Greeks, to whom the culture of Egypt next passed, had an acute sense of beauty and proportion. They attained a level of symmetrical sophistication unparalleled in history—best expressed in their statuary and architecture.

The Romans, who rose to world prominence after the Greeks, embraced and absorbed Greek art, architecture and sense of proportion, Figs. 148 & 149.

The ancients, particularly the Greeks, were keenly aware of the beauty, symmetry, and proportion of the human body. They were equally aware of the body's various numerical proportions.

At first, the numbers 5 and 10 which relate to the fingers, were regarded as ideal. Later it was felt that 6 and 10 had the same attributes of perfection. We see the inter-relationship of these numbers and their combination 16 to various parts of the body. For example, the foot is the 6th part of a man's height; the cubit consists of 6 palms and 24 fingers; the foot has 16 fingers, etc.

It is not surprising, therefore, that the ancients considered these proportions to be appropriate for purposes of design. Indeed, they can be noted today in surviving Greek and Roman art and architecture.

Vitruvius (circa 77 A.D.), a Roman, wrote on the topic of designing temples, Fig. 150:

"For if a man lies on his back with hands and feet outspread, and the center of the circle is placed on his navel, his fingers and toes will be touched by the circumference. . . . Moreover, they [the ancients] collected from the members of the human body the proportionate dimensions which appear necessary in all building operations, the finger or inch, the palm, the foot, the cubit."*

This does not mean that measurements were drawn directly from the human body; body dimensions were used only as models. As might be expected, the actual lengths of the units went through many mutations and modifications throughout the centuries —as described with the Egyptian cubit.

ROMAN EMPIRE UNIFIED STANDARDS

Along with the expansion of the Roman Empire went its culture, and, as might be expected, its disciplines governing measurement.

The Romans divided the Greek Olympic Cubit into 12 thumb-widths which were called "unciae" or inches.

As conquerors, the Romans were concerned with the longer distances and established the "mille", or 1000 double steps, as a unit of measurement. Since Britain was ruled by Rome for nearly 400 years, Roman influence pervaded for some time.

Our present numerical system, a vast improvement over the Roman system of numbers, appeared at a later date as a contribution of the Arab culture. The system was probably derived from the Hindus.

*Items 17, 23–24 of Vitruvius' "De Architectura" (see *Technological Studies in Ancient Metrology* by Eivind Lorenzen, p. 23).
It is interesting to note that Vitruvius was highly influenced by Hellenic architecture. His technique was studied by Michelangelo, Da Vinci and others.

FIG. 149—*Romano-Greek marble tablet is inscribed with the Olympic foot measure (300–500 A.D.). The Romans absorbed much of the Greek culture. Roman influence spread throughout the entire civilized world.*
Courtesy of Science Museum, London. British Crown Copyright.

Although the cubit and other early units of measurement have long since fallen into disuse, such units as the "foot" nearly as early in origin, and the "inch" have remained in use. They are still the standard units of length in English-speaking countries.

The decline of the Roman Empire ended the monolithic unity it had given the civilized world. The warring kingdoms that followed only fed on the remnants of the Roman order. Hardly any progress in the standardization of units can be noted. Up to the beginning of the sixteenth century, standards seem to have been forgotten. Measurements frequently reverted to the human body. Only France and England had what could be called official standards. Germany had no true standard until its adoption of the metric system in 1870.

The definition of a particular unit of length was frequently left to the whim of ruling monarchs. Some of the more comical examples are: A "yard" equals the distance from the end of the King's nose to the tip of his outstretched hand;* three grains of barley, dry and round, make an inch;** a "rod" is equal to the combined left feet of the first sixteen men out of church on a particular Sunday morning.***

EARLY STANDARDS IN FRANCE

The first evidence of a French national system of measurements is found during the reign of Charlemagne (768–814). Reproductions were made of the *Pied de Roi*, or royal foot, and divided into 12 inches (*pouce*) after the Roman system. The earliest record of a standard of length is the *Toise du Grand Chatelet* of 1668, said to represent one-half the distance (12 feet) [3.657 meters] between the walls of the inner gate of the Louvre. The genealogy of

*Definition attributed to King Henry I (1068–1135).
**Definition attributed to Edward I (1305).
***Germany, 16th Century.

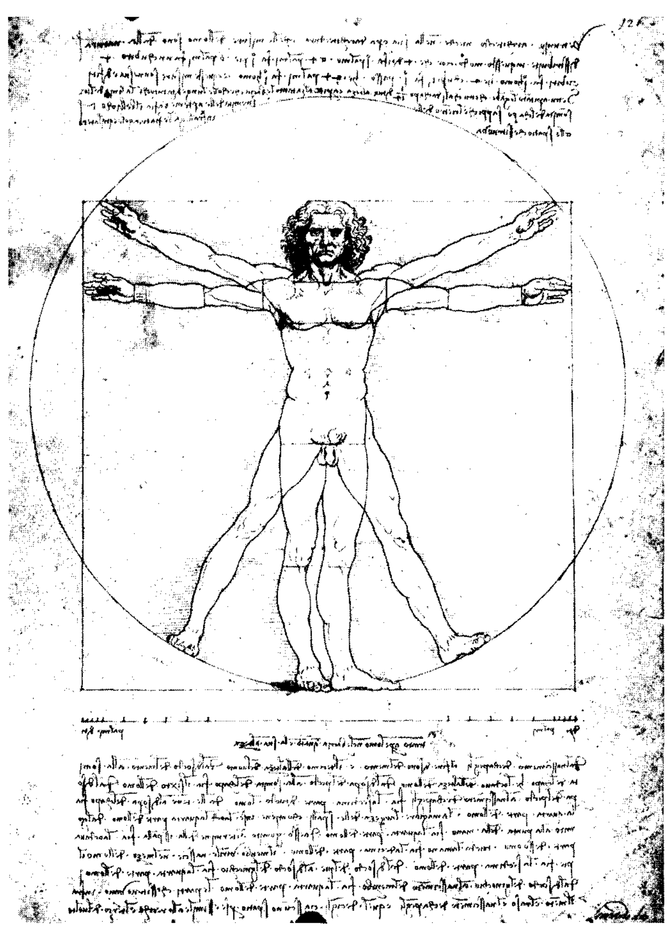


FIG. 150—*The human body was used as a model by the ancients for measuring and proportion. Numerical proportions found in the human form were thought most perfect and were applied to all endeavors, including engineering, art and architecture.*

Da Vinci, who sketched this canon of proportions about 1500 A.D., adhered to a description by Vitruvius 1400 years earlier.
Courtesy of the Science Museum, Boston, Mass.

the "toise", however, precedes this by a thousand years.

EARLY STANDARDS IN ENGLAND

English standards can be traced as far back as ancient Egypt and Mesopotamia. Roman influence had an impact on England in both a direct and indirect sense: directly, through Roman occupation, and indirectly through the Saxon invaders who used the Roman system of weights and measures. The Saxons brought to England such units as the "foot," or one-half cubit, in 410 A.D.

The foot is recorded by the Romans to have been in official use in lower Germany by 12 B.C.

Succeeding sovereigns, William I (1066) for example, seem to have maintained existing Anglo-Saxon weights and measures.

There are allusions to actual physical standards in England as early as the reign of King Edgar (958–975). Hallock suggests that these were the earliest authoritative Anglo-Saxon standards.* They were apparently housed in places of safekeeping where copies were dispensed. In the absence of clear, enforcing authority, it is doubtful that these standards were widely used. Standardization of units finally occurred, however, with the unification of the country. The "Yard of King Henry" (1496) a bronze end bar, might be considered the first official standard of length. The "Queen Elizabeth Yard," another kind of end bar, replaced the "Yard of King Henry" in 1588, and was in use until 1824.

Commenting on the crudity of the "Queen Elizabeth Yard" as a standard, Francis Baily, a metrologist, stated in 1834: "This curious instrument, of which it is impossible, at the present day, to speak too much in derision or contempt. A common kitchen poker, filed at the ends in the rudest manner by the most bungling workman, would make as good a standard. It has been broken asunder, and the two pieces have been dovetailed together, but so badly that the joint is nearly as loose as a pair of tongs. The date of this fracture I could not ascertain, it having occurred beyond the memory or knowledge of any of the officers of the Exchequer." Baily goes on to say, incredulously, that copies of this standard were in circulation throughout Europe and America as recently as ten years before, and were certified as *true copies of the English standard.**

*William Hallock and Herbert T. Wade, *Outline of Evolution of Weights and Measures and the Metric System,* p. 38.

In 1824, England decreed the "Yard of 1760," a line standard,** to be the official standard of length measurement. The primary reason this standard was accepted is apparently due to a claim by its originator, Bird. He maintained that it had been derived from a pendulum beating seconds of mean time at London latitude in a vacuum and at sea level. Because it was a natural standard, it could be reproduced according to a specific formula if destroyed. This standard of measurement represented the desire to equate length with some unchanging magnitude in nature.

THE METRIC SYSTEM

The quest for a "natural" standard began about the same time in France. In the 1790's, the "meter", one element of an integrated, decimalized system of mass, length and temperature, was introduced. This system of measurement came to be known as the metric system.

A scientific approach to measurement was evolving. Galileo had discovered the law of the pendulum in 1581, and by 1665 Huyghens devised a pendulum for recording time. In 1671, Picard suggested using the pendulum's beat as a recoverable standard of length. A length standard derived from a seconds pendulum, however, was disdained by the French because they recognized that gravity was not constant geographically. Instead, the meter was determined by years of painstaking surveying and calculation to be equivalent to 1/10,000,000th the length of the north polar quadrant of the Paris meridian (the distance between Dunkirk and Barcelona). A special platinum end standard, known as the "Metre des Archives," Figs. 151, 152, was constructed as the physical embodiment of this mathematical relationship.

*William Harkness, "The Progress of Science as Exemplified in the Art of Weighing and Measuring," *Smithsonian Institution Report,* July, 1888, p. 601.

**This standard is actually composed of dots or points which show wear from contact with a beam compass.

While this was an heroic scientific undertaking, subsequent geodetic calculations proved the meter slightly in error. At any rate, it became an impractical basis of comparison, since two bars could be equated with a greater degree of precision than they could be compared to the circumference of the earth. For this reason, the Metre des Archives itself came to be regarded as having primary status.

Attempts to enforce the metric system in France caused confusion, even civil disorder. As a result, the system was not revived for many years.

LATER ENGLISH STANDARDS

England's "natural" standard, the Yard of 1760, underwent a tortuous course similar to that of the French Metre des Archives. It was destroyed in a fire in 1834, and could not be reconstructed from Bird's formula which was found to be based on erroneous calculations.

A more practical course was chosen. Several copies of the Yard of 1760 (notably those belonging to Troughton and Simms, London instrument maker) were compared, from which five new line standards were constructed. Using a special alloy known as "Baily's Bronze," two wells, 36 inches [914.4 mm] on center, were sunk in the top surface of the bar. A gold plug

FIG. 151—*The "Metre des Archives" (1799) was a platinum end standard whose length was calculated to have an exact mathematical relationship to the circumference of the earth.*
Courtesy of the BIPM.

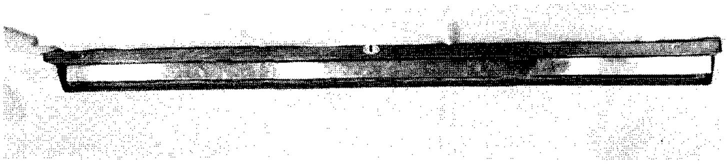


FIG. 152—*Plaque appearing on the container cover of the Metre des Archives.*
Courtesy of the BIPM.

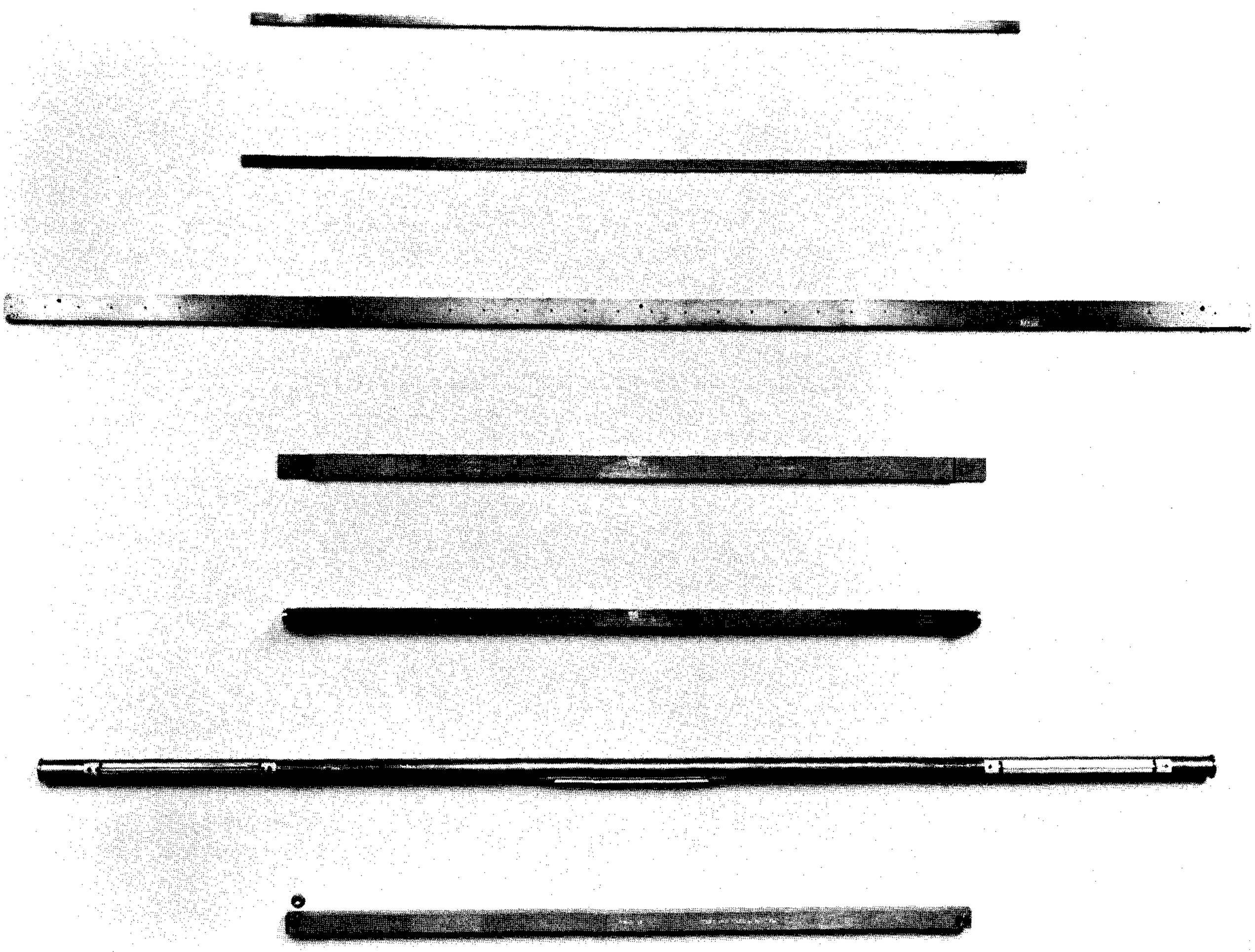
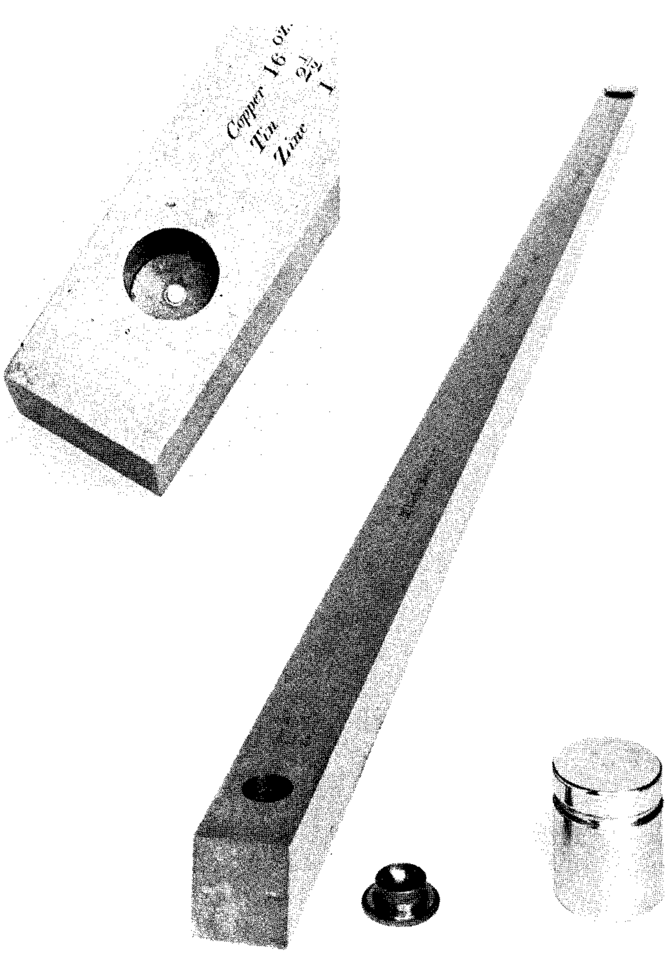


FIG. 153—*Baily's line yard along with other official Imperial length standards.*
Courtesy of Science Museum, London.

FIG. 154—*The Imperial Standard Pound and Yard are housed at the Board of Trade, London.*
Courtesy of Science Museum, London.
British Crown Copyright.



was inserted into each of these wells to a depth where the upper surface of the plugs coincided with the neutral bending plane of the bar. The distance between a finely scribed target line on the upper face of each plug of bar No. 1, at 62° F [16.67° C], was defined as the Imperial Standard Yard. Fig. 153 shows Baily's line yard along with other Imperial length standards.

In 1855, Baily's line yard became the official standard and remained so until the Weights and Measures Act of 1963. Interestingly, the four other bars, "Parliamentary copies," all differing in length, were each inscribed with the exact temperature at which they would equal the length of the Imperial Yard when at 62° F [16.67° C], rather than their lengths when at 62° F.

Though the Imperial Yard had undergone a secular change in length of .0002 inches [0.005 mm], suspected by the National Physical Laboratory as early as 1932 and confirmed in 1947, this was, nevertheless, by act of Parliament, the Standard of the Realm to which all working standards had to be calibrated, Fig. 154.

Metric standards of length were nevertheless maintained, Fig. 155.

EARLY STANDARDS IN AMERICA

In his first message to Congress, January 8, 1790, President Washington stated: "Uniformity in the currency, weights and measures of the United States is a subject of great importance, and will, I am persuaded, be duly attended to."*

Curiously, though the authority to fix weights and measures was constitutionally relegated to Congress, that body has historically failed to legislate.

Thomas Jefferson's proposal in 1790 when he was Secretary of State, to base the American units on a decimal system, the length standard of which would be derived

*William Hallock and Herbert T. Wade, *Outline of Evolution of Weights and Measures and the Metric System*, p. 111.

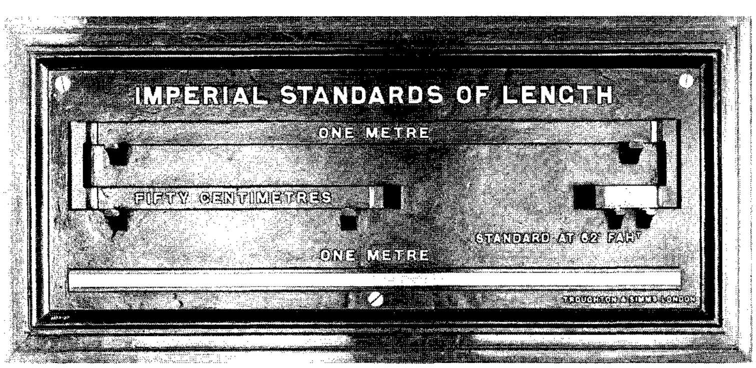


FIG. 155—*Even while England was officially using the "inch" system of measure, metric standards of length were maintained.*
Courtesy of Science Museum, London.
British Crown Copyright.

from a seconds pendulum, reflected the desire of the scientific community in the United States for some absolute standard. No official standard existed in post-revolutionary America. Consequently, standards in use seldom agreed.

In 1798, Eli Whitney was given a contract by the government to produce a number of muskets, the components of which would be interchangeable. Since this probably was the earliest attempt at manufacturing to *dimensions*, the question arose as to "whose dimensions?" To be sure, Whitney's own parts were perfectly interchangeable; yet components of the supposed same length made by another manufacturer, Smith, would not fit any of Whitney's muskets. Why? Whitney and Smith were not using the same scale (see page 146).

The United States was not to have what could be called a legal standard of measurement for some 60 years. Firstly, the American system of weights and measures was largely of English derivation, and unfriendly relations continued with England for about 40 years after the War of Independence. Secondly, the newly-emerged nation was reluctant to adopt a sweeping change of the kind that caused civil disorder in France when it adopted the metric system.

In response to a request by Congress four years earlier, a comprehensive report on the subject of weights and measures was issued by John Quincy Adams in 1821, then Secretary of State. While admiring the "uniformity, precision, and "significancy"* of the French metric system, Adams regretted its lack of relationship to any convenient unit of the human body, and overemphasis of decimal values. He recommended to Congress adherence to the English system with "no innovation",** and even urged closer use of it by acquiring a copy of the Standard Yard from the Exchequer of Great Britain.*

*Charles Davies, *The Metric System Considered with Reference to its Introduction to the United States* p. 229.

***Ibid.*, p. 300.

In 1830, Congress having failed to act, Ferdinand Hassler, a Swiss immigrant-engineer and the first Superintendent of Coast and Geodetic Survey, proceeded to establish his own standard. The length standard he had secured in 1814 was an 82-inch [2082 mm] scale prepared by Troughton of England, based on the Yard of 1588, the same as that scorned by Baily. The distance between the 27th and 63rd inch marks on the scale (seemingly most exact) were chosen to represent a yard.

As Perry observes: Setting up shop in an arsenal, Hassler began making copies of his standard, thenceforth known as the Troughton Scale, and issuing them to the several states and customs houses, without the least authority from Congress. When Congress became aware of this usurpation of its power, it quickly passed a resolution —urging Hassler to hurry!**

In 1856, the U.S. received, with presidential ceremony, Bronze No. 11, a yard standard, which had been calibrated to the Imperial Yard of England. Although Bronze No. 11 replaced the Troughton Scale as a national standard, it, too, was never authorized as an official standard.

**Ibid.*, p. 303.

**John Perry, *The Story of Standards*, p. 70.

INTERNATIONAL STANDARD

On May 20, 1875, an International Metric Convention was held in Paris. Attending nations agreed to jointly sponsor an International Bureau of Weights and Measures (BIPM) to be located at Sèvres, France, Fig. 156.

Since the time of its inception, the BIPM has expanded its scope to include numerous projects such as nuclear, time, weight, electrical, and gravity ("G"). The total staff of the BIPM is unbelievably small, with only 40 members. Its small organization, however, belies its tremendous contribution to the advancement of science and metrology. They have acted as coordinators and impartial arbitrators. In addition, they have been influential in such critical matters as the choice of light wave emissions of krypton 86 as the basis for a length standard.*

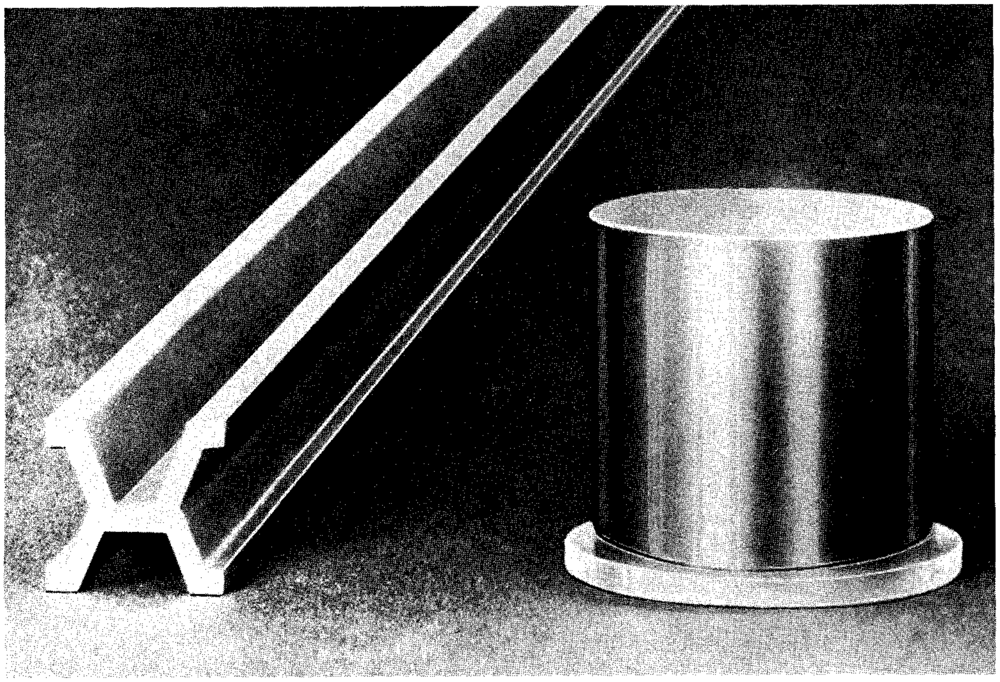
At the International Metric Convention, it was also agreed that the International Bureau would have the responsibility of preparing a special set of meter standards, Fig. 157. One of these bars, the closest in length to the Metre des Archives, was selected as the "International Prototype Meter." This standard was chosen without reference to measurements of the earth.

*Author's conversation with P. Carre at BIPM, October 4, 1968.

FIG. 156—*Le Bureau International des Poids et Mesures (BIPM), sponsored by many nations of the world, is located in international territory in Sèvres, France.*
Courtesy of the BIPM.

FIG. 157—*The International Prototype Meter and Kilogram were agreed upon as the official standards of length and mass for those nations attending the International Metric Convention, 1875. The Prototype Meter, a platinum-iridium line-standard of a "Tresca" design, was the official standard of length until replaced in 1960 by the light wave emissions of krypton 86.*

Courtesy of the BIPM.



The bar, made of 90% platinum, 10% iridium in an "X" or "Tresca" design, has two finely scribed lines set apart near its ends on a highly polished surface at its neutral bending plane. The separation of these lines was defined as one meter at 0° C. [32° F.], the temperature of melting ice. The "line" standard was felt to be less susceptible to damage than the terminal surfaces of an end standard.*

As a result of the 1875 conference, the signatory countries received copies of the International Prototype Meter. The U.S., a participant, received National Prototype Meter No. 27.

The Mendenhall Order,** issued April 5, 1893 in Bulletin No. 26 of the U.S. Coast and Geodetic Survey,* stated that the length standards of the U.S. thereafter have as their authority National Prototype Meter No. 27. The value of the inch would be derived therefrom by the following relationship: that 1 inch equalled 25.4000508 millimeters.

While the U.S. customarily used the English system of unit, the relationship of the British Imperial Yard to the meter at that time was such that 1 inch equalled 25.399978 millimeters. In 1922 this relationship was revised so that 1 inch equalled 25.399956 millimeters.

In 1951, Canada re-defined her inch so that 1 inch equalled 25.4 millimeters (exactly). By so doing, it meant that there were three different "inches"—that of the U.S.A., England and Canada.**

As recently as 1959, the English-speaking nations of the world compromised on the Canadian inch with its simpler conversion factor. It was longer than the English inch by .0000017 inch [0.00004 mm] and shorter by .000002 inch [0.00005 mm] than the U.S. inch.

LIGHT WAVES —AN ABSOLUTE STANDARD

The desire for an immutable standard dates, undoubtedly, to antiquity. Today we can only speculate on the coincidence of the ancient Babylonian cubit being equal (within two parts in a thousand) to the length of the Babylonian seconds pendulum. Similar scientific motivations prompted Jefferson in 1790 to propose the use of the pendulum, for the English to temporarily adopt it as a standard in 1824, and for the French to relate the Metre des Archives to the circumference of the earth.

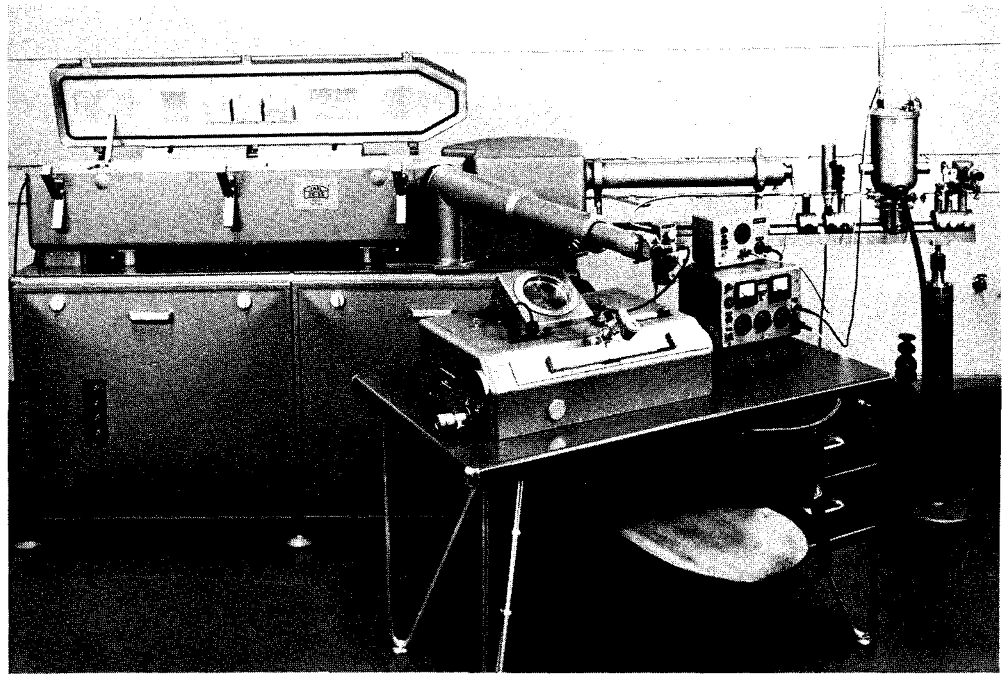
*T. R. Young of the National Bureau of Standards attributes reversion to a line standard to the fact that measuring microscopes were then being perfected. Their use made it possible to determine the position of the line with a great deal of precision. Author's conversation at NBS, November 26, 1968.

**It is evident from his language that Mendenhall was a strong advocate of the metric system, then almost completely sanctioned in continental Europe, and had no doubt that its adoption by the U.S.A. was imminent.

*The Office of Weights and Measures was given responsibility for standards shortly afterwards. In 1901, this became known as the National Bureau of Standards.

**Recently, both England and Australia have initiated plans to gradually convert from the English to the metric system of measure.

FIG. 158—*The "Koesters-Zeiss Interferometer" was in use at the Physikalisch-Technische Bundesanstalt (PTB) Germany by the early 1950's.*
Courtesy of the PTB.



Huyghens suggested the basic wave theory of light by 1665. The concept of using monochromatic light waves as a natural standard dates to 1827, when it was proposed by Babinet. Interferometric comparisons were made in 1892 by an American scientist, Michelson, and Benoit of the BIPM. They calculated the International Prototype Meter as being equivalent to 1,553,164.13 wavelengths of red cadmium light at 29.92 inches [760 mm] of atmospheric pressure at 15°C [59°F]. This calculation has since been found to be accurate to about one part in 10 million.

Benoit, Fabry and Perot in 1905–6 at the International Bureau also made interferometric comparisons of the meter and calculated one wavelength of the cadmium red line to be equal to 2534.825 x 10^{-8} inches [6438.4696 x 10^{-10} meters]. Perhaps on the basis of this work, the International Solar Union, in 1907, defined the angstrom, a unit used in expressing the length of light waves, as being:

1 wavelength of the cadmium red line = 6438.4696 angstroms.

So promising were the possibilities of light wave measurement that at an International Conference of Weights and Measures in 1927, it was proposed that the light wave emissions of red cadmium light be considered a "provisional" standard of length.

In the years that followed, pioneering work using the principles of interferometry was done by O'Donnell, of the United States, who had worked directly with Michelson; by Barrell, of England's NPL, and by Koesters and Engelhard, who developed the Koesters Interferometer, Fig. 158, which was in practical use at an early date in the Physikalisch-Technische Bundesanstalt (PTB), the German equivalent of the U.S. National Bureau of Standards.

At an International Convention in Paris, held on October 14, 1960, 32 states unanimously voted the new standard of length to be the light wave emissions of krypton 86. It was chosen over mercury 198 and cadmium because of its purity and clarity.

Fig. 159 shows Dr. E. Engelhard, who contributed greatly to the adoption of the krypton light source, with a krypton lamp.

The meter is today defined as ". . . . . equal to 1,650,763.73 wavelengths in a vacuum of the radiation corresponding to the transition between the levels:

$2p_{10}$–$5d_5$ of the krypton 86 atom."*

The immediate practical implications of this re-definition were small, but the long range effects from the viewpoint of the metrologist will be considerable. The In-

*The established relationship of the inch to the meter remains unaltered, but no longer refers ultimately to the International Prototype Meter. According to the U.S. National Bureau of Standards, one inch is now defined as "41,929.399 wavelengths in a vacuum of the reddish-orange radiation corresponding to the transition between levels $2p_{10}$–$5d_5$ of the unperturbed atom of krypton 86."

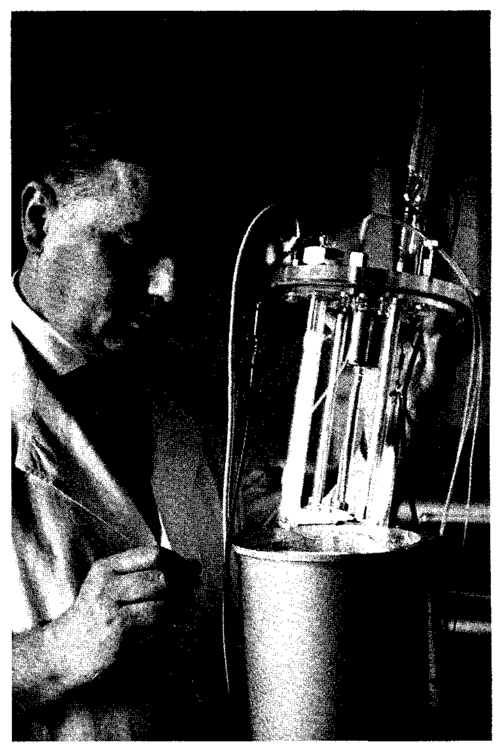
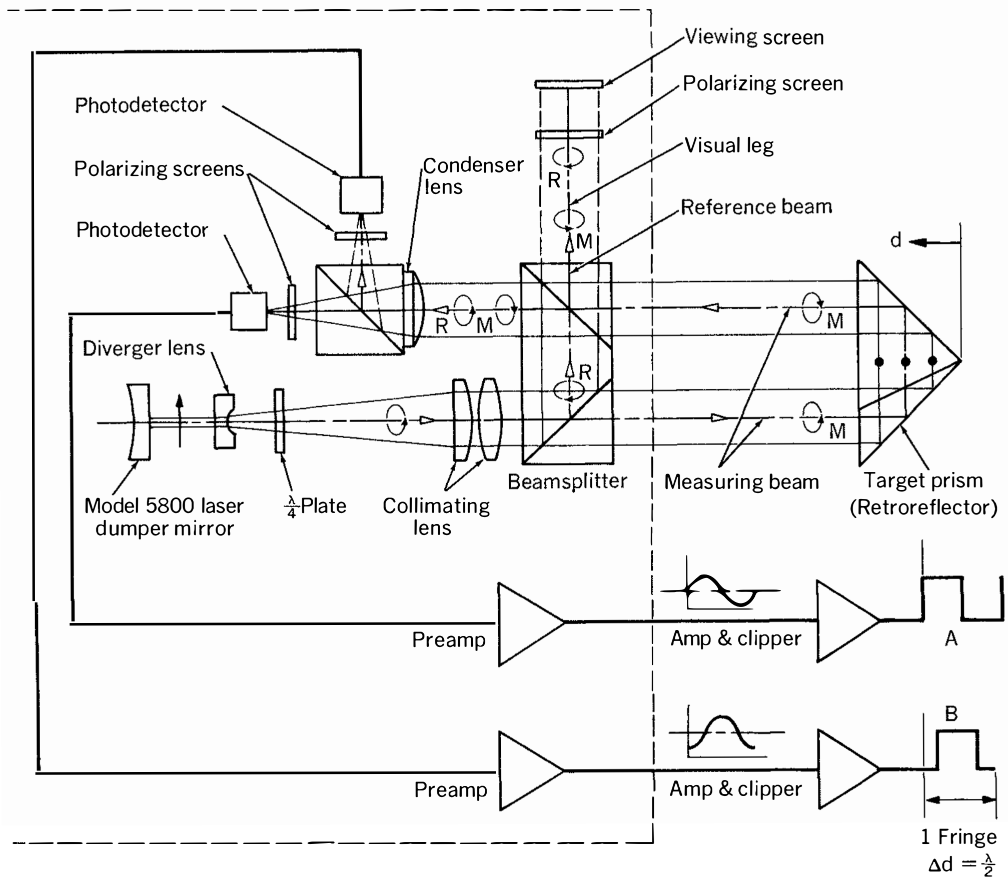


FIG. 159—*The krypton 86 lamp and its designer, Engelhard.*
Courtesy of the PTB.

FIG. 160—*Some metrologists feel that the present length standard (krypton 86) will eventually be replaced by the laser (light amplification by stimulated emission of radiation). The principle of the operation of a laser-interferometer is demonstrated in this schematic.* Courtesy Perkin-Elmer Corp.



ternational Prototype Meter of 1890, the old standard, while of exceptional quality and stability, could not be guaranteed immune to damage or secular change. Also, errors of determination when using a 100× microscope amounted to as much as 0.000008 (8 millionths) of an inch [0.0002 mm] or one part in 10 million (considerably less if a photo-electric microscope were used).

The present light wave standard has a potential accuracy of determination of perhaps 1 or 2 parts in 10^9. On the basis of observations made since 1892, metrologists are convinced that light waves are an unchanging magnitude.

Even so, the present standard may conceivably be replaced by the laser (Light Amplification by Stimulated Emission of Radiation), which some metrologists feel will make possible increased accuracies when measuring to greater lengths.

Fig. 160 shows a schematic view and Fig. 161 a cutaway view of a laser interferometer.

For measurement purposes, present techniques utilize the gas laser, and in particular, the helium-neon gas laser, married with a suitably designed interferometer. The great advantage of the gas laser compared to other light sources is its coherency and strongly defined fringe pattern over long

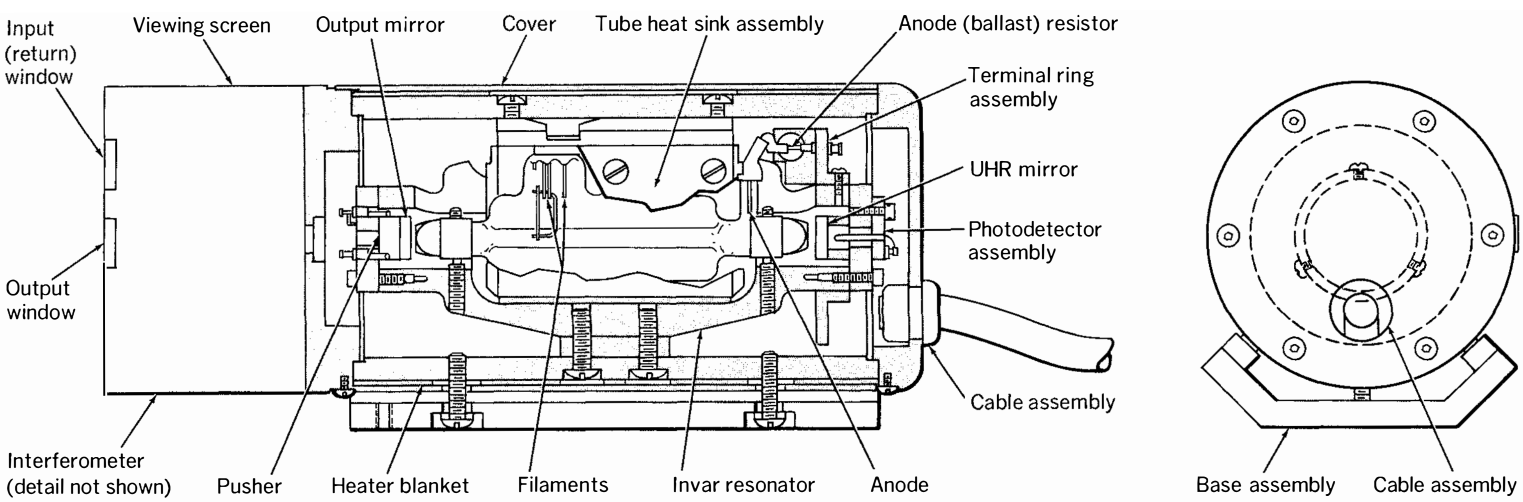


FIG. 161—*Cutaway of a laser interferometer.*
Courtesy Perkin-Elmer Corp.

FIG. 162—*The helium-neon gas laser has already been applied as a practical length-measuring tool, such as this "Automatic Scale Measuring Interferometer" of the National Physical Laboratory (NPL) in England.*
Courtesy NPL, British Crown Copyright.

optical paths. The gas laser is already established as a practical length-measuring tool in most of the national bureaus, Fig. 162.

The gas laser wave-length, however, is dependent—aside from the conditions of the environment—on the adjustment of the reflecting mirror "chamber", which acts as an optical resonator for the helium-neon atoms. While this may be adjusted very precisely by using piezoelectric or magnetostrictive mirror mounts, it means that the laser is not an "immutable" standard. In fact, it "drifts" over a period of time. For this reason, it is essential that it be periodically compared against the standard line of krypton 86. Engelhard suggests that it may be many years before a suitable gas laser can be developed for use as a primary standard. Theoretically, it could be used now if defined in terms of the infrared line; however, Engelhard feels that the line should be visible.*

Young and Strang of the NBS, on the other hand, maintain that since krypton is itself somewhat of an "artificially" derived standard, being an atomic isotope, there should be no objection to using an infrared spectrum laser under carefully specified conditions.**

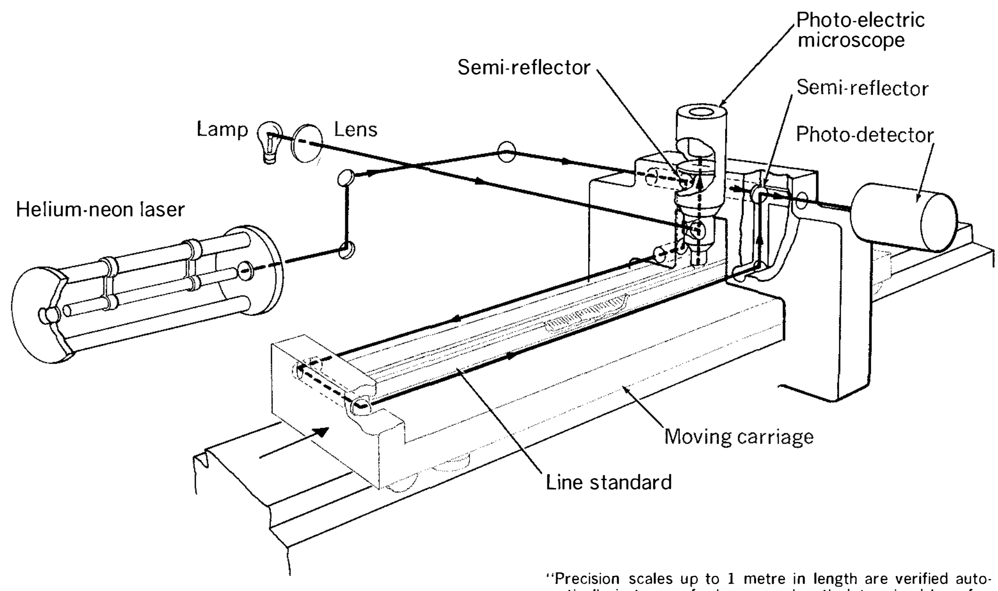
Reports indicate efforts by the NBS researchers to achieve stable laser wave-length output based on "saturated absorption in methane vapor of radiation from a 3.39 micrometer helium-neon laser."***

The specified equipment and environment required to perform length-measurements of *reference-caliber standards* by light wave method (measurements must be performed in a vacuum, or alternatively calculations made of the refractive index of the air surrounding the interferometer), means

*Author's conversation with Dr. E. Engelhard at PTB, October 2, 1968.

**Author's conversation with T. R. Young and Arthur Strang at NBS, November 26, 1968.

***See "Laser Technique Provides Precise Length Measurement," *Machine Design*, February 20, 1969.



"Precision scales up to 1 metre in length are verified automatically in terms of a laser wavelength determined by reference to the krypton-86 standard. The number of wavelengths in each scale interval is determined using a laser interferometer and electronic counting. The counts are punched onto paper tape which is processed by a computer to give a table of errors for the scale intervals."

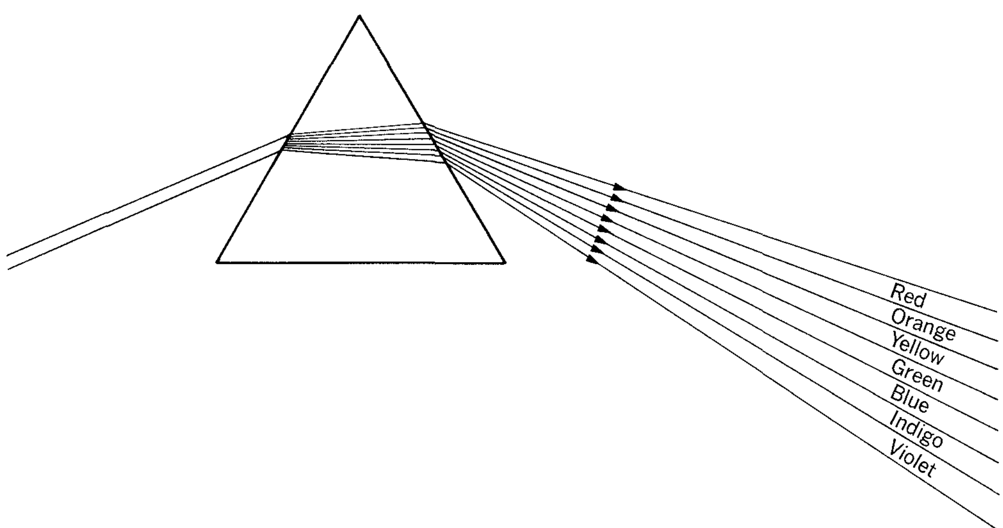
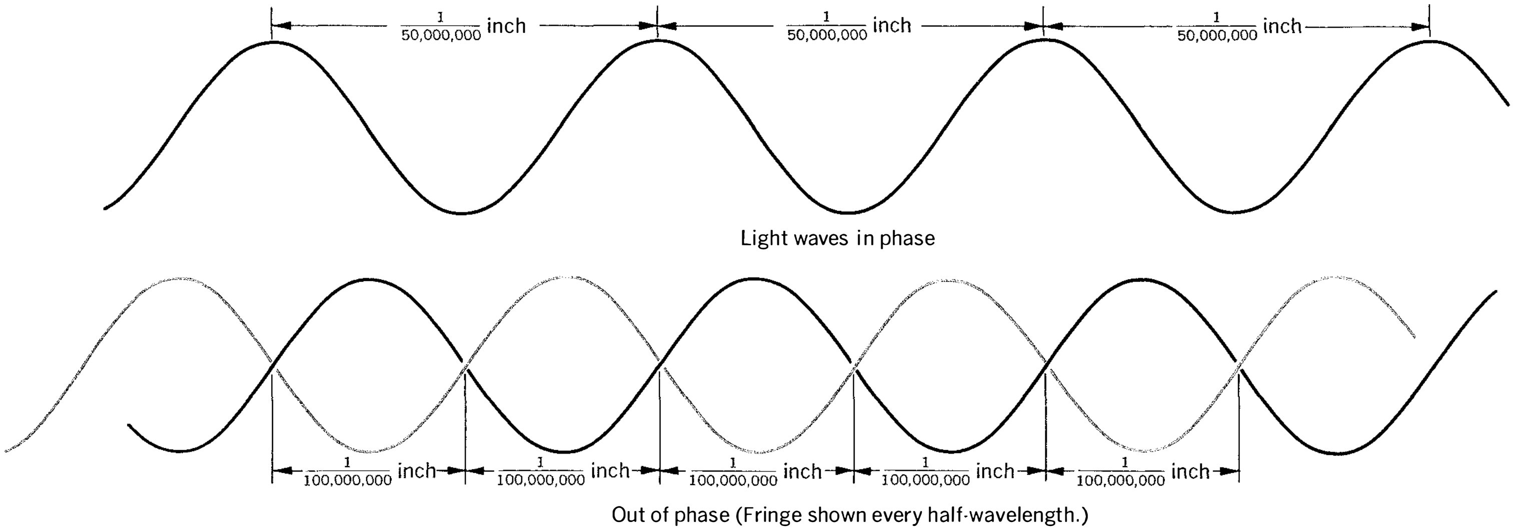
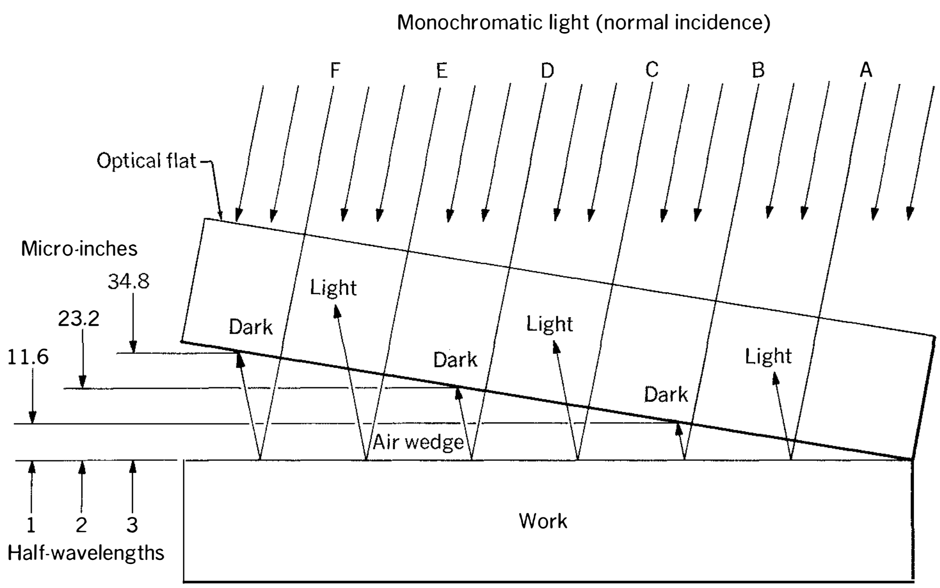


FIG. 163—*Ordinary white, or clear light, consists of a blend of different colored rays, made visible to the eye by passing light through a prism.*

FIG. 164—A widely-accepted theory maintains that light rays have undulations or waves (top). According to this theory, if a portion of a ray is made to travel a greater distance and then is returned to the same path, "interference fringes" are seen as the wave crest of one falls into the trough of another. An interference fringe thus has one-half the value of a light wave (lower).





"Diagram and caption presents a simplified mechanical analysis of WHAT happens when bands form between an optical flat and a reflective work piece under monochromatic light, for a basis of interpretation of work flatness using interference band patterns. (All academic-scientific details explaining the WHY of the band formation have been intentionally omitted.)

"Certain rays, B, D, F, etc., fall where wedge thicknesses are just one, two, three, etc., *half*-wavelengths, and are reflected partly from the flat and partly from the work. At reflection each of these particular rays interferes with itself, in accordance with optical laws, thus cancelling its own light and appearing from above as a narrow dark band. Since each dark band is like a contour line on a topographic map, it defines a path across the wedge wherever its thickness is exactly uniform. The dark bands are thus useful for precise measurement of work flatness. Other rays, A, C, E, etc., reflect their light upward without interference and appear as wide alternate bright bands."

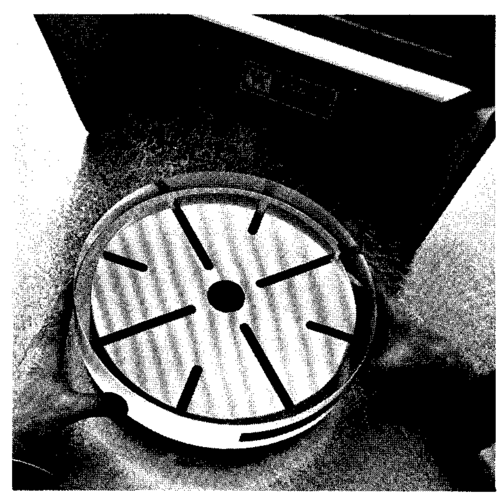


FIG. 165—*Interference band (or fringe) formation.*
Courtesy J. Kenneth Emery, Van Keuren Co.

FIG. 166—*The phenomenon of fringe formation caused by the interference of light waves can be applied to the measurement of length as well as to the measurement of surface flatness of a workpiece, such as this Spin Table top.*

that work in this direction will be carried on largely in the bureaus for some years to come.

Light Wave Measurement Described

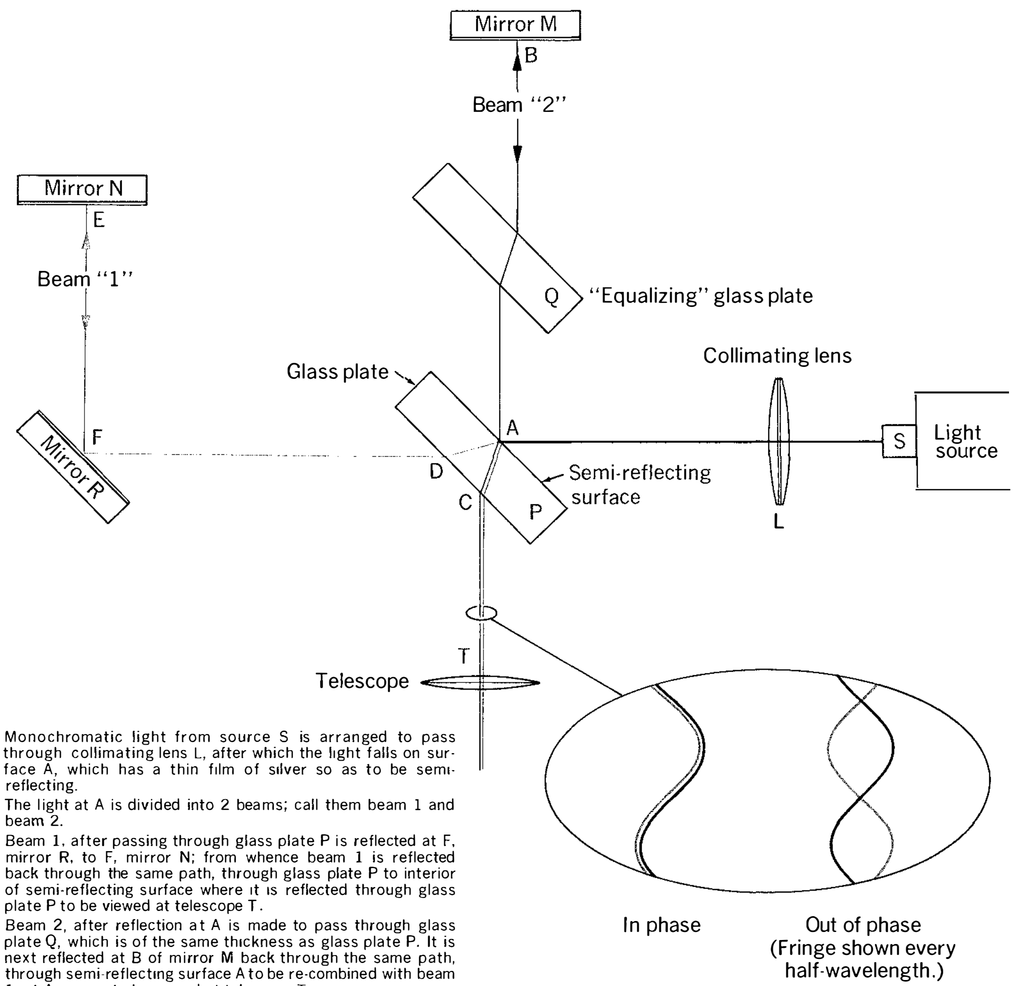
Ordinary white or clear light is a blend of varied colored rays, the latter sometimes made visible in nature as in a rainbow or a soap bubble, Fig. 163. Each of these rays has undulations, or "waves" of a specific length, such as 1/50,000 inch [one-half of a μm], from crest to crest. When a portion of a ray is made to travel a greater distance and then is returned to the same path, the phenomenon of "interference fringes" is seen as the wave crest of one falls into the trough of another, Fig. 164.

The phenomenon of fringe-formation caused by interference of light has long been applied as a practical method to measure surface flatness. Measurement is made by using an optical flat and light source. An explanation is included here as an aid to general understanding. In Fig. 165, an analysis of this process is given by J. Kenneth Emery. Fig. 166 shows a practical application, the inspection of a Spin-Table top for flatness through use of a monochromatic light source and a 12-inch [305 mm] master optical flat.

Once the value of a fringe is known, providing one is able to compute their number, or fractions, the metrologist has a convenient, versatile, and precise length-measuring tool. Since white light is a mixture of rays, it can be said to have only a mean wavelength; its use is therefore limited to extremely small distances. The slight difference in the accumulated length of the wave of each ray quickly becomes significant, obscuring the fringes.*

The solution is in the use of monochromatic (single color) light. The practical difficulty is in obtaining a light source which will emit monochromatic light of sufficient

*Fizeau used white light in the first accurate determinations of the coefficients of expansion of various materials—but over extremely small ranges.



Monochromatic light from source S is arranged to pass through collimating lens L, after which the light falls on surface A, which has a thin film of silver so as to be semi-reflecting.

The light at A is divided into 2 beams; call them beam 1 and beam 2.

Beam 1, after passing through glass plate P is reflected at F, mirror R, to F, mirror N; from whence beam 1 is reflected back through the same path, through glass plate P to interior of semi-reflecting surface where it is reflected through glass plate P to be viewed at telescope T.

Beam 2, after reflection at A is made to pass through glass plate Q, which is of the same thickness as glass plate P. It is next reflected at B of mirror M back through the same path, through semi-reflecting surface A to be re-combined with beam 1 at A, again to be viewed at telescope T.

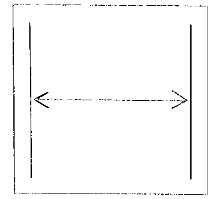
If, however, there is any difference in the length of the paths of beam 1 (ADFEFDAC) and beam 2 (ABAC), interference fringes result where the two beams combine, to be viewed in telescope T.

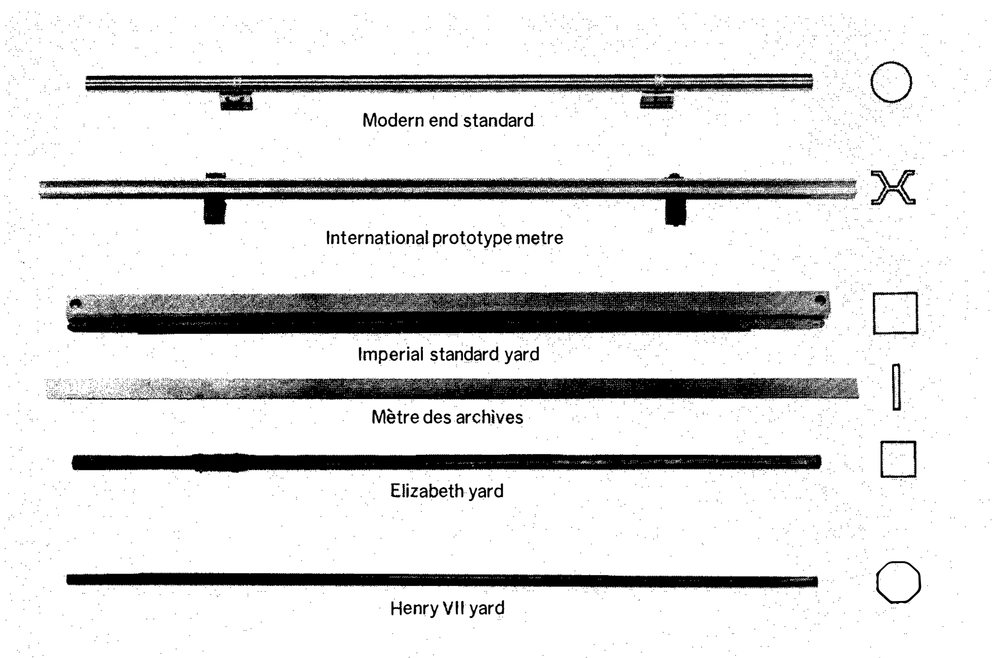
Professor Michelson measured the small path differences by displacing one of the mirrors a slight amount by means of a micrometer screw.

Using 3 kinds of light from the cadmium spectrum—red, green and blue, he was able to determine the length of each wave and also the number of times that each was contained in the standard meter.

FIG. 167—*The first true light-wave measurements were performed by Michelson and Benoit, using red cadmium light, at the International Bureau in 1892.*

FIG. 168—*Six physical length standards, each different in form. Physical standards of length of reference caliber are either (1) end standards or (2) line standards.*
Courtesy NPL, British Crown Copyright.





purity and clarity for measurements of length up to one meter. Fig. 167 shows the arrangement of a Michelson type of interferometer.

2. Physical Standards as Measured in the Bureaus

While we now have a "natural" standard, the need for *physical* standards remains. Moreover, the length of these physical standards must still be accurately established. They are basically in two forms, Fig. 168:

I. Precision scales
II. End standards

I. THE PRECISION SCALE

The Precision Scale of reference-standard caliber is usually of a *Tresca*, or sometimes an "H" section, designed to be supported and used horizontally, Fig. 169. Fine lines are engraved 90° to the longitudinal axis of the bar, on a highly polished, flat surface at the neutral bending plane of the bar, Fig. 170. A convenient line spacing would be .050 inch in the English system and 1 millimeter in the metric; but it is the *overall length*, notably of meter and yard standards, which is of particular interest to the bureaus. The gaging length is a function of the separation of these lines. To minimize the error due to out-of-parallelism of the lines themselves, only a certain portion of the line is used.

Engraving the Scale

A specially-constructed ruling engine is used for engraving the lines of the scale. Its spacing is governed by a precise, compensated lead screw, or alternately by reference to a master scale, using either an optical microscope or a photoelectric microscope.

Lines are scribed with a sharp diamond cutter to widths as small as 80 millionths of an inch [0.002 mm]. The trend in recent years has been to make these lines as fine as possible and to employ higher magnifications in reading the lines. Precautions are

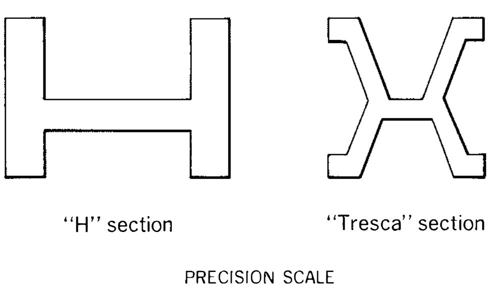


FIG. 169—*Line standards or precision scales, of reference quality, are usually of an "H" or "Tresca" design for rigidity.*

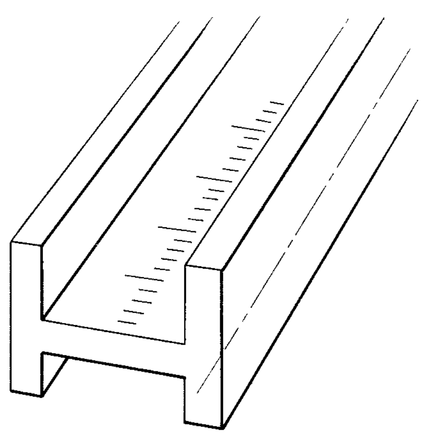


FIG. 170—*The lines of a reference caliber precision scale are placed on the neutral bending plane to minimize errors due to flexure of the bar. A convenient line spacing is .050 in. in the inch system and one millimeter in the metric system.*

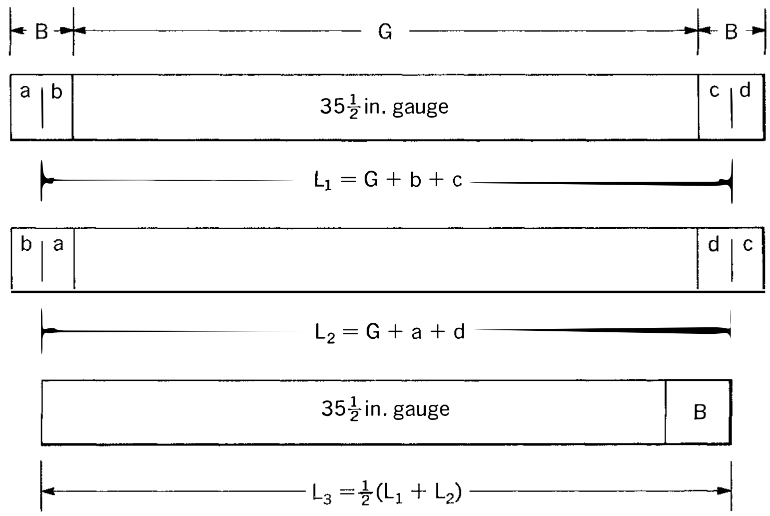


FIG. 171—*Until 1960, the official standards of length were in the form of line standards. End standards ultimately had to refer to existing line standards. This method of comparison was perfected by the NPL.*
Courtesy NPL, British Crown Copyright.

taken to produce lines of uniform thickness, parellelism and spacing. In order to achieve isolation from vibration, the entire ruling engine is usually mounted on a massive concrete foundation which is, in turn, mounted on springs. Temperature must be held to exactly 20° C [68° F] throughout the ruling period.

Method of Comparison

Inspection of the scale may be done by comparison to another reference scale. Calibrations of the highest order, however, can be accomplished through use of a Michelson-type of interferometer. The scale is mounted on a movable carriage. The mirror is fixed to one end of the scale, or to the carriage. As the carriage is moved, the lines of the scale are picked up by photoelectric readout, but the actual displacement is measured in terms of the number of wavelengths of light movement of the mirror.

II. THE END STANDARD

The end standard is usually rectangular or circular in section. Smaller sizes, such as the familiar gage blocks, are essentially used vertically, while the larger sizes are most often designed to be used horizontally. It is the terminal surfaces of the gage, in any case, which are the gaging surfaces.

Lapping of the gage is a cut-and-try process. Starting oversize, the ends of the standard are lapped progressively closer to exact size, but consideration is also given to microfinish, flatness, and parallelism of the ends. Temperature is not quite so critical during the lapping operation itself, as in the many intermediary inspections of the gage when the result of each lapping operation is determined.

Method of Comparison

Since the official standards of length were, until 1960, in the form of a precision scale, akin to the International Prototype Meter, many methods of comparing the end standard to the scale had to be devised. One metrological procedure involved wringing line-ruled block gages to the ends of the standard, and reversing the blocks to average their error, Fig. 171. The end standard can be measured more straightforwardly by comparison to another end standard, either by interferometric means, or by a comparator, such as the NPL's "Level Comparator," Fig. 172.

Highest order of accuracy, however, is obtained by measuring directly in terms of wavelengths of light. Terminal surfaces of the end standard, if near-perfect optically, can be used as interferometer mirrors. With the Koesters-Zeiss interferometer, for example, a larger flat block, serving as a reflecting mirror, is wrung to one end to make the ends "face the same way."

RELATIVE MERIT OF THE PRECISION SCALE AND THE END STANDARD

Subdividing

One obvious advantage of the line standard is that one bar can be subdivided into very small increments (such as .050 inch or 1 mm). This is not possible with the end

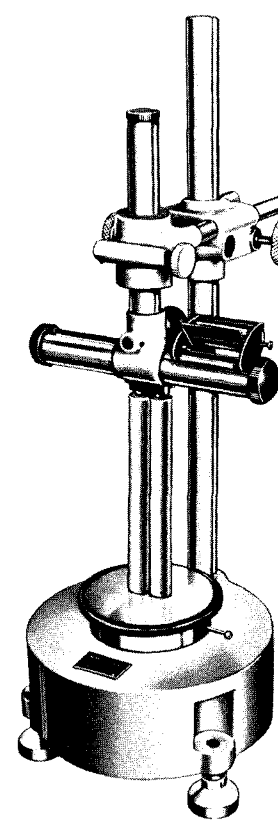


FIG. 172—*This "level comparator" was designed by the NPL, and enables the comparison of an end standard to a master end standard of known length.*
Courtesy of NPL, British Crown Copyright.

standard, nor is it desirable to simulate this by wringing a large number of blocks together.

In the greater lengths (over one yard or one meter), fabrication of the end standard becomes increasingly difficult. Moreover, this method, since it is restricted to determinations of only one size, is costly in relation to its limited use.

Problem of Making to Exact Length

Metrologists stress the importance of having a reference standard of such quality that an exact determination of length can be made. They perhaps do not place sufficient stress on the importance of making the standard to an exact *nominal* length (say 18 inches ±5 millionths of an inch [457 mm ±0.000127 mm]. The closer to exact length, the less is the influence of the comparators which must transfer its length to derived standards; also, the more fully does the standard fit the needs of science and industry.

The end standard can, in fact, be made in the greater lengths to within a few millionths of an inch [small fraction of a μm] of nominal size, though the precision scale may depart one-ten thousandths of an inch [0.0025 mm] or more from nominal. The reason for this disparity is that the end standard may be lapped progressively closer to nominal and as much time as required can be spent in inspection to determine what slight corrections should be made. Once graduated, the scale cannot be altered. Many factors could cause the line to depart from its prescribed position, including:

1. Error of the standard or error in reading the standard.
2. Deflection of the diamond in cutting.
3. Uniformity of line width.
4. Parallelism of lines.
5. Temperature (must be exactly 68° F [20° C]).
6. The reference standard and the standard to be ruled must be exactly the *same* temperature.

It should be noted that the above conditions must be exactly controlled during the instant of engraving.

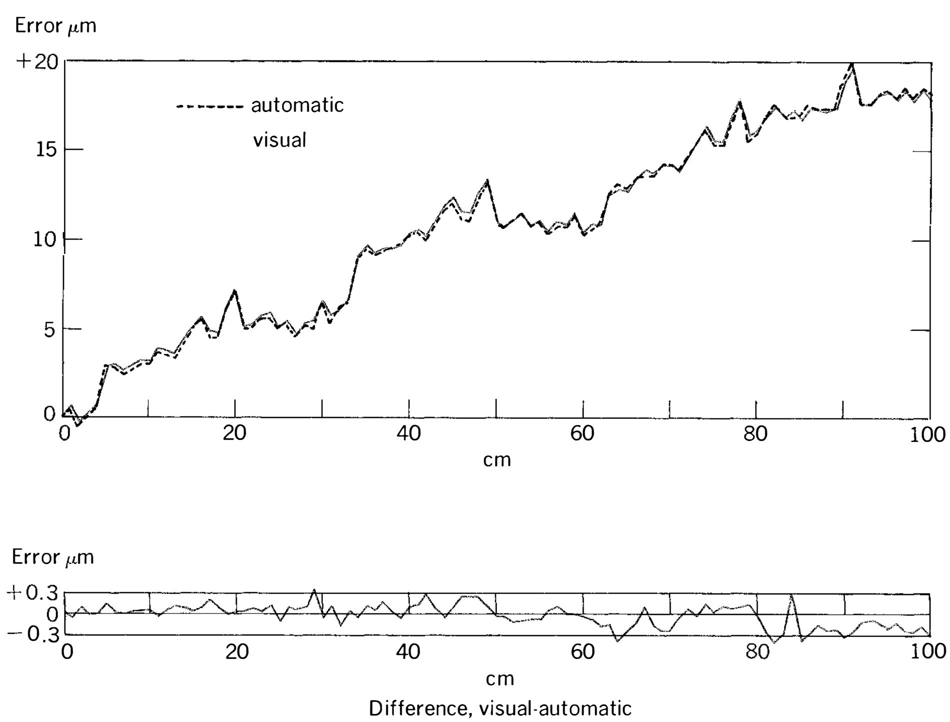


FIG. 173—*This chart was prepared on the basis of a controlled test conducted by the NPL. In the test, one particular precision scale was calibrated, first by referencing the line by optical microscope (visual), and then by photoelectric microscope (automatic). The difference in the calibration amounted to ±0.3 μm [±12 millionths of an inch].*
Courtesy NPL, British Crown Copyright.

Magnification

The ability to measure closely depends to a large extent on how much the error can be magnified. The end standard can be measured with comparators (such as the electronic indicator) of 100,000 to 200,000 magnification. The precision scale, on the other hand, can be read by microscopes limited to 50 or perhaps 100 power and then only where line quality is exceptional. The reason for this vast difference in magnification is that the terminal face of the end standard may be considered an infinitely thin line in space. The graduation on the line standard is a *groove,* which is a minimum of 80 millionths of an inch [0.002 mm] wide. 100× is the approximate limit of magnification because of lens distortion. At 100,000 power, the line would be 8 inches [203 mm] wide, and the line begins to look something like a rutted country road.

To overcome this limit of magnification when using an optical microscope, photoelectric microscopes of 10,000 times resolution have been developed. They are used with line standards whose quality and purpose justify their use. It is estimated that accuracy of determination increases 50 times.

There appears to be some difference, however, between what the photocell registers in picking up the line and how the human eye, using an optical microscope, interprets this same 80 millionths of an inch [0.002 mm] as a target. The scale, or any of its derivatives, calibrated photoelectrically, may thus have some other calibration when read by eye, Fig. 173.

RELATION TO THE INTERNATIONAL STANDARD —LIGHT WAVES

The end standard as a physical representative can be *directly* compared to wavelengths of light by *absolute* means (no mechanical movement, no time lag). This is accomplished by using its terminal surfaces as optical reflectors in the interferometric arrangement.

The line standard, on the other hand, is compared *indirectly* to the light wave standard through movement of a carriage holding the mirror. The line is picked up optically or photoelectrically. A fringe-counting interferometer, which takes a signal and commits it to a photo-sensitive cell, is required. The problem is to hold temperature drift, since there is a time interval while counting fringes. In addition, there is the error of the carriage itself such as to straightness of travel. Line standards thus cannot be compared to the official light wave standard by *absolute* means.

The techniques of relating the end standard and the precision scale to the krypton standard are compared in Fig. 174.

The problem of wear was considered sufficiently worrisome that the International Prototype Meter, unlike its predecessor, the Metre des Archives (see page 105), was in the form of a precision scale. This is not now as significant a factor, since the *ultimate* standard is no longer in physical form, and is reproducible.

CONDITIONS OF COMPARISON

Determinations of length must be made under certain specified conditions. The accuracy of determination is in direct proportion to how well these conditions are met and how rigidly maintained.

Environment

Elements within a standards room environment which may influence the comparison of linear standards include temperature, atmospheric pressure, humidity and vibration.

Temperature

The reader will recall that *non-uniform* temperature within a piece may cause distor-

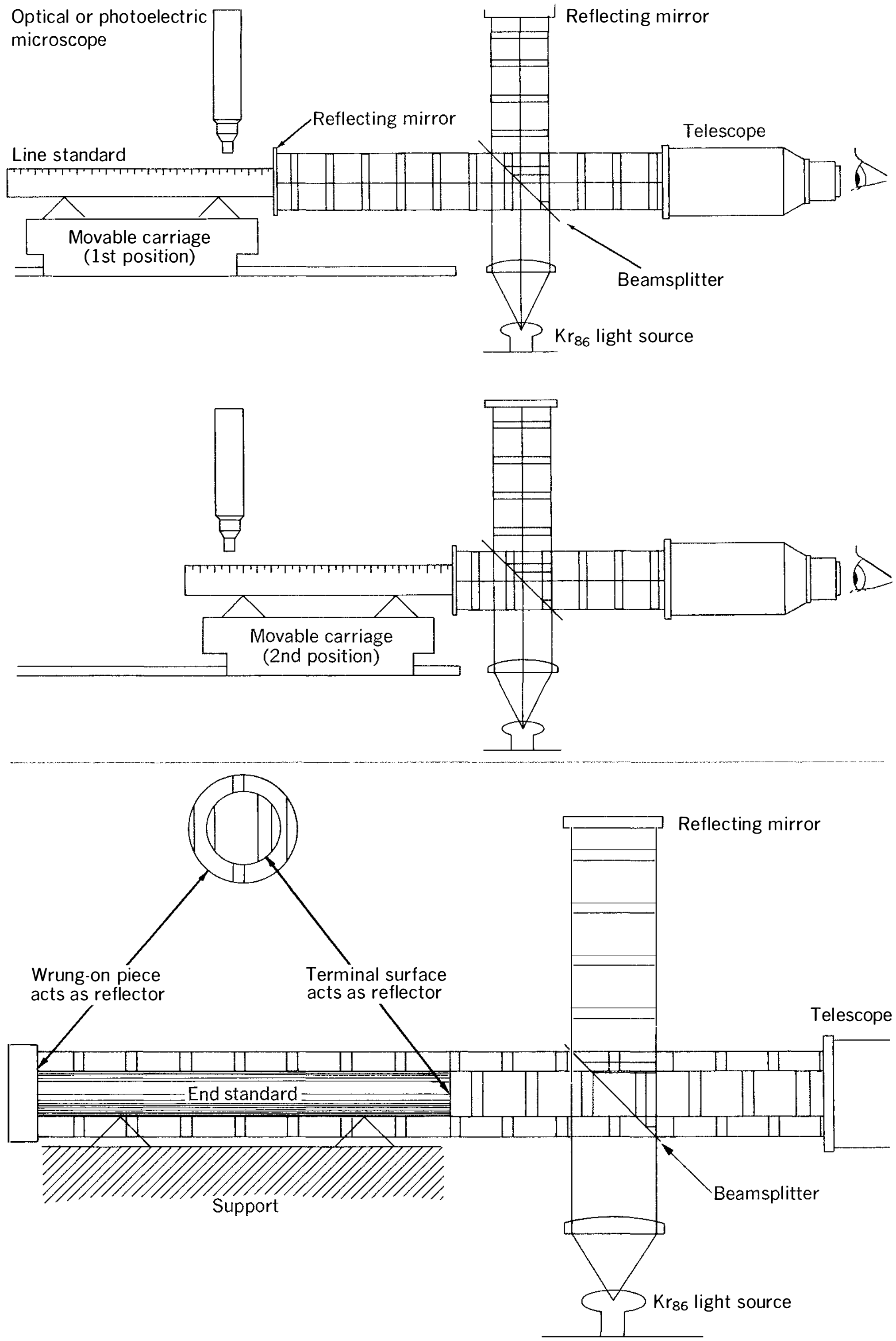


FIG. 174—*The techniques of relating the line standard and the end standard to the krypton light standard are compared.*

The end standard may be compared to the light wave standard "absolutely" with no movement (bottom). The comparison of the precision scale to the light wave standard necessitates the movement of a carriage, supporting the standard—not absolute (top).

FIG. 175—*Various materials expand or contract at different rates in response to temperature change. Tables of coefficients of expansion are less exact than would be desired, especially for the purpose of metrology.*

COEFFICIENT OF THERMAL EXPANSION
OF DIFFERENT MATERIALS

Aluminum	12.3	Linear expansion in millionths of an inch per inch of length, per degree F
Bronze	9.9	
Steel	6.2	
Cast Iron	6.0	
Tungsten carbide	3.3	
Invar	1.5	

tion. Measurements of length involve two *additional* considerations:

1. *Virtually all bodies will expand with an increase in their temperatures.* The reverse is also true.* It is meaningless, then, to attempt to state the exact length of an object without at once specifying the temperature at which this is so.
2. *Rates of thermal expansion vary with different materials.* For this reason, tables of "coefficient of thermal expansion" have been formulated for different materials. They enable calculation of the amount of expected linear change in a body, given its length and temperature change, Fig. 175. These tables, unfortunately, are only theoretically correct. If the composition is even slightly altered or is non-uniform, the stated coefficients may not apply. Moreover, the stated coefficients refer only to a change of *one degree*, from 0° to 1° C [32° to 33.8°F].

One would expect, then, that some specific temperature must be chosen at which all calculations of length are to be made. England, for example, used 62°F [16.67°C] for many years. Also the meter was originally defined at 0° C [32°F], the temperature of melting ice.

Today the internationally-accepted temperature at which length determinations are to be made is 68° F [20° C]. The choice of 68°F, while arbitrary, is convenient enough. At this temperature, there is a convenient numerical conversion between degrees Fahrenheit and degrees Celsius (Centigrade). Most importantly, everyone must agree to and adhere to this figure.

If the length standards have identical coefficients of expansion, it follows that when being compared they need only be alike in temperature. However, the more dissimilar the coefficient of expansion of the standards being compared, the more necessary it is that the temperature of both be exactly 68°F [20°C].

While corrections can be made to the extent temperature is not exactly maintained, the goal should be to eliminate or at least minimize departures from ambient. Ambient temperature change has three sources: *convection, conduction* and *radiation.*

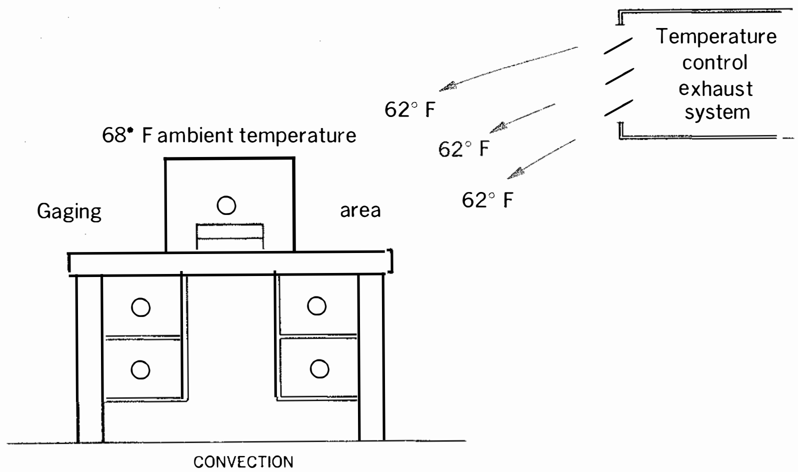
Convection, Fig. 176. Ambient temperature change of the standard due to convection might include the effects of opening doors or windows, drafts from the movement of personnel, or variations from the temperature-control unit itself in the form of non-uniform air currents, or even *stratification* within the room.

Conduction, Fig. 177. Temperature differentials may also be caused by conduction, the flow of heat within a body or from one body to another. Thus, the standard may itself depart from ambient when in contact with some object above or below ambient. An example of this would be the handling of the standard by personnel.

An unsuspected ambient error can arise from *stratified temperature* within the room. The surface on which the standard rests (such as a surface plate or machine table) may itself be exposed to convective air currents above or below 68°F [20° C] at some other level of the room.

*This excludes temperature variations wide enough to cause secular changes or changes in state.

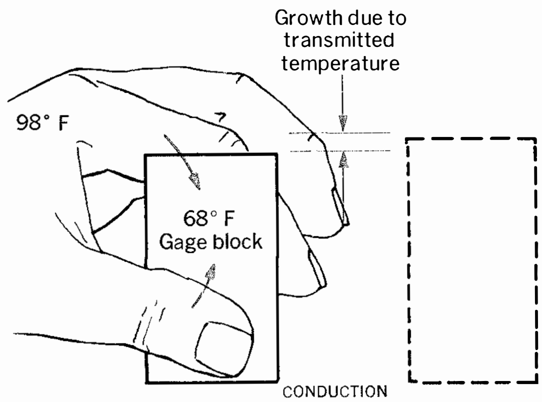
FIG. 176—*A badly-designed temperature-control system may cause greater errors than the absence of any controls at all, especially if the controlled air exhausts near machines or gaging areas. Errors are caused by convection.*



The principle of conduction, however, can be utilized to achieve stability. A surface plate or machine table of sufficient mass held to 68° F [20° C] can act as a "heat sink." Placing the standards in close proximity, or, better still, in contact with one another on such a surface contributes to conformity of their temperatures.

Radiation. The effects of radiant energy are especially troublesome, and often overlooked, where a high order of accuracy is to be attained. All objects in a given room environment emit and absorb energy in the form of electromagnetic waves traveling in a straight line, tending towards an equilibrium of temperatures. However, a body above ambient placed within this environment raises the temperature of other objects to the degree in which they are in the path of these waves, and also depending on their surface color and texture. A dark surface tends to absorb heat; a shiny surface to reflect. For example, due to absorption of radiant energy an unshielded gray granite surface plate will be 0.1 to 0.2°F. [0.055 to 0.11°C] above room temperature and a black granite plate as much as 0.4°F [0.2°C], Fig. 178.

Sources of radiant heat include lights, sunlight, personnel, electrical equipment, heaters or large masses above ambient brought into the environment. Aluminum foil or other guards may be used to shield the measurement set-up from radiant heat.



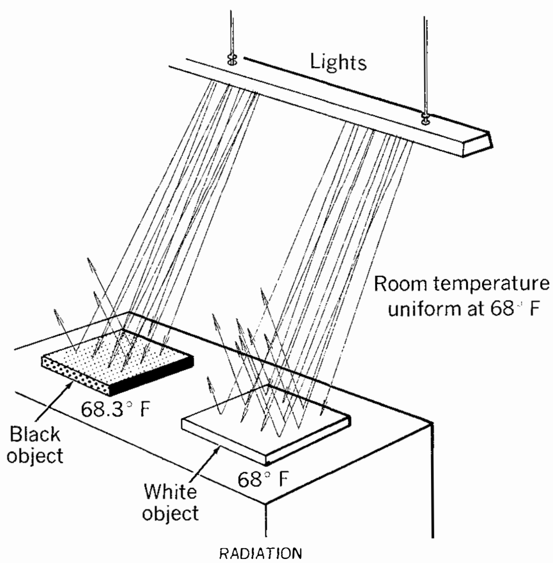
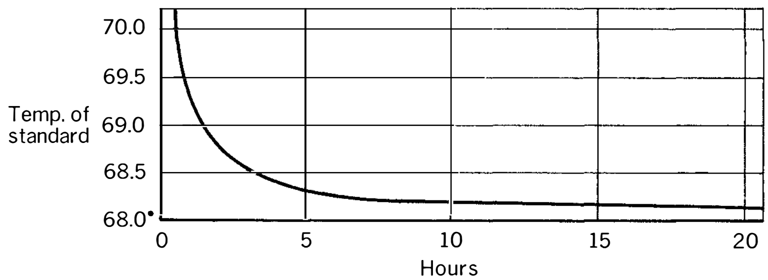


FIG. 177—(*center*) *The handling of standards by personnel may alter their lengths through conduction.*

FIG. 178—(*bottom*) *Objects in the direct path of light will vary in temperature depending on their rates of absorption or reflectivity of that light. Errors are caused by radiation.*

FIG. 179—*An above-ambient standard brought into a controlled environment, requires several hours to reach ambient.*



Temperature and Time

When the standard is allowed to depart from ambient temperature, whether due to handling, exposure to radiant heat or temporary removal from the controlled area, there is a time lag, depending on the thermal capacity of the standard, before it again reaches ambient.

Plotting the temperature of the standard against time, the curve is exponential, Fig. 179. It should be noted that an unsuspected temperature differential can exist for many hours after the source of heat is removed.

If the standard is placed with as much of its surface as possible in contact with a large mass at ambient within the room, the time required for the temperature differential to disappear lessens. Even so, where a few millionths of an inch accuracy [tenth of μm] is required, it is recommended to wait many additional hours to allow the standard to reach ambient.

Humidity

The presence of humidity within the measuring area is not apt to dimensionally change metallic standards which are most commonly used. Its effect, however, should not be completely discounted. Various nonmetallic substances are seriously effected dimensionally by humidity, and humidity will corrode many ferrous materials.

Vibration

Vibration, as with humidity, has no dimensional effect on the standard itself. Sufficient amplitude of vibration might cause a shift of the standard's position during the calibration. The presence of even the slightest vibration, however, can definitely frustrate the use of high magnification instruments, notably interferometers, and to a lesser extent mechanical and electronic indicators.

Atmospheric Pressure

Atmospheric pressure is not usually considered a factor in calibrations of length, except where comparisons are made interferometrically. Measurements are then either made in a vacuum or compensations are made which include corrections for the refractive index of the air.

When gages are measured in a vacuum, corrections must be made for the compression that occurs on return to normal atmospheric pressure. For a one-inch [25.4 mm] gage of steel, this amounts to one-third of a millionth of an inch [0.000008 mm].* This might seem a small amount until one considers that the value for a meter standard [39.37 inches] would be approximately one-third of a μm [13 millionths of an inch].

Engelhard performs many interferometric length measurements without vacuum, feeling that there may be less potential error in calculating the refractive index of the air than in compensating for the return to normal atmospheric pressure.**

Material of the Standard

Stability—Nothing is more disturbing, metrologically, than dimensional instability of the measuring standard. One comes to trust the standard as calibrated, when in fact it has undergone some long or short-run change in length. It might be remembered that the Imperial Yard underwent at least one modification in its length due to secular change.

Residual stresses, such as those from machining, may be later evidenced by a bending or twisting of the standard, altering its effective length.

End standards are usually hardened to facilitate lapping of their gaging surfaces, to minimize damage from being bumped, and to reduce wear in use. Usually, only surface hardness is required, the core remaining soft for greater stability. At times, only the terminal or support surfaces are hardened.

*Irvine C. Gardner, "Ten-millionths of an inch," *Ordnance*, May–June 1965.

**Conversation with Dr. E. Engelhard at PTB, Oct. 2, 1968.

Precision, hardened steel gage blocks may undergo astonishing changes in length with improper heat treatment. The presence of unstable austenite retained from the hardening cycle, or untempered martensite, may result in a crystalline phase change. This may either occur slowly over a period of time, or be suddenly triggered by a jar or variation of temperature.

Experiments by Meyerson and Sola* make clear that there remains much to be learned about dimensional stability. Included in their tests were many types of steels, such as 52100 modified, nitrided 410 stainless, and other materials, such as cermets and ceramics. Many of these materials were also analyzed for stability after subjection to varying treatments. Their experiments were not conclusive in all respects, yet the following groundwork was established:

1. Several materials, with prescribed treatment can be made ultra-stable (no more than .1 or .2 millionth inch/inch/year change), [0.0000025 or 0.0000050 mm/25.4mm/year].
2. Given the requirement of hardness of $65R_C$ or greater, for strength and wear, then the dimensional stability of the best surface-hardened steel will exceed that of any of the through-hardening steels.
3. The hard case of surface-hardened steels should not be removed, even from the sides. This applies to case-hardened as well as to nitrided specimens. The case apparently acts as a "protective envelope," minimizing damage and resisting stress from bumps or shocks. Meyerson and Sola hold to the interesting theory that the case also acts as a "restraining jacket," to eliminate any movement of the core. In the 410 stainless series, however, it is important that the thin white oxide film be removed from all surfaces of the specimen after being nitrided and hardened.
4. Metallurgical composition effects stability. For example, two titanium carbide blocks with nickel binders were tested. One with 25% nickel was stable, while the 40% nickel block was not.
5. Surface treatments, such as thermal spraying, chromium plating and flame plating were generally of inferior stability; if plating did not adhere properly, even greater instability resulted.

*Melvin R. Meyerson and Marcos C. Sola, "Gage Blocks of Superior Stability III: The Attainment of Ultrastability," *ASM Transaction Quarterly*, March 1, 1964.

Of note is the fact that nitrided and hardened "Nitralloy" was found to be among the ultra-stable materials, and is generally recommended for heavy-duty applications (see page 187).

The choice of materials and methods for fabrication and heat treatment must be made to assure maximum stability. Surely the diligence required to attain accuracy should be rewarded by some assurance of its permanence.

Coefficient of Expansion—Nickel-steel alloys have an interesting characteristic. As the percentage of nickel added to steel increases, the thermal coefficient of expansion drops rapidly. A minimum is reached at 36% nickel, where the coefficient is approximately one-sixth that of steel (see Table, Fig. 175). This alloy, Invar, was used by the national bureaus for some of their linear standards until found slightly unstable.

The choice of material for use as a linear standard is widely misunderstood. It is often supposed that the material must, like Invar, have a low rate of thermal expansion. The apparent assumption is that if temperature changes do not much alter the length of the standard, then temperature is eliminated as a source of inaccuracy.

Unfortunately, though, when such a standard is called upon to measure other standards and gages, usually of steel, we see that, in regard to temperature, we have lost rather than gained. Standards having dis-

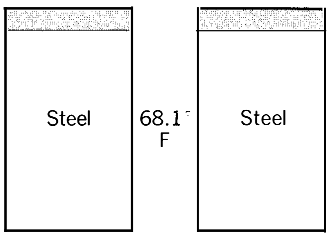


FIG. 180—*Two steel blocks, the same length at 68°F [20°C], will be virtually the same length at 68.1°F [20.05°C].*

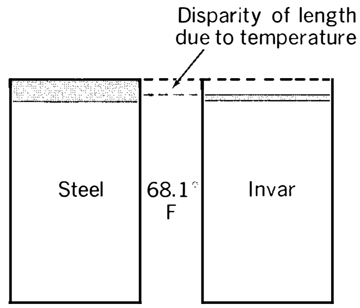


FIG. 181—*An Invar block and a steel block, the same length at 68°F [20°C] will not be the same length at 68.1°F [20.05°C]. Although this effect may be slight with smaller blocks, the disparity is significant with greater length.*

similar coefficients will only agree in length at one temperature—68°F [20°C]. When standards being compared have *widely different coefficients*, such as Invar to most steels, the slightest thermal uncertainty may result in sizeable errors of determination. Where two linear standards being compared have approximately the same coefficient of expansion, uncertainty is minimized. It is only necessary that they be as close as possible to the same temperature and reasonably close to 68°F [20°C], Figs. 180 and 181.

Precision scales for this reason are most often of 58% nickel steel, which is nontarnishable and has approximately the same coefficient of most types of steel. The same considerations govern the choice of material for an end standard.

Logically, then, we would have to say that the new light wave standard is not necessarily an improvement over the old physical standard as to its response to temperature change. Worse than Invar, light waves have *zero* thermal coefficient. Temperature is now more critical than it ever was when we compared physical standards. The accuracy with which we transfer the light wave standard to actual physical standards may be seriously limited by our ability to maintain and measure temperature, as well as by our insufficient knowledge of the coefficients of expansion of different materials.

Support of Length Standards

Relatively small standards, such as gage blocks less than three inches [76 mm] in length, undergo no appreciable alteration in length regardless of the method of support.

A long standard, if supported vertically, will undergo a significant foreshortening of length due to gravity (compression due to its own weight), Fig. 182. The amount of foreshortening increases with length, and is

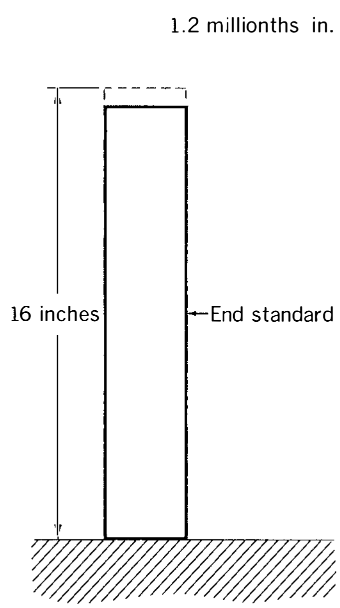


FIG. 182—*A 16-inch [406 mm] length standard undergoes a foreshortening of approximately 1.2 millionths inch [0.00003 mm] from the compression of its own weight when supported vertically.*

calculated as:

$$X = \frac{SL^2}{2E}$$

where:

X = foreshortening
S = density
L = length
E = Young's Modulus of elasticity

It is preferable to support long standards horizontally rather than vertically.* If the former, then the method of support is almost solely determined by the effects that gravity may have in changing its measured length.

Placing the lines of a precision scale at its neutral bending plane minimizes errors due to flexure of the bar when used on a surface which is not a true plane, Fig. 183.

However, if the line standard is supported on the "Airy points," ** an absolutely true plane is not required and the effect of gravity can be virtually discounted. The surface at the end of the bar will be in a horizontal plane and the separation of the lines will have its maximum value.

Similarly, an end standard, Fig. 184, when supported horizontally at the Airy points would have virtually the same length as when supported vertically (discounting compression), and its end faces, if parallel

*In a Test Report (No. 2.4/158197) by the NBS, one of a series of measurements of a 16-inch Moore End Standard involved its measurement in a vertical position, and a "... correction factor of .0000012 (1.2 millionths) inch was applied ...."

Deriving the correction factor:

$$X = \frac{SL^2}{2E}$$

$$X = \frac{.2818\ (16\ \text{in.})^2}{2\ (30{,}000{,}000)}$$

(approximate Young's Modulus for steel)

or

$$X = .0000012\ \text{in.}$$

**The "Airy points" are calculated to be equidistant from the ends, and separated by the factor .577L, where L is the length of the bar—a relationship arrived at by Sir George Airy while Astronomer Royal.

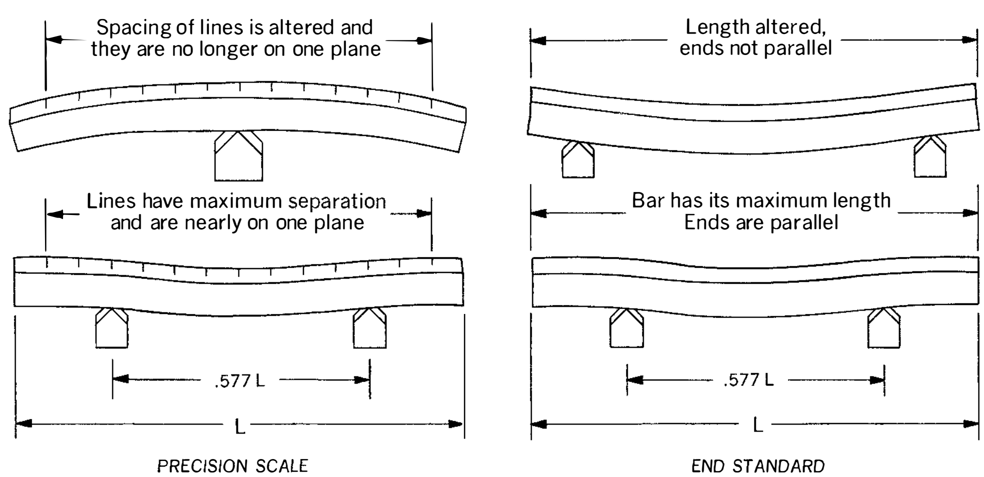
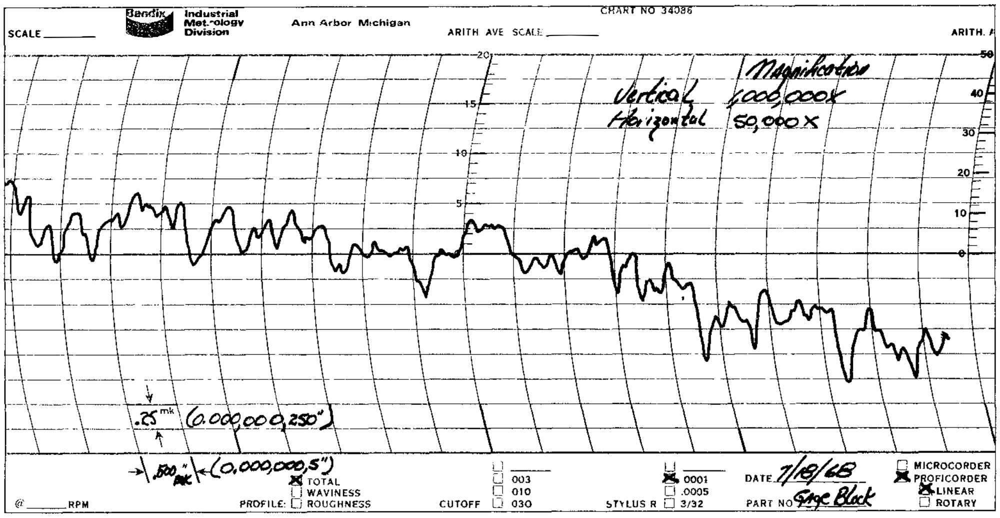


FIG. 183 (*left*), FIG. 184 (*right*)—*Examples of elastic deflection which occur in length standards, attributed to the method of support. Whether the gage is an end standard or a line standard, effective length is altered when support is at the ends or the middle. In the case of the line standard, it is evident that two errors occur: The first is a foreshortening of overall length from bending; the other can occur if the lines are placed on the upper surface of the bar, rather than on the neutral bending plane. Support on Airy points [.577L] virtually eliminates error from bending.*

FIG. 185—*A surface trace of a precision gage block at one million times vertical magnification. Can its true surface be defined?*
Courtesy of Bendix, Micrometrical Division.



when vertical, would be parallel when horizontal.

Bending is also prevented if both the standard and the surface on which it rests are absolutely flat, a method used with the Step Gage (see pages 184-185), where overall considerations dictate such an approach.

Micro-Geometry: Its Relationship to the Measurement of Length

Geometry vs. *Micro-Geometry*—Our ability to perform all manner of measurements to closer tolerances has progressed at a truly rapid rate. Within one man's life span, the standard level of precision has gone from "thousandths," to "ten-thousandths," to "millionths" of an inch [hundredths of a millimeter to several μm to small fractions of a μm]. For certain measurements, *fractions* of a millionth inch [hundredths of a μm] are now given serious consideration. In fact, an avowed goal of the National Bureau of Standards is to measure to the *tenth part of a millionth of an inch* [0.0000025 mm]!*

The reader might ask: "Is there no end of the road, no physical limitation to how closely we can resolve dimensional values?" An answer to such a question was first advanced by an associate, Frederick C. Victory, widely recognized for his pioneer work in metrology. He wrote many years ago:

"Accuracy, as a term, must necessarily imply degree. Absolute accuracy exists only in theory. Progress toward this unattainable goal can be compared to that of the frog which, starting from the middle of a table, covered half the distance from his last position to the edge with each jump, and could thus never reach the edge. In strides toward greater locational accuracy, the earliest gains were most impressive because there was so much room for improvement. Now, progress is slower, the gains proportionately smaller and the problems increasingly perplexing."**

*Irvine C. Gardner, "Ten-millionths of an inch," *Ordnance*, May–June, 1965.

**Frederick C. Victory and Richard F. Moore, *Holes, Contours and Surfaces*, p. 19.

We might also add that closer measurements will always depend on the status of many different "arts," all of which must advance together. But more specifically, there is an obstacle to ultra-fine measurement which can be put in the general category of "micro-geometry."

The term "geometry," by way of explanation, has been used thus far to describe overall shape, such as flatness, parallelism and support of masters and machine members. It will later be used with regard to roundness.

Gages and standards must also have good geometry. The level of perfection attained in the flatness and parallelism of terminal surfaces of an end standard determines to a large extent the "accuracy of determination" in calibrations by the national bureaus.

However, when measurements are to a few millionths of an inch [approximately 1/10 μm], innumerable minute variables, previously insignificant, become highly critical. With only a few ounces [hundred grams or so] of pressure, tips of indicators and gaging surfaces squash and bulge to millionths of an inch [tenths of a μm]. Surfaces which appear normal to the unaided eye, when magnified thousands of times, are seen to have "mountains, valleys, plateaus and craters" millionths of an inch [tenths of a μm] in magnitude! By way of illustration, Fig. 185 shows a surface trace of a precision gage block at 1,000,000 times magnification.

What can then be called a "true" surface? And for that matter, what is geometry?

Older techniques of measurement and more familiar terminology are not always adequate for analyzing and discussing the micro-inch. The term "micro-geometry" best describes the special set of problems and conditions having to do with measurements on this level.

The following analysis is given to indicate a major direction for further progress. It is moreover aimed at encouraging a more conservative attitude in those who make claims of working to "millionths"—revealing exactly how small a millionth of an inch actually is.

As E. G. Loewen points out, there are "confused concepts" with regard to micro-inch accuracy [tenth of a μm]*. Instruments can detect sensitively minute differences through high resolutions, but to obtain definitive values of measurement is more demanding. As an example, he uses the present limitations of 1 millionth of an inch certainty [0.000025 mm] in the measurement of gage blocks where conditions approach the ideal (two parallel planes). The measurement of the exact diameter of a cylinder is infinitely more complex. One aspect of this problem will be shown under "Deformation" (see page 129).

Surface Finish—Perhaps the most perplexing consideration involving measurement is that of surface finish, and applies to the manufacture of virtually every gage, whether optical or mechanical. The senses of sight and touch of a qualified inspector can evaluate surface finish of the average specimen with uncanny accuracy. Moreover, for the average specimen, there is generally agreement on means of measurement and definition. Usually its effects on accuracy or function are fairly obvious. As we shall see, however, with measurements of gages having a high micro-finish, the effect of surface finish is not generally so obvious relative to the accuracy sought; and there are even wide gulfs of disagreement among leading authorities as to measurement and definition.

*Erwin G. Loewen, "Micro-inch Accuracy . . . Really?", *American Machinist*, June 5, 1967.

Evolution of Surface Finish Measurement

Quality control of surface finish at first relied on pure judgment, followed perhaps by samples put aside for the workman or gagemaker to use as a comparison. Later, sight-touch standards (see Fig. 186) were used, but provided only rough limits within which to work. Moreover, since they relied purely on the senses, they did not truly measure. Schmalz probably made the first experimental attempts to measure the depths of surface irregularities in 1929 through an "optical lever." Both Schmalz and Nicolau,

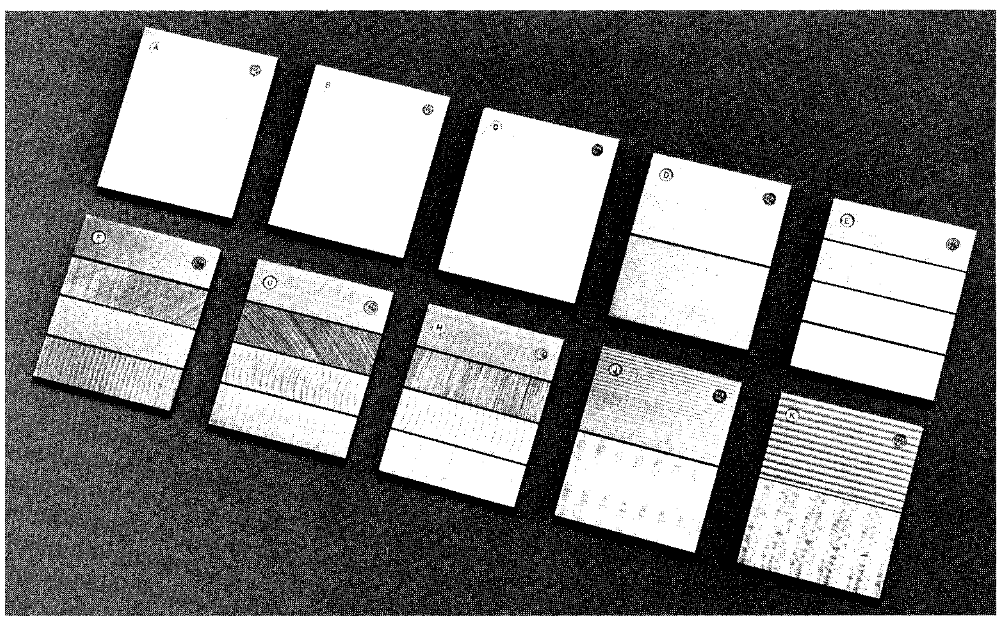
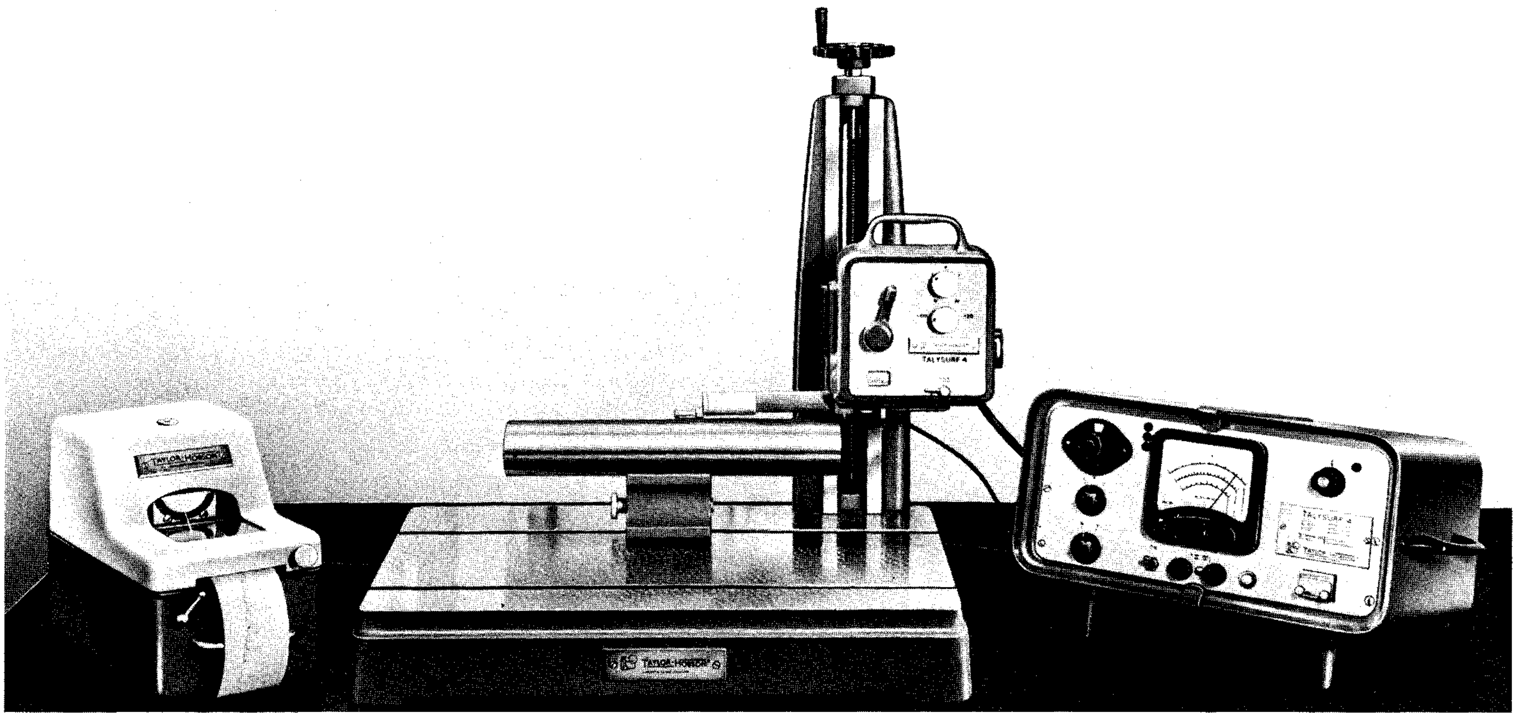


FIG. 186—*Sight-touch standards are convenient for judging surface finish. Since they rely purely on the senses, they do not provide measured values.*

FIG. 187—*The "Talysurf" measures surface finish by means of a follower stylus. Surface characteristics may be magnified thousands of times and are graphed through use of a linear recorder.*
Courtesy of Rank Industries, Ltd.



a contemporary, used "grazing lines" on graphical charted values as reference lines from which to measure—Schmalz from top down, Nicolau from bottom up.

In 1936, Abbot built the first shop instrument, the forerunner of the present "Proficorder" of the Micrometrical Division of the Bendix Corporation. This instrument employed a moving coil for electronic amplification and a supporting skid for a stylus. Because measurements taken with this instrument were instead in reference to a graphed "mean line" of the profile, a controversy over definition thus began.

The "Talysurf" of the Taylor-Hobson Company, England, Fig. 187, appeared in 1940. R. E. Reason of that company is today perhaps the most outstanding surface finish authority. Since that time, many new instruments to measure surface finish have been developed, but leaders in the field are still divided in opinion on how to express and measure surface finish.

Reason points out that ". . . a system which is perfect may be unattainable."* Nevertheless, some common ground and language was needed. In 1962, the American Standard Association issued "ASA B 46.1, Surface Texture," a technical bulletin which provided classifications for roughness, waviness, lay, and the symbols to be used.** The following is an outline (with the ASA's reference number) of some of the definitions agreed on, Fig. 188:

2.1 *Surface Texture*—"Repetitive or random deviations from the nominal surface which form the pattern of the surface. Surface texture includes roughness, waviness, lay and flaws."

2.4 *Center Line*—" . . . the line about which roughness is measured. A median line, mathematically."

*R. E. Reason, "Report on Reference lines for roughness and roundness," *CIRP Annalen*, 1962-63, pp. 95–101.

**Information on pages 126–127, including Fig. 188, is taken from "Surface Texture," Technical Bulletin ASA B 46.1, 1962, with permission of publisher, The American Society of Mechanical Engineers, New York.

2.5 *Micro-inch*—One millionth in., abbreviated MU in.

2.6 *Roughness*—" . . . finer irregularities in the surface texture, usually including those irregularities which result from the production process." (feed marks, etc.).

2.6.1 *Roughness Height*—" . . . arithmetical average (AA) (or CLA Center Line Average in British Standard), deviation expressed in micro-inches measured normal to the center line."

2.6.2 *Roughness Width*—"Predominant peak-to-peak pattern of roughness, expressed in inches."

2.6.3 *Roughness-width cutoff*—"A selected spacing; care must be taken to include all of the surface irregularities to be assessed. Can be as much as 1.000 inch [25.4 mm] but .030 inch [0.75 mm] if no value specified."

(The British use "Meter Cutoff," or "sampling length").

2.7 *Waviness*—" . . . widely spaced component of surface texture . . . wider spacing than the roughness width cutoff"—due to machine or work deflections, vibration, chatter, etc.

2.7.1 *Waviness Height*—" . . . rated in inches as the peak-to-valley distance . . . ."

2.7.2 *Waviness Width*—" . . . rated in inches as the spacing of successive wave peaks or successive wave valleys . . . ."

2.8 *Lay*—"The direction of the predominant surface pattern, ordinarily determined by the production method used."

2.9 *Flaws*—"Flaws are irregularities which occur at one place or at relatively infrequent or widely varying intervals in a surface." (scratches, cracks, random blemishes, etc.).

3.3 *The Surface Symbol*

3.3.1 "The symbol used to designate surface irregularities is the check mark with horizontal extension." $\surd\overline{}$

Symbols are used to indicate lay of the surface pattern. Relative to the surface to which the symbol is applied, it may be "parallel" ‖, "perpendicular" ⊥, angular in both directions ×, multidirectional **M**, circular relative to center **C**, or radial relative to center **R**.

Shop instruments measure all surface texture characteristics except "lay", which is observed by eye.

The ASA Standard would seem to have fallen short of perfection. For instance, it still has nothing to do with function, and does not allow meaningful comparisons between unlike specimens (milled vs. ground for example). It does not include methods of measuring other than the stylus-type.

In retrospect, however, it was probably wise to have some limitation of scope, since some consensus was obtained. At any rate, the stylus-type of measurement is still in most general use and is most convenient.

One limitation of the "arithmetical averaging" system, though, is that it minimizes extreme variations which may be significant to function. For this reason, although it has achieved international acceptance, most of the countries that use it admit to using supplementary peak-to-valley, or

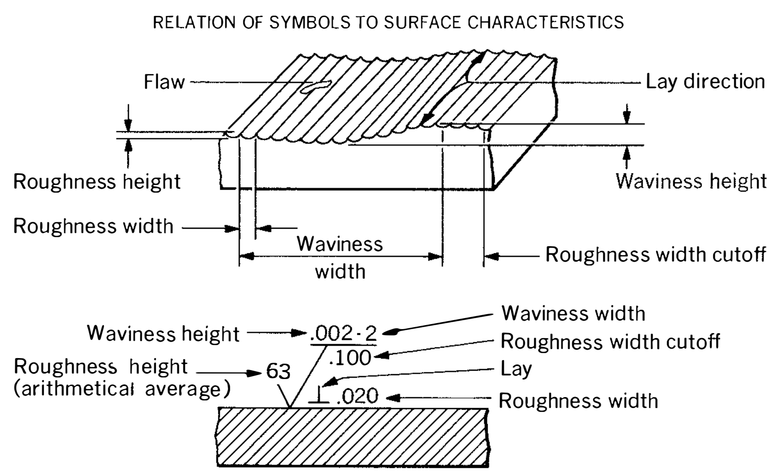
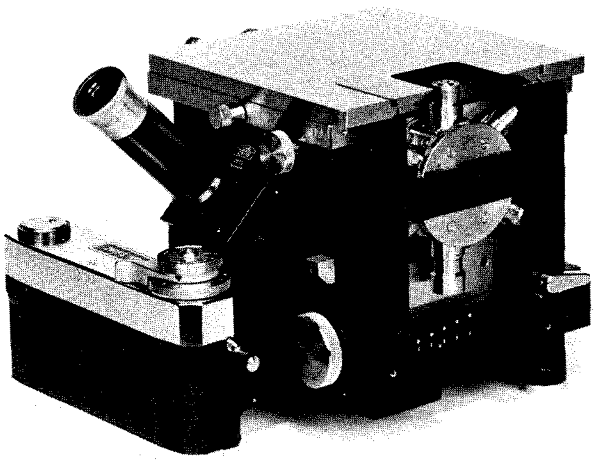


FIG. 188—*An example of terminology for surface texture and symbols used is shown here.*

FIG. 189—*An interference microscope is a valuable means of examining surface characteristics. Its advantage is that measurement requires no physical contact, and is 3-dimensional.*
Courtesy of Carl Zeiss Co.



"full profile" measurements—something of a compromise between the original concepts of Abbot and Schmalz. Considering that "full profile" is also employed, the claim often made that tip radius is of secondary importance is not exactly valid.

While there is still disagreement among the proponents of the stylus system, other authorities show that there are fundamental limitations to the stylus concept itself, in that it is only 2-dimensional.* They hold that an evolution to more sophisticated and exacting results will require supplementing such measurements with micro-interferometry (depth-measured interferometrically, and the fringe-pattern viewed through a microscope), Fig. 189. In other words, measurement must be 3-dimensional.

Fig. 190 shows a steel surface in vertical light with the comparison path of rays cut off, taken with 60-power objective in thallium light, $\lambda = 0.54\mu m$ [0.000021 inch]. Total magnification is 480× and the visual scale has a diameter of approximately 0.3 mm [0.012 inch]. Below is Fig. 191, showing the same section in the interference path of rays. The fringe shift is measured in fractions of the fringe spacing which multiplied by $\lambda/2$ is the roughness height in μm [40 millionths of an inch]. The irregularities of the fringes indicate the unevenness of the specimen.

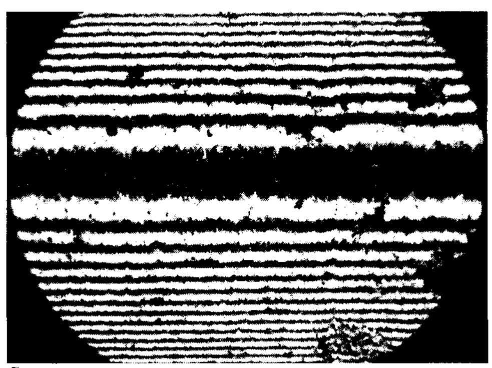
Fig. 192 shows a cylindrical surface. Fig. 193 shows a spherical surface; the irregularities are caused by a deformation of the ball.

Some studies show that the tracer-type and interference microscope may be in fairly close agreement.** Since micro-interferometry may not be as widely applied, the tracer-type is generally the most accepted method.

*James B. Bryan *et al.*, "State of the Art Report: Measuring Surface Finish," *Mechanical Engineering*, December, 1963, pp. 43–46.

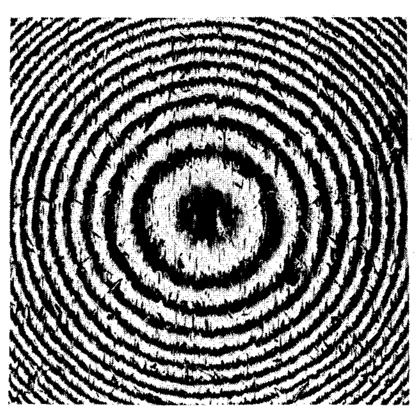
**F. H. Rolt, "Use of Light Waves for Controlling the Accuracy of Block Gauges," NBS Bulletin 581, April 1, 1957, pp. 27–41.

A



C

B



D

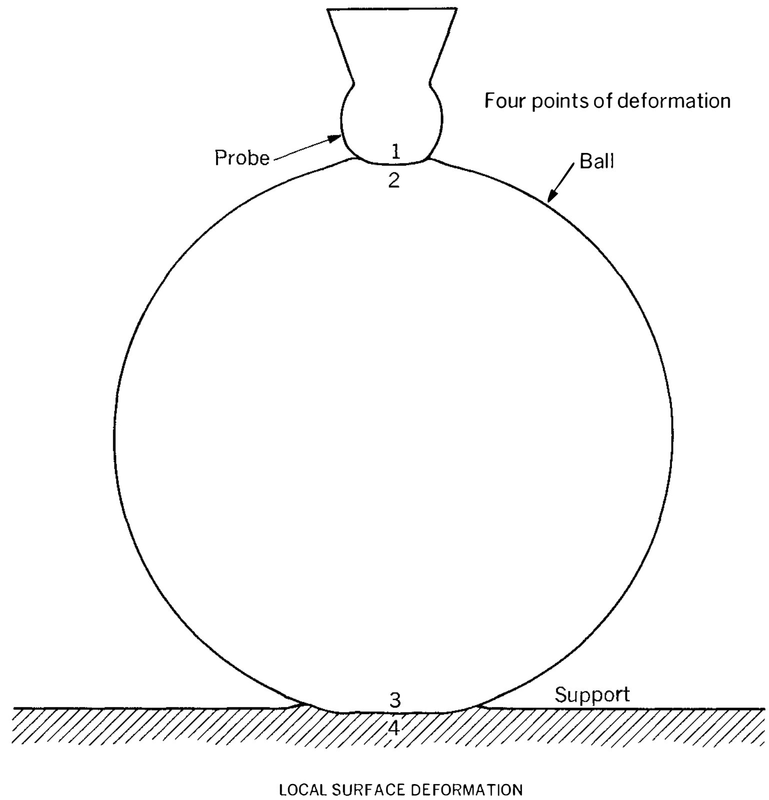
FIG. 190–193—(A) *A steel surface in vertical light with the comparison path of rays cut off. Photo is taken with 60-power objective in thallium light.* $\lambda = 0.54\mu m$. *[0.000021 inch]. Total magnification is 480×; the visual scale has a diameter of approximately 0.3 mm [0.012 inch].*

(B) *The same section of steel surface (see Fig. 190) in the interference path of rays.*

(C) *A cylindrical surface under an interference microscope.*

(D) *Irregularities of a spherical surface through an interference microscope.*
Courtesy of Carl Zeiss Co.

FIG. 194—*Local surface deformation occurs in the gaging process. In this exaggerated example, an indicator probe registers on top of a ball. Deformation occurs at 4 places: (1) On the surface of the probe (2) At the point on the ball where the force of the probe is applied (3) The area of the ball resting on the gaging platform, or support (4) The surface of the platen in contact with the ball.*



When there is an easily observable lay (the American Standard calls for visual recognition of lay, and measurements to be made across the lay), basic methods and definitions suffice; but when measurements are of surfaces having higher micro-finish, the surfaces are less apt to have a "definite lay," requiring smaller samples, resulting in less representative measurement.

Also, despite light following pressure, the stylus may damage the specimen. This risk increases the smaller the stylus radius (and the softer the piece).

In the area where surface finish measurements are most needed, such as for gages and standards, present techniques and definitions become less and less meaningful.

To conclude, the difficulty in measuring surface finish arises in being able to apply universal techniques and definitions to an almost indeterminate set of conditions. To distinguish between "flatness," "waviness," and "roughness" for all grades of surface from rough-machined to highly polished is indeed difficult. Standard terms are particularly difficult to relate to the most accurate gages. The solution requires either a synthesis of methods or having more than one fixed set of techniques and terminology for surfaces of widely different quality.

Elastic Deformation in the Gaging of Standards

Large mechanical members, such as surface plates, masters, and machine members, have been shown to compress, bend and twist from gravity or from other applied forces.

Despite the extremely light gaging force associated with high-magnification mechanical and electronic comparators, bending, squashing, compression and bulging are just as much of a problem when gaging standards—especially in terms of the accuracies sought, Fig. 194. Loewen cites the example of a bar of quartz, 1 inch

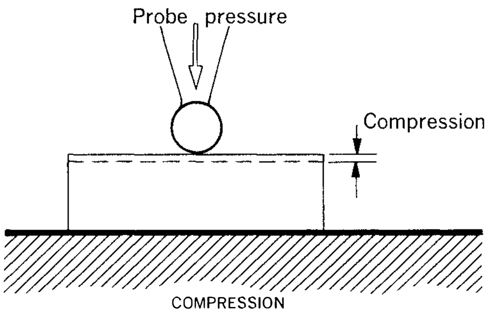
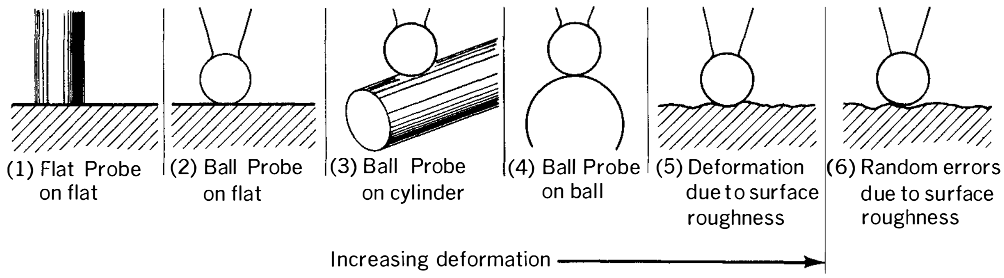


FIG. 195—*In most cases, compression of the gage, resulting from stylus (indicator) force, is negligible. Normally, it is discounted.*



FIGS. 196, 197, 198, 199, 200, 201—*6 examples of how micro-geometry effects micro-inch [values of 1/40th μm] measurement. Examples 1–5 depict situations where overall force remains constant; local surface deformation, however, becomes progressively greater due to the shape of the objects, causing greater unit pressure.*

Example 6 illustrates an error caused by the probe falling alternately into the hills and valleys of the surface irregularities. This is potentially the biggest single source of error because it is random in nature. Moreover, the situations pictured in Examples 5 and 6 may be working in combination to increase error.

[25.4 mm] in diameter and 10 inches [254 mm] long, resting on simple supports at either end; for every gram [0.035 oz.] load at center, the center-point sags 1 millionth of an inch [0.000025 mm].*

Robert Hooke in 1676 published a general law as the result of experiments, showing that "the extension is proportional to the force. Hooke's Law may be re-stated in terms of "Young's Modulus," or:

$$\text{Modulus of Elasticity} = \frac{\text{Stress}}{\text{Strain}}$$

"Young's Modulus" of a material is the quotient obtained by dividing stress per square inch by elongation in one inch caused by this stress.

The formula derived is: $M = \frac{Fl}{ea}$

where: M = Modulus of Elasticity
F = Force applied
l = Length
e = Elongation
a = Area (cross section)

Within their elastic limit, virtually all solid bodies are perfectly elastic. That is, when the force causing deformation is removed, the object returns to its normal shape. Hooke's Law applies to either elongation or to compression. This is not to say that the "elastic limit" cannot be exceeded in the gaging process. In fact, it can accidentally be exceeded even with comparatively light gaging force because of surprisingly high unit pressures which sometimes accompany these measurements.

It must be clearly pointed out here that this discussion is concerned only with forces that do not exceed the elastic limit (point of permanent deformation) of a specimen.

"Young's Modulus," though derived empirically, is extremely useful in deriving the amount of deflection, given the material and the force applied.

Heinrich Hertz, 1881, mathematically derived many of the formulas which are the basis of calculating deformations of various materials and shapes of bodies in contact. The classical Hertzian formula can be condensed into simple form*

as: $$Y = K\sqrt[3]{\frac{F^2}{D}}$$

where: Y = deformation
F = applied force
D = diameter of contact
K = a deformation variable depending on material, shape of bodies in contact, etc.

Today's closer tolerance requirements and the fact that parts are being made increasingly to *dimensions* rather than to *fit*, has caused these formulas to be re-evaluated in terms of *gaging*.

It is evident from the Hertzian formula that three elements influence deformation in *measuring*. (Compression from the measuring force, see Fig. 195, has been omitted from this analysis for simplicity, since it is normally a negligible amount).

1. *Measuring Force*—Deformation increases with increasing measuring force—(to the ⅔ power of the force).
2. *Measuring Contact Area*—With a total given force, the smaller the contact area on which this force is made to act, the greater the force per unit area (lbs./sq. in.) [kg/cm²]; thus the greater deformation.*
3. K—*Deformation Variable*—The "K" factor in actual practice may be composed of innumerable combinations of variables. For convenience they are classified below under two headings:

a. *Geometry of the Contact Area*—Illustrated in Figs. 196 through 199.

b. *Type of Material in Contact*—Deformation becomes progressively less depending on whether the piece to be gaged is aluminum, steel, or carbide; similarly, if the probe is steel, carbide, or diamond.

*Erwin G. Loewen, "Micro-inch Accuracy . . . Really?", *American Machinist*, June 5, 1967.

*R. V. Anderson and A. L. Lauerman, "Contact Force (Measuring Pressure); Its Effect On Micro-inch Measurements," Bulletin X7-995/070, North American Aviation, California.

*This mathematically demonstrates that when measuring surface finish, a needle type stylus probe may easily damage the specimen (exceed elastic limit) even under extremely light gaging force.

Providing certain assumptions are made, the most important of which is that the objects are perfectly smooth and homogeneous, the amount of deformation or compression is predictable mathematically. In fact, controlled gaging experiments by Nickols and Oakley of the NPL demonstrated surprisingly close correlations with Hertzian values, the closer the approach to "pure conditions."*

Surface Finish and Deformation—From Fig. 200 and Fig. 201, it can be seen that two types of error arise as a result of the quality of the surface.

In the first, and most serious instance, highly random errors arise from the probe falling alternately into the peaks and valleys of surface roughness.

The second type of error is due to the uncertain amount of local deformation, increasing according to the roughness of the finish.

Providing the exact same spot is gaged against, there should be little measured deviation, regardless of finish. In actual gaging practice, however, this is not always practical. A greater gaging force is recommended in proportion to the roughness of the finish, to partially flatten out the irregular pattern to some stable level. As a correlary to this, the lightest possible gaging force should be used where the very highest accuracy is desired of a surface finished to optical quality.

Referring again to Figs. 196 through 199, if Hertzian values were obtained from these examples, it would be found that when using only a few ounces [100 grams or so] of force, not only is deformation great, but moreover the *differences* in deformation amount to many millionths of an inch [tenths of a μm].

*L. W. Nickols and T. R. J. Oakley, "The Influence of Measuring Force, Stylus Radius and Surface Finish on the Accuracy of Measurement of Workpieces by a Comparator," *Proceedings of the Institution of Mechanical Engineers*, London, 1961, pp. 195–207.

To obtain the true correction values, complex calculations may be required. With today's technology, computers may be used to derive many of these values, Fig. 202.

From previous observations, two recommendations follow:

1. *Eliminate variables*—All elements of comparison in the measuring set-up should be kept as uniform as possible. The comparison of unlike materials, shapes or types can cause unforeseen errors. If, for example, the specimen differs too far from the nominal size of the master, not only will the *linearity* of the comparator introduce an error, but the different position of the comparator needle will change the "force" applied.
2. *Apply a correction factor*—If point No. 1 is not possible (seldom the case), either allow a larger margin of "uncertainty," or make a careful analysis of the variables and apply the appropriate correction factor.

It can be strikingly demonstrated just how careful an analysis should be: A probe of very small radius wears rapidly to a greater radius, in which case the theoretical deformation factor is completely changed. Worthen* mentions a less serious effect but nonetheless one which comes into consideration: a diamond probe, quite often used in millionths of an inch [tenth of a μm] measurements, is difficult to polish to a true radius because its degree of hardness varies in different axes.

Type of Probe—The choice of probe or stylus-type is a subject that is much debated and little understood. Nickols and Oakley** show that even its construction is important; a composite type of probe where the ball is restrained in a holder is itself under stress. This condition may alter the theoretical deformation correction factor.

*"Millionths Measurement Seminar" at Federal Products Co., November 19, 1968.

**L. W. Nickols and T. R. J. Oakley, *Idem.*

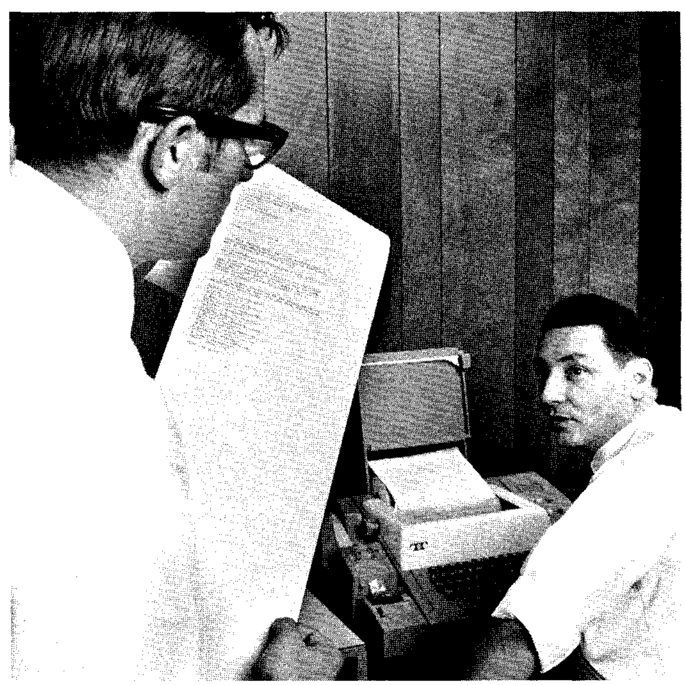
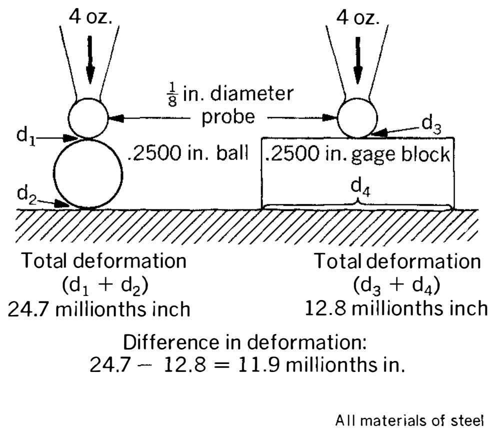


FIG. 202—*Today's technology enables the use of computers to more easily determine complex deformation values.*

FIG. 203—*The difference in deformation occurring when a 1/4 inch [6.35 mm] steel ball is compared to a steel gage block using a 1/8th inch [3.175 mm] diameter probe is calculated here. It is equal to approximately 12 millionths of an inch [0.0003 mm].*



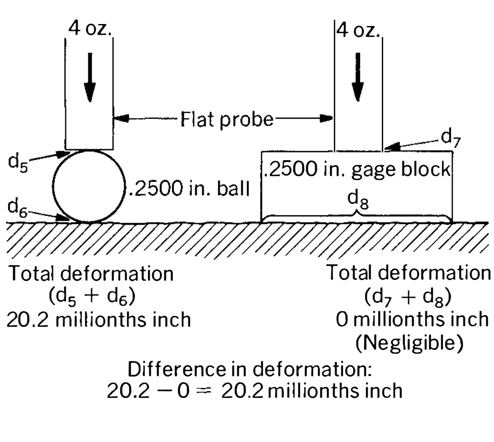


FIG. 204—*The difference in deformation which occurs when the steel ball shown in Fig. 203 is compared to the same gage block using a flat probe is approximately 20 millionths of an inch [1/2 μm]—almost twice as great as that when using a 1/8-inch [3.175 mm] diameter probe.*

Actually, no hard and fast rules can be applied as to the choice of probes. Each measurement problem requires separate analysis, as shall be shown.

Some metrologists, realizing that the amount of deformation is least when a flat anvil-type probe is used, assert that it should be used wherever possible. The value of a flat, anvil-type probe for most types of comparator measurement is of questionable value. The parallelism of probe to the opposing support surface is perpetually suspect. Errors in measurement may far surpass those due to "deformation."

As a rule, where objects having plane surfaces are compared, a large radius probe is preferred over one having a small radius for the following reasons:

1. The danger of brinelling is lessened.
2. Wear of the probe is minimized.
3. Deformation is less, requiring smaller corrections.

This does not necessarily mean that a large radius probe is preferred over a small radius under all circumstances. One obvious limitation is the internal measurement of small radii. It has been our experience that for general shop use of electronic indicators, where conditions are less than perfect, a large radius probe is inclined to collect minute dust particles, or to have slight oil films adhere; these would normally be "wiped off" with a small radius probe.

Nor should it be assumed that minimal deformation is to be sought at the expense of all other considerations. This can be proven in purely Hertzian terms and simultaneously give some idea of the magnitude of errors which occur through elastic deformation using a comparator.*

Case No. 1, Fig. 203—a 1/4 in. steel ball is gaged for size by comparison to a .250 in. steel gage block, using a probe-tip of 1/8 in. diameter and 4 oz. applied measuring force [3.17 mm, 113.4 grams].

*For further information on the deformation of various other geometrical shapes when in contact, see S. Timoshenko and J. N. Goodier, *Theory of Elasticity*, New York, 1951.

Referring to Fig. 203 again, deformation from applied measuring force on spherical contacts at d_1:

$$d_1 = 1.23 \sqrt[3]{\left(\frac{P}{E}\right)^2 \left[\frac{R_1+R_2}{R_1R_2}\right]}$$

which calculates to be 14.6 millionths inch.

Deformation from applied measuring force of ball to its support at d_2:

$$d_2 = 1.23 \sqrt[3]{\left(\frac{P}{E}\right)^2 \times \frac{1}{R_2}}$$

which calculates to be 10.1 millionths inch.

Total deformation, $d_1 + d_2 = 14.6 + 10.1$ or 24.7 millionths inch.

Now consider the deformation from applied measuring force of a 1/8 inch diameter probe against the gage block, Fig. 203.

Deformation at d_3:

$$d_3 = 1.23 \sqrt[3]{\left(\frac{P}{E}\right)^2 \times \frac{1}{12}}$$

calculated to be 12.8 millionths inch.

If we assume that the deformation of the gage block to its support (d_4) is negligible, then total deformation equals 12.8+0, or 12.8 millionths inch.

This means that if no correction factor were applied to allow for deformation, the error in the calibration of the 1/4 inch steel ball would amount to 24.7−12.8, or 11.9 millionths inch.*

Case No. 2—A 1/4 inch steel ball is gaged for size by comparison to a .250 inch steel gage block, using a flat anvil probe, 4 oz. applied measuring force.

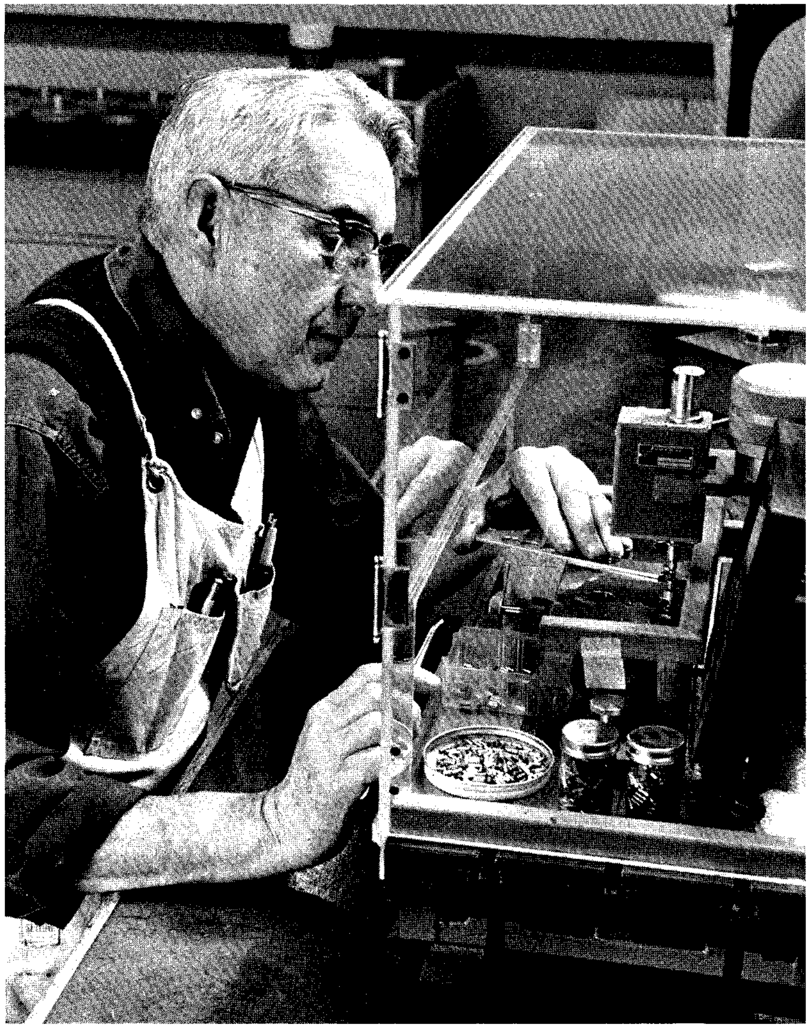
Referring to Fig. 204, deformation of ball to its support, d_5, as at d_2 is 10.1 millionths inch.

Since deformation at d_6 equals deformation at d_5, total deformation is 10.1 + 10.1, or 20.2 millionths inch.

Again, deformation both at d_7 and d_8 is negligible, or 0 millionths inch.

*See Figs. 203 & 204 for metric conclusions.

FIG. 205—*The roller-checking device uses a ⅛-inch [3.175 mm] radius diamond probe, and is able to detect differences of one or two millionths of an inch [$^1/_{20th}$ of a μm or less]. Rollers are used in many precision mechanisms, such as in spindles and roller-ways.*



This means that if no correction factor were applied to allow for deformation, the error in the calibration of the steel ball would amount to 20.2—0, or 20.2 millionths inch.

Comparing Case No. 1 to Case No. 2, the ***difference** in deformation is almost twice as much when using a flat probe as opposed to a ⅛ in. radius probe.*

Using 1 lb. load:	*Deformation*
⅛ in. dia. probe against 1 in. dia. ball	26 millionths in.
⅛ in. dia. probe against 1 in. gage block	25 millionths in.
1 in. dia. probe against 1 in. dia. ball	15.5 millionths in.
1 in. dia. probe against 1 in. gage block	12.5 millionths in.

In this latter case, the large radius probe would call for a 3 millionths in. correction, whereas the ⅛ in. probe would call for only a 1 millionths in. correction.

The author realizes that the above calculations need the clear light of experimentation to be truly meaningful; however, it is only intended to point out that:

1. Deformation values can be very great.
2. It is not always "obvious" what type of probe is preferred.

Deformation in itself is not necessarily deleterious to accuracy, so long as it is constant. An example is the roller-checking device, Fig. 205, diagrammatically shown in Fig. 206. An optically-polished diamond probe of ⅛ in. radius is used.

Although there is undoubtedly more deformation than if a flat probe were to be used, actual size is secondary in importance to holding all rollers alike in size.

Where actual size is to be determined, a master plug gage is preferred over a gage block.*

*See Figs. 203 & 204 for metric conclusions.

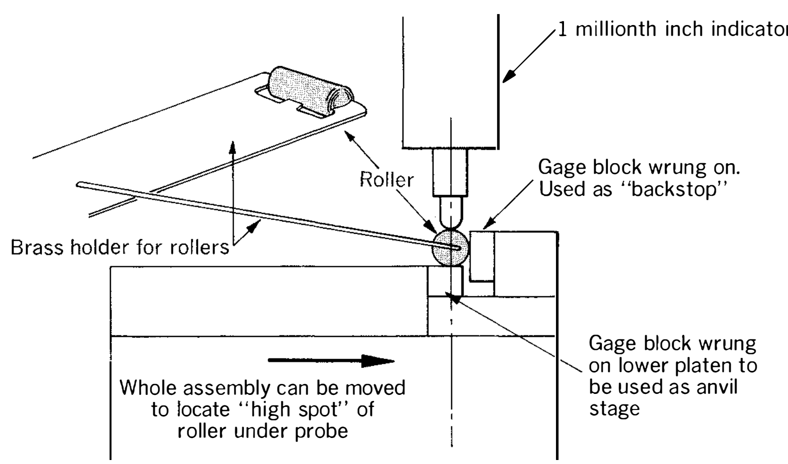
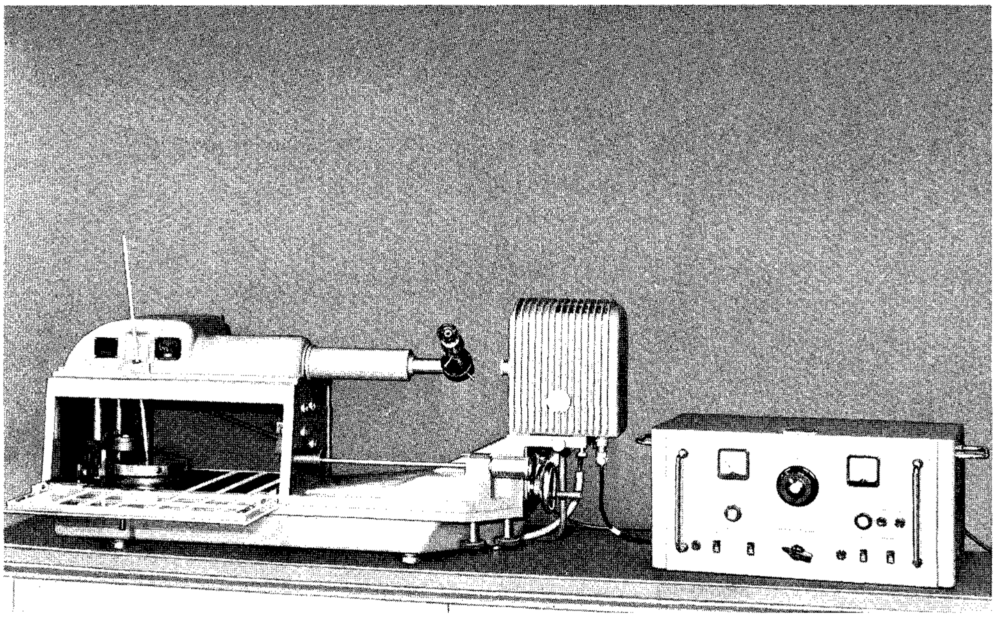


FIG. 206—*A schematic of the roller-checking device in Fig. 202. Although very simple and practical, it is believed this is the first design to employ the principle of gage blocks for an anvil and a "backstop."*

FIG. 207—*NPL-Hilger Interferometer*
Courtesy of Rank Precision Industries, Ltd.



Interferometric Measurement of Length

Gage blocks and other end standards may be calibrated to a high resolution of accuracy by interferometric means. Fig. 207 shows the NPL–Hilger Gauge Interferometer; Fig. 208 gives a diagrammatic explanation of the system. Fig. 209 shows the Tsugami Gage Interferometer; Fig. 210, its optical arrangement.

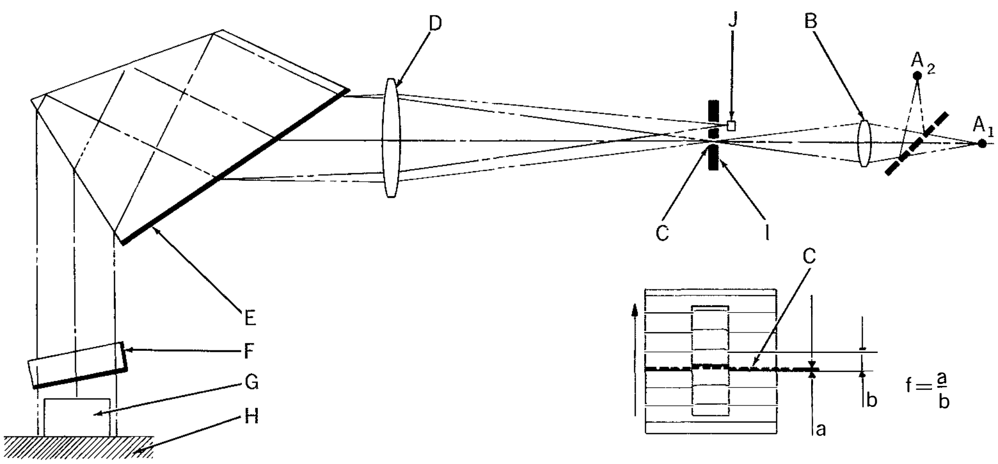
When measuring by "absolute" means, the case with the two systems illustrated, it is necessary to determine which particular half wavelength is registering, since only the fractional value of a fringe is evident to the observer. The possibility exists that there may be many multiples of $\lambda/2$ deviation.

This calculation can be accomplished fairly easily by one of two methods:

In the first, the gage block can be compared to another gage block whose length is known to less than one fringe. However, it is more common for the gage to be calibrated by 2 or 3 light sources of varying wavelengths; by a process of "coincidence", then, the correct wavelength is calculated. The manufacturer often furnishes a special slide-rule to facilitate this calculation.

Total Phase Correction—Just as mechanical measurements entail "corrections," the same is true for optical measurements. "Phase correction" refers to a correction which must be made due to a "phase shift" of light waves when the incident ray is reflected from materials other than optically finished glass or quartz (which have "zero" phase shift). In perfectly lapped steel, the phase change correction amounts to approximately .0000008 (.8 millionths) inch [0.00002 mm].

Total phase change correction generally includes the total amount that the incident ray of light appears to reflect from below what would be called the *mechanical* surface of the object, sometimes referred to as "penetration", Fig. 211.



Optical system

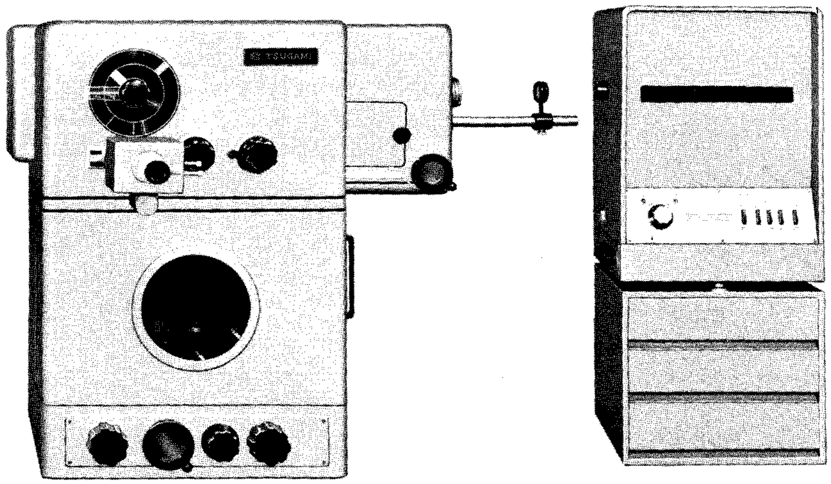
"The optical system is illustrated here. The light from one of two discharge tubes A is focused by a condenser lens B onto the entrance slit C which is set at the focus of an achromatic objective D. The light from the objective emerges as a parallel beam, is dispersed by the constant-deviation prism E, and finally reflected down to an optical flat F, which is supported above, and at a slight angle to, the upper surface of the gauge G. The lower surface of the optical flat is coated with a layer of bismuth oxide to allow for transmission and reflection of the light. The light then passes to the upper surfaces of the gauge and the steel platen H, to which the gauge is wrung. The rays from these two surfaces are reflected back in the reverse direction along a slightly different path so that they emerge from an exit slit above the entrance slit. A mirror J is situated behind the plate I to reflect the light into the telescope.

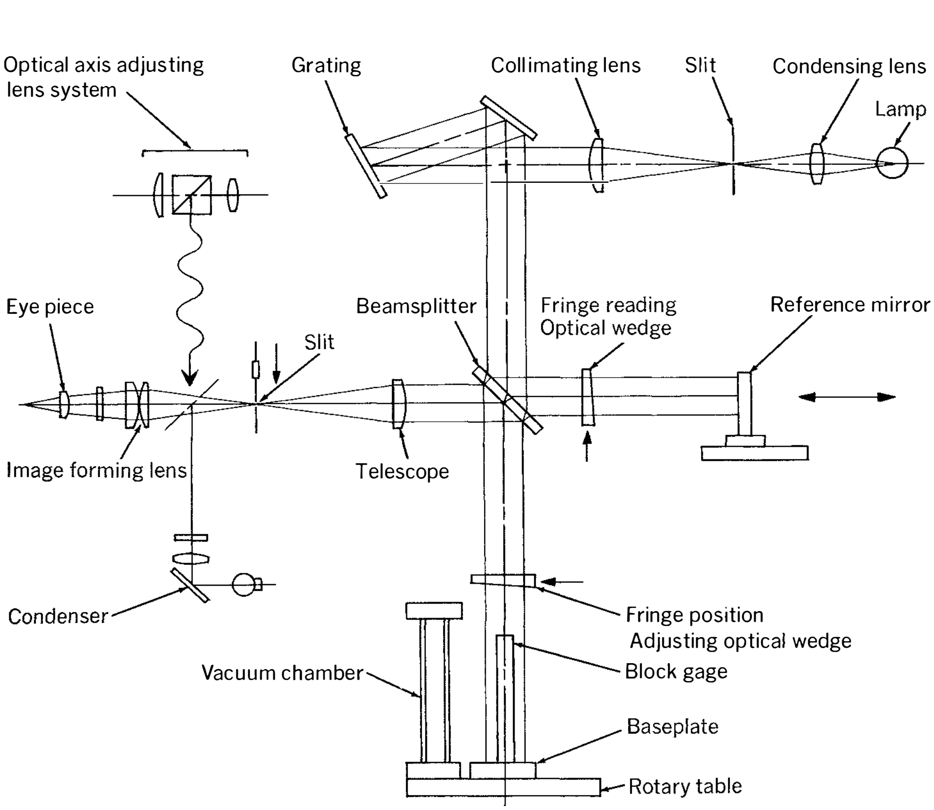
The optical flat can be moved up or down depending on the length of the gauge to be measured; this adjustment is necessary since brighter and sharper fringes are obtained with a reduction in path length. By inclining the optical flat, two sets of parallel interference fringes will be seen: one set from the face of the gauge, and the other from the surface of the platen. The fringes will be displaced, however, and in order to measure the length of a gauge it is necessary to determine the fringe fraction for three or four wavelengths—that is, the fringe displacement in terms of the fringe spacing.

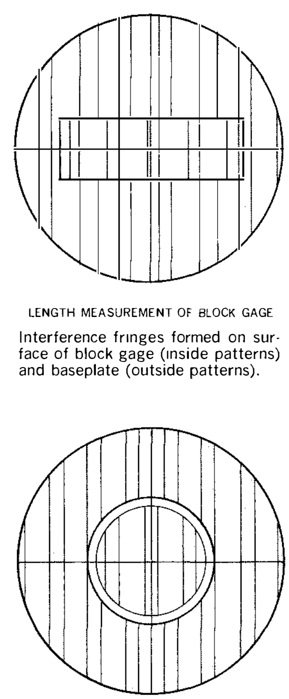
If a is the displacement, b the fringe spacing, the fringe fraction $f = a/b$ (above). This fraction can be estimated to $\frac{1}{10}$ of a fringe spacing or better. An adjustable cross-wire C may be used."

FIG. 208—*Optical system of the NPL-Hilger Interferometer*
Courtesy of Rank Precision Industries, Ltd.

FIG. 209—*Tsugami Gage Interferometer.*
Courtesy of Tsugami Mfg. Co., Ltd.







LENGTH MEASUREMENT OF BLOCK GAGE

Interference fringes formed on surface of block gage (inside patterns) and baseplate (outside patterns).

WAVELENGTH CORRECTION

Interference fringes formed on surface of baseplate by light passing through vacuum (inside patterns) and air (outside patterns).

FIG. 210—*Optical arrangement of the Tsugami Gage Interferometer.*
Courtesy of Tsugami Mfg. Co., Ltd.

The correction factor varies from one material to another. It also varies with the surface finish. In the case of gage blocks, the amount of phase change varies from manufacturer to manufacturer, or even for the gage blocks within a particular set. Total phase change correction may amount to as much as 2 or 3 millionths of an inch [0.00005 to 0.00007 mm] for gage blocks, depending on surface finish.

Wringing Film Thickness—By definition, the length of a gage block includes the thickness of one wringing film. The thickness of a wringing film is approximately ¼ millionth of an inch [0.000006 mm] regardless of the lubricant selected. However, an improper wring may easily result in a value many times that amount.

Silicone or filtered kerosene are two lubricants suggested, the latter perhaps the more preferable. It is sometimes specified that surfaces which are to be wrung together should be absolutely dry. While admittedly the lubricant should be wiped ever-so-thin, there is as much danger from too little lubricant as from too much. A truly clean surface, though difficult to attain, may not wring satisfactorily.

The necessity of being able to measure these thin films adds to the difficulty of interferometric measurements. Adding further to the complexity of this measurement problem is the difficulty of separating the effects of wringing film and phase "penetration," and at the same time measure each exactly. The refractive index of the film must also be known. There is even the possibility that the thickness of the film depends on the type of materials in contact, their flatness and surface finish.

Since light wave emission (krypton 86) is now the official standard of length, and since the surfaces of length standards are used as reflectors in the optical set-up, means are being sought to measure these values as exactly as possible. Young reports that "the uncertainties inherent in these methods presently limit the measurement of length to ±1 micro-inch [±1⁄40th μm].*

The above considerations are of greatest concern in measurements below the micro-inch range. P. Kogurt states that from his practical experience, and the author is inclined to share his view, the most important factor in obtaining reliability in the measurement of a gage block is simply that it must have good *geometry.***

3. Measurement in Science and Industry

The history of "official" length standards has been traced separately from the mainstream of the history of measurement for purposes of continuity. Standing alone, such a chronology is somewhat misleading and historically inaccurate. The evolution of measurement in all of its forms of which *length* is only one aspect cannot be comprehensively presented except when related to concurrent scientific and industrial development.

The history that follows pursues three main currents which will be seen to be continually cross-influencing: *measurement, machine tools,* and *interchangeability.*

Interchangeability is contingent on measurement. This fact should be readily apparent, for through interchangeability, parts can be made to match and to assemble without trial-and-error fitting, providing they are first made to exact dimensions. The relationship of machine tools to measurement, however, is less obvious.

*T. R. Young, "Analysis of Phase Correction In Interferometric Length Measurement," NBS Report No. 9022, September 30, 1965.

**Author's conversation with P. Kogurt, Chief Metrologist of the Eli Whitney Metrology Laboratory, Sheffield Corporation, May 21, 1969.

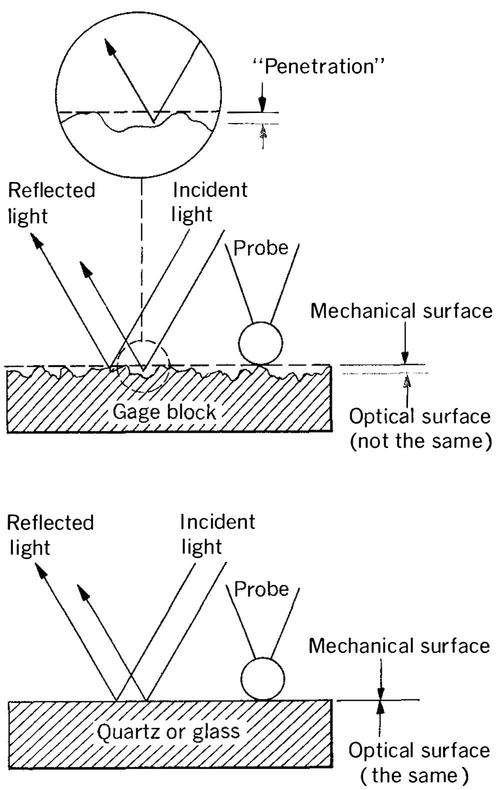
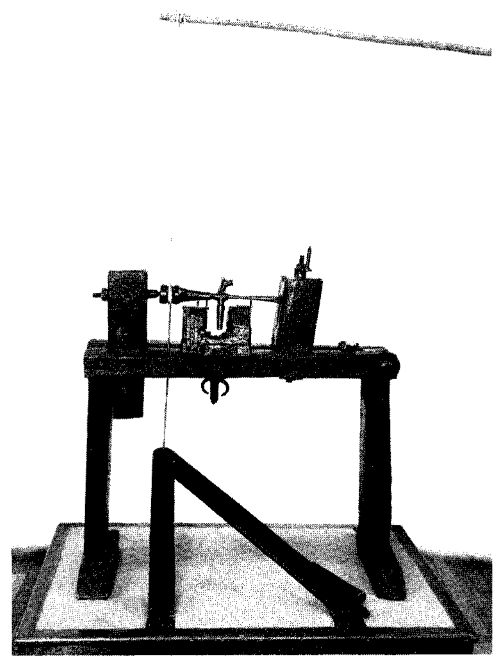


FIG. 211—*When measuring standards by interferometric means, a correction must be applied to relate optical to mechanical length.*

Incident light undergoes a phase change and appears to "penetrate" the surface, reflecting from a point below what might be called its mechanical surface. "Penetration" also varies with surface finish.

FIG. 212—The pole lathe, circa 1800, dates to antiquity. It employs principles common to the modern lathe.
Lent to Science Museum by Thomas Noaks and Sons, Ltd., London.



SIGNIFICANCE OF MACHINE TOOLS

Man is a tool-making animal. His tools are an extension of his limbs and his intellect; they enable him to perform tasks faster and more proficiently than his body alone is capable of doing. The entire physical level of civilization depends on the level of sophistication attained in making and using tools.

Machine tools are man's most significant tools, since their purpose is to create *other* tools, instruments and machinery. To make a distinction, machinery such as a weaving machine or a printing press may solve one problem, but have no heirs. A machine tool such as a lathe or jig borer, on the other hand, solves many problems in addition to generating a vast progeny. Indeed, one definition of a machine tool is that in the machinery family, only the machine tool can reproduce itself.*

Our present high standard of living is derived from mass-production. Mass-production is not possible without interchangeability. The level of interchangeability depends on accuracy of tools. The accuracy of a tool, such as a stamping die, depends ultimately on the machine tools which made it. Because the accuracy of machine tools is the essential consideration, it is revealing to trace the development of some of the more accurate machine tools and to note their historical contribution.

One notable characteristic of outstanding mechanics and machine tool builders would seem to be their obsession with accuracy. The significance of this relationship is an important part of the following chronicle.

The Industrial Revolution, conceded to have begun in England about 1710 with Newcomen's atmospheric steam engine, and to have reached full thrust by 1800, is one of the most important stages in man's history. It is at this time that man truly began to multiply his efforts through the use of machines. A major but too-little explored impetus behind the dynamic growth attending this period is the development of machine tools from 1790 to 1840, first in England and later in America. In point of fact, the designs of basic machine tools today are fundamentally the same as they were in the middle of the nineteenth century.

*Fred H. Colvin, *"60 Years with Men and Machines—An Autobiography"*, p. 6.

WHAT DELAYED THE DEVELOPMENT OF MACHINE TOOLS?

An Englishman named Maudslay, more than any other individual, deserves credit for the accelerated development of machine tools. This mechanic and machine tool builder was then at the peak of his inventiveness (see page 142). However, why did this development begin in England, and why not until the time of Maudslay?

The essential *ingredients* had long been in existence. To begin with, there were many skilled craftsmen. Early mechanical devices, such as a clock installed in Salisbury in 1386, showed a high degree of craftsmanship. These devices were built by skilled blacksmiths; they were not the products of machine tools.

Secondly, basic mechanical principles were known. The pole lathe, Fig. 212, for example, dates to antiquity. The screw thread, one of the most fundamental principles of a machine tool, traces to Archimedes, who introduced it as a means of raising water. An old illustration of 1483, Fig. 213, shows that mechanical means were used to produce screw threads out of wood with a true compound slide rest 300 years before the time of Maudslay, with whom this development is usually associated.*

Thirdly, there was no want of inventiveness. Renaissance man was fully as inven-

*Edwin A. Battison, "Screw-Thread Cutting by the Master-Screw Method Since 1480," United States National Museum Bulletin 240, Smithsonian Institution, Washington, D.C., 1964.

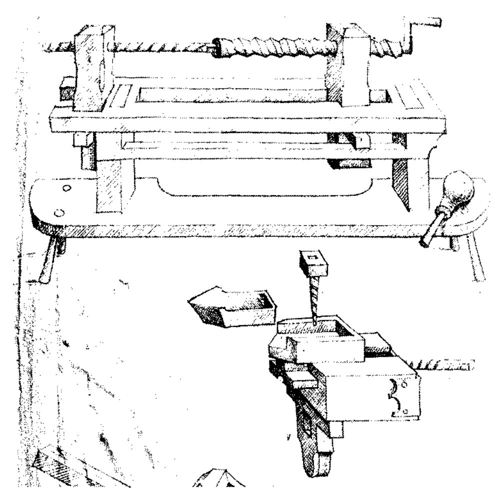
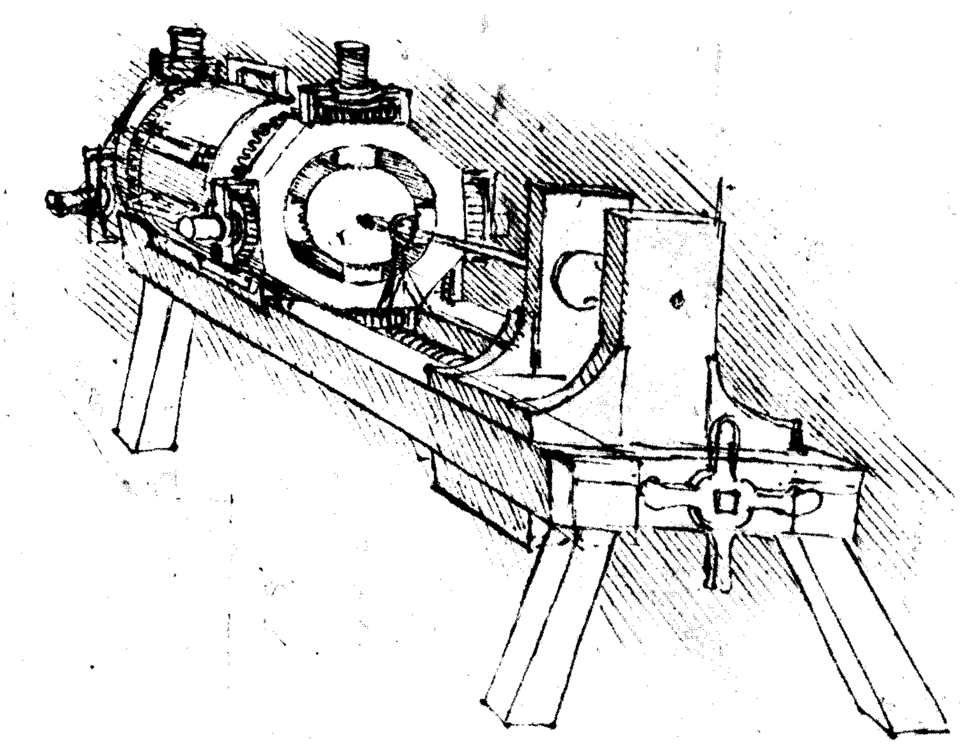


FIG. 213—Screw-cutting lathe dating to about 1483 produced screw-threads out of wood and employed a true compound slide rest.
Courtesy Hausbuch, Germany.

FIG. 214—*Da Vinci sketched a boring mill with a self-centering chuck about 1500.*
Courtesy of Science Museum, London.



tive as his counterpart of the Industrial Revolution. The world may never again see a DaVinci, who in 1500 anticipated in his sketches machine tool principles which would not evolve for nearly 300 years. Such devices as a boring mill with a self-centering chuck, Fig. 214, an internal grinding machine, and a screw-cutting lathe *with change-wheels to obtain different leads* Fig. 215 are among his many drawing-board inventions.

Finally, there was no want of scientific method. Early instrument and clock-makers in France, such as Jacques Besson (1569), who was known especially for ornamental turning, were making items requiring highly developed skills. Charles Plumier, moreover, published *L'art du Tourneur* as early as 1701.

Renaissance man, it should be noted, did not put into practice the products of his thinking. His complex mechanisms were rarely built. Consequently, no lineage or development ensued. It was not until machine tools were fashioned from metal and designed, in addition, to *cut metal* that machine tools came into their own. While the instrument-makers had precision equipment, often made of metal, their skills did not extend to machine tools. The machine tools they did use remained primitive, as a result.

The Chinese and Indians were familiar with the techniques of producing crucible steel before the time of Christ. Europe used crude methods of carbonizing steel until the process of producing crucible steel was rediscovered by Benjamin Huntsman in 1746.

Sweden had vast timber resources and a good supply of high grade iron; during one period she supplied England with as much as four-fifths of its wrought iron. Although definite proof is lacking, some records, such as those from the Swede, Polhem (1740), describe the use of heavy duty industrial lathes for turning rollers to roll strip and bar iron; they even trued by grinding. Swed-

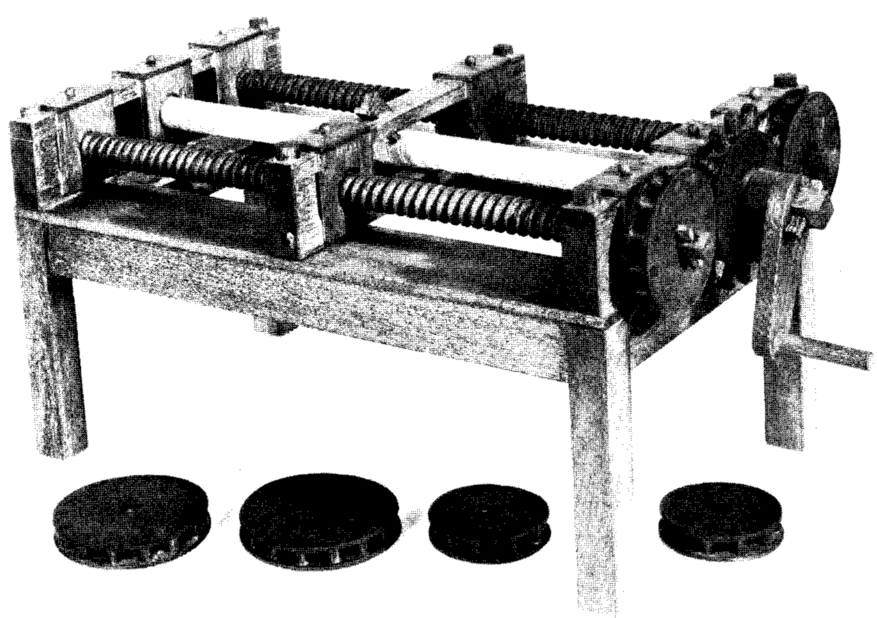


FIG. 215—*Renaissance man designed but often did not build his mechanical contrivances; note this screw-cutting lathe with change wheels to obtain different leads, modeled after sketch by Da Vinci.*
Courtesy of Science Museum, London.
British Crown Copyright.

ish influence was not spread, however. To be sure, the Swedes were great travelers, but they concerned themselves with looking for ideas, not spreading them.

Old records and prints indicate that many of the first machine tools, dating to the early eighteenth century, were invented by the French. A good example is Vaucanson's lathe of 1765, designed along modern principles using two 1½ inch [38.1 mm] square bars set on edge as prismatic guideways (an early double-V). While ingenious, these inventions rarely found application.

It is in England that machine tools were first given finished form and excellence. The first machine tools offered for sale were constructed in Matthew Murray's famous Round Foundry about 1800. Indeed, well into the nineteenth century, both France and Germany imported most of their machine tools from England.

EVOLUTION OF CANNON-BORING MACHINES

A sequence of events following the evolution of cannon-boring machines and the consequent development of the boring mill can be credited with sparking the Industrial Revolution. They also explain why the forces of change took hold in England and then spread throughout the rest of Europe.

The art of boring cannons goes back at least three or four hundred years. An old print of 1540 shows a water-powered cannon-boring mill. The earliest methods were not accurate primarily because the boring tool was guided by the cast hole. Maritz, a Swiss, invented a mill to allow boring from solid, probably about 1713. He went to the Netherlands Gun Foundry at The Hague, where the method was adopted. The technique was further improved in 1755 by Verbruggen, Fig. 216. After his discharge from The Hague Foundry in 1770, Verbruggen was appointed Master Founder at the Royal Arsenal of Woolwich, England.

By the early 1700's, England had virtually depleted its supply of wood. In 1711, Abraham Darby began to mine coal for the smelting of iron. Increased use of coal gave Newcomen the idea of developing a workable steam engine for mine-pumping. Newcomen's design was that of an "atmospheric" engine. Steam lifted a piston, and the pumping was accomplished on its fall, facilitated by a vacuum created by cooled, condensed steam. Most of the power from the steam, however, was wasted.

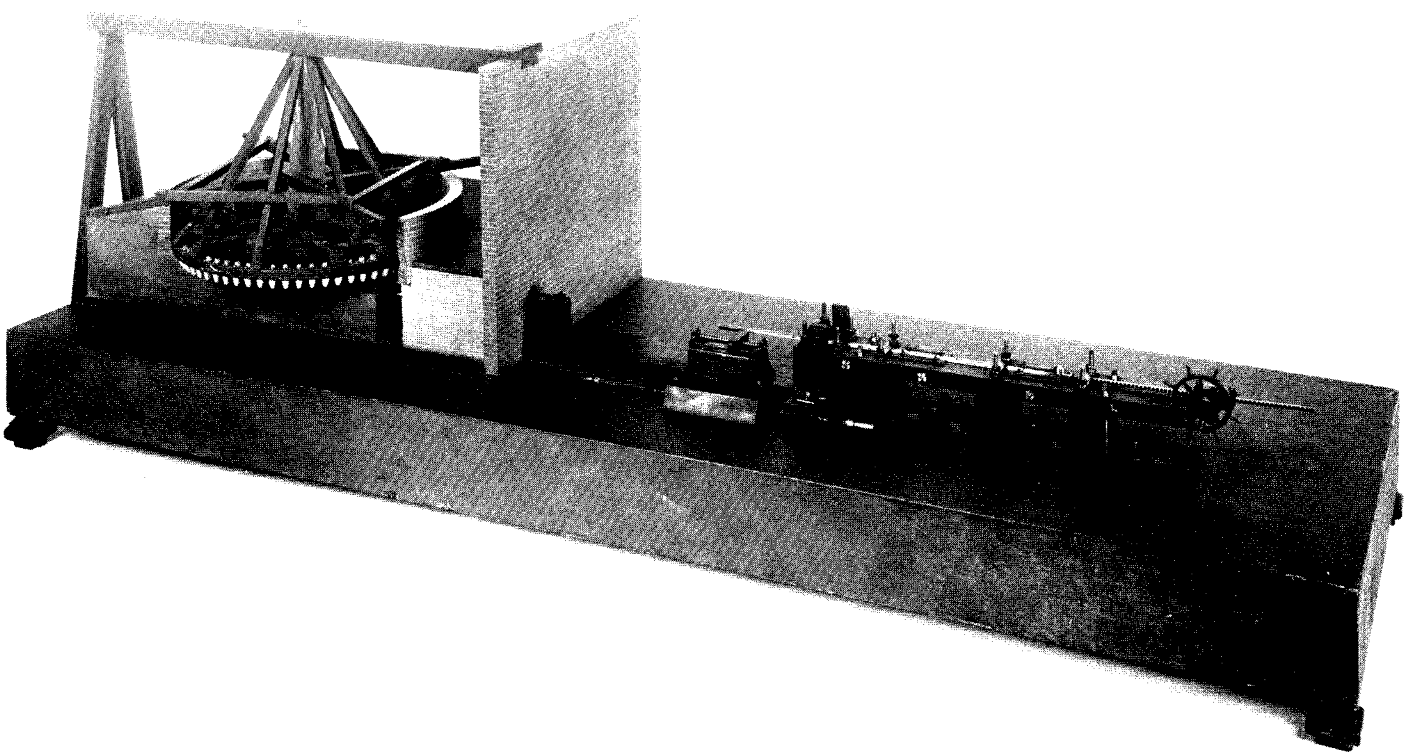


FIG. 216—*A gun-boring machine by Verbruggen (18th Century) was an important step in the evolution of boring machines.*

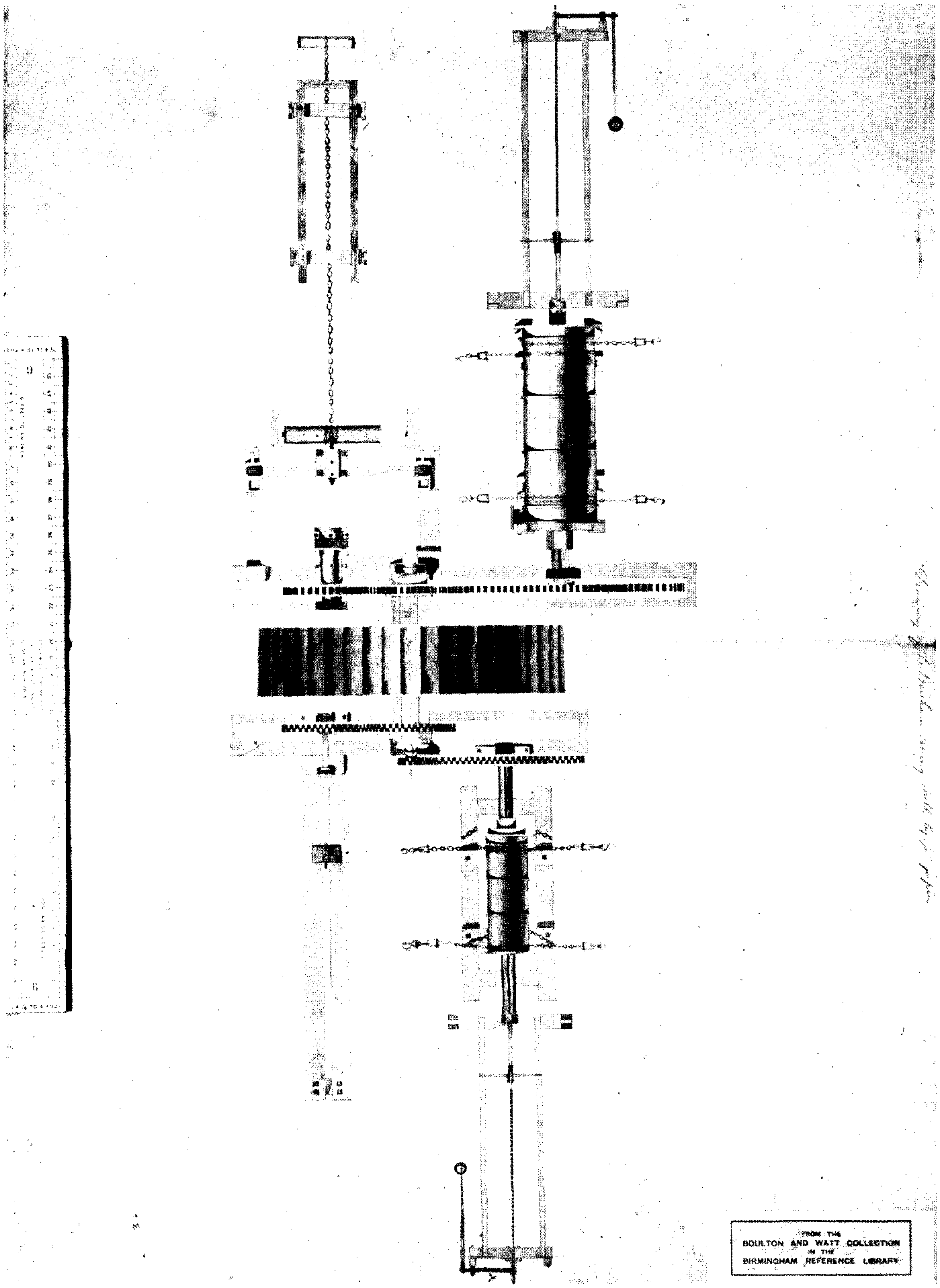


FIG. 217—*Wilkinson's gun-boring mill enabled Watt to establish a true bore for the cylinder of his steam engine, making possible its success.*

The steam engine helped spur the Industrial Revolution.
Courtesy of Science Museum, London.

James Watt

James Watt's steam engine had great historical impact, but its success had to await an improvement provided by machine tool technology. The design of Watt's steam engine differed significantly from Newcomen's. The piston stroke was powered by steam which required "that the cylinder be kept always as hot as the steam that entered it."* It was the first true steam engine as we know it today.

Watt was confronted with several problems in building his engine, but because of his early training as an instrument maker, he was always guided by scientific principles. Such refinements as the "condenser," for example, resulted from Watt's knowledge of the nature of steam.

The prime reasons Watt's engine was so long in the making is that, first of all, the finer workmanship required for its design was unavailable. Part of this problem was alleviated, however, by his alliance with a mechanic and foundryman, Matthew Boulton. Secondly, the success of his engine was contingent on establishing a true bore in his cylinder. Carnegie states the problem: "It was still the cylinder and its piston that gave Watt the chief trouble. No wonder the cylinder leaked. It had to be hammered into something like true lines, for at that day so backward was the art that not even the whole collective mechanical skill of cylinder-making could furnish a bored cylinder of the simplest kind."**

Wilkinson's Cannon-Boring Machine

Watt's greatest difficulty was finally solved in 1776 by John Wilkinson, an iron-master. Wilkinson's cannon-boring machine, used to bore Watt's steam-engine cylinder, was much like that of Verbruggen, with which Wilkinson was entirely familiar. The boring bar was guided from both ends, independent of the casting, Fig. 217.

*Andrew Carnegie, *James Watt*, p. 41.

***Ibid.*, p. 46.

His main obstacle overcome, Watt was elated: "Mr. Wilkinson has improved the art of boring cylinders," he exclaimed, "so that I promise you a 72-inch [1828.8 mm] cylinder being not further from absolute truth than the thickness of a thin sixpence in the worst part."* Commenting on Wilkinson's invention, J. Robert Moore wrote:

> "Wilkinson's contribution, in the light of present-day knowledge, appears exceedingly simple. Actually, it was a tremendous forward stride. It embodied, apparently for the first time, the idea of *generating* an internal cylindrical surface by boring around a fixed axis. This simple invention was an enormous contribution to mechanical progress. Without it, a host of present-day devices, especially those embodying hole *location* would be impossible to mass-produce."**

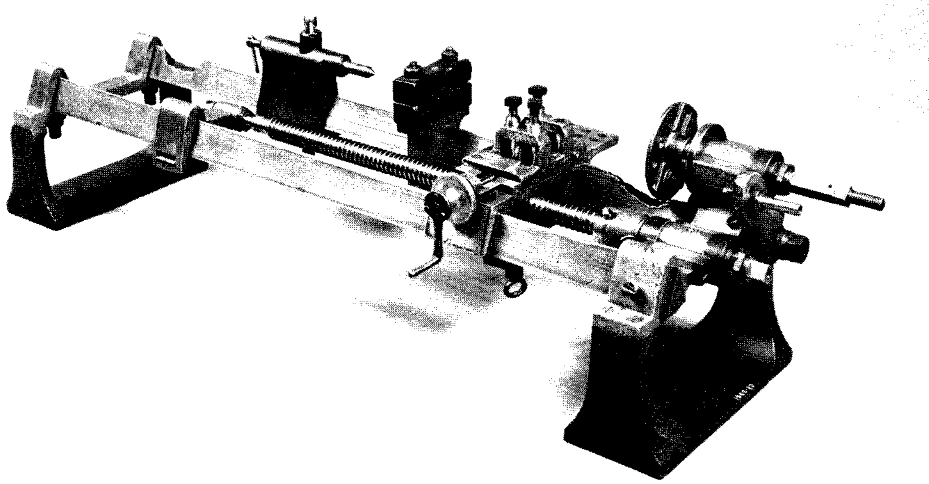
It is doubtful that Wilkinson was the first to generate a hole in this manner. More likely, the reason for this assumption is its association with boring the cylinder of the first truly efficient steam engine. In any case, this concept influenced the development of hole-location devices, and was an early ancestor of the jig borer.

Steam engines became the preoccupation of nearly every mechanic in England. Engineers such as James Nasmyth "cut their mechanical teeth" on this fascinating development. Steam engines accelerated the industrial growth of England. Power could now be brought to an industrial location instead of having to depend on proximity to water, as was the case in America. This was the reason for Boulton's initial interest in the steam engine. The shift to steam-generated energy prompted many technological advancements. The development of "self-acting" machine tools, for example, was a major product of steam technology.

*L. T. C. Rolt, *Tools for the Job*, p. 56.

**J. Robert Moore, *Precision Hole Location*, p. 55.

FIG. 218—*Maudslay's original screw-cutting lathe, circa 1800.*
Courtesy of Science Museum, London.



MACHINE TOOL DEVELOPMENT IN ENGLAND

Henry Maudslay (1771–1831)

In the significant period between 1790 and 1840, one man—Henry Maudslay—ranks above all others in mechanical skill and contributions to machine design. He was born in Woolwich, August 22, 1771 and, at an early age, learned many machine principles at Woolwich Arsenal. He is associated with the development of the lathe slide rest, as well as other machine tool innovations. Roe calls the slide rest "one of the great inventions of history!"*

The reasons for Maudslay's acknowledged fame as a mechanic have not always been understood. His prismatic way design in his first classic lathe was pre-dated by Vaucanson; the design of his screw-cutting lathe, Fig. 218, was strongly influenced by the work of Jesse Ramsden (1735–1800), an instrument-maker whose screws were used to make precision linear scales; Maudslay was never identified, as was Murray, with the development of machine tools for sale.

Maudslay's importance was actually two-fold. The essential characteristics of a machine tool builder came together in one man for the first time: He understood the concept of generously using iron, steel and brass, as opposed to wood, for making *metal* parts, and he brought to bear the skill and good design sense of the instrument maker. Secondly, he must be appreciated as an historical figure who greatly influenced subsequent events. The legacy of Maudslay, the machine tool builder, can be measured by the eminence of his disciples—Bramah, Clement, Whitworth, Nasmyth—all of whom either worked in his shop or came under his influence, Fig. 219.

An insight into the character of Maudslay comes from Nasmyth's notations of some of his favorite maxims:

*Joseph W. Roe, ***English and American Tool Builders***, p. 36.

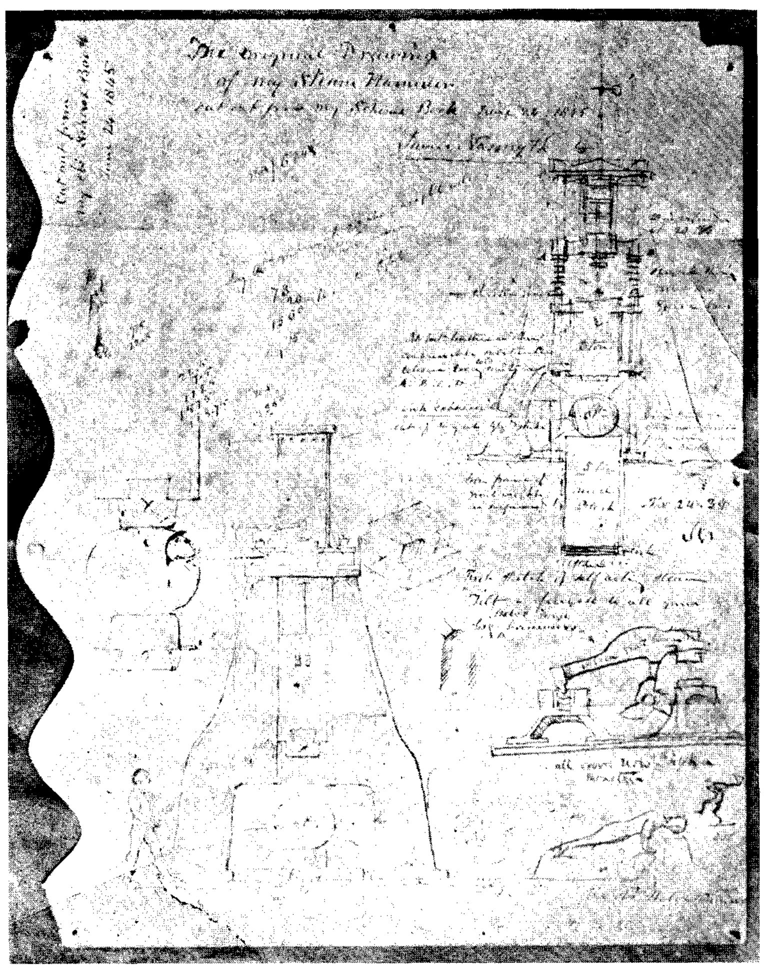
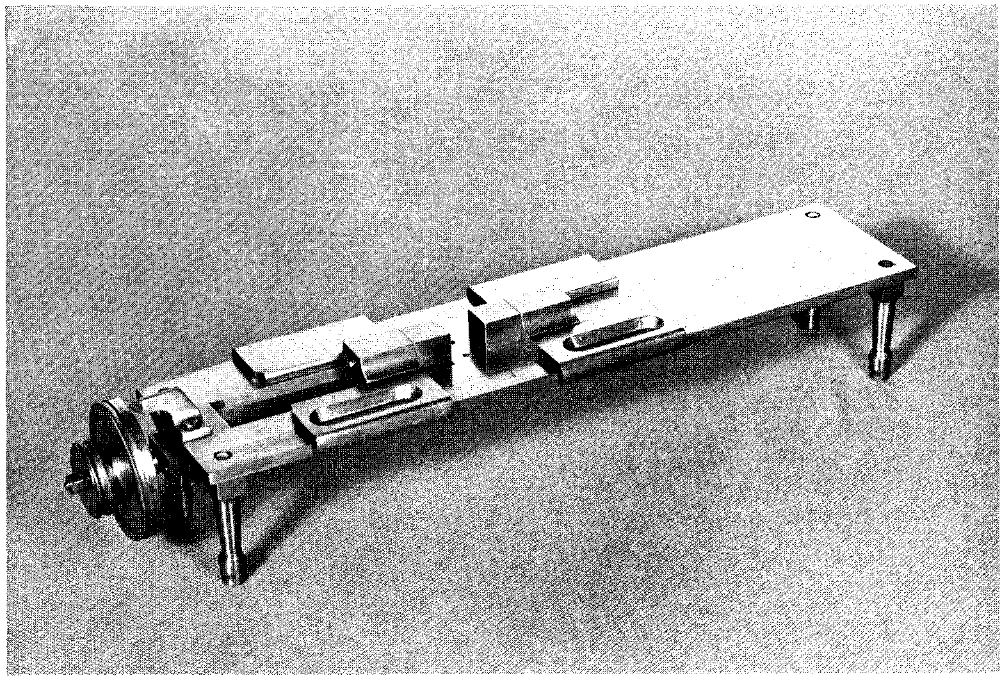


FIG. 219—*James Nasmyth, like many famed mechanics, was strongly influenced by Maudslay's principles. Shown is Nasmyth's original drawing of his invention—the steam hammer.*
Courtesy of Science Museum, London.

FIG. 220—*Believed to be Maudslay's "Lord Chancellor,"† a measuring instrument which employed a master screw having 100 threads to the inch [approximately 4 threads per millimeter]. It could detect minute differences in length, circa 1800.*
Courtesy of Science Museum, London.



"First, get a clear notion of what you desire to accomplish, and then in all probability you will succeed in doing it . . . . ."

"Keep a sharp look-out upon your materials; get rid of every pound of material you can *do without;* put to yourself the question, 'What business has it to be there?' Avoid complexities, and make everything as simple as possible . . . . ."

"Remember the get-at-ability of parts."*

These homespun remarks embody the very essence of good machine tool design.

Perhaps the most important factor contributing to Maudslay's success, however, was his devotion to accuracy, notably in the creation of *true planes.* Maudslay was also fascinated with the principle and use of the accurate screw-thread. Nasmyth acknowledges that the first to use a screw as a measuring element was William Gascoigne (1648). Yet he goes on to say: "The production of perfect screw threads was one of Maudslay's highest ambitions and his principal scientific achievement."**

Maudslay's "Lord Chancellor", Fig. 220, a measuring instrument having 100 threads per inch [approximately 4 threads per mm], was recently found to be amazingly accurate when tested by modern methods.***

Nasmyth describes the instrument:

"Not only absolute measure would be obtained by this means, but also the amount of minute differences could be ascertained with a degree of exactness that went quite beyond all the requirements of engineering mechanism; such, for instance, as the thousandth part of an inch [0.0254 mm]! It might also have been divided so far as a millionth part of an inch [0.000025 mm] but these infinitesimal fractions have really nothing to do with the effective machinery that comes forth from the workshops, and merely show the mastery we possess over materials and mechanical forms."*

*James Nasmyth, *Autobiography,* p. 127.

**W. A. S. Benson, "The Early Machine Tools of Henry Maudslay," *Engineering,* February 1, 1901, p. 134.

***C. S. Davison, "Report on Maudslay's Micrometer—1805," Science Museum, London, September 23, 1959.

While Maudslay was undoubtedly influenced by the works of others, he was nonetheless an originator of ideas.

Joseph Whitworth (1803–1887)

Perhaps better known than Maudslay, Joseph Whitworth, born in Stockport, Cheshire in 1803, deserves credit more for a high standard of accuracy, than for true inspiration. The ideas he espoused were primarily elaborations of principles first encountered while working in Maudslay's shop.

†Unpublished letter to author from Robin Gosling, Science Museum, London, August 26, 1966 indicates that researchers are assured this instrument is unquestionably Maudslay's "Lord Chancellor".

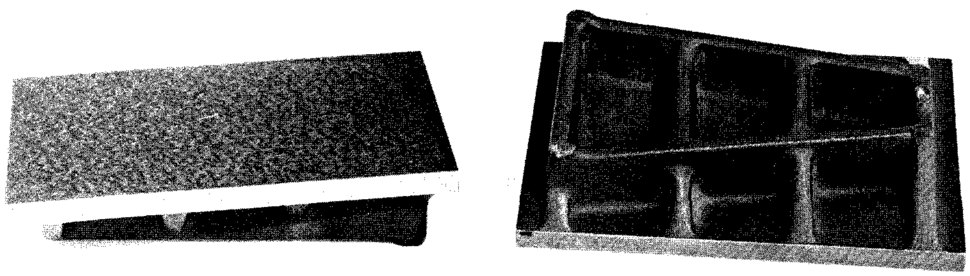
*James Nasmyth, *Ibid.,* p. 146.

In a Presidential Address to the Institution of Mechanical Engineers in 1856, Whitworth spoke of ". . . the vast importance of attending to the two great elements in constructive mechanics, namely, *a true plane* and *power of measurement.* The latter cannot be obtained without the former, which is, therefore, of primary importance . . . all excellence in workmanship depends upon it."*

The classical method of creating a flat plane by the three-plate method is usually credited to Whitworth, although Nasmyth,

*Joseph W. Roe, *English and American Tool Builders,* p. 99.

FIG. 221—*The three-plate method of generating a flat plane traces to Maudslay. Whitworth probably first employed hand-scraping to generate flatness, as in these scraped plates which he prepared.*
Courtesy of Science Museum, London, British Crown Copyright.



who apprenticed under Maudslay, attributes this development to his mentor Maudslay. It is likely that Whitworth substituted *hand-scraping* for "grinding" (lapping with abrasive powder) in the final finishing, and that he first did this while in Maudslay's shop, Fig. 221.

Whitworth exhibited in 1855 a "Measuring Machine," Fig. 222, based on "end measurement," which, it is said, could detect *differences* as small as one-millionth of an inch [0.000025 mm]. In all probability, this machine did not originate sizes, but simply compared minute differences.

Whitworth said this about the advantages of end measure:

> "We have in this mode of measurement all the accuracy we can desire; and we find in practice in the workshop that it is easier to work to the ten-thousandths of an inch [0.0025 mm] from standards of end measurements, than to one-hundredth of an inch [0.25 mm] from lines on a two-foot rule [610 mm]. In all cases of fitting, end measure of length should be used, instead of lines."*

The Whitworth Works rapidly grew in prestige, and by 1860 was the best-known throughout England. Its reputation began to wane after this date, however, largely because of Whitworth's autocratic approach to business. Nevertheless, his contribution was enormous and is fittingly commemorated in the "Whitworth Room", Fig. 223, of the Institution of Mechanical Engineers in the United Kingdom.

MEASUREMENT IN AMERICAN INDUSTRY—INTERCHANGEABILITY

While England was to achieve early prominence in machine tools and steam engines, quite another chain of circumstances was occurring in America, distinctive to Ameri-

*Joseph W. Roe, *English and American Tool Builders*, p. 101.

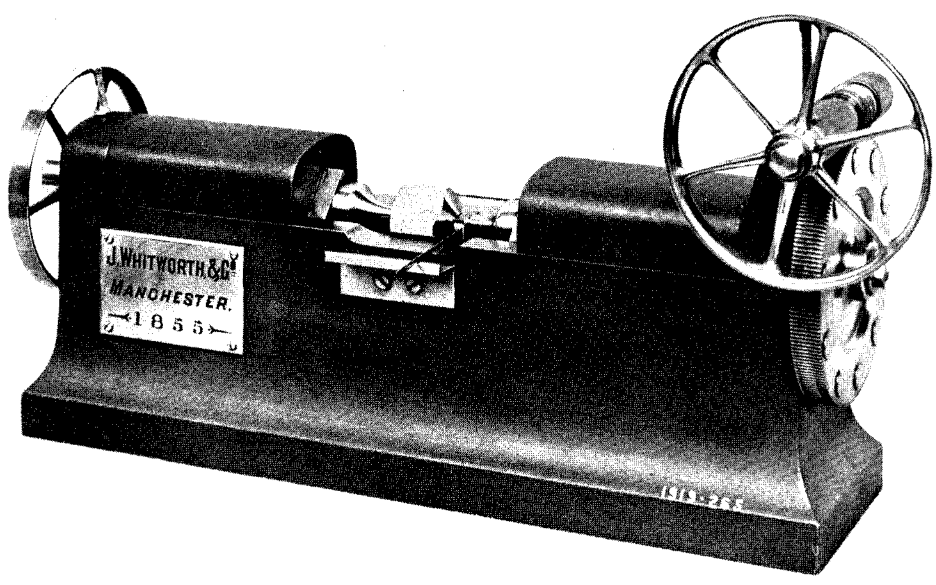


FIG. 222—*Whitworth's "Millionth of an inch" [$^{1}/_{40}$ µm] measuring machine of 1855.*
Lent to Science Museum by Sir W. G. Armstrong, Whitworth & Co., Ltd., London.

FIG. 223—*The "Whitworth Room" commemorates the enormous contributions of Joseph Whitworth to mechanics.*
Courtesy of Vickers, Ltd.

can conditions. These circumstances ultimately led to the concept of *interchangeability.*

America's adoption of the system of interchangeability quickly gave it world prominence and provided a standard of living the rest of the world never dreamed possible. Europe was not aware of this system until after 1850, by which time it had been so firmly established in America that it was designated "The American System."

While historians may disagree, the author is convinced that the adoption of this concept had more to do with America's rapid rise to world prominence than any other single factor.

The enthusiasm with which the interchangeable method of manufacture was embraced in America encouraged the development of machine tools. America's machine tool development, while not as early, was rapid, nearly paralleling that of England.

The idea of making parts interchangeable was first projected by armorers in France in 1717. Jefferson, while ambassador to France, saw this approach attempted by the gunsmith, Le Blanc, in 1785. With his mechanical bent, Jefferson was aware of the benefits to be had from this system, but he failed to persuade Le Blanc, through official channels, to emigrate to America. Interchangeability was also unsuccessfully attempted by Bodmer of France in 1811.

Eli Whitney

Eli Whitney "... came from that best school of mechanics, the New England hill farm."* He is justly credited with the first successful application of interchangeable manufacture.

*Joseph W. Roe, *English and American Tool Builders,* p. 146.

Whitney was far from being solely a farmboy, however. Yale-educated, he had mobility in select circles, and utilized his associations to secure contracts from the government for manufacturing rifles. After years of wearisome, frustrating and largely unsuccessful negotiations to secure remuneration from Southern cotton-growers for patent-infringement on his cotton gin, he turned his energies elsewhere.

In 1798, he was awarded a contract by the government to manufacture 15,000 muskets on an interchangeable basis. The government had two reasons for acceding to so unheard of a proposition: the first can be attributed to Jefferson's influence; he understood the principle, and encouraged Whitney through the difficult years. The second was the government's awareness of their dependence on French supplied muskets in the recent war against the British. Now that France herself was a threat to the new nation, the government could not dismiss the prospect of receiving so many needed muskets in the short delivery time promised by Whitney.

Whitney chose to set up his factory in New Haven, Connecticut. He deliberately employed essentially untrained workmen who had no preconceived notions about his system to "unlearn". With a minimum of resources, his undertaking called for heroic effort. Whitney built a dam for power, erected a factory, trained men and designed his own gages and machine tools.

This undertaking consumed him to a point where he worked endless days. As an apparent consequence, he did not marry until late in life. So immense was the task that completion of the musket contract was delayed many years; for unlike the mechanics in England, Whitney had to work out his principles alone.

In 1801, Jefferson wrote Monroe of Whitney: "He has invented molds and machines for making of his locks so exactly equal that take 100 locks to pieces and mingle their parts, and the 100 locks may be put together by taking the pieces which come to hand."*

Whitney's system did not achieve immediate acceptance. Captain Decius Wadsworth, later chief of the Ordnance Department, "... considered interchangeability pleasing to the imagination, rather than practically valuable."**

Nonetheless, by 1819, Major Dalliba, of the Springfield Armory, described *hardened gages* to pass on workpieces. In other words, acceptance of interchangeability had come quickly. In 1820, a government contract for 20,000 pistols awarded to Simeon North specified that any part of any pistol fit any of the 20,000.

It seems inconceivable that the system of interchangeability should have involved only Eli Whitney. More likely, as was the case with the development of machine tools in England, the seeds were there, ready to germinate. Although evidence is scant, it is believed that Simeon North was manufacturing by the interchangeable method at the same time as Whitney, but at least by 1808. Roe suggests that this may have been so.*** Another source puts it more definitely: "The Early Industrialist Simeon North, who was the first man to receive a contract for making government pistols (March 9, 1799), *as well as the first to apply the principle of interchangeable parts in arms manufacture.*"**** (*Italics added.*) This revelation proved interesting to the author since this same North family is part of his own lineage.

*Guy Hubbard, "Development of Machine Tools in New England," *American Machinist.* Series of 23 articles appearing from July 5, 1923 to September 18, 1924.

**Felicia Deyrup, *Arms Makers of the Connecticut Valley,* p. 87.

***Joseph W. Roe, *English and American Tool Builders,* pp. 162–163.

****Connecticut: *A Guide to Its Roads, Lore and People,* p. 112.

ARMS-MAKING, INTERCHANGEABILITY, MACHINE TOOLS

England attempted to stifle the industrial life of the American colonies with its mercantilist policy. An example of this policy was the "Act of 1750"; its purpose was to maintain the colonies as suppliers of such raw materials as iron. Iron-working was even prohibited under penalty of a fine.

Partly as a consequence of England's restrictions, machine tools were not even used before 1800 in the most important area for arms-making, the Connecticut Valley. By 1830, in contrast with England, little headway had been made with steam power.

Whitney's milling machine, Fig. 224, of about 1820—the first of its type—was crude by English standards of the same date. Nevertheless, it was an important forerunner in the rapid evolution of American machine tools.

The circumstances that led to the adoption of interchangeable manufacturing and then to accurate machine tools are closely tied to arms-making.

Frontier life stimulated Americans, already demonstrating great independence of spirit, to achieve even greater self-sufficiency. New settlements were founded around dams used for water power. From this followed grist-mills and then saw-mills. Next came forging-shops and blacksmith shops. Indeed, early gunsmiths were closely allied with blacksmiths, so much so that many sons of blacksmiths turned to gunsmithing.

Experienced gunsmiths accepted contracts and oversaw organized groups of workmen, each group making large lots of certain gun parts—a technique known as "division of labor." Methods of making interchangeable parts were by pattern weapons (samples), swages and jigs, drill jigs and filing jigs. As Hubbard observes in "Development of Machine Tools in New

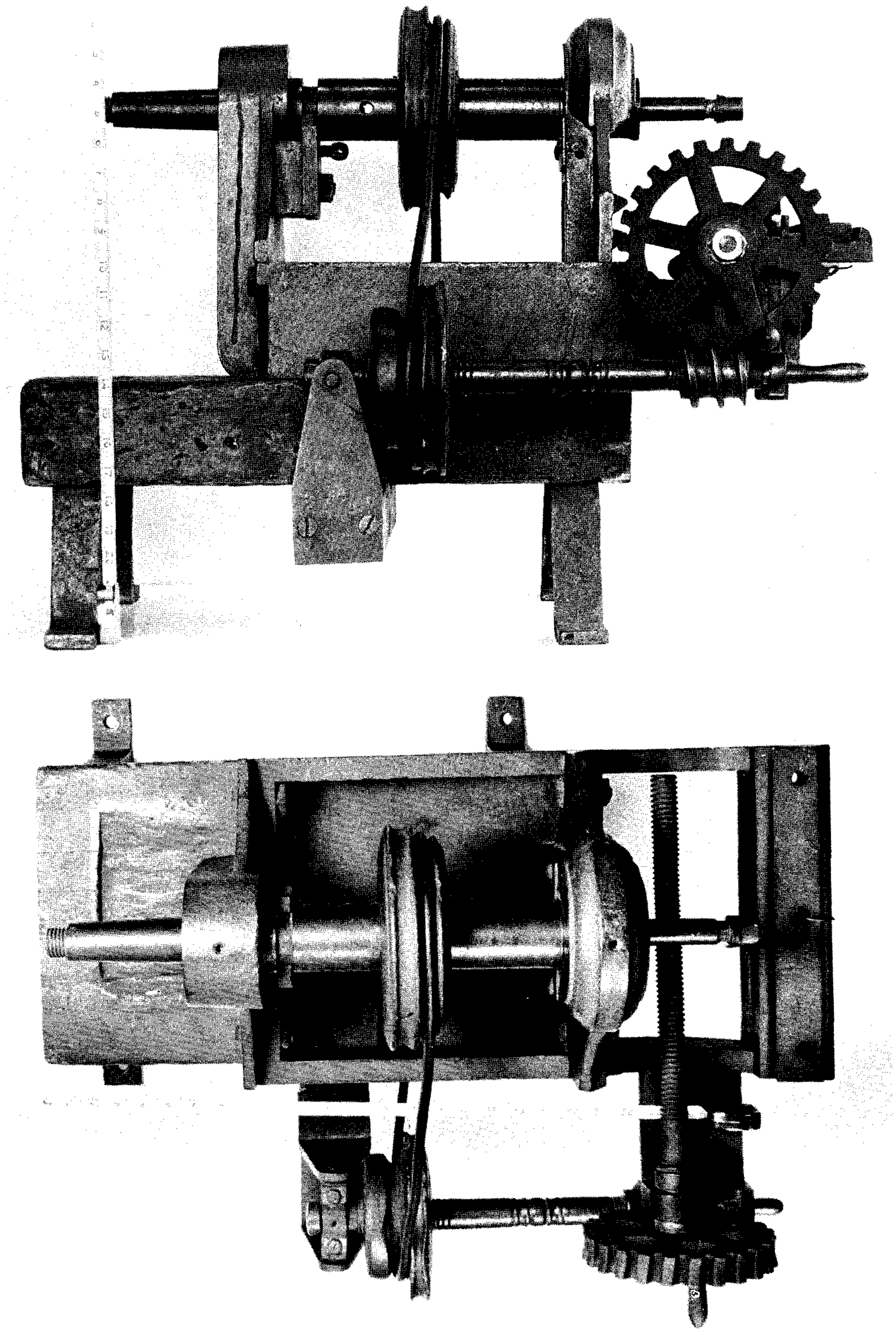
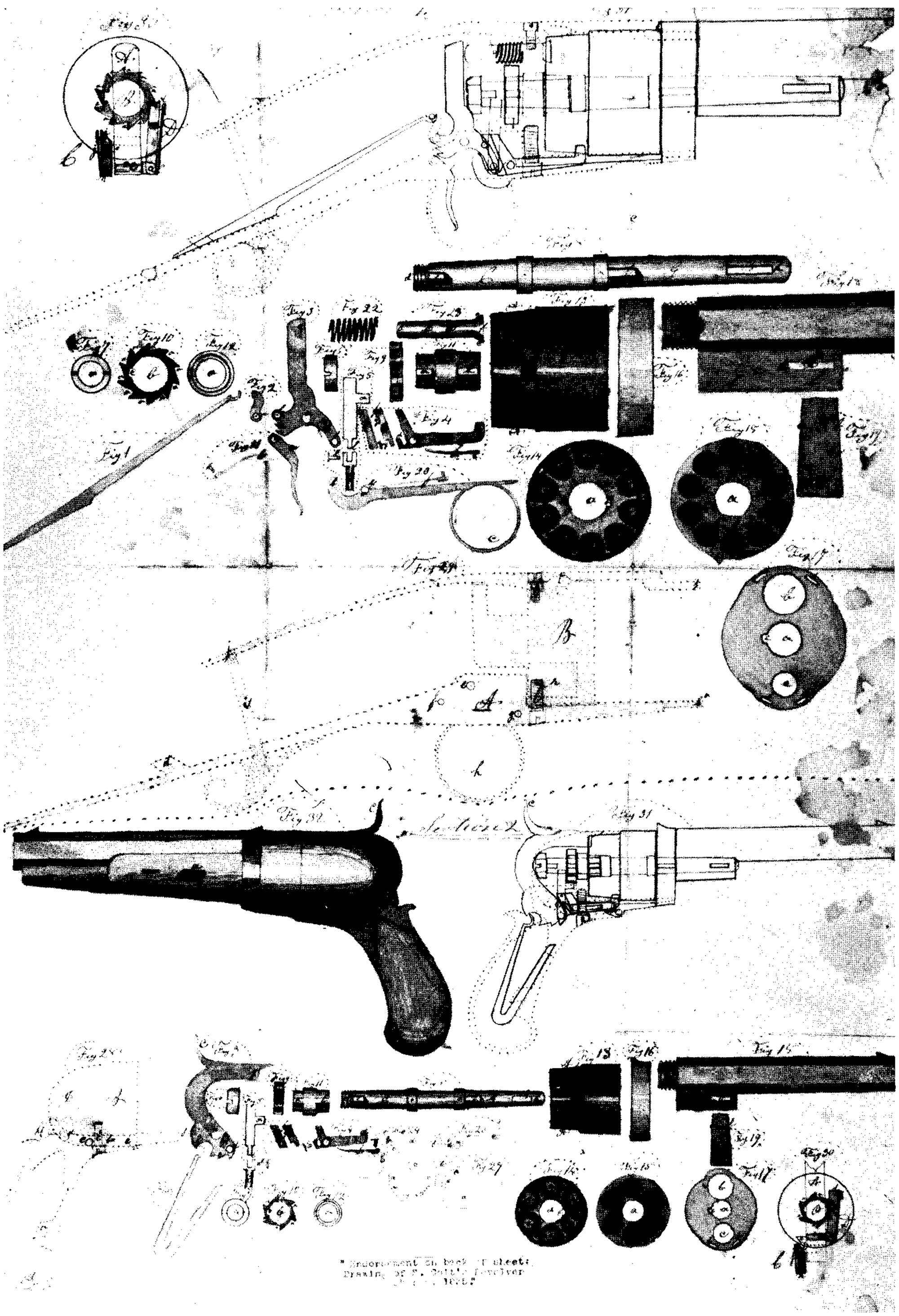


FIG. 224—*Eli Whitney's milling machine (about 1820) was crude by English standards of that date. It was, however, an important forerunner of machine-tools in America which immediately followed.*
Courtesy of New Haven Historical Society.

FIG. 225—*The Colt Revolver, manufactured in Hartford, Connecticut. All parts were made interchangeable, enabling quantity production. This was known as the "American System."*
Courtesy of American Heritage.



England": "Under this system it is evident that the quicker and more cheaply the contractor could do his work and still have it pass inspection, the more money he made and this was naturally a powerful incentive to the invention of improved tools, jigs, fixtures and methods, as well as to the cultivation of keen business and executive ability among the contractors."*

The next step in the movement toward interchangeable manufacturing was almost inevitable: the construction by armorers of special machines to *manufacture parts to dimension.* These machines were soon found adaptable to other processes, from which evolved the idea of *basic* machine tools.

Spurred on by this new approach to manufacturing, schools of inventors, master mechanics and master tool builders gradually emerged. A good example of how this trend took shape and mushroomed is seen in the Robbins & Lawrence Company, from which descended the Jones & Lamson Machinery Company. The firm traces to Windsor, a town which grew up around two dams in Vermont. It owes its origin to a gun made by Nicanor Kendall, the son of a blacksmith. Kendall, Hubbard and Smith later began to manufacture rifles on an interchangeable system, having barrels forged, bored and rifled by Eliphalet Remington, a skilled gunsmith in Ilion, New York.

The system was so effective that they finished one particular contract for rifles 18 months ahead of schedule, an unprecedented event for that time. This naturally led to other contracts; and by 1850, the firm, now known as the Robbins & Lawrence Company, was not only proficient in riflemaking, but had developed many advanced machine tool designs for their manufacture.

Robbins & Lawrence rifles were shown in the Crystal Palace Exhibition in London in 1851. They could be disassembled and all

*Guy Hubbard, "Development of Machine Tools in New England," *American Machinist.* Series of 23 articles appearing from July 5, 1923 to September 18, 1924.

parts interchanged. The official British report states:

"Of these rifles, manufactured by Robbins & Lawrence, it is but just to say that they are among the best, if not *the* best, of any rifles manufactured in the world. . . ."*

These rifles drew the startled attention of such British engineering and military authorities as James Nasmyth, Joseph Whitworth and the Duke of Wellington. At that time, all parts for British rifles were made by hand in different shops. They were then brought to the Tower of London, where each rifle was built up by laboriously filing, reaming and fitting individual parts. The result of this long and involved procedure were rifles that were not only crude, but non-uniform; no two were alike.

Determined to look further into this new approach to manufacturing, an official British commission was sent to America to study not only the plants of Robbins & Lawrence, but also those of Ames, Sharps and Colt, whose arms had also been displayed. The Colt company had been set up only three years earlier by Samuel Colt in Hartford, Connecticut, with the help of Root, a gifted mechanic. The company's primary interest was that of capitalizing on the interchangeable manufacture of revolvers, and no expense was spared in the facilities, Fig. 225.

The most significant result of the Commission's recommendations was a contract from the British government to the Robbins & Lawrence Company for virtually all the machine tools, 150 in number, as well as the tooling, to equip their new Enfield Armory.

No two of the sample rifles supplied to Robbins & Lawrence from England were alike. Moreover, the gages were of wood, accurate to perhaps 1/64th inch [0.4 mm]. The mechanics of the American firm made a master gun from these prototypes. Parts were kept uniform by accurate steel gages, hardened and carefully oilstoned to size.

*Ibid., p. 129.

THE DEVELOPMENT OF STANDARD MACHINE TOOLS

The machines built by Robbins & Lawrence for their own use form the basis of later standard machine tools, and their influence is clearly traced. One example is their plain milling machine, an improvement on Whitney's miller. Closely copied by the George L. Lincoln Company, it became a standard in its line, and for many years thereafter was known as the "Lincoln Miller." Pratt & Whitney was the next company to build the machine based on the Robbins & Lawrence prototype.

Tracing the ancestry of the jig borer in his book *Precision Hole Location,** Robert Moore begins with Wilkinson's cannon-boring machine of 1776. He then goes on to mention a Universal Boring Mill built for Clarke in 1896, Fig. 226. As with the jig borer, this machine generated a hole around the machine spindle axis and located by coordinates. Moore comments:

"The writer is not prepared to state that this is the first machine of this general design built; if not, it at any rate is undoubtedly typical of its day. Its inspiration appears to have been derived from the *Lincoln Miller*."*

The interchangeable system spread to other manufacturing—such as that of clock making. In 1855, America was exporting 400,000 clocks a year. As a result of this system, clocks were made so inexpensively

*J. Robert Moore, *Precision Hole Location*, pp. 52–63.

**Ibid.*, p. 57.

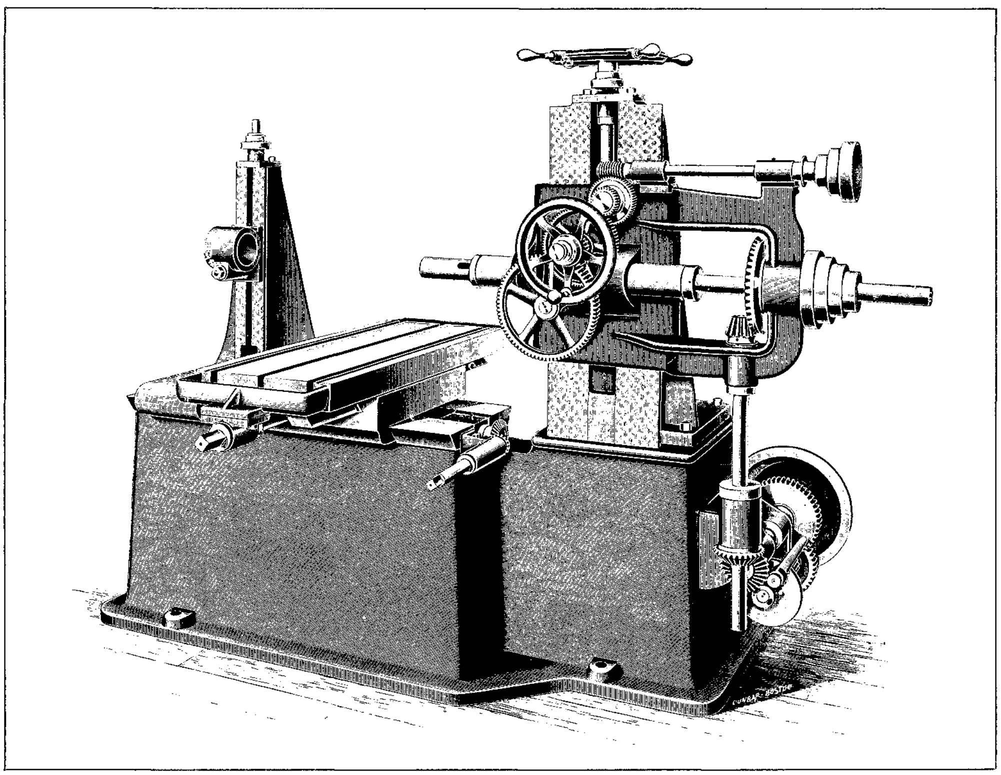
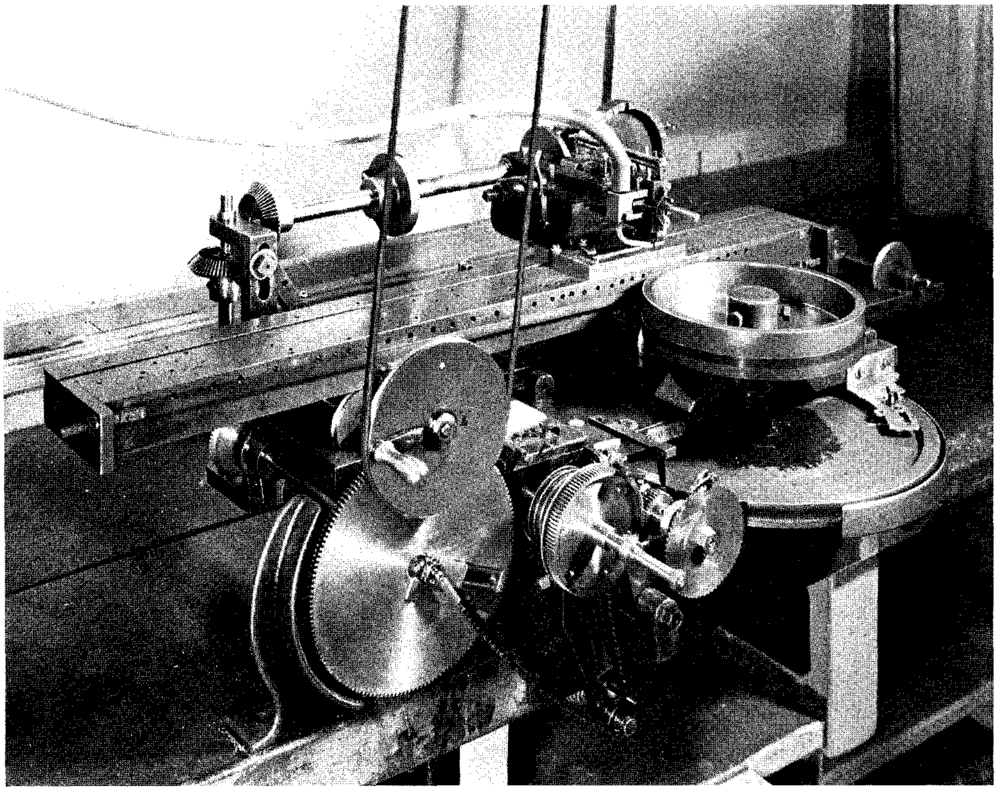


FIG. 226—*The Universal Boring Mill, first built around 1896, located by coordinates, and established the hole around the machine spindle axis as with a jig borer. However, it lacked the prerequisite accuracy to perform the functions of a jig borer.*

FIG. 227—*The Linear Dividing Machine, designed by Joseph R. Brown in 1850, graduated scales and steel rules for use by American industry. Its principle was kept secret until relatively recent times.*
Courtesy of Brown & Sharpe Manufacturing Co.



that it was less costly to discard one than repair it. Many basic machine tools also evolved from the clock and watchmaking industry.

Although by 1850 the United States was advanced in interchangeable manufacture, it was behind in certain other areas. Steel production, for example, was out of step with industrial progress. Initially, steel was derived from iron mined in Salisbury, Connecticut. However, demands could not be met and the quality failed to meet the user's requirements. Consequently, by 1855, the Springfield Armory was buying large quantities of steel from England and Scandinavia, to the consternation of American iron-masters. The Colt company even preferred English steel, which was better refined and more homogeneous.

DEVELOPMENT OF ACCURATE MEASURING INSTRUMENTS AND MACHINE TOOLS IN AMERICAN INDUSTRY

Nowhere was industrial backwardness more apparent in mid-nineteenth century America than in the unavailability of adequate established standards. America, as observed in the "History of Official Length Standards," was of necessity closely tied to England in the matter of weights and measures because of political circumstance. There was also a lack of measuring tools and even simple steel scales.

Charles Hildreth, superintendent of the Lowell Machine Shop, wrote:

> "The original standard unit of length adopted by the Lowell Machine Shop in 1824 for use in the construction of machinery is the English foot, according to a brass standard made by Cary of London, and preserved with care in the safe of the proprietors of the locks and canals of Merrimack River. This scale is un-

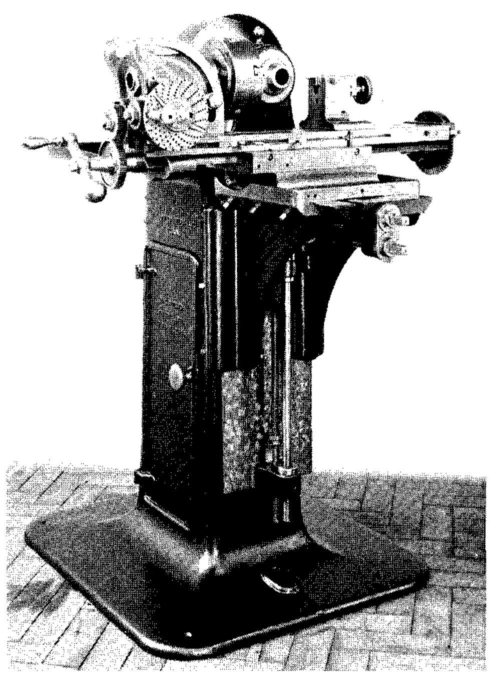
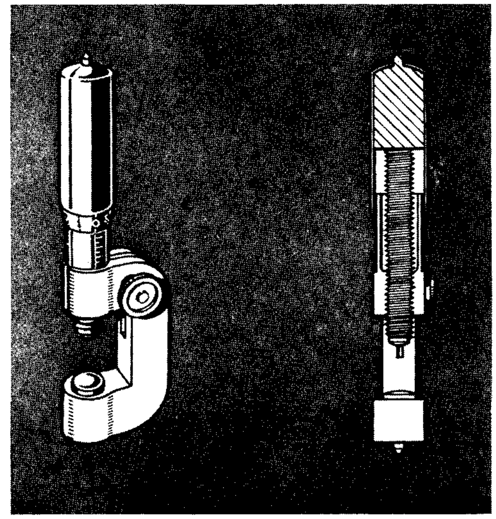


FIG. 228—*The Brown & Sharpe Universal Miller, a machine tool first produced in 1860.*
Courtesy of Science Museum, London.
British Crown Copyright.

FIG. 229—*L. Palmer's Micrometer, French Patent No. 3762, 1848.*
Courtesy of Science Museum, London.
British Crown Copyright.



dated, but has marked upon it, 'Cary, London, Fahrenheit, 62 degrees' [16.67° C]."*

Two questions arise:

1. Without "interchangeability," how could the development of machine tools in England have been so rapid?
2. Without *recognized* standards, how could interchangeability have reached such a high level in America?

The answer to the first question is that in England parts were made not so much to *dimensions* as to *fit*. In reply to the second, there was strictly *in-shop* standardization in America. Initially, in neither England nor America was the need apparent for interchangeability of parts between one manufacturer and another.

In England, the major proponent of standardization of such elements as length standards and screw-threads was Joseph Whitworth. In the United States, two machine tool builders, Brown & Sharpe Manufacturing Company and the Pratt & Whitney Company, were leaders in promoting and making available standards to industry.

Brown & Sharpe

Brown & Sharpe was founded in 1833 by Joseph R. Brown. By 1851, the company was manufacturing steel rules, scales and vernier calipers by using a linear dividing machine whose design features it long kept a secret, Fig. 227. It should be observed in passing that Brown's competitor, a man named Darling from Maine, had also constructed a dividing machine, and, like Brown, had his standards compared in the Coast Survey Office, Washington, D. C. Potential friction that might have developed was eliminated, however, when Darling joined forces with Brown & Sharpe.

In 1851, only four vernier calipers had been sold. Although introduction of Brown & Sharpe measuring tools was slow, their impact was felt. At Colt, when the vernier calipers were first put into service, enough discrepancies showed up in their standards for Colt to temporarily favor a certain amount of "tailoring" in their fits.

At the same time that Brown & Sharpe was making industrial measuring tools, it was also introducing important new machine tool designs. Its Universal Miller of 1860, Fig. 228, is considered a major accomplishment.

The "micrometer," developed to settle a dispute on sheet metal gaging, was first presented to Brown & Sharpe in 1867 by Wilmot, of Bridgeport Brass. Lacking graduated markings, its potential was not then apparent. When Brown and Lucian Sharpe saw the "Systême Palmer," Fig. 229, a true micrometer, at the Paris Exposition, they realized its commercial value. Shortly thereafter, the Brown & Sharpe company began to manufacture micrometers in large quantities, Fig. 230.

In the ensuing years, Brown & Sharpe built standards of even higher accuracy. In

*Ambrose Webster, "Early American Steel Rules," *American Machinist*, April 12, 1894.

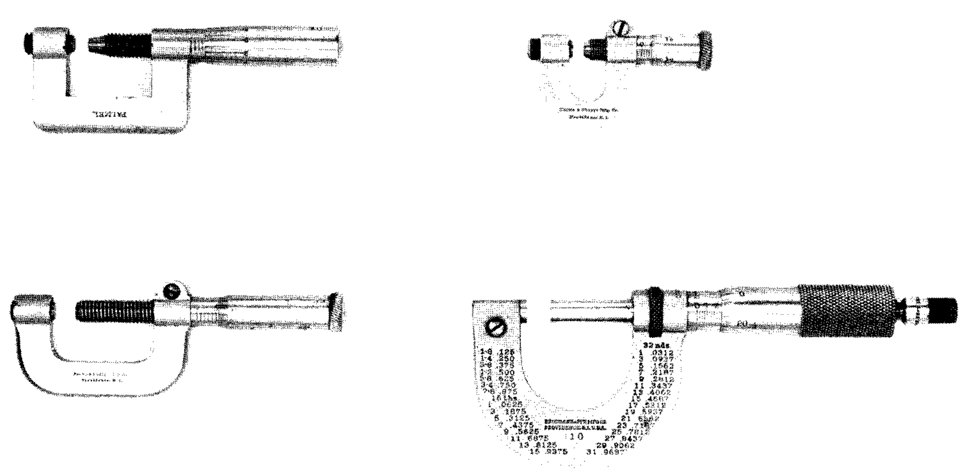
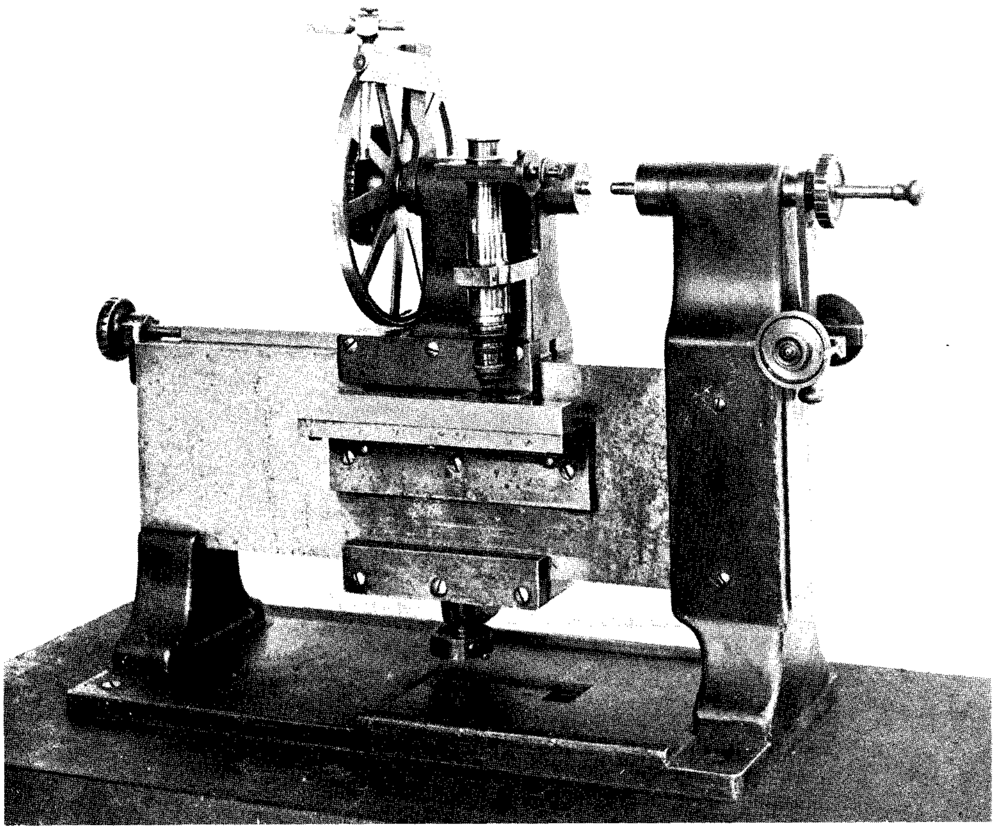


FIG. 230—*First Brown & Sharpe one-inch Micrometer, 1877. Also shown are L. Palmer's Micrometer and a modern Brown & Sharpe Micrometer.*
Courtesy of Science Museum, London.
British Crown Copyright.

FIG. 231—*Brown & Sharpe Measuring Machine, designed by Beale, 1878.*
Courtesy of The Brown & Sharpe Manufacturing Co.



1878 they constructed a more accurate Measuring Machine, Fig. 231, largely the work of a Mr. Beale. Its basis was the "Standard Yard," and had been compared with the standards of Washington.

A letter from the Brown & Sharpe company to J. E. Hilgard of the Coast Survey Office, Washington, regarding the metric standard in use by them at that time, reads: "Taking 39.370 as the standard, there is only 0.00023 inch [0.0058 mm] in the meter difference in our comparison, which perhaps is as close as may be expected. We shall now consider your comparison of our steel bar with the standard of Washington as correct, and in our comparison with it we shall be able to detect errors as small as 0.000025 inch [0.0006 mm]."*

Pratt & Whitney

In *Accuracy for 70 years*, published by the Pratt and Whitney Company, appears a statement that might at first seem presumptuous, but understood in historical context, is not without justification. That statement is: *"Pratt & Whitney established the inch."***

By way of background, Amos Whitney, a distant relative of Eli Whitney, and Francis Pratt were first trained at Colt. They met at the Phoenix Iron Works, and while employed there set up a partnership to build machinery. At first they did so on a part-time basis. Later, when the partnership was operating successfully, they gave it full attention. From the start, they were committed to accuracy, and were leaders in the establishment of standards.

During the Civil War, Pratt & Whitney made rifles by the interchangeable method. The experience gained encouraged them to apply the concept to the manufacture of machine tools such as lathes, horizontal shapers, and the "Lincoln Miller."

*Luther D. Burlingame, "Pioneer Steps Toward the Attainment of Accuracy," *American Machinist*, August 6, 1914.

***Accuracy for 70 Years—1860–1930*, p. 35.

Not long after 1870, Mr. Pratt secured a $350,000 order from the German government for machine tools. This was followed three years later with a $1,250,000 order for more. The German government later wrote: "The Pratt & Whitney Company has furnished the Royal Armories of Spondan, Erfurt and Donsitz with plants of machinery which execute the work with such nicety and precision as to save one half the wages, and to render the government in no small degree independent of the power and skill of the workmen."*

In establishing its standards, Pratt & Whitney soon realized, however, that no two standards in America were alike. Professor William A. Rogers, an astronomer at Harvard University, and Roger M. Bond of Pratt & Whitney set about establishing standards of their own in all areas of mechanics.

*Ibid., p. 31.

As J. Robert Moore observes:

"The man of science turned his attention from the planets and the measurement of distances counted by millions of miles, to listen to the imprecation, perhaps, of the humble car repairer, lying on his back and swearing because a ⅝ inch nut—'a leetle small'—will not screw on a bolt—'a trifle large.' "*

*J. Robert Moore, *Precision Hole Location*, p. 62.

Clarifications in the matter of length standards were made. For the "inch," standard bars were compared to Bronze No. 11, thus indirectly related to the Imperial Yard. For the "meter," comparisons were made to the working meter of the Conservatoire des Arts et Métiers, as well as to other bars which had been compared to the Metre des Archives. The result of three years of effort and thousands of dollars was the Rogers-Bond Comparator, Fig. 232. It was transported to the bureau in Washington to duplicate conditions of comparison; standard temperature was then 62°F. [16.67°C], after the English.

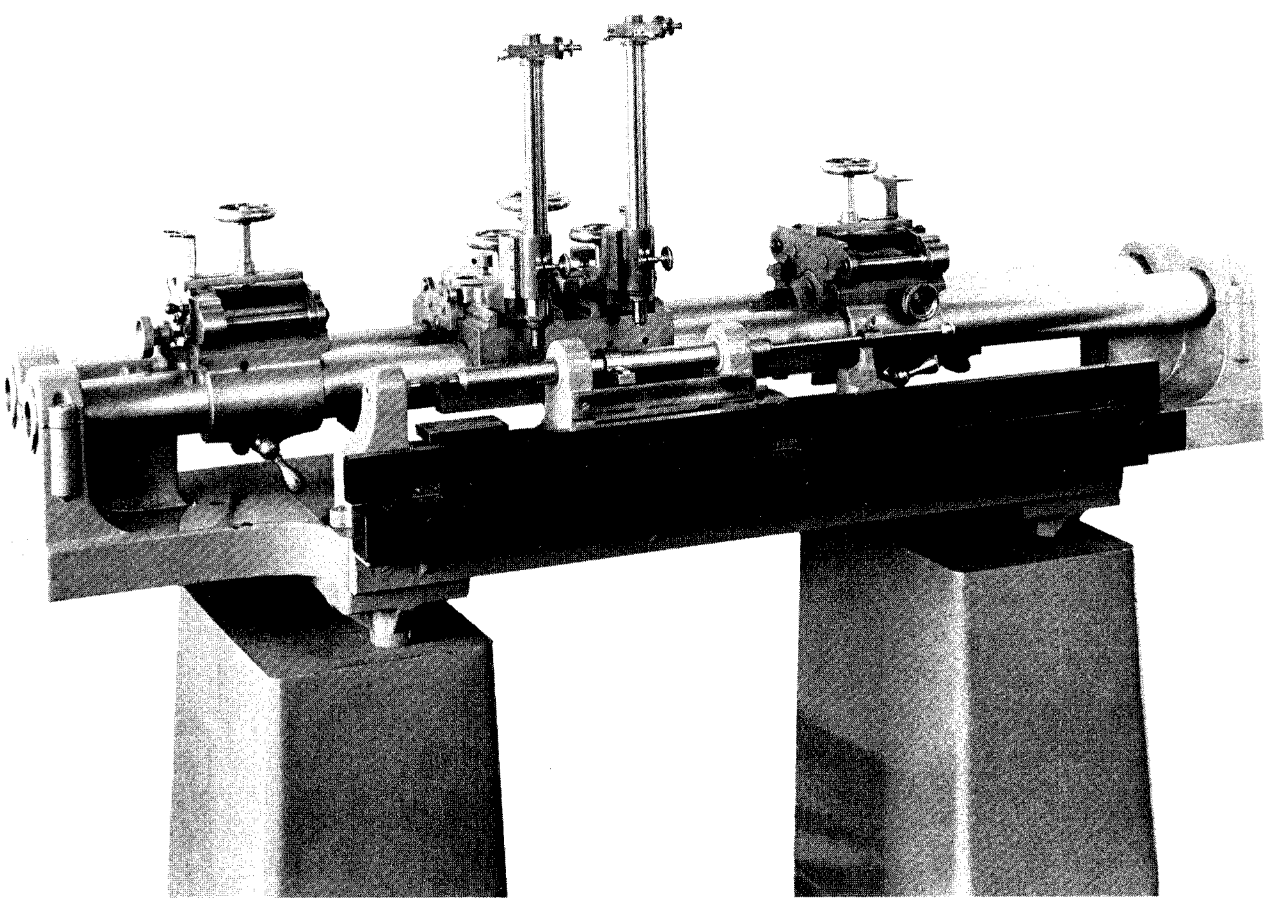
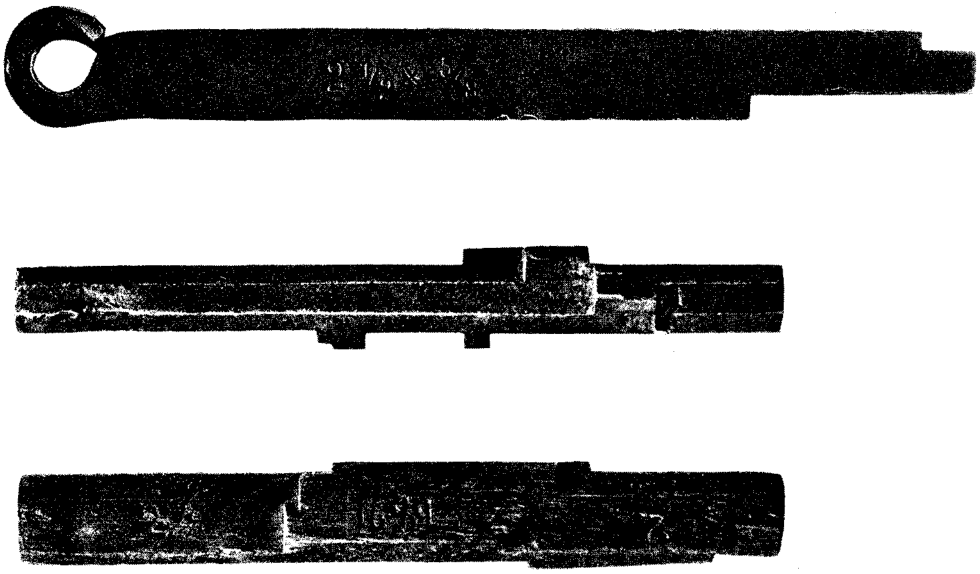
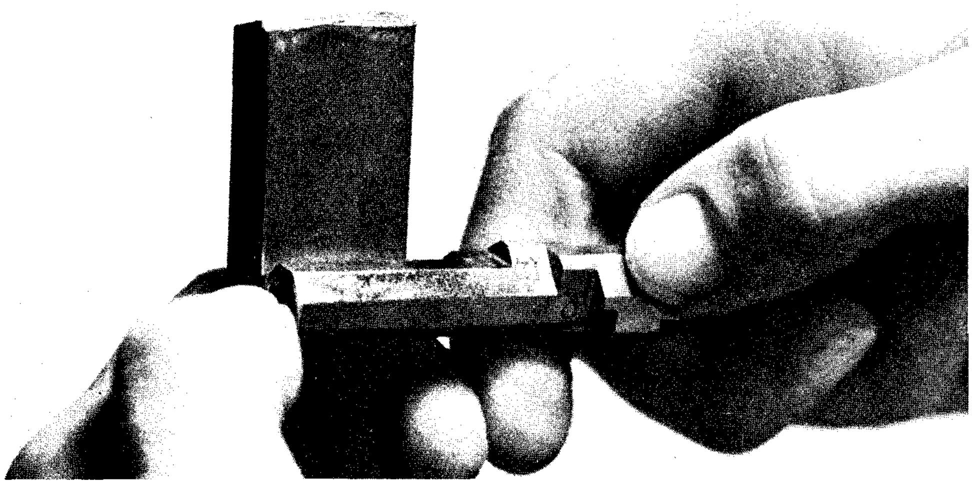


FIG. 232—*The Rogers-Bond Comparator was the result of three years' work by Professor William A. Rogers of Harvard University and Roger M. Bond of the Pratt & Whitney Company.*
Courtesy of Pratt & Whitney Co.

FIG. 233—(*top*) *Swedish "Polhem Sticks," preceding Johansson's invention by at least 150 years, enabled many different measurements to be made with one "gage."*
Courtesy of Johansson Co.





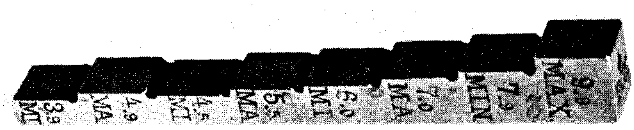


FIG. 234—(*middle*) *Johansson's Gage with measurement stud held in hand, illustrating size and use.*
Courtesy of Johansson Co.

FIG. 235—(*bottom*) *A small gage of steel with measurement studs, allowed several sizes in one bar. Made by Johansson, it was one step toward his concept of the gage block set.*
Courtesy of Johansson Co.

In a report of the American Society of Mechanical Engineers, Bond and Rogers were acknowledged for having "solved the problem of exact and uniform measurement."*

The Rogers-Bond Comparator became the basis of Pratt & Whitney Measuring Machines for years to follow.

CARL EDVARD JOHANSSON

Sweden can be credited not only with supplying some of the world's finest quality steel, but also with giving it some of its greatest mechanics. One such mechanic contributed an innovation to measurement second only in significance to the concept of interchangeability—namely the "gage block," created in the 1890's by Carl Edvard Johansson. Today, the term "gage block" has become almost synonymous with "measurement."

The importance of the gage block cannot be over-emphasized. On a practical level, it is one of a shop's most useful length-measuring tools, and is more often than not its first direct representative of the official length standard. Where higher-level measuring accuracy is concerned, as is the case with the national bureaus, it is usually somehow related to the gage block.

Much has been written about the gage block, but no greater insight can be gained into its significance than by following Johansson's footsteps as he developed it.

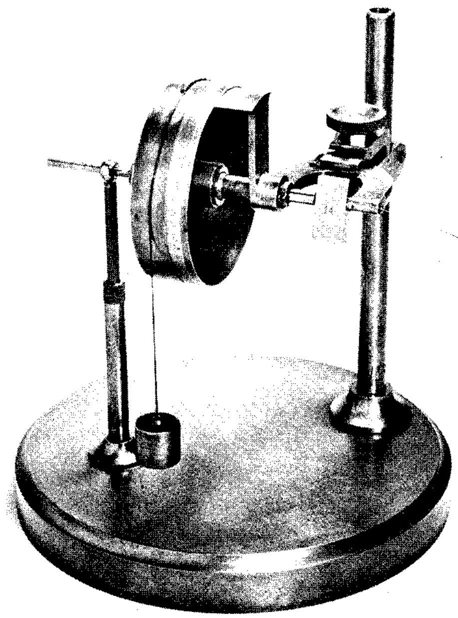
Eskilstuna Rifle Factory

Arms manufacturing in Sweden, as was the case in other countries, stimulated interest in greater precision, which in turn led to important mechanical development. In Sweden, as well as the rest of the world during the 1880's, the single most important item produced in quantity—even surpassing the clock and the sewing machine—was the rifle.

The principle of interchangeable manufacture was known in Sweden for some time,

*Joseph W. Roe, *English and American Tool Builders*, p. 182.

FIG. 236—*Using a special counterweighted micrometer, Johansson was able to measure his gage blocks with a constant force.*
Courtesy of Johansson Co.



having been introduced by Hilge Palmcrantz. Thus in the Eskilstuna rifle factory, where the Remington rifle was then manufactured, "fixed gages" were used. In fact, there was only one Brown & Sharpe micrometer in the whole Eskilstuna plant. The rest of Sweden and other countries still relied upon *in-shop standardization.*

To understand the emergence of the gage block requires knowledge of its predecessors, beginning with the "Polhem Stick." "Polhem Sticks," Fig. 233, first made of wood and later of iron, were an old principle; they enabled many separate measurements with one "gage."

Johansson, an apprentice at Eskilstuna who quickly became its chief armorer, knew the "Polhem" method of measurement, Fig. 234. It is known, furthermore, that he fashioned a small gage of steel with measurement studs, Fig. 235, which allowed for several sizes in one bar. This gage stands as the first step toward his significant invention.

The Eskilstuna plant was then planning a change from the Remington rifle to the German Mauser. The prototype of this model was made to Mauser's specifications at Pratt & Whitney. The Mauser was a more complex gun, requiring higher accuracies. Johansson was appointed to the commission which went to the Mauser plant in Germany to study their methods. On his return, Johansson pondered the overwhelming task of duplicating for the Eskilstuna factory the *thousands* of gages he had seen at the Mauser works at Oberndorf.

Before his return, he conceived of the idea of a set of gage blocks, 102 in number, that would enable him to make 20,000 different combinations of measurement.

In 1875, Professor Tyndall demonstrated to the Royal Institution in England that Whitworth's polished plates would adhere, and that the force of adherence was greater than atmospheric pressure. Whether Johansson was at first aware of this phenomenon is not certain. In any event, the fact that finely lapped gage blocks adhere, or "wring," made his system both possible and practical.

The preliminary work for the first set of blocks was done in the rifle factory. For the final finishing, however, Johansson worked nights at home, often aided by his wife. Lapping was accomplished with a modified sewing machine, and measuring with the aid of a special counter-weighted micrometer (for consistent gaging force), Fig. 236. Blocks were stress-relieved for stability, probably by exposing them to alternate heat and cold. The entire operation was kept secret, and all tools were put carefully away and left behind locked doors.

The Sandvik Steel Company of Sweden furnished the steel (chrome-nickel bar steel) used for Johansson's blocks, and all heat treatment was overseen by Peterson, Johansson's chief metallurgist.

To achieve stability in the gage blocks, they were heated, then allowed to return to room temperature. Next, they were deep-frozen and again allowed to return to room temperature. This cycle was repeated nine times. Johansson recounted his theory of stress-relieve in a metaphor that is uncannily close to modern concepts:

> "The molecules in the steel are like little children. When they get warm, they dance and jump around. When they get cold, they quiet down and go to sleep. After you wake them up and put them to sleep enough times they get tired, and the last time they stay asleep. In this manner the gage blocks are made stable and "stay."*

Commenting on Johansson's shop technique, particularly his sense of the practical, his biographer, Althin, observes: ". . . in all his designs he avoided working with gauges that had to be adjusted according to a graduated scale."**

*Author's conversation with Gilbert L. Danehower circa May 1, 1969.

**Torsten K. W. Althin, *C. E. Johansson 1864–1934: The Master of Measurement,* p. 105.

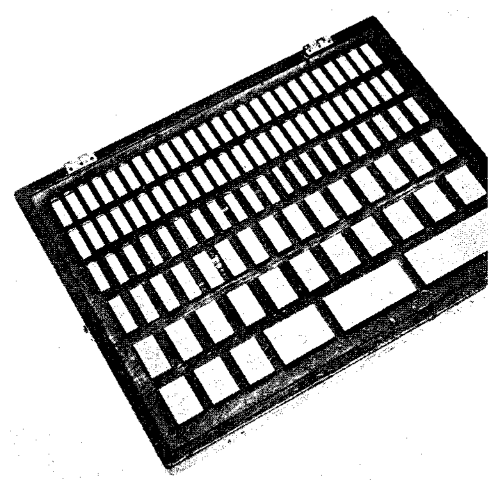


FIG. 237—*Johansson's first set of gage blocks to be sold. His principle was to revolutionize the concept of length measurement.*
Courtesy of Johansson Co.

For the first gage set, only those standards readily available were used for calibration of his blocks. This set alone *was the basis for all measurements of the Mauser 6.5 mm rifle.*

As he gained confidence in his system, he gathered more assistants for the manufacture of what had now become a product, Fig. 237, finally resigning his position to devote full time to the new concept.

The slow acceptance of his idea and his dogged determination find expression in a letter Johansson sent to his father in 1899: "I do not think they understand the benefit of my measurement system. All the same, it is a thing of the future, and *I will have it recognized.*"*

The next step Johansson took was more crucial. The motivation for this step most likely relates to his inability to secure a patent protecting a system which could be easily copied. As a result, its uniqueness could only be established by what would today be called "traceability."

Johansson constructed a 100 mm gage [3.937 inch]. Its length was established by comparison to several standards, including one by Brown & Sharpe. The gage was brought to the Swedish Bureau, where the Chief of Office compared it to their standard at 20°C. [68°F.], a temperature considered a mean. The reaction of the Chief is an amusing commentary on those "warm-blooded" individuals who want a new temperature-standard above this chilly figure: "20°C.? We must fire up to get that temperature."**

When Johansson calibrated his gage at the International Bureau at Sèvres, France, he had almost reached his goal of traceability. A few discrepancies arose, however, because his blocks were lapped at 20°C. [68°F.], while the BIPM was then using 0°C. [32°F.] as a standard. A new rod was made, set at 0°C. [32°F.], and in April, 1903, it was sent to the BIPM. In Johansson's letter to a friend, Ternström, who arranged for the testing, he said:

"If the people of the Bureau measure correctly, they shall find that each block lies within 0.001mm [40 millionths of an inch] limit of accuracy in relation to the 100 mm [3.937 inches] measure."

He further added:

"If they arrive at any other result, then they had better adjust their measuring appliances."*

Johansson's gage was successfully calibrated by the BIPM, establishing "traceability." His long-sought goal was finally attained.

Johansson then proceeded to promote his gages throughout the world, Fig. 238, including the U.S.A., where he was aided by his brother, Arvid. He also went to the National Physical Laboratory in Teddington, England, where Dr. Glazebrook, its head, enthusiastically accepted the "gauge block set."

The BIPM measured Johansson's blocks over a period of several years by many different techniques, including interferometry. At first, they publicly stated that the accuracies quoted by Johansson were impossible. Benoit of the BIPM, said to Spangberg, who promoted Johansson's system:

"Young man, if you had any idea of the enormous difficulties we are confronted with in our laboratory in reading with certainty a micron [40 millionths inch], you might perhaps speak a little less lightly of this high grade of precision."**

Benoit later became a foremost advocate of Johansson's system, and in a summary of the BIPM's findings reported:

"One cannot get away from the finding that the accuracy of these gages is remarkable, so for one and the same magnitude it amounts to the degree of accuracy of the interference measurements, and adjustment only displays errors less than one-tenth of a micron [0.000004 millionths of an inch]."*

Commenting on the success Johansson enjoyed in France, Althin notes:

"It was natural for the French character to understand the clear logic of the Johansson system, and French scientists were the first to recognise the wide importance of it."**

By 1907, improvements in finishing the blocks enabled them to be wrung together with a force of up to seventeen atmospheres; and by 1916 with up to thirty-three atmospheres.

In 1914, an American, Gilbert L. Dannehower, became fascinated by the Johansson system while still in technical college. After graduation, he worked his way to the position of being Johansson's Sales Manager in the U.S. At first, Dannehower encountered difficulty explaining the use of the blocks, so he organized a sales force consisting of twelve former inspectors and toolroom foremen. Nevertheless, a common reaction of prospective customers on being informed of a $900 price tag for the set was: "What are they made of, gold?" This kind of reaction was not that of men of vision. Commented Charles Kettering when the system was presented to him at the Delco plant in Dayton, Ohio:

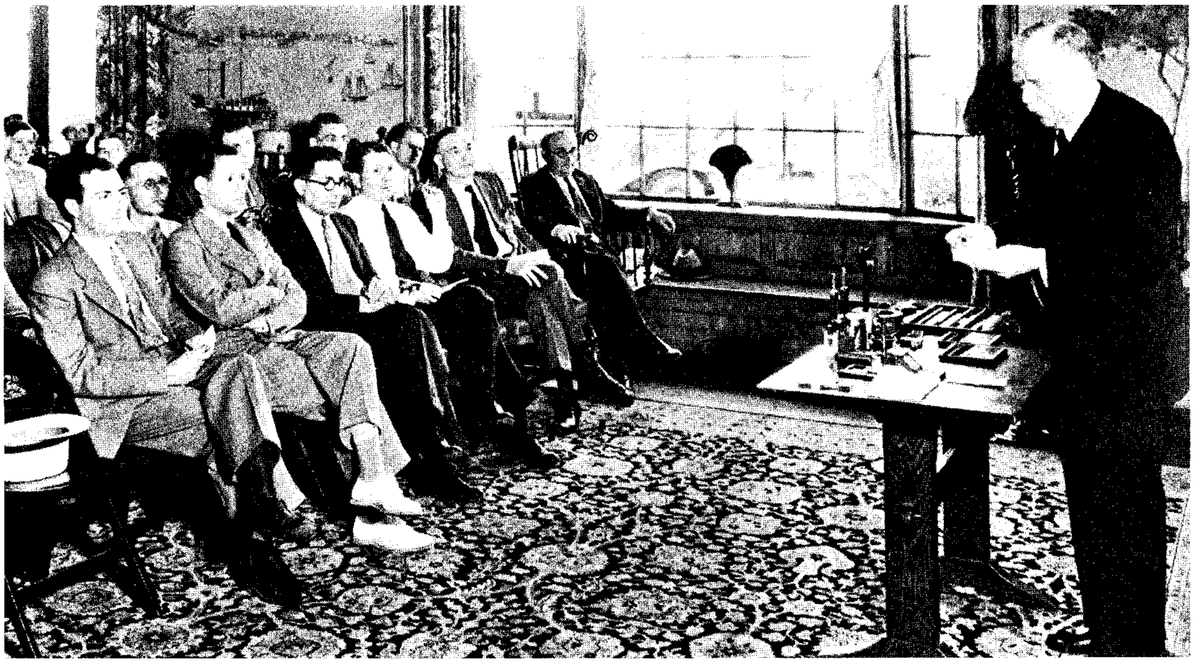
"Gentlemen, this is the finest measuring tool in the whole world. The sooner we learn to use it, so much the sooner we can stop 'fitting' parts together and simply 'put' them together. The day is now not far off when every toolmaker will have to have a set of these blocks at his elbow, or he just won't know what the hell he is doing. Let's buy ten sets and get them

*Torsten K. W. Althin, *C. E. Johansson 1864–1934: The Master of Measurement*, p. 70.
**Ibid.*, p. 74.

**Ibid.*, p. 81.
***Ibid.*, p. 126.

**Ibid.*, p. 86.
***Ibid.*, p. 89.

FIG. 238—*The gage block concept was not accepted without salesmanship. Johansson lectured throughout the world to promote the idea of his gage blocks.*
Courtesy of Johansson Co.



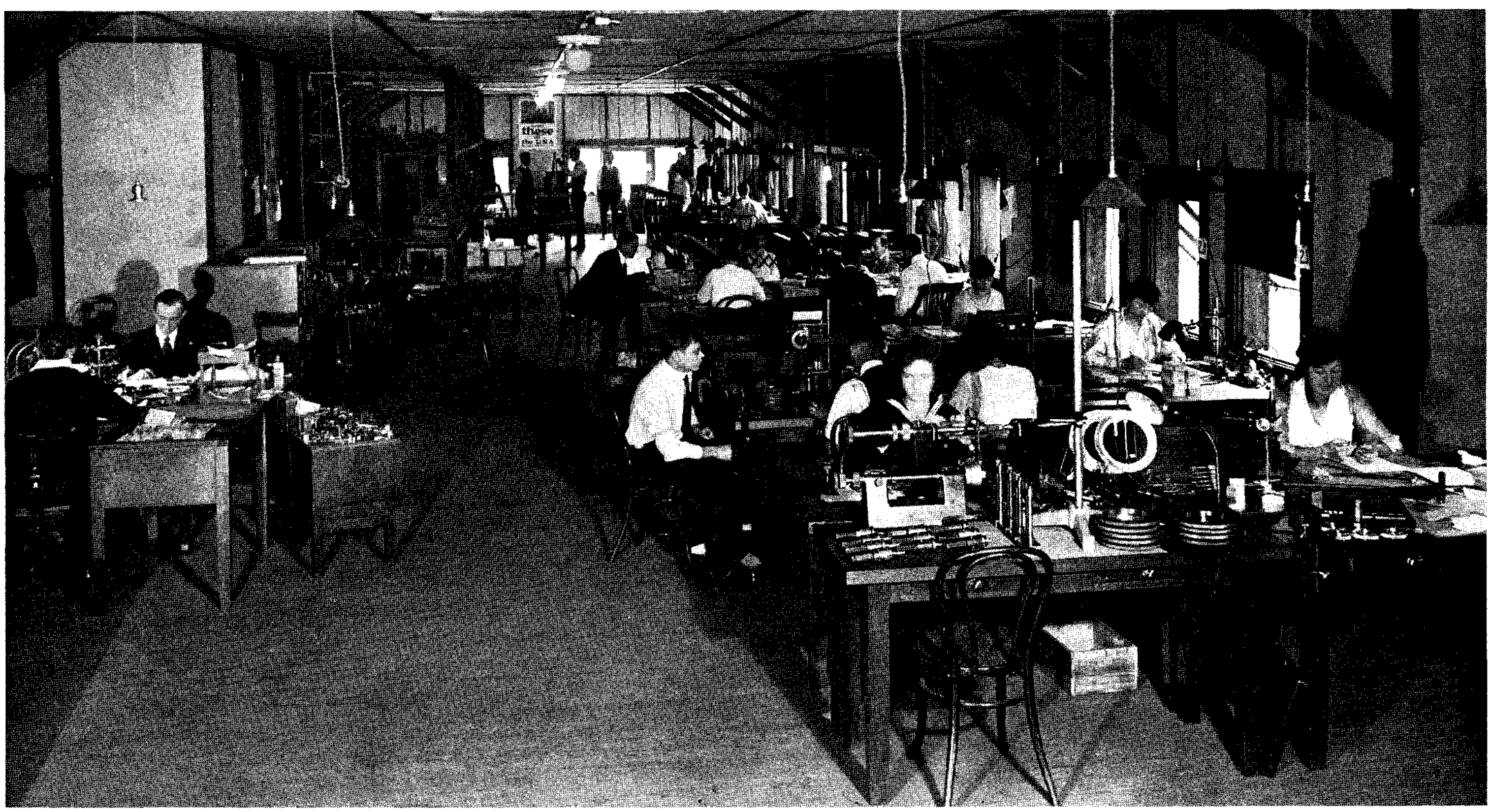


FIG. 239—*Facilities and personnel of the NBS were devoted toward aiding industry during World War I.*
Courtesy of the NBS.

FIG. 240—*G. Dannehower stayed at the Johansson home in Bolviken, Sweden, several times during World War I while securing gage blocks for the United States.*
Courtesy of G. Dannehower.

FIG. 241—*G. Dannehower recalls with great affection the memory of his friend the "Eskilstuna Blacksmith," as Johansson modestly referred to himself.*
Courtesy of G. Dannehower.

out in the toolroom and inspection departments!"*

During the First World War, the unavailability of "Jo Blocks" from Sweden, because of German submarine blockades, caused a near-crisis in the United States, then girding industry for war-time production, Fig. 239. Dr. Stratton, Chief of the National Bureau of Standards, realizing the critical importance of gage blocks, got Dannehower released from army duty, whereupon he was immediately sent to Sweden. He was instructed to "stay there and get blocks made in the English system and bring them home."**

*Unpublished letter from Gilbert L. Dannehower, April 15, 1969.
**Idem.*

Dannehower went to live with the Johansson family in Eskilstuna (Figs. 240 and 241) where work quickly proceeded to produce inch gage blocks. A total of 128 sets were made after four weeks. Dannehower managed to smuggle the blocks aboard ship on his return to the U.S., despite the presence of German inspectors. He was apprehended, however, by Canadian officials and upbraided by Jacobsen, the president of the Norwegian-American Line, for risking ship and passengers with contraband. The matter was soon cleared up when Dr. Stratton was contacted by the officials.

Dannehower made two additional trips ". . . to keep supplies coming . . . and mass-production and interchangeability was possible, because we had our supply of blocks," as he describes it. When the War was over, Henry Ford observed:

> "This must not happen again; we must have the secret methods within our country's boundaries. I will buy the manufacturing rights."*

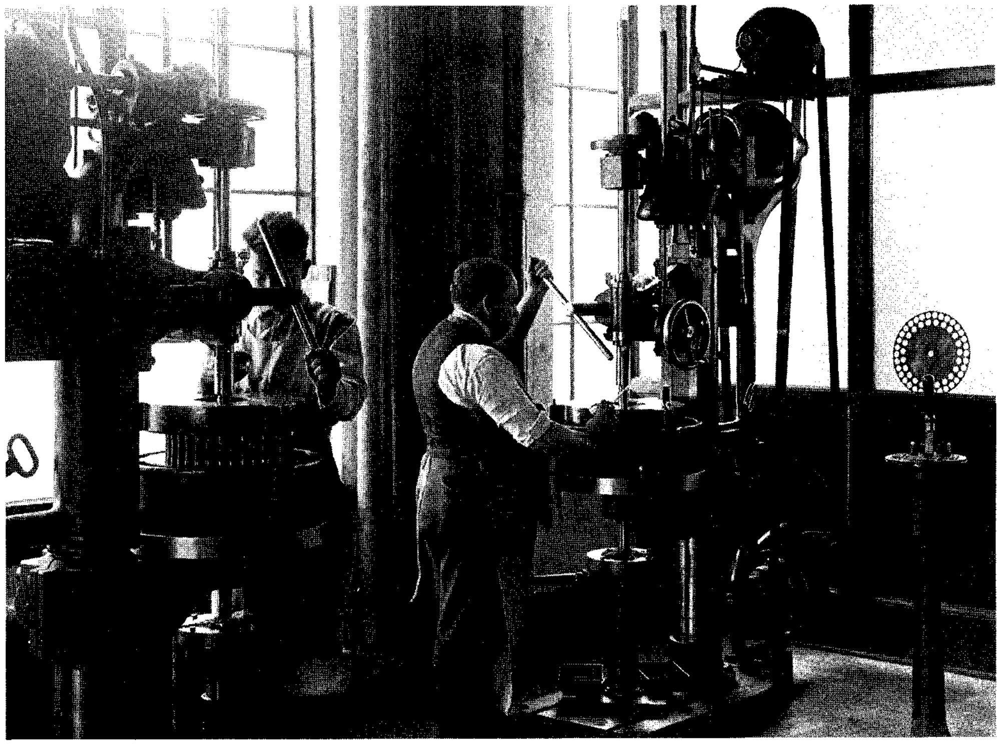
In 1923, Johansson became associated with Henry Ford, applying his skill and energy to the greatest single product of mass-production through interchangeability—the automobile.

During the war years, all-out efforts were made to produce gage blocks in the U.S. At this time, Major Hoke, an inventor, came to the National Bureau of Standards with an idea of making gage blocks on a large scale. The project was somewhat successfully pursued over several years as an important part of the war effort, Fig. 242. Later, the "Hoke" blocks were taken over on a mass-production basis by the Pratt & Whitney Company.

Since that time, there have been countless worldwide entrants into the field of gage-block manufacture, attesting to their widespread, indispensable use.

**Idem.*

FIG. 242—*"Hoke" blocks were manufactured at the NBS during World War I to help supply U.S. industry's urgent need for length-measuring standards.*
Courtesy of the NBS.



EVOLUTION OF COORDINATE-LOCATING MACHINE TOOLS—JIG BORER

The jig borer was not the earliest, nor is it today the only machine tool to position by means of coordinates. Nonetheless, it is recognized as the most accurate of hole-locating machine tools. Certainly its introduction was a major step forward in the hole-location process, itself a key to interchangeability.

Every standard machine tool underwent a long evolution before reaching its most current design. Some of the ancestors of the jig borer have already been mentioned.

The jig borer combines two essential functions:

1. Single-point boring, meaning that the tool generates a hole as it is rotated about its own axis. Wilkinson's boring mill is a good example, Fig. 217.
2. It established location by means of coordinates, as in Clarke's horizontal boring mill, Fig. 226.

Yet a machine tool that would *accurately* locate and bore, the two requisites of a jig borer, were very late in coming. In *Precision Hole Location*, J. Robert Moore details the problems inherent in hole location in a chapter entitled "They Got Holes In Somehow." He furthermore examines why hole location equipment was so late in development. The chapter's title suggests that the task was still a craft and not an engineered solution.*

In the clock industry, for example, methods of establishing holes *correctly spaced* required laborious processes, such as laying out with a scriber, prick-punching, drilling, reaming, wiggling, buttoning, etc., Fig. 243. As evidence that these methods could position at least more accurately than existing machine tools, Joseph Woodworth, au-

*J. Robert Moore, *Precision Hole Location*, pp. 15–51.

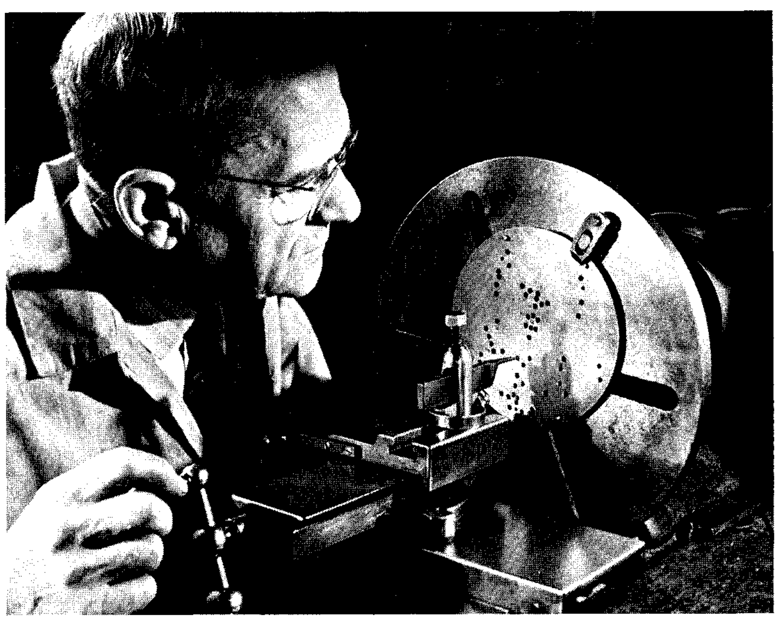


FIG. 243—*Prior to the jig borer, accurate hole location such as required in the clock industry was established by transferal methods. Depicted is a hole being bored in the master plate after the model has been "wiggled up" and removed. When the master plate is finished, it is used as a reference for positions of all holes in tools used to make finished parts for clocks.*
Precision Hole Location.

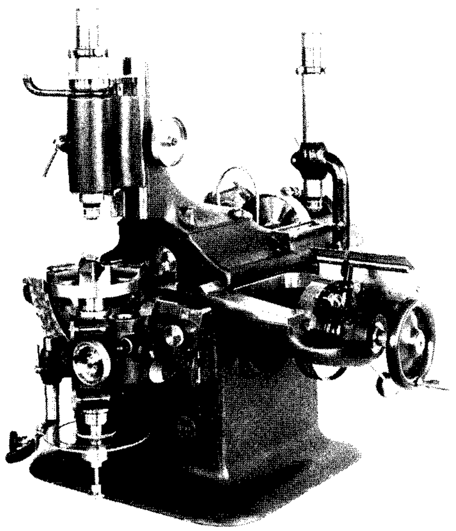


FIG. 244—*Early "Machine à Pointer" (jig borer), the Dixi company, date given as 1905. In initial design, holes were first "pointed," or punched, then removed from the machine for drilling.*
Courtesy of Dixi.

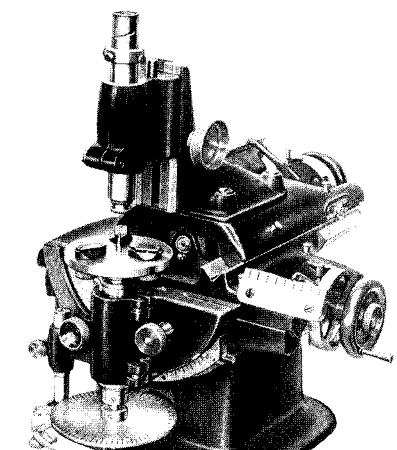


FIG. 245—*Jig borer, the SIP (Société Genevoise d'Instruments Physique) company, produced about 1912. The similarity between the SIP and Dixi designs, apparently produced independently, is striking. Later, the "pointing machine" was fitted with a spindle to enable machining holes in place.*
Courtesy of SIP.

thor of *American Toolmaking and Interchangeable Manufacture,* stated in 1911:

> "There is only one method for locating bushing holes in small and medium-sized jigs accurately and expeditiously . . . and this is known as the button method."*

Switzerland—Machines à Pointer, SIP company and Dixi company

Shortly before World War I, several independent efforts were leading toward the creation of today's jig borer. The Swiss, long famous for clock and watchmaking, appreciated precision, fine mechanisms and instruments. As in the United States, the "master plate" and other transfer methods were accepted as the only way of establishing interchangeability, such methods dating back over 100 years. Parts were thus made *alike,* but not to *dimensions.*

The Société Genevoise d' Instruments Physique (SIP) was founded in 1860, in Geneva, Switzerland. Geneva was already a center of scientific, scholarly research. Composed primarily of instrument-makers, SIP introduced a small instrument in 1912 "designed to accurately measure distances and angles between a fixed point and other points located anywhere around it.** This instrument was created at the request of watchmakers, who needed a device for placing holes in exact position.

It might be mentioned that Dixi, S.A. of Le Locle, Switzerland, had earlier (about 1905) designed an instrument for a purpose similar to that of SIP. The similarity between the designs is striking, Figs. 244, 245. Location was established by coordinate movement, but in true watchmaking fashion the holes were first center-punched, then removed for drilling. Later, this "pointing machine" (the French term for jig borer is still *Machine à Pointer*) was

*Joseph V. Woodworth, *American Toolmaking and Interchangeable Manufacture,* p. 45.
**Burnham Finney, "Coming: The Decade of Metrology," *American Machinist,* July 9, 1962.

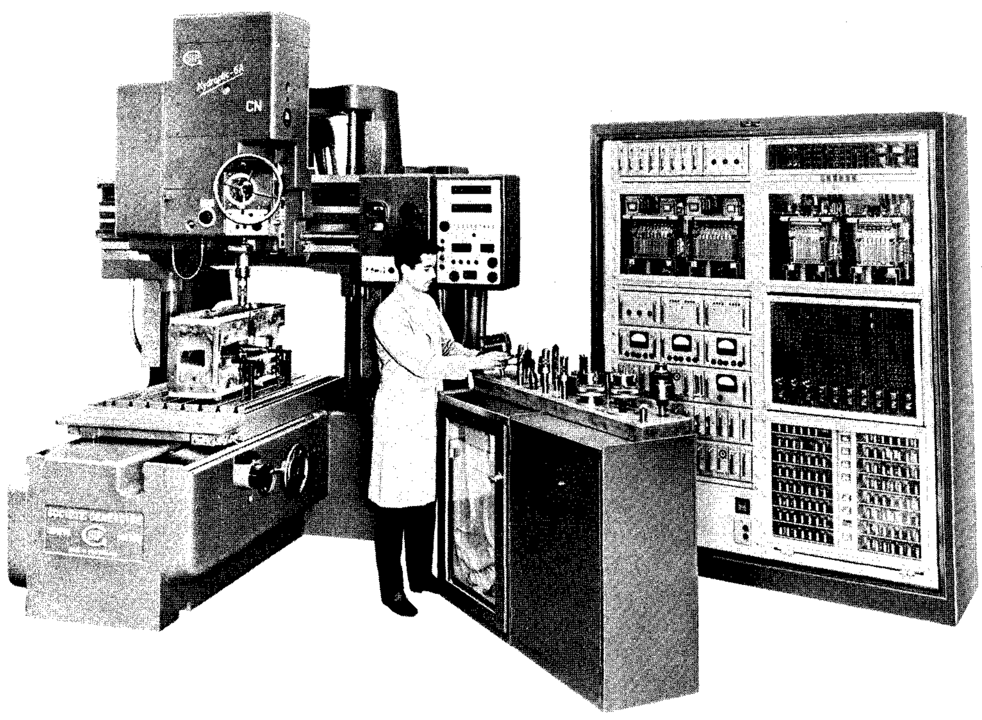
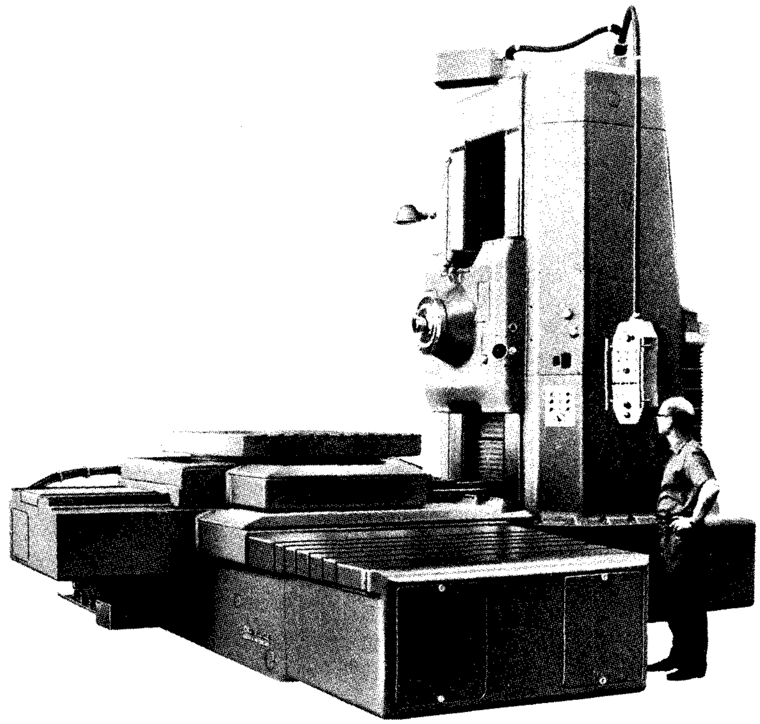


FIG. 246—*Modern SIP Jig Borer (planer-type) adapted to numerical control.*
Courtesy of SIP.

FIG. 247—*Modern Dixi Jig Borer (horizontal spindle-type).*
Courtesy of Dixi.

fitted with a drilling spindle, and holes were cut *in place*, saving time of removal from the machine and enabling greater accuracy.

At first, lead screws with compensators for lead error were used. The principle of the scale and microscope was later adopted by both firms. More modern jig borers of SIP (planer-type) and Dixi (horizontal spindle) are shown in Figs. 246, 247.



Pratt & Whitney Jig Borer, 1917

The Pratt & Whitney Company, meanwhile, was in the process of equipping various foreign arsenals for the manufacture of arms. Required were large quantities of jigs, fixtures and gages where holes had to be drilled, reamed, or bored to pre-determined location.

Since existing methods, such as "buttoning" of jigs, were too slow, Pratt & Whitney constructed a machine with a vertical spindle which would bore to location. The result reflected the Company's machine tool tradition. Conceived by a Swede, B.M.W. Hanson, the Pratt & Whitney "Yig Borer," as he referred to it, was, compared with the original Swiss versions, more a machine tool than an instrument, Fig. 248.

Drawing upon its 30 years' experience with measuring machines using both end standards and line standards, Pratt & Whitney decided on end measures for even spacings and a micrometer and dial for subdivisions. Because of its dual origin, it can be understood why the jig borer still retains the characteristics of both machine tool and instrument.

From the 1930's on, the jig borer received rapid acceptance. Since it was a precise and expensive machine, many felt at first that the jig borer should be made massive enough to handle from the smallest to the largest size workpieces. This concept naturally increased the cost of using a jig borer. As a result, it was not unusual to have only one jig borer servicing an entire geographic area, with attendant prestige to

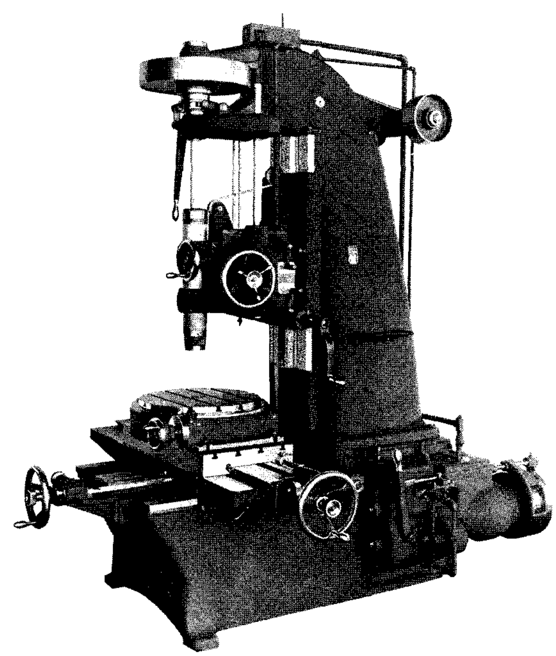
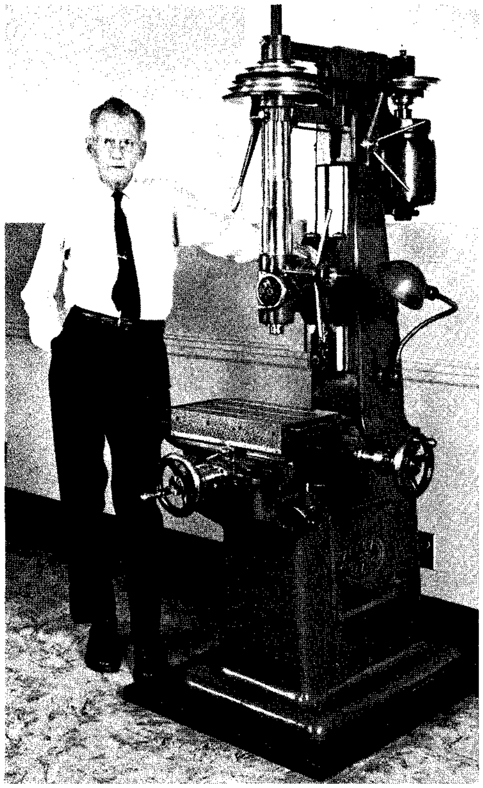


FIG. 248—*The jig borer, produced by Pratt & Whitney, 1917, was designed from the beginning to have a boring spindle.*
Courtesy of Pratt & Whitney Co.

FIG. 249—*The Moore Special Tool Company produced its first jig borer (Model No. 1) in 1932. The machine was small, fast and employed hardened, ground and lapped lead screws. Richard F. Moore, founder and president with the first jig borer.*



its owner. All precision hole location work had to await the time when it could be put through his jig borer.

Naugatuck Valley

It has been previously mentioned (pages 149–150) that America very early adopted interchangeability in the manufacture of clocks, and shipped large quantities to Europe. Roe traces the development from buttons to brass, to clocks and watches, concentrating on the important clock-making area of Naugatuck Valley.*

Moore Jig Borer 1932

A small firm, the Moore Special Tool Company, was founded in Bridgeport, Connecticut, in 1924, specializing in highly accurate gages and dies. Much of its early work was for the clock and brass shops of the Naugatuck Valley. By 1932, Richard F. Moore had designed and built a jig borer for his firm's own use, and then for sale to "adapt to toolrooms and jobbing shops making tools and dies for clocks, locks, small electric devices, typewriters, adding machines, toys, instruments and many other small and moderate-sized parts." He had set for himself the requirement that "the price should be low, so that the machine will pay for itself in a short time."*

The No. 1 Moore jig borer was small, accurate and fast. Its great innovation was the use of hardened, thread-ground and lapped lead screws, which gave greater security to measurement than the soft, compensated ones. In a small machine, the lead screw provided many advantages over either a scale or end measure, most notably in faster setting. The simplicity of design enabled the machine to be offered at a reasonable price, and it soon achieved acceptance. This contributed to the jig borer becoming a basic machine tool.

Moore Jig Grinder, 1940

In 1940, Moore invented the jig grinder, Fig. 250. This machine tool overcame the problem of having to jig bore parts in a soft state and somehow trying to compensate for the resultant hardening distortion. Now with the jig grinder, holes could be *ground* to location after hardening, a capability especially needed for such accurate work as progressive motor-lamination dies, watch and clock dies, and hardened jigs, fixtures and gages.

By 1946, the National Cash Register Company had specified that all dies, where accurate hole-location was involved, had to be "jig-ground." From today's perspective, this would seem a logical requirement, but considering the then recent introduction of the jig grinder, such a specification required great perception by management.

By 1950, Moore had introduced "contouring" features to the jig grinder in a patented design, Fig. 251. So revolutionary was the contouring feature as applied to diemaking that Frederick C. Victory and Richard F. Moore felt it necessary to devote a part of their book, *Holes, Contours, and Surfaces*, to an explanation of the process.*

At this time, the jig borer was also enlarged and improved, Fig. 252.

Without doubt, the basic locating features of the jig grinder evolved from, and are identical with the jig borer. Yet the jig grinder is considered by some to be more accurate or more sophisticated than the jig borer. This may possibly be attributed to the higher finish achieved with ground surfaces.

Introduction of the Universal Measuring Machine

The writer is often asked, particularly by jig borer owners: "Why is the Universal Measuring Machine necessary at all, given the accuracy of today's jig borers? Isn't my jig borer sufficient for any measuring task?" The answer may be found in the nature of the jig borer itself, since it evolved toward a design which seeks the ultimate in positioning accuracy. Certainly, one can measure with the jig borer. Indeed, the very function of boring to accurate location involves the measuring process. The most accurate inspection which can be made of a jig-bored part, outside of a Universal Measuring Machine, is right on the jig borer after machining.

The jig borer does have limitations, however, notably in its column, housing and spindle design. Although the spindle must be accurate for measuring purposes, it must also be capable of taking a substantial machining cut. Therefore, weighed in with the requirement for accuracy are the additional requirements of rigidity, reliability and

*Joseph W. Roe, *English and American Tool Builders*, pp. 231–238.

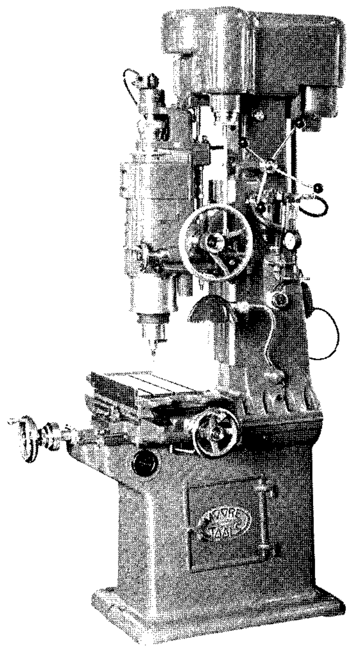
*Private conversation with Richard F. Moore, founder and president, Moore Special Tool Co.

*Frederick C. Victory and Richard F. Moore, *Holes, Contours and Surfaces*, pp. 139–159.

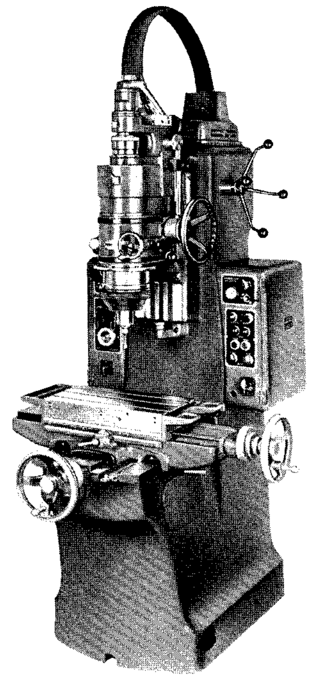
FIG. 250—*The jig grinder (Model No. 1) invented by Moore in 1940. The term "jig grinder" was selected to imply the machine's jig borer ancestry. It enabled holes to be ground to location, including taper, after the piece was hardened.*

FIG. 251—*The No. 2 Jig Grinder revolutionized die-making by enabling contours (portions of radii, both male and female) to be ground to location.*

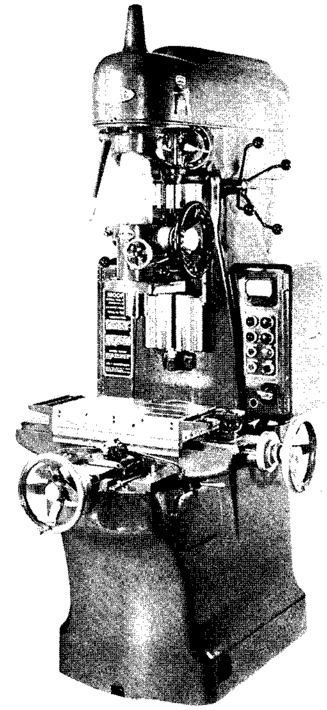
FIG. 252—*The No. 2 Jig Borer utilized the same principles as the Model No. 1 Jig Borer, but was larger overall, with an infinitely variable spindle speed; moreover it introduced the use of Nitralloy lead screws.*



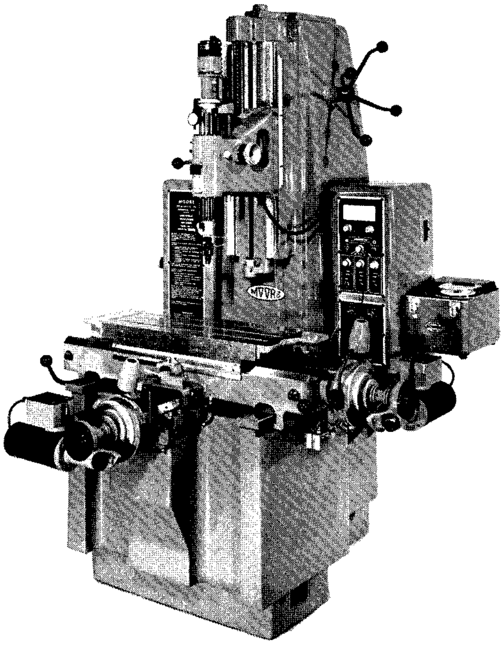
No. 1 Jig Grinder



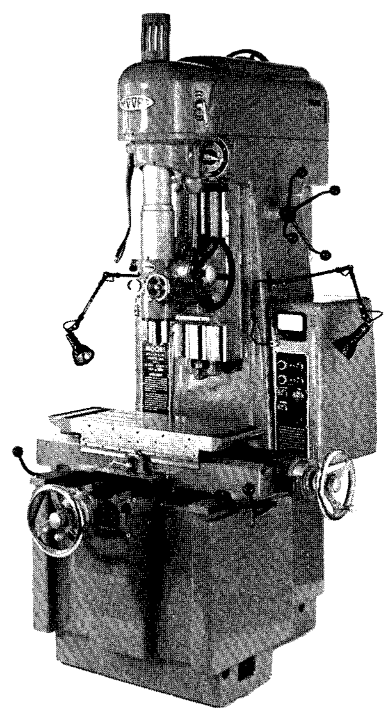
No. 2 Jig Grinder



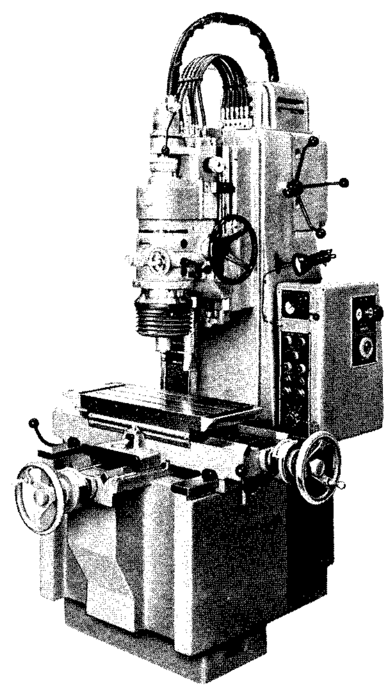
No. 2 Jig Borer



No. 3 Measuring Machine



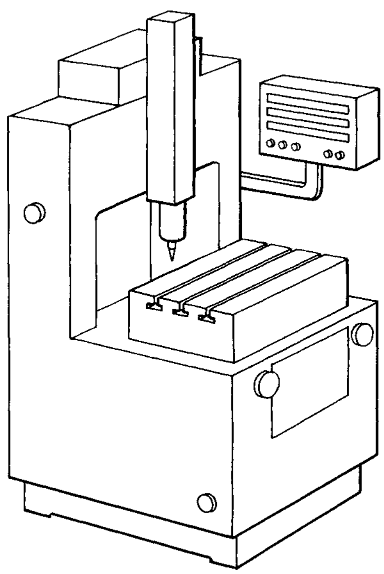
No. 3 Jig Borer



No. 3 Jig Grinder

FIG. 253—*The No. 3 Universal Measuring Machine successfully tested the principle of hardened, ground and lapped double V-ways, as well as other advanced features of the Model No. 3 design. Once proven, these new features were incorporated into the Model No. 3 Jig Borer,* FIG. 254, *and Jig Grinder,* FIG. 255.

FIG. 256—*Coordinate Measuring Machine (CMM's) measure hole location many times faster than a Universal Measuring Machine. However, they are less accurate and of more limited application.*



COORDINATE MEASURING MACHINE (CMM)

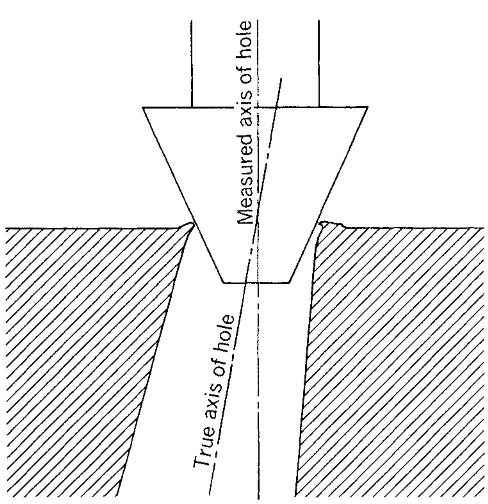


FIG. 257—*The taper-probe of a CMM records hole location quickly but does not truly establish the axis of the hole, nor analyze hole "geometry."*

serviceability. Another unavoidable factor to be taken into account in using a jig borer is the presence of heat-producing elements. Because of the high RPM's involved, the spindle bearings have a tendency to warm up. Moreover, heat from motors, gears, belts and pulleys impose certain modifications in design.

One distinguishing modification to be noted is the use of a cast Invar spindle housing (a costly 36% nickel alloy) with No. 3 Jig Borers and Jig Grinders. It is used not so much to *prevent* heat, but to minimize its *effect* on accuracy. A measuring machine spindle housing of cast Invar, on the other hand, would be an improper and unnecessary use of this material.

Since errors are introduced during the machining operation, holes cannot be put in as accurately as their location can be measured.

In contrast, the design of the measuring machine is concentrated around the singular function of measuring. As a result, it is more accurate and more efficient. It is natural that the measuring machine should "borrow" those design principles that contribute to accuracy in a jig borer. However, just as the jig grinder is a distinct type of machine, though it "borrows" from the jig borer, so too is the Universal Measuring Machine. It is quite understandable, thus, that Dr. Farago would describe this machine as a "Jig Borer-type Measuring Machine."*

Figs. 253, 254 and 255 show the No. 3 Measuring Machine, No. 3 Jig Borer and No. 3 Jig Grinder respectively. Base construction is virtually the same; differences are principally in the nature of column and spindle construction plus the three-times greater accuracy of the Measuring Machine.

Another reason for the emergence of the Universal Measuring Machine is the fact that the jig borer came to be increasingly used in inspection processes. Some were used totally for that purpose. It was inevitable, therefore, that demand would arise for a machine which would *just measure* and, with all the controls and capabilities built in, do the measuring job more efficiently.

A further reason for increased use of the Measuring Machine relates to the need to remove special, ultra-accurate parts from a machining environment into an environment devoted exclusively to inspection. Here a "fresh look" can be given the part in a clean, temperature-controlled environment by a machine designed strictly for measuring and used by personnel with a strong bent for inspection.

Taper-Probe Measuring Machine (CMM)

The so-called "Coordinate Measuring Machines," Fig. 256 are of a different evolution. They seem to have emerged out of the need for checking parts made in production to thousandths of an inch tolerance [several hundredths of a mm]. Prior to their introduction, it was often the case that it took longer to measure a part than to produce it. This was an intolerable condition with production parts.

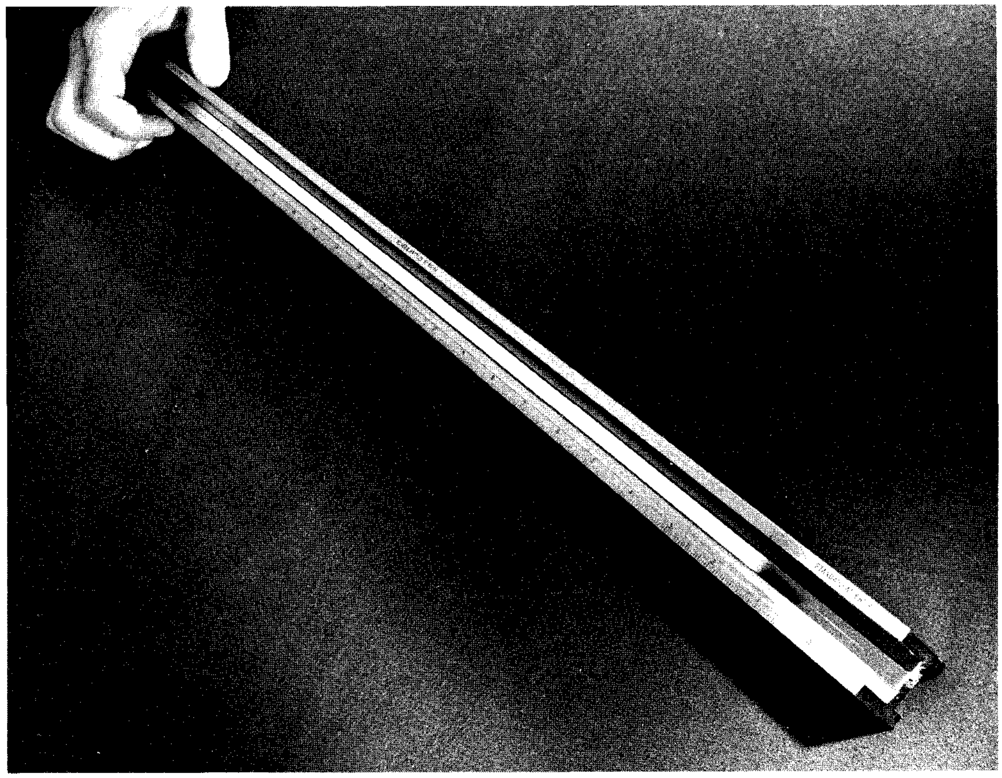
Coordinate Measuring Machines are useful for measuring parts with great speed. They can measure many times faster than would be possible with a Universal Measuring Machine. Their stated accuracies are to several ten-thousandths of an inch [a hundredth of a mm]. Dr. Farago lists its *discrimination* at 100 micro inches [2.5 μm].*

These machines must make certain compromises to attain speed in picking up a hole. No rotatable spindle, as such, is used, but a vertical slide carries a taper-probe which seats in the hole. Since only the top rim is picked up, which measurement might include a burr or a chamfer, they do not

*Francis T. Farago, *Handbook of Dimensional Measurement*, pp. 284, 298–306.

**Ibid.*, p. 284.

FIG. 258—*The precision scale is an important and convenient form of length standard. Its accuracy-potential does not equal that which can be achieved with an end standard, now that the ultimate standard is the wave length of krypton 86.*



truly measure the axis of the hole, Fig. 257. Errors in hole "geometry" can therefore go undiscovered. Reliability of measurement is also dependent on the accuracy and concentricities of the various style probes used. A study of their construction reveals that no real geometric accuracies can be attained, and none are usually given.*

ESTABLISHMENT OF MOORE LINEAR STANDARDS

The level of tolerance in the early days of the jig borer was to about ±.0002 inches [±0.005 mm]. Such a tolerance allowed sufficient margin to use the best commercially available gage blocks and end standards as final length masters. A Universal Measuring Machine, as conceived, made such length standards no longer adequate.

In 1950, Moore started to upgrade its linear standards in preparation for coordinate-locating machines to work to millionths of an inch [hundredths of a μm]. There was a vast difference between the requirements for "tenths" [several μm] and that of "millionths" [hundredths of a μm].

Hand-lapped Step Gages of 1 inch increments [30 mm steps in metric Step Gages] were in use, but they were not accurate enough. It was at once apparent that the first requirement would be to secure standards the lengths of which were known to a few millionths of an inch [a few hundredths of a μm].

The first gages obtained were a sixteen-inch gage block and 16 separate one-inch blocks. It was intended that the ends of the inch-blocks would be tied together, but it was quickly learned that gage blocks were made to be used vertically and not to be fastened together for horizontal use. The following limitations of these gages became apparent from this initial effort:

1. The support surfaces were not flat, and the gages would bend.
2. The ends were not square to the support surfaces.
3. If screwed together, the gages were compressed.
4. If the gages are wrung together, there is no true support; not to neglect the wringing film of ¼ millionth of an inch [0.000006 mm] per wring and the *added uncertainty when that many are wrung together*.
5. The 16-inch [metric end standard is 480 mm] gage block accuracy was simply not there.
6. The gages could not be compared adequately.

Moore next secured gages with squared ends, so that they could be laid down. The micro-finish of the gages was high, but the accuracy was only .0001 inch [0.0025 mm]. Moreover, the square ends were not parallel and flat. Efforts to rework the gages were not successful, since the unsymmetrical ends could not be lapped accurately.

In 1955, a precision scale of "H" section, exceptionally high in quality and workmanship, Fig. 258, was purchased. Serious thought was given to making this the final reference standard, especially in view of the dissatisfaction with previous standards secured. Reading *repeatability* of the scale, however, was only about ±20 millionths of an inch [0.0005 mm]. Even this dropped off

*"Measurement: quick vs. close," *American Machinist*, July 3, 1967.

FIG. 259—Chart records the calibrations by identical means of two Step Gages in the laboratories of Moore, the NBS and NPL. Through use of a No. 3 Universal Measuring Machine, overall length of a known 18-inch standard [the master metric end standard is 480 mm] was transferred to the 18-inch [480 mm with metric] increment of the Step Gage. The remaining steps were secured by a process of subdivision.

CALIBRATION OF MOORE 18″ STEP GAGE BY MOORE, NPL and NBS Unit: 0.000001 (1 millionth) inch			
Inches, zero to	Gage No. 54	Gage No. 54	Gage No. 55
	Moore	NPL	NBS
1	0	0	0
2	0	+1	+1
3	0	0	−1
4	0	−1	+3
5	0	+1	+5
6	0	0	+5
7	0	0	+7
8	+1	−1	+3
9	0	0	+3
10	0	0	+4
11	−1	−1	+6
12	−1	+1	+7
13	0	−1	+7
14	+1	0	+6
15	0	−1	+2
16	−1	+1	+2
17	0	+4	+1
18	0	+2	−3

due to eye fatigue, especially during prolonged microscope use. Two other factors were disturbing:

1. Working to the calibration chart was not only inconvenient, but risky. There was a danger that the correction factor be used with the wrong sign. This was not felt to be a desirable *system* as part of a production operation.
2. "Accuracy of determination" of a scale by the national bureaus was low.

About this time, Frederick C. Victory, then Chief Engineer, charged with the responsibility of securing linear standards, was informed, when visiting the NPL, of a gage-maker in Coventry who was making end standards of round design. The two Airy points were round and to size. The parallelism of the terminal surfaces thus could be determined by autocollimation; turning 180° reversed the error. Since the ends were symmetrical, better lapping for flatness was possible.

It was decided to have this gage-maker make a series of gages of the highest quality without regard to cost. At the same time, a gage-maker in Germany did likewise. All gages were intercompared by the NBS, NPL and PTB.

Several new series of standards were made. Between 1952 and 1961, Mr. Victory made 14 trips to NPL, the same number to the NBS and several to the PTB.* Each time he hand-carried the gages, working with the manufacturer, the NPL, the NBS, and the PTB to produce progressively better results. For instance, some of the first 16 and 18 inch gages [master metric end standard is 480 mm] were within 50 millionths of an inch [0.0013 mm] from nominal. Determinations were close, because they were of excellent geometry, but it was not felt safe to have such an error from nominal. Consequently, the gages were returned and new ones made.

The end standards in use at Moore were 30 millionths of an inch plus. With the pronouncement of the "International Inch" in 1959 (page 108), it meant that the 18-inch* end standards would be 18 x 2 millionths of an inch, or 36 millionths of an inch *longer*, or a total of 66 millionths of an inch long. This was felt to be too great a gap to rely on the linearity of the electronic indicators then in use. The gages were returned to their makers to be re-worked to the new inch to less than 20 millionths of an inch from nominal.

By this time, the No. 3 Universal Measuring Machine had been built and was in use. Through the use of the Measuring Machine, a technique had been worked out to transfer the overall value of the end standard to a Step Gage, the inch increments [30 mm increments with metric Step Gages] being established by sub-division (see pages 180–185).

Fig. 259 shows the result of a calibration of two of these Step Gages by the NBS and the NPL. The error from nominal is quite small and provides the desired 10 to 1 ratio to the Measuring Machine, guaranteed to an accuracy of 35 millionths of an inch [0.0009 mm].

However, the various national bureaus were reluctant to give an "accuracy of determination" closer than ± 15 millionths of an inch [0.00038 mm], because of the unknown metal and unspecified coefficient of expansion of the end standard to which the Nitralloy Step Gages were calibrated. This was something Moore did not think it could accept. As a consequence, *Nitralloy* end standards were made, hardened, ground, stabilized and brought to the gage-maker

*Extremely accurate checks were being made at an early date at the PTB with a new design Koester's Interferometer—largely the work of Dr. E. Englehard.

*The master metric length standard used is 480 mm in length. This standard was unaffected by the change to the "International Inch"; no metric figures are therefore listed.

FIG. 260—Master end standards are hand-carried to the major national bureaus of the world for intercomparison and certification. Albert Johnson, Chief Project Engineer at Moore, is responsible for standards.

FIG. 261—*Calibration of end standards at the major bureaus is done on a continuous basis to assure a current record of traceability within each major nation. Close agreement by the bureaus gives greater confidence to the calibrations obtained. Note that the NPL, NBS, PTB and the BIPM agree on the length of End Standard No. 1-18 within one millionth of an inch [0.000025 mm].*

to be finish-lapped. This meant that the end standard, the Step Gage and the lead screw of the Measuring Machine were all of the *same material,* and thus had the *same coefficient of expansion.*

Four sets of 12-inch and 18-inch [as well as 480 mm] end standards were made. The best of two of these gages were selected—the two closest to nominal having the best "geometry" as to micro-finish, flatness, and parallelism of the ends.

After Mr. Victory's death, the task of establishing standards fell to Mr. Albert Johnson, Chief Project Engineer, Fig. 260. Mr. Johnson was to hand carry these gages to the NPL, the PTB, BIPM and the NBS for calibration.

Note that agreement is to 1 millionth of an inch [0.000025 mm] for gage No. 1-18, Fig. 261. This historical chart also provides one of the most accurate tests made on the dimensional stability of a material (Nitralloy, in this case). Fig. 262 shows a Moore End Standard at the BIPM in preparation for measurement by interferometric means.

These end standards calibrated by the bureaus are ultimately the authority for measurements of length performed with the Moore Measuring Machines.

The reader may now appreciate that *accurate linear measurement* is synonymous with accurate temperature-control, and that the latter is deserving of as much attention as the former. Before proceeding, then, to linear measurement at Moore, it is necessary to delineate the "environment" where it is performed.

TRACEABILITY OF MOORE STANDARDS

Deviations from nominal are expressed in millionths of an inch.

16 in. End Standard No. 2-16	**Bureau**	**Calibration**
November 1958	(Started)	—
June 1959	NPL	+1
July 1959	PTB	+1.5
August 1959	NBS	+3
July 1960	NBS	+2
March 1963	NBS	+2
October 1964	NBS	−2

18 in. End Standard No. 7587	**Bureau**	**Calibration**
November 1958	(Started)	—
June 1959	NPL	+2
July 1959	PTB	+10
August 1959	NBS	+3
July 1960	NBS	+6
March 1963	NBS	−1
October 1964	NBS	−2

16 in. End Standard No. 2-16	**Bureau**	**Calibration**
December 1962	(Started)	—
November 1963	PTB	−23.5
March 1964	NPL	−26
October 1964	BIPM	−22.1
August 1965	NBS	−22

Four Bureaus in agreement to 0.000004 (4 millionths) in., or 1 part in 4 million.

18 in. End Standard No. 1-18	**Bureau**	**Calibration**
December 1962	(Started)	—
November 1963	PTB·	−21.2
March 1964	NPL	−21
October 1964	BIPM	−22.1
August 1965	NBS	−22

Four Bureaus in agreement to 0.0000011 (1.1 millionth) in., or 1 part in 16.4 million.

480 mm End Standard No. 2-48CM (Metric)	**Bureau**	**Calibration**
December 1962	(Started)	—
November 1963	PTB	−32
March 1964	NPL	−31.2
October 1964	BIPM	−28.3
August 1965	NBS	−31.1

Four Bureaus in agreement to 0.0000037 (3.7 millionths) in., or 1 part in 5.1 million.

NBS—U.S. National Bureau of Standards, Washington, D.C.
NPL—National Physical Laboratory, Teddington, England
PTB—Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany
BIPM—Bureau International Des Poids et Mesures, Sevres, France

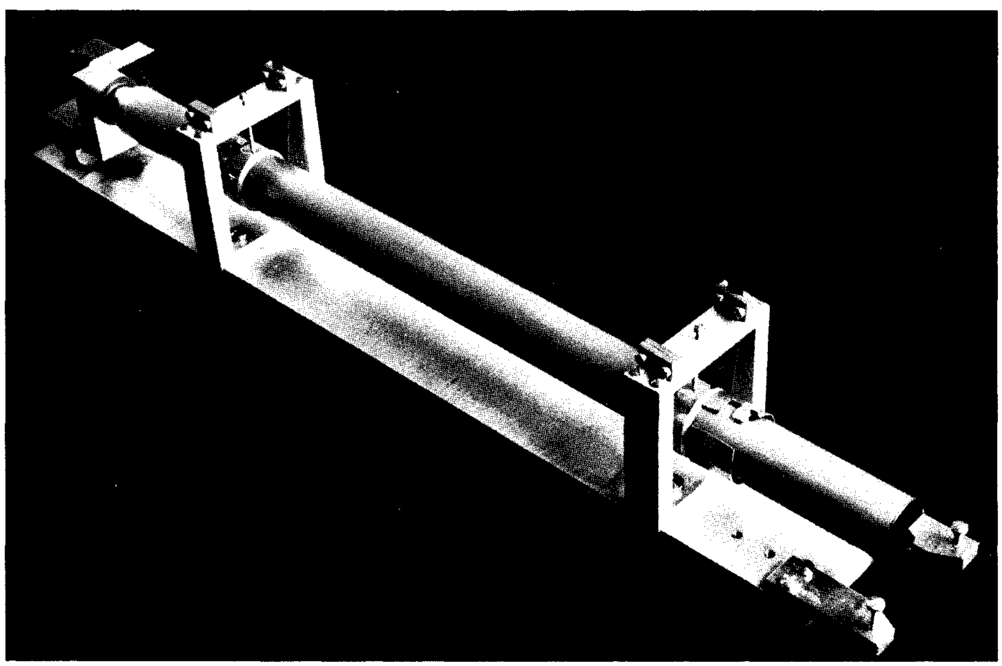
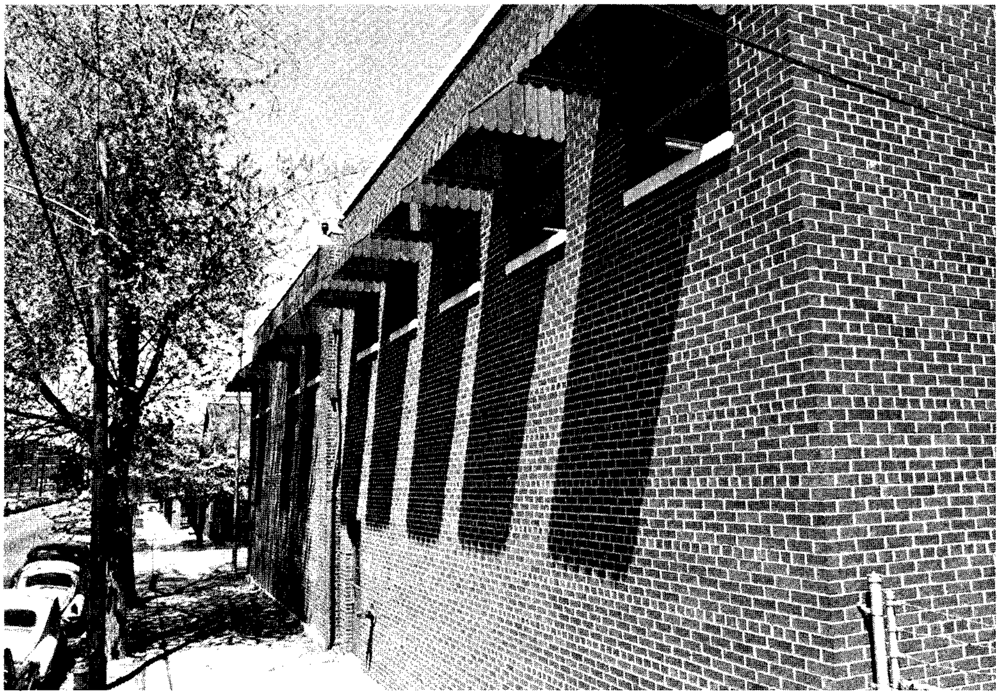


FIG. 262—*A Moore End Standard at the BIPM prior to measurement by interferometric means.*
Courtesy of BIPM.

FIG. 263—*The Moore Measuring Machine Laboratory is windowless, contributing to greater temperature uniformity.*



4. Temperature Control

Moore's temperature-controlled building, Fig. 263, is a two-story plus basement structure, 40 ft. by 70 ft. [12.19 meters by 21.3 meters], with a brick exterior. All the floors are of 12 in. [305 mm] reinforced concrete to give strength and stability. The basement and first floor are windowless.

Within the structure are five separate temperature-controlled areas, with varying degrees of refinement, each designed to meet a special need. They are:

Contract Inspection
Instrument Assembly
Standards Room
} Below Ground

Measuring Machine Laboratory—1st floor

Jig Boring and Jig Grinding—2nd floor

While the individual temperature-controlled areas are self-sufficient, they are integrated with one another as to power source and fresh air, Fig. 264. Moreover, they are connected with adjoining manufacturing areas.

MEASURING MACHINE LABORATORY (First Floor)

The Moore Measuring Machine Laboratory, Fig. 265, was originally designed and constructed expressly for assembly, inspection and final corrections of Nos. 1½, 3, 4 and 5 Measuring Machines (the latter two are now made in a separate laboratory). This room, while accommodating many persons using lights, tools, hoists and inspection instruments—all heat producers—still maintains accurate temperature. From the beginning, the problem of how to control a room's temperature to the closest possible tolerance and still have it a *working* room was uppermost. A temperature-controlled area is of little value if no one may use it or work in it.

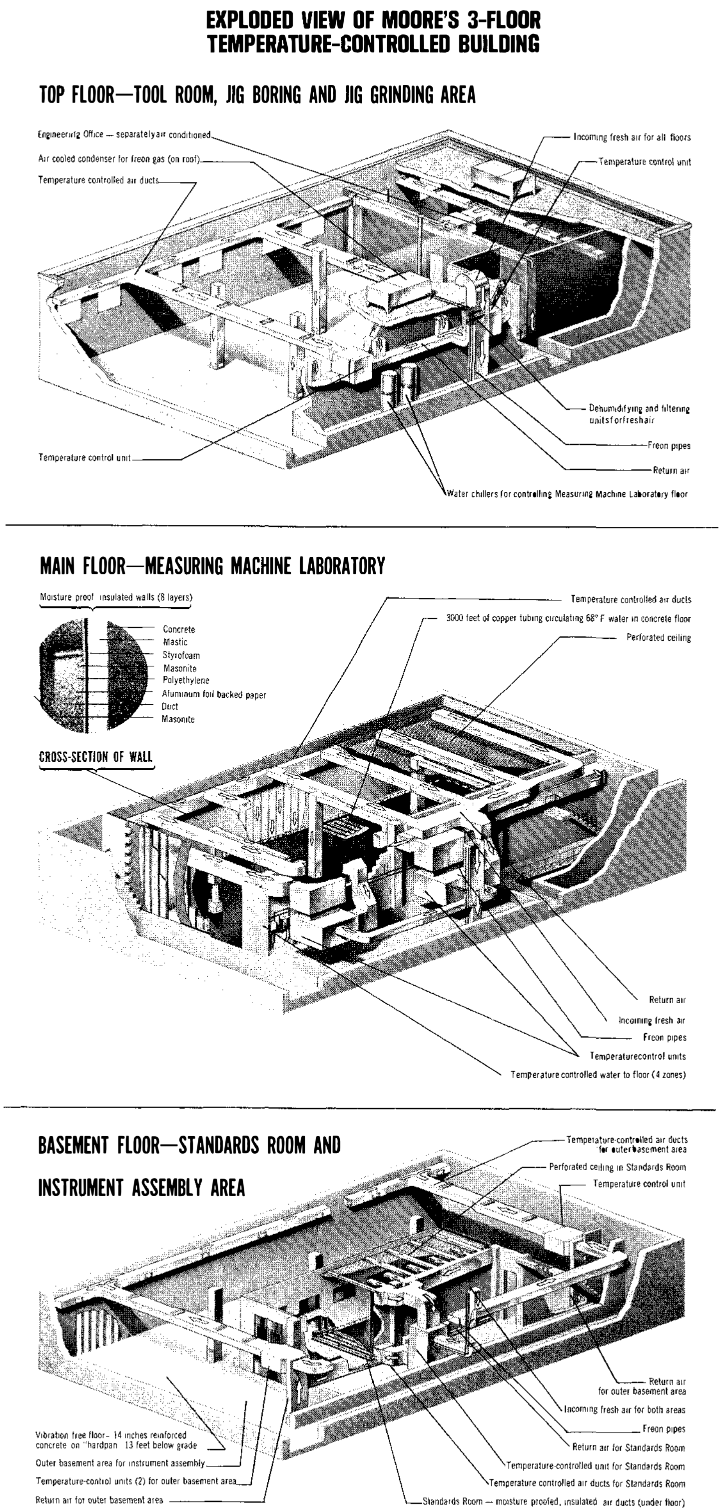
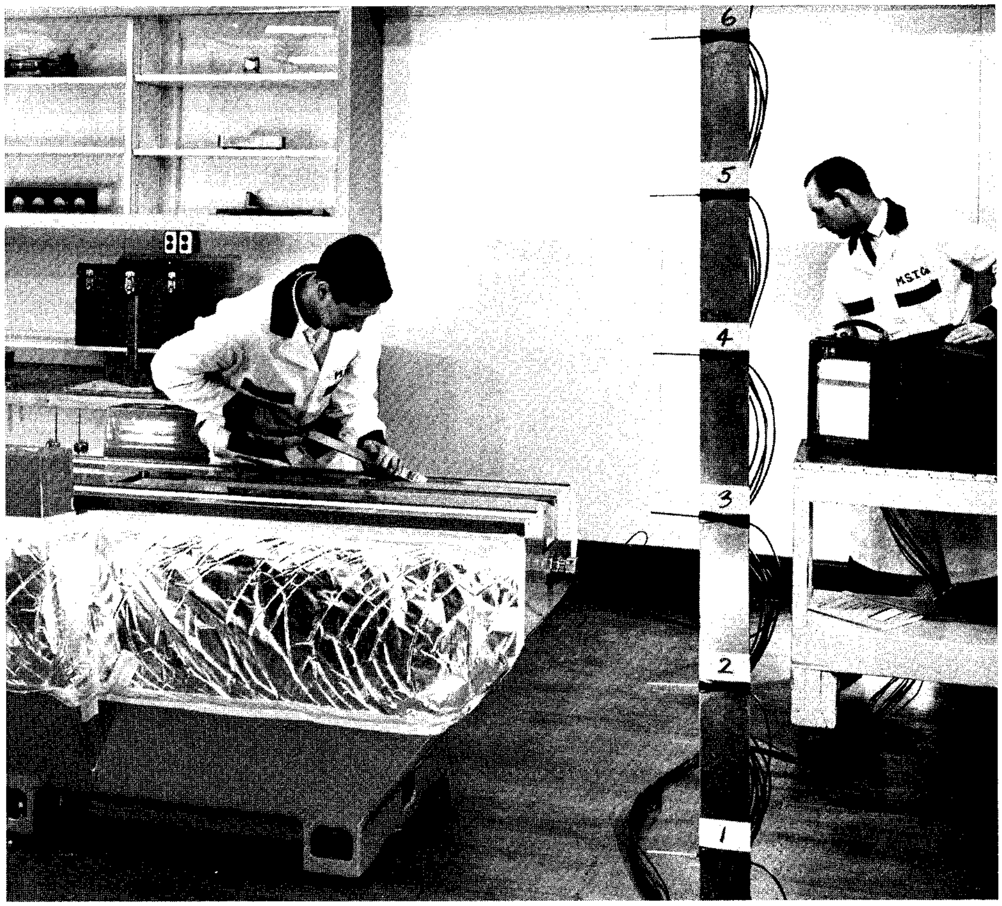


FIG. 264—*The Measuring Machine Laboratory Building is temperature-controlled with separate systems on each floor. Each floor contributes to the stability of the others.*

FIG. 265—*Universal Measuring Machines are assembled and inspected in a temperature-controlled working laboratory (first floor).*

FIG. 266—*"Stratification" of room temperature is most difficult to prevent and is best achieved by the "reverse-flow" principle introduced by Moore. Note that the No. 4 Measuring Machine base has been insulated to guard against body heat while being scraped.*



Problem of Stratification

Because the Measuring Machines to be calibrated stand at least 6 feet [2 meters] high, it was particularly important to eliminate "stratification" of room temperature, which could cause machine distortion and other inaccuracies, Fig. 266. The usual concept of a temperature-controlled room calls for rectified air to be introduced from the ceiling, spill out into the room, and be carried away either at the sides or near the floor, Fig. 267. However, rectified air coming down into the room is at once met by the heat from lights and other rising heat currents. By introducing temperature-controlled air at the top, heat is *prevented* from being carried out and instead is *brought back* into the room. The rectified air is, therefore, not necessarily introduced at 68°F. [20°C], but at some lesser temperature. By the time air reaches work level, mixing within the room is depended on to create an average temperature of 68°F. [20°C].

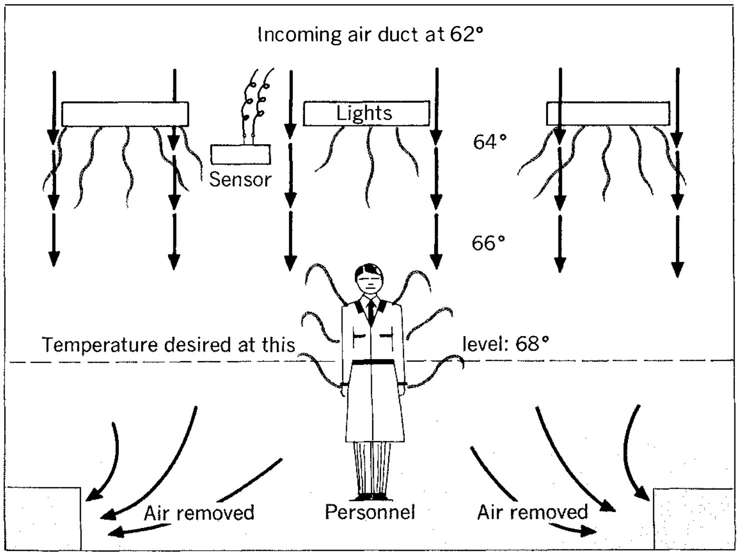
When working with instruments, gages and smaller parts, a limited amount of stratification is permissible. The 68°F. [20°C] temperature is then held only within the narrow band at which measuring is performed, usually work-bench level.

During Moore's history of striving for ever-closer measuring tolerances of its locational machines, the ability to control temperature had to progress hand-in-hand. From 1940, when its first temperature-controlled room was constructed, Moore has experimented with temperature control. There are now at least 20 separate systems placed strategically in the plant, varying in design and refinement.

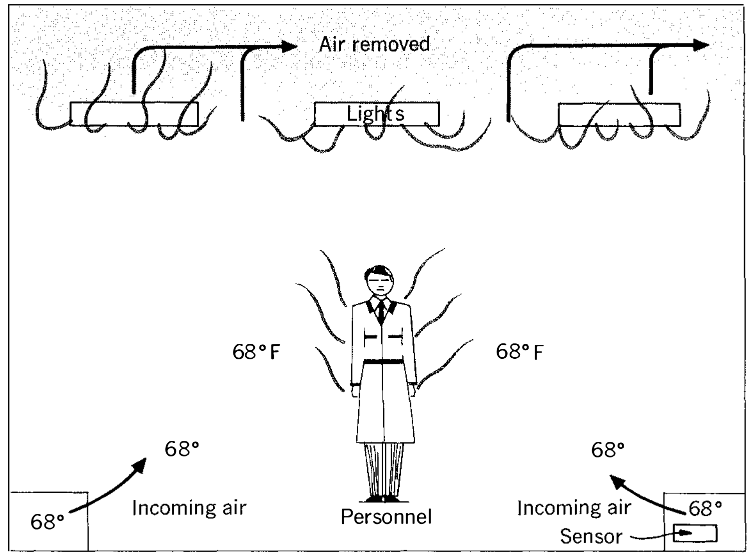
Considerable data was accumulated. It was noted that with the ceiling-to-floor air flow, while possible to control temperature to $\pm 1/10$°F [less than $1/20$°C] at *one* room level, it was virtually impossible to do so at *all* levels. Much effort was expended on the stratification problem. Maintenance of high static pressure greatly reduced the variance

FIG. 267—*In the usual conception of temperature-control, air is brought in at the ceiling and expelled at floor level. The disadvantages of this system are:*
1. *Heat is brought back into the environment.*
2. *The sensor acts slowly after averaging.*
3. *Since the air cannot be brought in at 68° F [20° C], some of the cold air may sink to the floor, causing "stratification."*

FIG. 268. *The principal difficulty in an environment that is controlled by "reverse-flow" of air is to obtain sufficient "mixing"; however, this system has the following advantages:*
1. *Heat is removed from the environment.*
2. *The sensor acts immediately and must only correct incoming air.*
3. *Air can be brought in at 68° F [20°C].*



CONTROLLED ENVIRONMENT
STANDARD AIR FLOW



CONTROLLED ENVIRONMENT
REVERSE AIR FLOW

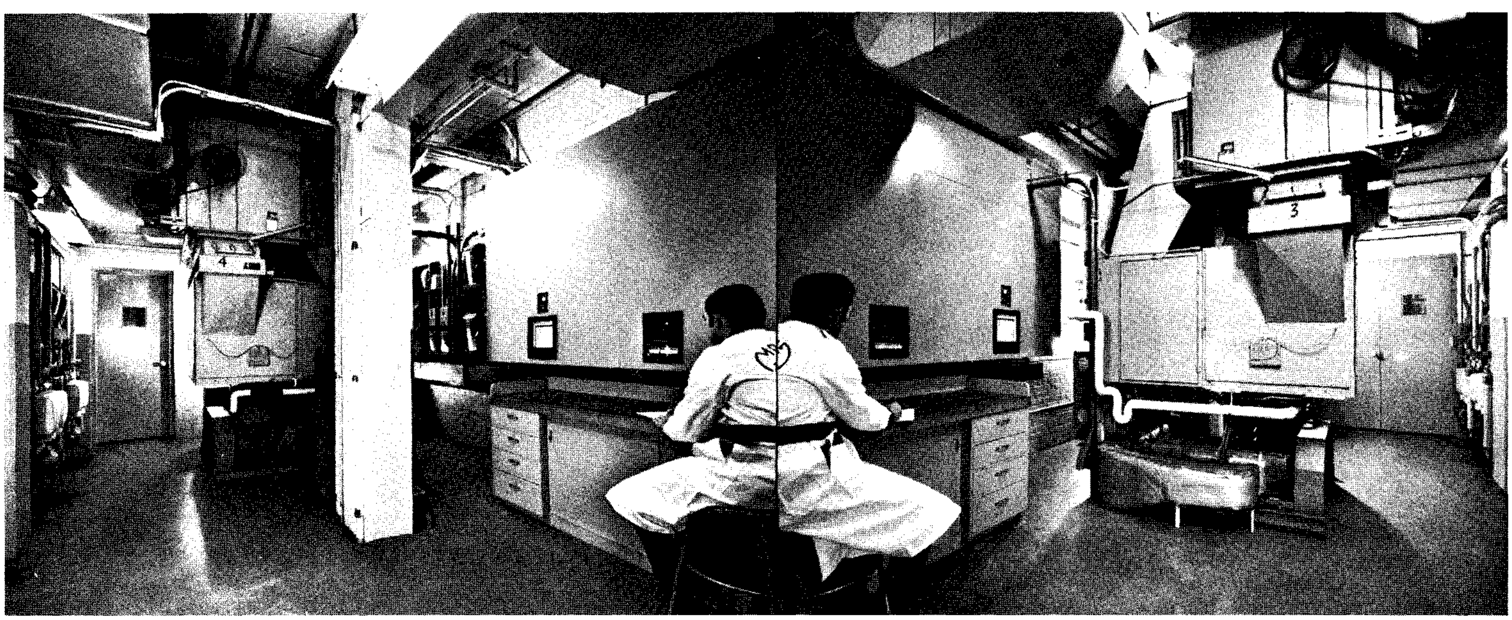


FIG. 269—*Two separate temperature-control units maintain the temperature of the Measuring Machine Laboratory. Each unit consists of a heat and refrigeration cycle. These photos taken from mid-point of the room are combined to show one unit to the left and the second unit to the right.*

of temperature from floor to ceiling. The conviction arose that the *direction of air flow* was the limiting factor to progress. One of Moore's temperature-controlled rooms was then modified as a test area, where air was *introduced* at floor level and taken out at ceiling height. The results exceeded expectations; not only was stratification cut by 80%, but temperature was maintained closer to ambient with the same control unit, Fig. 268.

Design Features

The laboratory itself was designed to incorporate this new principle, as well as those other features culled from Moore's experience, research, and study of other outstanding systems. Two independent temperature-control units, Fig. 269, were installed in an adjacent area, each consisting of a refrigeration and a heat cycle. *The refrigeration cycle* is believed to be a first-of-its-kind design. A variable speed compressor controls the "boil-off" rate of freon in a "flooded-coil" type of system. The "suction pressure" thus maintained has a direct relationship to the temperature of the liquid freon. Instrumentation converts this suction-pressure to an electric signal which, in turn, varies the speed of the compressor, Fig. 270. The refrigeration cycle thus is a self-contained temperature-control system. Test-runs have shown it capable by itself of maintaining room temperature to $\pm\frac{1}{4}$°F [$\pm\frac{1}{8}$°C approx.].

The heat cycle, consisting of heating coils which heat the air once past the cooling coils, is activated by temperature-sensitive probes. The heating coils are capable of pulsing on and off at the rate of 120 times per second, further reducing the limits of temperature deviation, Fig. 271. Each unit is zoned independently to control one-half of the room, but has more capacity than is needed to control the whole room by itself.

Through a "fail-safe" system of control vents in the feed ducts, either unit can be switched over to maintain the room in the event of a break-down or for repairs or adjustments of the other unit. The long "soak-out" period which would be necessary to bring the machines and gages back to equilibrium after an ambient temperature change makes such a precaution economically justified.

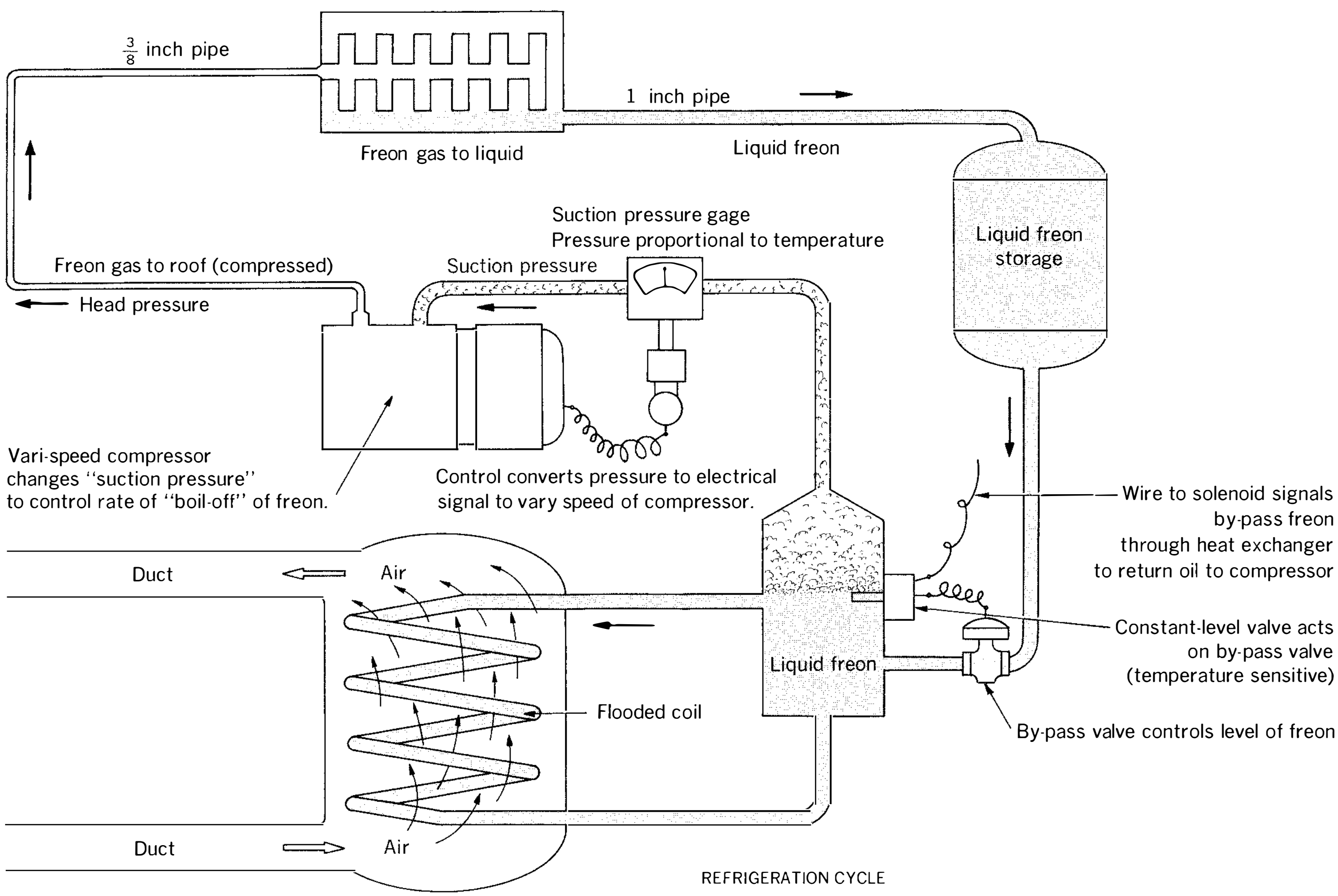
The sides of the room are actually a wall of individual ducts, 16 inches [406 mm] on center and individually adjustable, taking temperature-controlled air to the floor around the complete periphery of the room. The air is also fed down on four sides of three structural columns spaced apart in the middle of the room. It was found that this system did not provide as much "mixing" of air as hoped for and at a later date a series of vents were added to discharge rectified air over the work-benches.

Temperature-controlled Floor

68°F [20°C] water flows through over $\frac{1}{2}$ mile [800 m] of copper tubing in the 12-inch [305 mm] thick reinforced concrete floor. This network of piping, in four zones, contributes to stabilizing the temperature of the air at floor level, the most difficult area for eliminating stratification.

The temperature-controlled rooms which sandwich the Measuring Machine Laboratory further contribute to stabilizing its temperature. These rooms, together with the circulating water in the floor, also prevent the outdoor temperature, whether heat of summer or cold of winter, from creeping into the room via the steel reinforcing rods in the concrete.

FIG. 270—*The refrigeration cycle, unlike most systems, is capable of reacting independently to control temperature.*



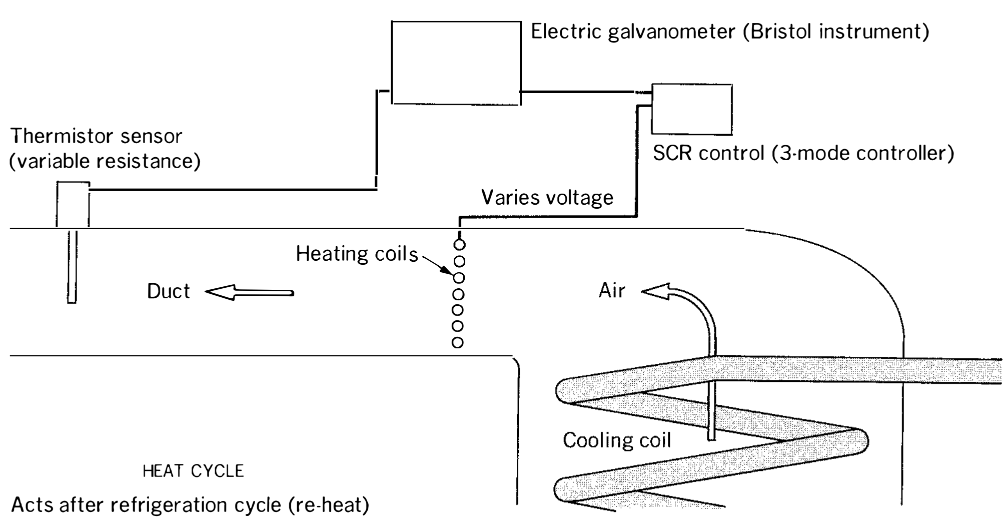
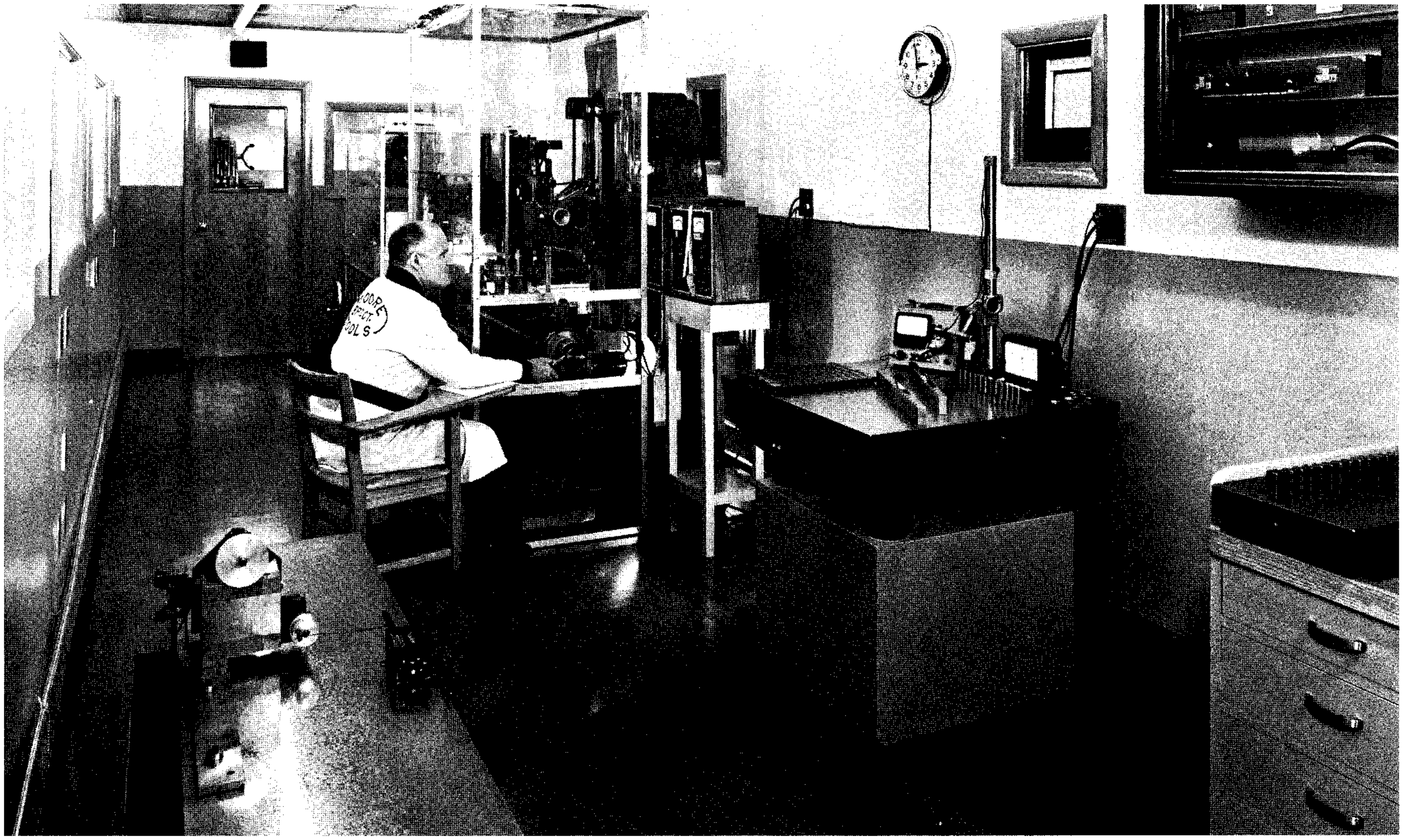


FIG. 271—*The heating cycle acting on air which has already been closely-controlled by the cooling cycle.*

FIG. 272—*The Standards Room is located below-ground, and is a temperature-controlled room within a temperature-controlled room. Moore length standards are maintained here.*

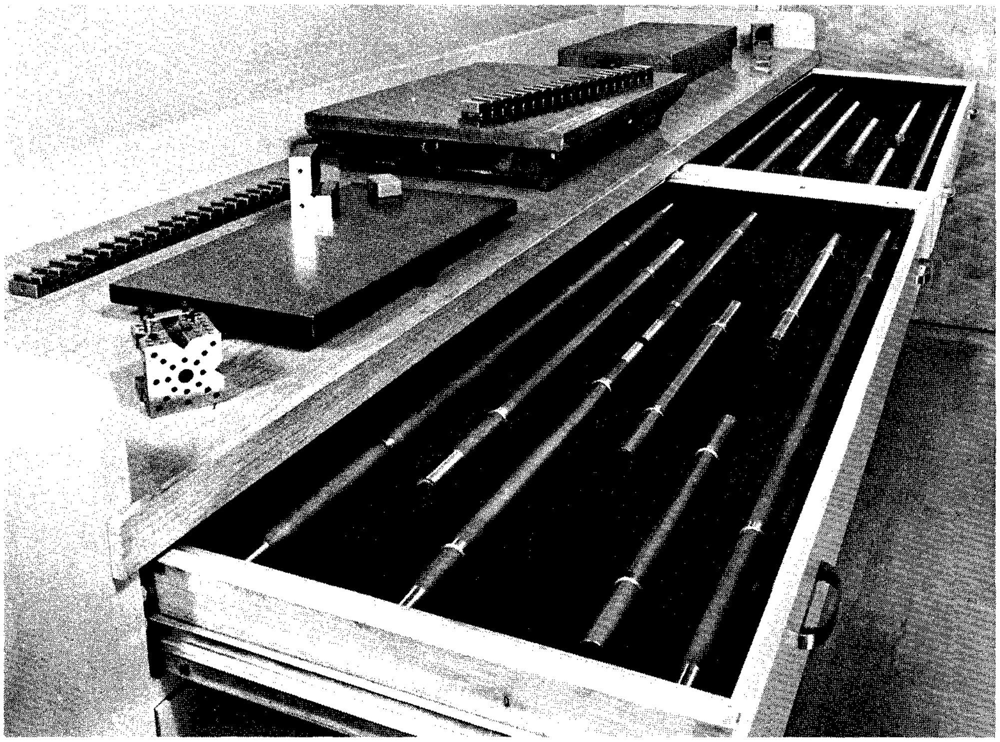


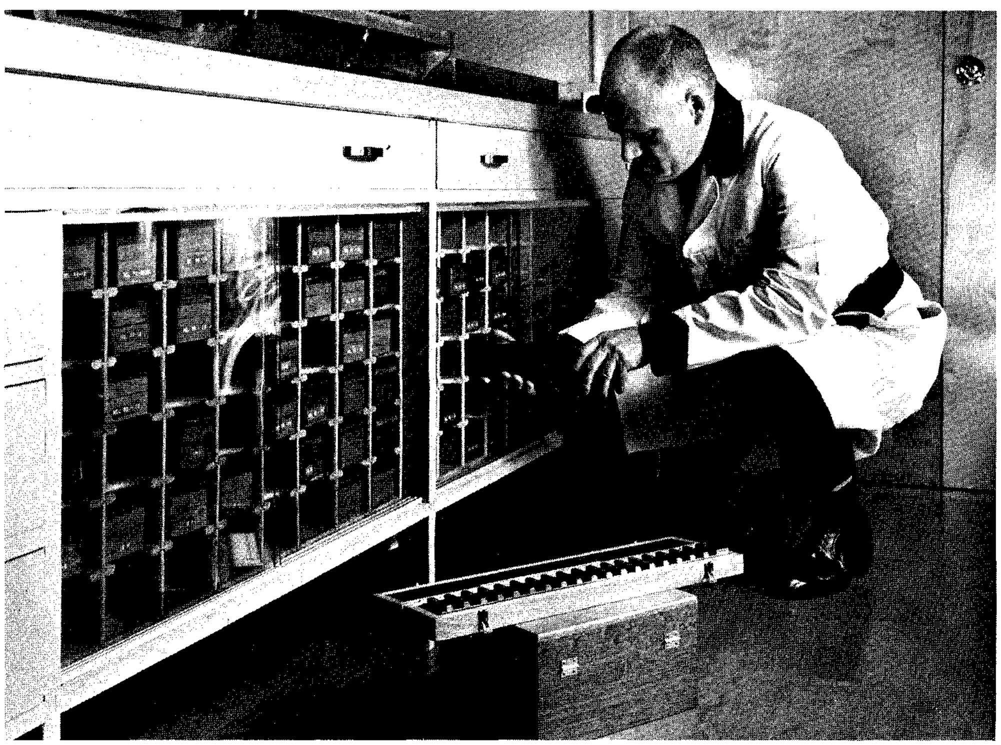
STANDARDS ROOM
(Below Ground)

In the Standards Room, Fig. 272, are kept the following linear standards, the authority for length measurements performed on Moore Jig Borers, Jig Grinders and Measuring Machines:

1. A series of master end standards, such as 9 in., 14 in., 16 in., 18 in., and 480 mm, inter-compared by Moore and certified by the National Bureau of Standards, Washington, and the National Physical Laboratory, Teddington, England, at regular intervals, Fig. 273.
2. Moore Master Step Gages, which are a derivative of the end standards, but

FIG. 273—*Master end standards, which have been hand-carried to various bureaus of the world for calibration, are stored for safe-keeping in the Standards Room.*





calibrated in turn by the NBS, PTB, BIPM and the NPL, Fig. 274. These gages are accurate to a few millionths of an inch [tenth of a μm]. In this room is performed the transferal of accuracy from master standards to Step Gages by measurement, calibration and correction.

Importance of 68°F [20°C] Temperature

Consider that an 18 inch [457 mm] Step Gage whose accuracy must be in the realm of 2 millionths of an inch [0.00005 mm] will be in *error* by 2 millionths of an inch [0.00005 mm], when its temperature differs by as little as 1/50°F [1/90°C] from that of the master standard to which it is being compared. Then it will be appreciated that the very highest order of temperature control system must be used in the Standards Room.

A location below ground level was preferred for the Standards Room because of (1) the naturally low level of vibration and (2) the fact that ground temperature would contribute to the stability of the room. While the location below-ground was advantageous, it was recognized that the walls and floor of the room, which had to be held to exactly 68°F [20°C], could actually be exposed to ground temperature, normally 55°F [13°C].

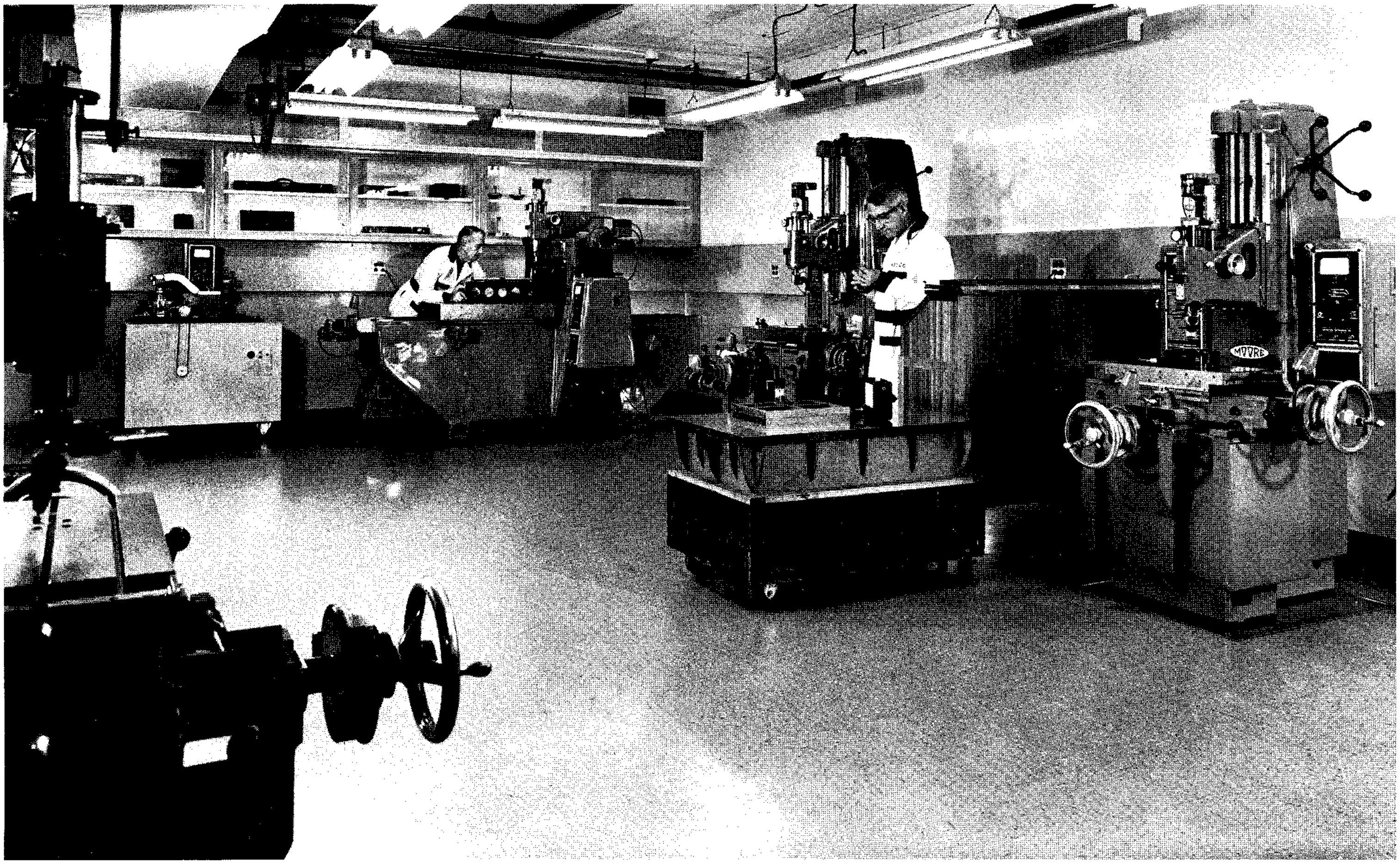
Consequently, it was decided to make the Standards Room a "room within a room." The space surrounding it would become a new area having its own temperature control system and would encompass instrument assembly, Fig. 275, rotary table calibration, Fig. 276, and contract inspection, Fig. 277. For this area, the requirements would be less stringent, but would contribute to stabilizing the temperature of the Standards Room. Also, the wood floor of the Standards Room would be elevated from the concrete, and the space between insulated, moisture-proofed, and utilized to

FIG. 274—*Moore Master Step Gages, whose lengths are derived from master end standards, are lapped to final accuracy, calibrated and stored in the Standards Room.*

FIG. 275—*The Rotary Table Assembly Room adjoins the Standards Room on one side. The Standards Room can be seen through the windows.*

FIG. 276—*Adjoining the Standards Room is the rotary table lapping and calibration area.*

FIG. 277—*The Contrad Inspection Room, located adjacent to one end of the Standards Room, specializes in unusual inspection tasks performed with Universal Measuring Machines. All the instruments, gages and standards at Moore are at the disposal of its personnel.*



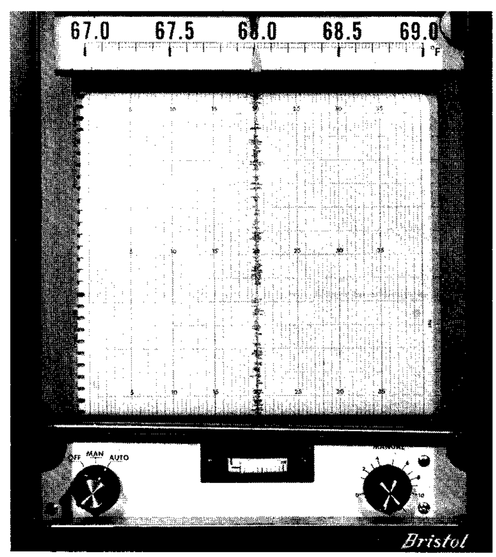


FIG. 278—*A typical recording of incoming-air to the Standards Room. Each line on the chart is equivalent to 1/40° F [9/200th° C].*

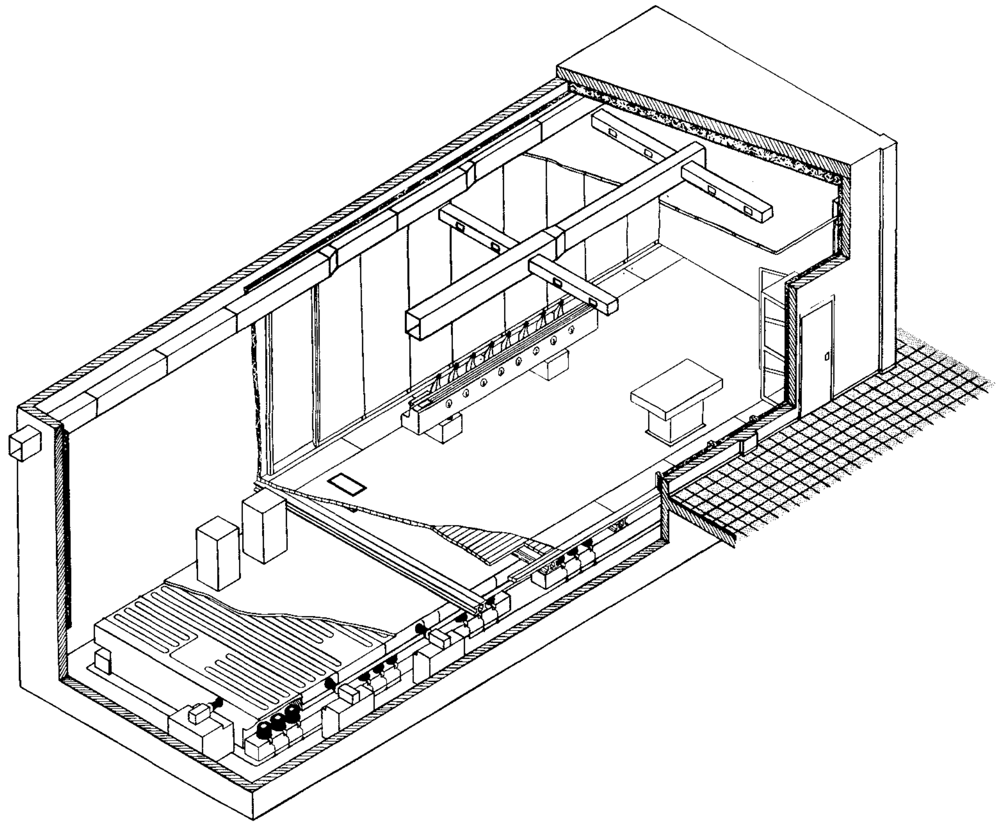


FIG. 279—*The success of the Moore reverse-flow air principle encouraged its adoption by other leading laboratories, such as the Instituto Galileo.*
Courtesy Prof. Raffaele Ciambrone, Instituto Galileo Galilei, Milano, Italy.

conduct the rectified air to the opposite wall. These precautions isolate the Standards Room from external temperature conditions.

68° F [20° C] is controlled to the highest order, Fig. 278. The success of the reverse-flow principle in the Measuring Machine Laboratory, especially in minimizing stratification, encouraged the adoption of a similar system in the Standards Room. In the transferal of accuracy, master gages are set up on the table of a Moore Measuring Machine, the latter being employed only for straight-line movement. If the room were to be subjected to stratification, the temperature of the lower strata of the room would tend to be conducted through the machine, influencing the gages. By *minimizing* stratification, the mass of the machine then acts as a stabilizing "heat sink," assuring that the gages being compared are as close as possible to 68°F [20°C], and even more important, of identical temperature.

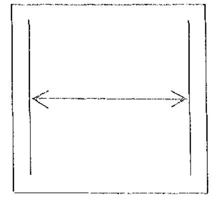
In conclusion, three main design features assure the Standards Room being controlled at 68°F [20°C] to the highest order:

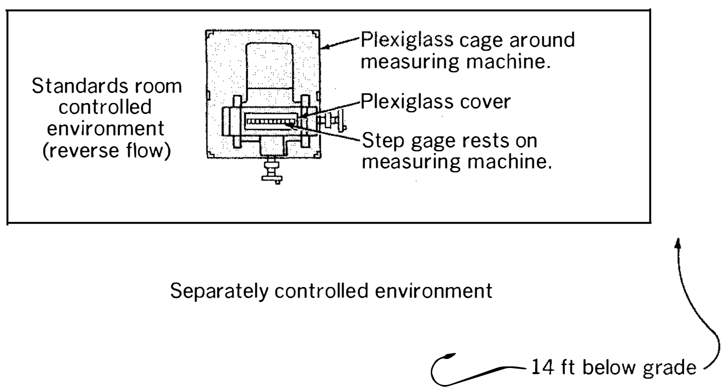
1. The reverse air-flow system;
2. The exclusion of heat-producing elements;
3. The greater length-to-width ratio of the room enables the rectified air introduced at floor level to be more completely infiltrated in the room.

The inherent logic of the "reverse-flow" system has influenced the adaption of this system in other leading standards laboratories, such as the Instituto Galileo Galilei, Milan, Fig. 279.*

*Professor Raffaele Ciambrone informed the author at the 1969 Microtecnic Exposition, Zurich, that it was operating to complete satisfaction.

FIG. 280—*Illustrated is the manner in which the step gage is isolated from external sources of temperature-differential during calibration.*





5. Transferal of Accuracy*

TEMPERATURE PRECAUTIONS

Fig. 280 shows the location of the Step Gage during transferal of accuracy from end standard to Step Gage. The floor is 14 feet [3.6 meters] below grade on "hardpan."

The Instrument Assembly Area and the Inspection Center Area surrounding the Standards Room are separately temperature-controlled. A plexiglass cage surrounds the machine. The end standard and Step Gage to be compared both rest on the Measuring Machine table. The gages themselves are "buried" behind a plexiglass cover, Fig. 281, leaving only a small slot to permit indicator movement. Aluminum foil, used as a reflective shield over the cover, was removed in the picture to show the setup.

Thus isolated, the Step Gage assumes table temperature fairly quickly. The end standard, having less surface contact, requires more time to reach ambient. This potential source of a temperature differential is minimized by placing the end standard in contact with the Step Gage.

Although the temperature of the air about the length standards is probably not held closer than 1/50th of a degree Fahrenheit [1/90°C, approx.] from ambient, with the above temperature precautions, the gages, once "soaked out," are virtually identical in temperature. However, as an added precaution, and for convenience, it is useful to be able to probe for temperature differentials with thermocouples anywhere within the immediate gaging environment, Fig. 282. Each thermocouple can be made to register on a galvanometer inside a "black box" located in the Standards Room, Fig. 283. The thermocouple can also be compared to a certified master thermometer which is buried in a copper block inside the black box.

*Most metric equivalents are omitted from this section by intention for the sake of clarity, since the same procedure described is also followed for metric gages.

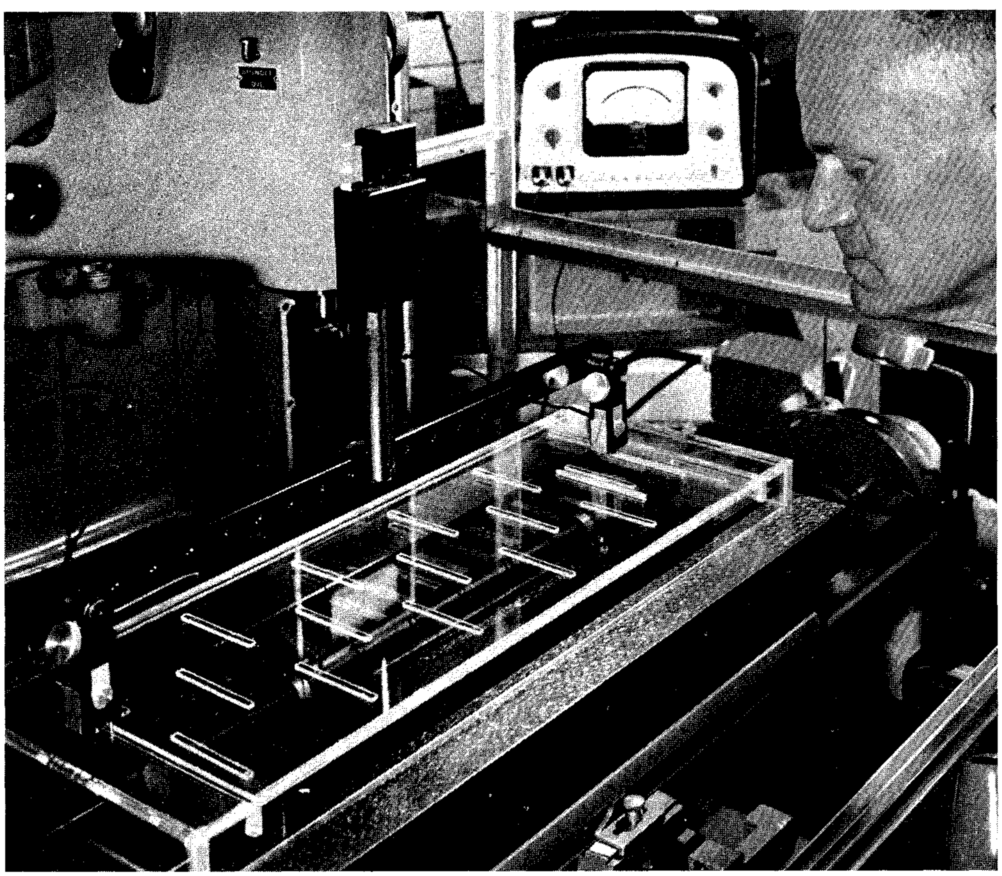
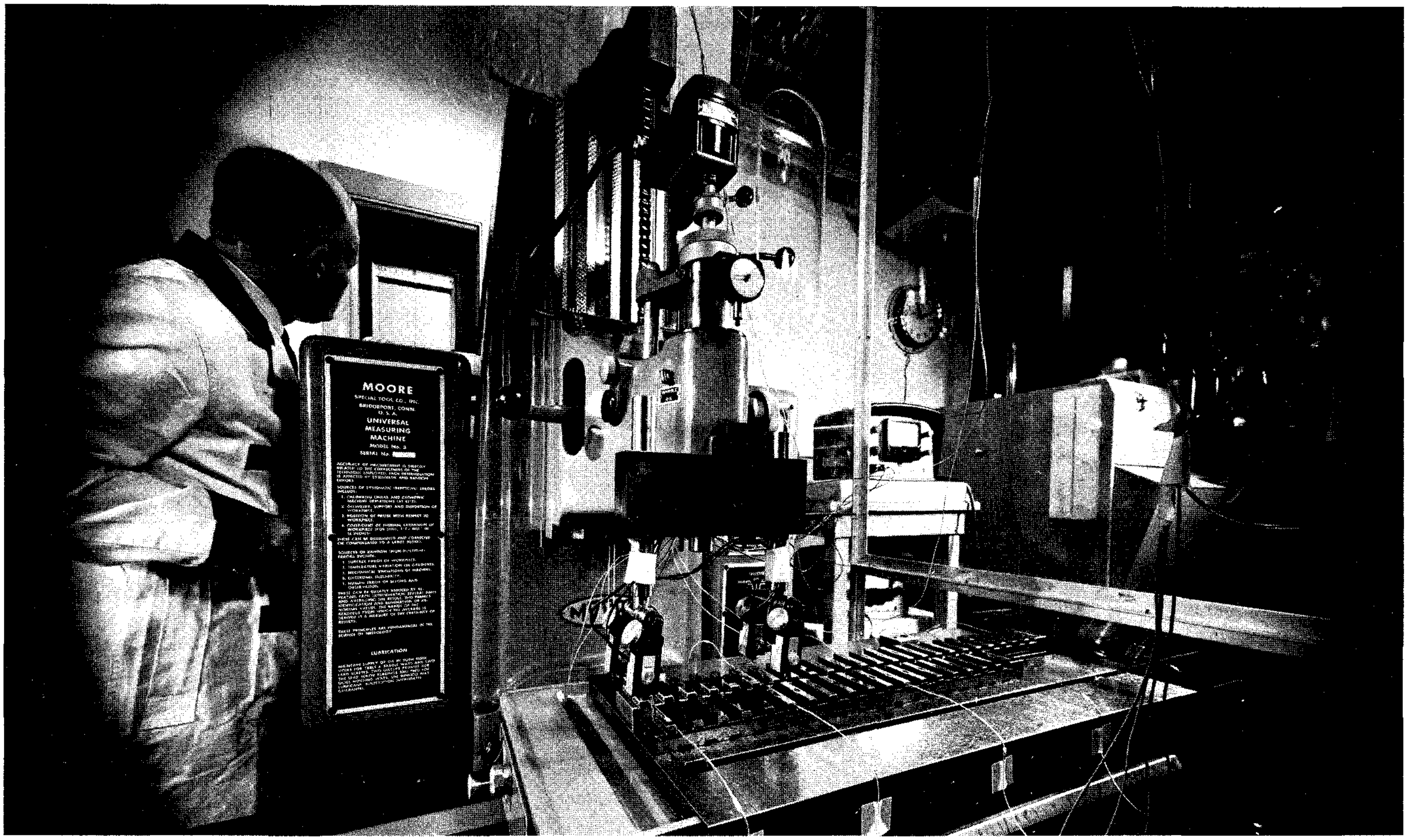


FIG. 281—*The Step Gage is compared to the end standard while both rest on the table of the Universal Measuring Machine. Slots in the plexiglass cover are only wide enough to facilitate indicator movement. Aluminum foil, which in practice is placed over the cover and used to reflect radiant heat, was removed for the photograph.*

Photograph courtesy American Machinist.

FIG. 282—*Thermocouples are used to probe the Step Gage along its length and also other areas of the gaging set-up in order to detect any temperature differentials.*



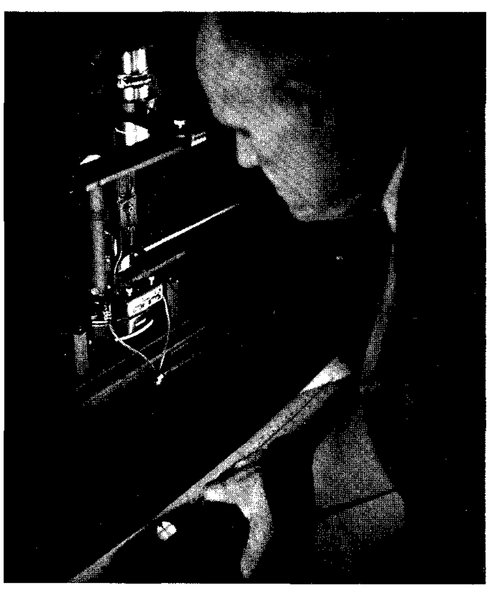
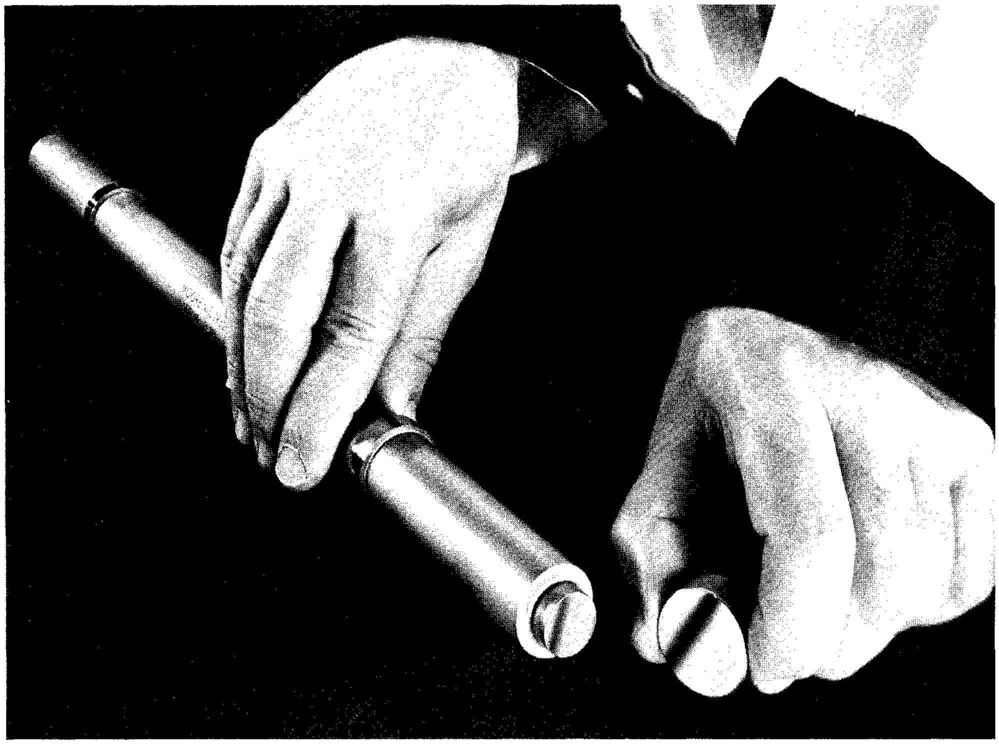


FIG. 283—*Each thermocouple in the gaging area can register temperature through switching by means of a galvanometer inside a "black box." Thermocouples can also be compared to a calibrated master thermometer buried in a copper block inside the "black box."*

FIG. 284—*The ultimate standards of length at Moore are end standards of various lengths. The purpose of the "wrung-on piece" is to act as a reflector in the optical arrangement when compared to the krypton 86 standard. The same wrung-on piece is also used in "transferal" of accuracy from end standard to Step Gage.*



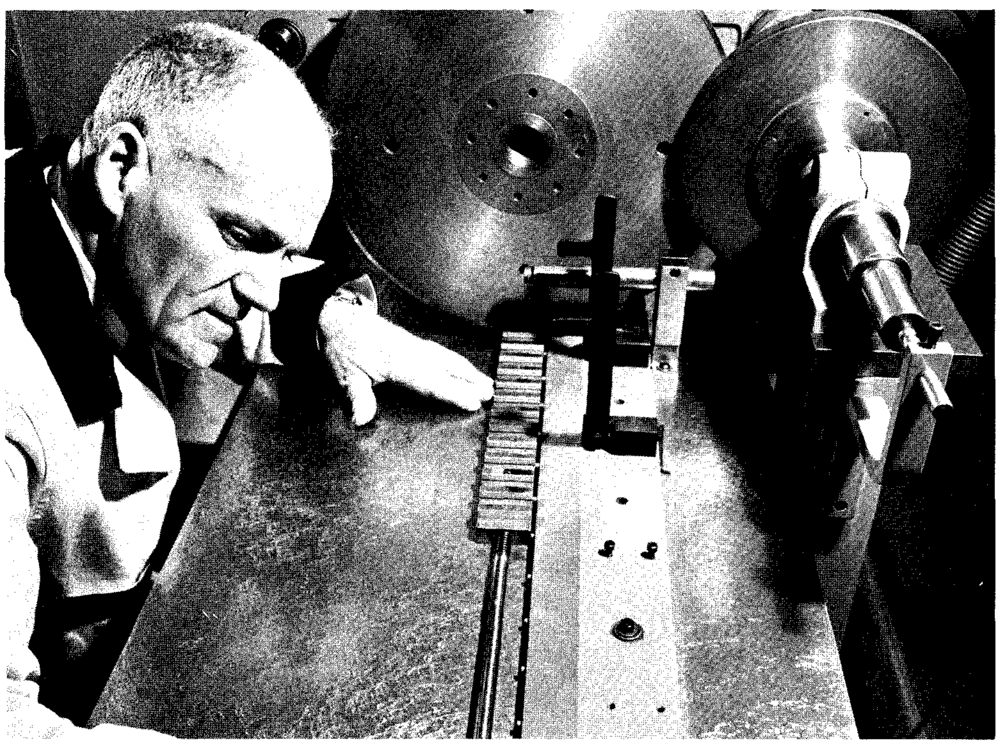


FIG. 285—*Gaging faces of the Step Gage are lapped on a special fixture. Great care must be taken in the lapping operation to maintain the "geometry" of the faces. If one step is reduced only a few millionths of an inch [tenth of a μm] more than intended, the only means of correction is to reduce all the other steps a like amount.*

METHOD OF TRANSFERAL

For the transferal of accuracy, two electronic indicator gage heads are fastened to a steel bar, which is, in turn, fixed to the Measuring Machine spindle housing. A series of tapped holes are provided in the bar to enable separation of the gage heads in nominal 1 inch increments up to 18 inches and 30 mm increments up to 480 mm.

The electronic indicator used is of the differential-type, reading to 1 millionth of an inch [0.000025 mm]. The meter shows the *difference* between the length of the 18-inch End Standard, and the 0–18 inch step of the Step Gage.

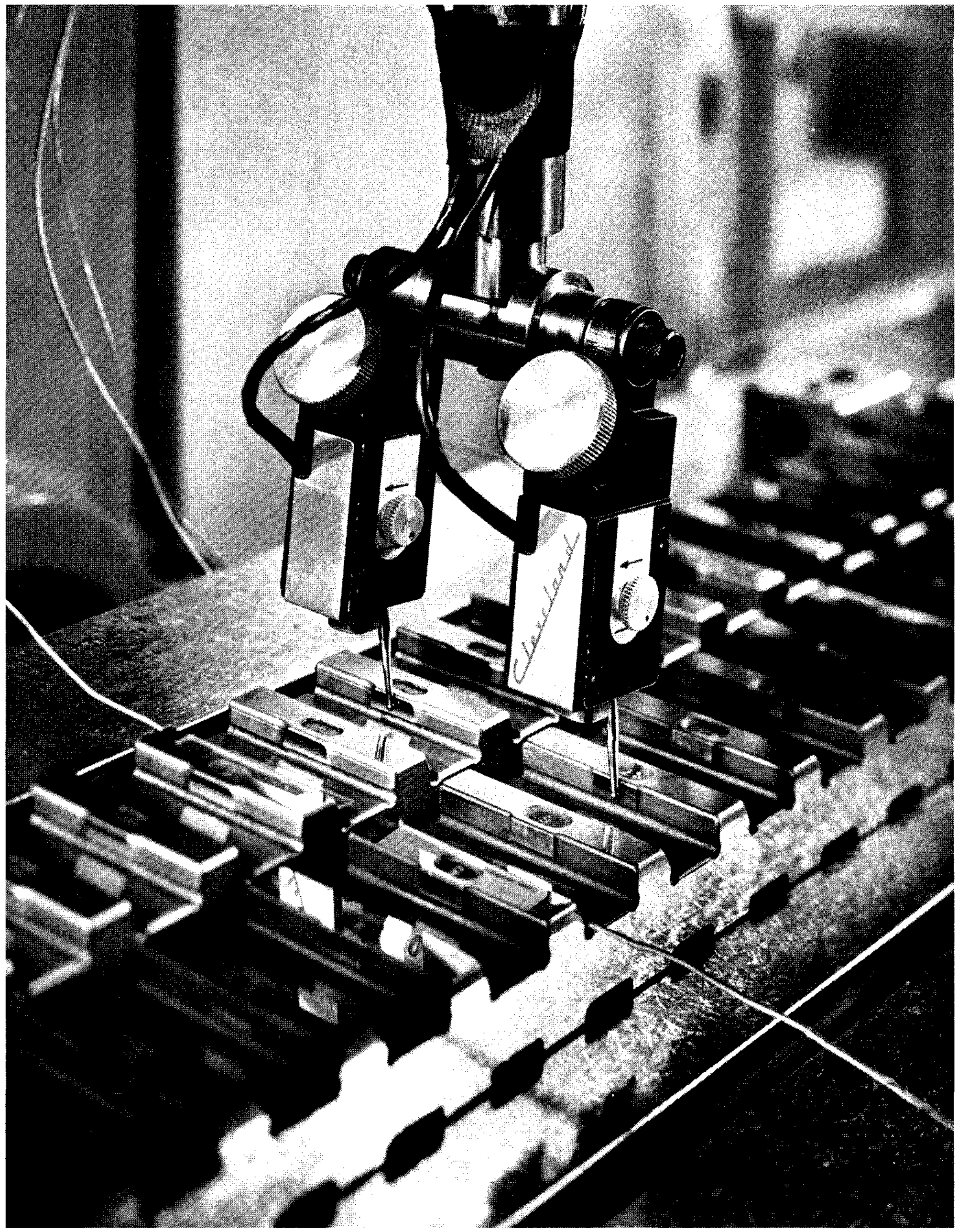
To compare the two gages, the 0–18 inch tapped holes of the support bar are used, and a "zero" is set against one end of the end standard and the lapped wrung-on piece at its other end (the wrung-on piece was used previously as an optical mirror for light-wave calibration at the bureaus). The purpose of the wrung-on piece in this case is to have both indicators "face the same direction" as the pads on the Step Gage, Fig. 284.

Only a short movement of the Measuring Machine cross-axis is needed to bring both indicators into contact with the 0 to 18 inch pads of the Step Gage. The difference in length is noted.

Next, the Step Gage is removed for lapping either its zero or 18 inch pad, depending on whether long or short, Fig. 285, taking into account the calibration of the end standard. This sequence is repeated many times. Once the 18-inch step is established, the 16-inch End Standard is used to secure the 16th inch step in a like manner.

The transferal of the 16 and 18 inch lengths requires three or four months of elapsed time due to the time required for the Step Gages to return to ambient each time after being lapped and handled, and to make the many necessary cross-checks.

FIG. 286—*"Second Generation Step Gages" are calibrated by being compared step-by-step to the Master Step Gage.*



SUBDIVIDING THE STEP GAGE

Once the 16 and 18 inch steps are secured, the remaining steps can be established by subdivision. Absolute temperature is not as important as is uniformity of temperature throughout the length of the Step Gage.

Using a different set of tapped holes in the support bar, 0 to 9 inch and 9 to 18 inch steps are compared by moving the longitudinal axis of the Measuring Machine 9 inches. By lapping the 9 inch step until halfway between the 0 and 18th inch steps, it thereby becomes exactly 9 inches. The inspection is sensitive: If the 9-inch step is not midway between 0–18 inch, it shows as a double indicator error.

The advantage of the 16-inch End Standard is now apparent: 16 inches being divisible to obtain 8 inches, 8 inches to get 4 inches, etc. This classical method of subdivision is preferred since rather than *accumulate* errors, as is inherent where several smaller blocks are added together, the steps theoretically become closer to "truth."

Many cross-checks are made. For instance, all the three-inch steps should now agree. The 16th and 18th steps are established by comparison to the 16-inch standard and 18-inch standard, respectively. Since the 17th inch step is secured by subdivision, the increments 16–17 inch and 17–18 inch should both be exactly one inch.

Total elapsed time for creating a Master Step Gage is 9–12 months.

STEP GAGES INSPECTED BY THE BUREAUS

The Master Step Gage is next calibrated at the national bureaus. After once again determining the length of the end standard by light-wave measurement, the Step Gage is calibrated by the same method of subdivision, again using a Moore Measuring Machine.

FIG. 287—*The design of the Step Gage enables 1 inch [30 mm in metric] "steps" to be contained in a single bar. Because it is an "end-measure," great accuracy can be achieved.*

SECOND GENERATION STEP GAGES

The Master Step Gage, after calibration by the national bureaus, is used for the creation of Second Generation Step Gages. While both rest on the Measuring Machine table, the Step Gage to be lapped is compared against the Master Step Gage inch by inch over its whole length, Fig. 286. Ten millionths of an inch [0.00025 mm] accuracy is achieved relatively quickly. The greatest amount of time is consumed in bringing a Step Gage from this stage to about 1 or 2 millionths of an inch [0.000025 to 0.00005 mm] accuracy.

It must be remembered that correcting a Step Gage is unlike the problem of correcting a standard made up of many small one-inch [25 mm, for example] blocks. If one of the pads of the Step Gage is lapped 2 millionths of an inch short [0.00005 mm], for instance, the only means of correction is to reduce all the other steps a like amount.

The procedure in transferal, subdividing and lapping metric step gages is similar to that employed with inch step gages, except that the master end standard is 480 mm and the increments of the Step Gage are 30 mm.

MOORE STEP GAGE

Design Considerations

The design of the Moore Step Gage, Fig. 287, allows *end standard accuracy* to be obtained, while avoiding the inaccuracies which can result from fastening a number of gages together. One inch [30 mm in metric] "steps" are *contained in a single bar.*

Step Gages are made in a number of lengths, 12 in., 16 in., 18 in., 24 in., and 480 mm corresponding to the travel of Moore machines. Note in Fig. 287 again that the gaging surfaces are as close as possible to the neutral bending plane, commensurate with rigidity of the bar. Both sides and also the bottom of the Step Gage are lapped straight, parallel and square to 10 millionths

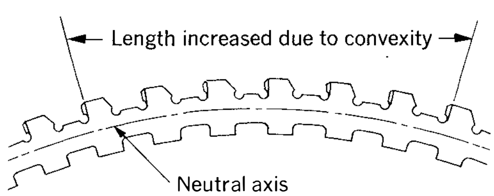
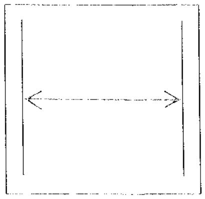


FIG. 288—*Because the gaging surfaces of the Step Gage are not on its neutral axis, when it rests on a surface that is not flat, its effective length is altered through bending. If the surface on which it is supported is convex (as illustrated), effective length is increased; if concave, effective length is decreased. The additional effort required to establish true surfaces (rather than the use of "Airy points") is rewarded by greater control of temperature of the Step Gage.*



of an inch [0.00025 mm]. The gaging pads are lapped square to the sides and bottom.

Step Gage designed to be used flat. During calibration, the Step Gage is supported its full length on the Measuring Machine table to gain maximum surface contact. The Measuring Machine, a large mass at ambient and slow to change, acts as a "heat sink," and lends stability to the standards in contact with it. For this additional reason, the Step Gage is given a low profile to avoid being influenced by air temperature.

Two Step Gages, compared while resting on the Measuring Machine, will automatically be closer in temperature than if either or both are supported on Airy points. Similarly, when the Step Gage is itself used to calibrate the measuring elements of a machine tool, it will more likely assume machine temperature, rather than air temperature. This manner of support requires a perfectly flat surface, since bending of the Step Gage alters its length, Fig. 288. The requirement of a flat support surface would at first seem a needless inconvenience when Airy points support could more simply be used, until one considers that the additional effort is compensated for by much more control in the temperature of the Step Gage.

6. Choice of Length-Measuring Element for Moore Measuring Machine

The positioning accuracy of Moore Jig Borers and Jig Grinders up to the early 1950's was in the order of one or two ten thousandths of an inch [3 to 5 μm]. The goal, however, was for machine positioning *within 35 millionths of an inch* [0.0009 mm]. At this juncture in the company's history, there was naturally some reflection as to what sort of measuring system could be used to meet this accuracy.

The measuring elements used in the most accurate coordinate-locating machine tools are many and varied: the standard precision scale, Moiré-fringe type of scale, end rods, lapped pins in a trough read against an indicator, lead screws, ball screws and many more. In general, though, they fall into one of three categories: *scale, end measure* and *lead screw.*

END MEASURE

The end measure system, however excellent when used purely as a length standard, loses much of its desirability when used with a machine tool. In all its forms, the end measure system is slow and cumbersome; since the rods must be accessible, they are exposed to air temperature and to heat from handling, as well as to dirt and dust.

Positioning accuracy depends on how well the several bars that make up each measurement are matched end-to-end. The smallest increments of movement require a micrometer and an indicator, a further division of responsibility for positioning.

PRECISION SCALE

The advantages attributed to the precision scale, see Fig. 258, are twofold: first, that a single standard can be divided into many small increments; second, since used only as a *reference* for positioning (unlike a lead screw which both positions and measures), there is no build-up of heat in the scale from movement or wear from use.

With large machines requiring fast movement for many varied positions, the precision scale has much in its favor. However, as noted earlier (pages 165–166), repeatability is only 20 to 30 millionths of an inch [0.5 to 0.7 μm]. Errors from nominal are as much as 80 millionths of an inch [2 μm]; a calibration chart would have to be used. Since the lines, once ruled, cannot be altered, no adjustment can be made to match the scale to the minute individual characteristics of each machine. Finally, a micrometer screw still must be used to position to thousandths and ten thousandths of an inch [hundredths and thousandths of a millimeter]—an additional source of error.

Even supposing a photoelectric pick-up to be used for the even 50 thousandths of an inch line divisions [1 mm when metric], the increments *within* 50 thousandths of an inch [1 mm] are given no increased accuracy.

LEAD SCREW

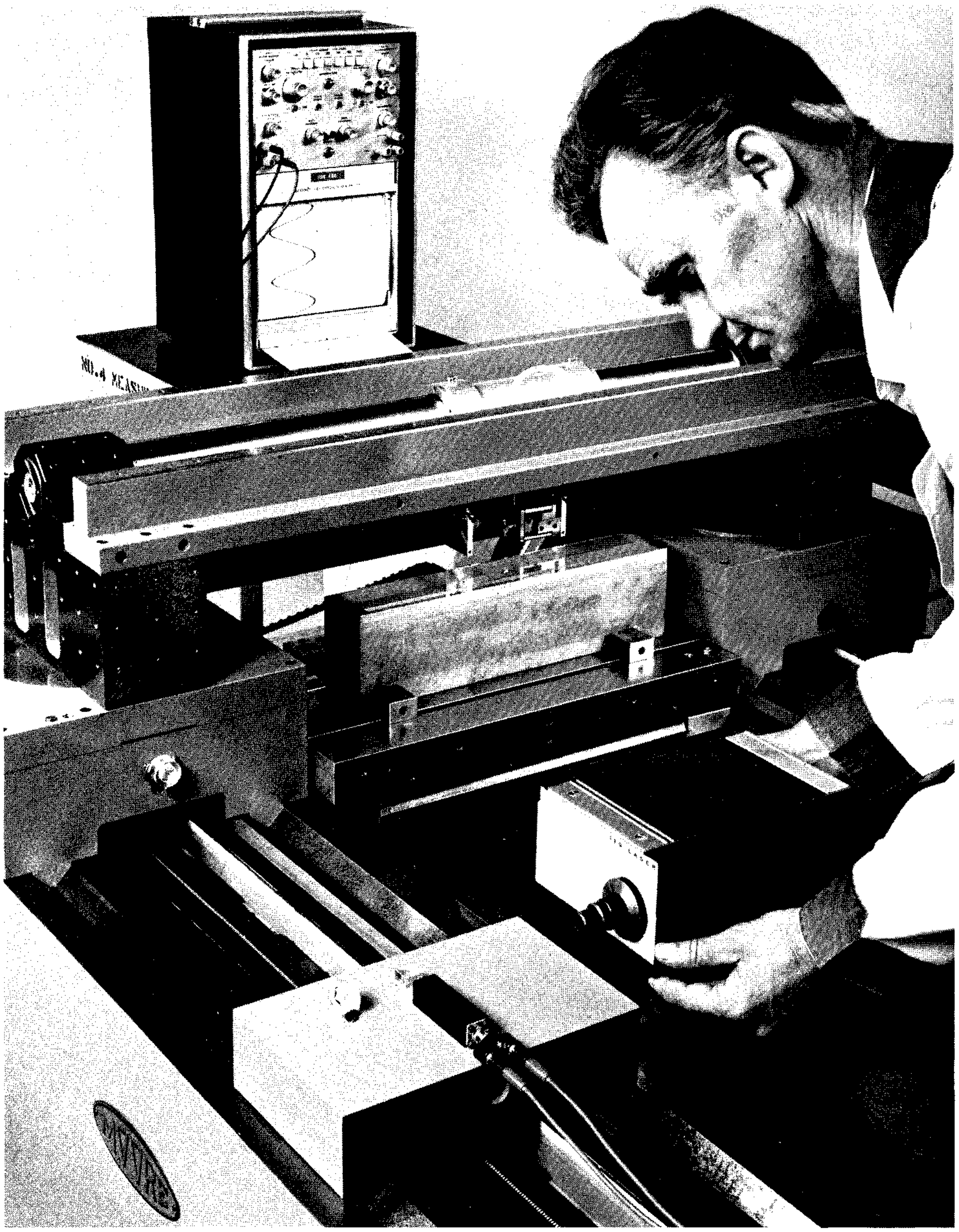
The lead screw has many inherent advantages—high magnification of setting (as much as 100 or 200 to 1), "stepless" measurement; single, undivided authority for positioning and measuring; ease and speed of setting. If properly constructed and assembled, repeatability can be to a few millionths of an inch [tenth of a μm].

Problem of Wear. A primary consideration with regard to the lead screw is its wear in use. Often, when the *wear* of a lead screw is mentioned, what is actually being considered is an *unhardened* lead screw, whose thread has been chased in a precision lathe. Compensation for initial lead error, or from wear in use, is through a follower cam and linkage which advances and retards either the nut or the vernier-dial. Common practice is to refile this cam yearly.

Moore had never considered this sound *machine tool* design. Soft screws give no permanence of accuracy. Cams or linkages are likely to *introduce* as much error as they were intended to remove. It is unlikely that periodic errors (errors within one turn of the screw) can be compensated for in this manner.

Problem of Heat. Another disadvantage to the lead screw sometimes cited is the possibility of its warming up from over-zealous use, causing a slight linear increase in its length. However, considering the precision scale as an alternative, errors due to warm-up of the lead screw *in its full travel* would

FIG. 289—*For specialized purposes, and when conditions are rigidly controlled, exceptional accuracy may be attained by employing a laser interferometer to measure displacement. This ruling engine for diffraction-gratings was built in cooperation with Professor George Stroke of the State University of New York, Stony Brook.*



be no more serious than the repeatability of the scale *at one position.* In addition, the light required to read the scale is a source of heat, so must be immediately turned off once settings are made, sometimes accomplished automatically with a time-delay switch.

Thus, regardless of the linear system used, the problem of heat is not entirely absent.

LASER INTERFEROMETER

Actually a fourth system of measurement should be mentioned, that of light waves, or fringes. Only recently, the laser interferometer has been used, not only to calibrate machine tools, but to monitor or measure their movement. Some foresee this as the ultimate for machine tool positioning. It is not effected by wear, nor heat from movement, and works directly with an unalterable standard.

The laser interferometer has already been applied to the Moore Measuring Machines built for Dean George Harrison of M.I.T. and Professor George Stroke of the State University of New York, Stony Brook, for use in ruling engines, Fig. 289, and for additional highly specialized purposes. Under specific, controlled conditions, this may work quite well. It should be emphasized again, however, (see pages 121-122) that using light-wave measurement, temperature control must be superb or the temperature of the piece to be machined or measured must be exactly determined so that precise compensation can be made to the extent the piece varies from 68°F. [20°C.], taking into account the coefficient of expansion of the piece. When the workpiece under consideration has nearly zero coefficient, as in ruling glass or quartz, the advantage is then with light-wave measurement, which theoretically can be considered to have "zero" coefficient of expansion.

CONCLUSION—Regardless of the measuring

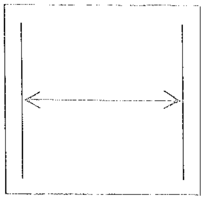
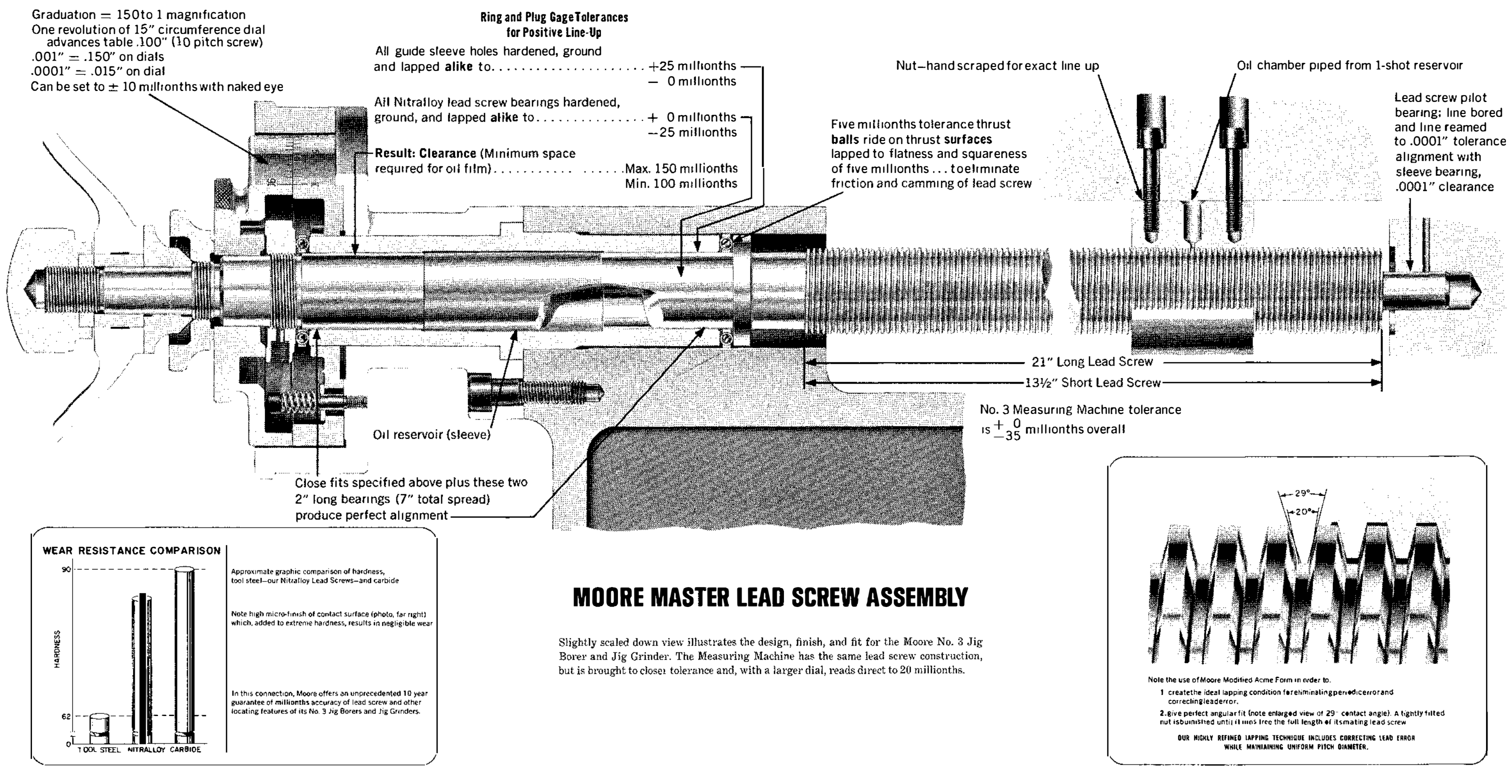


FIG. 290—*The accurate performance of the lead screw is dependent on the rigid adherence to many exacting design specifications.*



element used, repeatability is still dependent on sensitivity and the ability to control fine increments of movement—for which a hardened, ground, and lapped lead screw, properly supported, can hardly be surpassed. This being so, it would seem logical to put the additional effort required into making the lead screw accurate as well.

Moore finally decided that the accuracy sought could only be achieved, not through an alternate system, but by the principle of the hardened, ground and lapped lead screw which had been pioneered as early as 1931. The Master Lead Screw which evolved is explained in the following section.

7. Moore Master Lead Screw

The Moore Master Lead Screw, assembled in the Measuring Machine, Fig. 290,* represents the culmination of the efforts to establish the most accurate measuring element possible, at once traceable to the several major bureaus of standards. The lead screw has a 0.100 inch lead in the inch system and a 3 mm lead in metric machines.

*"Moore Master Lead Screw," Moore Special Tool Company, Inc., 1960.

MATERIAL OF THE LEAD SCREW

Moore Master Lead Screws are made of a nitrided steel—"Nitralloy" (see page 121).

Characteristics of Nitralloy: A surface hardness on the Rockwell "C" Scale of approximately 75, or 94 on the 15N superficial hardness scale, or 84 in the 30N scale. The case depth is only 0.020 inch [0.5 mm], supported by a Rockwell "C" 23–32 tough core.

The hardened case approaches carbide in wear-resistance, yet its coefficient of expansion, 0.0000066 inch per inch per degree Fahrenheit [0.000012 mm/mm/°C], agrees with that of most steels.

During the hardening cycle, the lead

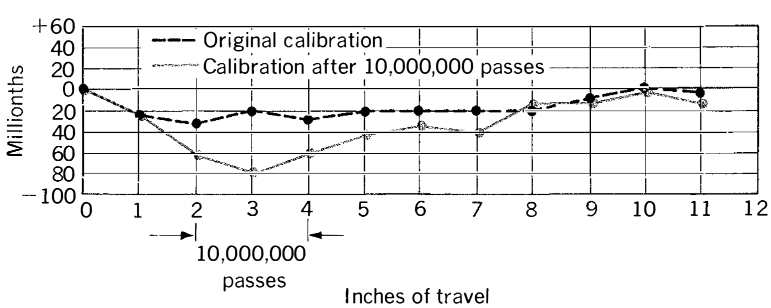
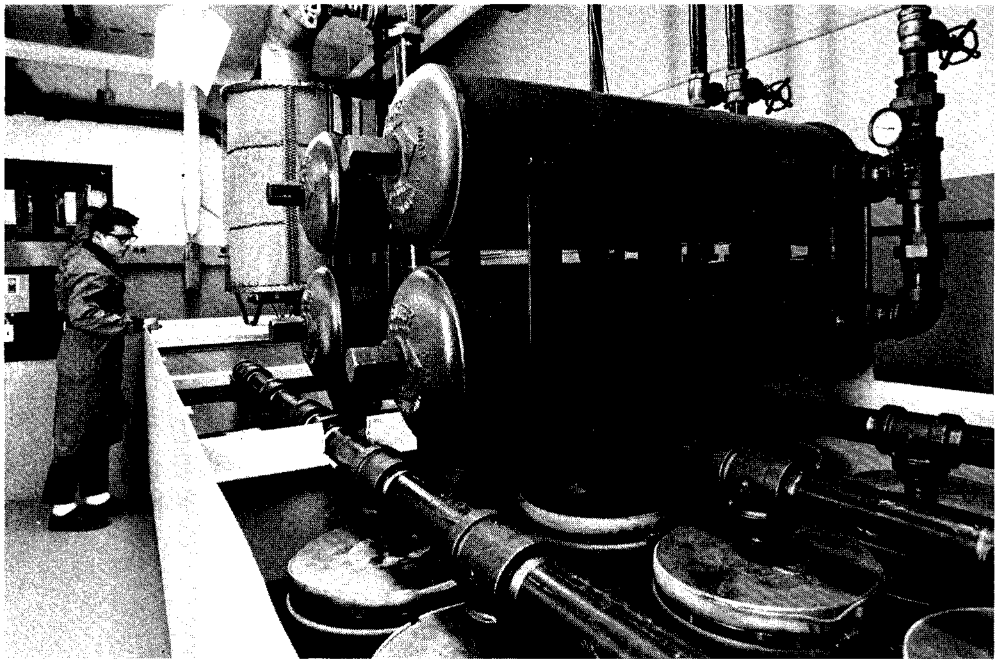


FIG. 291—*Chart shows the initial calibration of a lead screw, and then its calibration after 10,000,000 passes on only a two-inch [50.8 mm] section of its length. This severe test is estimated to be equivalent to 800 years of normal use.*

FIG. 292—*A tremendous investment in supporting equipment is necessary to produce accurate lead screws, such as the filtered temperature-controlled oil that floods the lead screw while being thread-ground.*



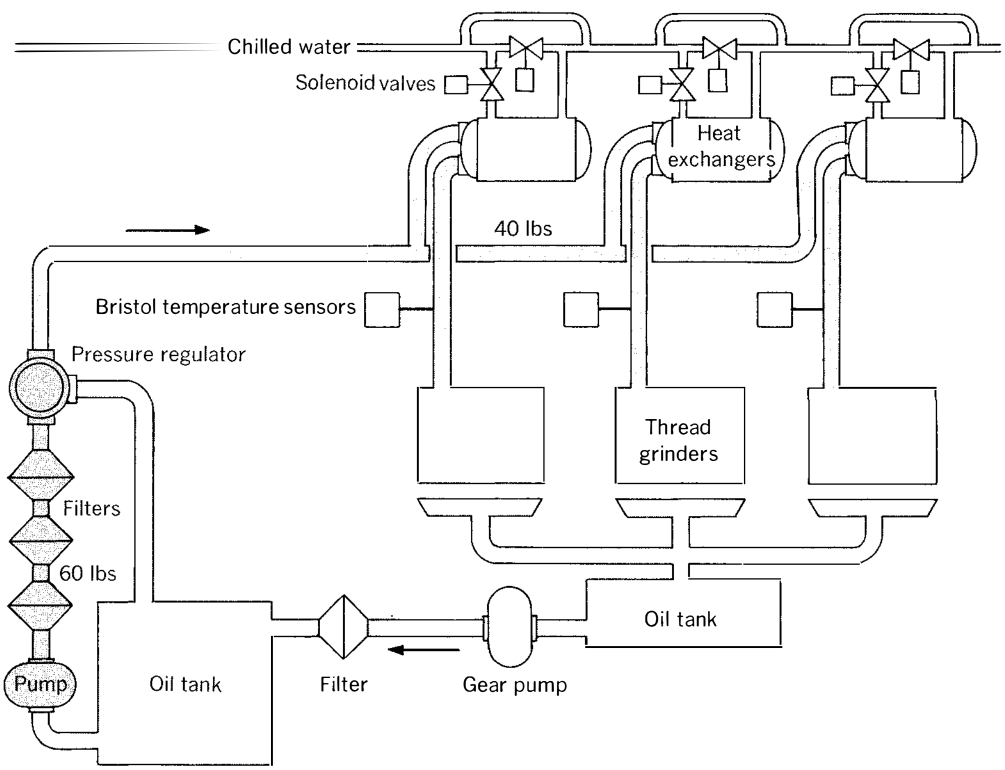


FIG. 293—*Diagrammatic illustration of the system used to control the temperature of the lead screw while being thread-ground.*

screw is hung vertically in a furnace having a gaseous nitrogen atmosphere. A thermochemical diffusion process takes place. It requires 48 hours at 975°F [524°C] in the furnace for nitriding penetration to a depth of 0.012 of an inch [0.305 mm], after which it is allowed to cool slowly. Additional hours in the furnace do not increase hardening depth appreciably.

After nitriding, the lead screw is stress-relieved in raw ammonia dissociated, approximately 50% at 1000°F. [538°C] for two hours at heat.

Nitralloy has only minimum distortion in the hardening cycle and is thereafter of exceptionally high dimensional stability. This can be attributed not only to its metallurgical composition, but also to the low hardening temperature and the absence of a quenching "shock."

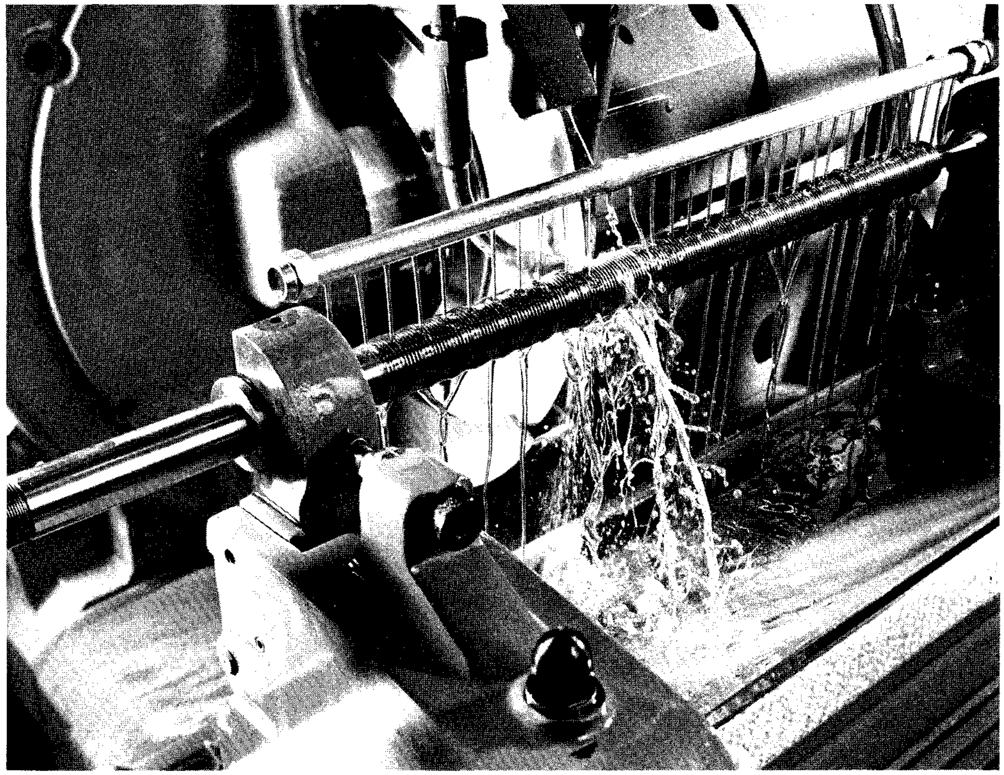
Innumerable Nitralloy end standards and Step Gages and thousands of lead screws have already been manufactured at Moore. With the ability to measure as accurately as possible, and on the basis of very careful records, it must be concluded that Nitralloy—when properly machined and properly heat-treated—does not measurably change in length over many years. The history of Nitralloy end standards maintained by Moore and calibrated at the national bureaus is also another proof of Nitralloy's stability. In addition, Nitralloy is virtually immune to wear, as evidenced by the chart of a lead screw calibrated after undergoing the equivalent of 800 years of use, Fig. 291.*

Nitralloy thus possesses three prime requisites to be the material for a machine's measuring element:

1. Coefficient of expansion equivalent to most steels;
2. Immunity to wear;
3. Dimensional stability.

*"150 Year Old Lead Screw," Moore Special Tool Company, Inc., 1965.

FIG. 294—*When being thread ground, the lead screw is supported carefully to assure concentricity of support to thread, and flooded with temperature-controlled oil to maintain exact lead.*



THREAD-GRINDING OF THE LEAD SCREW

All outside diameters of the lead screw are ground in the soft state, the thread being ground from the solid. After the hardening and stabilizing cycle, only a few thousandths of an inch [several hundredths of a millimeter] are reground off the thread to establish lead.

The nitrided "skin" decreases in hardness roughly proportional to the amount of material removed in grinding. To maintain maximum hardness, then, the lead is deliberately ground in error a calculated amount in the soft state to allow for change in length in hardening. The thread is carefully picked up after hardening to balance out stock removal.

In attempting to thread-grind relatively long pieces to any degree of accuracy, there are many thermal variables to contend with: changing room temperature; heat from motors, from gear boxes, from the grinding head or from cutting. All diminish the accuracy that is sought quite apart from the errors inherent in the thread grinder.

Controlling air temperature is essential, but only a beginning. Much experimentation was conducted to generate accurate leads in thread-grinding. Three such experiments were: grinding the screw long in an attempt to compensate for heat developed during grinding; operating at artificially elevated temperatures, and manipulating lead through gearing. Some of these methods produced modest success.

It was finally resolved, however, that the only true solution would be to *flood the lead screw with a cutting oil of a closely controlled temperature* during the thread-grinding operation. A major investment was made to accomplish this. The advantage of this method is that the temperature of the lead screw is now *dominated* by the cutting fluid. Further, with the increasing skills which developed at Moore with temperature-control systems, it was found that very

FIG. 295—*After thread-grinding the lead screw, thread drunkenness and lead error are corrected by hand-lapping.*

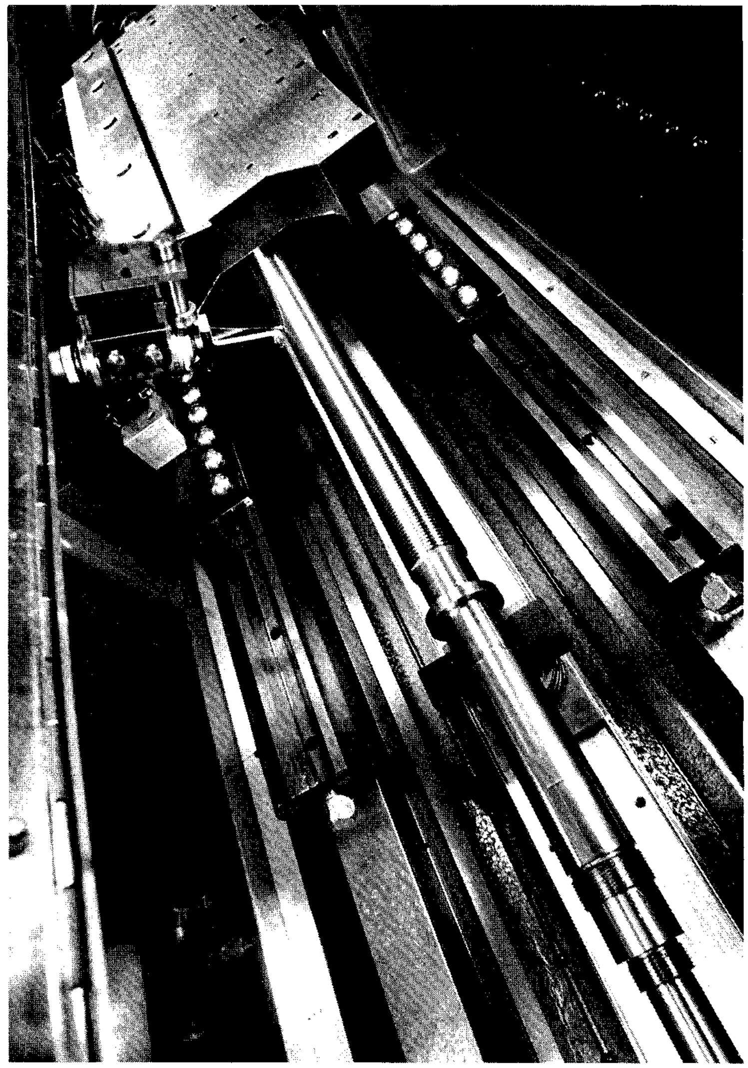


FIG. 296—*Overall lead and periodic error are inspected in a special lead-checker. After the nut is fitted and the lead screw is assembled in the Measuring Machine, the lead screw undergoes final calibration and correction.*

FIG. 297—*Two charts of a lead screw made on the lead-checker are shown. Left chart was made of a lead screw after thread grinding. Right chart was made after hand-lapping.*

FIG. 298—*The lead screw thread is lapped many times until correct lead is established, so that actual pitch diameter may vary from one lead screw to the next. A series of taps in gradual increasing pitch diameters is used to mate the nut to the lead screw. Once mated, the nut stays with the lead screw "for life."*

sensitive and immediate corrections in lead could be effected through slight adjustments in the temperature of the cutting oil. See the photo of the plumbing system, Fig. 292, and the diagram of the oil-control system, Fig. 293.

To be able to grind a lead screw to within 0.0002 inch accuracy [0.005 mm], many additional requirements must be met. Most importantly, dressing diamonds must be replaced often to maintain free-cutting wheels; grinding wheel and drive motor must be dynamically balanced.

To ensure concentricity of thread to journal, the lead screw rotates on its own lapped journal bearing, supported on a lapped carbide bushing while the lead is being ground, Fig. 294. Thus supported, the centers are not critically related to the accuracy of the thread. However, the spindle must run true and be free of camming.

LAPPING OF THE THREAD

Following thread-grinding to 0.0002 inch accuracy [0.005 mm], the thread is hand-lapped to further correct lead. The cast-iron split lap used, Fig. 295, has a useful life sufficient to correct only one lead screw. A Moore-designed Lead-Checker, Fig. 296, provides a continuous record of overall lead error, including periodic error. Fig. 297 shows a comparison of ground and lapped lead screws. The Moore method of lapping corrects lead while maintaining uniform pitch diameter.

LEAD SCREW NUT

The material used for the lead screw nut is an aluminum bronze alloy, which is extremely resistant to wear.

The procedure in threading the nuts is as follows: First establish an accurate bore to fit the pilot of the first tap. Follow by a series of taps, each with the same lead as the screw, but having slightly greater pitch diameters. Gradually increase the size of the taps until the nut has the same nominal

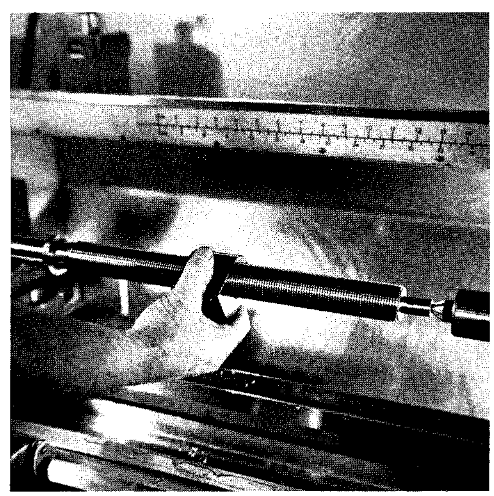


FIG. 299—*The nut has been tapped until it can be just forced on the lead screw. Following this, the nut is burnished to the lead screw using only light oil to achieve a perfect fit.*

FIG. 300—*Approximately 1000 lead screws are produced at Moore each year. After lead is corrected, the nut is fitted and remains with the lead screw (far right), later to be part of the lead screw assembly.*

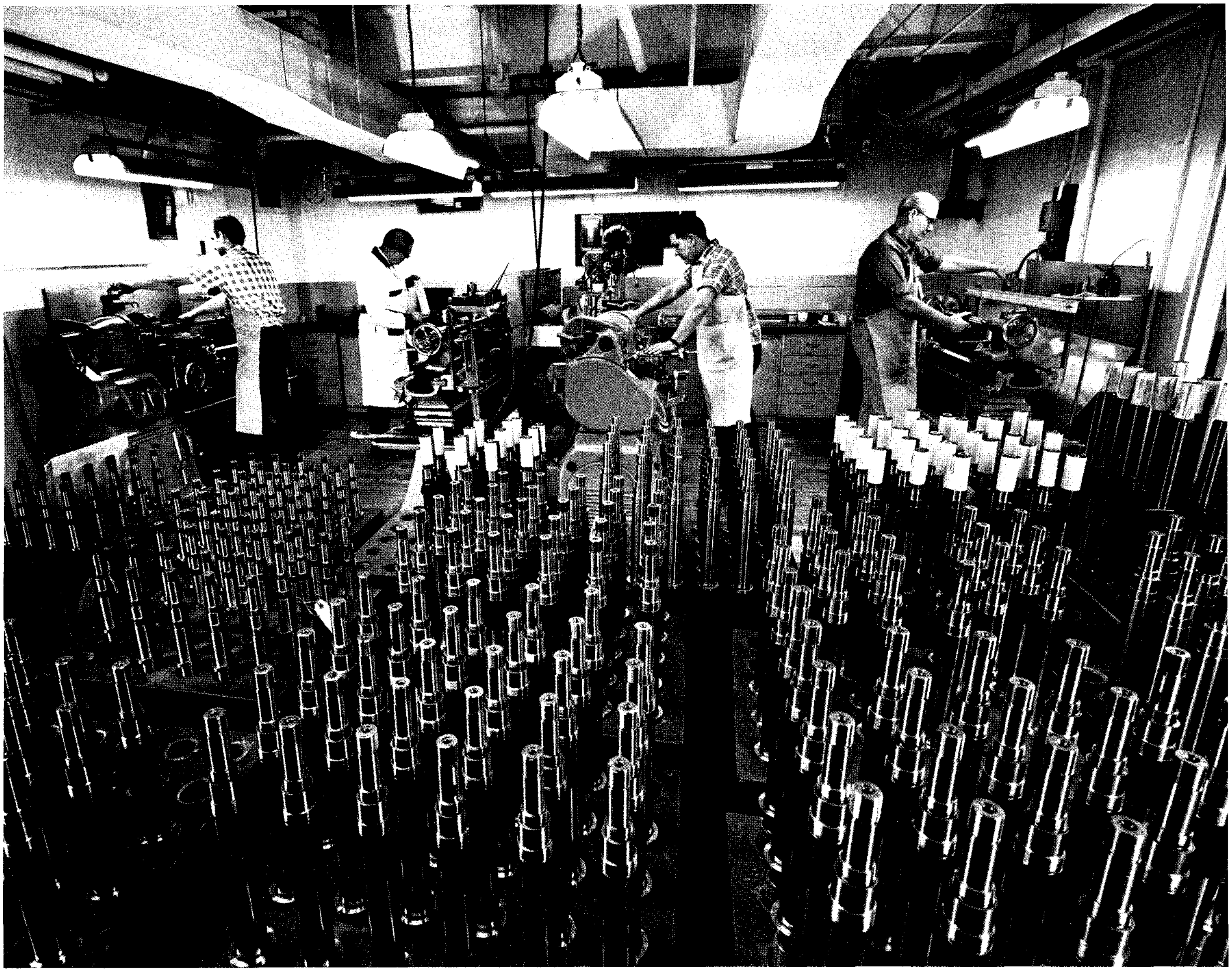


FIG. 301—*Highly specialized equipment used to align the lead screw precisely in the base of the Measuring Machine.*

pitch diameter as the screw, and thread onto the lead screw with a tight fit, Fig. 298. The nut is run back and forth on the lead screw for hours using light oil only while the screw is supported on centers in a lathe. This continues until the nut is burnished into perfect thread flank contact with its mating lead screw, Fig. 299.

As a final test of fit, the lead screw and nut together are rotated slowly on centers. The nut body is unsymmetrical; that is, it has a flange which is used for mounting to the machine. If too tight a fit, the nut will rotate with the lead screw; if too loose, the nut will hang with its mounting flange straight down.

A perfect fit is attained when the nut flange is maintained within a prescribed position while run the whole length of the lead screw; that is, a balance between gravity pulling it straight down and friction tending to cause it to rotate with the screw. Once fitted, the nut remains with the lead screw "for life," Fig. 300.

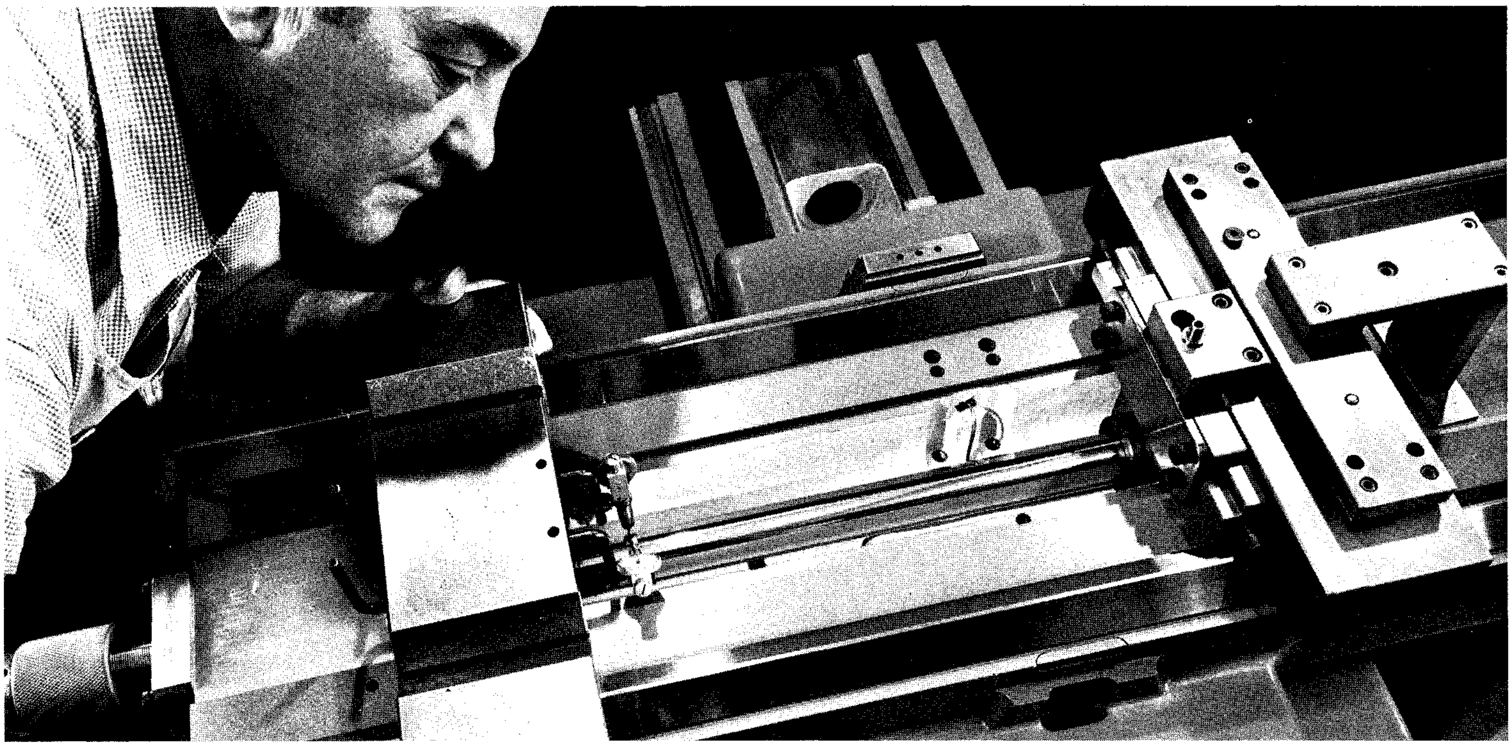
LINEUP OF THE LEAD SCREW

In Fig. 301 is shown some of the specialized equipment used to align the lead screw. A hardened, ground and lapped steel test bar is supported at the dial-end by a lapped steel bushing and further down its length by a lapped carbide bushing. The carbide bushing is adjusted until the test bar, when indicated, is exactly parallel to the ways. The test bar is replaced with identical bars that have cutting tools to bore and ream the end journal from the same support, Fig. 302.

After boring, the alignment is inspected with the test bar in a manner similar to that shown in Fig. 302, except that instead of being supported in the carbide bushing, the test bar is supported in the end journal just bored. This inspection can be seen at a later stage in Fig. 323.

The bottom flange of the lead screw nut is hand-scraped to align its axis with these journals, Fig. 303. With the close fits speci-

FIG. 302—*The test bar is first indicated parallel in two directions to the machine axis using an adjustable, lapped carbide bushing. Once the test bar is aligned, the bushing is locked in place. The test bar is followed by identical bars that hold cutting tools used to bore and ream the end journal in-line.*



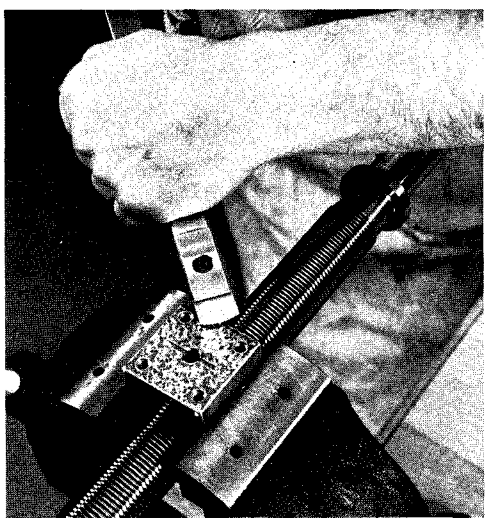
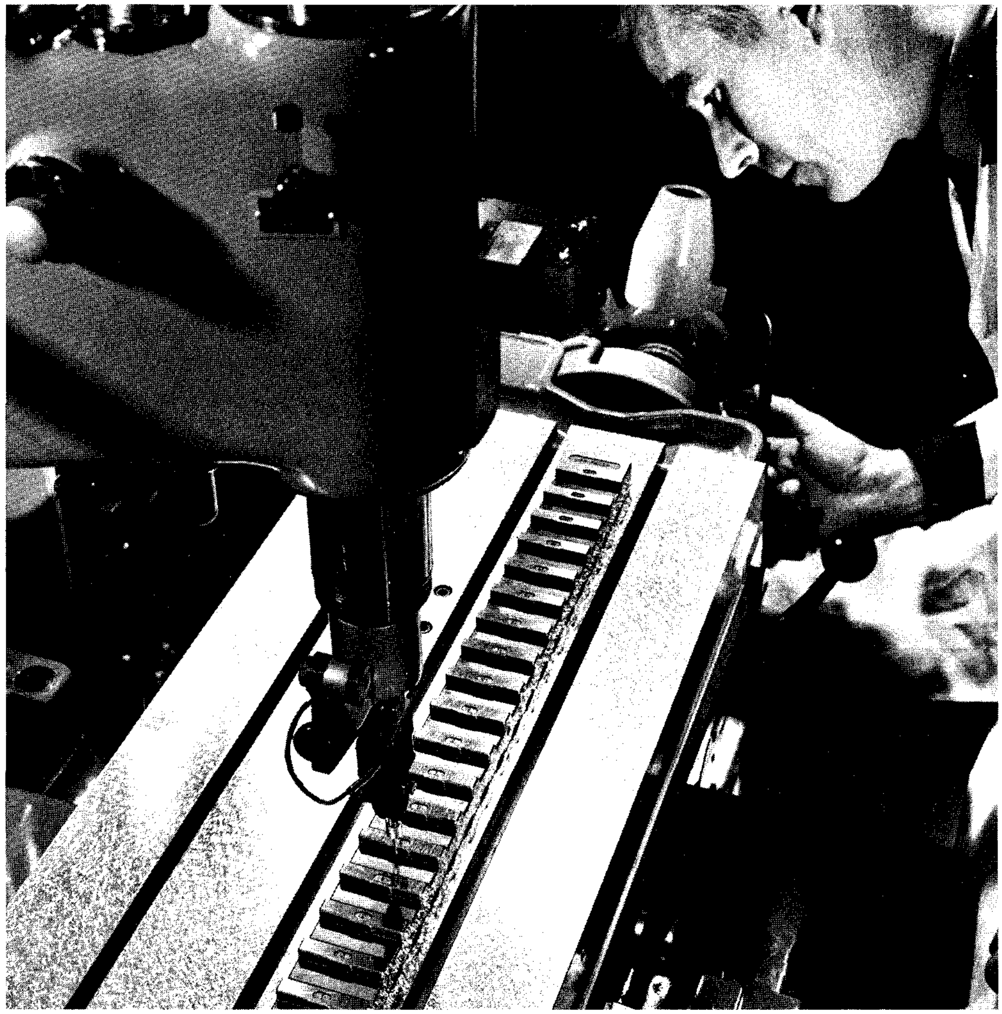


FIG. 303—*The mounting surface of the lead screw nut is hand-scraped to align its axis with that of the lead screw.*

FIG. 304—*The final test for line-up of the lead screw is severe but simple. A slightly eccentric "dog" must fall free of its own weight on either side of center. With the close fits specified, only a slight misalignment would cause the lead screw to bind.*

FIG. 305—*In the final Step Gage calibration of the Measuring Machine for positioning accuracy, actual displacement is measured. The lead screw is disassembled only a few times at this stage for careful corrective lappings of lead.*



fied (see Fig. 290), the lead screw will "bind" in rotation with only the slightest misalignment.

The test for line-up is severe, but simple: a slightly eccentric "dog" must fall free of its own weight when released from either side of top-dead-center, Fig. 304. With the close fits specified, a 0.0001 in. misalignment [0.0025 mm] would cause the lead screw to bind. This operation is very critical, entailing partly an engineered solution and partly a high degree of craftsmanship.

STEP GAGE CALIBRATION OF LEAD SCREW

It will be remembered that the lead screw had been lapped to approximately 0.0001 inch [0.0025 mm] accuracy using the lead checker. For final calibration, the lead screw is assembled in the Measuring Machine, and actual *table displacement* is measured, using the Moore Step Gage, Fig. 305.

Advantages of the Step Gage method include:

1. Allows use of high magnification electronic indicators;
2. Lead screw can be compared to Step Gages of 2–3 millionths of an inch accuracy [0.00005 to 0.00007 mm];
3. Only a few careful lapping operations are necessary so that the fit of nut to lead screw is maintained;
4. Calibration is made under the identical conditions in which the lead screw is to be used, allowing corrections for individual characteristics of each machine.

Calibration of the lead screw takes place in a 68°F [20°C] temperature-controlled environment. Although Step Gage and lead screw have an identical coefficient of expansion, to further guard against the effects of a temperature differential between them, the Step Gage is left to "soak" on the Measuring Machine table for 24 hours prior to calibrations. It is not removed for

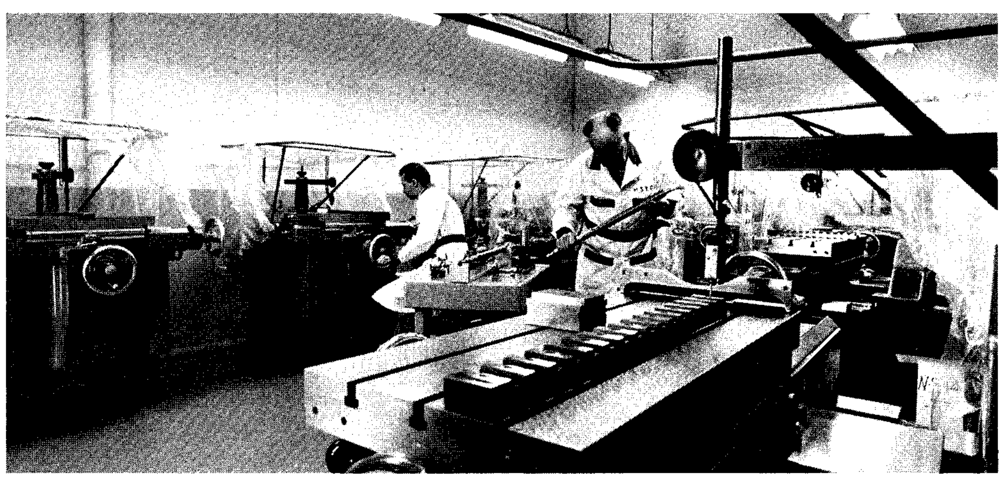
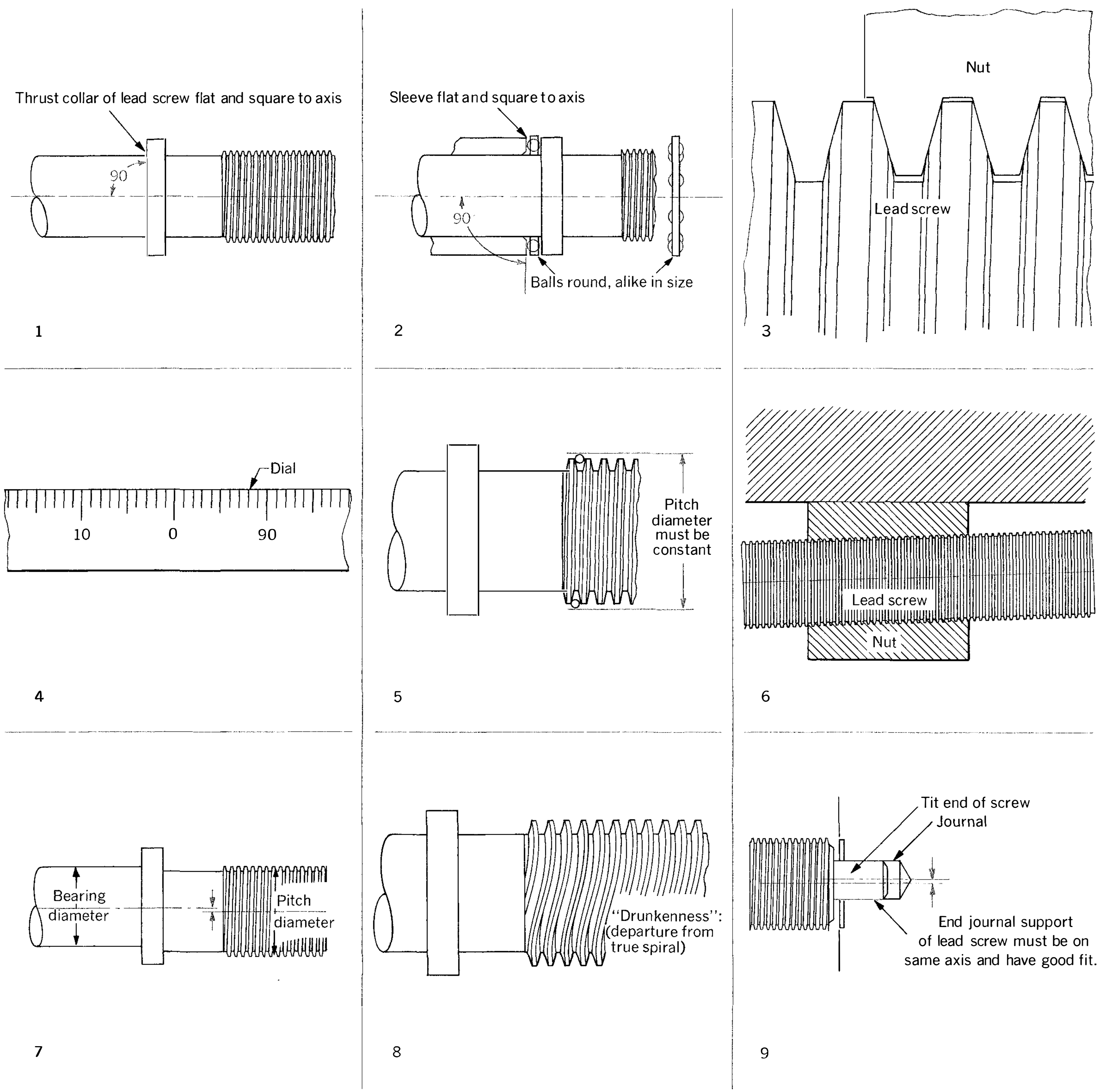
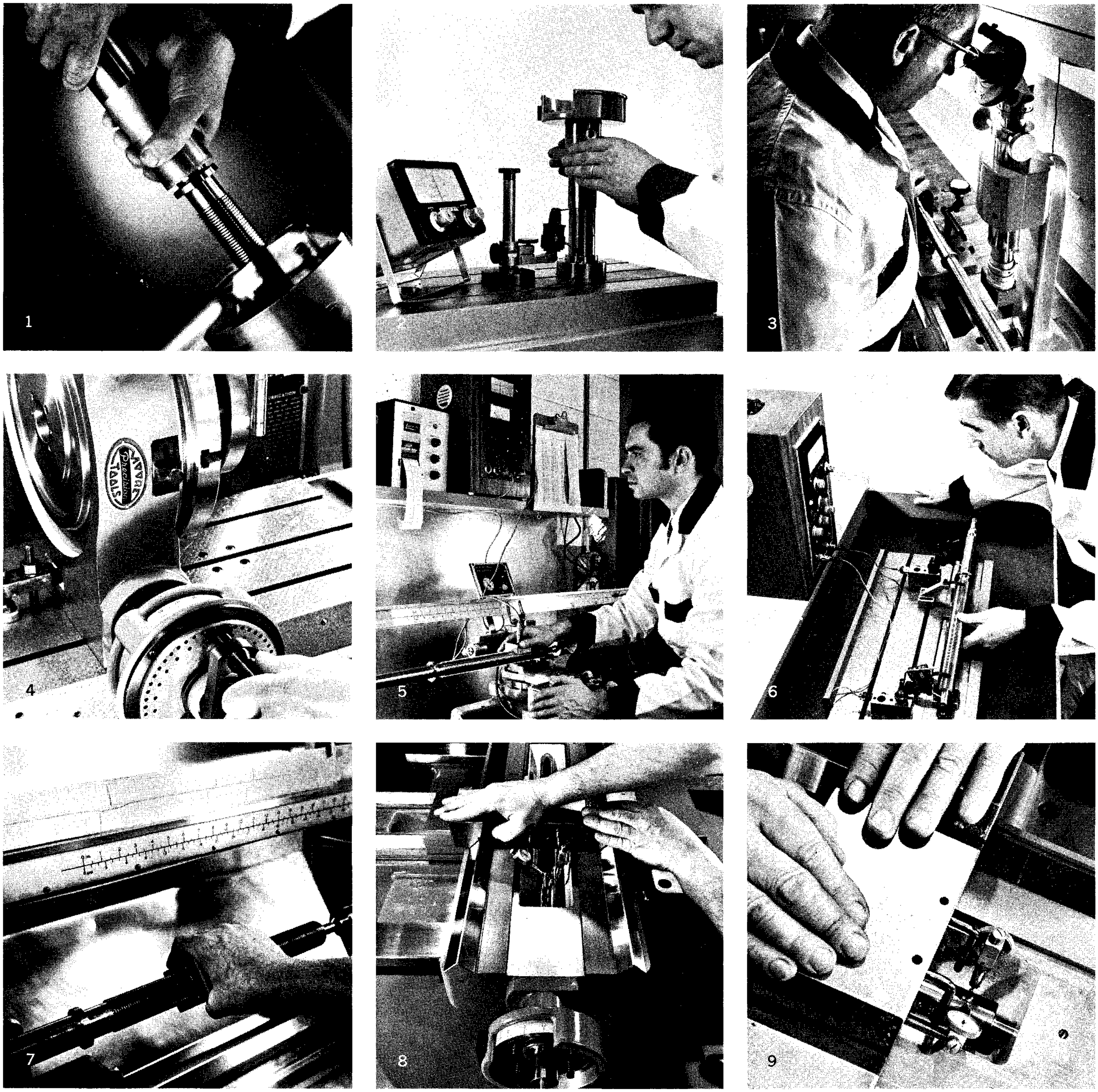


FIG. 306—*The Step Gage is left on the Measuring Machine table until corrective lapping of the lead screw is complete. This practice is also followed with jig borers and jig grinders for maximum efficiency and accuracy. Since many jig borers and jig grinders are being carried through calibration at one time, this entails a large inventory of Step Gages.*

9 SOURCES OF PERIODIC ERROR

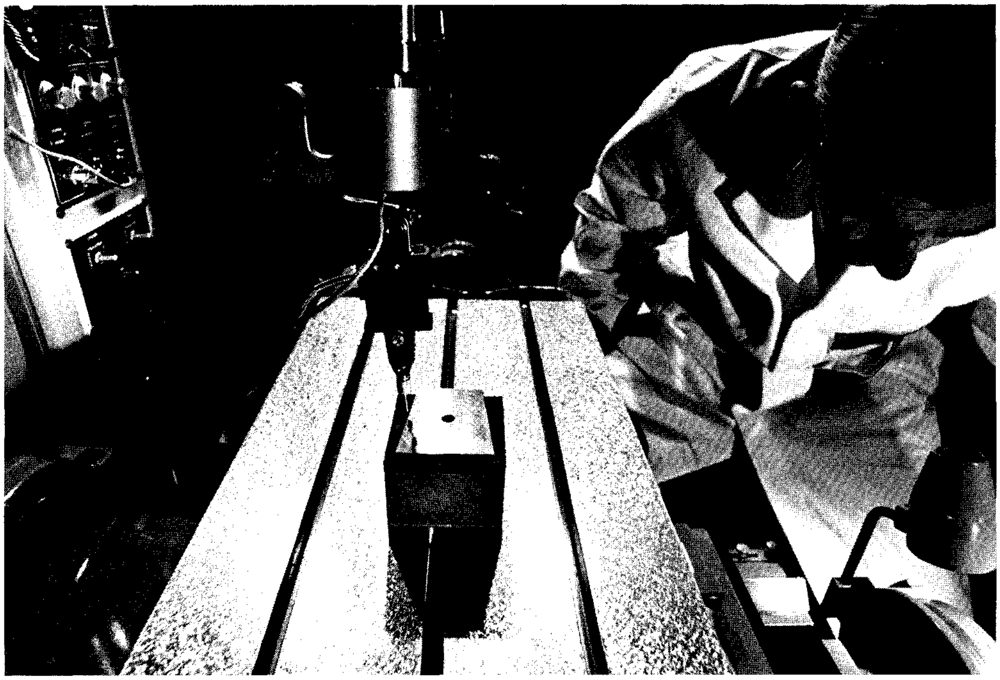


FIGS. 307 TO 315. *No. 1—The thrust collar must be flat and square to the lead screw axis. No. 2—The thrust shoulder of the dial housing (containing support journal) must be flat and square to its axis. The balls which take the thrust must be round, and alike in size. No. 3—Thread form must be perfect and uniform. No. 4—Spacing of the lines of the dial must be uniform. Periodic error amounts to approximately 1/220th of the line spacing error. No. 5—Lead screw pitch diameter must be uniform over the full length of the lead screw. No. 6—Misalignment of the lead screw causes both lead error and periodic error, but the exact nature of the error is unpredictable. No. 7—The pitch diameter of the lead screw must be on the same axis as the bearing diameter to avoid "crankshaft" error. No. 8—Thread drunkenness, or departure from a true spiral, is commonly thought of as the only component of periodic error. In reality, it is only one of many sources. No. 9—The end journal support of the lead screw must be on the same axis as the lead screw and be a good fit.*



FIGS. 316 TO 324. *No. 1—The thrust collar of the lead screw is lapped flat and square to the axis of lead screw. No. 2—The bearing sleeve thrust is inspected to assure flatness and squareness to the bore. No. 3—Form of the lead screw is viewed through the microscope and compared to the master 29° form. No. 4—Lines of the lead screw dial are cut on the jig borer with a .003 inch [0.076 mm] wide saw, and the spacing is controlled by a rotary table of ±2 seconds accuracy. No. 5—Pitch diameter of the lead screw is inspected for uniformity. No. 6—The lead screw is inspected for concentricity of the pitch diameter to the bearing diameter. No. 7—The slight thread drunkenness, unavoidable in thread-grinding, is removed by hand-lapping. No. 8—A lapped test bar is substituted for the lead screw to inspect the alignment of the lead screw support journals. No. 9—Inspection of the test bar at the far end from the dial housing support verifies the alignment of the end journal.*

FIG. 325—A wedge-shaped gage, having precisely .10000 inch taper over 1 inch [The metric gage has 3 mm taper over 27 mm], enables the lead screw to be inspected for periodic error anywhere over its full length.



the duration of the calibrations. This precaution necessitates a fairly large inventory of Step Gages, Fig. 306.

The lead screw, after disassembly for corrective lapping, is put in a cleaning tank whose solvent is held to 68° F [20° C] as a means of rapid temperature normalization. Nevertheless, re-calibration does not take place until 24 hours after the lead screw is re-assembled.

PERIODIC ERROR

The term "periodic error" as applied to the lead screw refers to a constant repetitive error(s), occurring within one turn of the lead screw. Although usually a constant error, repeating itself on each successive revolution, "periodic" can also gradually shift in phase over the length of a lead screw.

"Periodic" is a disturbing type of error—first, because it can be of considerable magnitude; second, because it occurs within such a short travel; and third, because it is seldom given sufficient consideration by designers of machine tools and instruments. A common misapprehension is that periodic error is traceable only to thread "drunkenness." In reality, there are many potential sources of periodic error, as shown in Figs. 307–315, inclusive. Only by adherence to strict standards of design and manufacture can its occurrence be prevented (see Figs. 316–324, inclusive).

Inspection for Periodic Error

The Step Gage calibrates the error of every inch increment of the lead screw.* Although the lead checker has furnished a comprehensive calibration of overall lead error, including periodic, it is desirable to inspect the lead screw for ***effective periodic error after assembly***, and to the same accuracy of de-

*Metric equivalents are omitted by intention. The procedure for metric machines is similar, except that a wedge having 3 mm taper over 27 mm is used, and 6 points in one turn of the lead screw are checked.

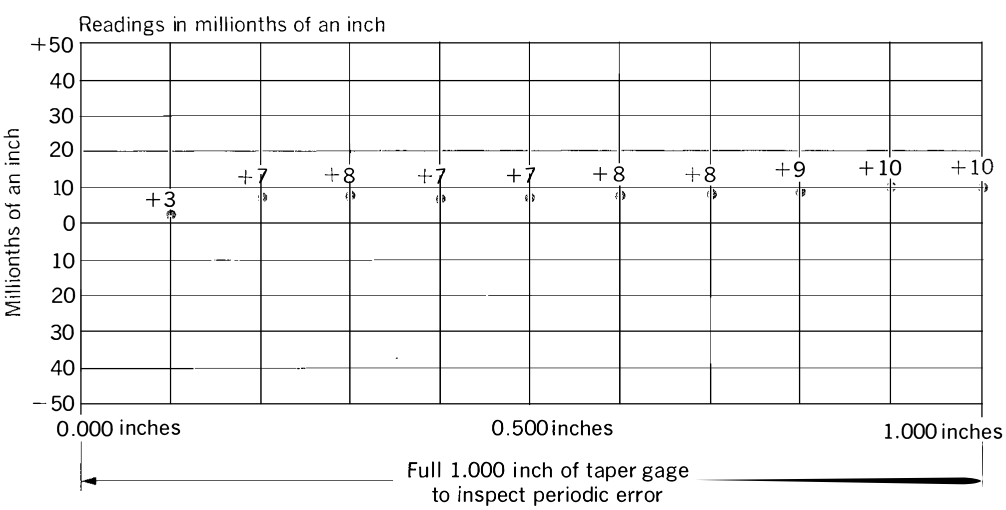
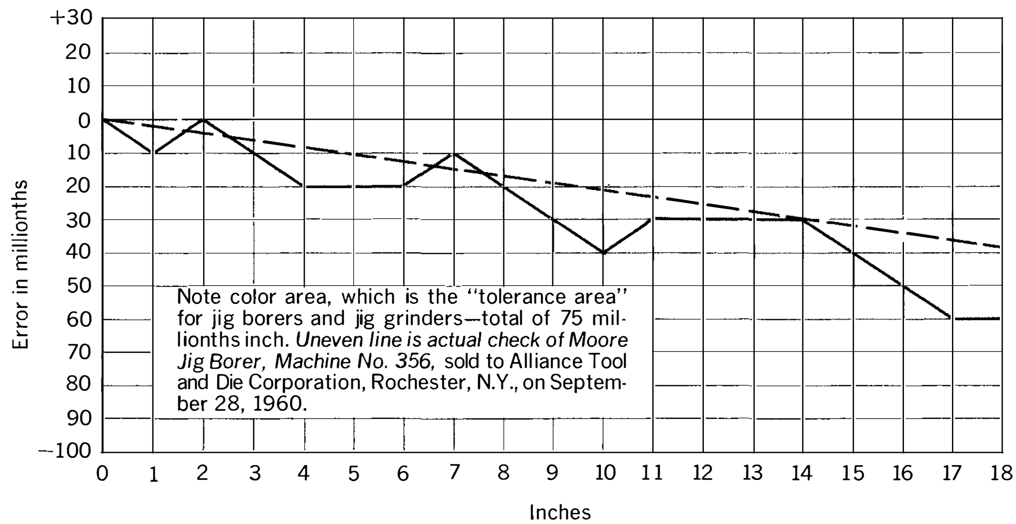


FIG. 326—The tapered gage used for checking periodic error is precisely aligned with the machine axes. Note, however, that any slight misalignment is compensated for by charting the readings obtained.

In this example, the gage has been misaligned by 10 millionths of an inch [0.25 μm]. The maximum error is at .300 inch where the reading was ±8 millionths of an inch [0.2 μm]. Actual periodic error at this point is approximately 6 millionths of an inch [0.15 μm].

FIG. 327—Although the published guarantee is that jig borers and jig grinders be held within 90 millionths of an inch [0.0023 mm] on each axis, note that the lead screw lapping specialists are given a much narrower shop tolerance band.



termination as accomplished with the Step Gage.

A gage having precisely 0.10000 inch taper in one inch is mounted on the Measuring Machine table, Fig. 325. The purpose is to inspect the "Y" or cross axis for periodic error. Suppose that the "Y" axis displacement from 5.0000 inch to 5.1000 inch is to be inspected. A reference surface of the gage (surface to the right in photo) is first aligned parallel to the "X" axis. The "Y" axis lead screw is set at 5.0000 inches while the indicator is set to "zero" against one end of the tapered gaging surface (surface to the left in photo). Each *nominal* 0.100 movement of the "X" axis lead screw and 0.010 inch movement of the "Y" axis will again register the indicator against this surface. This process is repeated ten times over the length of this gaging surface. This inspection yields a graph as shown in Fig. 326.

Although in practice the gage is always precisely aligned, note that a slight misalignment does not effect the accuracy of the check. This method of inspecting periodic error necessitates good repeatability, and good machine "geometry."

MOORE LAPPING SPECIALISTS

The guaranteed tolerance of the Moore Measuring Machine Master Lead Screw is 35 millionths of an inch [0.0009 mm]. In fact, lapping specialists have a narrower working tolerance of $\pm 12\frac{1}{2}$ millionths of an inch [$\pm$0.0003 mm]. It is stipulated that only small, progressively minus lead errors be allowed, Figs. 327 and 328.

There are three reasons for lapping the lead screw progressively "minus":

1. It is possible that from overzealous use by machine operators (applying more to jig borers and jig grinders, where the speed of movement is not monitored), that the lead screw will warm up slightly. However, a temperature rise would tend to make a "minus"

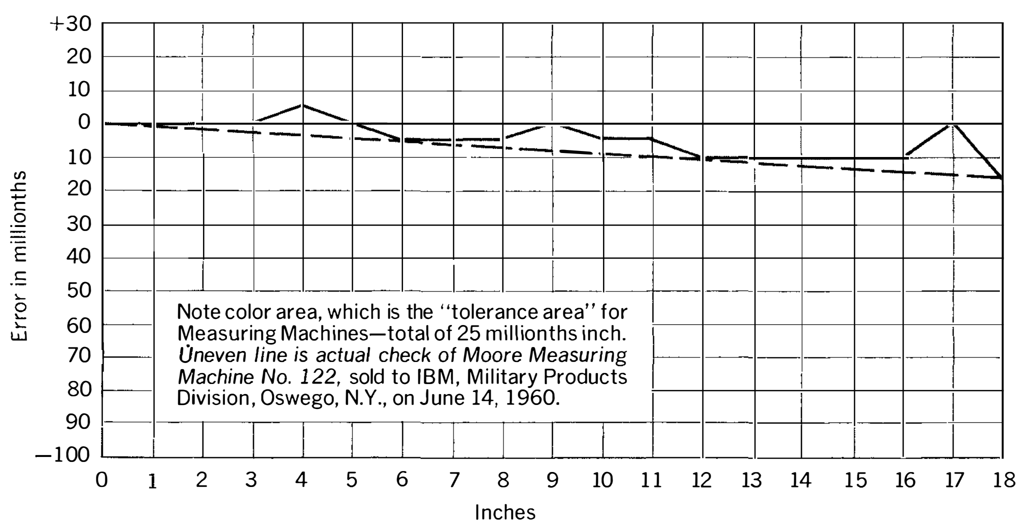
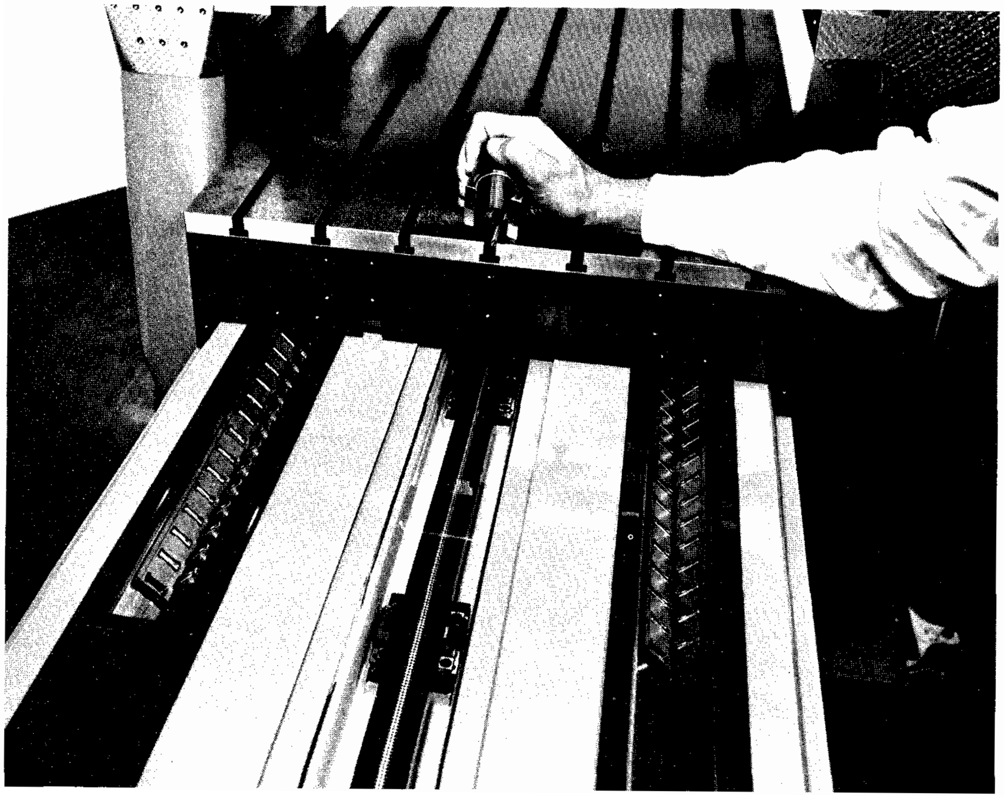


FIG. 328—The Measuring Machine lead screw is guaranteed to be within 35 millionths of an inch [0.0009 mm] overall. Note, however, that the nature of the narrower tolerance band given the lapping specialists further enhances the actual performance-accuracy of the Measuring Machine.

FIG. 329—*In larger measuring machines, friction of movement is avoided by the use of roller-ways. The temperature of the lead screw is now more critical because of its greater length, so is controlled by being immersed in a bath of continually circulating oil.*



screw progressively longer. In other words, a slight temperature rise would, if anything, make the screw closer to zero.

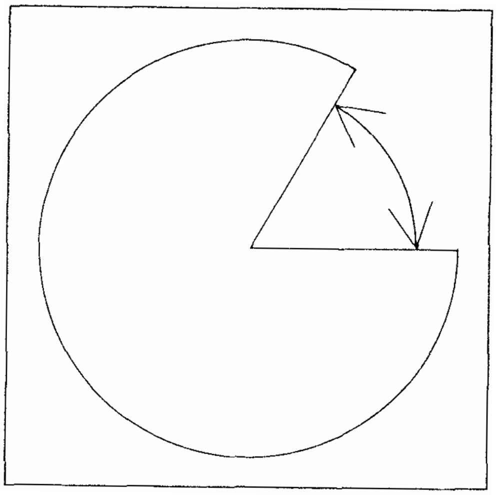
2. All Moore machines in the field will be alike. If machines were allowed to be indiscriminately plus or minus, they might *disagree* (in the case of jig borers and jig grinders) by 150 millionths of an inch [4 μm].
3. It permits only minute errors from inch to inch. The extremely good *linear* characteristic of the Moore Lead Screw fits the requirement that smaller measurements are necessarily of a higher order of accuracy. Note again Fig. 328. Any location between the fifth and twelfth inch [127 mm to 305 mm] would have no more than 10 millionths of an inch error [0.00025 mm].

Occasionally, closer accuracies are required, and it is then necessary to entirely eliminate the slight build-up of heat in the lead screw. In this case, roller-way construction is employed to virtually eliminate friction of movement.

In larger measuring machines, such as No. 4 and No. 5 designs, or for ruling engines, the temperature of the lead screw itself must be maintained by immersing it in a heat sink of circulating oil, Fig. 329.

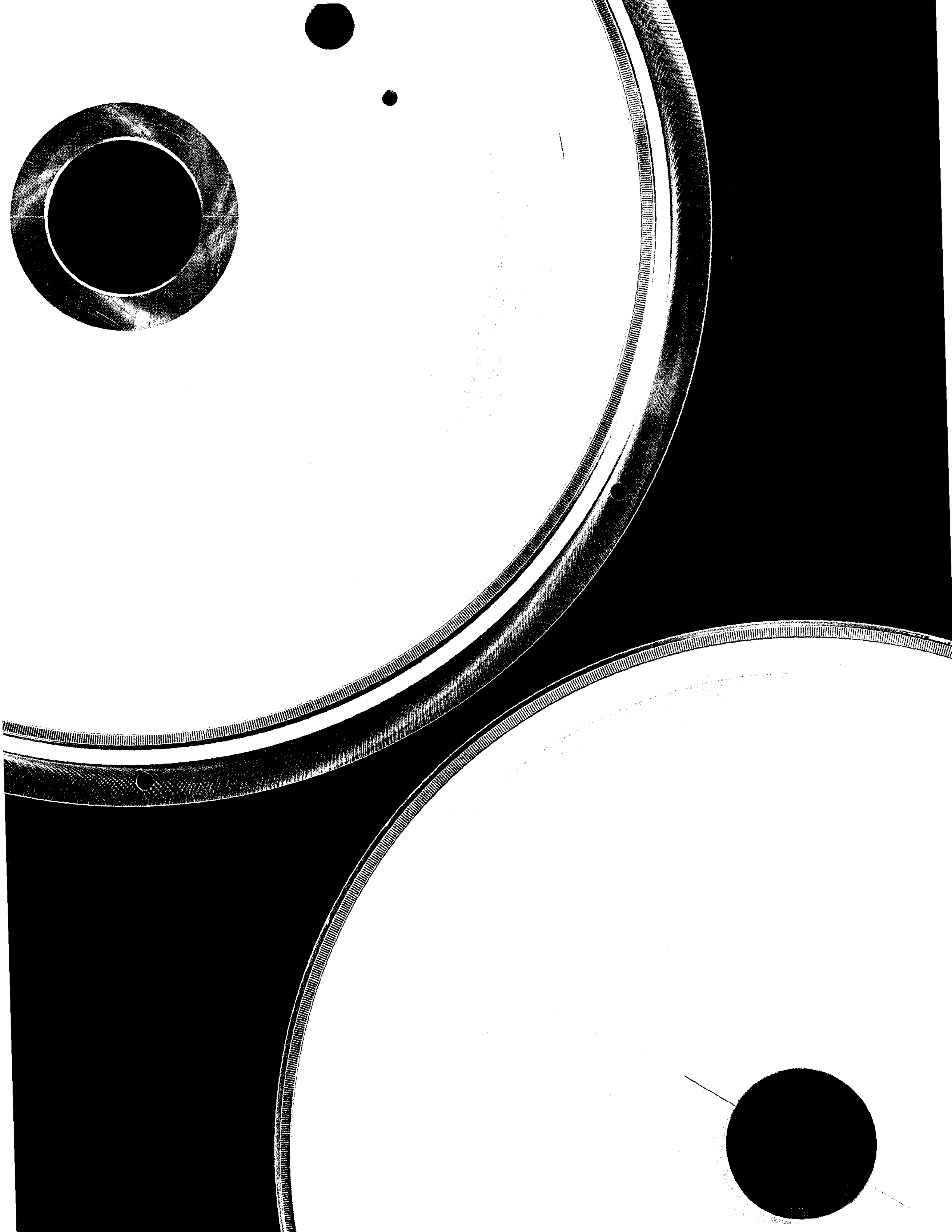
DIVIDING THE CIRCLE

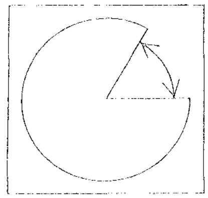
3



The authority for "angles" of angle gages, rotary tables, or the angular relationships in mechanical parts and assemblies is derived from the self-proving principle of dividing the circle.

FIG. 330—*Mating elements of a disassembled 1440 Index. Because the instrument is considered a principal angle standard and is of such exceptional accuracy, it is an appropriate symbol of the self-proving principle of circle-dividing to establish angles.*





1. The Nature of the Third Mechanical Art

The third mechanical art to be considered is *dividing the circle.* A more appropriate designation of this art might be *angles,* since the measurement and description of angular magnitudes are fundamental to most aspects of engineering metrology.

Angular relationships are inherent in geometric considerations (see pages 73–75). They are essential, for example, in the construction of masters and squares, in the use of angle-measuring autocollimators or levels, and in determining 90° relationships and the straightness of machine ways. Angles also come into consideration in measurements of length or size. Circle-dividing may be employed, for example, in the indexing of a lead screw, or in measuring the angle of a taper.

Angle is frequently a prime consideration with mechanical parts—machine tool spindle tapers, gears, splines, cams and tapered bearings, to name a few. The measurement of angle may be accomplished in many ways with a variety of equipment from simple protractors and sine bars to precision instruments such as autocollimators, theodolites, clinometers and electronic levels.

Without surveying every technique by which angles are measured, this section will be concerned with the foundation on which the measurement of angles rests. Included will be descriptions of (1) the principles of establishing angle, (2) primary angle standards and (3) accurate angle-measurement tools and instruments (see Fig. 330, which shows in disassembled form the mating segments of a 1440 Precision Index—a primary standard for dividing the circle).

The analysis will show, in addition, that the division of the circle is so uniquely self-proving that it is distinct from other techniques of establishing angle. Moreover, this method of division is the only one inherently capable of deriving primary standards.

DIVIDING THE CIRCLE VERSUS THE SINE PRINCIPLE

Any proof of angle can usually be traced to one of two methods used to generate angles—the sine principle and dividing the circle.

The sine principle uses the ratio of the length of two sides of a right triangle in deriving a given angle. Theoretically, any scale of units may be chosen for this purpose for it is the *proportions,* not the actual length of the sides, which determine the angle derived.

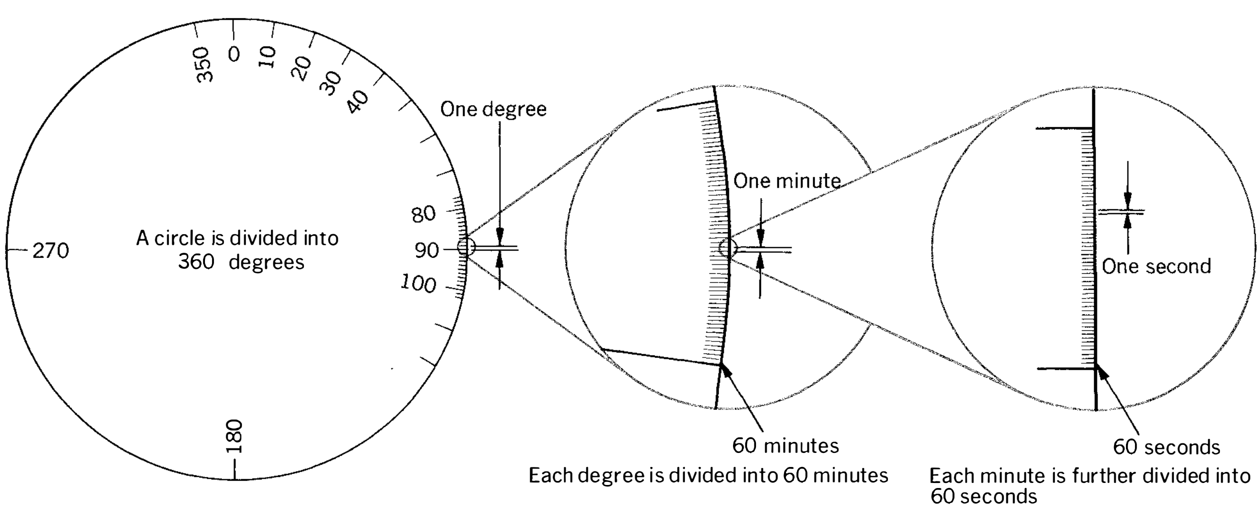
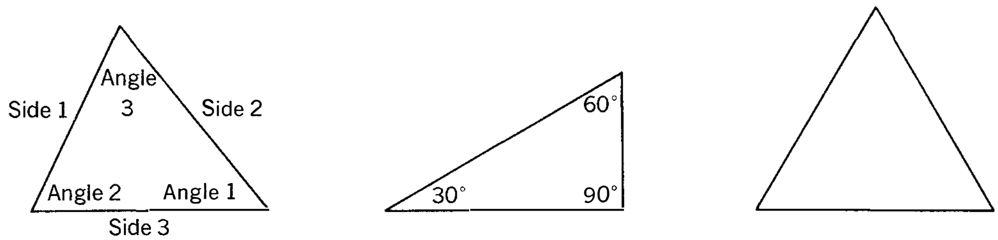


FIG. 331—*The sexagesimal system is the accepted international method in science and engineering of relating angular magnitudes. This system is based on the numbers 3 and 6 and their multiples.*

FIG. 332—*One historical explanation for the adaptation of the sexagesimal system is that the ratios found in the numbers 3 and 6 predominate, as is the case with triangles. Some ratios are shown. The number 360, moreover, has many factors.*



A triangle consists of 6 parts; 3 sides and 3 angles

A 30° right triangle has angles of 30°, 60°, and 90° (a proportion of 1–2–3)

An equilateral triangle has three 60° angles

The second method is based on the fact that a circle can be divided into any number of parts. The accuracy with which this is performed is proven once the circle is "closed."

Both methods, at least in theory, are capable of self-resolution. No outside authority such as a national bureau of standards is necessary for final verification of angles obtained by either method. In practice, however, the sine principle is dependent on an established system of length measurement. The degree of accuracy achieved is consequently dependent on the "traceability" of the length-measuring elements which may be part of this system.

To divide the circle into any number of parts, it is unnecessary to consult with the various national bureaus, though this may be done for credibility or for impartial verification from a recognized authority. Unlike standards of length, where the magnitude of units has been arbitrarily established, the circle can be divided into any number of units and be "self-proved." The level of accuracy depends only on the precision of available equipment and the techniques employed.

DERIVATION OF PRESENT SYSTEM OF RELATING ANGULAR MAGNITUDES

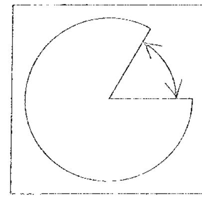
Today there is general acceptance of an established system wherein the circle is divided into 360 parts or degrees (°); each degree is divided into 60 parts or "minutes" (′); and each minute is further divided into 60 parts or seconds (″), Fig. 331.

The origin of the sexagesimal (units of 6) system pertaining to angles is usually credited to the Babylonians. It is sometimes claimed that the number 360 was chosen because the Babylonians, like other ancient peoples, were sun worshippers. Supposedly, they calculated the days, or appearances of the sun within a year, as 360. Consequently, 360 became a sacred number.

The writer believes that the calendars of the ancients were more exact than is recognized. A discrepancy of 5 days in calculations of the number of days in a year is therefore unlikely—a viewpoint supported by some historians. Hawkins presents convincing evidence that early astronomers in England (circa 1300 B.C.) were able to compute important lunar and solar occurrences (possibly eclipses) with amazing precision.*

The sexagesimal system has gained such universal acceptance in the recording of time, in the measurement of angle, in geodetics, in navigation and in all practical measurements for engineering, that another explanation of its acceptance is suggested. The number 3 and its multiples predominate in the mathematical and trigonometric calculation of angles. A triangle is made up of six parts (three angles, three sides); a 30° right triangle has angles of 30°–60°–90° (a proportion of 1–2–3); an equilateral triangle has three 60° angles, Fig. 332.

*Gerald S. Hawkins, *Stonehenge Decoded*, New York, 1965.



Toward the end of the 18th century, Lagrange introduced the "centesimal" (units of 100) system of angular unit. As in the sexagesimal system, the basic unit is the right angle ". . . defined as the angle between two straight lines which intersect so as to make the adjacent angles equal."* One would expect the right angle to be prominent in any system, since it is unique and self-proving (see page 34).

The following compares the sexagesimal to the centesimal system:

Sexagesimal System

1 right angle = 90 degrees (°)
1 degree = 60 minutes (′)
1 minute = 60 seconds (″)

Centesimal System

1 right angle = 100 grades (g)
1 grade = 100 minutes (^{c})
1 minute = 100 seconds (^{cc})

Some of the numerical conveniences of the sexagesimal system are apparent once there is an alternative system for comparison. The factors in the number 360 are: 1-2-3-4-6-8-9-10-12-15-18-20-24-30-36-40-45-60-90-120-180-360—twenty-three in all, compared to only twelve (1-2-4-5-8-10-20-25-50-100-200-400) in the four hundred grades which make a full circle in the centesimal system.

A right angle in the sexagesimal system is 90°, compared to one hundred grades in the centesimal system. When 90° is divided into thirds, the value is 30°, compared to 33 1/3g (33g, 33^c, 33^{cc}, 0.33. . .^{cc}). When it is further divided by three, the value is 10°, compared to 11 1/9g. Many of the more important triangles, such as the equilateral triangle, are not described in terms of whole numbers in the centesimal system.

Angular magnitudes may also be expressed as a ratio of the length of the arc of a circle to its radius. In this system, the unit is called the "radian": ". . . the angle subtended by an arc of length equal to the radius."* In any given circle, therefore, the following relationship exists:

$$\frac{\text{Circumference of a circle}}{\text{diameter of circle}} = \frac{22}{7} \text{ or } \pi^{**}$$

then 2π radians = 360 degrees
1 radian = 57° 17′ 44.8″
—or—
1 degree = 0.017453 radian

The "millieme" or "mill" (1/1000 radian) system is used by the United States Military, and is noted here to point out the existence of alternative systems of describing angular magnitudes.

General acceptance of the sexagesimal system as applied to angles may well be compared to Darwin's theory of survival of the fittest. The survival of a species is related to its adaptability. Similarly, because of its adaptability and greater mathematical convenience, the sexagesimal system has survived and is the most commonly used. The centesimal system, on the other hand, is rarely used today.

MATHEMATICAL INCONVENIENCE OF THE SEXAGESIMAL SYSTEM

Under the sexagesimal system, if the circle is divided into 10 equal sectors, then each sector would have an angle of 360°/10, or 36°. In this case, the fractional relationship to the full circle is readily apparent and the angle easily calculated. However, to divide the circle into, say thirteen parts, not altogether an infrequent requirement, there are irritatingly inconvenient numerical values. The 13th part of a circle is (1/13) x (360°), or 27 9/13°, requiring conversion first to 27° 41 7/13′ and then to 27° 41′ 32″. The 2/13th, 3/13th parts and so on are calculated similarly.

Imagine the millions of additional hours, not to mention the toll from miscalculations which have occurred over the centuries because of this clumsy system! There have been proposals to completely decimalize the angle system, but as noted, more serious mathematical disadvantages are perhaps involved. A better compromise would be to decimalize only parts of a degree. For example: 352° 20′ 24″ = 352.34°. In this manner, a great deal of convenience could be gained without disrupting a system which is fairly convenient.

The foregoing analysis, seemingly elementary, will be seen to be of fundamental significance in the design and use of circle-dividing equipment such as rotary tables.

2. The Principle of Self-Proving the Division of a Circle

The principle of self-proving the division of a circle is fundamental to metrology and is one with which the reader should be familiar before proceeding to an analysis of angle-measuring equipment. The principles involved are best understood by using the familiar example of a pair of dividers to step off a circle.

ESTABLISHING THE DIVISIONS OF A CIRCLE USING DIVIDERS

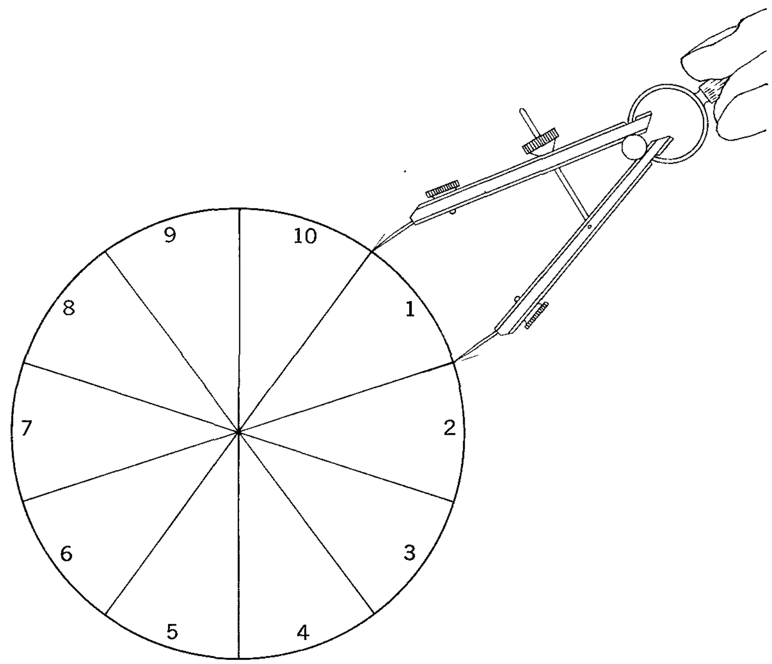
Imagine for the moment that no angle standards exist, and that we have before us the task of establishing a master divided circle by using only simple tools. Assume that a circle *A*, Fig. 333, is to be divided into ten equal sectors.

The dividers are first set to an estimated tenth part of the circle. If the dividers are

*J. C. Evans & C. O. Taylerson, "Measurement of Angle in Engineering," NPL Notes on Applied Science, p. 1.

**Ibid.* p. 2.
**$\frac{22}{7}$ is an approximation. π is actually equal to 3.14159265.

FIG. 333—*The use of dividers is a classical example of how a circle may be divided into a number of sectors by self-proving methods.*



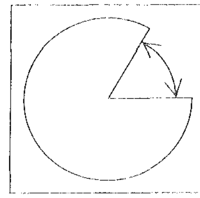
carefully stepped off around the circle and closed on the starting point, the tenth step will be long or short (plus or minus) ten times the original setting error. By simply adjusting the dividers slightly to eliminate only part of the error, and repeating the stepping-off process again and again, the circle comes ever-closer to being divided into exactly ten sectors. Finally, a scribed line or some other mark can be made to denote the ten divisions.

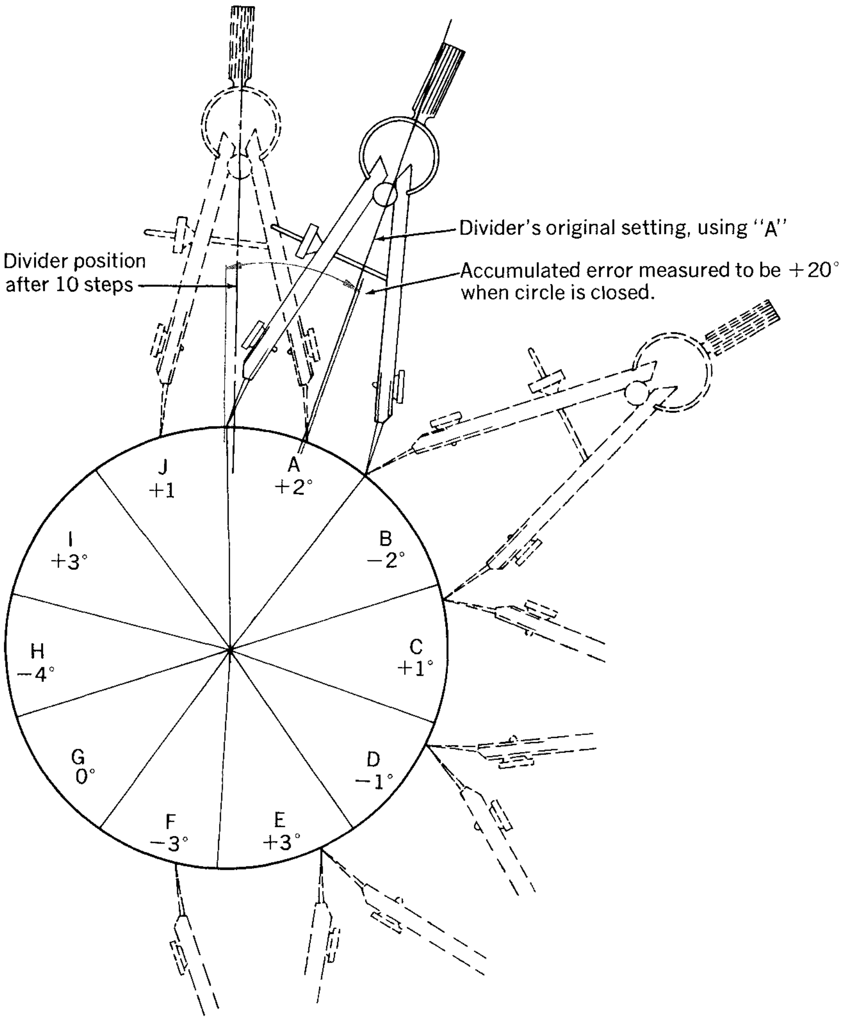
A slight variation in procedure divides the circle into ten equal parts much more rapidly. Only one trial stepping-off of the circle is made. When the circle is closed on the tenth step, the accumulated error is measured exactly, using a graduated rule, for example. The dividers are finally adjusted by precisely 1/10th the total error, and the circle marked in ten equal sectors after only one trial.

THE THEORY OF CALIBRATING A DIVIDED CIRCLE

Let us now suppose that circle *A* has been divided into ten sectors, nominally 36°, as accurately as is considered practical by using dividers, and that it is known there have been errors in placing the marks denoting each sector. The usefulness of that divided circle may be further enhanced if the error of each of the ten sectors is exactly determined or *calibrated.*

In a first method of calibration, the dividers are set to a nominal 1/10 part of the circle, either in reference to one of the sectors of the circle considered most correct, or to a 1/10 sector of some other master divided circle. It is important to note that this sector need not represent exactly 36°.





First the value of angle "A" is calculated:

10A=380° (360°+20°)

A=38° (or 2° error) and applied to column (5)

(1) Angle	(2) Nominal included angle	(3) Measured difference (at each step)	(4) Apparent included angle	(5) Applied correction for angle A	(6) Actual included angle from original setting	(7) Value of sector	Error of sector
A	36°	0	36°	+ 2°	38°	38°	+2°
B	72°	− 4°	68°	+ 4°	72°	34°	−2°
C	108°	− 5°	103°	+ 6°	109°	37°	+1°
C	144°	− 8°	136°	+ 8°	144°	35°	−1°
E	180°	− 7°	173°	+10°	183°	39°	+3°
F	216°	−12°	204°	+12°	216°	33°	−3°
G	252°	−14°	238°	+14°	252°	36°	0
H	288°	−20°	268°	+16°	284°	32°	−4°
I	324°	−19°	305°	+18°	323°	39°	+3°
J	360°	−20°	340°	+20°	360°	37°	+1°

FIG. 334—*Using dividers, the value of each of the 10 angular sectors of the above circle is calculated or calibrated by comparison to a master sector which itself is stepped off around the circle. The value of the master sector is determined on closing by measuring its accumulated error.*

Let it be assumed that the dividers are set equal to sector A, and the circle is once again stepped off. The accumulated difference between A and each of the other sectors is recorded, as well as the total accumulated error on closing. Once the initial setting error at A is determined (closing error divided by 10) it is applied to determine the true calibrated value of each sector, Fig. 334.

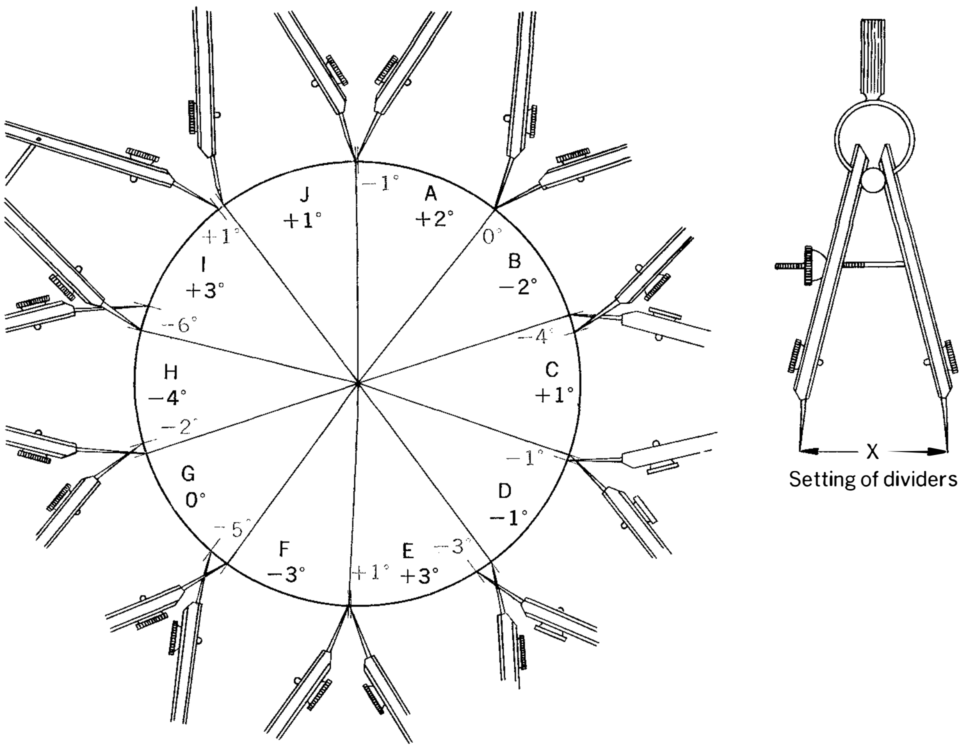
A variation of this method is more usually applied to the calibration of circle-dividing equipment. Again, A may be designated temporarily as master X, whose true value is as yet undetermined. Sector X is not stepped off but only *compared* to each of the sectors A,B,C,D,E,F,G,H,I,J. Each difference is measured exactly and recorded. The value of X is now determined algebraically and applied to derive the true angle of all the included sectors, Fig. 335.

The previous techniques may be applied to establish or to calibrate any chosen division of the circle, whether it be 13, 20, 160, or 1440 parts. The verification of the most accurate circle-dividing instruments relies ultimately on such elementary proofs, regardless of the expressed magnitude of error.

3. The Sine Principle

It has been observed that, in addition to the principle of dividing the circle, angles may be established or calibrated through use of the sine principle. The practical application of the sine principle for the measurement of angle will be analyzed here with respect to four essential points:

1. Devices that operate on the sine principle, just as those that divide the circle, are capable of "self-generation."
2. Unlike the division of the circle, angles established by means of the



Recorded errors of sectors

(1) $A-x= \ 0°$
(2) $B-x=-4°$
(3) $C-x=-1°$
(4) $D-x=-3°$
(5) $E-x=+1°$
(6) $F-x=-5°$
(7) $G-x=-2°$
(8) $H-x=-6°$
(9) $I-x=+1°$
(10) $J-x=-1°$

Adding $(A+B+C+D+E+F+G+H+I+J)-10x=-20°$
But $(A+B+C+D+E+F+G+H+I+J) = 360°$
Substituting $360°-10x=-20°$
$x= 38°$

Substituting $x=38°$:

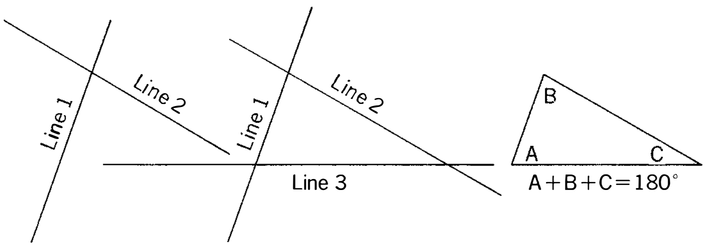
(1)	$A-38°= \ 0°$	$A=38°$
(2)	$B-38°=-4°$	$B=34°$
(3)	$C-38°=-1°$	$C=37°$
(4)	$D-38°=-3°$	$D=35°$
(5)	$E-38°=+1°$	$E=39°$
(6)	$F-38°=-5°$	$F=33°$
(7)	$G-38°=-2°$	$G=36°$
(8)	$H-38°=-6°$	$H=32°$
(9)	$I-38°=+1°$	$I=39°$
(10)	$J-38°=-1°$	$J=37°$

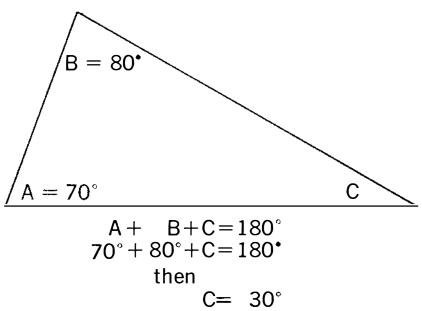
FIG. 335—*Calibration of the 10 sectors of the above circle may proceed by comparing a master sector "X" to each of the other sectors, and measuring the difference at each step. The value of the master sector is determined algebraically and then applied against the readings obtained to find true error of each sector.*

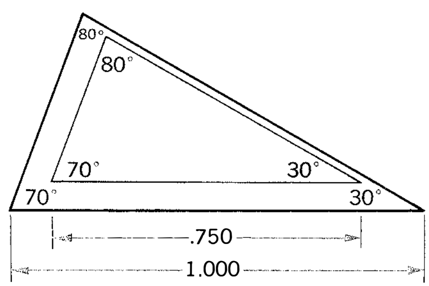
FIG. 336—*Some elementary concepts relating to angles: left, the formation of an angle; center, the formation of a triangle; right, the numerical value in degrees of the included angles of a triangle.*

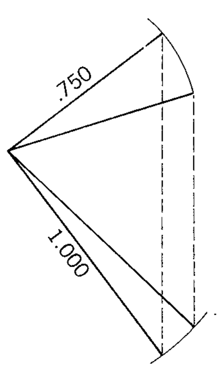
FIG. 337—*(center left) Shape of a triangle is not known until the magnitudes of at least two of its included angles are specified.*

FIG. 338—*(center right) Size of a given triangle is not known until the length of one side is specified.*









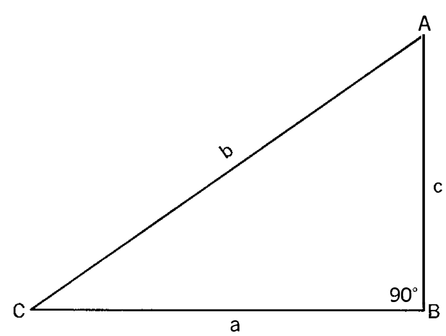


FIG. 339—*Specifying the length of two sides of a triangle is not sufficient to determine angle. The length of the third side must also be known.*

FIG. 340—*The right triangle is particularly useful in determining angular magnitudes; the principle is applied in such tools as sine bars, sine blocks and sine plates to establish angle.*

sine principle are limited in practice to only 90° (1/4 of a circle).

3. Devices that operate on the sine principle, even within their 90° useful range, in practice diminish in accuracy the greater the angle. The loss of accuracy is particularly rapid after the angle exceeds 45°.
4. The accuracy with which the sine principle can be put to use is dependent, in practice, on some form of linear measurement.

It is not our purpose to delve at length into geometric or trigonometric relationships. However, the practical application of the sine principle in engineering metrology does require an understanding of a few simple premises: the intersection of two straight lines forms an angle. A triangle is formed when the two sides of this angle are joined by a third straight line, Fig. 336. Included angles $A+B+C$ always total exactly 180°. The *shape* of the resulting triangle is not known until the magnitudes of two of its angles are specified, Fig. 337. The relative *size* of the triangle is not known until, in addition to two angles, the length of at least one side is specified, Fig. 338. It can also be seen that the length of two sides does not help us to determine angle, Fig. 339. When the length of the third side is specified, then the three included angles may be determined.

THE RIGHT TRIANGLE

It has been shown (see "Geometry Section") that the 90° angle is the basis of the orthogonal relationships which exist in the movable members of a machine tool; also, that the right angle is uniquely self-proving by reversal methods.

The right triangle is of particular interest to engineering metrology since it allows a simple, convenient calculation of most of the angular and dimensional relationships commonly encountered. These relationships can be expressed in terms of trigonometric functions, usually given as follows, Fig. 340.

$$\text{Where Sine } C = \frac{c}{b}, \text{ or}$$

$$\text{Sine of the angle} = \frac{\text{opposite side}}{\text{hypotenuse}}$$

$$\text{Cos } C = \frac{a}{b}, \text{ or}$$

$$\text{Cosine of the angle} = \frac{\text{adjacent side}}{\text{hypotenuse}}$$

$$\text{Tan } C = \frac{c}{a} \text{ or}$$

$$\text{Tangent of the angle} = \frac{\text{opposite side}}{\text{adjacent side}}$$

The inverse ratios are given as:

$$\text{Cot } C = \frac{a}{c} \text{ or}$$

$$\text{Cotangent of the angle} = \frac{\text{adjacent side}}{\text{opposite side}}$$

$$\text{Sec } C = \frac{b}{a} \text{ or}$$

$$\text{Secant of the angle} = \frac{\text{hypotenuse}}{\text{adjacent side}}$$

$$\text{Csc } C = \frac{b}{c} \text{ or}$$

$$\text{Cosecant of the angle} = \frac{\text{hypotenuse}}{\text{opposite side}}$$

These relationships are useful in the calculations of angles or dimensions. If, for example, angle C and side b are given, then the length of side a is derived by the formula:

$$\text{Cos } C = \frac{a}{b}$$

—or—

$$\text{Cos } C \times b = a$$

If the lengths of sides b and c are known, then the angle at C may be determined by calculating the sine, using the formula, and then referring to a table of trigonometric functions.

THE PRACTICAL APPLICATION OF THE SINE PRINCIPLE

Three important angle-measuring devices are based on the latter sine relationship—the simple sine bar, the sine block and the sine plate.

The sine bar and sine block are essentially single elements, and are mounted on an auxiliary flat surface. The sine bar is primarily a gage or angle reference. The sine block is designed to make angular measurements of mechanical parts mounted upon it. The sine table as with the sine block, is meant to measure angles of workpieces. Unlike the other two devices, however, the sine table consists of two elements—a base and a table. These are permanently hinged at the sine angle. All the legs of the right triangle are self-contained within the sine table. Since the three devices are closely related, the principles involved can be demonstrated using the sine bar as an example.

The Sine Bar

The sine bar is composed essentially of one piece or bar, Fig. 341. The hypotenuse, or side b is established in construction as the center-distance of two hardened gage pins. The desired angle C is set according to the formula:

$$\text{sine } C = \frac{c}{b}$$

If the angle desired is 30°, and a 5-inch sine bar is used the dimension at c is:

$$c = \text{Sine } C \times b$$
$$c = 0.500 \times 5 \text{ inches}$$

—or—

$$c = 2.500 \text{ inches}$$

Most commonly, a stack of gage blocks is set in the proper combination to form side c, or the right angle. Any convenient plane surface may be selected to support sine bar and gage blocks. Preferably, the surface should be hardened, ground and

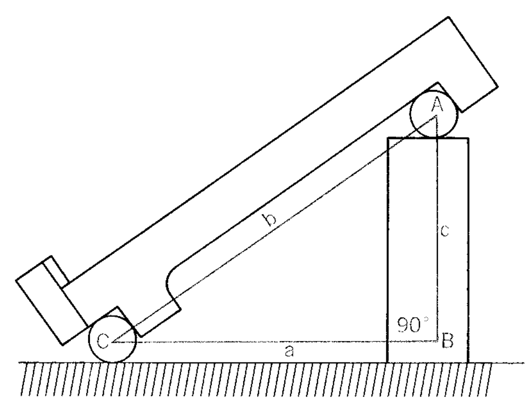
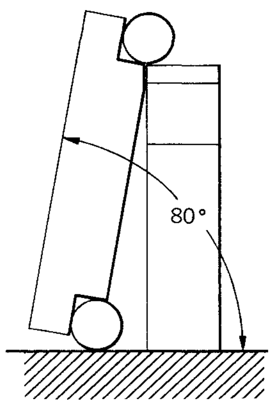


FIG. 341—*The simple sine bar is an example of the use of the sine relationship to establish angle. The right triangle is shown superimposed.*

FIG. 342—*Angular setting devices which operate on the sine principle, inherently become increasingly more inaccurate as the angle exceeds 45°. Depending on design, many become virtually impractical to use, as with the sine bar set at 80°.*



lapped to a high degree of flatness. The use of gage blocks is not absolutely necessary, since various other convenient length-measuring tools may be employed.

It is the *ratio* of the lengths which is important, not the actual lengths of the units involved. If metric units are used, the same ratios are still obtained. Provided that all units are accurately subdivided and applied to both legs of the triangle, any system of length-measurement is applicable. It is most convenient to utilize the established inch or metric systems for sine bar measurements, since accurate gage blocks and other types of length-measuring devices are readily available.

The sine bar is not a complete measuring instrument in itself. It only presents its top surface, or that of some mounted workpiece, to the required angle. Another datum such as a surface plate or machine axis is needed, as well as other auxiliary equipment, notably indicating devices, to make measurements.

Historically, the use of the sine bar to establish angle was considered preferable to the use of circle-dividing equipment. Preference for the sine bar can possibly be explained by three factors—its simplicity, the great progress made in length-measuring techniques since the introduction of gage blocks by Johansson, and the fact that it is only in recent years that circle-dividing instruments and allied equipment have been made to any degree of perfection.

LIMITATIONS OF THE SINE PRINCIPLE

The establishment of angle by the sine principle is essentially a length-measuring process. Therein lies its greatest virtue and its greatest weakness. The virtue of the sine principle for the measurement of angle is that very accurate end standards (gage blocks) are readily available, and can be put together in almost any desired increment to establish the length of the side containing the right angle.

The factors which limit the accuracy of the sine principle, in practice, are typical of those encountered in almost any length-measuring situation. The length of the sine bar is represented by the center distance (normally 5-inch, or 10-inch) of two precision rollers. Although it is not a required condition that these rollers be to some exact *nominal* size, they must be alike in size, and round, parallel-sided, parallel to each other, and parallel to the working surface of the bar. The required accuracy of these functional elements is defined in Commercial Standard No. 141-47 issued by the United States Department of Commerce in cooperation with the National Bureau of Standards.

In "Standards of Length" (pages 129–131), was discussed the difficulty of measuring the true size or length of a geometrical shape other than the separation of two parallel planes. To measure the size of a simple single gage pin becomes a complex problem. It should now be apparent that the geometrical condition involved in measuring *the exact, effective center distance existing between two rollers* of the sine to a certainty of a few millionths of an inch [fraction of a μm] is an *infinitely* complex problem. This fundamental limitation alone precludes the use of the sine bar as a primary standard of angle.

Devices which operate on the sine principle are fairly reliable at lower angles (i.e., less than 15°) but become increasingly inaccurate as the angle increases. This characteristic is best understood by analyzing the operation of the sine bar, as well as some of the trigonometric relations which exist at different angular settings.

At an angle of 10°, the required stack of gage blocks is small, hence measurements are fairly reliable. Whatever in-built error may exist in the length of the sine bar is not critical. For example, at this angle, an error of 0.0001 inch [0.0025 mm] in the center-distance of the rollers of a 5-inch sine bar [127 mm] would introduce an error of only 0.728 second. It should be noted also that the gage block increments are almost linear. The difference in height of the gage block stack for a 5-inch sine bar from 10° to 10° 30′ is 0.0429365 inch [1.0906 mm], and from 10° 30′ to 11° is 0.0428675 inch [1.0888 mm].

Compare now the conditions when the sine bar is set at 80°.* As evident in Fig. 342, sine bars inherently become increasingly impractical and inaccurate as the angle exceeds 45°. The reasons are:

1. *The sine bar is physically clumsy to hold in position.*
2. *The body of the sine bar obstructs the gage block stack, even if relieved as shown* in Fig. 342.
3. *Slight errors of the sine bar cause large angular errors.* For example, at 80°, an error of only 0.0001 inch [0.0025 mm] in the separation of the rollers causes an error of approximately 23.3 seconds, or 32 times greater than the error when at 10°.
4. *Long gage blocks or stacks are not nearly as accurate as gage blocks shorter than 1 inch.*
5. *Temperature is more critical.* It is now absolutely essential that the temperature of the sine bar body separating the two rollers be identical to that of the selected stack of gage blocks. A disparity in temperatures may exist from handling the gage blocks, or possibly from storing the gage blocks in an environment warmer or colder than where the sine bar is to be used.
6. *A difference in deformation occurs at the point of roller contact to the support surface and to the gage blocks.* Assuming that the relative load on each roller is equal and constant, no appreciable difference in deformation occurs. However, as the angle increases, the weight-load is shifted more toward the fulcrum roller (angle *C*). The difference in deformation becomes quite appreciable if workpiece weight is added. Such is the case with the sine block.

*Sine bars should not be set to angles over 45°. Instead, they should be used in conjunction with a mounted square. This analysis does apply to the sine table, which often is set over 45°.

The Sine Table

The size of gages, instruments or parts that a sine bar can inspect is limited, since it is not designed to support large or heavy objects. The sine block, being of one-piece construction, is also limited since it may safely carry workpieces only to about 45°.

The sine table is the most convenient and accurate design for sustaining relatively heavy loads, since (1) the weight of the unit plus that of the workpiece is given fuller, safer support; (2) the gaging platforms are self-contained and can be highly refined; (3) the table may be safely swung to any angle from 0° to 90° by pivoting it about its hinged end.

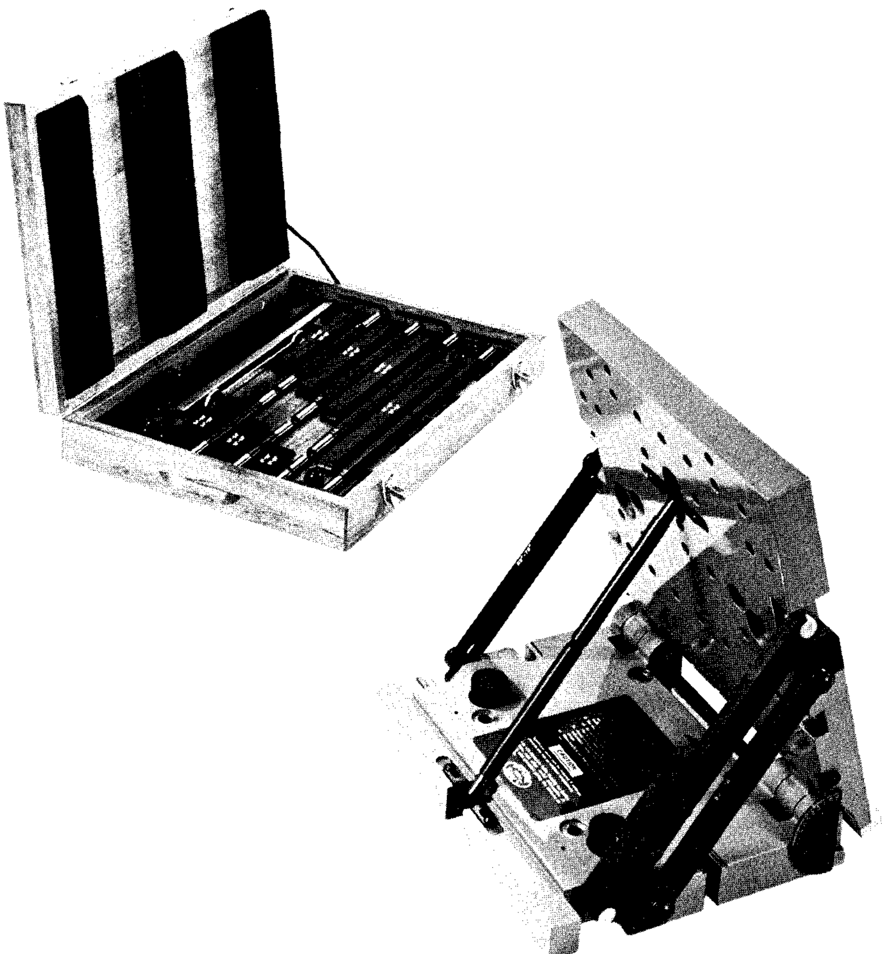
It is exceedingly difficult to absolutely verify the angle set by a sine table. Some of the reasons for this have already been shown to be inherent in the nature of the sine principle itself. The sine table has the additional problem of size and weight of its own table. In effect, the table is a long lever which bends and twists when put through various angles while supporting all sorts of shapes, sizes and weights of workpieces. The clamping mechanism of the sine table may also cause distortion, varying the angle from that intended.

Unfortunately, these errors go undiscovered unless they are relatively large. Only two angles, 0° (flat) and 90° (right angle)—the limits of travel—are verified with any amount of certainty. At all other angles within those limits, even angles accessible to inspection, any known means of inspecting the sine table are not appreciably more reliable than the sine table itself.

The best recourse for the sine table user is simply to satisfy himself that: (1) the construction principles of the sine table are correct; (2) all elements of the sine table are made accurately; (3) the sine table is used properly; and (4) the gage block stack is accurate and at the same temperature as the sine table. Having determined these things, all the user can do is trust the device.

The 8-inch [203.2 mm] sine table shown in Fig. 343 was designed to avoid the potential sources of inaccuracy normally associated with a sine table. It is of interest that the use of integral gage pins in base and table, rather than a gaging platform, enables up to a full 90° without obstruction. The "double sine" design, Fig. 344, also minimizes the errors normally inherent in a sine instrument involving greater angles. At 80°, for example, an error of +0.0001 inch [0.0025 mm] in the center distance of the gage pins causes an error of only −4.33 seconds. The double sine design is robust. Its base and table are each

FIG. 343—This sturdy Micro-Sine Table departs from standard design by being gaged and supported on both sides. In this manner, accurate angles and parallelism of its table to base at all heights is assured.



1 15/16 inches [49.21 mm] thick and it weighs 130 lbs. [58.97 kg]. Total profile height and weight are kept at a minimum (commensurate with rigidity) to achieve the greatest possible convenience and versatility in use.

The sine table may be used for the inspection of angular relationships while mounted on a surface plate, Fig. 345. It may also be mounted on a machine tool or measuring machine by itself or with a rotary table for the inspection of compound angles (see page 315). The low profile of the sine table avoids using up spindle-to-table capacity when it is mounted on jig borers, jig grinders or measuring machines. Two sets of sturdy noninfluencing clamps are provided for supporting the table on both sides over the whole range of the sine table.

The most important innovation in its design is the incorporation of a pair of protruding gage pins set at the 8-inch [203.2 mm] sine distance *on each side of the plate.* A special, four-spindle machine accurately locates the holes which are to receive the protruding gage pins, Fig. 346. A series of rods, threaded at both ends, enables very fine height adjustments to be made over the full 90°. Rapid settings may be made where great accuracy is not required, simply by working to a graduated reference plate on the side of the sine table, or by gaging the height with vernier calipers.

The sine table is capable of exceptional accuracy. The user should first be satisfied with the accuracy of the particular gage block stack in use, handling them with gloves. The sine table is elevated or lowered, using the fine adjustment feature to attain the desired "feel" between the gage blocks and pins on one side. This side is then clamped, a step repeated on the other side. At this time, the operator may compare both sides to insure they are identical in height and to make any final minor adjustment.

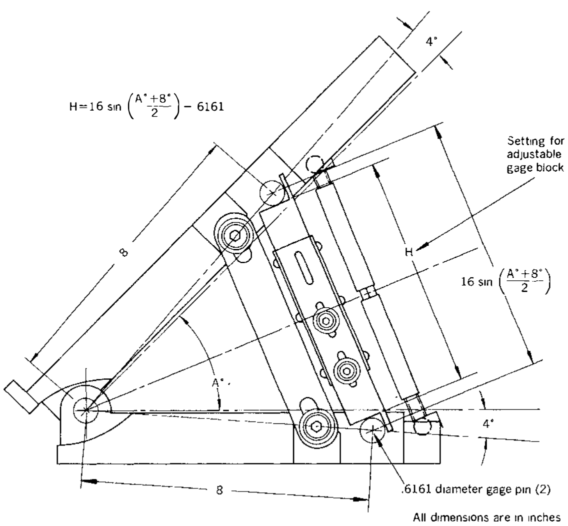
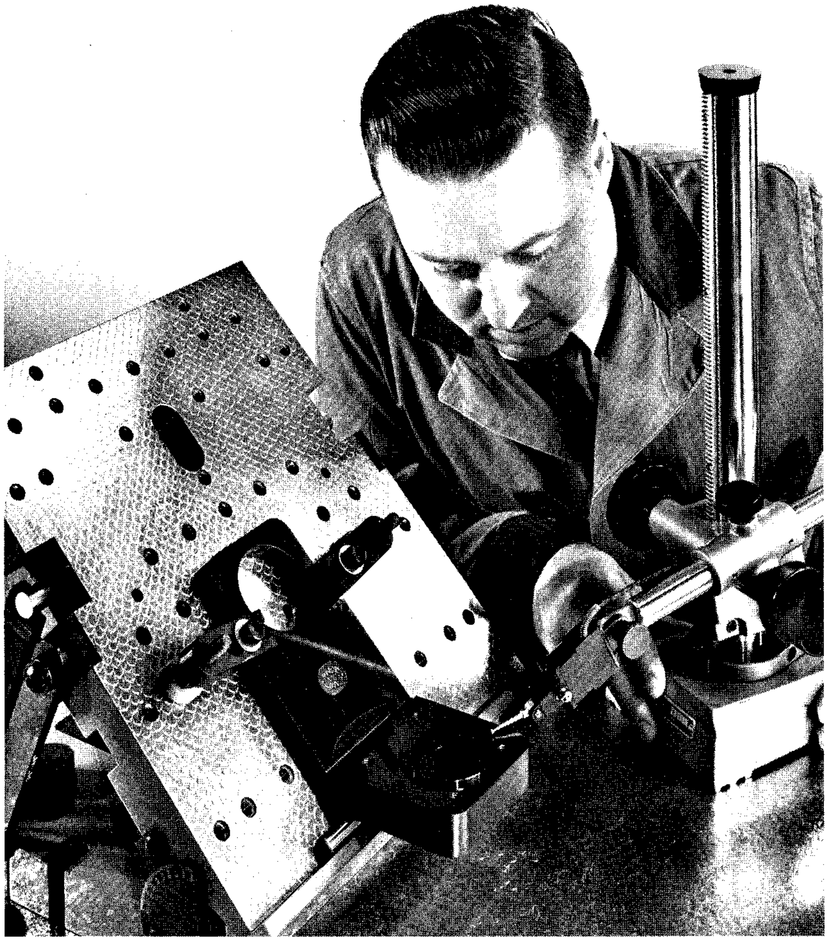


FIG. 344—The "double-sine" principle employs gage pins rather than a gaging platform in both table and base of the sine table. This design allows angular settings to a full 90°, and minimizes the errors normally inherent in a sine table at greater angles.

FIG. 345—*Micro-Sine Table is useful for surface plate work in measuring angular relationships. Here, a 45° angle attachment used on jig grinders for generating ball sockets is inspected.*



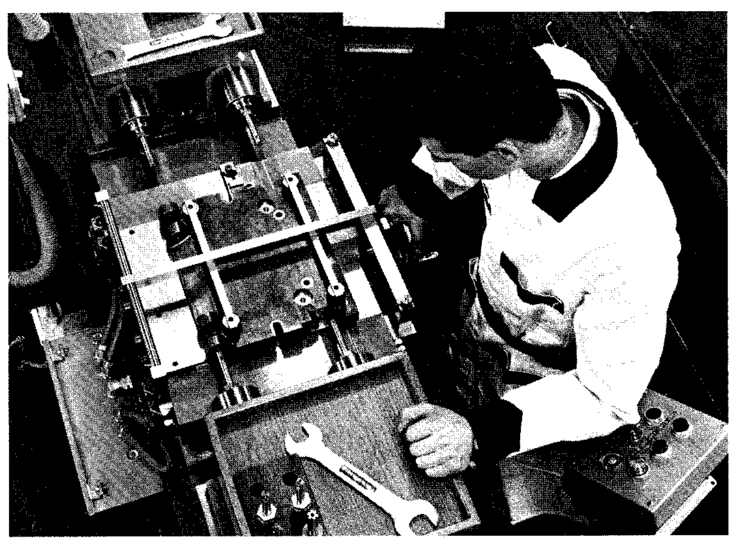
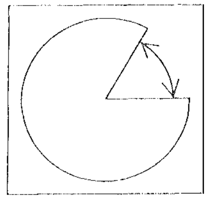
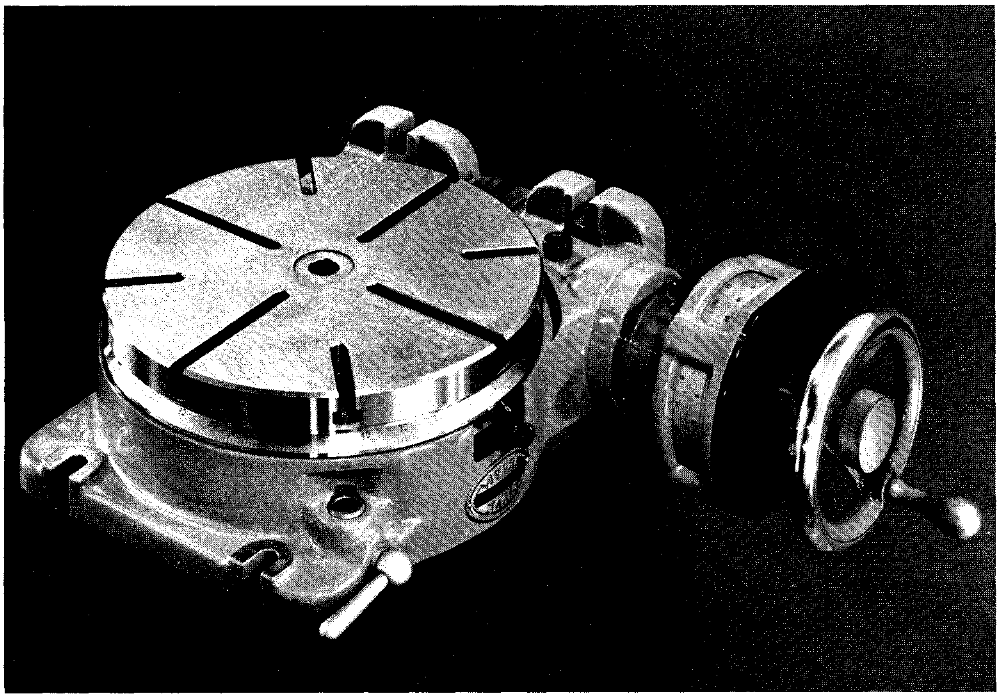


FIG. 346—*Special 4-spindle machine used to establish location of 4 functional holes of both table and base of the Micro-Sine Table.*

FIG. 347—*The rotary table, the best-known and most widely applied circle-dividing instrument.*





4. Circle-Dividing Instruments

THE ROTARY TABLE

There are innumerable types of instruments, optical devices and mechanical contrivances which generate or measure angles by dividing the circle. There is none, however, which has more general use and significance to practical engineering and metrology than the familiar rotary table, Fig. 347.

The three categories of rotary tables are:

1. Optical, or other types having circular scaled graduations, Fig. 348.
2. Mechanical, cam-compensated, Fig. 349.
3. Mechanical, accurate worm-and-gear, Fig. 350.

Optical Rotary Tables

The term "optical" is a slight misnomer, and is used here only because this primary type of rotary table is usually thus described. It is optical only in the sense that a microscope is employed to read the essential measuring element, a precision circular scale. Within this category may also be included other circular scale-measuring rotary tables which employ electrical (inductance) or optical (Moiré fringe) averaging of the circular graduations. All differ slightly, but have similar characteristics.

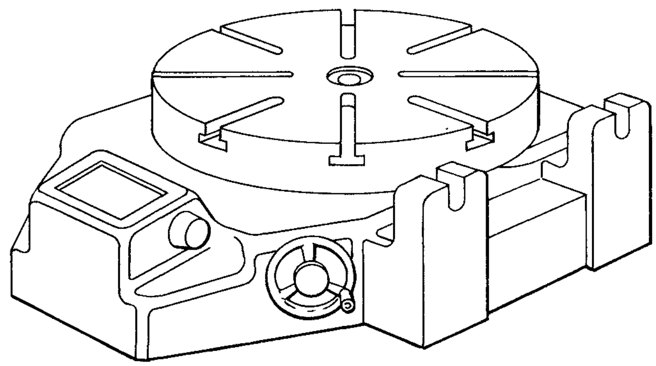
The number of lines which can be placed about the main circular scale of an optical rotary table depends on its diameter, the width of the lines and the magnification of the integral microscope. The lines are usually at intervals of 1/6 or 1/3 of a degree. A graduated drum or other optical vernier arrangement enables settings to be made to finer increments of minutes and seconds of arc. In the "averaging" type, smaller increments of angle are achieved by the sine curve generated by electronic or optical pulsing.

Since the circular scale or disc is usually manufactured separately before being mounted on the rotating member of the rotary table, the most advanced systems read the circular scale simultaneously from opposite sides to compensate for errors which may occur from eccentric mounting. Usually, a worm-and-gear is used to impart rotation, but is not made to any great accuracy.

Two advantages attributed to the optical rotary table are: (1) the measuring element is free from wear and (2) the table may be positioned from either direction. Some of the disadvantages are: (1) its reduced accuracy or inability to be employed for automatic indexing when using an index plate (see pages 218–220); (2) eye fatigue from prolonged use (if optical).* "Repeatability" is also dependent on the rotary table's ability to make very fine dis-

*Much of this analysis is similar to that where various linear measuring elements are compared in "Standards of Length," pages 185–186.

FIG. 348—*The optical rotary table employs a circular scale read by microscope as its angle-measuring element.*



placements and this, in turn, is dependent on many factors, such as the type of radial and axial bearing used, lubrication, and the perfection of the *total worm-and-gear assembly.*

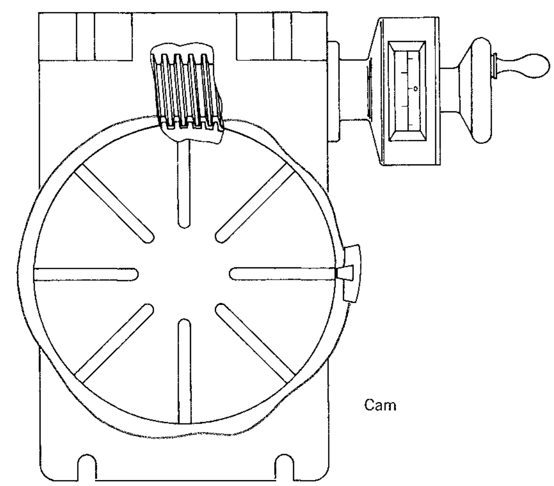
Mechanical, Cam-Compensated Rotary Table

In this type of rotary table, accuracy is directly related to the accuracy of the worm-and-gear, except that the final unresolved errors are overcome by compensation, rather than by perfection of the gear.

Attached to the rotating member is a circular cam. Its shape is adjusted according to the calibrated error of the rotary table. Working against the cam is a follower which, through a linkage, advances or retards the vernier dial or "zero" to match the error of the gear at that particular angle. For example, if at 230°, the inherent gear error is −10 seconds, then the cam advances the "zero" 10 seconds at that point, causing the operator to feed the worm through an additional 10 seconds in setting to his dial reading. With proper design, this system can have fairly good repeatability.

The greatest advantage of the cam-compensated rotary table is the fact that it can offer the user reasonable accuracies at minimum cost. This principle of construction has a limited potential of accuracy, however. The primary reason is that *periodic error* (error within one turn of the handwheel) is not taken into consideration. This is the most difficult error of all to eliminate, since it is effect ed by so many factors—the thread form, drunkenness, pitch, lineup, and runout of the worm, and also by the errors of eccentricity, tooth form, and tooth-spacing of the gear.* The errors of the worm alone, exclusive of the gear

*The reader might refer to the analysis of periodic error of a lead screw, pages 196–199, since the comparison is similar. The main difference between the two conditions is that periodic error is much more difficult to control in a rotary table than with a lead screw due to the lack of any averaging.



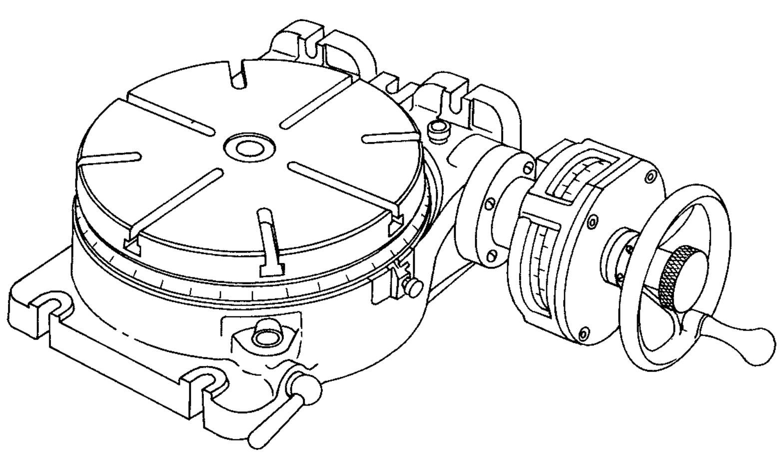


FIG. 349 (*Center*)—*In the cam-compensated rotary table, the angle-measuring element is the worm-and-gear. Final accuracy, however, is established by cam-compensation of gear error.*

FIG. 350 (*Bottom*)—*In the accurate worm-and-gear rotary table, the gear is machined or lapped to final accuracy.*

error, may easily amount to many seconds.

The very process of resolving periodic error involves an expensive, exhaustive inspection of at least several hundred positions. One would not expect this exhaustive checking of a design which has been made with minimum cost the prime consideration. It is also doubtful that periodic error could be corrected by a cam and follower. For example, consider a 180-tooth, 10-inch [254 mm] diameter rotary table. One turn of the worm represents an arc in the cam of only about 3/16 inch [4.75 mm]—a very small space within which the follower must work.

Cam-compensation may be a suitable means of removing gross errors. When accuracies to 1 or 2 seconds are required, however, the action of the cam, follower and linkage itself is likely to introduce serious errors. The cam and linkages are also vulnerable to chips and dirt if exposed, and are subject to wear if unhardened.

Accurate Worm-and-Gear Rotary Table

Both the worm and the gear of this type of rotary table are made highly accurate and no corrective mechanism is applied. One disadvantage of this design is the difficulty and expense of manufacturing an accurate worm-and-gear. The unavoidable presence of backlash, necessitating a unidirectional approach when setting, is also frequently cited as a disadvantage of this design as well as of the cam-compensation design. The writer takes issue with such criticism, based on personal experience in the machine shop. A habit worthy of cultivating is that of *always* taking a unidirectional approach where practicable, whether the device operated is mechanical, optical or electronic.

The reader may satisfy himself on this point if he has occasion to test a measuring instrument that is supposedly free of reversal error. Simply employ some auxiliary means (such as an electronic indicator and a suitable gaging surface) and compare the range of readings obtained with settings from one direction, then from the other. The discrepancies are sometimes great, sometimes slight, but almost always measurable.

The advantages of the accurate worm-and-gear are: (1) trouble-free operation; (2) good repeatability; and (3) a high potential of accuracy.

Advantage of the Index Plate

The accurate worm-and-gear has one additional advantage for the generation and

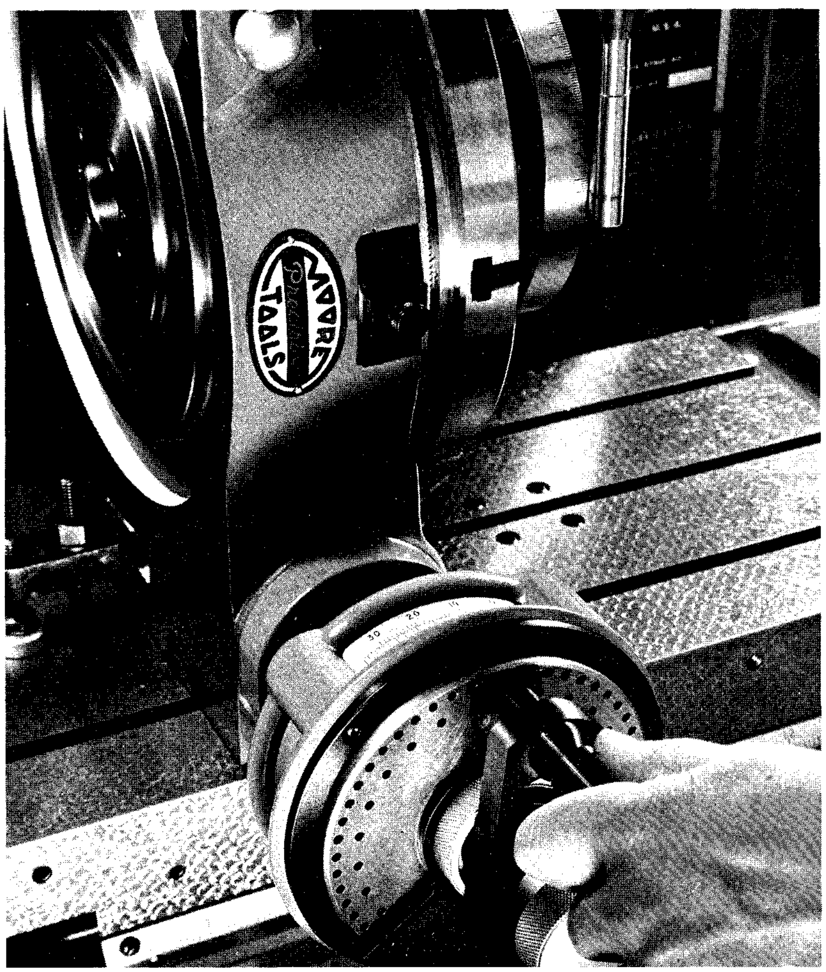


FIG. 351—*The accurate worm-and-gear type rotary table is unique in that it may be used together with an index plate to divide the circle, without the necessity of reading angles, and without loss of accuracy. Here, 500 lines of a dial are being accurately generated.*

inspection of angles. It was previously stated (see page 206) that the potential mathematical inconvenience of the official sexagesimal system might influence the design and type of circle-dividing equipment selected as well as its manner of operation. A practical example will illustrate what was meant. In Fig. 351, five hundred lines 0.003 in. thick [0.0762 mm] are cut, equally spaced around a 6½ inch [165.1 mm] diameter workpiece. The calculations necessary to generate *or inspect* these lines are:

First setting $\frac{1}{500} \times 360° = \frac{18°}{25} = 43'\ 12''$

Second setting $\frac{2}{500} \times 360° = \frac{36°}{25} = 1°26'24''$

Third setting $\frac{3}{500} \times 360° = \frac{54°}{25} = 2°\ 9'\ 36''$

Each position must be read off the dial. In calculating the angles, or in setting these angles on the dials, an error can easily occur and go undetected.

The laboriousness of having to *read* the angles is in sharp contrast with the convenience of the index plate method. The value of the five hundred settings do not really have to be calculated. The rotary table used for generating the lines has a 180-tooth gear (2° per turn), so the formula is: 180/500 = 9/25.

This means simply that a 25-hole index plate is used and that the operator indexes ahead nine holes at a time. In use, the handwheel is replaced by an index plate having a 25-hole pattern and an index attachment.

In summary, the advantages of using the index plate are:

1. All that is required is a repetitive movement of the indexing pin, nine holes ahead per setting, aided by sector arms locked at that spread, Fig. 352.
2. No readings are necessary and no special skills are required.

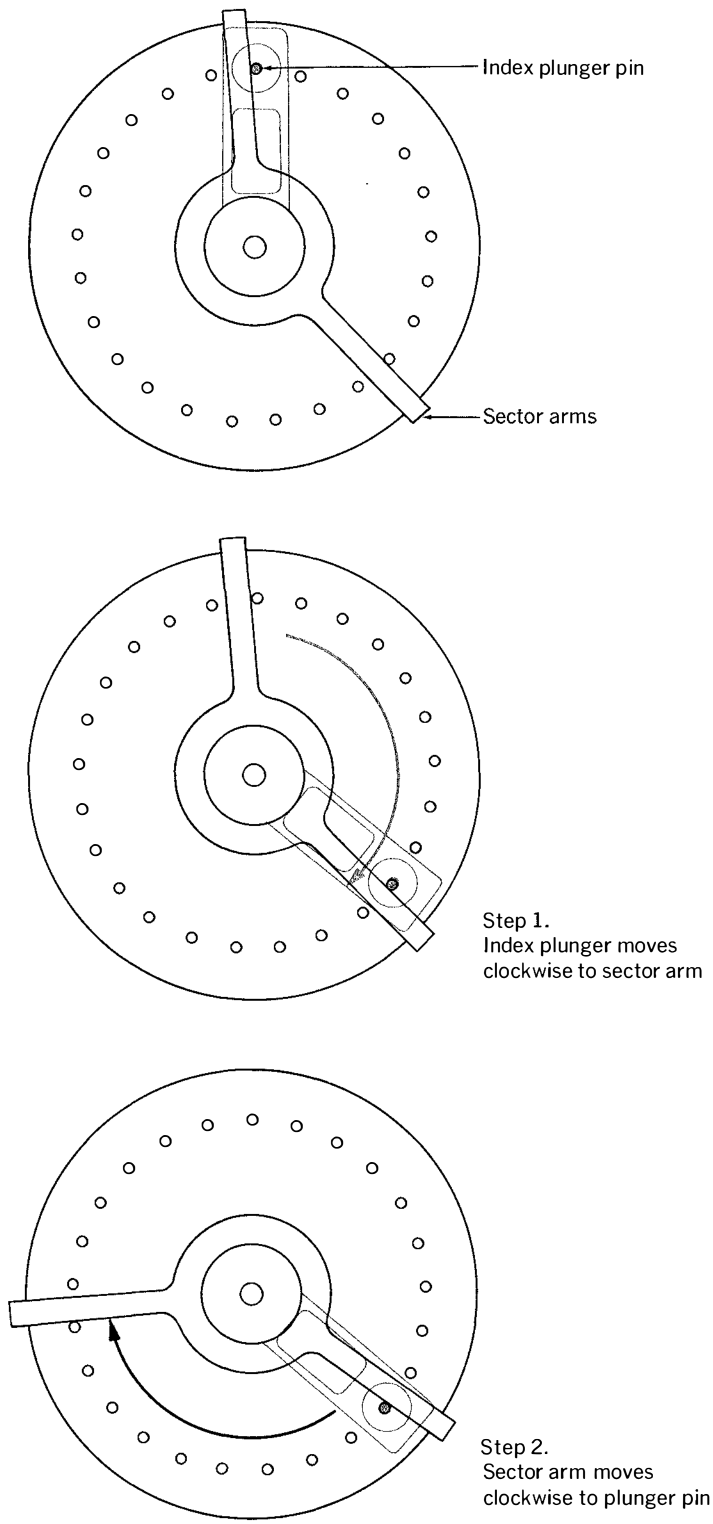


FIG. 352—*For either the inspection or the generation of angles, the index plate aids accuracy and reliability. Here, the sector arms are set to enable 500 divisions of a circle using 9 holes at a time of a 25-hole plate. The divisions are self-proved upon closing of the circle.*

3. If the circle closes during a trial run, the setup is proved.
4. An indexing error which may have occurred in any one of the five hundred steps during the operation does not go undetected, because the circle does not close.
5. At any indexed position, angular location can be double-checked against the dial reading.
6. The accuracy of the index plate is not critical, but need only be of second-order accuracy. An error of 1.6 minutes in the index plate results in only about 0.5 second actual error in table position.

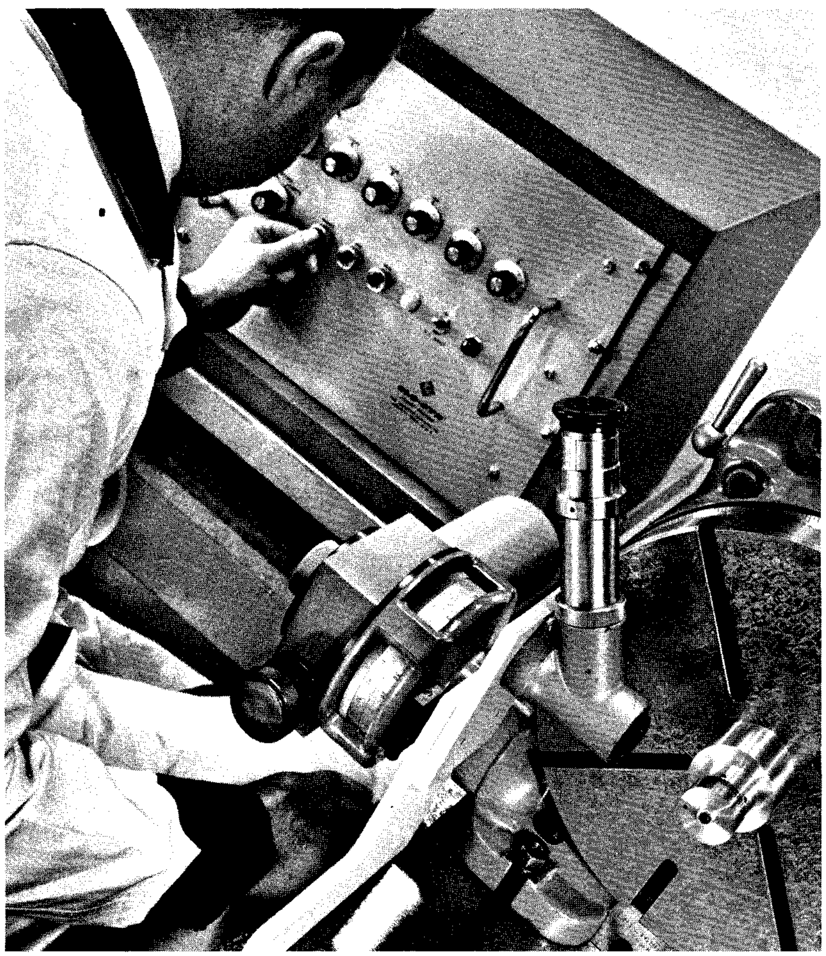


FIG. 353—*The accurate worm-and-gear type rotary table allows simple indexing controls to be applied, as with this stepping motor. The rotary table is indexed automatically to measure non-uniform line spacing of a dial, using a 30-power microscope.*

Normally, a cast-iron index plate which has been drilled and reamed is furnished. In its place may be used a hardened, jig-ground index plate in which all holes are held to close tolerance of size, spacing and concentricity with its locating hole on the worm-shaft. In the latter case, repeatability far exceeds the ability of the eye to set by using the dial.

The optical rotary table is not appropriate for index plate use, since no effort has usually been put into refining its worm-and-gear. Similarly, the usual method employed with a cam-compensated rotary table is to shift the zero dial. In using an index plate, then, accuracy reverts back to that of the worm-and-gear, making the compensation mechanism completely ineffectual.*

An indexing attachment can be used with the accurate worm-and-gear without sacrificing the optimum accuracy of the rotary table. This is not true of the other designs. Use of indexing attachments allows the accurate worm-and-gear design to be adapted with little or no loss of accuracy to many automatic or automated operations simply by controlling the whole and fractional number of worm rotations. For example, the worm may be indexed accurately by attaching a crank arm to the end of the shaft, using it to stop rotation positively by registering against an anvil. Another method is to use a stepping motor to control indexed position. In the simplest arrangement, the stepping motor is fastened directly to the wormshaft. For finer discrimination of angle, intermediate reduction gearing is used between worm-shaft and stepping motor.

The angular increments set by the stepping motor may be uniform, which is most

*The writer has seen cam-compensated rotary tables that shift the whole dial housing, which would automatically correct for index plate use as well. This design would seem to have a low potential of accuracy, since worm alignment would certainly be altered during the rotation of the housing.

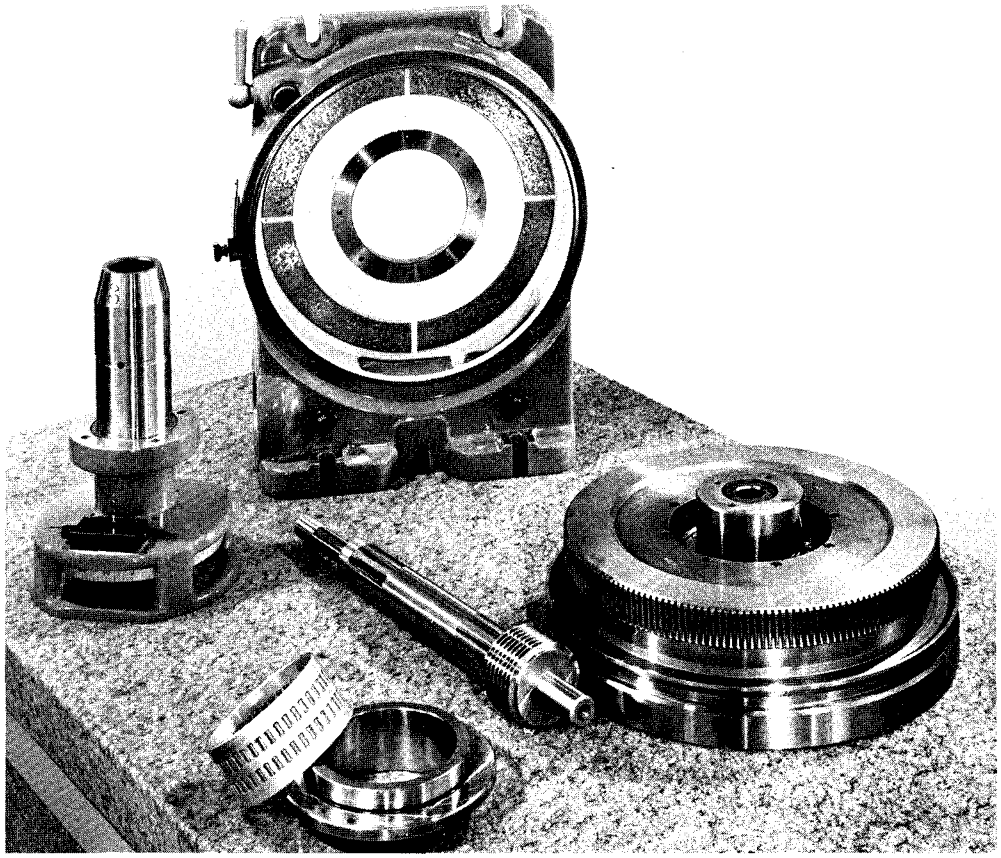


FIG. 354—*The accurate performance of a rotary table is made possible only by controlling the accuracy of all the mechanical parts which make up its assembly.*

often the case when machining or inspecting a circular cam. By applying additional controls to the stepping motor, Fig. 353, a rotary table has been programmed to enable the inspection of *nonuniformly spaced* lines scribed around a circular part. The microscope used is 30-power.

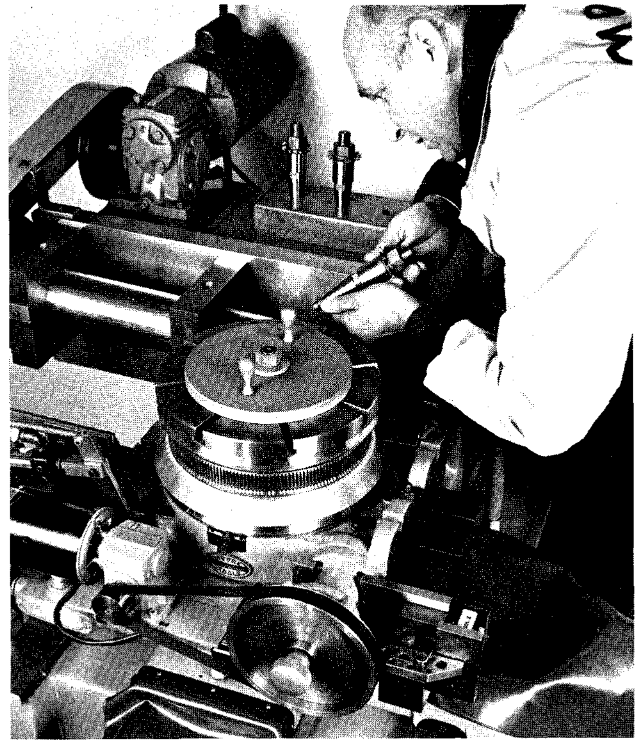
A ruling engine for the generation of diffraction gratings is shown in Fig. 555. The final performance of the engine depends to a large extent on an accurate master worm-and-gear, which is applied to index the leadscrew automatically, allowing table displacements as fine as 0.0000001 in. or 0.1 millionth of an inch [0.0000025 mm].

Construction of the Rotary Table

Only by closely controlling all mechanical elements which make up a rotary table can a high order of angular and rotational accuracy be attained. Fig. 354 shows the construction features of the disassembled parts of a rotary table. The manufacturing tolerances of these parts as listed below should be noted (read from left, clockwise).

	Tolerance	
1. Hardened, ground and lapped (ID)	+ 25 millionths in.	[0.0006 mm]
bearing sleeve	− 0 millionths in.	[−0 mm]
2. Cast iron base (47 lbs. [21.3 kg])		
scraped flat	20 millionths in.	[0.0005 mm]
and parallel	20 millionths in.	[0.0005 mm]
3. 9¾ in. [247.65 mm] gear—	± 4 seconds (Precise)	
gashed, hobbed, then lapped to	± 2 seconds (Ultra-Precise)	
Hardened, ground and lapped		
center hub (inner race) to size		
and roundness	5 millionths in.	[0.000127 mm]
4. Wormshaft bearing lapped for exact lineup in	+ 25 millionths in.	[0.0006 mm]
bearing sleeve above	− 0 millionths in.	[−0 mm]
5. Hardened, ground and lapped 3-in.	± 5 millionths in.	
[76.2 mm] ID center bushing (outer race)	size	[0.000127 mm]
lapped to	5 millionths in.	
	roundness	[0.000127 mm]
6. Eighty lapped rollers (in bronze retainer)	± 2½ millionths in.	
	(identity)	[0.0000635 mm]

FIG. 355—*The rotary table gear is indexed and gashed automatically on a special machine constructed from a modified measuring machine base.*



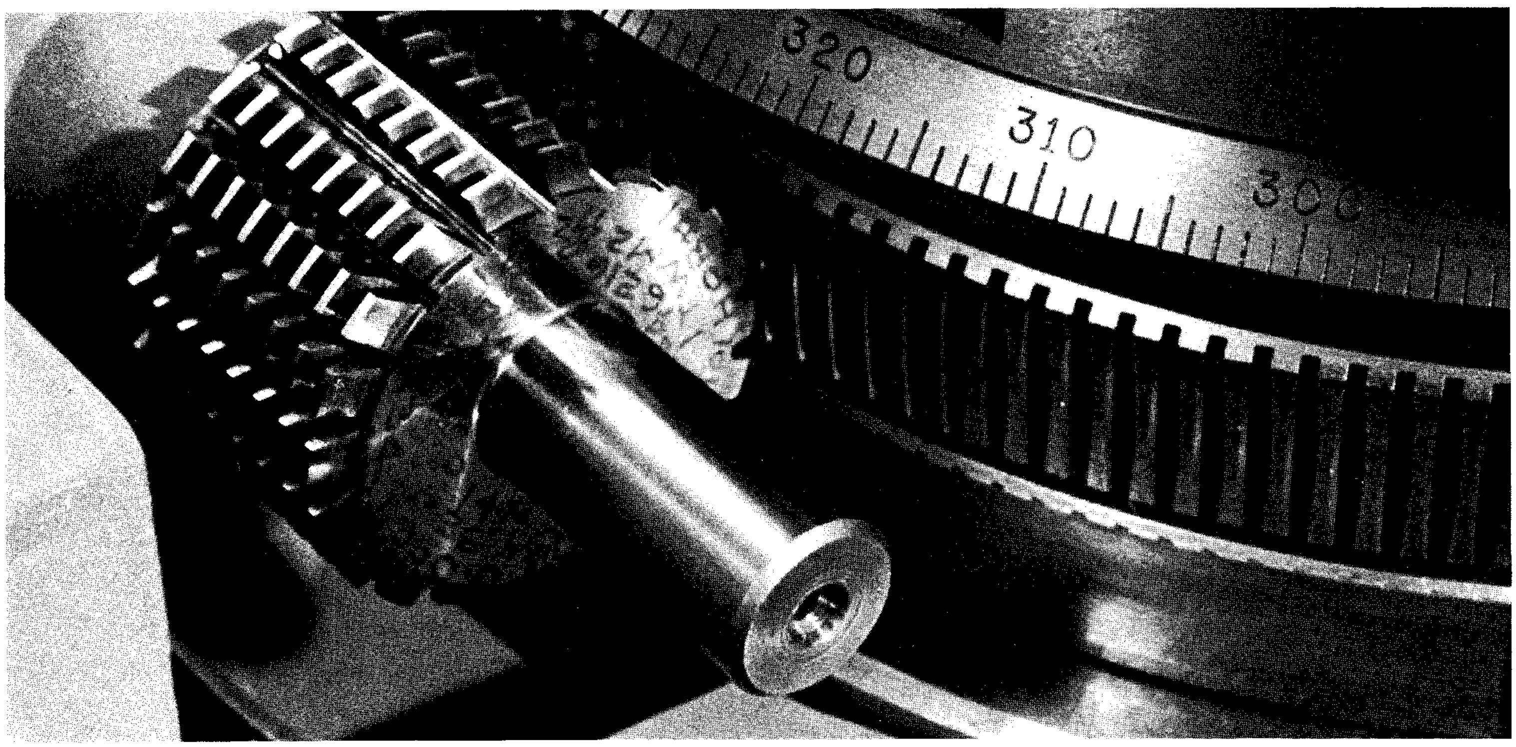
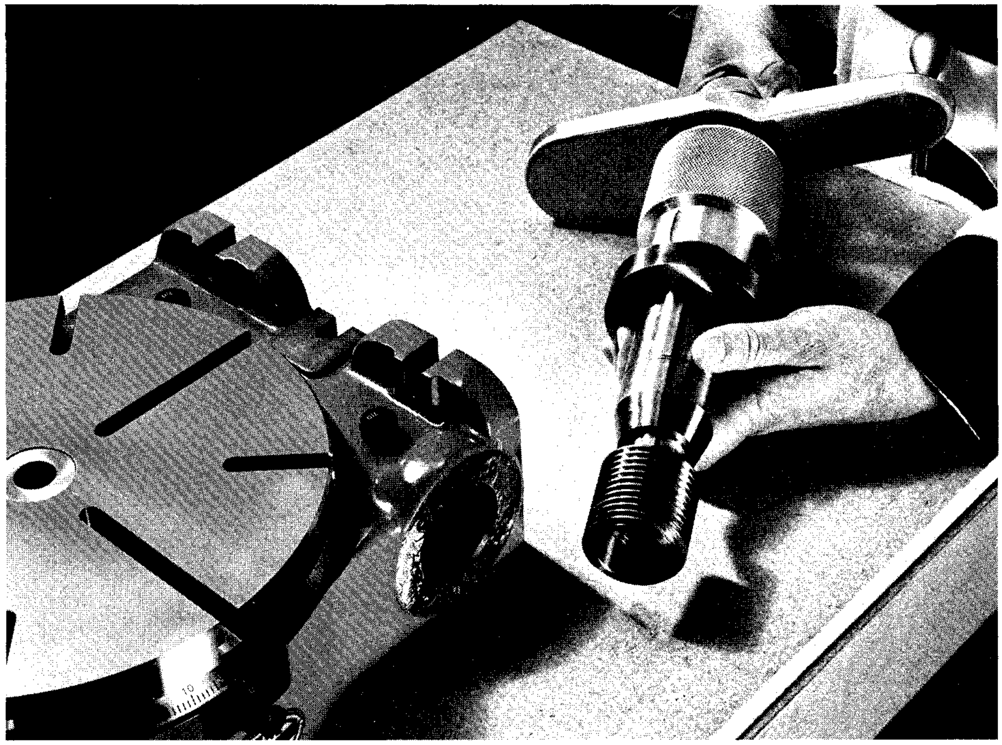


FIG. 356—*The rotary table gear is hobbed while rotating synchronously with a master rotary table on which it is mounted.*

FIG. 357—*Final accuracy of the rotary table gear is achieved by careful lapping while in its own assembly. The worm-lap is used only for one gear, then discarded, yet must be made with virtually the same care as the worm itself.*



Manufacture of the Rotary Table Worm and Gear

Since the worm and gear represent the two most important elements of the rotary table, it is valuable to briefly examine how they are manufactured.

The Gear—The gear of the rotary table begins as an exceptionally close-grained cast iron blank. The gear blank is ground flat and parallel and an accurate hole is bored in its center. The gear blank is located from this hole on a special machine where the teeth are gashed, Fig. 355.

This single-purpose machine consists of a modified measuring machine base, a rotary table for indexing the gear automatically through 2° increments, and a precision spindle holding a gashing cutter fixed at the correct helix angle.

The gear, after being gashed on the machine, is removed to a second machine, located accurately from the center hole and hobbed. The second machine consists essentially of a master rotary table which carries the gear, revolving synchronously with a spindle-mounted hobbing cutter, Fig. 356. The hobbing operation develops a true involute form on the teeth.

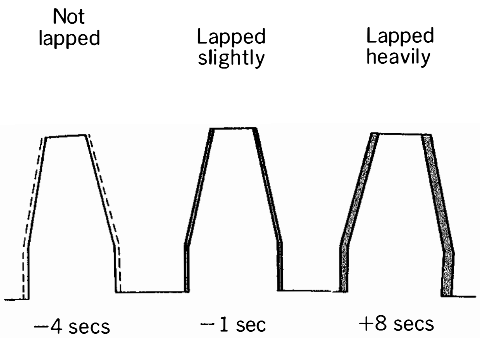
Although both gashing and hobbing are closely controlled, the gear error still exceeds specifications. Final accuracy of the gear is attained only after it becomes part of a full rotary table assembly. Once mated to the parts which make up the full construction, especially its own worm, the most accurate calibration of the gear can be attained. Final correction proceeds by hand lapping. The cast iron lap used, Fig. 357, is made with great care, and is assembled in exact alignment during corrective lapping to insure matching its involute form with that of the gear being lapped. The lap has a very short working life, since during lapping, thread form wears rapidly. The gear itself must be corrected with as few lapping operations as possible, lest its involute form be destroyed.

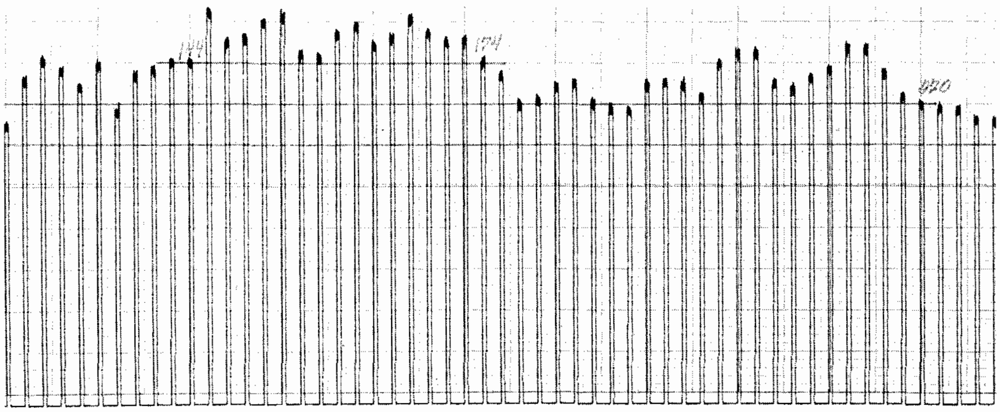
The gear teeth are lapped by working always to the smallest tooth, shown schematically in Fig. 358. Theoretically, the smallest tooth is not lapped at all. The other teeth are lapped in increasing proportion to their "thickness" (or the amount they are "plus"). The inspection chart used by the lapping expert is shown in Fig. 359. The derivation of this chart is shown on page 239.

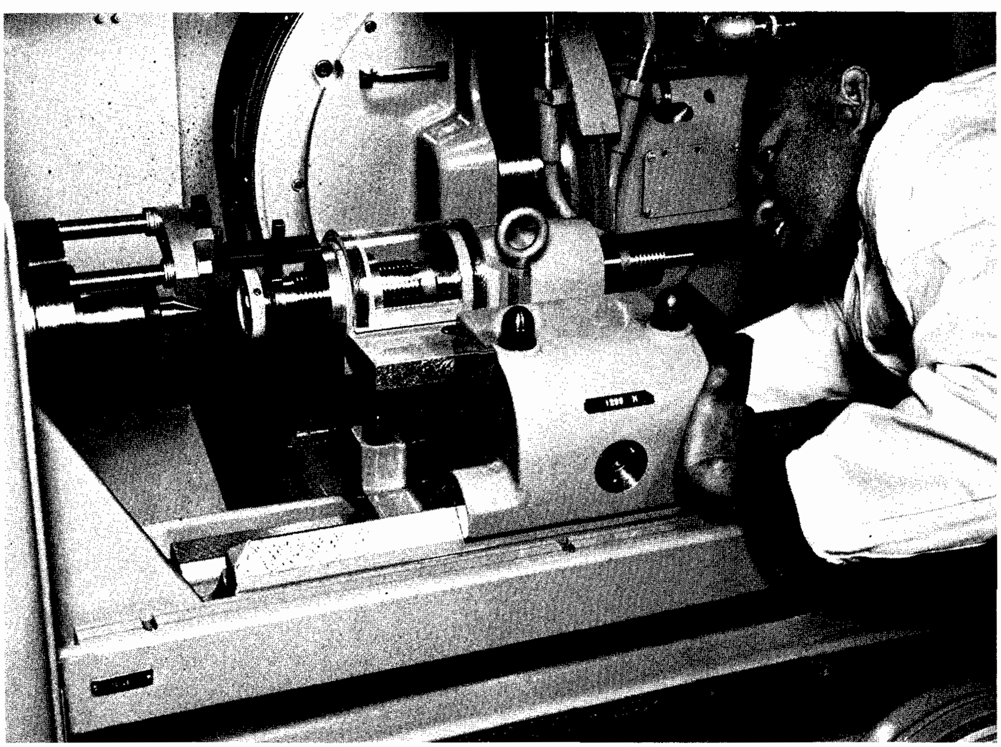
The Worm—Perfection of the worm is essential for overall accuracy of the rotary table, especially with regard to periodic error. Pitch diameter must be concentric

FIG. 358—(*top*) *The gear teeth of the rotary table are lapped in proportion to their "thickness" as determined by calibration with the 1440 Index.*

FIG. 359—(*center*) *The lapping specialist is provided with a complete graph of the rotary table error before each lapping operation. He analyzes the chart carefully before proceeding to lap, bearing in mind the results of any previous lapping operations.*







with its own journal (support) bearing, lead must be precise, and the worm must be exactly aligned with the gear in assembly.

Just as in thread grinding the leadscrew, the worm is flooded with temperature-controlled oil. Worm lead, however, is controlled by a master worm in a special fixture, Fig. 360. If inspection reveals errors, the worm is correctively lapped.

The Importance of Accuracy of Rotation in a Rotary Table

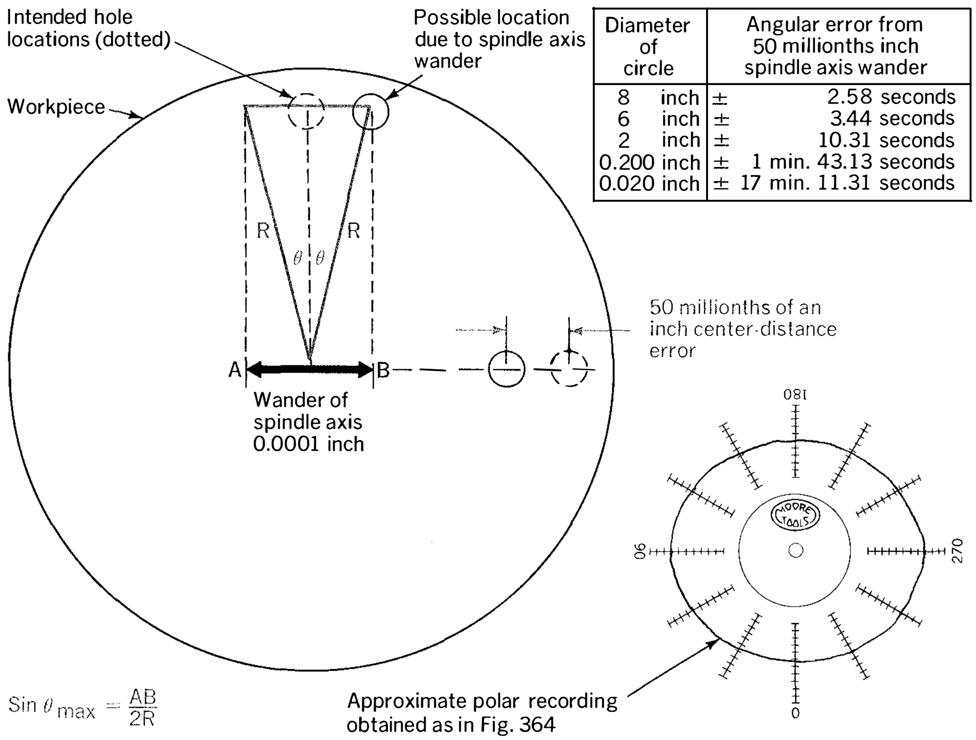
Trueness of rotation is seldom encountered on any rotary table manufacturer's list of accuracy specifications. Yet in almost every rotary table application, lack of true spindle rotation results in both angular error and center-distance error. The nature of this error is illustrated in the hypothetical workpiece in Fig. 361. Assume that the actual angle generation of the rotary table is perfect, but that the axis of rotation wanders from A to B and back to B for each revolution. This would appear approximately as in the lower right of the diagram if a polar recording were obtained by centering a round master gage to the spindle as in Fig. 364.

If the rotary table had an eccentricity radially of 0.000050 inch (0.00125 mm), the center-distance of the holes would, of course, be in error by 0.0001 inch (0.0025 mm). As shown in the diagram, an angular error might also result, amounting to a maximum of $\sin\theta = \frac{AB}{2R}$.

The angular error which results is even more interesting. On an 8-inch [203.2 mm] diameter circle, the included angular error of the holes from the true center point is 2.577 seconds. If the holes had been machined in a pattern of 3-inch [76.2 mm] radius from center the error would be 3.44 seconds; at 1 inch [25.4 mm] 10.31 seconds; at 0.100 inch [2.54 mm] 1 minute and 43.13 seconds; and at 0.010 inch [.254 mm], 17 minutes and 11.31 seconds.

FIG. 360—*The overall performance of the rotary table is greatly dependent on perfection of the worm. Lead and concentricity of each worm are controlled from a master worm-grinding fixture which mounts on the thread grinder.*

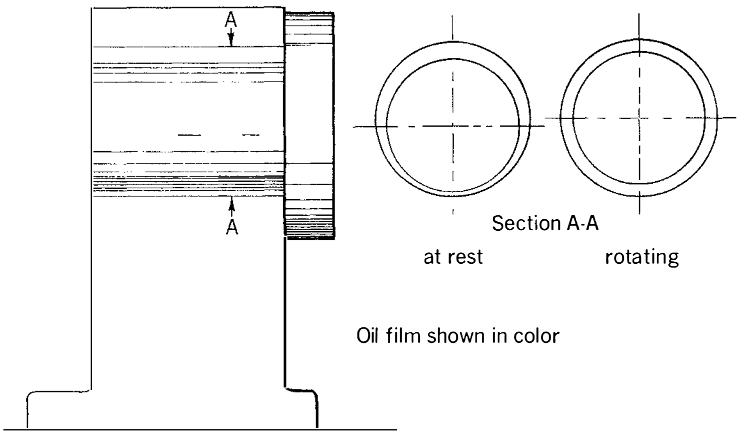
FIG. 361—*A rotary table spindle that does not rotate "true" introduces an additional angular error quite apart from the inherent angular errors specified by the rotary table manufacturer. This becomes apparent by citing as an example a rotary table with a spindle axis wander of 50 millionths of an inch [1.2μm]. Shown is an approximate scaled up representation of one type of angular spacing error which could result in a part.*



Diameter of circle	Angular error from 50 millionths inch spindle axis wander
8 inch	± 2.58 seconds
6 inch	± 3.44 seconds
2 inch	± 10.31 seconds
0.200 inch	± 1 min. 43.13 seconds
0.020 inch	± 17 min. 11.31 seconds

$$\sin \theta_{max} = \frac{AB}{2R}$$

FIG. 362—*A plain-bearing spindle, used horizontally, has two axes, one while at rest where the oil is squeezed out at the bottom; the other displaced higher, where the oil is evenly distributed while rotating.*



As the pattern of holes is put on an increasingly smaller-diameter circle, a hypothetical condition is approached in which all holes are in a straight line, or an error of 180°.

It is generally known that an angular error decreases the effective error *linearly,* the smaller the radius. The previous example makes clear a lesser known fact. Runout has the effect of increasing the *angular error,* the smaller the radius. The angular errors which result in practice from rotary table eccentricity are *in addition* to its calibrated angular errors.

Rotary tables are usually constructed with a small plain (metal-to-metal) bearing. The interfaces are separated by a thin lubricating oil film. This type of journal must allow at least 100 millionths of an inch [0.0025 mm] clearance to permit free rotation, since the oil film increases in thickness and stiffness as rotational speed increases. If a clearance of approximately 50 millionths of an inch [0.00127 mm] or less is used, seizing and galling almost always occur.

Trueness of rotation is absolutely dependent on the uniformity of the oil film. While it is true that a thin oil film, if confined, strongly resists compression, it is equally true that oil can roll or slide quite easily—either axially or circumferentially—when carried along between rotating or sliding members. If the load on the spindle is inconstant, as is the case when the rotary table is carrying a heavy unsymmetrical workpiece or when it is mounted on the sine table, the oil film tends to be thicker on one side. The thicker film of oil acts as a solid body, causing sideways displacement of the rotating member.

A plain-bearing spindle, when used horizontally, actually has two axes—one when it is at rest and all the oil is squeezed out at

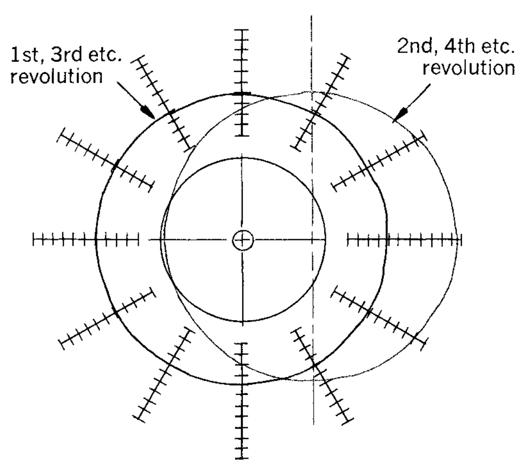


FIG. 363—*A typical characteristic of any plain-bearing spindle is for it to shift its axis on every other revolution.*

the bottom, and another at a higher point when it is rotating and the oil is evenly distributed, Fig. 362.

Even under ideal conditions the oil film is never truly uniform. It tends to build up and disperse in waves. Typically, the axis is displaced at every other revolution, Fig. 363.

In order to attain a trueness of rotation commensurate with the ± 2 seconds accuracy of the rotary table, Moore uses a roller spindle, with a guaranteed rotational accuracy of 10 millionths of an inch [0.00025 mm] or less. The construction of this spindle has previously been shown in Fig. 354. The rollers which make up the assembly are held alike in size to less than 3 millionths of an inch [0.000076 mm] (see page 133) and under stiff preload between inner and outer race.

Each rotary table is calibrated for trueness of rotation in both a horizontal and a vertical position, Fig. 364. A circular chart of trueness of rotation accompanies each rotary table along with its calibration chart of angular accuracy, Fig. 365.

Rotary tables were first developed for use with milling machines and then with jig borers and jig grinders, and find their greatest number of applications in the toolroom and the machine shop. Typical applications of this type are shown in "Universal Measuring Machine Techniques and Applications," pages 310-313. Today, rotary tables are found in the inspection laboratory, too. One inspection application is seen in Fig. 366. Here the built-in right-angle feature of a rotary table is being utilized in the inspection of a master template. In another inspection application, Fig. 367, a rotary table equipped with an accessory tailstock is used to inspect the angular spacing of the splines on a piece. The piece mounted between centers is 35 inches [889 mm] in length

FIG. 364—*A polar recording of rotary table "trueness of rotation" is made by reference to a master ball, round to .000001 inch [0.000025 mm]. The rotary table spindle is checked with axis vertical (shown), and while horizontal by using its built-in right angle feature.*

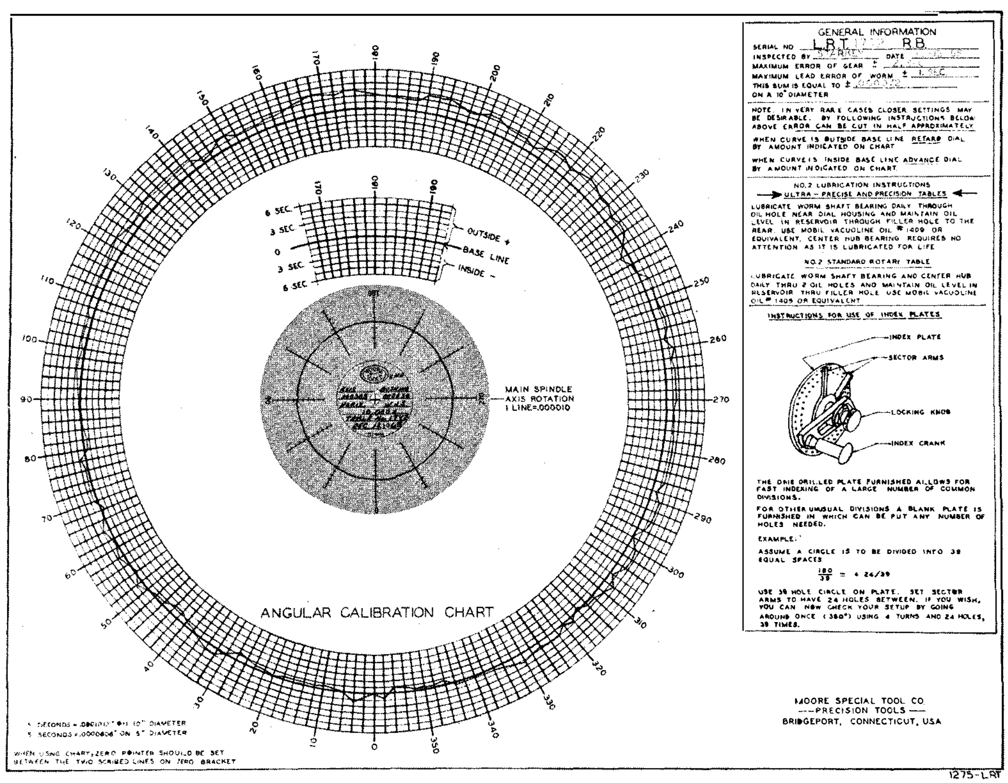
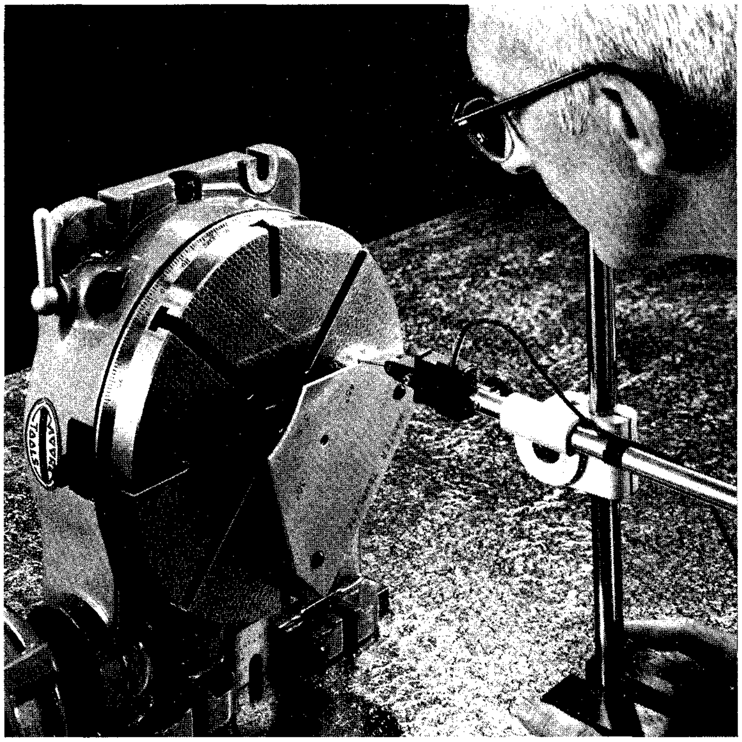
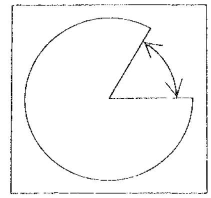


FIG. 365—*A circular chart of trueness of rotation as well as the angular calibration chart of each Precise and Ultra-Precise Rotary Table is supplied to the user.*

FIG. 366—*A master angle template is inspected while the rotary table is mounted at right-angles, using a surface plate, indicator and stand.*





5. Principal Angle Standards

As shop tools, the rotary tables are employed in the machining of an almost infinite variety of mechanical parts where angular relationships are to be generated to a high degree of accuracy. When more accurate rotary tables are used as metrological instruments, they often provide the "final word" on angular accuracy.

Manufacturers of rotary tables verify the accuracy of their products through the use of angle standards. The principal types of angle standards (suggested by the National Physical Laboratory, England) are shown in Fig. 368. An analysis of the angle standards that might conceivably be applied to the calibration of rotary tables follows.

ANGLE GAGE BLOCKS

A useful type of angle standard is the angle gage block, Fig. 369. This standard consists of a hardened-and-lapped steel block, generally wedge-shaped, with a specific included angle between two flat working surfaces. Angle gages are available in sets consisting of a number of blocks, each with a different included angle.

The first set of angle gages was devised by Tomlinson of the NPL in 1939. It consisted of twelve blocks having included angles of 3, 9 and 27 seconds; 1, 3, 9 and 27 minutes; and 1, 3, 9, 27 and 41 degrees. A single square block was also included in the set.

Angle gage blocks were doubtless inspired by the familiar Johansson type gage blocks used in length measurements. Just as with Johansson type gage blocks, angle gages can be wrung together to form fixed standards—in this case for angle, rather than for length.

These two types of standards differ in other respects, however. Relative length is

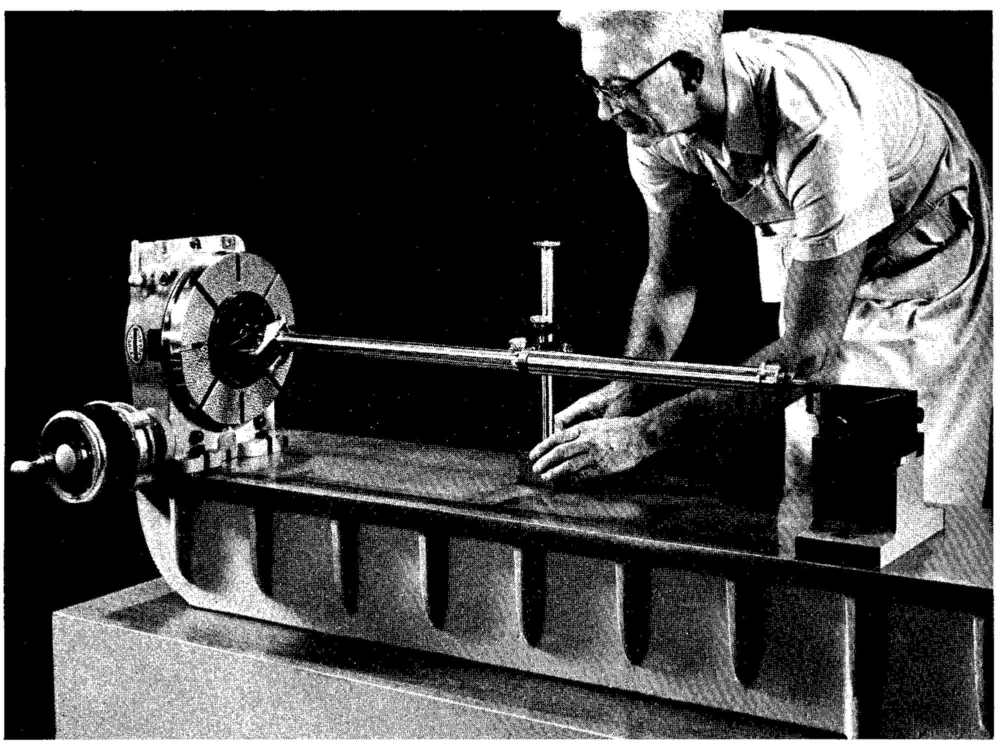


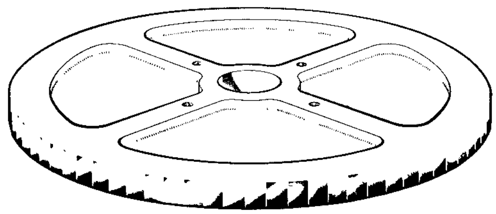
FIG. 367—*An accessory tailstock feature converts the rotary table into a "dividing head" with capacities and features not found in most "dividing heads." The piece mounted between centers is 35 inches [889 mm] in length.*

FIG. 368—*Principal types of angle standards.*
Courtesy of the NPL. British Crown Copyright.

Principal Types of Angle Standards

Polygon

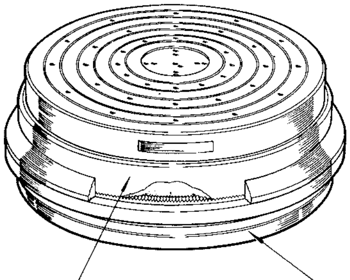
Angle standards of polygonal form have a number of equally inclined and optically flat facets. Polygons are manufactured having up to 72 facets, i.e., the smallest exterior angle which can be defined in practice by the adjacent faces of a polygon standard is 5 degrees.



The exterior angles between adjacent faces of a polygon standard can be calibrated from first principles, with the aid of two auto-collimators, to an accuracy of ±½ sec of arc.

Indexing Devices

Serrated Type



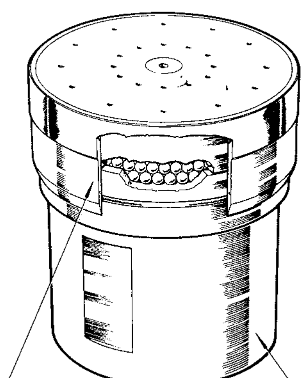
Rotatable Table

Base

Different indexing positions are obtained by means of two matched sets of either equally spaced radial serrations or contacting balls of the same diameter arranged in a circle mounted in the fixed base and the upper rotatable table. Any angle corresponding to a number of serrations or balls can be indexed to an accuracy within ±¼ sec of arc for the serrated type and ±1 sec of arc for the ball type device.

The ball type device as shown has been designed to operate in either the horizontal or vertical plane.

Ball Type



Rotatable Table

Base

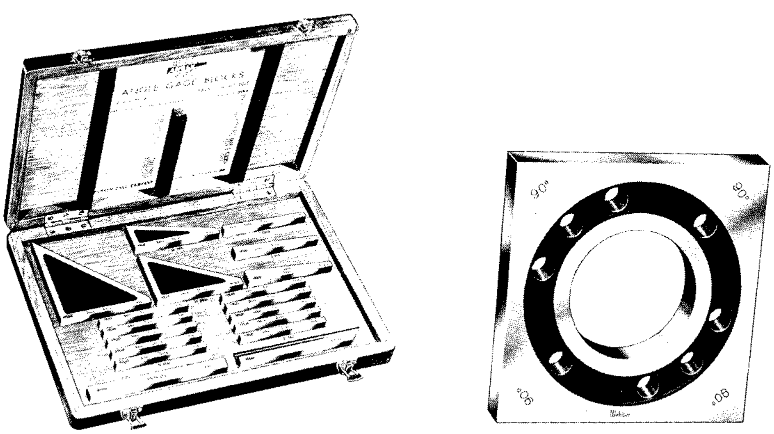
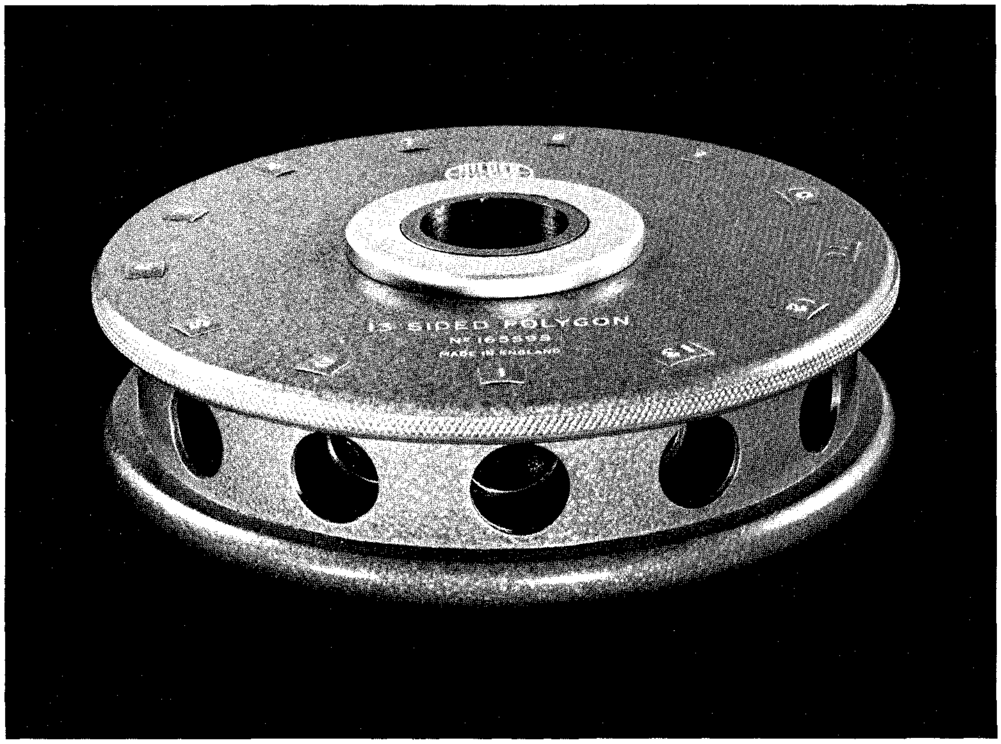


FIG. 369—*Angle gage blocks can be obtained at a moderate expense and can be wrung together additively or subtractively to form almost any required angle.*
Courtesy L. S. Starrett Co. Webber Gage Div.

FIG. 370—*The polygon is a principal circle-dividing standard, having a number of reflective surfaces on its periphery set to a specified angle for use in conjunction with an autocollimator.*



not significant with angle gages—only the included angle effects the measurement. Thus angle gages can be wrung together additively, or be turned end-for-end, subtracting from angular values. For this reason, far fewer angle blocks are required in a set than is the case with a set of length-measuring blocks. Tomlinson's set of only twelve blocks allowed any angle to be set, in increments of 1½ seconds.

While angle gage blocks have many useful applications, such as refining the settings of tilt tables and serving as angular references in surface plate inspection, the range of possible applications is limited. Angle gage blocks are not as widely used as length-measuring gage blocks.

Angle gage blocks seem to lack the requisites for use as primary standards because: (1) errors are easily compounded when angle blocks are wrung in combination; (2) the absolute verification of angle blocks is usually dependent on some other primary standard.

THE POLYGON

For many years, and until quite recently, the polygon, Fig. 370, which is used in conjunction with an autocollimator, was considered the most accurate device for the calibration of circle-dividing equipment, including the most accurate rotary tables.

Polygons are usually no more than 6 inches [152 mm] in diameter—small enough to be given full support when centered on the smallest rotary table (polygons with smaller and larger diameters are sometimes made as "specials"). Most polygons are not over 1 or 2 inches high [25–50 mm]. Because of this low profile, the magnification of angular errors caused by "wobble" is excluded as much as possible from the inspection of pure angle.

The earliest model polygon, developed by Taylerson of the NPL* consisted of a hardened steel block. A series of optically flat reflective faces was lapped directly on the block. Later commercial models were of glass. The faces were coated to improve their reflectivity. Recently, the trend has been toward the use of separate, optically flat mirrors, which are individually mounted on the periphery of the polygon. These are mounted carefully to attain as exact angular spacing as possible. They must be perpendicular to the mounting surface, and mounted in a manner that does not create distortion.

The number of flats or mirrors in a polygon depends on the particular division of a circle that is sought. To insure certainty of calibration, the primary consideration in accuracy is not how closely the mirror agrees with the nominal angle, but how flat and square it is.

*J. C. Evans & C. O. Taylerson, "Measurement of Angle in Engineering," NPL Notes on Applied Science, p. 6.

FIG. 371—*Polygons were developed for calibrating circle-dividing equipment, notably rotary tables. Rotary tables are now calibrated most authoritively by use of the 1440 Precision Index.*

It is generally agreed that seventy-two mirrors (5°) is the maximum number that can be employed on the largest practical polygon (about 12 inches [304.8 mm] in diameter) while still maintaining adequate reflectivity and flatness. Usually the number of divisions is quite small—six (60°), nine (40°), or twelve (30°) for maximum reflective area and accuracy.

Calibration of the Polygon

Accuracy of the polygon can be proved by first principles (see "Theory of Calibrating a Divided Circle," page 207). To calibrate the polygon, it is mounted on a turntable and the angle segment being checked is contained between two rigidly fixed autocollimators nulled on the nominal angle. The polygon can also be calibrated directly by using a Moore 1440 Small Angle Divider, as demonstrated on page 249.

Criteria Effecting Polygon Accuracy

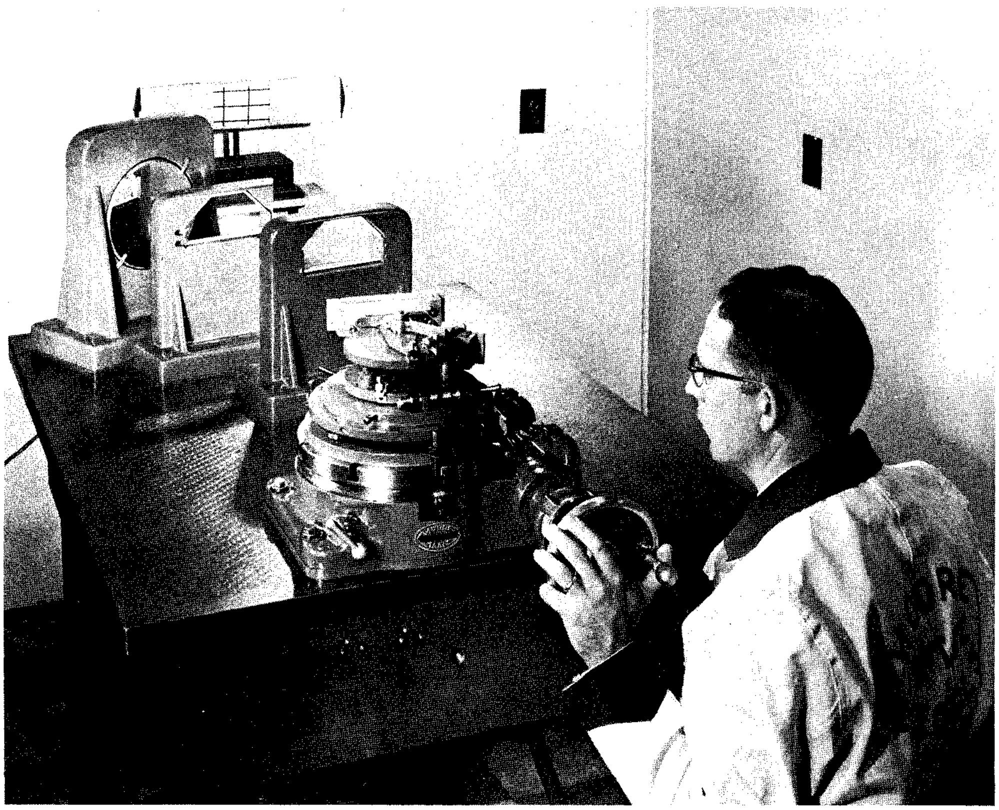
When selecting a polygon, there are four major criteria:

1. The reflecting surfaces (flats or mirrors) should be within 4 or 5 seconds of the correct or nominal angle.
2. The reflecting surfaces should be flat to 0.000005 in. [0.000127 mm].
3. If individual mirrors are used, they should be mounted in such a way that there is no distortion.
4. The mirror position should be permanent. There should be no possibility of alterations of mirror position from bumping or jarring, from poor mounting, or from secular change (instability of the body of the polygon).

Polygons Applied to the Calibration of Rotary Tables

To calibrate a rotary table, the polygon is mounted concentrically on the table, Fig. 371. Theoretically, imperfect centering has

FIG. 372—*Moore Rotary Tables were first calibrated interferometrically. This method of calibration was superseded by the 1440 Precision Index.*
From "Holes, Contours and Surfaces."



a negligible effect on the accuracy of calibration. In practice, it is found that the small amount of time required for perfect centering is well spent. It makes it possible to avoid any errors caused by variables of polygon form.

The fixed autocollimator is nulled on the center of the first face of the polygon. Next the rotary table is rotated through the prescribed angles, corresponding to the increments (number of faces) of the polygon. Angular deviation shown by the autocollimator is recorded at each angle sector. The calibration is valid only if a zero reading is obtained when returning to the original setting face.

A correction factor (error of each polygon face from nominal) furnished by the manufacturer is applied to the readings to find the actual error of the rotary table at the sectors calibrated.

Limitations of Polygon for Calibrating Rotary Tables

1. *Calibration or correction factor*—Ordinarily, it is specified that the center of the mirror be used in calibration in order to obtain agreement with the polygon manufacturer's correction factors. However, there is no means of reference to assure the user that this centering is exact.

It is not uncommon for the calibration factor to change considerably if the target area used for calibrating the rotary table differs slightly from that used when the polygon was originally calibrated. Because of the number of mirrors in use, each with its own geometrical characteristics and reflectivity, any irregularity may alter the supposed calibration value of the polygon. Examples of irregularities are "wobble" of the rotary table, imperfect leveling, or reading the autocollimator by eye rather than by photoelectric readout.

2. *Limited number of angles*—It is impossible to make a full comprehensive calibration of the rotary table with one polygon because the angular sectors are limited to

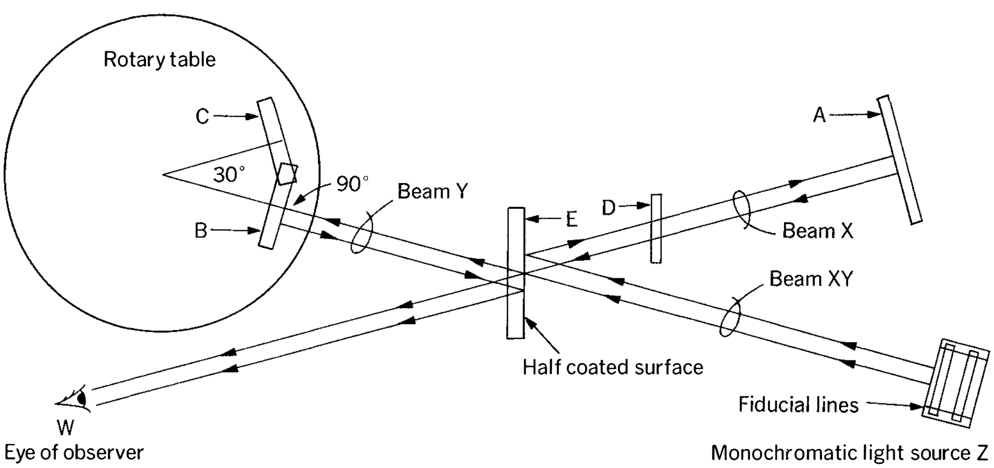


FIG. 373—*Diagram of the optical arrangement for interferometric calibration of rotary tables.*
From "Holes, Contours and Surfaces."

a maximum of about 72 in number. Even a 72-sided polygon would not detect periodic error of a mechanical rotary table. Also, not all of the lines of the circular scale of an optical rotary table are inspected for error. The secondary graticule or optical vernier used for finer minute and second increments are not inspected.

The 13-sided polygon is often used because it gives a random check more likely to show cumulative errors of the total rotary table system, whether optical or mechanical. Its disadvantage is that it does not by itself differentiate between, for example, worm-and-gear error. More than one polygon is usually employed, such as one 12-sided and one 13-sided.

3. *Undesirability of working with calibration values, which may amount to as much as several seconds.*

4. *Overall certainty of rotary table calibration based on the polygon as an angle standard is not much better than one or two seconds, after applying the correction factor.* Such accuracy is not always significantly greater than that of the rotary table it is intended to calibrate.

INTERFEROMETRIC CALIBRATION OF THE ROTARY TABLE

A system employed successfully for many years at Moore for the calibration of rotary tables made use of monochromatic light waves as a means of comparison. The method was worked out by Frederick C. Victory, then chief engineer, in consultation with T. J. O'Donnell of the University of Chicago. It was an adaptation of the Michelson interferometer. This was the first industrial use of light waves for the inspection of angles. A photograph of the optical arrangement is shown in Fig. 372. A schematic diagram appears in Fig. 373.*

*Richard F. Moore and Frederick C. Victory, *Holes, Contours and Surfaces*, p. 52.

A classic circle-dividing technique was employed. A pair of adjustable mirrors, acting as "dividers," was mounted on the rotary table to be inspected. The interferometer was used as an extremely sensitive comparator. It was arranged so that, as the eye scanned between two reference lines, the value of each fringe observed equaled 1 second of arc.*

Interferometric calibration of rotary tables represented an advanced state of the art for some time. Its greatest advantage over the polygon was in its ability to inspect many different angles with one instrument, since the mirrors could be set to any angle. Secondly, as a comparator, the interferometer provided a degree of sensitivity which was not at that time attainable by the autocollimator or by any other means. There were, however, disadvantages in its use:

1. It was not a direct inspection of the angle. The circle first had to be "closed" before the value of the segment set by the mirrors was determined. Since it was impractical to close the circle with increments as small as 2°, "tie-down" points were first established at larger angle sectors, such as 90° and 18°, from which further subdivisions were made. Small errors could therefore accumulate.
2. It was difficult to resolve worm error since it was not inspected *directly.*

SERRATED-TOOTH CIRCLE-DIVIDER

Credit is due the A. A. Gage Co. for perfecting an old principle for application as a precise circle-divider. The principle is as follows: two "face-gears" are generated, each identical in diameter and in number and shape of teeth. When the two opposed faces of the gears are brought into forced engagement (root-to-crest), they become

*Ibid., p. 50.

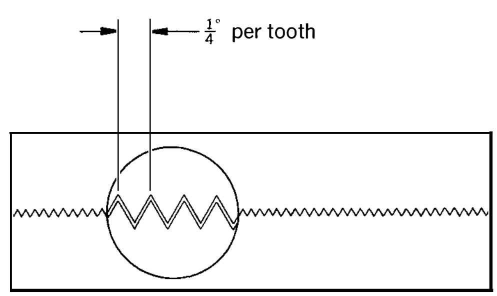


FIG. 374—*The serrated-tooth divider employs two face gears of identical shape and spacing of teeth. One member is displaced axially to disengage the teeth, then rotated radially to the desired nominal angle. The "rotating" member need only be approximately located over its mate (by reference to scale and vernier on its periphery) when re-engaged because of the "homing" characteristics of the multiple teeth.*

FIG. 375—*The 1440 Precision Index allows 1440 angles (every 1/4°) within a circle to be set to ±0.1 second of arc accuracy.*

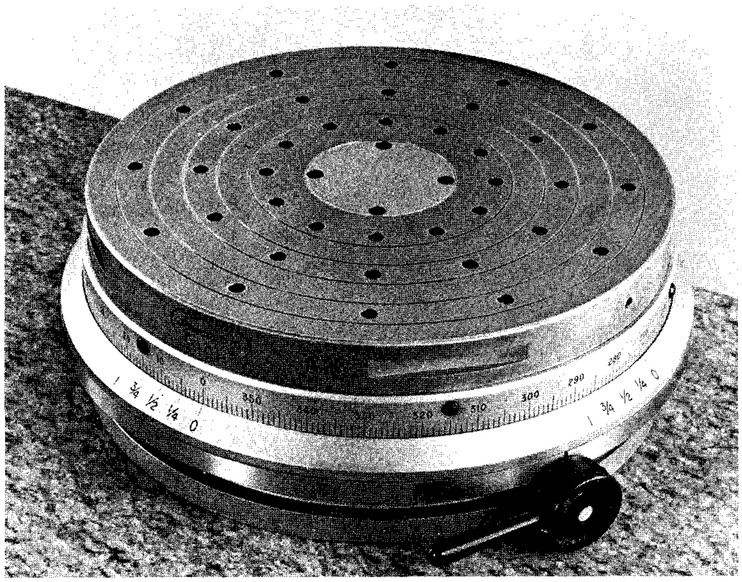


FIG. 376—*To attain the ±0.1 second accuracy of the 1440 Index, the teeth of each member must be ground as accurately as possible, prior to lapping. At this stage, a measuring machine base is used for controlled geometric movement. Angular spacing is established by the master indexer on which the face gear is mounted while grinding the serrations.*

locked in place, preventing rotation or side movement. When the teeth are disengaged, rotated and brought into contact once again, the angular displacement corresponds to the number of teeth through which it has been indexed, Fig. 374.

High precision comes about in two ways:

1. The averaging effect of all the teeth in meshed contact generates an indexing accuracy far surpassing that existing in the angular spacing of individual teeth.
2. When the teeth are lapped in random contact, even greater accuracy through averaging takes place, since the tendency is for all the teeth to conform in size, shape and pitch (the "fat" teeth are lapped heavily; "thin" teeth are lapped lightly).

Moore 1440 Precision Index, Fig. 375

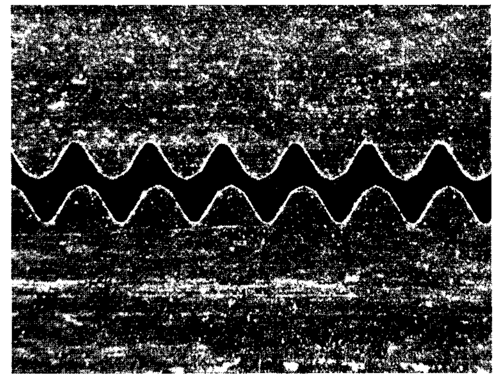
The "serrated tooth circle-divider," used in conjunction with an autocollimator, appeared to have tremendous potential when applied to the calibration of rotary tables. However, the existing serrated tooth circle dividers were limited to 360 teeth. This number of teeth was deemed inadequate for a comprehensive rotary table calibration.

It was decided to develop a serrated tooth indexer* in 1/4° increments having 1440 teeth, (4 x 360). Since Moore Rotary Tables have 180 teeth, this would allow an eight point check of the worm. An 8-inch [203 mm] diameter was selected as the best compromise for the size of the 1440 indexer. When of this diameter, it was small enough to fit on any rotary table, yet large enough to support small parts and gages.

Technically, it was feasible to put 1440 notches around a 24-inch [610 mm] circumference. Practically speaking, however, engineering difficulties were encountered in

*A. A. Gage Co., Detroit, Michigan, are holders of the serrated tooth patent.

FIG. 377—*Teeth (magnified) are disengaged showing their shape. Tooth-to-tooth spacing is approximately .017 in. [0.432 mm]. Radii at root and crest must be held to less than .0015 in. [0.038 mm].*



accomplishing this with anything approaching perfection because of the small tooth size. Tooth-to-tooth spacing with this design was only 0.017 in. [0.432 mm], allowing only a few thousandths of an inch [hundredths of a mm] contact on each tooth flank.

Tooth geometry and tooth spacing would have to be exactly maintained over all 1440 teeth for the device to perform to expectation. For example, radii on the root and crest of the teeth could not exceed 0.001 in. [0.0254 mm] to achieve flank contact of the teeth and avoid "bottoming."

The goal was an accuracy fine enough that no calibration factor need be applied when calibrating rotary tables, and one that would also satisfy the "gage-maker's 10 to 1 rule"—namely ±0.1 second accuracy.

Within 6 months of research, a 1440 Index was built to ±0.3 second accuracy. It was evident from the experience gained that the principles employed to produce the 1440 Index were correct, but that the sought-after ±0.1 second accuracy would only be achieved by even more closely refining each element of the manufacturing process from start to finish.

A special grinding machine was constructed, using a measuring machine base, Fig. 376. A special-purpose grinding wheel headstock and dresser were incorporated into the modified column. To attain the utmost uniformity and accuracy, all cycles, including rotary indexing, were made completely automatic and free of operator variables (it had been found that the generation of 1440 teeth by manual operation was beyond the endurance of the machine operator).

The grinding wheel itself was an object of prolonged study. It is of a specific grade that will maintain free-cutting qualities, yet keep its size and shape without redressing over the final one thousand, four hundred and forty passes.

Very close tolerances of roundness, cylindricity and concentricity of all surfaces must be maintained. A Spin Table (see "Roundness," page 259), was under development at the same time, and had just been perfected. Its use, together with the jig grinder, enabled the roundness and flatness of certain surfaces of the 1440 Index to be refined to an accuracy previously unattainable. This is a further example of how the progress of one mechanical art depends on the refinement of another.

Stability, Heat Treatment

It is sometimes presumed that a serrated tooth circle-divider, once completed, will continue to improve in use because of the continuing averaging effect of wear. There is no denying that the nature of its operation tends to improve accuracy. However, the amount of controlled wear given it during lapping so far exceeds that which would occur during normal use that the validity of this claim is doubted.

The 1440 Index is made to engage and disengage automatically for hours at a time. At first, a lapping compound with relatively coarse grit is used. As the teeth match closer and closer, lapping compound with progressively finer grit is employed. At certain strategic stages, the lapping operation is interrupted and the OD's of the teeth and secondary reliefs are reground. Finally, all lapping compound is flushed out and only kerosene is used. At the very last, the mating sections are made to engage and disengage for hours while completely dry and clean to achieve perfect engagement, Figs. 377 and 378.

Exactly how long the 1440 Index can maintain its accuracy is unknown at present. Many more years of experience will be required. It is doubtful that wear of the teeth will either significantly improve or reduce accuracy. More than likely, any change will be caused by metallurgical instability, not by wear.

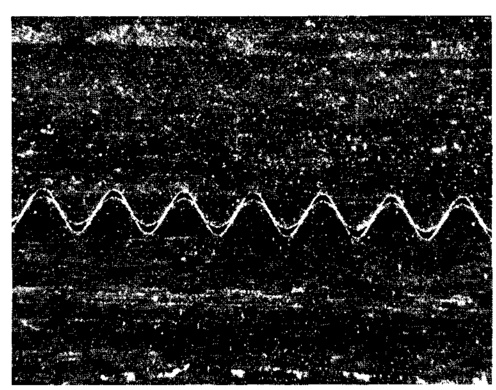


FIG. 378—*In the engaged position, all the teeth of each member of the 1440 Index mesh perfectly. Accuracy cannot otherwise be attained.*

FIG. 379—*Two 1440 Indexes must be employed to calibrate the 1440 Index. The classical circle-closing technique used is identical to that employed by the world's leading standards bureaus.*

In view of this, all possible precautions are taken in the heat-treatment of the parts to insure long-range stability. The method of normalizing the mating sections of the 1440 Index does not differ appreciably from the stabilizing process Johansson used to put his gage blocks "to sleep" nearly a century ago.

Harden;
Draw to 375°;
Freeze to −60°F.;
Heat to 340°F.;
Let cool to room temperature.

This heat-and-freeze cycle is repeated three times, the last being the heat cycle.

Calibration of the 1440 Index

The 1440 Precision Index is guaranteed to be accurate to within ±0.1 second of arc at all 1440 indexed positions. One might at first assume that to assure 1/10th-

	0/0		30/0		60/0		90/0		120/0		150/0		180/0		210/0		240/0		270/0		300/0		330/0	
30	0	0	−1	−1	−5	−5	−8	−8	+8	+8	+5	+5	−1	−1	+8	+8	−1	−1	+2	+2	0	0	+9	+9
60	+3	+3	−9	−8	−9	−4	−8	0	+10	+2	+2	−3	+4	+5	+9	+1	0	+1	+9	+7	+8	+8	+8	−1
90	+3	0	−11	−2	−7	+2	−3	+5	+11	+1	+8	+6	+9	+5	+22	+13	+3	+3	+22	+13	+19	+11	+19	+11
120	−2	−5	−11	0	−2	+5	−8	−5	+12	+1	+1	−7	+10	+1	+18	−4	+12	+9	+27	+5	+18	−1	+12	−7
150	−4	−2	−13	−2	−9	−7	−6	+2	+9	−3	−2	−3	+9	−1	+21	+3	+12	0	+25	−2	+7	−11	+4	−8
180	−5	−1	−15	−2	−8	+1	−8	−2	+16	+7	+1	+3	+18	+9	+28	+7	+19	+7	+21	−4	0	−7	+7	+3
210	−7	−2	−9	+6	−9	−1	−3	+5	+18	+2	+11	+10	+20	+2	+25	−3	+11	−8	+13	−8	+6	+6	+10	+3
240	−8	−1	−11	−2	−11	−2	−2	+1	+19	+1	+9	−2	+19	−1	+13	−12	0	−11	+9	−4	+5	−1	+5	−5
270	−13	−5	−9	+2	−10	+1	−1	+1	+16	−3	+11	+2	+11	−8	−1	−14	−8	−8	+5	−4	−3	−8	0	−5
300	−13	0	−15	−6	−4	+6	−2	−1	+12	−4	+1	−10	0	−11	0	+1	−8	0	0	−5	−3	0	−7	−7
330	−9	+4	−10	+5	−2	+2	0	+2	+7	−5	−5	−6	0	0	+1	+1	−8	0	+2	+2	−5	−2	−8	−1
Repeat 0	0	+9	0	+10	0	+2	0	0	0	−7	0	+5	0	0	0	−1	0	+8	0	−2	0	+5	0	+8

FIG. 380—*A typical matrix of readings obtained when one 1440 Index is compared to another. 144 separate readings are taken to allow calibration of 12 indexed positions.*

second accuracy and still conform to the gage maker's "10-to-1 rule" the 1440 Index would have to be inspected with some other master accurate to 1/100th second. This is impossible, of course, since no such master exists. Nonetheless three factors enable such a guarantee to be stated legitimately:

1. The 1440 Index will *repeat* to at least 1/50th of a second.
2. Present technique allows the employment of monochromatic autocollimators, which are sensitive enough to detect differences as small as 1/100th second and repeatable to about the same order of accuracy.
3. The 1440 Index can be calibrated by self-proving (circle-closing) methods.

The method of self-calibration employs two 1440 Indexes, Fig. 379. One is mounted concentrically on the table of the other. On the uppermost 1440 Index is placed a single mirror of optical quality, which is shielded from temperature variations within a protective housing. The mirror is used in conjunction with a monochromatic, photoelectric autocollimator. The autocollimator and mirror housing are close-coupled, with a minimum air gap to avoid variations which may arise from air currents passing between them.

By rotating one of the 1440 Indexes clockwise and the other counterclockwise, each through the same nominal sector of arc, the mirror is returned essentially normal to the autocollimator. The slight angular change in the attitude of the single mirror, as recorded by the autocollimator, represents the *difference* between the particular angular segments of each 1440 Index which have been selected for comparison.

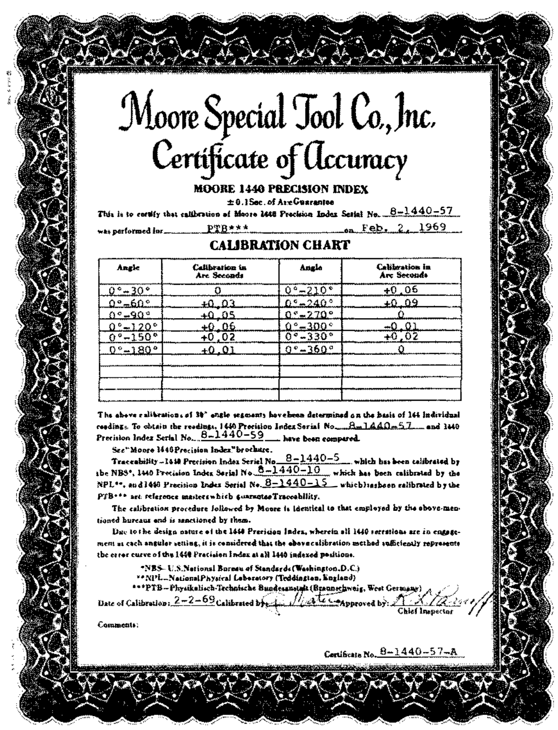
From a matrix of readings obtained in this manner, Fig. 380, (the circle also having been "closed"), both 1440 Indexes are self-calibrated. The reader is referred to Fig. 333 for the theory of self-proving the division of the circle. A typical calibration certificate is shown in Fig. 381. The calibration theory and method just described are identical to that employed by the NPL, the NBS and the PTB in their own calibration of the 1440 Index, and are sanctioned by them. The results of two such calibrations are shown in a report by the NPL, Fig. 382, and by the NBS, Fig. 383.

Rotary Table Calibration with the 1440 Index

Fig. 384 shows a 1440 Index mounted on a rotary table for calibration. A single shielded reflecting mirror and autocollimator, much the same as that employed for

	1440 # 53			1440 # 60		
	Sum	Step errors	Accum. errors	Sum	Step errors	Accum. errors
0-30	+.16/12	+.013	+.01	+.30/12	+.025	+.03
30-60	+.11/12	+.009	+.02	+.15/12	+.013	+.04
60-90	+.68/12	+.057	+.08	−.78/12	−.065	−.03
90-120	−.08/12	−.007	+.07	−.91/12	−.076	−.10
120-150	−.34/12	−.028	+.04	+.11/12	+.009	−.09
150-180	+.21/12	+.018	+.06	+.13/12	+.011	−.08
180-210	+.11/12	+.009	+.07	−.38/12	−.032	−.12
210-240	−.39/12	−.032	+.04	+.33/12	+.028	−.09
240-270	−.49/12	−.041	0	−.26/12	−.022	−.11
270-300	−.37/12	−.031	−.04	+.30/12	+.025	−.08
300-330	+.02/12	+.002	−.03	+.18/12	+.015	−.07
330-360	+.37/12	+.031	0	+.83/12	+.069	0

Readings are in hundredths of a second.



Moore Special Tool Co., Inc.
Certificate of Accuracy
MOORE 1440 PRECISION INDEX
±0.1 Sec. of Arc Guarantee

This is to certify that calibration of Moore 1440 Precision Index Serial No. 8-1440-57 was performed for PTB*** on Feb. 2, 1969

CALIBRATION CHART

Angle	Calibration in Arc Seconds	Angle	Calibration in Arc Seconds
0°-30°	0	0°-210°	+0,06
0°-60°	+0,03	0°-240°	+0,09
0°-90°	+0,05	0°-270°	0
0°-120°	+0,06	0°-300°	-0,01
0°-150°	+0,02	0°-330°	+0,02
0°-180°	+0,01	0°-360°	0

The above calibrations of 30° angle segments have been determined on the basis of 144 individual readings. To obtain the readings, 1440 Precision Index Serial No. 8-1440-57 and 1440 Precision Index Serial No. 8-1440-59 have been compared.

See "Moore 1440 Precision Index" brochure.

Traceability—1440 Precision Index Serial No. 8-1440-5 which has been calibrated by the NBS*, 1440 Precision Index Serial No. 8-1440-10 which has been calibrated by the NPL**, and 1440 Precision Index Serial No. 8-1440-15 which has been calibrated by the PTB*** are reference masters which guarantee Traceability.

The calibration procedure followed by Moore is identical to that employed by the above-mentioned bureaus and is sanctioned by them.

Due to the design nature of the 1440 Precision Index, wherein all 1440 serrations are in engagement at each angular setting, it is considered that the above calibration method sufficiently represents the error curve of the 1440 Precision Index at all 1440 indexed positions.

*NBS—U.S. National Bureau of Standards (Washington, D.C.)
**NPL—National Physical Laboratory (Teddington, England)
***PTB—Physikalisch-Technische Bundesanstalt (Braunschweig, West Germany)

Date of Calibration: 2-2-69 Calibrated by: Approved by: Chief Inspector

Comments:

Certificate No. 8-1440-57-A

FIG. 381—*The standard "Certificate of Accuracy" of the 1440 Index, furnished to the user.*

FIG. 382—A report by the National Physical Laboratory on the calibration of two indexing tables.

NATIONAL PHYSICAL LABORATORY

Teddington, Middlesex, England

REPORT

THE CALIBRATION OF TWO PRECISION ANGULAR INDEXING TABLES

Made and Sent by:- Moore Special Tool Co., Inc.
Bridgeport, Conn. 06607. U.S.A.

Description:-
Two precision 8-inch diameter angular indexing tables. The angular indexing of each table is effected by engaging two serrated plates, one being integral with the rotatable (upper) member and the other integral with the base of the table. One table has 2160 serrations, enabling angular increments of 10 minutes of arc to be indexed, whilst the other table has 1440 serrations enabling angular increments of 15 minutes of arc to be indexed. An exterior degree scale and a vernier scale are provided on each table to enable the appropriate indexing position to be located prior to engaging the serrations.

The 2160 serrated table has a hydraulic system for raising and lowering the top rotatable member whilst that of the 1440 serrated table is controlled by means of a cam manually operated by a lever.

To facilitate the calibration of each table the manufacturer submitted them with the 2160 serrated table accurately mounted on top of the 1440 serrated table.

Identification:-
The 2160 serrated table :- 8 - 1440 - 10
The 1440 serrated table :- 8 - 1440 - 3

These two precision angular indexing tables have been calibrated at the National Physical Laboratory in the following manner.

To minimise the effect of temperature variations during the calibration the mounted tables were placed inside a fabricated enclosure, and the necessary controls for indexing the two tables were arranged to be operated from outside this enclosure.

A quartz reflector, with a reflecting face flat to within 0.000 001 in over its 1½ in diameter, was mounted on the working surface of the top table. This reflector was observed with a Hilger TA 5 Monochromatic Autocollimator.

Each table was then calibrated at intervals of 22½ degrees with respect to its zero position by comparing every 22½ degrees interval of the top (2160) table with each 22½ degrees interval of the bottom table. The results of these 256 comparisons were formed into a matrix and the angular indexing errors of each table at intervals of 22½ degrees were calculated: these errors, expressed to the nearest 0.05 second of arc are given in the following Table.

NATIONAL PHYSICAL LABORATORY

CONTINUATION
OF REPORT
CALIBRATION OF TWO PRECISION ANGULAR INDEXING TABLES

TABLE

Table Setting	Indexing error 2160 serrated table	Indexing error 1440 serrated table
degrees	second of arc	second of arc
0	0	0
22½	0	0
45	+0.05	0
67½	+0.10	-0.10
90	+0.05	-0.10
112½	0	-0.05
135	-0.05	0
157½	-0.05	+0.10
180	-0.05	+0.10
202½	-0.05	+0.05
225	-0.05	+0.05
247½	0	+0.05
270	-0.05	+0.05
292½	0	0
315	0	0
337½	0	-0.05

It is estimated that the accuracy of determination of the errors quoted above is 0.2 second of arc.

DATE 29th October, 1965

REFERENCE M 542/2
ST 4030

for Director

U.S. DEPARTMENT OF COMMERCE L7101-B
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

NATIONAL BUREAU OF STANDARDS

REPORT OF CALIBRATION

for

One Angular Indexing Head
Moore Serial Number
8-1440-5

submitted by

The Moore Special Tool Co., Inc.
800 Union Avenue
Bridgeport, Conn. 06607

The deviations from nominal indexing angles for the table are listed in the following table. The zero index mark from which the angles are indexed is the one on the opposite side of the table from the hydraulic lift hose connection.

Index Angle	Deviation from Nominal Angle
degrees	seconds
0-11 1/4	-.03
0-22 1/2	-.04
0-30	.00
0-33 3/4	-.03
0-45	-.03
0-56 1/4	-.05
0-60	-.05
0-67 1/2	-.05
0-78 3/4	-.05
0-90	.00
0-101 1/4	+.02
0-112 1/2	+.06
0-120	+.02
0-123 3/4	+.07
0-135	+.10
0-146 1/4	+.08
0-150	+.05
0-157 1/2	+.08

One Angular Indexing Head - 2 -
Serial No. 8-1440-5

Index Angle	Deviation from Nominal Angle
degrees	seconds
0-168 3/4	+.09
0-180	+.07
0-191 1/4	+.04
0-202 1/2	00
0-210	-.03
0-213 3/4	-.02
0-225	00
0-236 1/4	+.01
0-240	00
0-247 1/2	+.05
0-258 3/4	+.07
0-270	+.09
0-281 1/4	+.08
0-292 1/2	+.09
0-300	+.04
0-303 3/4	+.10
0-315	+.11
0-326 1/4	+.07
0-330	+.01
0-337 1/2	+.05
0-348 3/4	+.01

A positive (+) sign indicates that the indexed angle is larger than nominal.

It is estimated that the listed values are accurate to 0.3 seconds.

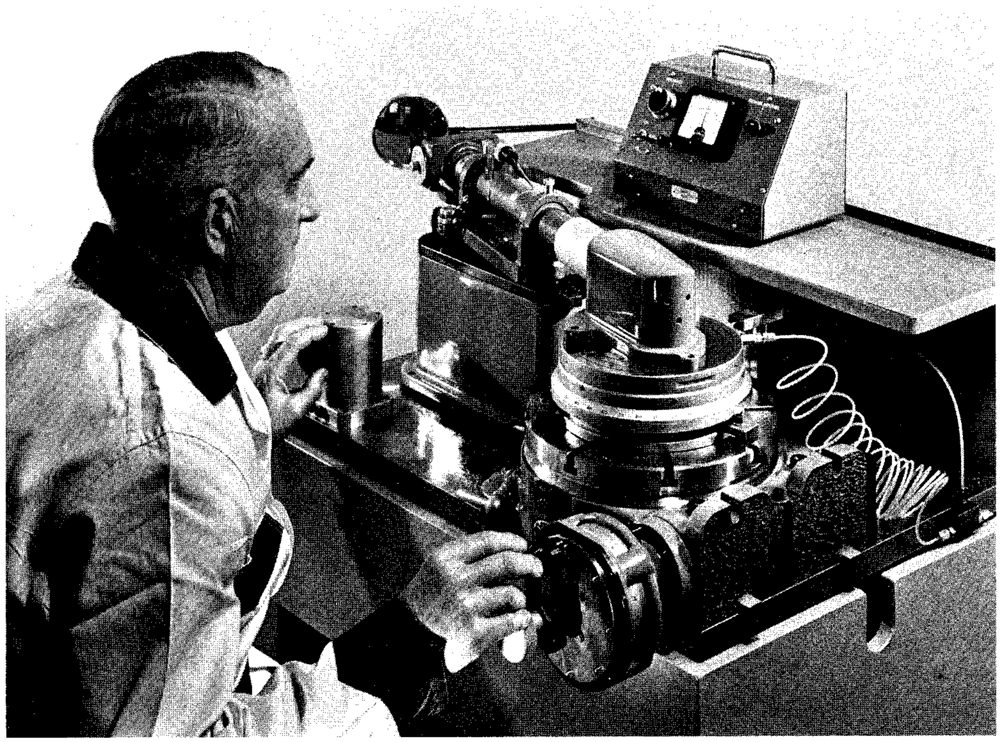
For the Director,

A. G. Strang, Acting Chief
Engineering Metrology Section
Metrology Division

Order No. C19992
Test No. 212.22/181886
October 26, 1964

FIG. 383—A calibration report of 1440 Index No. 5 by the National Bureau of Standards.

FIG. 384—*The 1440 Index can be considered a 1440-faceted polygon for use in inspecting rotary tables. Advantages over the polygon for rotary table calibration are: (1) the use of a single mirror (2) greater number of indexed positions (3) far greater accuracy.*



self-calibration of the 1440 Index, are used. The arrangement is typical of that already supplied by Moore to rotary table manufacturers and to the leading national bureaus for inspection of rotary tables.

In this arrangement, the standard cam-operated disengagement of the 1440 Index teeth has been replaced by a hydraulic lift. The hydraulic lift performs two functions—disengagement and reengagement of the two halves of the 1440 Index during operation, and simultaneous feeding of a plunger into a V-type indent in the upper member of the 1440 Index carrying the single mirror.

Once its upper member is restrained, the lower member of the 1440 Index, being clamped to the rotary table, rotates integrally with the table as it is cranked to position. When the hydraulic lever is retracted, the upper member of the 1440 Index carrying the mirror floats down into mesh once again with its mate. The restraining plunger is also automatically retracted lest it influence the teeth as they engage. The position of the upper member relative to its base must only be approximate prior to being re-engaged because of the "homing" characteristic of the multiple teeth.

Errors of the rotary table are read *directly* on the autocollimator, requiring no "closing of the circle," nor use of calibration factors. Errors of the 1440 Index in this application may be considered negligible.

Fig. 385 provides an overall view of a unique rotary table calibration facility,* recently perfected. The principle of its operation, seen in Fig. 384, is based on the 1440 Index, except that all operations have been refined and automated, and the errors automatically charted. A close-up view of the mechanics of the system is shown in

*Albert E. Johnson, "Incremental Calibration of Rotary Tables goes Automatic," *Quality Assurance*, July, 1969.

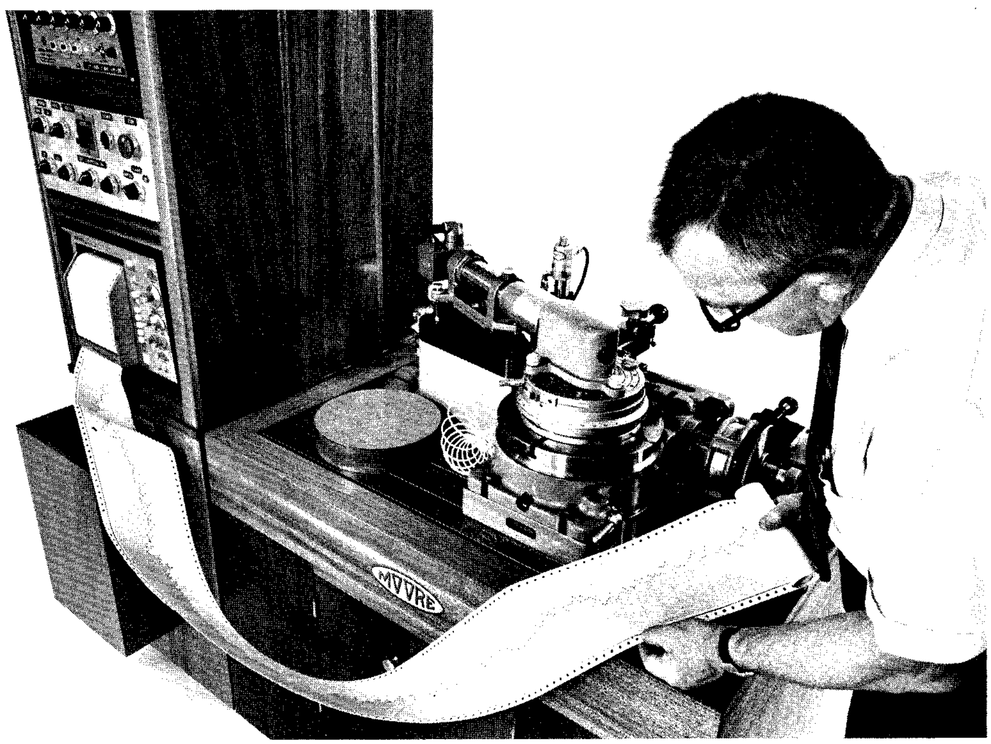
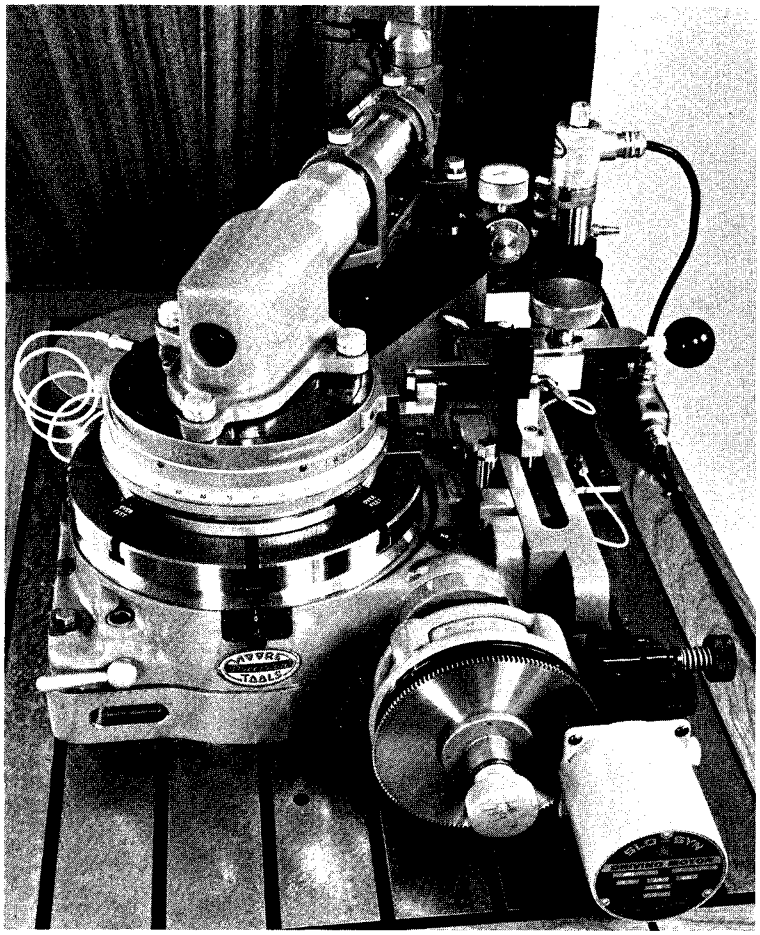
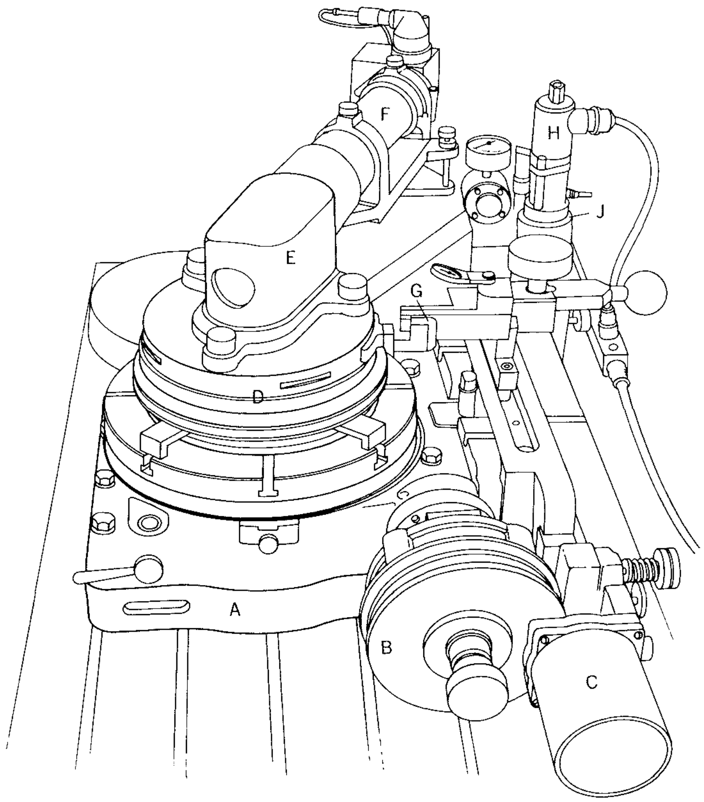


FIG. 385—*The rotary table is calibrated and the error charted over one thousand, four hundred and forty positions in this automatic set-up. Time: 80 minutes. Note that worm-and-gear errors are clearly shown.*

FIG. 386—*Close-up of mechanics of the automatic rotary table calibration. The rotary table, to which is mounted a large gear, is driven by a swing-away stepping motor. A small probe retains the upper member of the 1440 Index after being disengaged hydraulically; the lower half is fixed to rotate with the rotary table. The restraining probe is retracted prior to the upper half of the 1440 Index descending into re-engagement.*

FIG. 387—*The essential elements comprising the automatic rotary table calibrator.*





This is what the apparatus looks like in close up. **Mounting platform** "A" accommodates the rotary table. **Large gear** "B" is mounted on a precise hub which concentrically locates it on the worm shaft. **Swing-away stepping motor and pinion** "C" can be adjusted to mesh properly. The **1440 index** "D" is clamped to the top of the rotary table. **Mirror housing** "E" is totally enclosed except for a slight gap to allow rotation between itself and the **automatic position sensing autocollimator** "F". If the gap exceeds ⅛ in., ordinary air currents would cause the collimator output to wander. Small **hydraulically actuated probe** "G" keys the upper half of the 1440 to an approximate null while it is axially separated from the lower portion. The probe is retracted when the 1440 is lowered into engagement, allowing its teeth to mesh without outside influence. **Electric solenoid valve** "H" supplies power to a **hydraulic piston** "J" mounted below. This enables the operation of the 1440 remotely from the programmed microswitch.

Fig. 386 and a diagrammatic explanation is found in Fig. 387. Manual operation of the rotary table by index pins has been replaced by a programmed stepping motor, adapted by means of a non-influencing coupling only for the duration of the calibration. The responses of the photoelectric autocollimator are converted into an electric signal which is amplified and recorded on a linear graph.

Calibration may be programmed for increments of 2° (180 positions), 1° (360 positions), ½° (720 positions), or ¼° (1440 positions). Fig. 388 shows a calibration chart being made of an Ultra-Precise Rotary Table in ¼° increments, over 1440 individual positions. Worm-and-gear error are clearly defined. Time elapsed for this total calibration was only 80 minutes. It is not conceivable that a calibration this accurate and this comprehensive could be achieved by any other means.

The automatic inspection of rotary tables has relieved the lapping specialist of a great burden. Previously, many hours were required for inspection following each lapping operation. There was much less certainty of total rotary table condition at each stage in the refinement.

Advantage of the 1440 Index for Rotary Table Calibration

The 1440 Index is undoubtedly the preferred method for the calibration of rotary tables. The most important advantages, compared to other methods of calibration, can be summarized as follows:

Compared to the Polygon:

1. *Cost savings.** One self-contained unit is the equivalent of the following 35 polygons:

1440	240	96	48	30	15	6
720	180	90	45	24	12	5
480	160	80	40	20	10	4
360	144	72	36	18	9	3
288	120	60	32	16	8	2

2. *Far greater accuracy.* At best, the polygon can be relied on to 1 or 2 seconds, compared to the ±0.1 second accuracy of the 1440 Index.
3. *The absence of a calibration factor with which to contend.* Miscalculations, notably from transposing signs, are avoided.
4. *Smaller angular increments can be calibrated.* Also, *combined* errors are shown (most "plus" to most "minus"). The ability to discriminate angular errors of ¼° arc allows the determination of the *source of error* in the rotary table. For example, when calibrating an optical rotary table, the errors attributable to the main circular scale are separated from those of the graticule or optical vernier. When calibrating a mechanical rotary table, worm error is easily differentiated from gear error. A rotary table having a 180-tooth gear (2° per revolution) is inspected at eight points of the worm.
5. *Only one mirror is used.* The importance of the single mirror cannot be overemphasized. A large flat mirror may be perfected for maximum reflectivity. Effort need only be expended to assure that it is absolutely flat without having to consider simultaneously its angular position. The same spot in the mirror is always used, instead of shifting from mirror to mirror. The mirror actually becomes of secondary importance.

*Albert E. Johnson, "The Reference Circle Divider," Paper presented at AOA Standards and Metrology Meeting, Florida, April 1966.

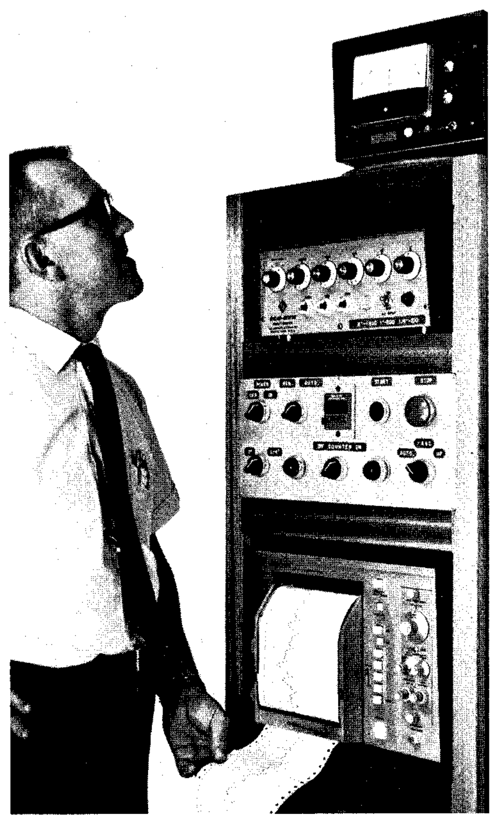
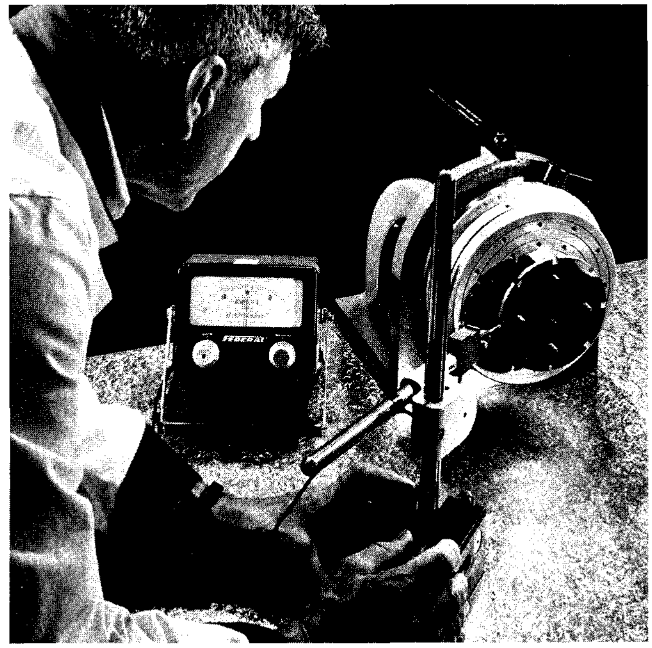


FIG. 388—*The chart flowing from the automatic rotary table calibrator provides an unmistakable, comprehensive picture of rotary table error for purposes of corrective lapping.*

FIG. 389—*The 1440 Index inspects the 30° included angle of an angle gage block, using the lapped, flat surfaces of the gage itself as reflectors.*

FIG. 390—*The 1440 Index is mounted on a special angle iron to make possible surface plate inspection of a master notched index plate.*



Compared to the Interferometer, the 1440 Index has the following advantages:

1. *Errors not accumulated;*
2. *There is greater resolution of periodic errors;*
3. *Simplicity, speed, compactness;*
4. *Any angle can be inspected directly;*
5. *Greater accuracy;*
6. *No need to compute error upon "closing."*

The 1440 Index, although originally designed to calibrate circle-dividing instruments, has also been found suitable for other laboratory type applications. Examples are the calibration of a 30° angle gage block, Fig. 389, and of a master notched indexing plate, Fig. 390. Additional applications are possible when the 1440 Index is fitted with the Small Angle Divider, Fig. 391. These are shown in "Universal Measuring Machine Techniques and Applications," pages 315–316.

6. The 1440 Small Angle Divider

An obvious limitation of the 1440 Index is in not being able to divide the circle into any number of parts other than the factors contained in the number 1440. For example, it cannot divide the circle into thirteen parts.

The integration of an auxiliary small angle dividing facility to the 1440 Index allows any 0.1 second increment to be generated and read directly, or to 12,960,000 parts in a circle. The nature of the design is such that the 0.1 second accuracy of the 1440 Index is not altered at its indexed positions in any way.

The accumulated error of the small angle facility and the 1440 Index working together as an integral assembly does not exceed ± 0.5 second of arc for the full circle.

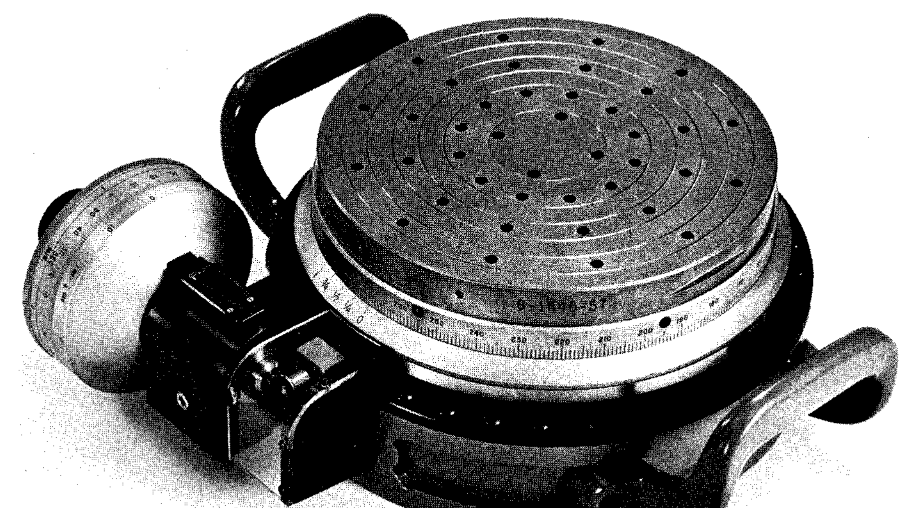
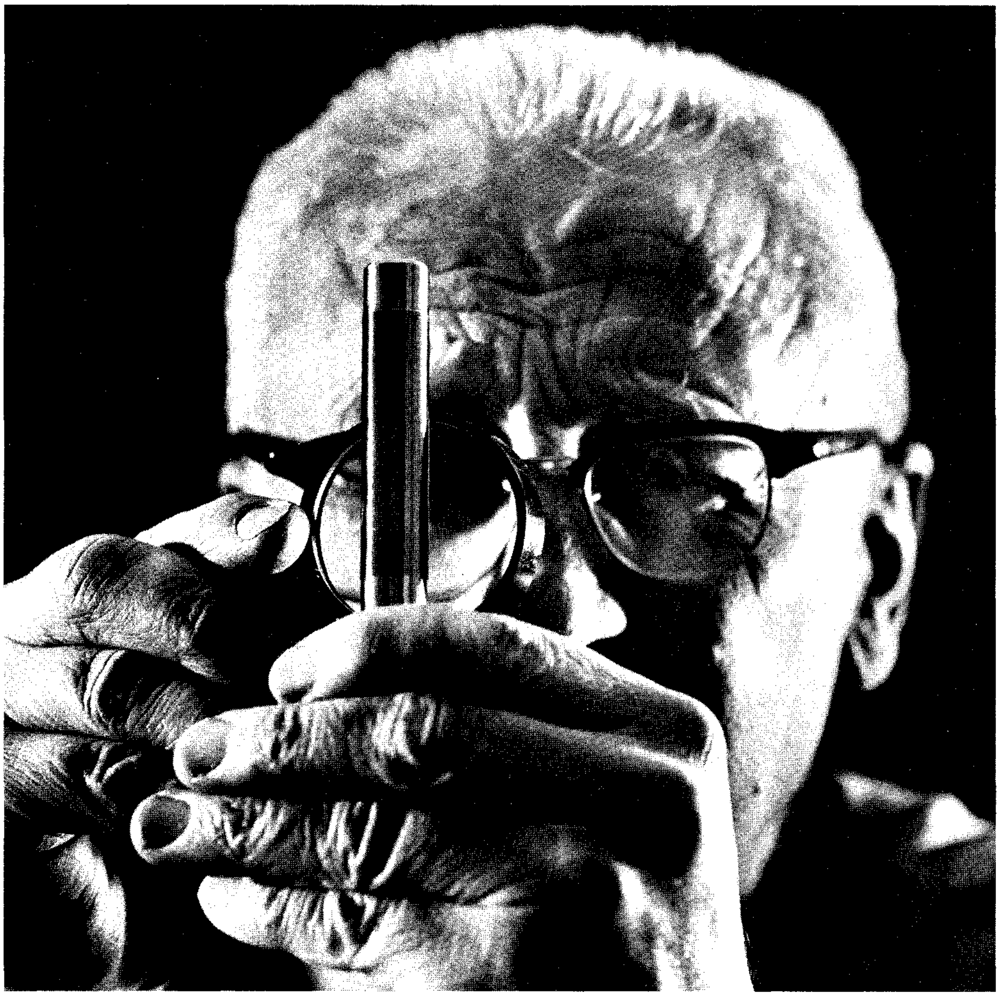


FIG. 391—*The 1440 Small Angle Divider provides all the capabilities of the 1440 Index, but will also set to any angle in 0.1 second of arc increments. It has two intended uses: (1) In the laboratory for the inspection of standards and gages (2) for use with a Universal Measuring Machine where it will perform most of the functions of a rotary table but to much greater accuracies.*

FIG. 392—*The 1/120th inch pitch [approximately 5 threads/mm] micrometer screw of the Small Angle Divider produces extremely high resolution of angle. Thread-size proportions resemble that which would be obtained by winding a human hair around a 5/8 inch [15.875 mm] cylinder.*



DESIGN PRINCIPLES

In the light of the analysis made in the early part of this section, it is interesting to note that all the principles employed in generating the small angle are essentially functions of length measurement; also that the relation of length to angle finally depends on a master ¼° segment which has been established by dividing the circle.

The Small Angle Divider feature is constructed as an integral submember of the 1440 Index, held true radially and axially by precision rollers under preload. It has a common axis of rotation with the 1440 Index.

High magnification of movement (approximately 1400 to 1) is achieved through use of a 1/120th inch pitch [approximately 5 threads per millimeter] micrometer screw, Fig. 392. Adjustable, double micrometer nuts hold backlash to less than 0.2 second. Setting accuracy is enhanced by an accurately graduated, 4-inch [100 mm] dial which stays flush to a sliding vernier.

The lapped-flat terminal face of the micrometer screw thrusts against a small carbide wheel fastened to an arm, which is in turn fixed to the base of the 1440 Index. Contact of the wheel with the anvil of the micrometer screw is maintained by a constant-pressure spring.

The carbide wheel is nominally 5.72 inches [145.3 mm] from the center of rotation. By altering the thickness of a spacer, the distance of the wheel from center is adjusted slightly until ¼° movement—as read by the Small Angle Divider—is exactly equal to any one of the ¼° movements of the 1440 Index (a built-in master ¼° segment). The wheel actually travels only ⅛° on either side of the tangent point of the micrometer on this 5.72-inch [145.3 mm] arc. A diagram of the system is shown in Fig. 393.

The ability of the 1440 Index to be set in increments as small as ¼° is now seen as an immense benefit. When the 1440 Index is used in conjunction with the Small Angle Divider, the difference between the length of an arc of ¼° at 5.72-inch radius [145.3 mm] and a straight line at that radius, is negligible (0.012479104 inch vs. 0.012479094 inch) [0.31696924 mm vs. 0.31696899 mm]. In angular values, the difference is only 0.000359 second (the angular variation caused by the sliding of the wheel against the thrust face of the micrometer anvil, being even more negligible, was left

FIG. 393—The Small Angle Divider assembly is a sub-member, and rotates the 1440 Index through any angle within 15 minutes of arc to an accuracy of 0.1 to 0.2 second. The principle of its operation is illustrated.

out of these calculations). Micrometer readings may be taken directly; no calculations are necessary, Fig. 394.

Setting an Angle with the 1440 Small Angle Divider

One revolution of the micrometer screw of the 1440 Small Angle Divider equals 5 minutes of arc, three turns being equivalent to exactly 15 minutes (¼°) of arc. Each full turn, or 5 minutes, is recorded by a small pointer against a white dot on the barrel of the micrometer. Minutes and seconds are read on the dial and tenths of a second on the vernier.

As an example of setting to a particular angle, suppose that a 13-sided polygon is to be calibrated using the 1440 Small Angle Divider, the first angle of 13 is:

$$1/13 \times 360° = 27°\ 41'\ 32.3''$$

In this case, the 1440 Index is disengaged and rotated from 0° to 27° 30′ as read on its side reference graduations and dropped into position. The Small Angle Divider is rotated from 0° to 11′ 32.3″.

Contrast this design and setting convenience with a similar device having only 360 indexed positions and in which gage blocks are used to generate the smaller angles within 1°. The difference in length between an arc of 1° and a straight line at that radius is no longer negligible. Therefore, the required combination of gage blocks would have to be calculated with trigonometric tables. To set to increments of 0.1 second to an accuracy of 0.2 or 0.3 second would require the availability of gage blocks with increments as fine as 1 millionth of an inch [0.000025 mm], and the correct sizes to enable 36,000 different combinations to be selected.

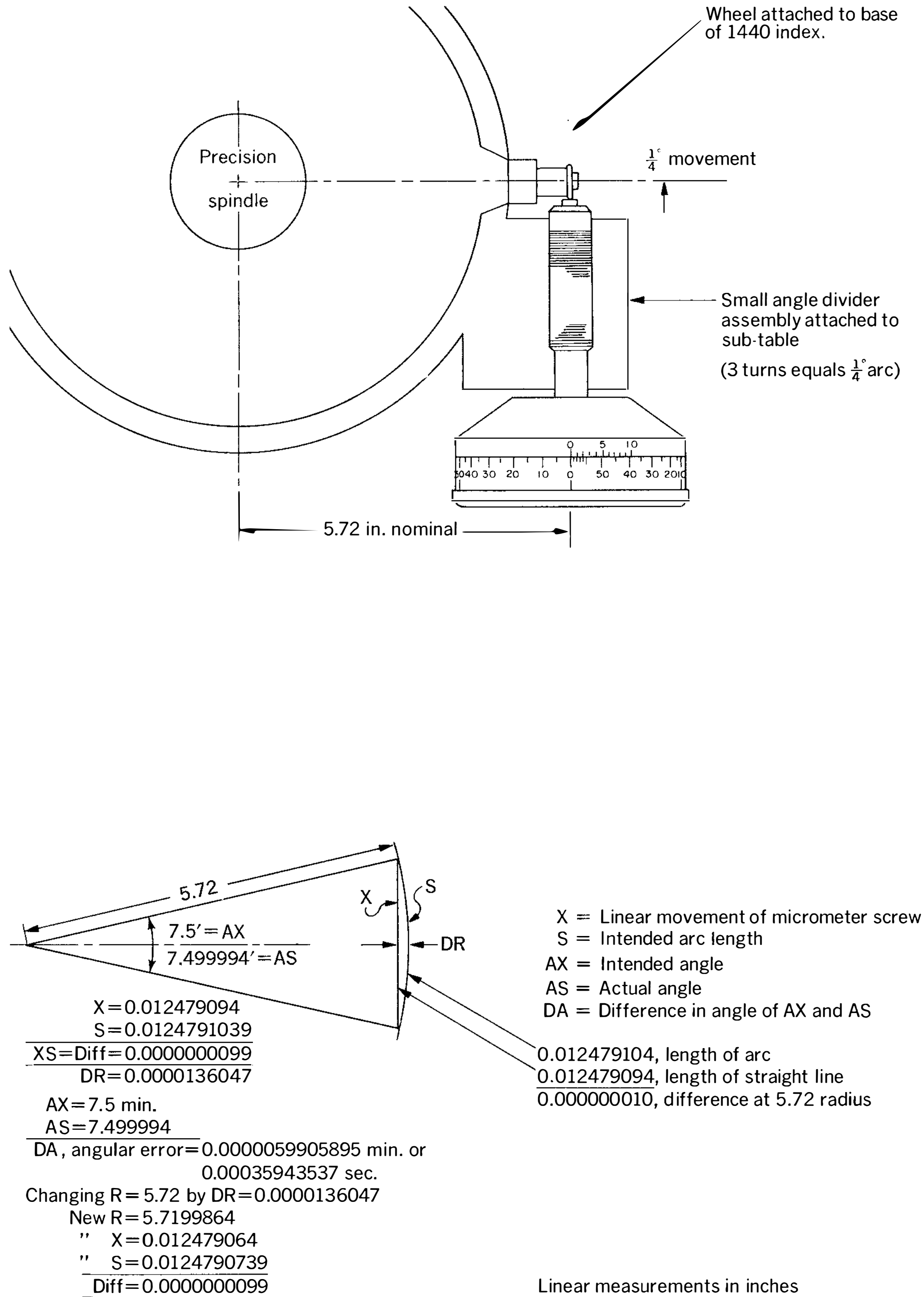


FIG. 394—The Small Angle Divider is fixed tangent to the 1440 Index at a nominal radius of 5.72 in. [145.3 mm]. At this radius, the difference in length of an arc of ¼° and a straight line is 1/100 of a millionth of an inch [1/4000 μm], or 0.00036 seconds of

METHOD OF CALIBRATION OF THE 1440 SMALL ANGLE DIVIDER

Calibration of Overall 15 minutes

Overall travel of the micrometer screw is easily self-calibrated against any one of the ¼° increments of the 1440 Index, using an autocollimator and a mirror mounted on the table. First the autocollimator is nulled. The Small Angle Divider is made to generate an angle of exactly 15 minutes. The 1440 Index sets to ¼° of an arc in the opposite direction, returning the mirror nominally to the original setting. Error of the Small Angle Divider is read directly with the autocollimator.

Millionth Micrometer

To calibrate the Small Angle Divider *within the 15 minutes* was a much more difficult task, since there was no device available to match its accuracy.

Inspections were made by comparing the Small Angle Divider to the lead of a Universal Measuring Machine. One 1440 Small Angle Divider was actually transported to the NPL in England for calibration against an autocollimator of known error.

Considering the accuracy of these methods, they only seemed to verify that the Small Angle Divider, in conjunction with the 1440 Index, could work safely within an overall accuracy of ± 0.5 second; *but they did not actually calibrate* the Small Angle Divider.

A special, horizontally-operating "Millionth Micrometer" capable of calibrating the Small Angle Divider, Fig. 395, was finally designed and constructed. This device consists of a 1-inch [25.4 mm] OD, 100 threads-per-inch [approximately 4 threads per millimeter] lead screw having double-adjustable nuts and a frictionless indicator carriage. All parts were hardened, ground, lapped and stabilized. The 7½-inch [190.5 mm] micrometer dial and vernier enable direct readings to 1 millionth of an inch [0.000025 mm].

The Millionth Micrometer itself has been calibrated against a series of 26 gage blocks of varying lengths. They had previously been sent to four leading gage laboratories, and also to the National Bureau of Standards for calibration.

Although disagreement among the four gage laboratories on the length of the gage blocks was a surprising 5 millionths of an inch [0.000125 mm], by discarding the extremes, certainty of the gage block lengths was felt to be approximately ± 1 millionth of an inch [0.000025 mm].

Error of the Millionth Micrometer, calibrated by the gage blocks, appeared not to exceed 3 or 4 millionths of an inch [approximately 1/10 μm], including periodic error over its full one inch [25.4 mm] of travel.

Since the Millionth Micrometer is used for a maximum of 0.050 inch [1.27 mm] travel for calibration of the Small Angle Divider, the discrepancies introduced by lead error of the former can be considered negligible.

Calibration Technique—Fig. 396 shows the method and Fig. 397 offers a schematic of the arrangement used to calibrate the 1440 Small Angle Divider over 15 minutes of its travel.

A long tangent arm is affixed to the table of the 1440 Small Angle Divider. The Millionth Micrometer carries an electronic indicator reading to 1 millionth of an inch [0.000025 mm], which is positioned to gage at right angles to a lapped-flat surface on the tangent arm.

The Millionth Micrometer is positioned to gage on this tangent-arm surface at a nominal radius of 11.458 inches [291.03 mm] from the center of rotation of the 1440 Small Angle Divider. This is just twice the radius of the thrusting point of the Small Angle Divider 1/120th inch pitch [approximately 5 threads per millimeter] micrometer screw.

The Millionth Micrometer is physically moved to such a radius that five turns, or 0.050 inch [1.27 mm], equals a ¼° step of the 1440 Index.

The Small Angle Divider 1/120th inch pitch [approximately 5 threads per millimeter] micrometer screw and the Millionth Micrometer screw, both set to the same master ¼° increment, are now equal to one another overall, in a ratio of 5 to 3. In other words, five turns of the Millionth Micrometer equals three turns of the Small Angle Divider. Each full turn of 0.010 inch [0.254 mm] of the Millionth Micrometer equals 3 minutes on the Small Angle Divider. This relationship is ideal, since the Small Angle Divider can be calibrated in five increments (at 3-6-9-12-15 minutes) for lead as well as periodic error without introducing the negligible periodic errors of the Millionth Micrometer.

In practice, however, the Small Angle Divider is calibrated at every 36 seconds of arc to obtain a more complete calibration over the 15 minute movement, corresponding to 0.002 in. [0.0508 mm] travel of the Millionth Micrometer. A calibration certificate is shown in Fig. 398.

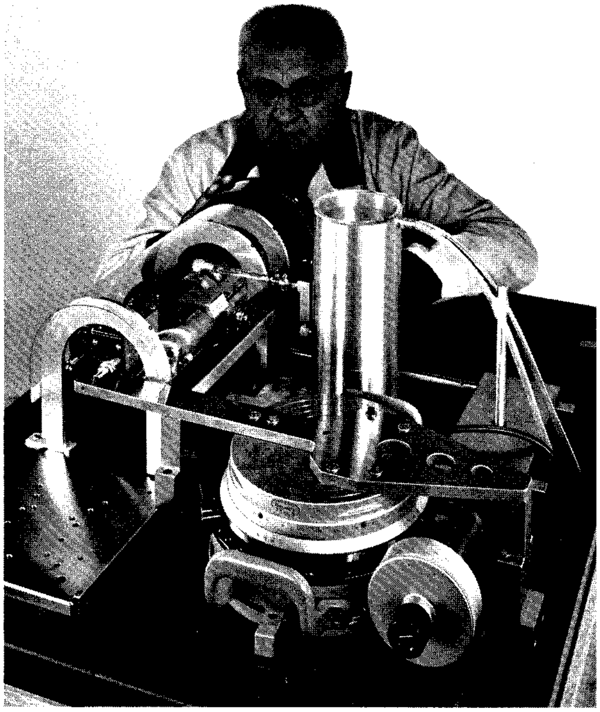


FIG. 395—*When fired tangentially at the correct radius, the Millionth Micrometer calibrates the full 15 minutes of arc generated by the Small Angle Divider.*

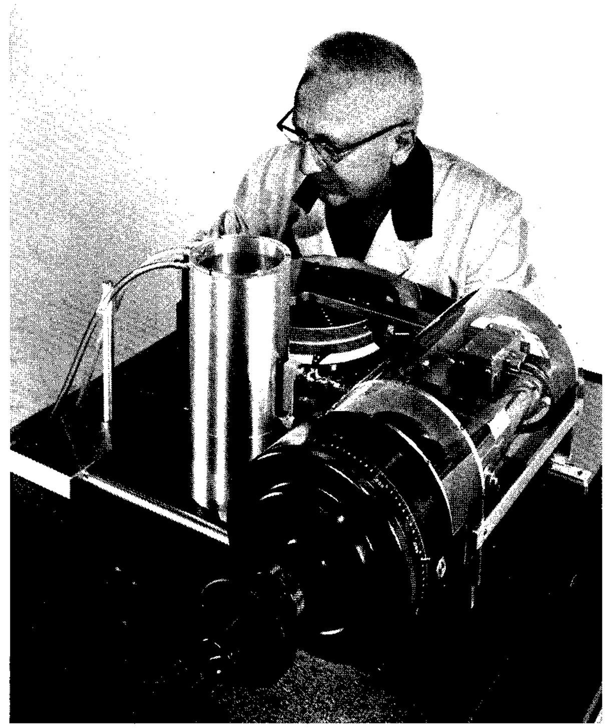


FIG. 396—*The "Millionth Micrometer" used to calibrate the Small Angle Divider has a 1/100th inch pitch [approximately 4 threads/mm] micrometer screw. It will read directly to 0.000001 inch [0.000025 mm]. Circulating oil maintains the temperature of the micrometer screw.*

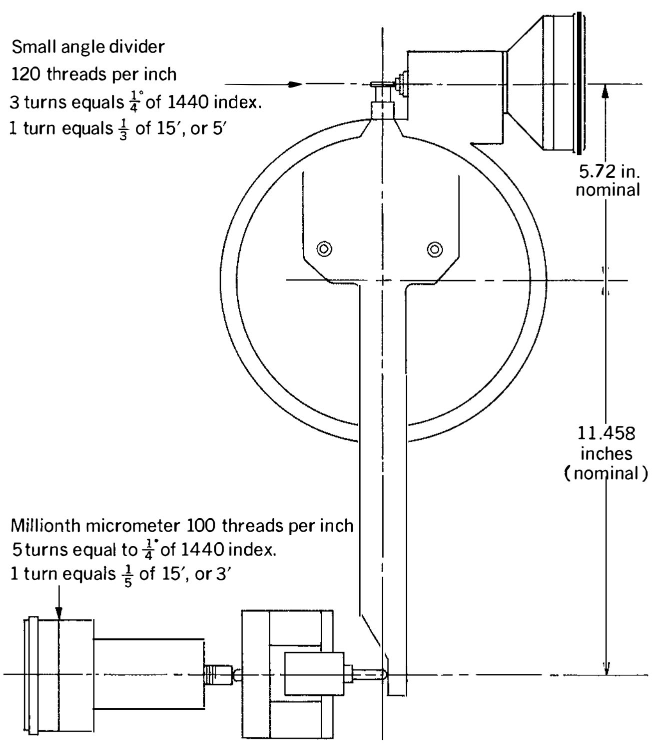
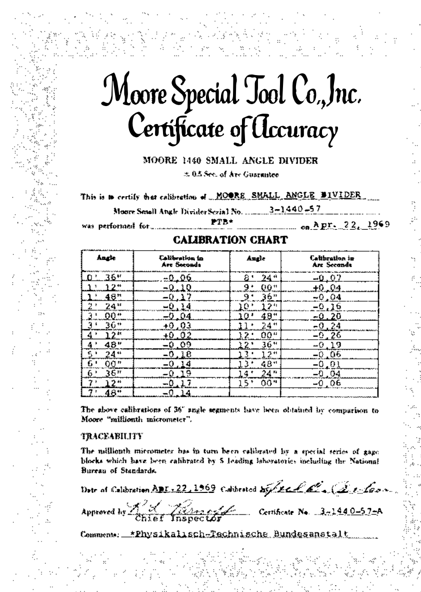


FIG. 397—*Arrangement of the Millionth Micrometer as used to calibrate the Small Angle Divider.*



Moore Special Tool Co., Inc.
Certificate of Accuracy

MOORE 1440 SMALL ANGLE DIVIDER
± 0.5 Sec. of Arc Guarantee

This is to certify that calibration of MOORE SMALL ANGLE DIVIDER
Moore Small Angle Divider Serial No. 3-1440-57
was performed for PTB* on Apr. 22, 1969

CALIBRATION CHART

Angle	Calibration in Arc Seconds	Angle	Calibration in Arc Seconds
0′ 36″	-0.06	8′ 24″	-0.07
1′ 12″	-0.10	9′ 00″	+0.04
1′ 48″	-0.17	9′ 36″	-0.04
2′ 24″	-0.14	10′ 12″	-0.16
3′ 00″	-0.04	10′ 48″	-0.20
3′ 36″	+0.03	11′ 24″	-0.24
4′ 12″	+0.02	12′ 00″	-0.26
4′ 48″	-0.09	12′ 36″	-0.19
5′ 24″	-0.18	13′ 12″	-0.06
6′ 00″	-0.14	13′ 48″	-0.01
6′ 36″	-0.19	14′ 24″	-0.04
7′ 12″	-0.17	15′ 00″	-0.06
7′ 48″	-0.14		

The above calibrations of 36″ angle segments have been obtained by comparison to Moore "millionth micrometer".

TRACEABILITY

The millionth micrometer has in turn been calibrated by a special series of gage blocks which have been calibrated by 5 leading laboratories including the National Bureau of Standards.

Date of Calibration Apr. 22, 1969 Calibrated by

Approved by Chief Inspector Certificate No. 3-1440-57-A

Comments: *Physikalisch-Technische Bundesanstalt

FIG. 398—*Calibration Certificate of the Small Angle Divider, furnished to the user as well as the certificate shown in Fig. 381.*

FIG. 399—*The 1440 Small Angle Divider is furnished with all necessary equipment, including a mahogany box.*

USE OF THE 1440 SMALL ANGLE DIVIDER

The unique construction of the 1440 Small Angle Divider makes a dual usage possible. First, it is small enough to be mounted on rotary tables as a calibrating standard with the capacity to divide the circle into virtually an infinite number of parts. Second, the fact that the small angle dividing feature is a submember, rather than being mounted on the table of the 1440 Index (the case in a first Moore prototype design), leaves the table clear for the mounting of parts and gages. It will thus perform all the functions of a rotary table for inspection, but to many times greater accuracy.

Because of the dual functions of the 1440 Small Angle Divider, it is offered in two different basic sets of equipment. It is furnished in a mahogany box for portability when used, for example, with a Universal Measuring Machine, Fig. 399. Also, it is available with a granite plate, mahogany cabinet and plexiglass cover when used essentially for calibration purposes, Fig. 400. Considering the special nature and cost of the 1440 Small Angle Divider, the greater protection and convenience offered by the mahogany cabinet makes it preferable.

Examples of practical applications of the 1440 Small Angle Divider when mounted on a surface plate are shown here. Calibrations are performed on a "tilting" rotary table, Fig. 401, on an autocollimator, Fig. 402, and on a 13-sided polygon, Fig. 403. Fig. 404 shows the 1440 Small Angle Divider being used with an autocollimator for the exact determination of the included angle of an optical prism. A wide range of applications is possible when the 1440 Small Angle Divider is mounted on a Universal Measuring Machine (see pages 315–316).

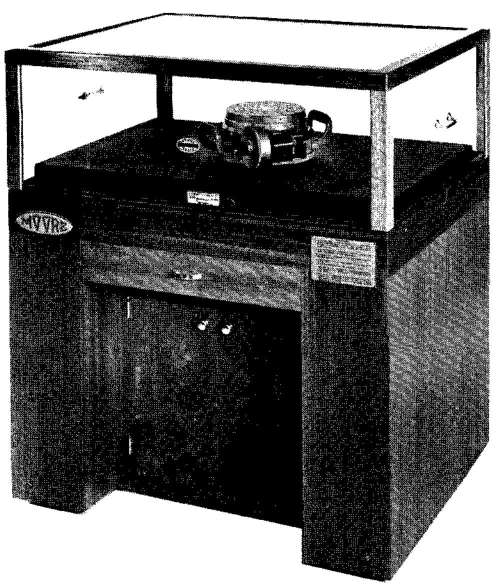
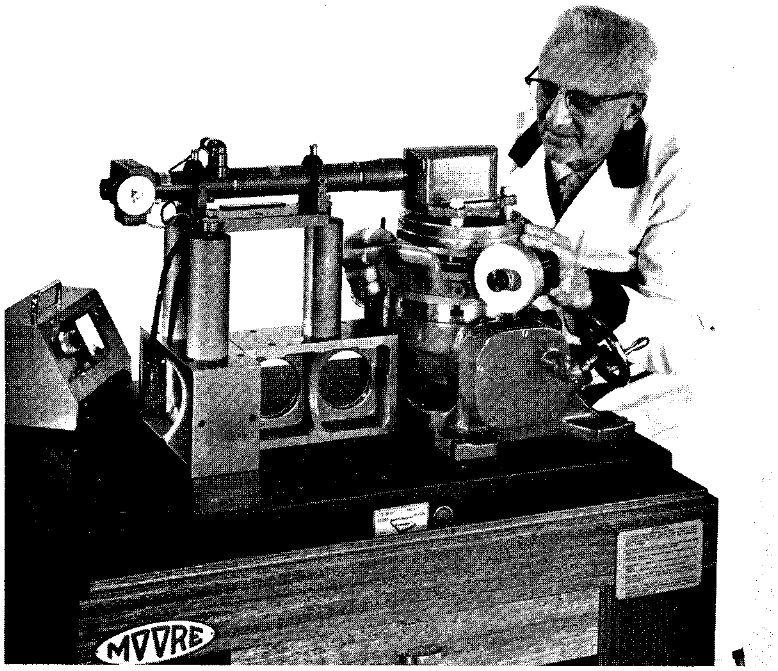
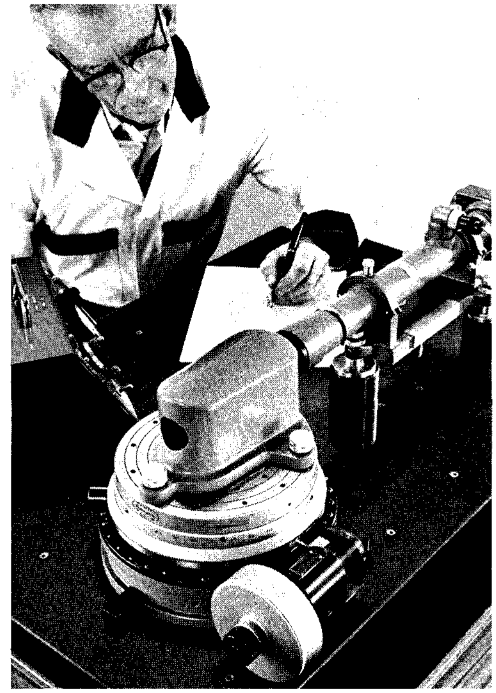


FIG. 400—*For laboratory use, the 1440 Small Angle Divider is furnished with granite plate, mahogany cabinet and protective plexiglass cover.*

FIG. 401—*The 1440 Small Angle Divider together with the standard granite plate in order to calibrate a precision rotary table.*

FIG. 402—*The 1440 Small Angle Divider is mounted on the granite plate for the purpose of calibrating a photo-electric autocollimator over its full range.*





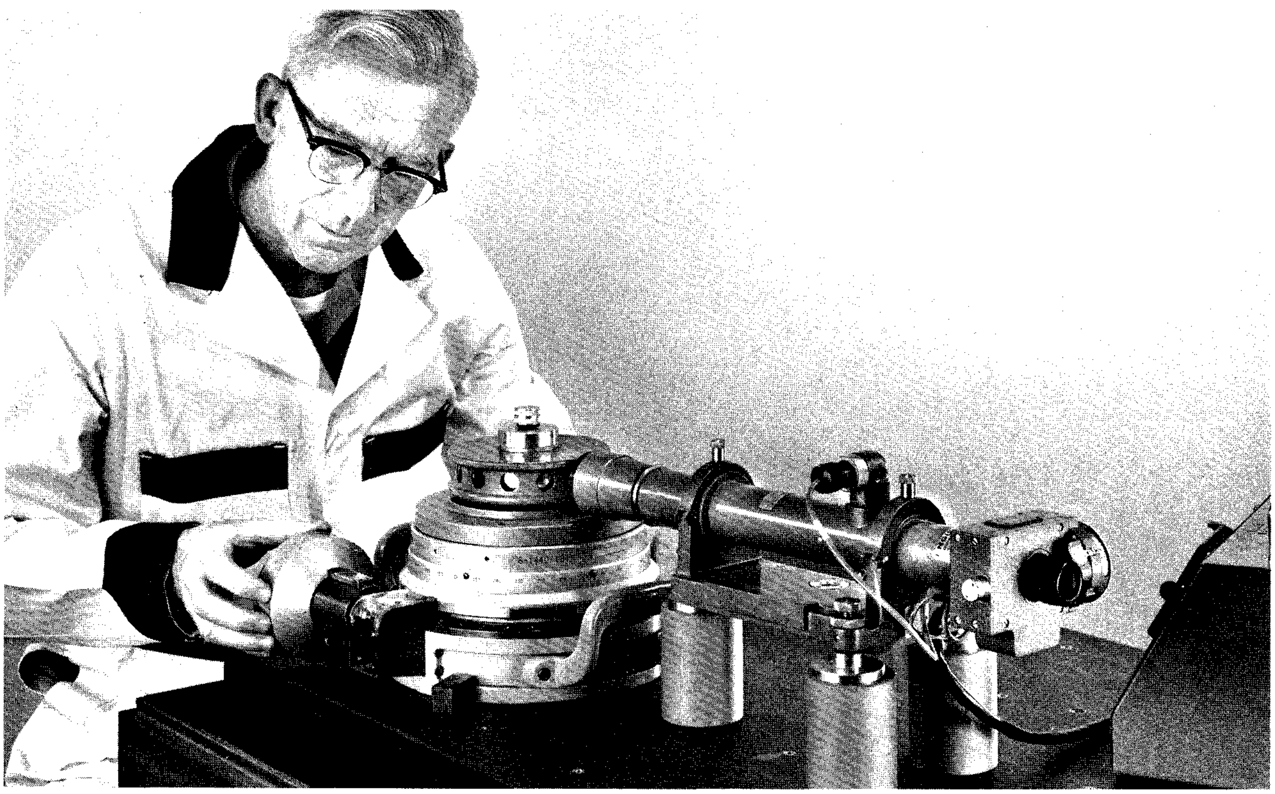
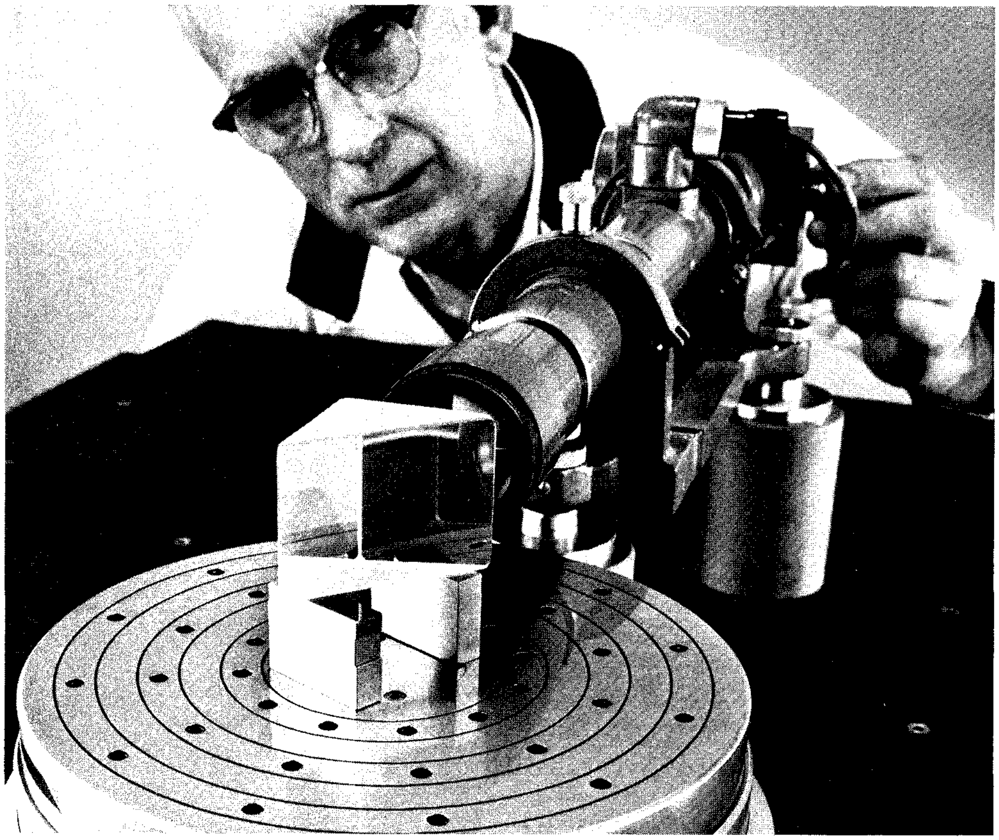


FIG. 403—*A 13-sided polygon is calibrated through use of the 1440 Small Angle Divider.*

FIG. 404—*Optical prisms of any angle are ideally inspected with the 1440 Small Angle Divider.*



PRECISION INDEX CENTER

A circle-dividing instrument of a somewhat different configuration is shown in Fig. 405. The Precision Index Center employs a horizontal roller bearing spindle of exceptional accuracy. Included in the design is a hardened, ground and lapped tool steel tailstock, and an accurately ground base plate to allow changing center-distance.

This device is designed for fast, accurate indexing by means of a lapped carbide pin fitting into a lapped carbide hole in the back plate. Indexing increments are determined by master index plates with accurately jig-ground holes. An index center plate is selected with the desired number of holes in a circle (such as 24) and mounted concentrically with the spindle.

While the number of indexed positions is limited by the selection of the index center plate, the emphasis in this design is on fast, repetitive, accurate indexing.

The low profile of this device and the accurate centers in both head stock and tailstock make it especially suitable for the generation or inspection of angles of arbor-mounted parts.

The Precision Index Center is shown in use in "Universal Measuring Machine Techniques & Applications," page 313.

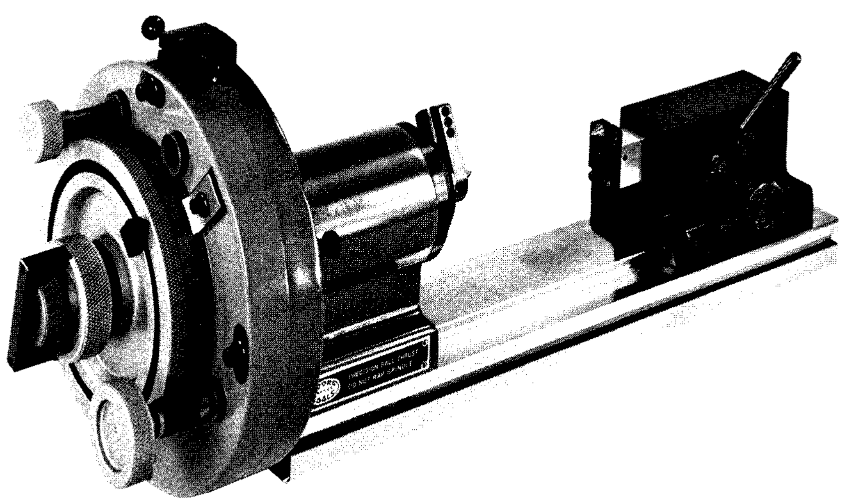
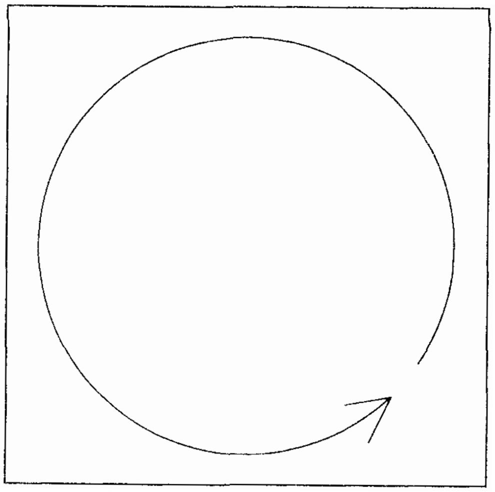


FIG. 405—*The Precision Index Center is used especially for indexing parts having centers or those that are best inspected while arbor-mounted. Its design enables very rapid, accurate indexing.*

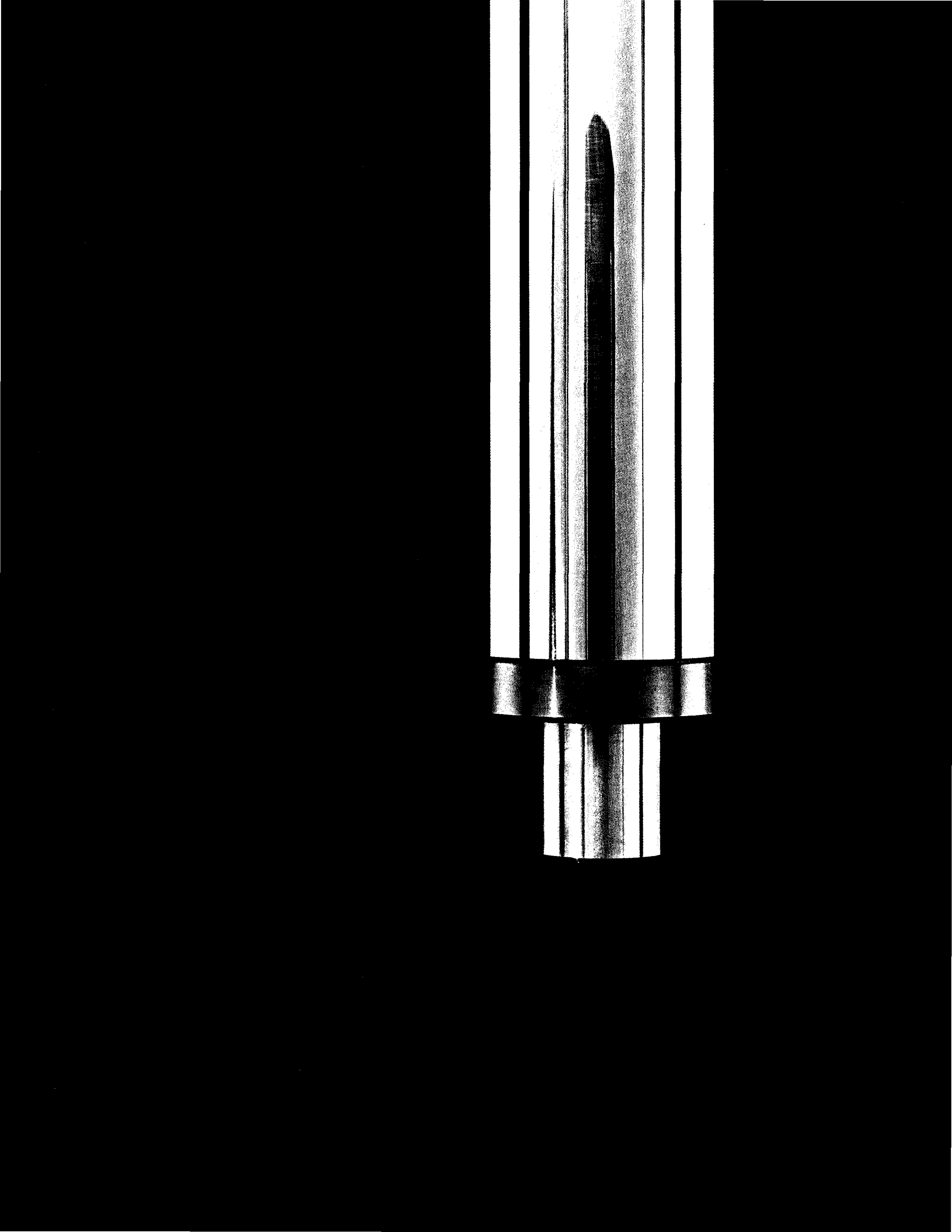
ROUNDNESS

4



Roundness is required in many mechanical parts, as is trueness of rotation in spindles and many mechanical assemblies. The authority for roundness usually traces to a precision measuring spindle.

FIG. 406—*The Universal Measuring Machine Spindle, an essential element in the location process, is also employed in the inspection of roundness and form of circular parts.*



1. Why Consider Roundness?

The generation and measurement of the roundness of mechanical parts is the fourth art in the foundations of mechanical accuracy. The authority for roundness is a precision spindle, such as that of the Universal Measuring Machine, Fig. 406.

The importance of roundness has already been discussed in relation to circle-dividing equipment. It is difficult to choose the exact terminology. Some authorities suggest "trueness of form" or "cylindricity." However, since the intention here is to describe the generation and measurement of mechanical parts wherein *roundness* is the essential form, it seems to be the appropriate term. For example, "trueness of form" might apply to many geometrical shapes unrelated to roundness; "cylindricity" does not encompass many categories within this art, such as the measurement of the roundness of tapered, circular bodies. Roundness has only recently been included in specifications of accuracy. Several years ago, when tolerances were generally expressed no closer than a thousandth or even to several ten-thousandths of an inch [hundredths of a millimeter to thousandths of a millimeter], the actual roundness of holes, shafts and balls was seldom critical in a mechanical assembly. Machines and techniques in use generated shapes round enough to meet requirements. Under these conditions, there was little need for toolmakers, for example, to understand the *nature* of roundness.

Tolerances of parts today, however, are commonly in the category of millionths of an inch [fractions of a μm]. In retrospect, it would appear that space exploration stimulated the demand for higher precision. Now, increased accuracy is essential to sustaining a higher level of technology.

The fact that "roundness" becomes proportionately more critical as tolerances become tighter is best proven by the simple example of fitting a shaft to a hole. Suppose we wish to determine the size of hole A to a tolerance of 50 millionths of an inch [0.0013 mm] for the purpose of interchangeability, allowing little clearance with a perfect shaft B. Suppose, in addition, that inspection reveals hole A is out-of-round by 50 millionths of an inch [0.0013 mm], but without a description of the *nature* of out-of-round.

From studying two possible conditions, exaggerated in Fig. 407, it is seen that given a certain condition of roundness:

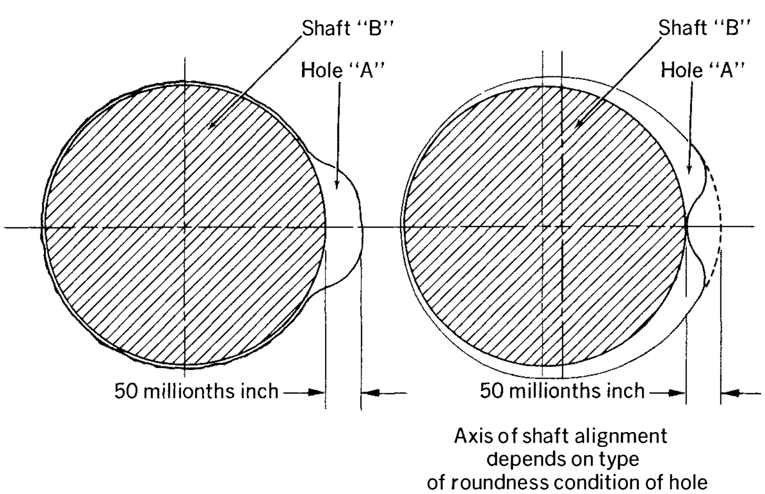


FIG. 407—(left) Location, effective size and the fit between mating parts are all dependent on the ability to measure and define the condition of roundness. Hole "A" is out-of-round 50 millionths of an inch [0.0013 mm]. From the two hypothetical conditions, it is apparent that more can be known of the functional relationship of hole "A" to mating shaft "B" if the roundness condition is clearly defined.

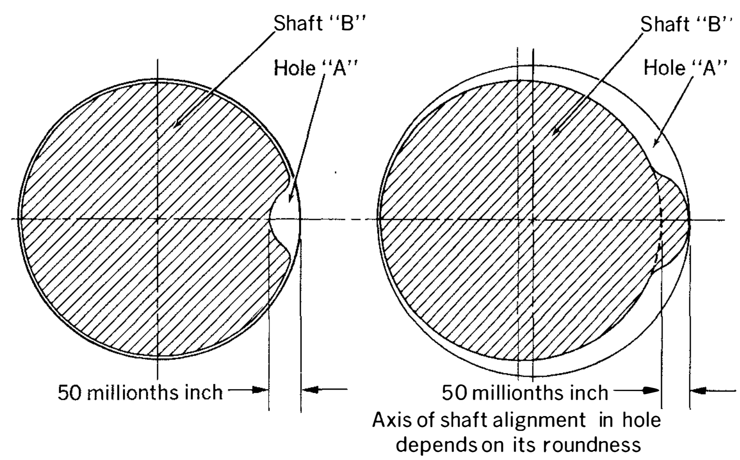


FIG. 408—(right) Shaft "B" in this case is out-of-round 50 millionths of an inch [0.0013 mm]. How shaft "B" will function with mating perfect hole "A" can be predicted with more certainty if its roundness condition is specified.

1. We are unable to specify the true or at least the effective size of hole A.
2. The type of fit achieved, or clearance, is dependent on the roundness of hole A.
3. Depending on the nature of the roundness of hole A the axis of shaft B may be shifted. If this hole required reference to some other hole in the part, its *location* would be in doubt.

Where shaft B is not round and hole A is perfect, Fig. 408, it is obvious that similar limitations are imposed.

It can also be noted by comparing Fig. 407 to Fig. 408 that effective size and location of axes depends on whether the round shape is male or female. In most practical conditions, *both* mating parts will be imperfect to varying degrees.

Bearing in mind the limitations imposed by out-of-round conditions, some authorities suggest that *the tolerance of roundness be five times closer than other related dimensional tolerances.* If, for example, the shaft shown in Figs. 407 and 408 were a plug gage and a size tolerance of 50 millionths of an inch [0.0013 mm] were specified, then it would first have to be *round* within 10 millionths of an inch [0.00025 mm]. If the hole shown in Figs. 407 and 408 were a ring gage specified to a tolerance of 25 millionths of an inch [0.0006 mm], then roundness of the ring gage must be within 5 millionths of an inch [0.00025 mm]. Given this 5 to 1 ratio, it is clear that geometric conditions of roundness quickly limit other related tolerances, particularly size.

Whether the suggested 20% ratio or some other proportion be used depends on the intended function of the part. What cannot be ignored is that there is a degree of uncertainty about other related tolerances of a part, unless roundness is also maintained. Since the tolerance on roundness should be much closer than that of the other dimensional tolerance which it effects, it is critical.

SOURCES OF OUT-OF-ROUNDNESS

There are many causes of out-of-roundness when machining mechanical parts. Some common ones are: clamping distortion, spindle run-out, failure to "clean-up", imbalance, heat and vibration. Their characteristic roundness shape varies greatly depending on the *method* of generation.

NATURE OF OUT-OF-ROUNDNESS

When the apprentice toolmaker carefully measures a dowel pin with a micrometer, he is puzzled when it will not slip into a hole measuring 0.0001 in. larger [0.0025 mm]. A higher quality gage pin which "mikes" the same size as the dowel pin, however, slips into the hole easily. Herein lies a lesson with regard to the nature of roundness. Lack of fit is due to the different methods of *generation* of the gage pin and the dowel pin. The gage pin is ground and *lapped round.* Dowel pins, mass-produced, are only centerless-ground, for economy of manufacture. The shape of the latter is typically triangular, sometimes described as three-lobed, Fig. 409.

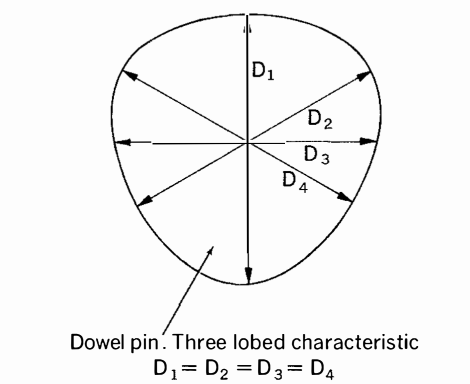


FIG. 409—*(top right) Dowel pins, mass-produced in a centerless-grinding operation, are typically of constant diameter but 3-lobed out-of-round.*

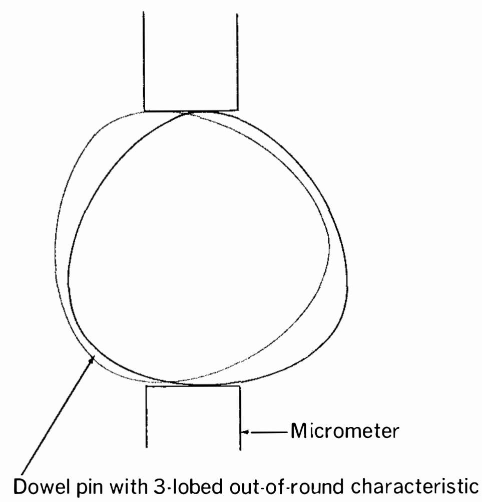


FIG. 410—*(center) The measurement of a dowel pin by micrometers shows a fairly constant diameter at whatever point the measurement is made. Diametral methods, employing gaging points 180° apart, will not reveal odd-numbered lobing.*

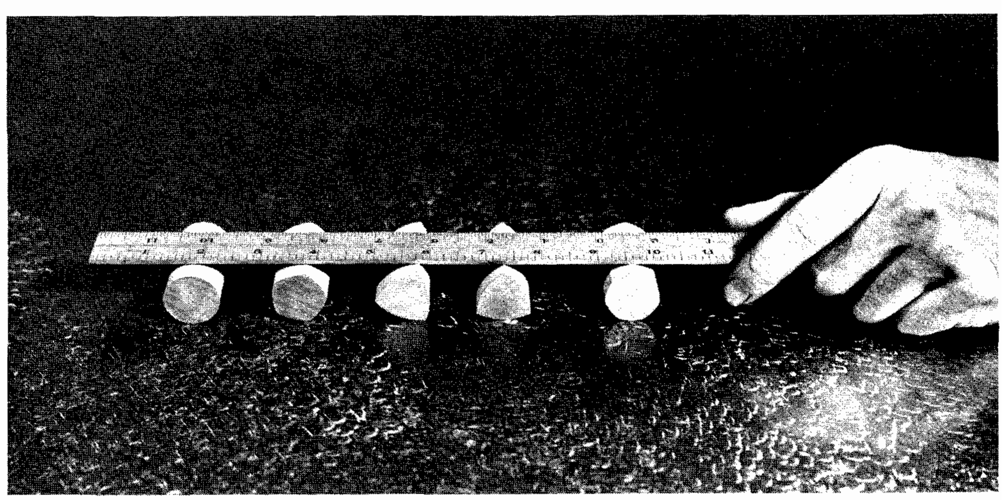


FIG. 411—*Demonstration pieces prepared by the Van Keuren Company represent cylindrical pieces of constant diameter, each having a different number of odd-lobing. All the samples will stay in contact with the ruler when rolled through a full 360°.*

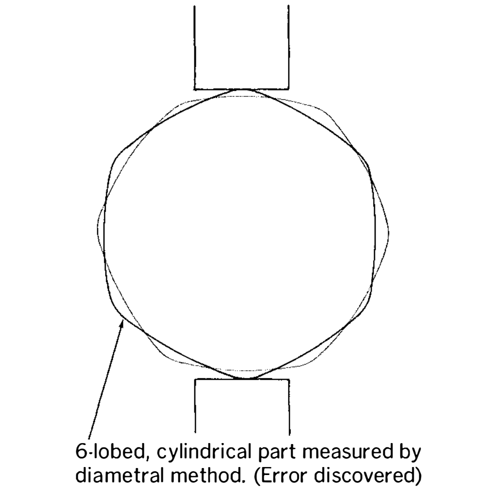


FIG. 412—Out-of-roundness of parts having even-numbered, symmetrically arranged lobes, as with this 6-lobed cylindrical part, can be revealed by diametral methods.

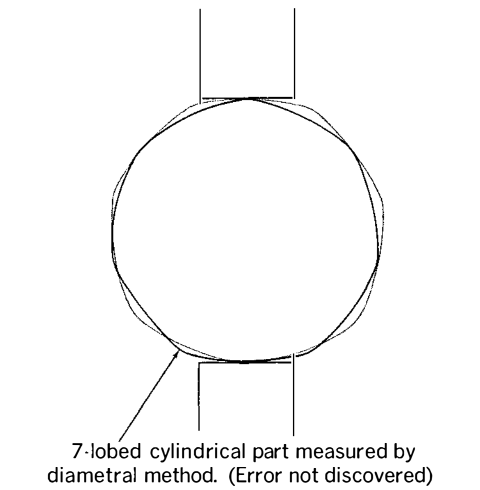
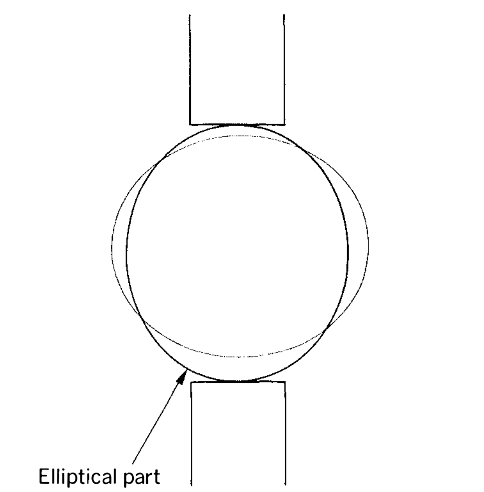
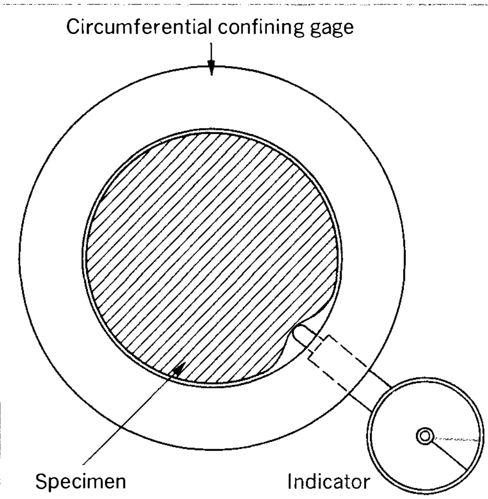
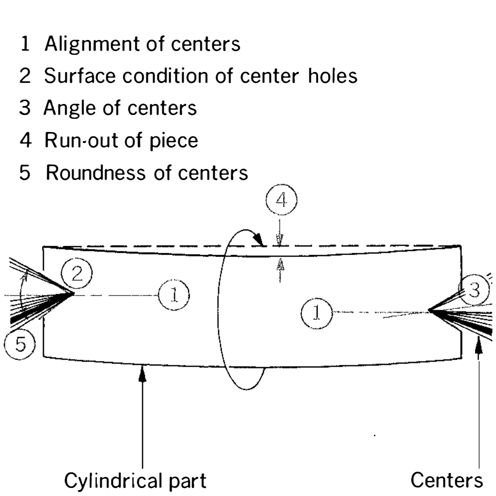


FIG. 413—Out-of-roundness of parts having an odd-number of lobes, as with this 7-lobed cylindrical part, is not revealed by diametral methods.







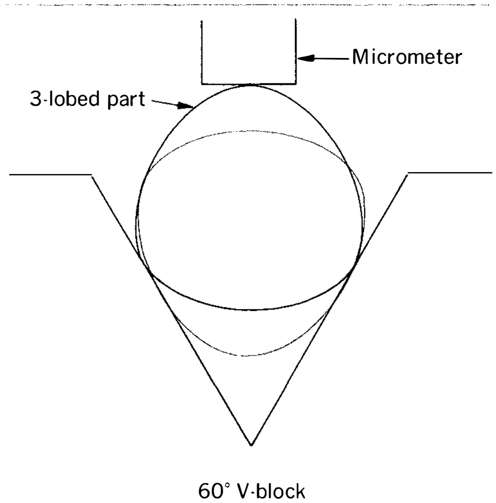


FIG. 414—(center, left) Out-of-roundness of an elliptical part becomes apparent by measuring across one diameter, turning the piece 180° and measuring across the second diameter.

FIG. 415—(center, right) A circumferential confining gage when used to measure roundness requires a separate highly accurate master for each size part to be measured. Other related geometrical characteristics may not be shown.

FIG. 416—(bottom, left) Some parts may be inspected for roundness while mounted on centers. As here, there are many potential sources of inaccuracy which may lead to misleading results.

FIG. 417—(bottom, right) A 60° V-block is best for inspecting the out-of-roundness of 3-lobed cylindrical parts, since error is exaggerated.

Strangely enough, the centerless grinding operation produces dowels of a fairly constant diameter. No matter at which point one measures, the same diameter is always recorded, Fig. 410.

Other shapes are shown in exaggerated form in demonstration pieces prepared by the Van Keuren Company, Fig. 411. All the samples will stay in contact with the ruler as they are rolled through a full 360°.

If one tried to determine the size of a pin which was oval in section (or two-point out-of-round), he would discover a discrepancy by rotating the pin 90° and measuring once again.

The point here is basic:

1. All *even-numbered* (2, 4, 6, 8 etc.) symmetrically arranged lobes in a part can be discovered by a diametral check, as in the six-lobed part of Fig. 412.
2. All *odd-numbered* symmetrically arranged lobes in a part will not be found by a diametral measurement, Fig. 413.

It may be further concluded, then, that any *diametral* check will not necessarily disclose *effective* size or *roundness*. This conclusion applies to a cylindrical shaft, a ball, a hole, or to any other radial or spherical shape.

All tools and instruments, regardless of magnification, which measure size by diametral methods (points 180° apart), are unreliable monitors in determining roundness.

2. Measuring Roundness

Since diametral methods are inadequate, how then can roundness be measured? An *American Machinist* article* contained a symposium of opinions of gaging authorities on the subject of roundness. This article provides a basis on which to make

*"And Must be Round Within . . .", *American Machinist*, December 1, 1958.

observations, since practically all methods used for gaging roundness were described. The article is also interesting historically, since it reflects a general awakening to the need for understanding roundness.

The six methods of determining roundness discussed in the article are:

1. *Diametral.*
2. *Circumferential confining gage*—a shaft is confined in a ring gage and rotated against a set indicator probe.
3. *Rotating on centers.*
4. *V-block*—piece rotated against a set probe:
   a. of fixed angle;
   b. of adjustable angle.
5. *Three-point probe* (120° spacing).
6. *Accurate spindle.*
   a. part fixed, exterior spindle with probe rotates;
   b. probe fixed, part rotates with spindle.

Each of the six methods can be analyzed as to their effectiveness in measuring roundness:

1. Diametral, Fig. 414

It has been shown that the diametral method of measuring roundness is only suitable when the specimen is elliptical or has an even number of lobes.

2. Circumferential Confining Gage, Fig. 415

While this method may be useful for inspection of roundness in production* it demands a separate, highly accurate master for each size to be inspected. The clearance between part and gage is critical to reliability.

This technique does not allow for the measurement of other related geometric characteristics, such as concentricity, flatness of shoulders, etc. The values obtained are still dependent on the shape of the specimen.

3. Rotating on Centers, Fig. 416

Certain parts, such as shafts or the OD's of arbor-mounted parts, may be inspected for roundness while rotated on centers. Just as with the circumferential confining gage, this is far from being a universal method. Reliability is dependent on many factors, such as the angles, alignment, roundness and surface condition of the centers and center holes. Out-of-straightness of the part will cause a doubling runout effect and appear to be a roundness error.

Any or all of these factors may combine in a given inspection, creating a high degree of uncertainty as to the exact nature of the error.

4. V-block

a. *Fixed angle.* Appleby and Worthen** recommend the use of a 60° V-block for discovering three-point out-of-roundness. Calculations would show that five-lobed parts are best measured by a 108° V-block and seven-lobed parts by a 128° 34′ V-block. See Figs. 417, 418 and 419.

b. *Adjustable V-block,* Fig. 420. C. A. Whitney** observes that, considering the variety of machines and methods for generation of parts, often the *number* of lobes is not known. To rectify this situation, he suggests a V-block which can be *adjusted* to the correct angle to show out-of-roundness after the number of lobes of the piece has been determined.

Limitations of V-block method

Use of a V-block of *any angle* is limited in the determination of roundness of parts,

*Canfield, a contributing author of "And Must be Round Within . . .", notes an accuracy "within 10% of the 10% tolerance permitted by quality review," p. 111.

**Idem.*
***Idem.*

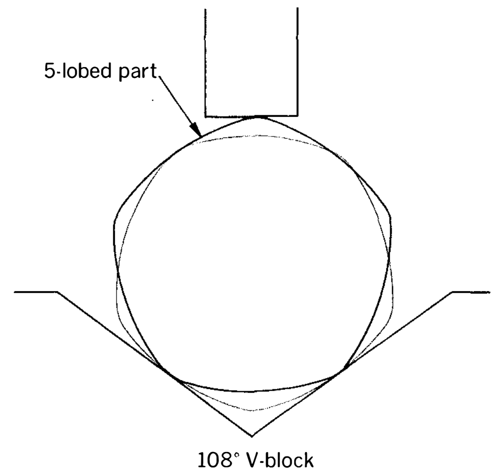


FIG. 418—(*top*) *A 108° V-block is recommended to measure the roundness of 5-lobed cylindrical parts.*

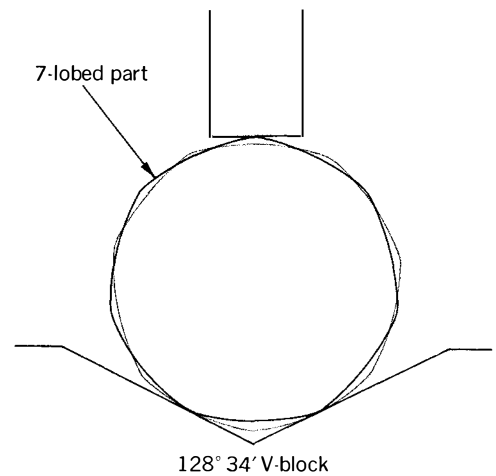


FIG. 419—(*center*) *A 128° 34′ V-block is recommended to measure parts which are 7-lobed.*

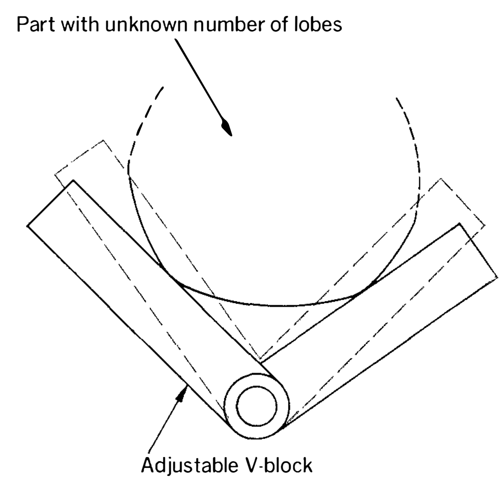
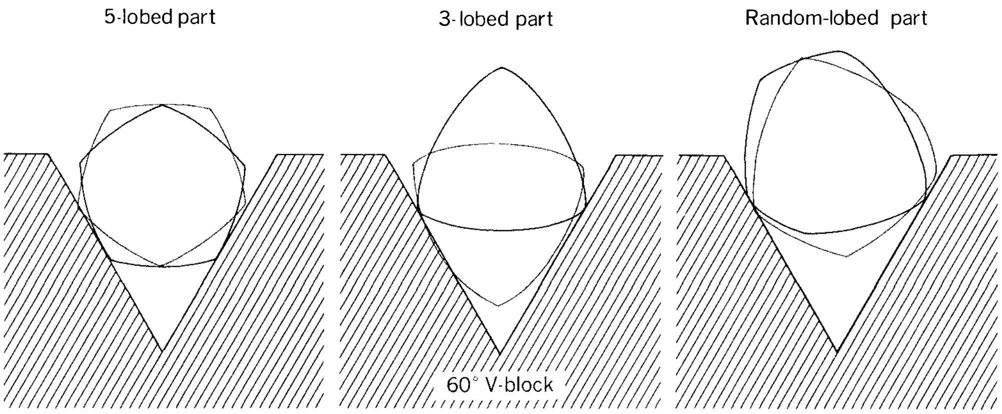


FIG. 420—(*bottom*) *When the number of lobes is unknown, a cylindrical part may be inspected by a V-block whose included angle is adjustable.*

FIG. 421—*Although a 60° angle V-block is often thought most perfect for revealing an out-of-round condition, results obtained are highly uncertain. Depending on the number of lobes in the part, that which actually may be shown is: no error (left), the error exaggerated (middle) or partial error (right).*



since it is based on the assumption that the number of lobes is known and uniformly arranged.

The 60° V-block is often suggested as the best compromise to discover most types of out-of-roundness. However, depending on the number of lobes of the part being inspected, it may show, Fig. 421:

a. No error (5, 7 lobed).

b. The error magnified (3-lobed).

c. Partial error (randomly spaced lobes).

Seldom will the 60° V-block show *true error*. Similar uncertainty results when using V-blocks of other included angle. The 90° V-block, for instance, will hide a seven-lobed characteristic.

5. Three-point Probe

The three-point probe with 120° spacing, Fig. 422, is very useful for determining effective size where there is doubt as to the geometry of the part. The more common examples of a three-point probe are a three-jaw inside micrometer, or three-jet spindle for gaging lobing of a hole, or three-jet ring gage for gaging a shaft. When used for inspecting roundness, such gages do show three-lobing; however, having gaging points 120° apart, they perform like a 60° V-block, with similar limitations.

Production Methods vs. Absolute Methods of Measuring Roundness

A distinction between *production* versus *absolute* methods of measuring out-of-roundness should be made. All the previous methods are suitable for production, and fairly inexpensive. The real danger in their use, however, is that those responsible for quality control may accept these methods as comprehensive checks. As previously observed, if a certain geometric condition of the part varies, then the roundness condition may be hidden or misinterpreted.

None of these methods is satisfactory for measuring roundness absolutely. It is

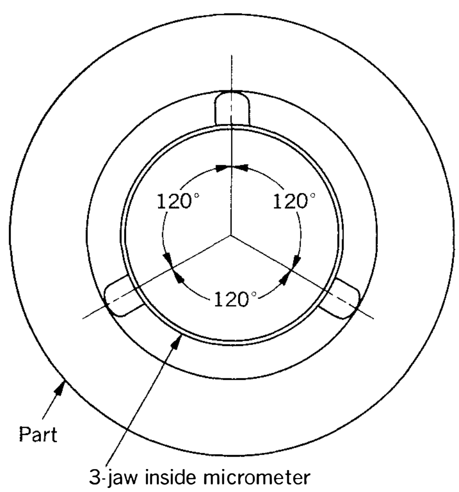
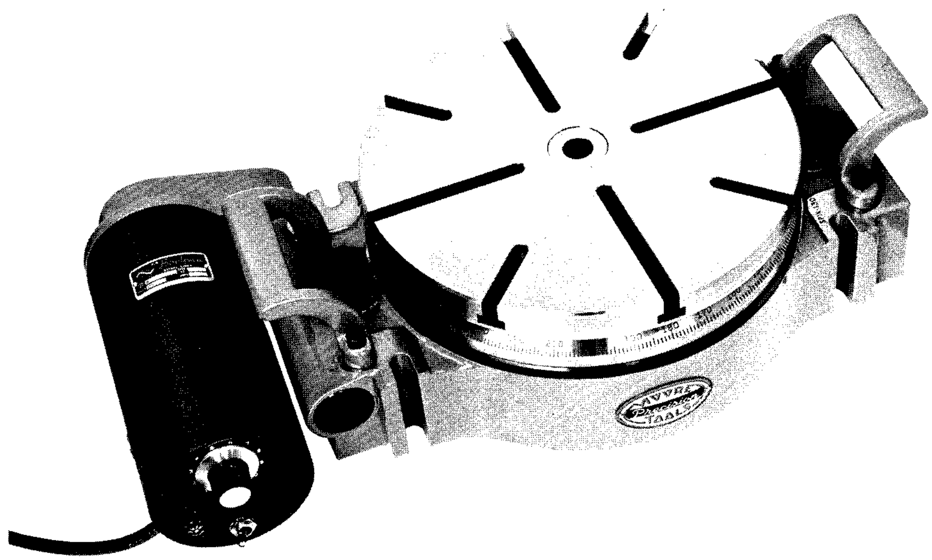


FIG. 422—*3-point probes (points 120° apart) have similar limitations in measuring the roundness of holes as do V-blocks for measuring the roundness of cylinders.*

FIG. 423—*The Spin Table is one example of the highly precise spindles which have become necessary to generate and to inspect round shapes. The Spin Table is a rotating table-type of spindle, useful for generating cylindrical, conical and spherical shapes when mounted on the jig grinder.*



therefore understandable that a demand arose for some universal means to provide a definitive *value* or *calibration* of roundness, beyond the mere discovery of out-of-roundness conditions.

6. Accurate Spindle

It is now recognized that the only *absolute* method of calibrating roundness is with an accurate spindle.* There are innumerable types of spindle designs available today for the *generation* and *inspection* of round shapes. Various designs in use include: ball-bearings, roller bearings, plain ball spindles, plain bearings (journal type), metered oil flow and fluid-bearing (gas-bearing and oil-bearing). These spindles are available in a wide range of tolerances, down to a few millionths of an inch [fraction of a μm]. Moreover, they vary widely in capability so as to meet particular needs.

Spin Table

An example of the "accurate spindle" is the "Spin Table," Fig. 423. While the Spin Table may perform inspection operations, it has been designed for the generation of essentially round shapes. It is most versatile when used with the jig grinder for grinding highly accurate holes, outside diameters and shoulders. When the Spin Table is mounted on the Micro-Sine Table (see pages 213–215), tapers and conical shapes are ground round and to an exact included angle. If the Spin Table is placed on the jig grinder so that its spindle is horizontal, either by mounting it on an angle iron or on the Sine Table, spherical or aspherical shapes may be ground.

The conventional design for this type of spindle includes the use of balls. For maximum rigidity, and for minimizing the danger of brinelling, the Spin Table instead uses precision rollers under stiff radial and axial preload.

Trueness of rotation of the Spin Table is held to 5 millionths of an inch [0.000127 mm] Total Indicator Reading (TIR) and 20 millionths of an inch [0.0005 mm] maximum axial deviation, including the effects of camming, flatness and parallelism.

Of particular interest to metrologists are those spindles designed strictly for the purpose of calibrating roundness. In rotation, these accurate spindles describe a perfect circle to which the part may be compared at all its radial ordinates.

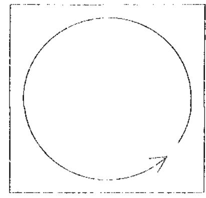
Out-of-roundness is shown by the movement of high-magnification comparators. It often suffices to merely observe and note indicator readings. However, the memory can hardly be trusted to visualize the geometry of a part as the spindle rotates, especially if its axis and that of the spindle do not coincide. Consequently, these spindles are usually equipped with means of recording the results. Sometimes linear recorders are used but polar recorders provide a better mental picture of the part, and perhaps for this reason have gained widest acceptance.

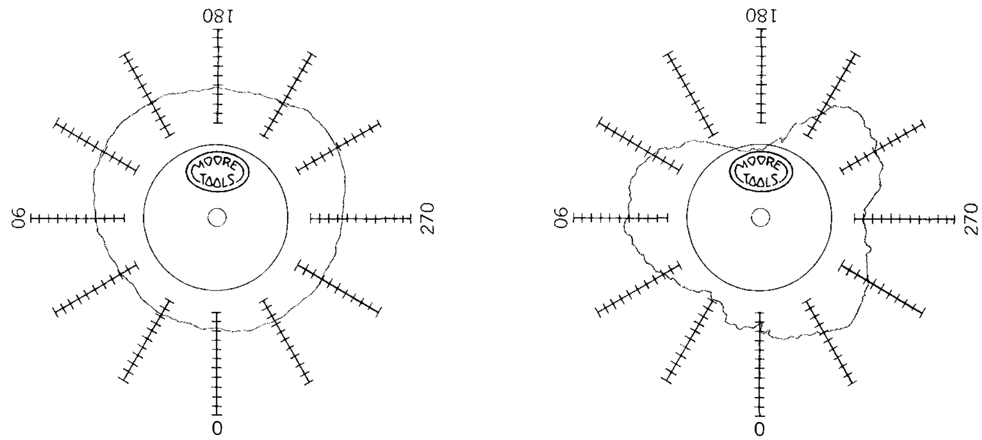
The polar recorder is an auxiliary device having several rotational speeds, synchronous to those of the measuring spindle. Deviations from true roundness registering on the indicator are traced on circular graph paper at magnifications up to 20,000× to provide a permanent physical record.

By overlaying a special transparent template where there are concentric circles representing calibrated values (such as 1 line = 0.000010 in. [0.00025 mm]) to the graph, deviations from roundness may be

*A recent development is a computerized device which enables roundness to be inspected on the machine on which the part is generated, regardless of the accuracy of rotation. While useful for production, lesser accuracies are quoted with this method, and there are apparently certain lobing characteristics which are still hidden.

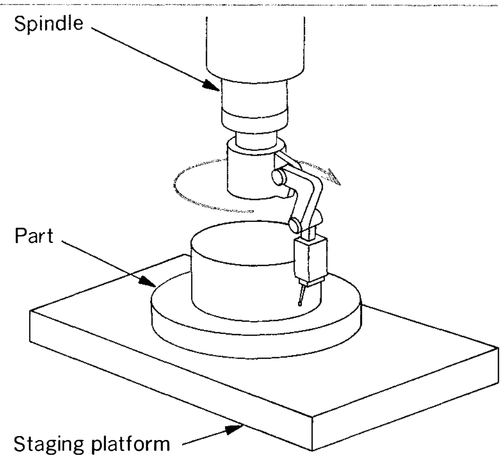
FIG. 424—*When visualizing the roundness condition of a part as represented in a polar tracing, a perspective of the magnitude of the error must be kept in mind. The more the error is magnified, the more exaggerated the "star-shaped" picture.*



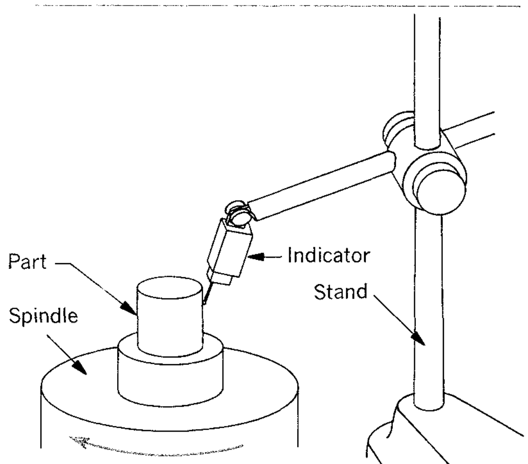


Polar tracing of out-of-round part, low magnification

Polar tracing of same out-of-round part, high magnification



OVERHEAD SPINDLE



ROTATING TABLE SPINDLE

FIG. 425—*(center) When using the Overhead Spindle to measure roundness, the part is fixed, while the spindle carrying the comparator rotates about or within the part.*

FIG. 426—*(bottom) The rotating table-type of spindle carries the part to be measured for roundness, and the measuring probe is fixed, usually on an indicator stand.*

easily understood and analyzed. This can be accomplished even without exact alignment of the part with the spindle.* An alternative to the template method simply is to strike a circle on the chart with a drawing compass. The dimensional value put upon roundness, as well as the final center of the graphed circle, depends on the system adopted to assess roundness (see pages 272–276).

A perspective of the *magnitude* of the error must be maintained, since the graph, while truthful, is an enlarged, distorted representation of the error. The more scaled-up the representation, the more star-shaped it is, Fig. 424.

3. Two Types of Measuring Spindles

Roundness-measuring spindles are of two configurations:

1. *Overhead spindle, Fig. 425.* The part is fixed while the overhead spindle, to which the comparator is attached, rotates separately from the part.
2. *Rotating table, Fig. 426.* Integral to the spindle is a rotating table which carries the part and rotates it past a fixed comparator.

MEASURING SPINDLES COMPARED

Rotating Table

It becomes apparent—compare Figs. 427 and 428—that the rotating table spindle will determine more geometric characteristics without having to move the part. It measures such factors as: roundness, con-

*R. E. Reason's "*Talyrond Handbook*" examines the effect of non-centering and concludes that the shape of the graph is altered negligibly when the part is slightly off-center—up to 0.3 inch [7.62 mm] of the graph. Over this amount, distortion increases rapidly, becoming intolerable, when greater than 0.5 inch [12.70 mm] of the graph.

centricity, and camming (circular flatness). Squareness inspection requires sliding the indicator and stand, or an auxiliary horizontal movement.

Unless there is a means for accurate vertical adjustment, it will not measure large tapers, Fig. 429.

Since the indicator and its stand can be placed or adjusted conveniently to gage at any point, the allowable height of the workpiece is limited only to the extent that it becomes unwieldy. It is not restricted by the parameters of the setup.

The rotating table must also carry the part. Therefore, the variable of *workpiece load* is introduced. When small parts such as bearings, small balls, miniature gyros, or ring gages are measured, no loss of accuracy is likely to occur. With heavy or eccentrically-mounted pieces, spindle accuracy may be reduced by deflection or by shifting loads, Fig. 430. Although at present air-bearing tables seem to have the greatest potential for sheer roundness accuracy, there is also evidence that this design may be the least able to absorb unsymmetrical or changing loads.

A ball-loaded spindle, on the other hand, presents the greatest risk of brinelling critical bearing elements when mounting heavy workpieces.

Overhead Spindle

It can be seen from Fig. 428 that the overhead spindle will determine roundness as well as camming. Since concentricity is inspected only by extending the indicator from the spindle, the range of this check may be less than with the rotating table spindle. Flatness and squareness are inspected only by physically sliding the workpiece past the indicator as on a surface plate; this latter technique may be employed providing one is confident that the datum surface used is flat. However, this is not a desirable method since it is best not to touch the part, once mounted,

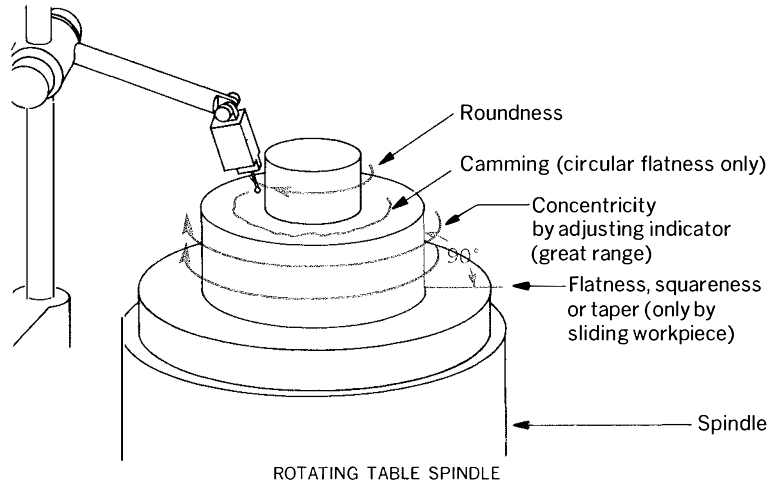


FIG. 427—*(top) The geometric features of a part that can be inspected with the rotating table-type of spindle are shown. This design allows the inspection of concentricity over a great range along the part axis.*

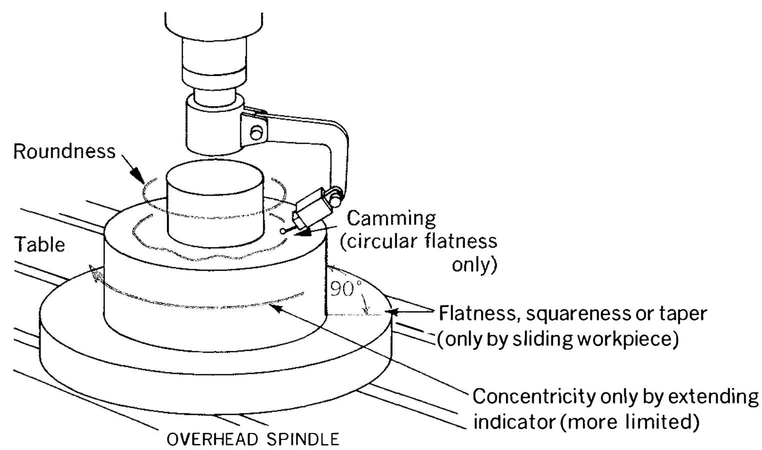
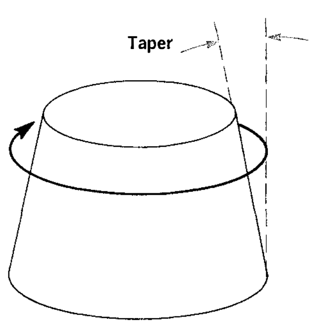


FIG. 428—*(center) Shown are the geometric features of a part that can be inspected with the rotating table-type of spindle. This design is especially suited to the inspection of roundness of large, heavy workpieces, or those where the part features to be inspected are off-center.*



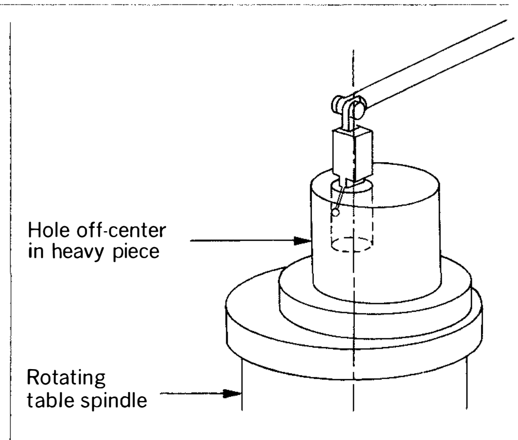
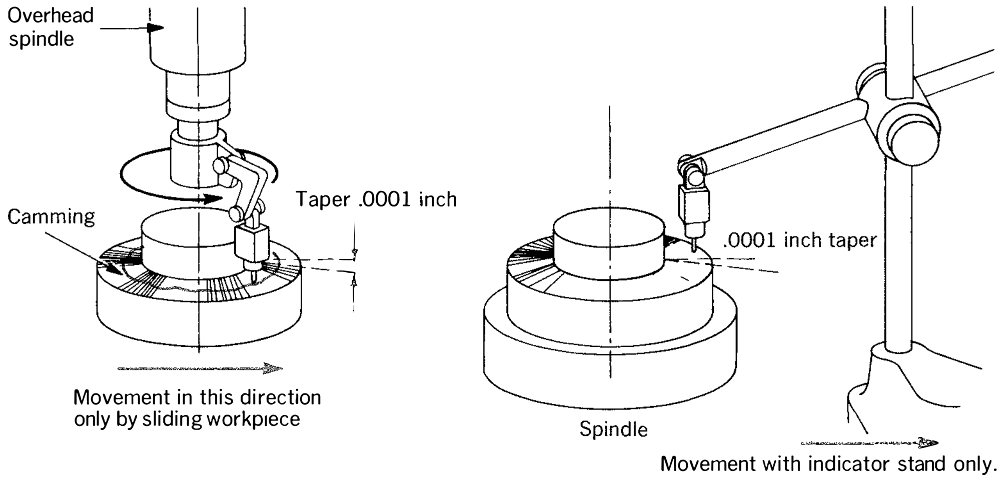


FIG. 429—*(bottom, left) Neither the overhead spindle nor the rotating table spindle, by themselves will reveal taper in the specimen.*

FIG. 430—*(bottom, right) Since the rotating table spindle must carry the part, spindle accuracy may be deteriorated by heavy, eccentrically mounted pieces; damage may occur when mounting the workpiece. No loss of accuracy should occur and the chance of damage is slight when mounting heavy workpieces to be measured by the overhead spindle.*

FIG. 431—*The overhead spindle (left), will inspect camming. Unless an accurate horizontal movement is provided, the inspection of squareness, taper and flatness is accomplished only by sliding the workpiece, which is usually a disadvantageous technique in practice. The rotating table (right), will inspect camming as with the overhead spindle. Squareness, taper and overall flatness are inspected only by sliding indicator and stand, which is poor workshop practice.*



until all inspection is completed to avoid thermal change. Moreover, the mounting surface will wear if this technique is practiced often, and in moving the part, its orientation to the spindle axis is disturbed. Unlike the rotating table-type, there are limitations to the height of the workpiece which can be inspected with the overhead spindle.

The overhead spindle does have advantages in use. Since the workpiece is stationary and separate from the spindle, the spindle does not have the variable of workpiece load. There is no deterioration of spindle accuracy when measuring a part which is heavy or eccentrically mounted. Moreover, there is scarcely any danger of damaging the spindle during mounting of the piece.

Measurement of Camming, Flatness and Squareness

A commonly-held misconception is that both these types of spindles can inherently determine squareness and flatness. Both can measure *circular flatness* (variations in an axial direction in concentric circles from center), but without a controlled measuring movement in a horizontal direction, certain geometric errors may not be shown. For example, in Fig. 431, the shoulder of the piece is uniformly tapered (not square to the shaft) in the amount of 0.0001 inch [0.0025 mm]. The vertical spindle (left) may make circular tracings at selected increments along this shoulder. However, since the indicator adjustments are not related or oriented, only camming, not squareness or flatness is shown unless the piece is manually moved.

The rotating table has a slight advantage (right) in that it can show squareness, by sliding the indicator and stand, Fig. 431. This technique also is not good workshop practice.

In Figs. 446 through 450, a study is made of other shapes that might be inadequately inspected with roundness-measuring spin-

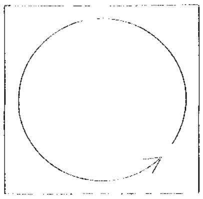
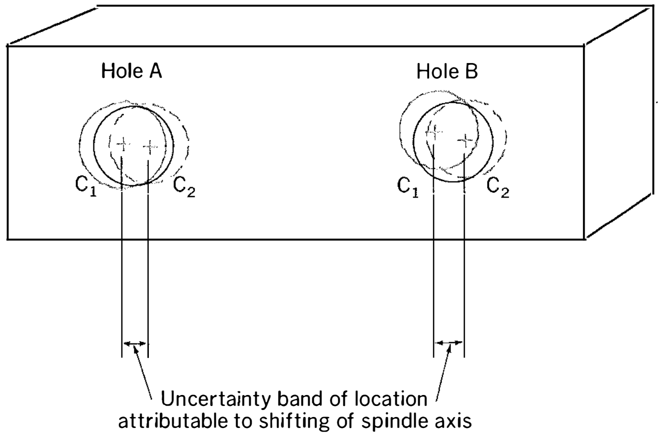


FIG. 432—*The locating process is dependent on the use of an accurate spindle. This spindle does not have a constant axis of rotation, shifting from C_1 to C_2 on every other revolution. The uncertainty of center-distance of hole "A" to hole "B" is attributable to spindle error.*



dles that do not include accurate horizontal movements.

It is interesting that although very sophisticated roundness-measuring instruments had been available for many years, only the Universal Measuring Machine could truly measure taper, flatness and squareness. Not until the Microtecnic Exhibition in Zurich, Switzerland, 1969, did the author see the introduction of controlled vertical and horizontal movement by manufacturers of these instruments.

Effect of Temperature

The rotating table is sometimes claimed to be inherently immune to the effects of temperature because the axis of the part and that of the spindle are mutually fixed. There may be truth to this claim where a time-lag exists between start and finish of a check. However, most roundness inspections require only a few minutes. The effect of temperature variation on the column of the overhead spindle should not be substantially more serious than the effect of temperature-variation on the indicator stand used in conjunction with the rotating table.

4. Moore Universal Measuring Machine Spindle

NEED FOR AN ACCURATE SPINDLE

It is absolutely essential that any measuring machine employed for *accurate hole location* be fitted with a spindle that rotates *true*. The importance of this requirement, often overlooked, is demonstrated in Figs. 432 and 433. In Fig. 432, the spindle does not have a constant center of rotation, shifting from *C1* to *C2* on every other revolution. In Fig. 433, the spindle does not rotate true. Both examples reveal that when aligning the axis of the spindle with

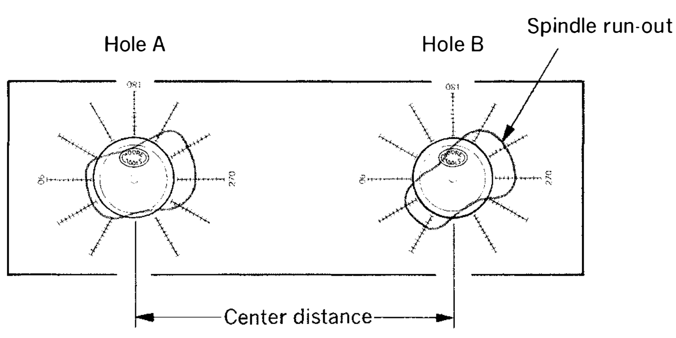
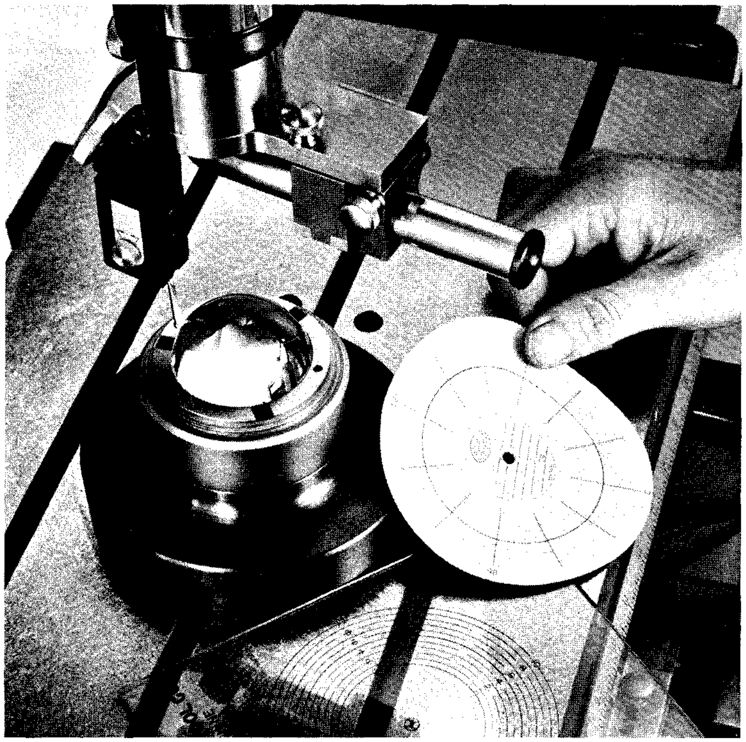


FIG. 433—*This spindle does not rotate true, causing uncertainty of actual center-distance of hole "A" to hole "B".*

FIG. 434—*Accuracy of the Universal Measuring Machine spindle is verified by comparison to a master glass hemisphere, the latter round to 1 millionth of an inch [0.000025 mm]. The hemisphere itself is proved if an identical tracing results when it is rotated and compared once again to the spindle. The transparent template in the foreground is useful in analyzing polar tracings.*



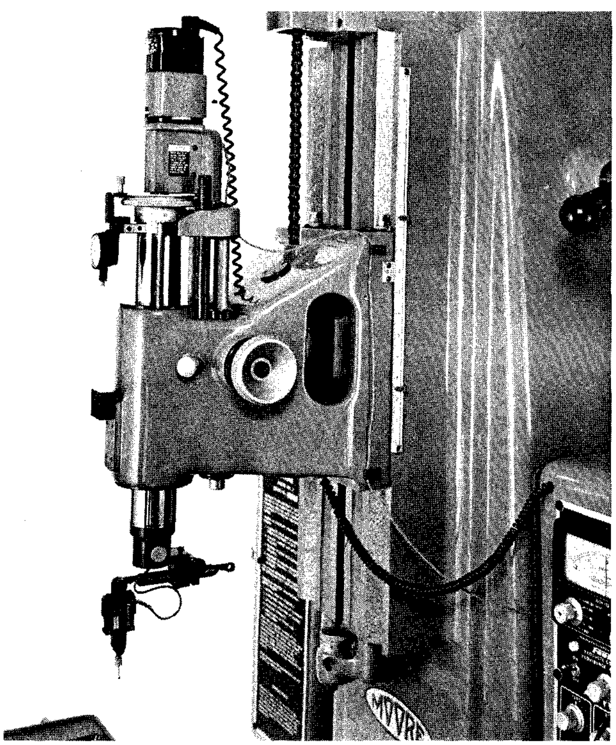


FIG. 435—*The Spindle Housing is of such a design that when used in conjunction with other capabilities of the Measuring Machine, virtually any characteristic of size, form, roundness or location may be determined to a high degree of accuracy.*

the axes of holes *A* and *B* for the purpose of measuring center distance, the error in the spindle makes it unlikely that the holes have been truly "picked up." The center distance measurement will most certainly be in error. Similarly, if the holes *A* and *B* are out-of-round, a true spindle will most accurately determine the correct centerline of the hole.

Considering that the Universal Measuring Machine measures hole location to less than 35 millionths of an inch [0.9 μm], its spindle must be accurate to a few millionths of an inch [fraction of a μm] if the 5 to 1 ratio of roundness to length is to be maintained. Accurate spindles are inspected by a master round hole, or ball, such as the glass hemisphere of Fig. 434. A polar recording is made as the spindle is compared to the master. Accuracy of the ball is self-proved by turning it 90° and making a second polar chart. If the ball is not perfect, its error is shown displaced 90° on the second polar trace.

MEASURING MACHINE SPINDLE HOUSING DESIGN, Fig. 435

Spindle and Quill

The two main elements of the Measuring Machine spindle are the spindle shaft and the quill. The tolerance of these parts as to size, straightness, and roundness is to a few millionths of an inch [fraction of a μm]. Although the housing bore, the spindle shaft, and quill ID and OD are all ground accurately, especially as to straightness, the final accuracy can only be achieved by hand lapping, Fig. 436. Lapping produces an inherent accuracy that so far seems to be unattainable by alternative methods of machine generation. The reason for the superiority of the lapping process is that an averaging effect takes place. The random motion of the lapping produces surfaces rounder and straighter than either the lap or the part is to begin with, Fig. 437.

FIG. 436—*Final accuracy of spindle housing elements is achieved by hand-lapping. Spindle housing is mounted vertically while its bore, consisting of two hardened and ground bushings, is lapped round, straight and to size.*

Of course, accuracy is only attained if the results of the lapping can be precisely determined at each stage. In Fig. 438, the spindle shaft is being measured for size and uniformity over its full length, following a lapping operation. In Fig. 439, the ID of the quill is inspected by an air gage in reference to a master ring gage.

Between the spindle shaft and the quill ID are four hundred, ⅛ inch [3 mm] diameter balls held in a brass retainer, Fig. 440. To establish the correct preload, the size of the balls must be determined precisely. Uniformity of ball size is also a prerequisite to rotational accuracy of the spindle.*

Balls of ⅛ inch [3 mm] diameter are used as a thrust between a collar on the spindle, and a shoulder on the quill to enable spindle rotation free of axial camming.

The quill assembly slides vertically within the housing, guided by two lapped sleeves. Clearance is held to a maximum of 50 millionths of an inch [0.0013 mm], allowing only enough space for oil film thickness.

The Yoke

The spindle is elevated and lowered by means of a separately guided yoke assembly. The yoke has a double rack and integral guide rods, and acts upon the spindle through a non-influencing pivot.

Normally, instead of such a yoke design, a spindle is elevated and lowered by a pinion which works against a rack set into the quill itself. By eliminating the rack from the spindle, accuracy is enhanced three ways:

1. It allows more perfect geometry of the quill to be established in lapping.
2. The rack and pinion do not distort the spindle when it is elevated or lowered.

*Many other designs were tried and discarded before that described here was adopted. For example, a plain bearing oil-film spindle was found to develop an oil-wedge, causing a shift in spindle axis on every other revolution. The conclusion was reached that this is a characteristic of this type of design.

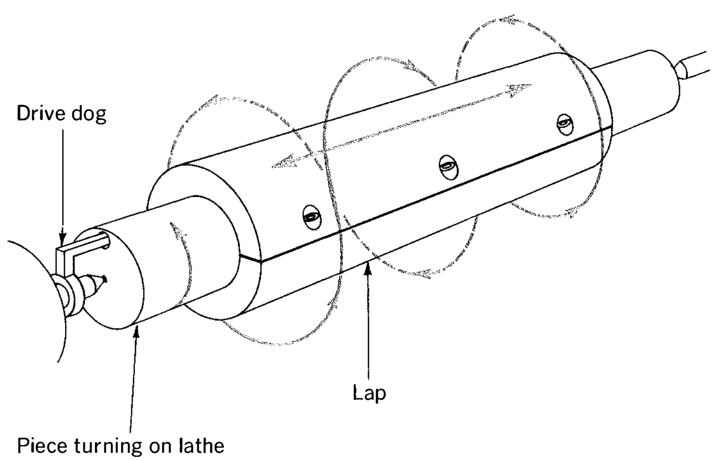


FIG. 437—*The random motions which are imparted during the lapping process produce an averaging effect, resulting in shapes which are superior in roundness, straightness, uniformity of size and finish.*

FIG. 438—*Following a lapping operation, size and taper of the spindle shaft are inspected using an electronic indicator and stand.*

FIG. 439—*The lapping operation is performed in conjunction with accurate gages. Here the size of the inside diameter of the quill is determined by comparison to a master ring gage, using an air gage.*

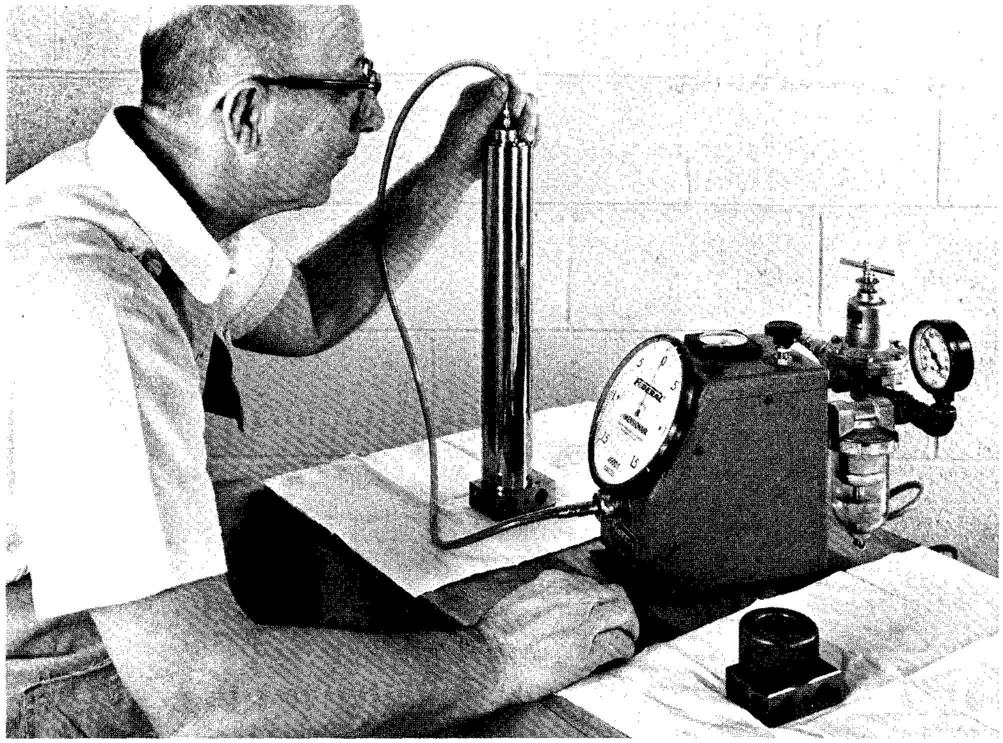


FIG. 440—*Several hundred balls of identical size under an exact pre-load are used in the Universal Measuring Machine spindle. The balls are being loaded in a brass retainer.*

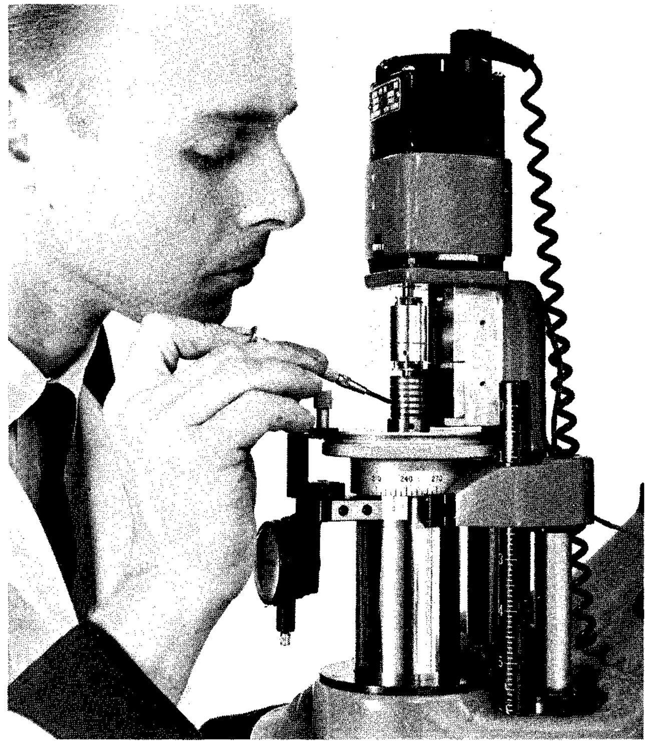


FIG. 441—*The slip ring allows an electrical signal to be passed from the gage head of the electronic indicator to the display meter mounted on the column of the machine. Electrical contacts must be frictionless lest spindle rotation be influenced.*

3. The guide rods and guide-rod bushings, accurately made and located, prevent rotational movement of the quill during its vertical adjustment.

The quill and yoke design described makes it possible to attain a vertical quill movement which is straight, aligned with the spindle housing travel, and square to the table top.

Rotation of the Spindle

The spindle is rotated by hand through a knurled knob at the top of the spindle for normal measuring applications, such as hole location or exploring the geometry of a hole. When a roundness measurement is made, the spindle can be trammed under power at the rates of ½, 1, 2, or 4 revolutions per minute. A slip ring passes the signal from indicator gage head to amplifier, to allow for continuous rotation in one direction without the inconvenience of an electric cord wrapping itself around the spindle. The slip ring is positioned at the top of the spindle (the cord passes through the hollow spindle) to avoid using up spindle nose to table height. The design of the slip ring, Fig. 441, prevents the slightest influence on spindle rotation.

Spindle Housing Travel

The spindle housing is elevated or lowered by a large handwheel at the right of the column. Although primarily an adjustment to accommodate larger workpieces, the housing travel is accurate and straight (60 millionths of an inch over 17 inches [0.0015 mm over 432 mm]). It is often convenient to have an accurate vertical movement beyond the range of vertical adjustment of the quill. For example, the inside diameter of the large stainless steel part in Fig. 442 is measured top and bottom for concentricity and straightness.

The construction features outlined assure that there is "good geometry" of the movable elements of the spindle housing in the

FIG. 442—*An accurate spindle housing travel at times proves convenient when the piece to be measured requires a range of vertical adjustment beyond that of the quill alone, such as with this large stainless steel part.*

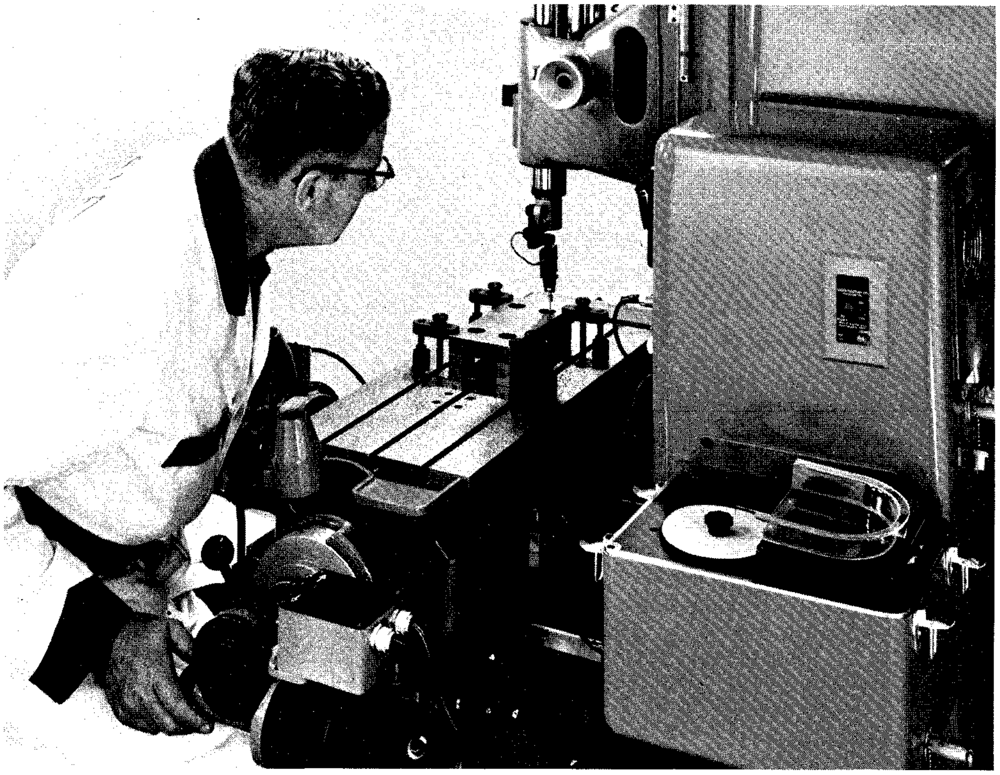
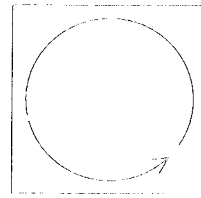


FIG. 443—*The polar recorder, fastened to the right of the Measuring Machine, allows a permanent graphic record to be made of part features, such as roundness.*

The Universal Measuring Machine, thus equipped, can measure all required features of the part shown, such as hole size, location, roundness, straightness, squareness, and concentricity.



process of coordinate measurement, contributing to overall accurate performance.

Polar Recorder

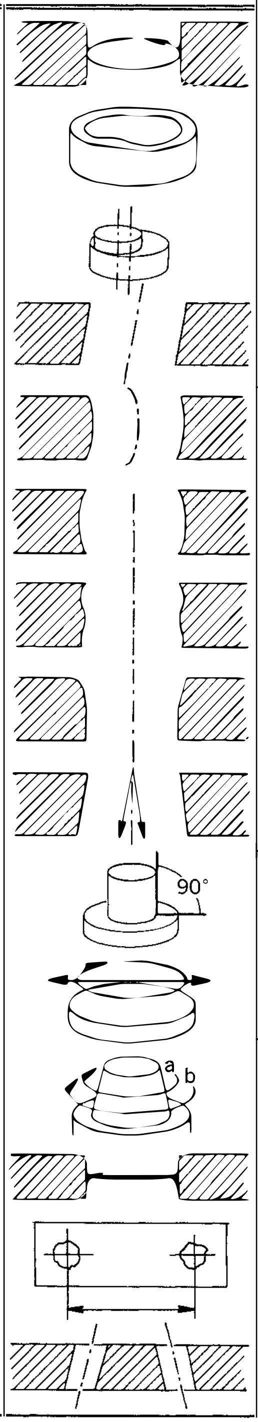
The polar recorder, Fig. 443, fastened to the right of the Measuring Machine, has rotational speeds synchronous to that of the Measuring Machine spindle. It produces a permanent graphic record of roundness, or other features of a part, such as concentricity, squareness and taper.

5. Not Just Roundness, but Geometry

Only recently has it become apparent that roundness specifications are a necessity. This may explain the present preoccupation with roundness considerations, often to the exclusion of other equally important geometric features of a part.

Out-of-roundness may not be the dominant error of the part. The fact that a hole is *tapered* by 20 millionths of an inch [0.0005 mm] may be much more significant than being out-of-round by only 3 millionths of an inch [0.00008 mm]. As previously observed, however, it was not until the late 1960's that design features were included in roundness instruments to enable some of these additional geometric features to be measured. Although the Universal Measuring Machine was designed primarily to measure coordinate location, it was ten years ahead of roundness instruments in having the capability of measuring *complete hole geometry.*

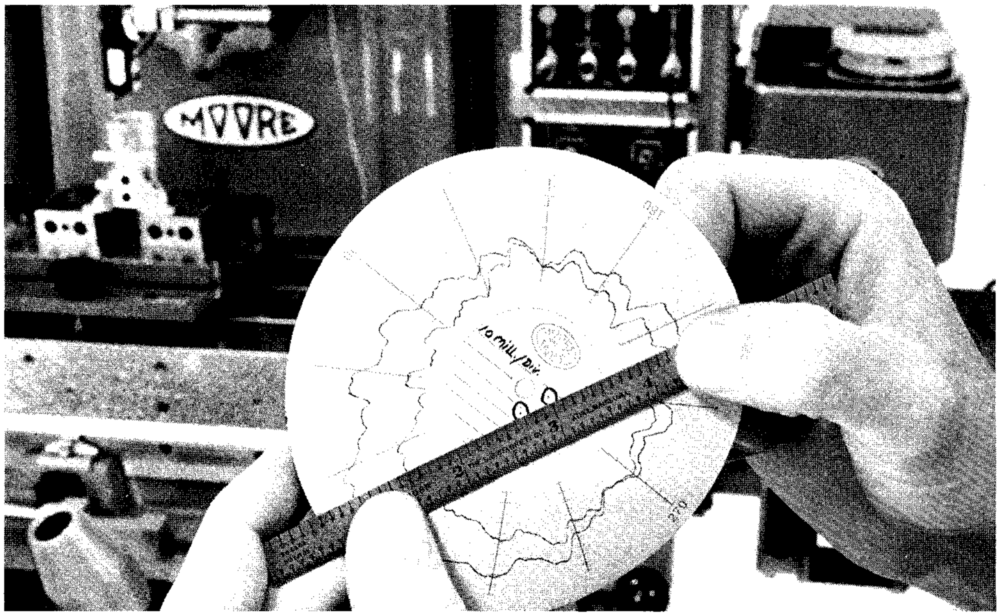
The significance of this point is best understood by reference to Fig. 444, which contains a comparison of the inherent capability of the rotating table, the overhead spindle and the Universal Measuring Machine to inspect various characteristics of form. An example of location relative to roundness is given in "Universal Measuring Machine Techniques and Applications," page 285.



Characteristic of form to be inspected	Overhead spindle (With no auxiliary vertical or horizontal movement)	Rotating table (With no auxiliary vertical or horizontal movement)	Universal Measuring Machine
Roundness	●	●	●
Camming	●	●	●
Concentricity	●	●	●
Alignment	●	●	●
Straightness (directly)	Only with auxiliary accurate vertical movement		●
Barrel shape			●
Hour glass			●
Bell mouth			●
Taper			●
Squareness	Only by sliding workpiece (overhead spindle) or indicator and stand (rotating table) or with auxiliary horizontal movement		●
Flatness			●
Relative size			●
Absolute size			●
Location (relative to roundness)			●
Lean (relative to other part features)			●

FIG. 444—*Three devices, the rotating table, the overhead spindle, and the Universal Measuring Machine, are compared as to their inherent ability to inspect various geometric forms relating to "roundness."*

FIG. 445—*Concentricity of two diameters is shown being measured on this polar tracing. The center of each diameter has been established by centering the glass template in turn over each tracing, then piercing the chart with a pin through a hole in the center of the template.*



MEASURING MACHINE FOR THE INSPECTION OF HOLE GEOMETRY

The advantage of the Measuring Machine when used for the inspection of geometry of a hole, cylindrical shaft, or other round forms is that, in addition to a highly accurate spindle rotation, all movements of the quill and housing are straight and parallel. Also, these movements are mutually square to the table top and to the plane of travel of the base slideways.

Thus the Measuring Machine spindle, rotated by hand, shows roundness. Moreover, when used to probe along the length of a hole (or outside diameter), it shows the "shape" of any side. In this straightforward manner, taper, squareness, concentricity and straightness are measured directly. This type of inspection is oftentimes much easier to interpret and more enlightening than a polar chart.

Where a graphic record is desired, however, these same geometric features may be shown on a circular chart using the Polar Recorder. For example, Fig. 445, concentricity of two diameters at different heights is determined by making a polar trace on the first diameter, then adjusting the quill vertically to make a trace of the other on the same chart. The transparent template is balanced out over the circular tracing representing each diameter, after which the graph paper is pierced through a pinhole in the center of the template. Lack of concentricity is then shown by the separation of the pinholes with an ordinary tool-maker's scale. Such a measurement might appear crude until one remembers that the forms are represented at up to 20,000× magnification.

Very sensitive slideway movements of the Measuring Machine may be introduced at will where needed. For example, probing a shoulder for flatness, or centering a part under the spindle can be accomplished

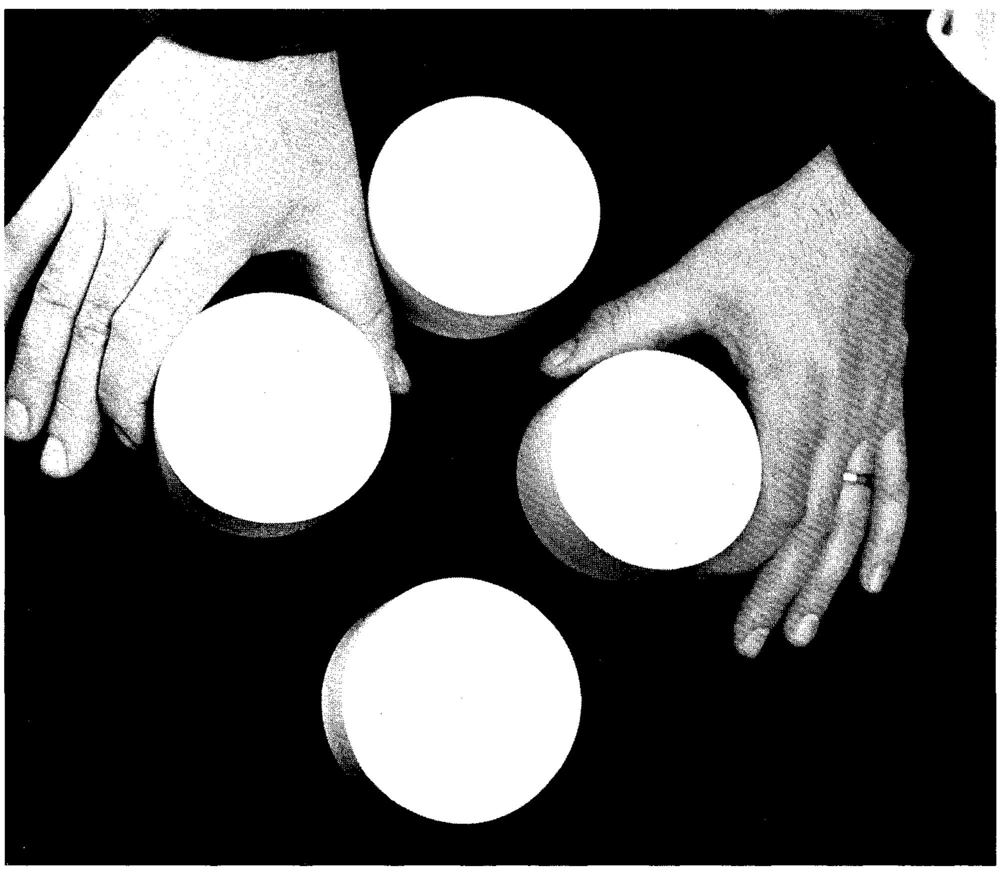


FIG. 446—*There are errors of flatness on the faces of these models of lathe-turned pieces prepared by the Lawrence Radiation Laboratory of the University of California. The nature of the error has been deliberately obscured, as it would appear to the inspector.*

without loss of orientation of spindle to part. An interesting example of the need for this latter capability can be demonstrated by models.* These models represent exaggerated errors which might occur in lathe-turning.**

Fig. 446 shows the four lathe-turned models, their errors deliberately obscured as it would be to an inspector. In Fig. 447, the most interesting of the samples is mounted on a Moore rotating table-type of spindle. An indicator probe is registered on the outside diameter, for measuring roundness. It is apparent, however, that if polar tracings are made at only concentric circles from center on the top surface (one of which is represented by the dotted line), the piece would appear "flat." Yet the top surface is obviously *not* flat. The top of the piece could be inspected for flatness by simple surface plate methods, such as the lathe-turned aluminum piece of Fig. 448. However, when the piece is removed from the roundness-checker for inspection by totally different means, various part features, including the relation of the top face to the outside diameter are not correlated.

Fig. 449 shows the four models mounted on the Universal Measuring Machine table where a variety of movements—rotational, vertical and horizontal—can be made. In addition, *all such movements can be related.* With this capability, virtually no geometric irregularity goes undiscovered.

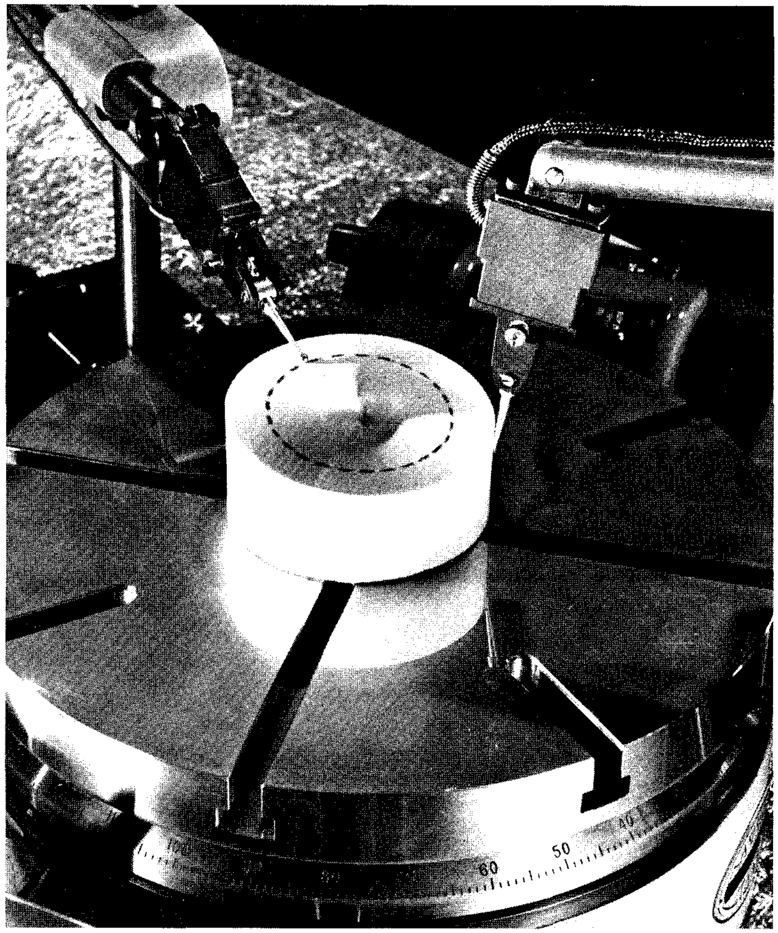
In Fig. 450, an actual part (outer race of rotary table spindle), requiring these capabilities, is mounted on the Universal Measuring Machine. The indicator probe is positioned for a circular trace of the shoulder by spindle rotation; taper (squareness) and flatness of the shoulder are inspected by

*Loaned by James Bryan, Chief Metrologist of the Lawrence Radiation Laboratory, University of California.

**James Bryan, *et al.*, "Spindle Accuracy," *American Machinist*, December 4, 1967.

FIG. 447—*The most interesting sample prepared by the Lawrence Radiation Laboratory is one that has circular flatness over concentric circles of any diameter from center, represented by the inked-in dotted line.*

Overall, the piece is not flat. Accurate spindles, such as the Spin Table, show roundness of the outside diameter. Overall flatness is shown only by manually sliding the piece.



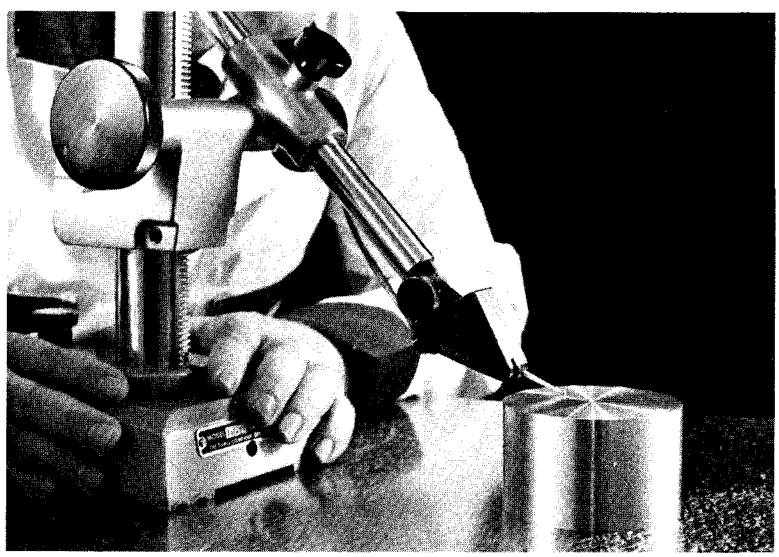
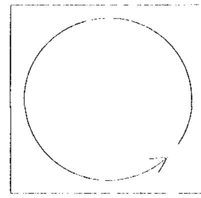
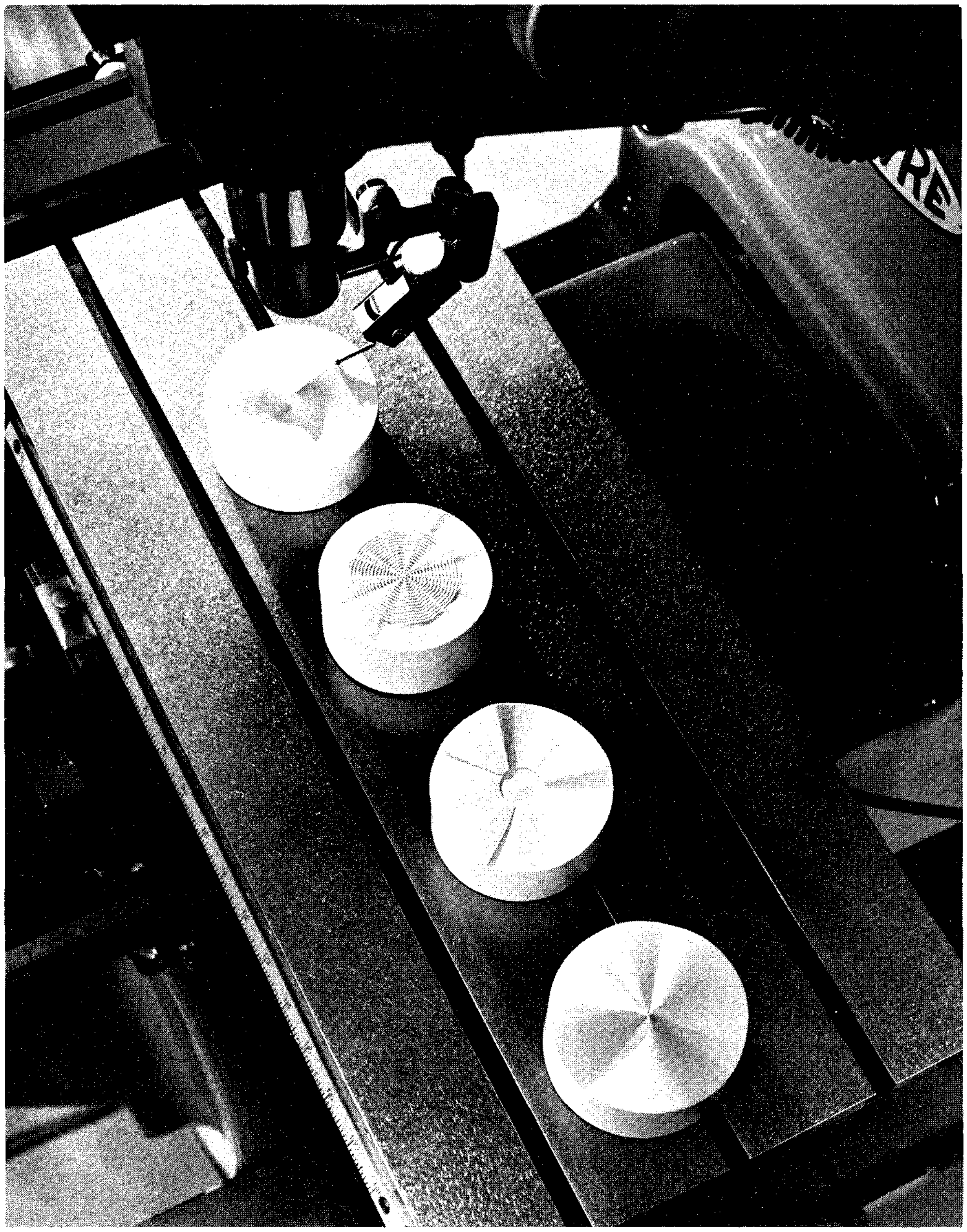


FIG. 448—*Flatness may be inspected separately from roundness by means of a surface plate, indicator and stand. When inspecting circular parts, however, as with this aluminum lathe-turned piece, other geometric features are not clearly related.*

FIG. 449—*The models mounted on the Measuring Machine Table represent exaggerated forms of typical errors which may occur in surfaces generated by turning. They clearly illustrate why related vertical and horizontal movements are required in addition to spindle rotation when measuring circular forms.*
Models courtesy of James Bryan of the University of California, Lawrence Radiation Laboratory.





traversing the X-axis across the shoulder width. Other irregularities, as in the demonstration models, are inspected by moving both X and Y axes to probe anywhere around the shoulder. All other geometric features—roundness, straightness, flatness and concentricity—are inspected *without moving the piece.* Moreover, the *size* of the hole, top and bottom, and the size of the outside diameter are also inspected and can be correlated with overall hole geometry.

Fig. 451 shows roundness and size of the outer race of an angular contact ball bearing being determined. In Fig. 452, the bearing race is mounted vertically on a form of V-block; a bent probe is employed. The piece is held in place with only light spring pressure, so that it may be rotated by hand to determine race geometry and size at any cross-section. To the right are a pick-up block and wrung-on gage block, necessary to relate the indicator probe offset to the spindle when measuring size.

Hole location, where required, may be correlated with size and roundness, *all to virtually gage block accuracy.* The techniques employed with the Measuring Machine for establishing location and size as well as other uses are explained more fully in "Universal Measuring Machine Techniques and Applications," pages 287–319.

6. How to Define Roundness?

RELATION TO SURFACE FINISH

Unfortunately, as noted with the definition of "surface finish," "roundness" has no universally accepted set of standards. In fact, surface finish itself becomes a consideration in gaging roundness. For example, it may be decided in the case of a lathe-turned piece, that the helical grooves which are typically produced in that operation only relate to texture, not to actual out-of-round. It may also be decided that the probe tip used be of greater radius, so that the crest and root of the grooves are spanned, giving a truer picture of roundness, Fig. 453.

In analyzing a ball-bearing race for roundness, however, even finer considerations of surface texture are important criteria. It may be desirable, for example, to have a probe tip of smaller diameter, Fig. 454.

In each of the two examples cited, roundness values may be altered depending on the methods employed.

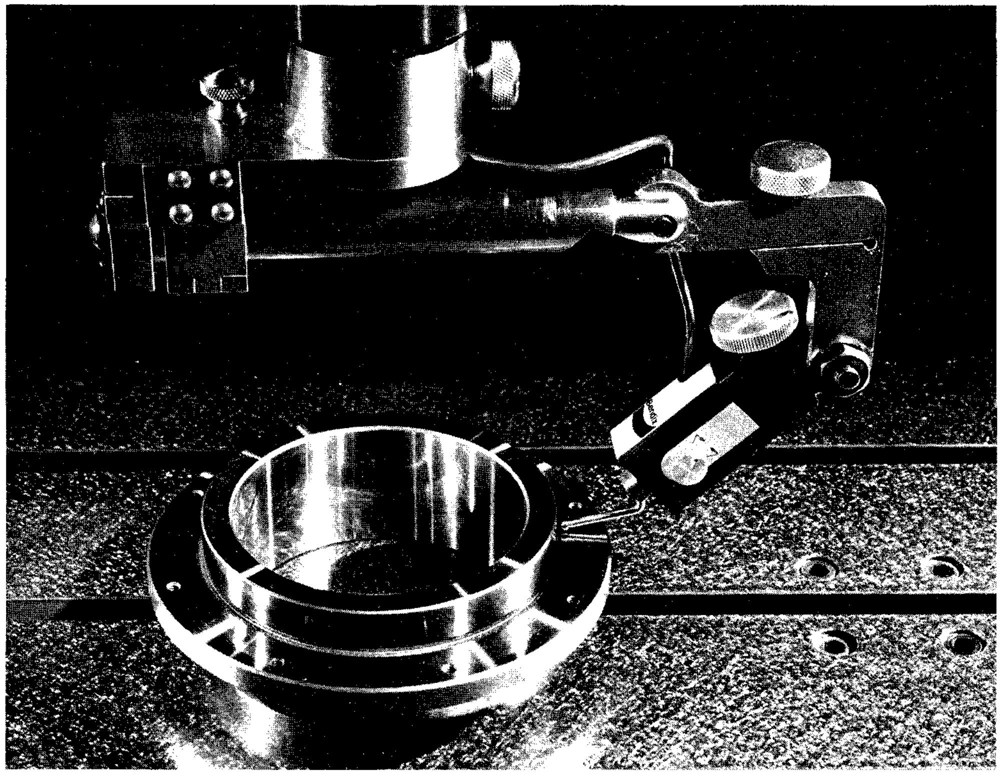
DEFINITIONS OF ROUNDNESS COMPARED

The definition of roundness is a highly complicated matter. It is not the purpose of this text to discuss the subject in great detail nor its relation to the allied subject of surface texture. However, it is instructive to briefly describe a few of the proposed definitions as well as the problems which may accompany any attempted definition.

Assessments of roundness most often relate to polar tracings produced by a roundness-checker. Although it is generally agreed that *radius*, not diameter, should be the basis of roundness measurement, this one premise may still result in different interpretations.

Some authorities, notably those in Germany, propose a "zonal" method where (1) the out-of-roundness value is the greatest deviation from the largest *inscribing* circle (a hole), Fig. 455; (2) out-of-roundness is the greatest deviation from the smallest *circumscribing* circle (a shaft), Fig. 456; or (3) out-of-roundness may be defined as the difference in radius of two concentric circles (having the same center), Fig. 457, one of which is the maximum which can just lie within the tracing and the other the mini-

FIG. 450—*An actual part requiring geometric accuracies on all surfaces. In addition to its accurate spindle for measuring roundness, the Universal Measuring Machine has accurate horizontal and vertical movements to reveal any geometric irregularity.*



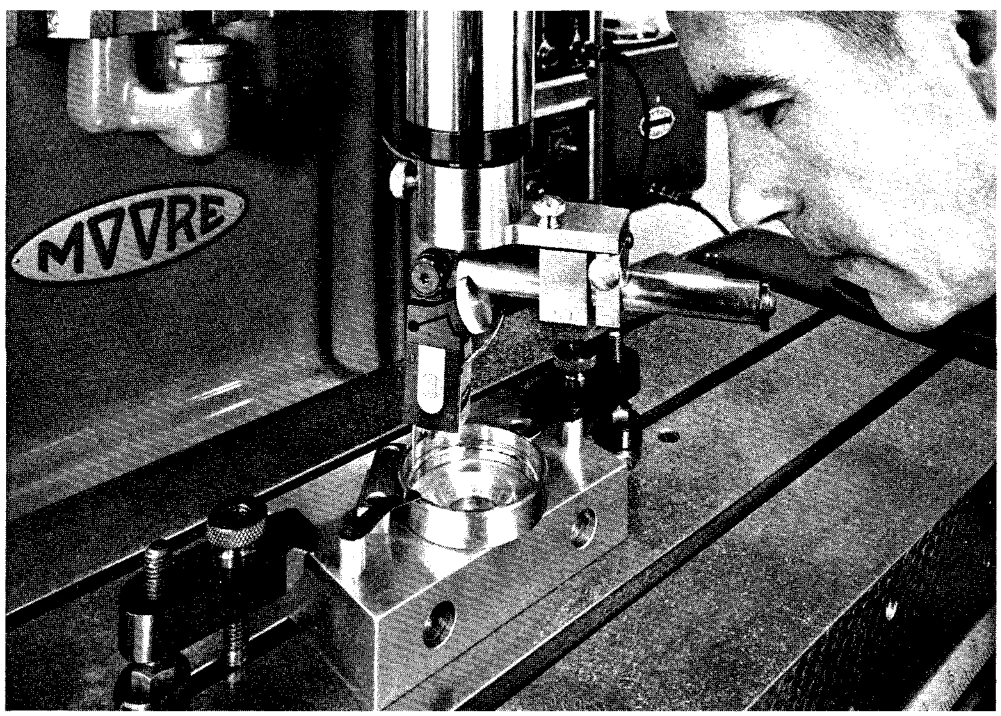


FIG. 451—*Roundness and size of a ball-bearing outer race are inspected on the Universal Measuring Machine.*

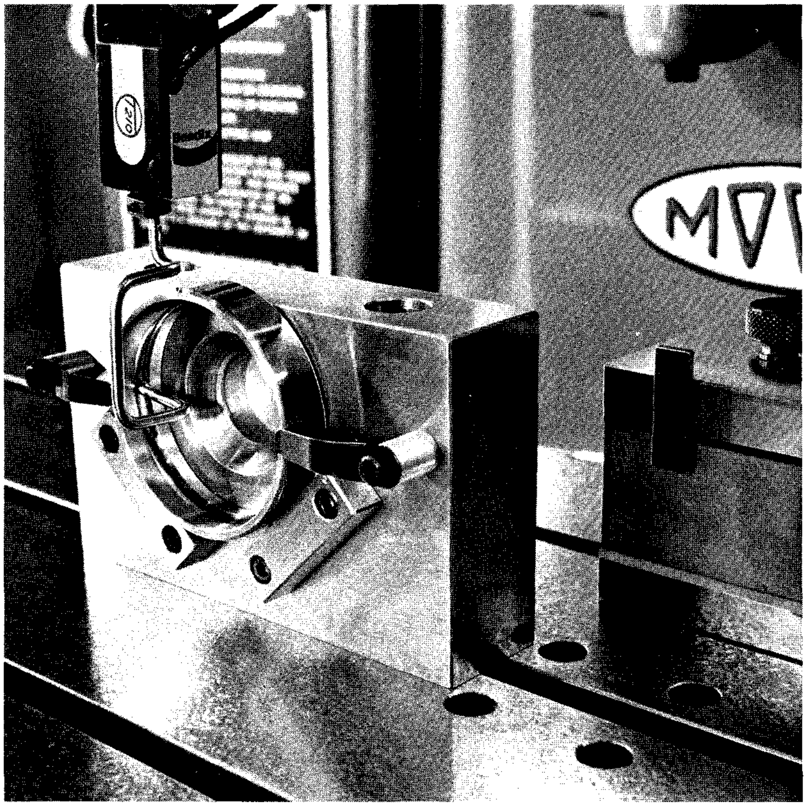


FIG. 452—*The ball-bearing race is mounted vertically and a cross-section of the ball-bearing race is measured for roundness and size, using a bent probe. Note the pick-up block and wrung-on block (right) used when measuring size (the gage block is required only to obtain a flat reference edge).*

mum which can lie just without the tracing.

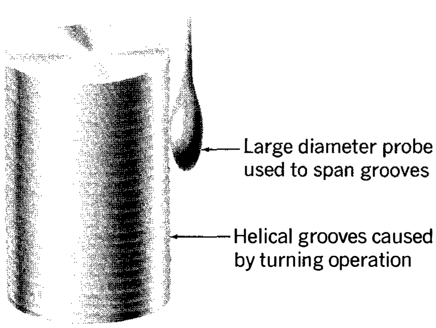
Others propose that the *difference in diameter* between the largest inscribing and smallest circumscribing circle is the amount of out-of-roundness, Fig. 458.

Some metrologists in the United States favor a "maximum radial deviation" definition of roundness, essentially the same as the zonal method. R. E. Reason* points out that with the zonal method, it must be specified whether the chart is of a hole or a shaft, since each may have a different center, and thus different values may be obtained. The point is borne out by comparing the tracings of Figs. 456, 457 and 458. Reason shows that under certain circumstances, the "radial" method also lacks a unique center. Perhaps because of these discrepancies, England has officially adopted the more mathematically precise "mean circle" definition, or that of "... a circle such that the sum of the squares of equally spaced ordinates measured from it has a minimum value," as originally suggested by R. E. Reason,** Fig. 459. The advantage of this system is that it does have a unique center. Its disadvantage is that it does not necessarily relate as well as radial methods in utilizing roundness measurements to determine *effective* size. The "mean circle" definition is not that helpful in determining, for example, where the axis of a shaft is most likely to be located in a hole.

An approximation of the mean circle may be made by using transparent template or pencil compass. However, a true interpretation of values requires use of elaborate computer instrumentation, indicating that this definition cannot be as universally applied, particularly for ordinary workshop requirements. This definition, for

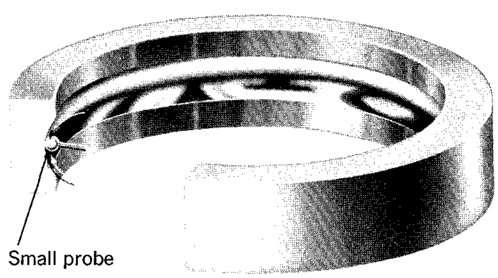
*R. E. Reason, "Some Basic Principles of Surface Metrology," Engis Equipment Co., Chicago, Illinois, October 1, 1960.

***Ibid.*



Lathe turned piece

FIG. 453—*A large-diameter probe may be preferred when measuring the roundness of lathe-turned pieces so that the helical grooves typically produced in feeding the tool (surface finish) are excluded as much as possible from actual roundness.*



Ball bearing race

FIG. 454—*When measuring the roundness of a ball-bearing race, a small-diameter probe may be preferred so that more local variations (surface finish) are included in the roundness inspection.*

example, is not easily applied to visual assessments of roundness using only spindle and indicator.

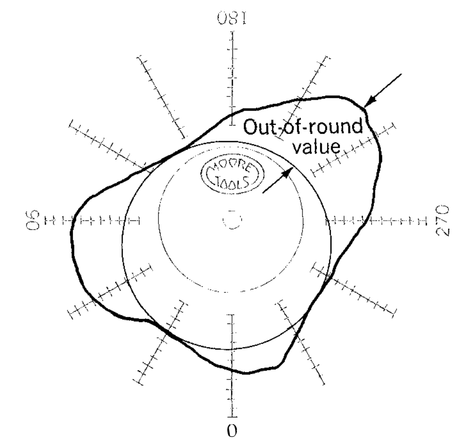
The preference of United States officials was given in "Military Standard Dimensioning"—MIL-STD 8 C, Oct. 1963. From *1.3.16 Roundness Tolerance*—"A zone defined by two concentric circles, within which an actual surface must lie."

This definition is qualified in 7.6.10.1: ". . . either the difference in diameters of two concentric circles . . . between which the surface so toleranced must lie (diametral method) or the width of the annular zone between such concentric circles (radial methods)."

From 7.3.5 relating to true position and roundness, "Either . . . may be specified. Such abbreviations or terms as DIA, TOTAL, WIDE ZONE, TIR, ON DIA. must be used in symbols and notes to indicate that the total tolerance has been specified for true position, concentricity or roundness." Such symbols as R, EITHER SIDE, or ON R are used for "half tolerance" on roundness. Where either is not specified it will be interpreted as on "diameter."

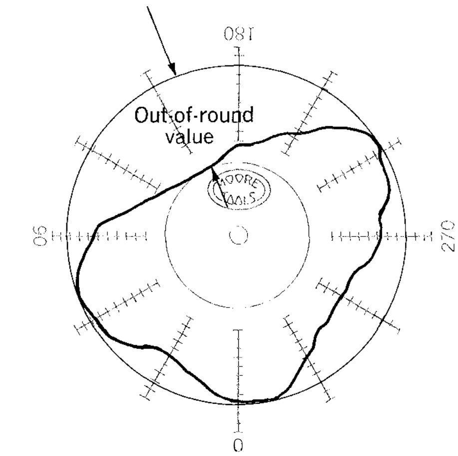
The introduction of the term "diameter" in the above definition may be misleading, since without careful perusal, it could connote an acceptance of *diametral methods* of checking roundness. This, of course, was not intended.

Use of the concepts of "total zone," or the difference in diameters of concentric circles, however, is convenient in that approximately the same dimensional *value* can be used when describing the roundness of parts, whether inspected by diametral methods or by a precision spindle. Such is not the case when "radial deviation" is used since this is a "half-tolerance." "MIL-STD-8," then, appeared at least to favor the "zonal method," while giving flexibility to the specifier as to whether it is a "diametral" or "radial zonal" deviation that is called out.



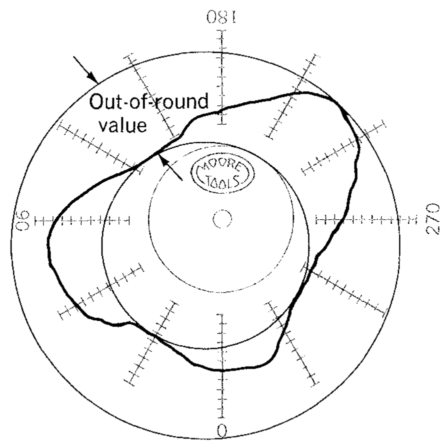
Inscribing circle (hole)

FIG. 455—*(top left) The zonal method, favored by many in continental Europe, is sometimes recommended for defining roundness. When describing roundness of a hole, deviation should be related to the largest inscribing circle.*



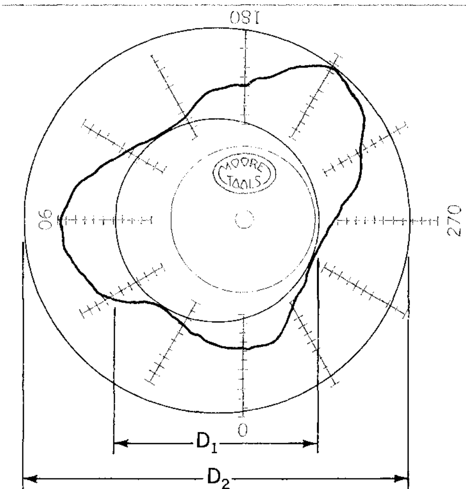
Circumscribing circle (shaft)

FIG. 456—*(top, right) When the zonal method is used to describe the roundness of an outside diameter, then the deviation should be related to the smallest circumscribing circle.*



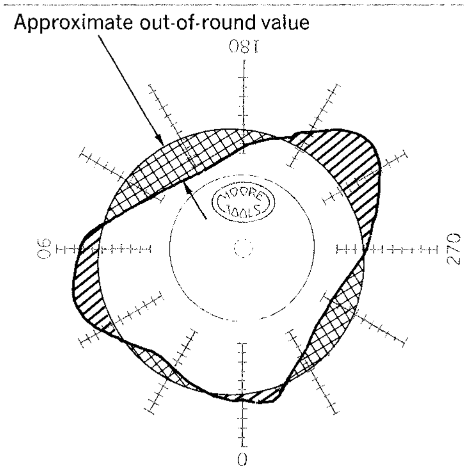
Two concentric circles (on radius)

FIG. 457—*(center, left) Out-of-roundness may also be described in terms of the difference in radius of two concentric circles, one being the maximum which can be inscribed within the tracing, the other being the minimum which can be circumscribed about the tracing.*



Two concentric circles (on diameter)
$D_2 - D_1$ = Out-of-round value

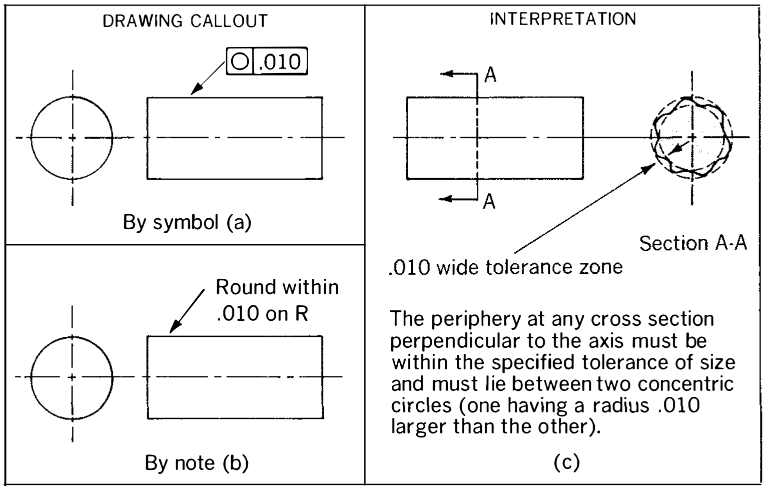
FIG. 458—*(center, right) Roundness may be defined as the difference in diameter of two concentric circles, one a maximum (within the tracing), the other a minimum (without the tracing).*



Mean circle

FIG. 459—*(bottom, left) The "mean circle" definition of roundness is officially sanctioned in England. The advantage of this system is its unique center. Its disadvantages are that it (1) does not by itself relate as clearly to function; (2) is not as universally applied.*

FIG. 460—*The United States standard of roundness. Diagrammatic of United States Standard Drafting Practices, Dimensioning and Tolerancing for Engineering Drawings (USASI Y14.5-1966).*



In a notice of January 1, 1968, "MIL-STD-8 C" was inactivated and superseded by USASI Y14.5-1966. According to "U.S.A. Standard Drafting Practices, Dimensional Tolerancing for Engineering Drawings, USASI Y14.5-1966"—*5.5.4 Roundness Tolerance:* ". . . a roundness tolerance specifies a tolerance zone bounded by two concentric circles in that plane within which the periphery must lie . . . ." It is noteworthy that no mention is made in the USASI definition of "Diametral" or total deviations, but it has not been determined if this method is *excluded.* The interpretation of *that* tolerance as applied to a cylinder is shown in Fig. 460. Size, it should be observed, is also made part of the specification of roundness. Roundness of cones, cylinders and spheres is interpreted similarly.

Neither the inactivated MIL-STD-8C nor the USASI definition of roundness attempt to resolve some of the finer aspects relating to the definition under varying conditions. At the time of writing, committees of the U.S.A. Standards Institute are involved in composing an acceptable, more comprehensive definition of roundness. Any forthcoming definition, however, would be expected to include specifications for defining the trueness of a spindle.

The disturbing element in this lack of agreement on standards is that the roundness of a part or trueness of a spindle cannot be judged or compared unless an accepted definition of roundness is made. To illustrate, Fig. 461 shows three methods of specifying roundness, as applied to a polar tracing. It is most revealing that a part may be represented as approximately 80 millionths of an inch, 40 millionths of an inch, or 20 millionths of an inch [0.002 mm, 0.001 mm or 0.0005 mm] out-of-roundness, *depending on the method used for specifying roundness.* The need for universal agreement on a definition of roundness is apparent.

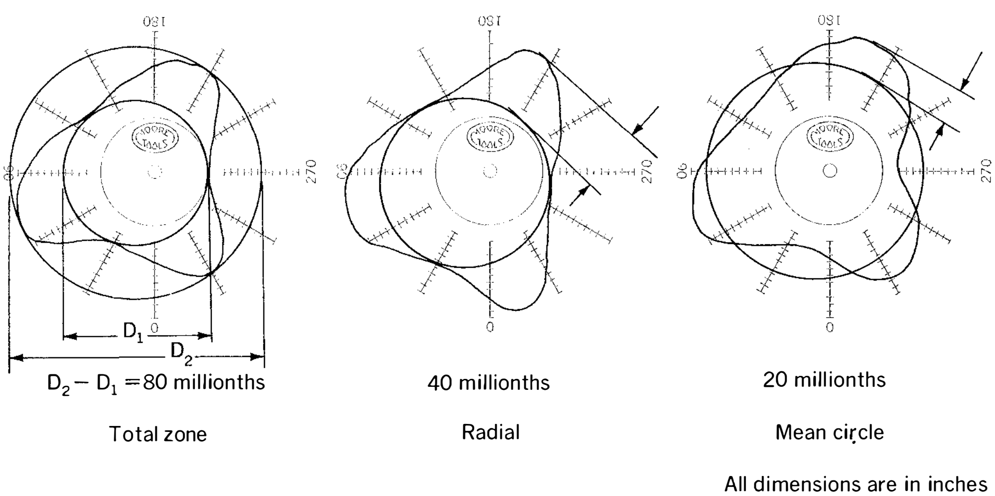
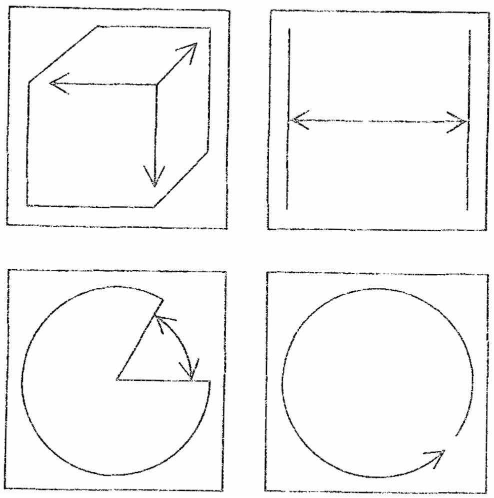


FIG. 461—*Three different methods of specifying roundness are applied to the same out-of-round part.*

Depending on the definition, out-of-round may be approximately 80 millionths of an inch, 40 millionths of an inch, or 20 millionths of an inch [0.002 mm, 0.001 mm, or 0.0005 mm].

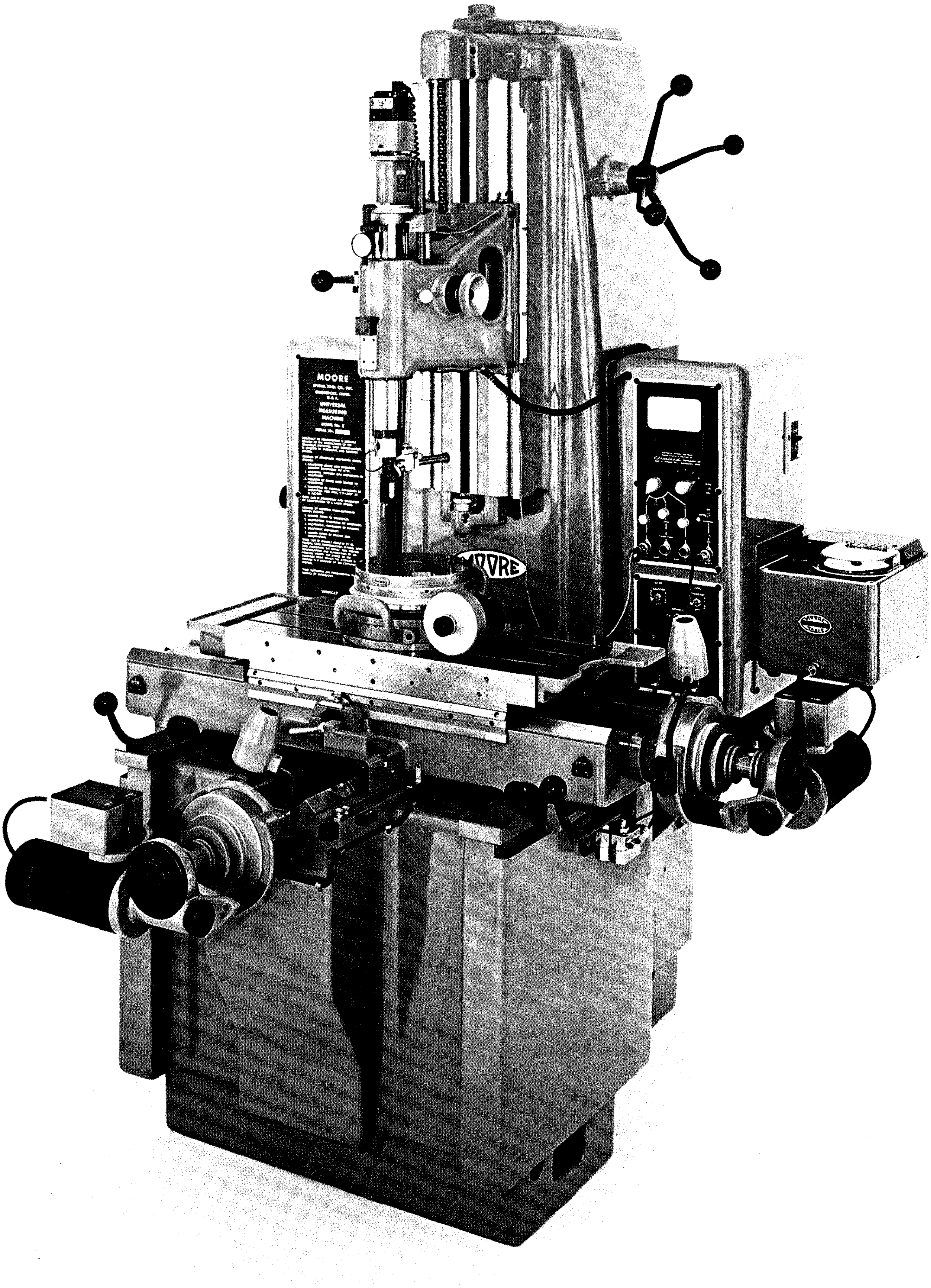
UNIVERSAL MEASURING MACHINE TECHNIQUES AND APPLICATIONS

5



The No. 3 Universal Measuring Machine represents the four mechanical arts brought to their highest level and embodied within a single facility.

FIG. 462—*The No. 3 Universal Measuring Machine is shown with the 1440 Small Angle Divider mounted on its table and the polar recorder fastened to the right. When the four mechanical arts—geometry, length, dividing the circle and roundness—are each brought to their highest level and used in combination in this single facility, a unique measuring capability results.*


MOORE
MOORE

1. The Philosophy of the Universal Measuring Machine Use

From the time that the principle of interchangeable manufactured parts was first applied by Eli Whitney, the level attained in interchangeability has been dependent on existing measuring capability. The establishment of size and location of holes, contours and surfaces has been a most important part of the measurement scheme.

At first, tolerances dealing with *location* were to hundredths of an inch [tenths of a millimeter], then to thousandths of an inch [hundredths of a millimeter]. During World War II, dimensions began to be expressed in one ten-thousandths of an inch [μm's] tolerance, to be quickly followed in the post-war period by "split-tenths". Now, specifications of millionths of an inch [fractions of a μm] are common.

For many years, the jig borer and jig grinder could *establish* locations to millionths of an inch [fractions of a μm], closer than it was possible to *inspect* these same locations by alternative means. It was necessary that inspection move into this area of locational accuracy.

The Universal Measuring Machine, introduced for this purpose, was first thought of as only a laboratory instrument. Few firms seemed to require accuracy beyond that attainable with a jig borer. However, the tolerances which were once sought only in the metrology laboratory are now required in the manufacture of parts in the workshop. Consequently, inspection on the Universal Measuring Machine has increasingly become an integral part of the manufacturing process. It is this aspect of its application which will be stressed here.

Relationship of the Four Mechanical Arts. The foundations of mechanical accuracy have been shown to be composed of four elements: geometry, length, dividing the circle and roundness. In previous sections, they have been analyzed as if they were distinct entities. Only occasionally has attention been drawn to the relationship of one mechanical art to another—such as the importance of roundness in dividing the circle, or the effect of geometry on length-displacement of a machine tool. In actual practice, such a fine distinction does not exist.

This section, in contrast to those preceding, will examine the practical application of these mechanical arts, brought to their highest level and used in *combination* in one facility. Once combined, a nearly infinite variety of measuring tasks can be performed to a higher level of accuracy than could be attained by applying any of the arts singly.

Such a combination is shown in Fig. 462. The No. 3 Universal Measuring Machine embodies *geometry* and *length.* The 1440 Small Angle Divider mounted on its table *divides the circle.* The machine spindle, used in conjunction with the polar recorder fastened to the right of the machine, measures *roundness.*

The first part of this section will be devoted largely to the techniques utilized in measuring a wide range of sizes, forms and configurations through use of this single facility and its ancillary equipment. The last part of the section will point out the dependency of advanced measurement (as in a ruling engine) on all of the mechanical arts, working together.

Various geometric and linear accuracies which are incorporated into the Measuring Machine and which come into play in the measurement process (aside from those to do with "roundness," already described) are cited in the Measuring Machine "Certificate of Accuracy," Fig. 463.

The Universal Measuring Machine. Before describing the types of applications to which the Measuring Machine is best suited, it is important to distinguish clearly between the reasons for its selection in preference to, say, a Coordinate Measuring Machine (CMM).* Both concepts of inspection are useful, but in different ways. As stated in a previous section (page 164), the CMM is intended for rapid inspection of production parts. Since geometric features of the part are not inspected, and since the CMM is not always significantly more accurate than the machine which may have generated the part, usually it can only determine whether the parts in a production lot "pass"; if they do not pass, the CMM will not necessarily reveal *why.*

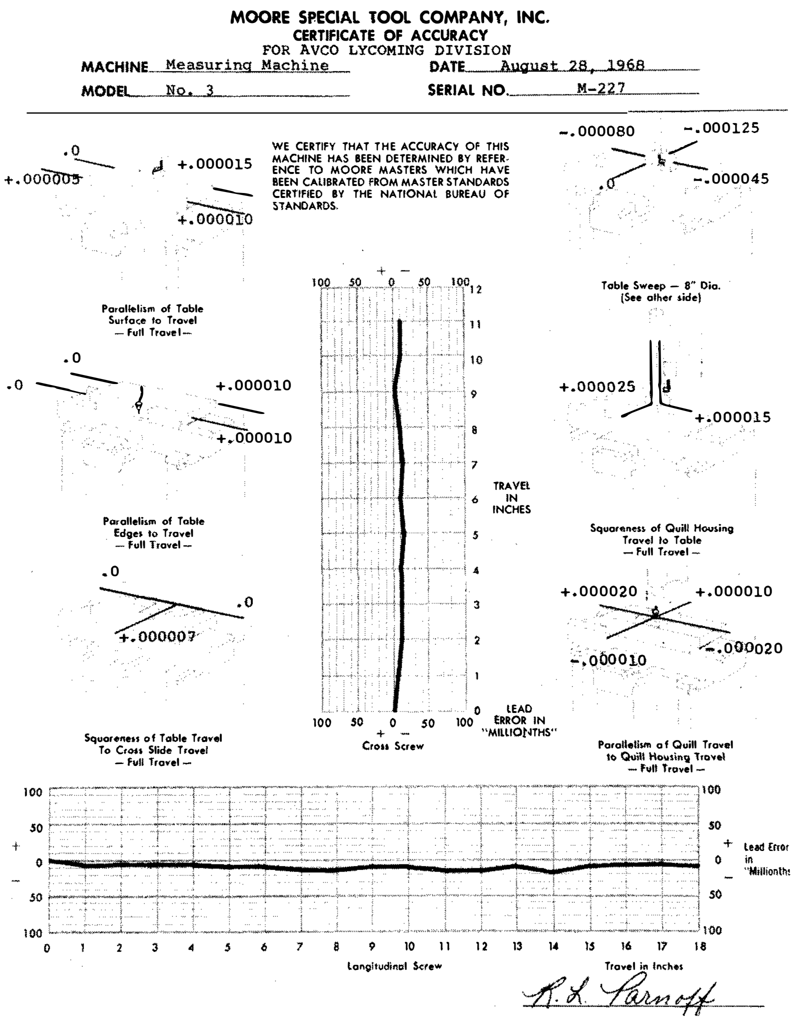
However, where quality review demands that all of the parts in a lot be inspected, the CMM has made possible a great improvement in quality control, and a great reduction in the time required for quantity inspection.

The Universal Measuring Machine, in contrast, is too slow for quantity inspection. Yet it measures many times more accurately than the machine or technique used to generate the piece, even in the case of very precise gages. For the calibration of hole location gages, it is virtually a primary standard. For example, CMMs, tape-controlled drills, and similar coordinate-system machines, are best calibrated by a hole-location gage, so that the complete system error is included. Many leading manufacturers of these machines now specify that the Universal Measuring Machine be applied on a regular calendar basis to calibrate the hole-location gage, which in turn inspects the Coordinate Measuring Machine, Fig. 464.

The Universal Measuring Machine is sometimes thought to be useful only as a "final referee," for instance when there is a disagreement as to the accuracy of a part. While there may be some satisfaction and confidence imparted in knowing that there

*"Measurement: quick vs close," *American Machinist,* July 3, 1967.

FIG. 463—*"Certificate of Accuracy" of a typical No. 3 Universal Measuring Machine, indicating built-in accuracies.*


MOORE SPECIAL TOOL COMPANY, INC.
CERTIFICATE OF ACCURACY
FOR AVCO LYCOMING DIVISION

MACHINE Measuring Machine DATE August 28, 1968
MODEL No. 3 SERIAL NO. M-227

WE CERTIFY THAT THE ACCURACY OF THIS MACHINE HAS BEEN DETERMINED BY REFERENCE TO MOORE MASTERS WHICH HAVE BEEN CALIBRATED FROM MASTER STANDARDS CERTIFIED BY THE NATIONAL BUREAU OF STANDARDS.

R. L. Parnoff

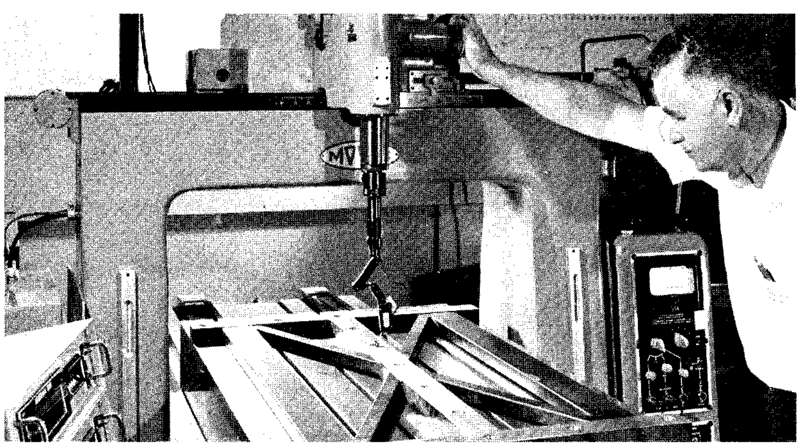
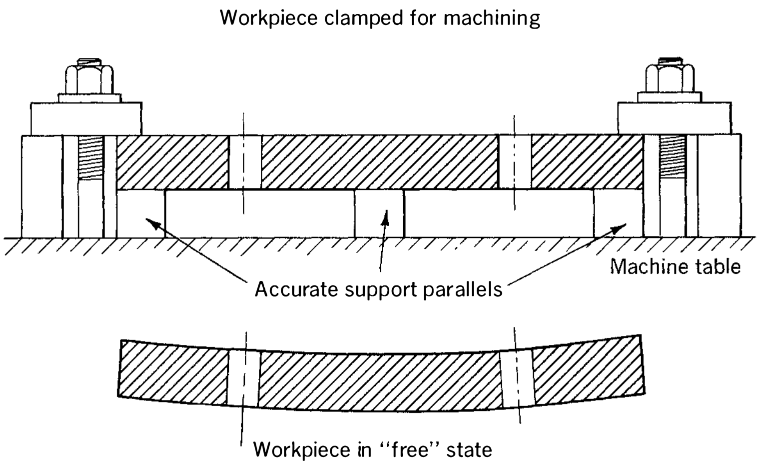


FIG. 464—*A hole-location gage used to inspect a Coordinate Measuring Machine (CMM) is calibrated on a No. 5 Universal Measuring Machine. A precision ball is the most accurate means of determining the axes of the tapered holes.*
Courtesy of Brown and Sharpe Manufacturing Company.

FIG. 465—*Locational errors in this workpiece are due to its lack of flatness. Such an error is more readily found through use of the Measuring Machine, since clamping pressure can be greatly reduced compared to that needed for machining.*



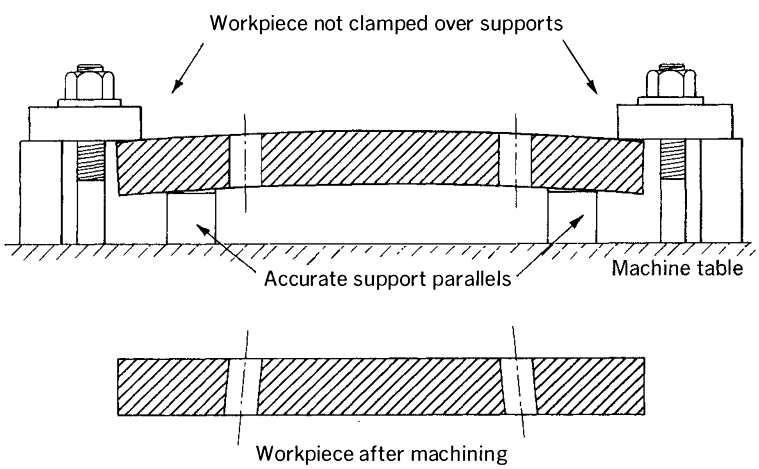


FIG. 466—*Inspection of workpiece using the Measuring Machine reveals that the holes are out-of-parallel, traceable to faulty clamping procedure in the machining operation.*

exists a means by which disagreements as to accuracy can be resolved, the applications of a Universal Measuring Machine have evolved far beyond such a narrow concept.

BENEFIT TO THE MANUFACTURING PROCESS

Any given inspection function is performed essentially for the purpose of improving the manufacturing process in some way. The objective is to make it possible for parts to be produced more accurately, at less cost, or to make them of higher or more consistent quality.

The Universal Measuring Machine does not usually make "chips." Its unique capability is in being able to resolve the exact nature of the error of all part features, regardless of complexity. The most valuable function of the Universal Measuring Machine is to disclose measurement information which in turn permits the improvement of the machines or methods by which the part is actually brought to finished form.

The manner in which the Measuring Machine may aid the manufacturing process is best understood by referring to a few examples.

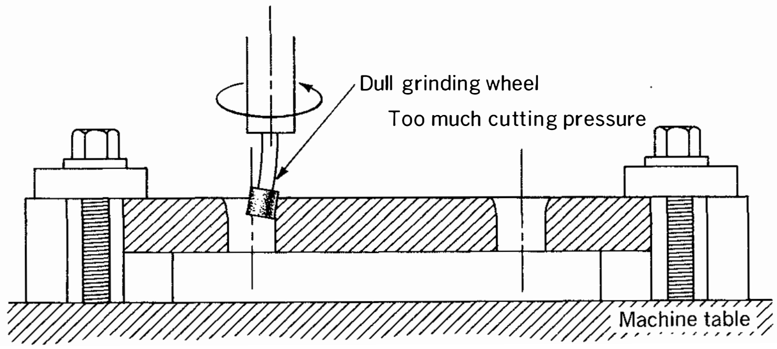
Example No. 1—Workpiece Flatness

Fig. 465. A series of holes was jig bored in a rectangular part which was clamped to accurate parallels. Without unclamping or disturbing the part in any way, hole location was inspected and found to be within tolerance.

Subsequent inspection of the part on the Measuring Machine revealed locational errors as a result of holes being out-of-parallel.

Closer inspection revealed that the piece was not flat, and had been bent flat only when clamped firmly for machining. Since the piece was mounted on the Measuring

FIG. 467—*Holes in this workpiece are to location, but of poor "geometry," caused by a dull grinding wheel and excessive wheel pressure. Such errors are easily discovered through use of a Universal Measuring Machine.*



Machine solely for inspection, clamping pressure could safely be reduced. In its free state, the holes were not truly parallel.

Solution: Improve flatness of the piece prior to machining holes to location.

Example No. 2—Clamping Distortion

Fig. 466. The workpiece was flat, yet the Measuring Machine found that the holes in the piece were not parallel. By retracing the operations performed on the piece, it was found that when the holes were bored in the piece, it was not clamped over its support, causing the holes to be out-of-parallel once the clamps were released.

Solution: The operator was made aware of the importance of clamping directly over the support parallels.

Example No. 3—Grinding Techniques

Fig. 467. Inspection with the Measuring Machine revealed that the holes in a hardened, jig-ground die were bellmouthed. The error was attributable to a dull grinding wheel and too much wheel pressure on the finish hole-grinding operation.

Solution: The operator was instructed to dress the wheel more frequently and to "spark out" on the final grind.

Example No. 4—Temperature Distortion

Fig. 468. A polar tracing made on the Measuring Machine of a relatively thin-section internally ground part revealed a three-lobed out-of-round condition. The piece had been ground while clamped over three accurate support pads.

At first, it was suspected that the error was due to distortion at the three clamping points. However, the condition was repeated with subsequent pieces even with greatly reduced clamping pressure.

It was finally discovered that uneven temperature was causing the error. The piece was cooler in the area surrounding the three support pads, where heat from

Heat flow during grinding operation indicated by red arrows.

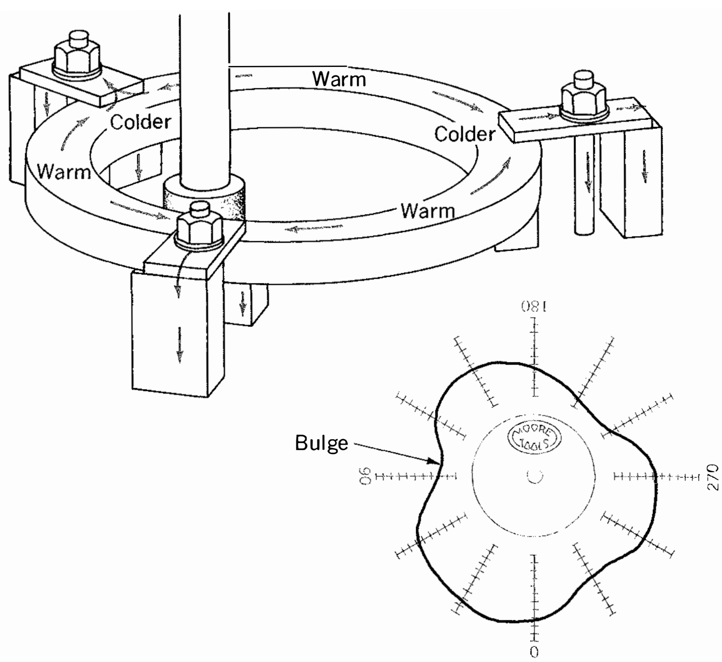


FIG. 468—*An out-of-round condition in this part, recorded with the Measuring Machine, was traced to uneven temperature distribution during grinding.*

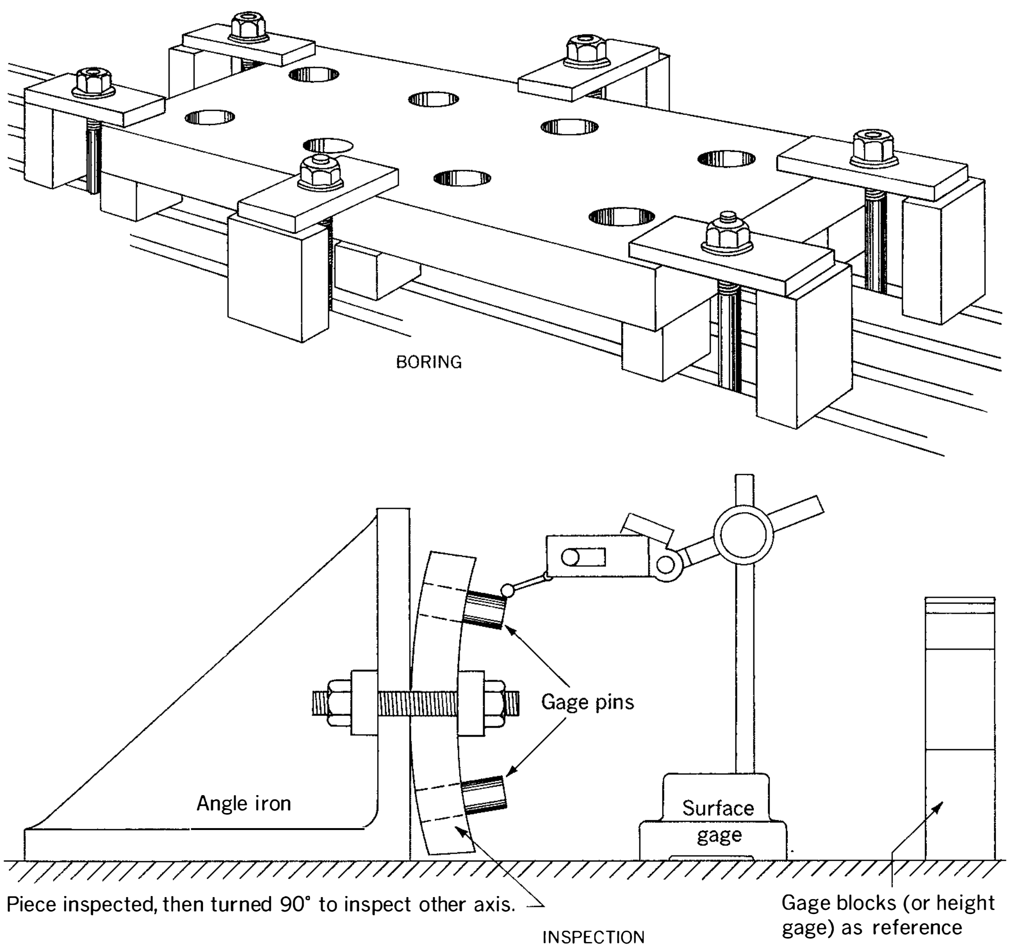


FIG. 469—*This cast iron blank was jig bored, then measured by surface plate methods to test the accuracy of the machine on which it was bored. Machining methods were not performed carefully enough. Use of a Measuring Machine far surpasses surface plate inspection in determining hole location.*

grinding was more quickly dissipated. When the piece returned to uniform temperature, local areas of the hole contracted by different amounts.

Solution: The part was given full support on a lapped surface to help dissipate heat and to assure greater uniformity of temperature during grinding.

Example No. 5—Inspection and Machining Techniques

Fig. 469. For the purpose of verifying the accuracy of a jig borer under working conditions, a flat, cast iron part was mounted on its table, and holes were drilled and bored to a nominal size at random locations.

This test piece was next inspected by surface plate methods, with the piece mounted on an angle iron. An indicator and stand, gage blocks and height gage were employed in the inspection.

On the basis of this inspection, the inspector concluded that the jig borer in question was capable of working only to a ± 0.0002 inch [± 0.005 mm] tolerance.

Inspection of the piece by the Universal Measuring Machine disclosed errors in hole location, but in addition that the holes were not the same size, had been only rough-bored, and were not normal to the top of the workpiece. Moreover, the piece was not flat.

From the nature of the errors revealed, it was a simple matter to reconstruct step-by-step the incorrect procedures by both the operator and the inspector. For example, when the test piece was measured in the unclamped position the holes were not to location and not parallel. However, when the test piece was clamped, *duplicating the conditions under which it was jig bored,* the holes were parallel and the locational error greatly reduced.

Solution: The operator was informed that for such a critical purpose the machining techniques should be performed with utmost care. All the rough machining

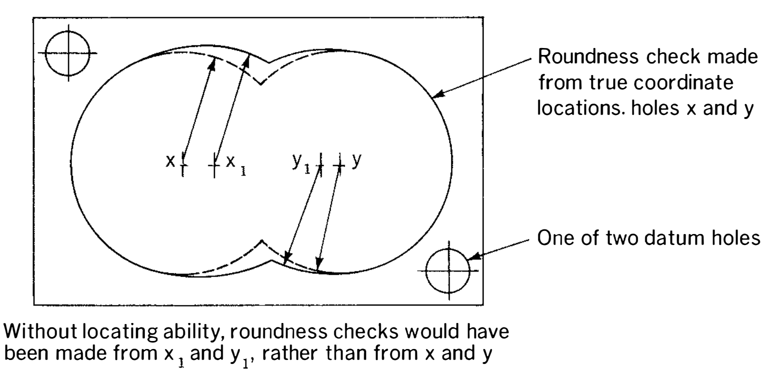


FIG. 470—*This drawing of an actual workpiece demonstrates the importance of relating roundness and location—a capability found only in a Universal Measuring Machine.*

should be done first to remove stresses and get rid of heat. The clamps should be loosened next. The test piece is clamped once again very lightly, followed by a finishing feather-cut, with all holes held to exact size. If the highest possible accuracy is sought, the piece should be stress-relieved after rough machining, then remachined flat on its mounting surface, and lastly finish-bored to size with several light cuts.

The inspector was advised that his method of inspection was not even as accurate as the means by which the test-piece was generated. Surface plate inspection of hole location has many potential sources of error, such as: the degree of flatness of the surface plate or workpiece, or errors which occur when sliding the indicator stand. Size and parallelism of the holes also influence measured location. It is unlikely that the piece has been exactly oriented once turned 90° on the angle iron to measure the other axis.

Such test-pieces are best calibrated on a Universal Measuring Machine, or failing that, on an accurate jig borer or jig grinder.

Example No. 6—Roundness in Relation to Location

Fig. 470. Upon inspection with the Universal Measuring Machine, two half-holes which "run into" one another in a special hardened and ground part were found to be out-of-round by 150 millionths of an inch [0.004 mm] when measured from their specified coordinate position. This condition was attributable to the interrupted cut of the grinding wheel.

Solution: A more open, softer grinding wheel was chosen; the wheel was dressed more often; and lighter cuts were taken on the finish grind.

Note that the use of conventional roundness-measuring instruments would have resulted in entirely misleading conclusions as to the amount or nature of the error since they lack locational capability. In fact, such instruments would have assumed the axes to be approximately at X_1 and Y_1, obtained by balancing the polar trace, rather than at X and Y, the true axes.

In this type of workpiece, roundness and location should be measured *simultaneously.*

Example No. 7—Close Measurement and Mass Production

Fig. 471. In order to increase die life, increase press speed and enhance quality, all the tools for the Model 24 Timex watch introduced in 1966 were specified to closer tolerances than previous tools. The front and back watch frame dies, particularly difficult progressive dies having many small punches and holes as well as embossing features, were specified to locational accuracies of 100 millionths of an inch [2.5 μm].

The Universal Measuring Machine enabled the Moore Tool Room Division to assure that such accuracy was being met. Occasionally, holes were even shifted slightly to conform to Measuring Machine inspection. In reference to this die, Mr. George Turley, Chief Tool Engineer of the U.S. Time Corporation states: "It is most important to have exact alignment between punch holder, stripper plate, and die block. Straightness of holes is particularly critical to prevent wear."* Turley attests to the success of his insistence on *locational accuracy* (together with systematic die maintenance), by pointing out that 5 years later, this die had produced 20 million watch frames (average 400,000 a month) and would produce at least 50 million more over its life. Obviously, the additional cost of the few hours on the Measuring Machine can be considered negligible when compared to total cost savings. Turley equates the importance of measurement to production in the true directness of the mechanic: "Without accuracy, you don't automate."*

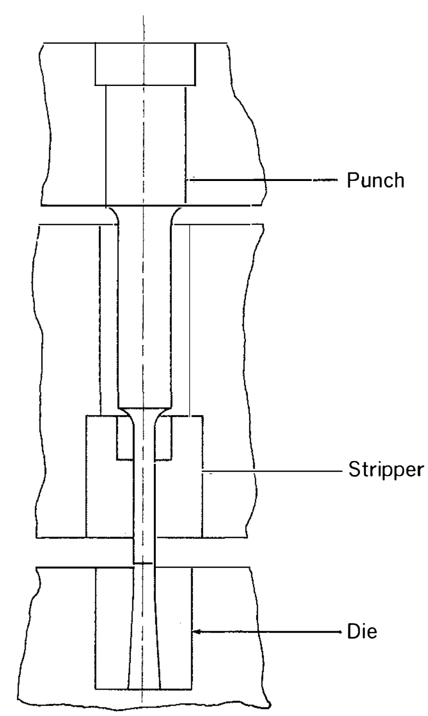
*Author's conversation with George Turley, *circa* December, 1969.

Example No. 8—Economics Achieved by Close Measurement

A dramatic example of the benefit to high-precision manufacture from improved inspection occurred in the early stages of the space program and coincidentally, shortly after the introduction of the Universal Measuring Machine.

A precision parts manufacturer was faced with an unusual dilemma. The performance of many future space vehicles was dependent on the gyroscope he was to build, as part of the inertial guidance system. Accuracy requirements were not yet resolved. At this time, there was no available means of inspecting the part with any greater accuracy than the jig borer used to produce it.

**Idem.*



Greater concentricities add tremendously to die life.

FIG. 471—*The Universal Measuring Machine, by assuring greater concentricities between punch plate, die and stripper, may add greatly to the life of ultra-precise progressive dies. In this way, the Measuring Machine makes a substantial contribution to lowering the cost of production.*

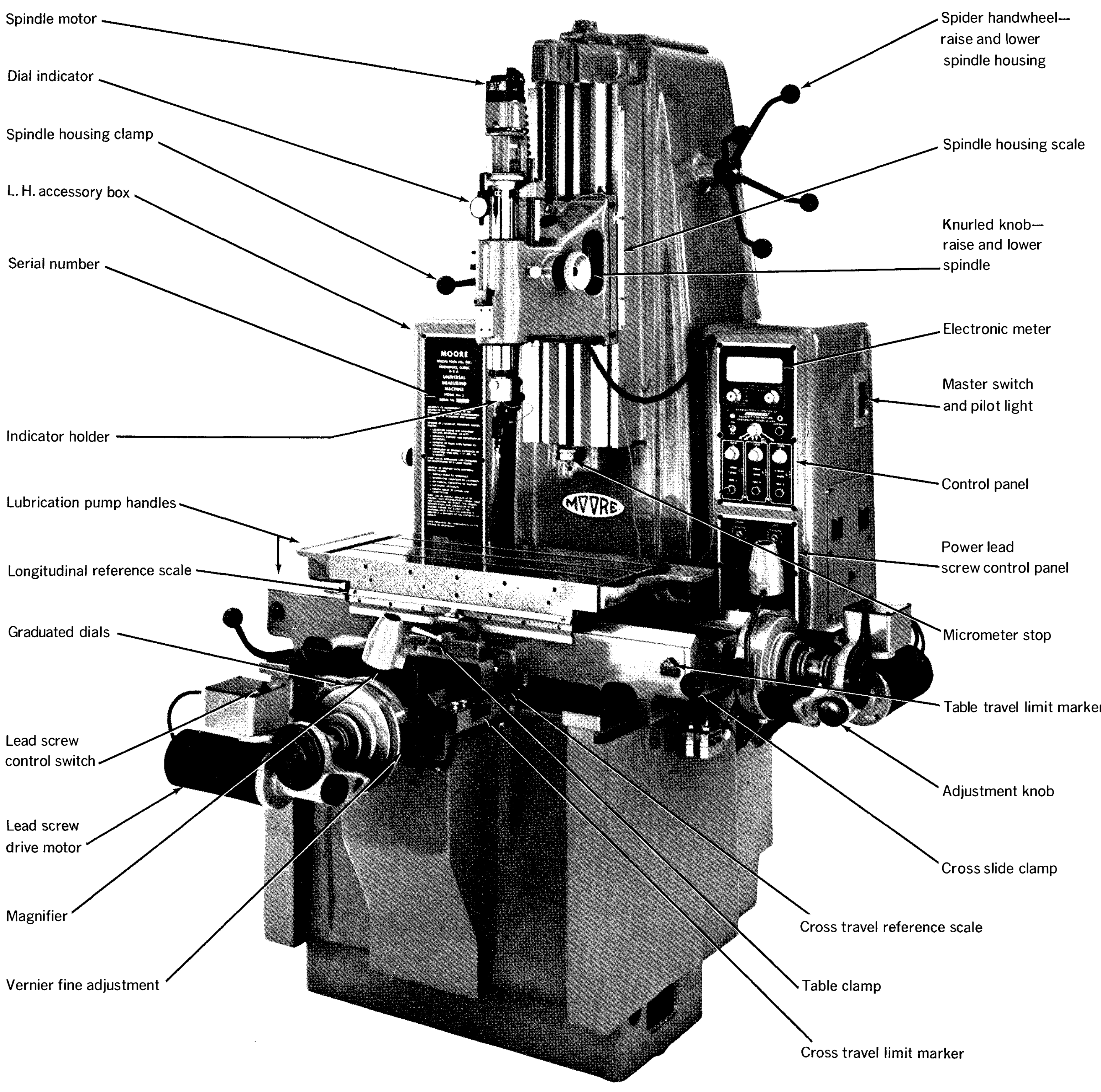


FIG. 472—*Design and construction of the base axes were described in "Geometry"; the lead screw and the derivation of its accuracy was traced in "Standards of Length"; and the design of the housing and spindle elements were described in "Roundness." All these elements are combined and assembled with the proper controls into one operational Universal Measuring Machine.*

The essential controls used in operating the Universal Measuring Machine are listed.

Given this uncertainty and the high stakes involved, quality control engineers of this firm felt they had no alternative but to specify much closer machining tolerances. They were, of course, reluctant to do so, since this would result in a tremendous increase in cost of the project. Frederick C. Victory, then Chief Engineer of the Moore Special Tool Company, induced the firm's project engineer to try what was at that time a new concept in inspection—the Universal Measuring Machine. Through its use, the deviation of all features of the part from specified tolerance was determined with a much higher resolution and certainty than previously attained. By keeping careful records of the inspection of all parts produced, as well as results of their respective performance tests, it was found that certain tolerances instead of being closer, could be safely *increased*, resulting in great savings.*

In the author's observation, and as these previous cases would suggest, the most successful installations of Universal Measuring Machines have been in facilities where a close working relationship existed between the production and inspection departments.

2. Universal Measuring Machine Techniques

The measuring and control facilities which are used in operating the Universal Measuring Machine are called out in Fig. 472, included here as an aid to understanding the techniques to be discussed. Additional information is also found in "Maintenance and Operation Manual: Model No. 1½ and No. 3 Moore Universal Measuring Machine."**

*Frederick C. Victory, *The Moore Universal Measuring Machine—A New Concept in Measurement and Inspection*, Publication of Moore Special Tool Company, *circa* 1959.

**Publication of Moore Special Tool Company, 1967.

MOUNTING

A description of the techniques of using the Measuring Machine most properly starts with the mounting of the workpiece.

The piece to be measured must be flat and supported on accurate parallels. If its flatness is in doubt, it can be checked directly by registering the indicator against the surface under consideration, and examining its accuracy while traversing the machine axes.

Clamping pressure on the workpiece should always be directly over its supports, and only finger-tight. A set of special knurled clamping nuts, a sampling of which is shown in Fig. 473, is furnished with the machine to assure adherence to this practice.

FIG. 473—*A special set of workpiece clamps is furnished with the Universal Measuring Machine; a few such items are shown. An important feature of the set is the use of knurled nuts to avoid distortion of the workpiece through clamping-pressure.*

FIG. 474—*This simple demonstration piece, measuring 4 inches by 8 inches overall [101.6 x 203.2 mm] and having four 1-inch [25.4 mm] holes, may be used to show most of the fundamental Universal Measuring Machine techniques.*

BASICS OF MEASURING HOLE-LOCATION THROUGH THE USE OF COORDINATES

The coordinate system provides a most perfect way to measure location, since through its use the configuration of virtually any shape in one plane can be expressed in numerical terms.

The simple, rectangular part, Fig. 474, may be used to demonstrate most of the basic procedures. The nominal dimensions of this part are, 4 inches in width by 8 inches long [101.6 by 203.2 mm]. The four 1-inch diameter holes are 5 inches apart on its length and 2 inches apart on its width [25.4 mm holes, 127 by 50.8 mm apart].

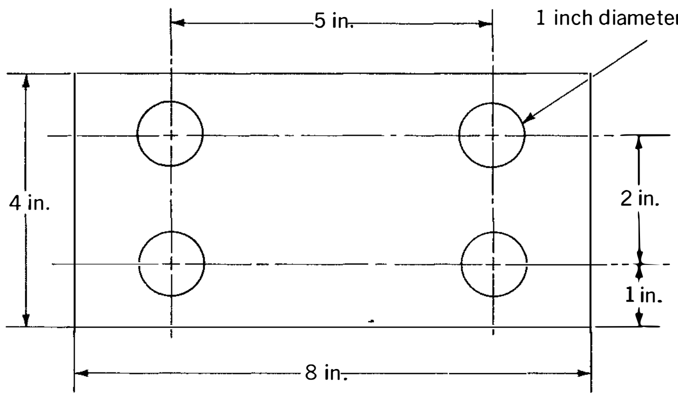
Example No. 1

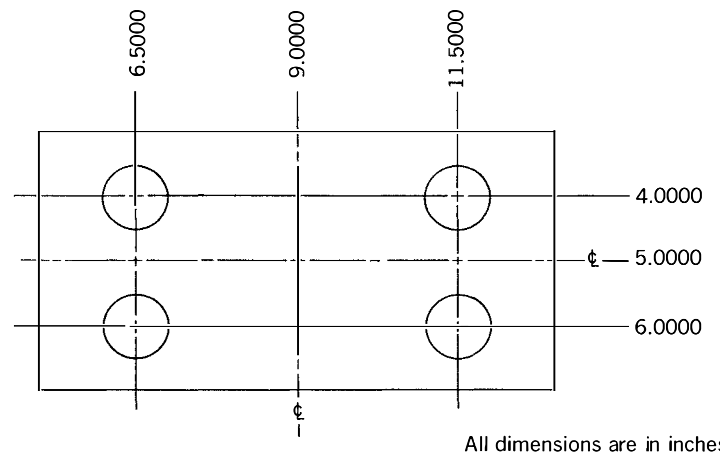
Measure the location of the four holes with respect to a datum given as the center of the part itself. First the dimensions are converted to coordinate locations, referencing from the centerline of the part, as in Fig. 475. The whole-inch figure [convenient metric number] is selected simply by approximating by eye the centerline of the part, when mounted, with respect to the nearest whole inch [or convenient whole millimeter figure] on the reference scale of each axis (see also readout page 309).

Procedure

1. Register the indicator probe on the side of the piece, and traverse the long axis. Hold one end of the piece and tap its side at the opposite end to bring it into alignment with the axis, Fig. 476. Clamp the part and repeat this process.
2. Move the long axis until the spindle by eye seems centered over the piece longitudinally. This is accomplished by extending the indicator linkage and noting if the indicator probe appears to be directly over each end when swung through a 180° arc.

FIG. 475—*To measure by coordinates, center-distances are first converted to coordinate-locations, as shown with the demonstration piece.*





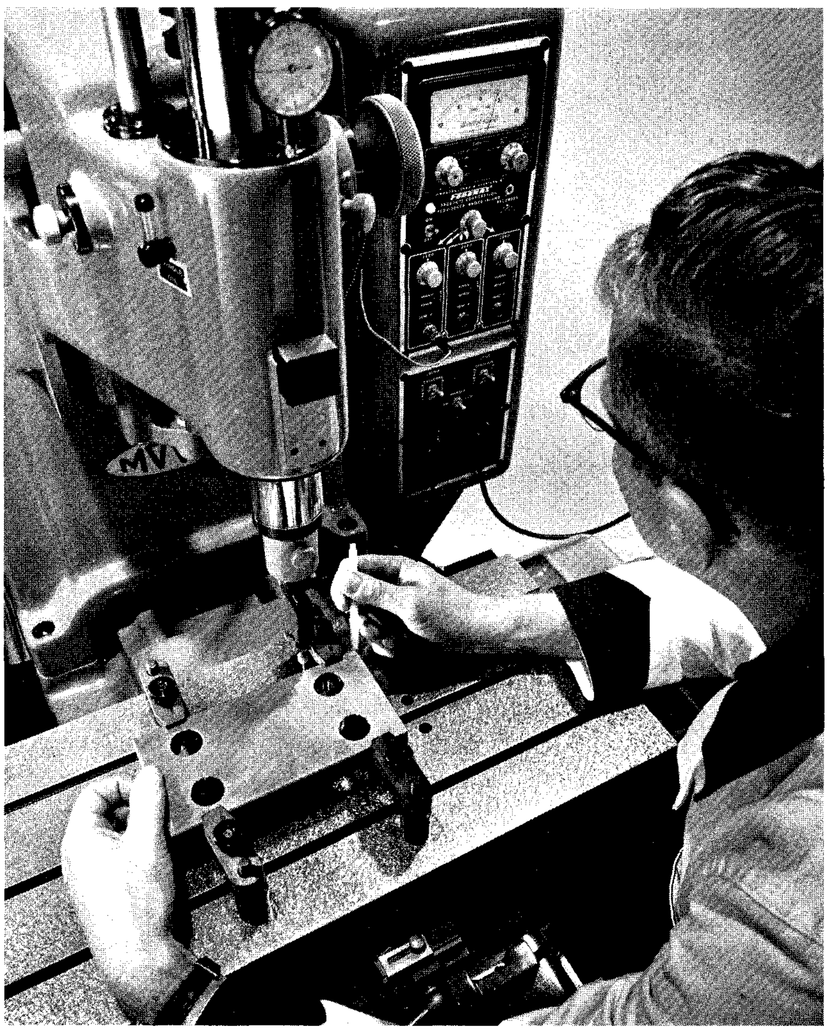


FIG. 476—*To relate the part dimensions with the measuring axes, the workpiece is first tapped into alignment; the operator is guided by readings on the electronic indicator meter.*

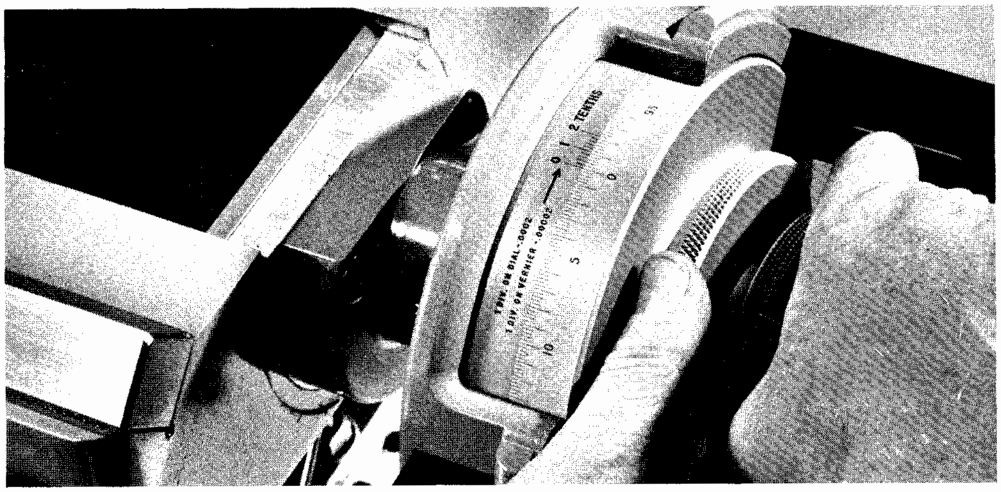
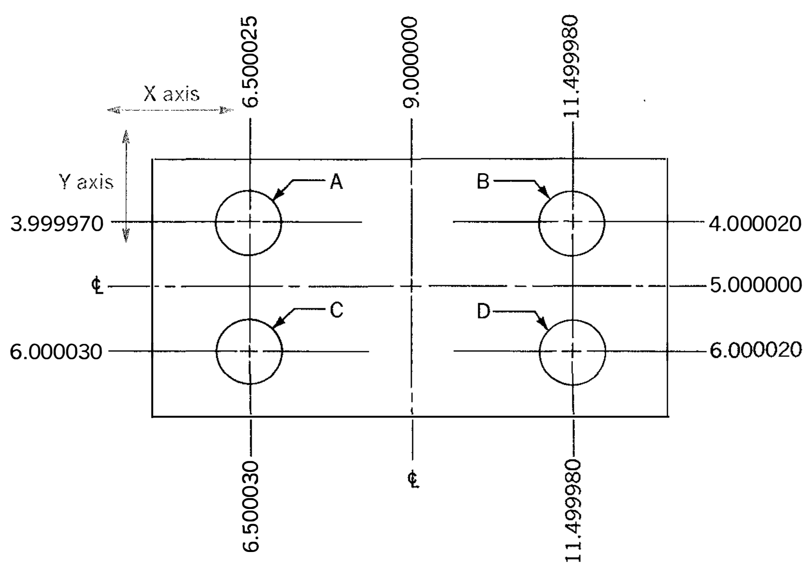


FIG. 477—*Once the demonstration piece has been "picked up," the reference scale is set to a convenient inch [mm] figure, and the dial, as shown, set to a "zero," or to whatever dimension is used as a reference.*

FIG. 478—*When "picking up" a hole, indicator readings are noted at points 180° apart; the lead screw is then moved to the mid-point of the readings. The fine adjustment knob enables the operator to move in increments of a few millionths of an inch [fractions of a μm].*

3. Using the lowest magnification, 1 line = 0.0005 inch [1 line = 10 μm], register a "zero" on one end of the piece at the lowest reading of the arc.
4. Without moving the long axis, note the lowest reading of the indicator against the other end when swung through an arc.
5. Leave the indicator set against the latter end and move exactly half-way between this reading and zero on the meter. The fine-setting knob facilitates moving in such fine increments. Note: If the indicator does not register "on the meter" when swung to the opposite end from which the zero had been set, move the long axis until the indicator is brought up to zero at the highest point of the arc. Add the first coordinate setting to the second coordinate setting and divide by 2. Move to this position. *Backlash.* Backlash has been intentionally built in at the factory and has no effect on accuracy, provided that all final approaches are in a direction indicated by the arrows on the lead screw dials.
6. Repeat the previous process to center the spindle over the part in the direction of the short axis.
7. Switch to a fine scale on the meter; one division = 10 millionths inch [1 division = 2/10th μm on metric machines] is a convenient magnification. Then, reset each axis as before.
8. Clamp both axes of the machine.
9. Set the rough reference scales to the nearest "even inch" (or nearest 10 mm increment). Next, set the dial and vernier to "zero," Fig. 477.
10. Re-verify the setting. Use vernier fine adjustment for the final adjustment of the vernier.
11. Traverse to the nominal X-Y coordinate for one hole. Adjust the indicator against one side of the hole to

FIG. 479—*The required dimension of the holes is their distances from the centerline of the part (top). Once the coordinate values are determined, they are easily calculated (bottom).*



Hole A is 5.000000 −3.999970 or 1.000030 from the ℄ on the Y axis
and 9.000000 −6.500025 or 2.499975 from the ℄ on the X axis

Hole B is 5.000000 −4.000020 or 0.999980 from the ℄ on the Y axis
and 11.499980 −9.000000 or 2.499980 from the ℄ on the X axis

Hole C is 6.000030 −5.000000 or 1.000030 from the ℄ on the Y axis
and 9.000000 −6.500030 or 2.499970 from the ℄ on the X axis

Hole D is 6.000020 −5.000000 or 1.000020 from the ℄ on the Y axis
and 11.499980 −9.000000 or 2.499980 from the ℄ on the X axis

All dimensions are in inches

get a zero on the meter. Rotate the spindle 180° so that the probe registers against the other side of the hole. The meter will read double the amount that the hole is off-location on that axis. Then, move half the amount with the lead screw as in Fig. 478 and set zero on the indicator once again.

12. Repeat this process for the same hole on the other axis.
13. Record coordinate settings of both axes.
14. Repeat steps 11–13 to find the coordinates of each of the other three holes.
15. The distance of the holes from the center of the piece on each axis is now evident simply by subtracting the coordinate values obtained, Fig. 479.

Example No. 2—Two Line-Up Holes as a Datum

In Fig. 480, the datum is specified to be the holes themselves, the outside of the part not being functional.

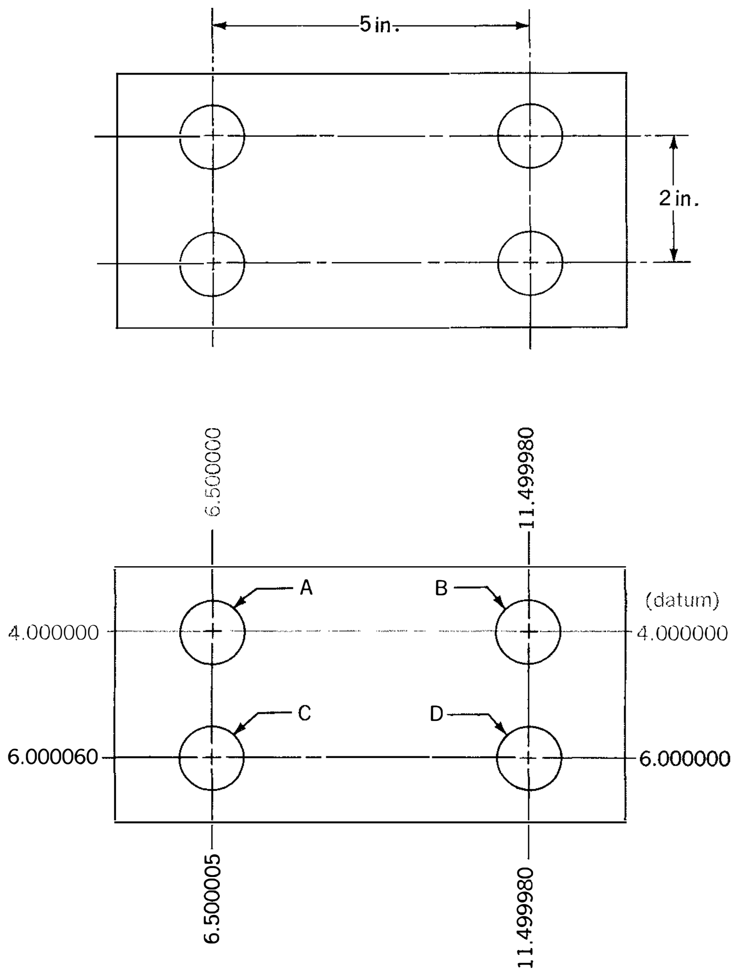
The best procedure is still to start with the previous steps (Example 1, Steps 1 through 7). Machine operators will usually bore or grind the holes in an approximate relation to the edges of the piece, even if this is not specified. It is more convenient to tap the piece into rough alignment by using an edge rather than two holes.

Once the edge is aligned, and the spindle centered, the holes themselves will almost always fall within the coarse range of the meter, which is ± 0.010 inch [± 0.2 mm in metric], unless drastically out-of-line with the edges of the part.

Orient the spindle so that the indicator registers against the back side of one hole. Set a zero at the lowest point of the hole found when traversing the long axis. Traverse the long axis to the other end

FIG. 480—*Frequently, the edges of a part are nonfunctional, requiring only hole location (top). Two holes, (A & B), are chosen for a datum for line-up and for convenience (bottom); the nominal "zero" may be set at hole A. Once coordinate locations are determined, distances from datum hole A can be calculated arithmetically.*

FIG. 481—*The same techniques used to determine hole location of the 4-hole demonstration piece are applied to determine locations of more complex parts such as this precision progressive die.*



Distances from hole-to-hole are determined in the following manner (for instance from A to B on the X axis):
11.499980 −6.500000 = 4.999980

All dimensions are in inches

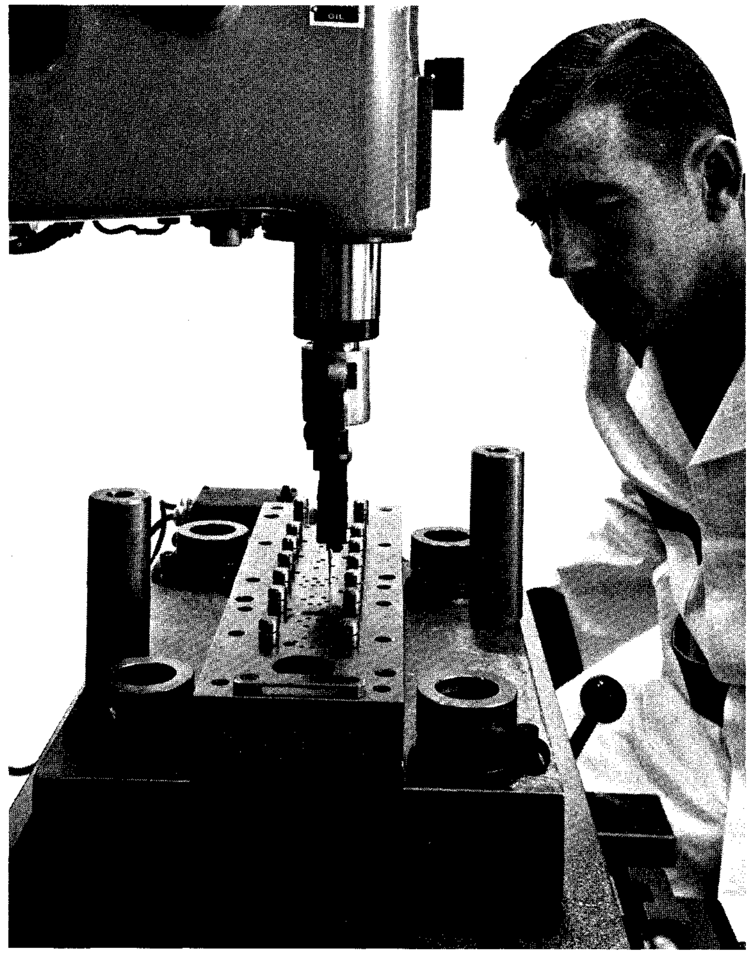


FIG. 482—*The rotary table may be used to facilitate line-up of datum surfaces or holes of workpieces for measurement by rectilinear coordinates; in such cases, rotary table accuracy is not essential. When the rotary table is employed to measure by polar coordinates as shown then it must be accurate as well.*

and drop the probe into the other hole. Note the meter reading at the low point of the hole, again found by moving the long axis back and forth.

Leaving the indicator set at the low point, hold the other end of the piece and tap it on the side at the end adjacent to the indicator probe until the meter records the previous zero.

Switch to a high magnification. A slight final tapping adjustment may have to be made by indicating the full circumferences of both holes if they are still not exactly in line, due to slight differences in size or out-of-roundness.

If the datum holes are not the same nominal sizes, initial line-up is still facilitated by using one side of the holes. The cross axis in this case is moved an amount equal to half the difference in their nominal diameters to register the indicator probe. Final line-up is again accomplished by indicating the full circumference of the holes, except that the offset of the indicator probe is physically adjusted in order to register on the meter.

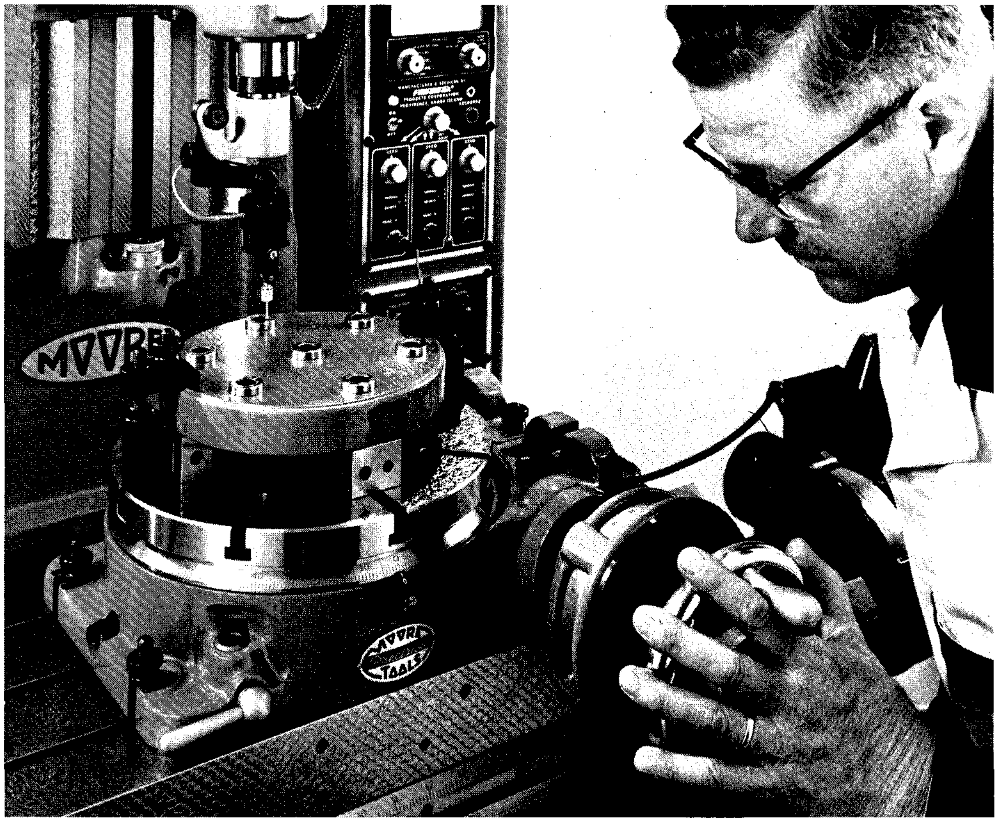
These same techniques may be employed in measuring the location of holes in any workpiece, such as a large die section, Fig. 481.

The location of outside diameters, such as those seen in Fig. 481, is accomplished using the same principles of operation.

Example No. 3—Rotary Table Techniques

A. *To Facilitate Line-Up*

Some workpieces are too awkward in shape to tap into alignment; such a part is shown in Fig. 482. Besides, they may have no convenient reference edges to obtain an initial coarse alignment, and occasionally, the specified datum holes may not be in line. In these cases, a rotary table is used to align reference holes or surfaces with the measuring axes, as illustrated in Fig. 483.



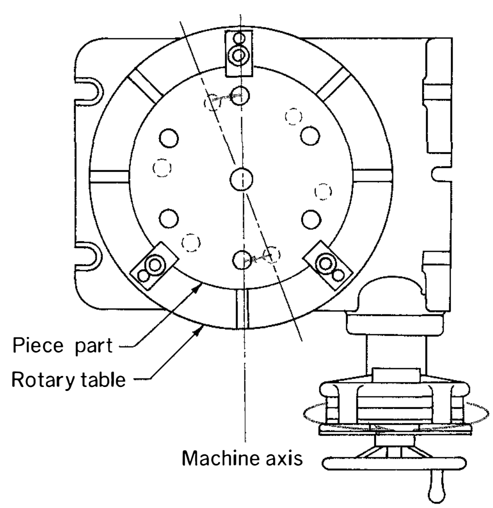
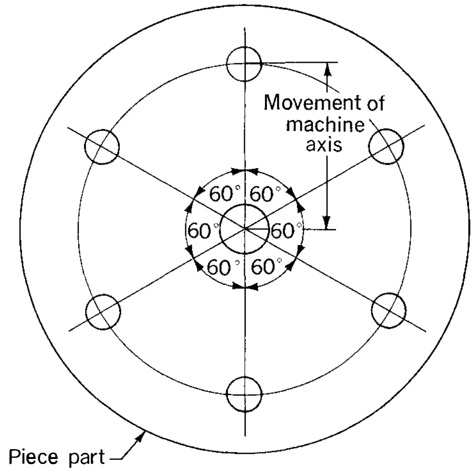
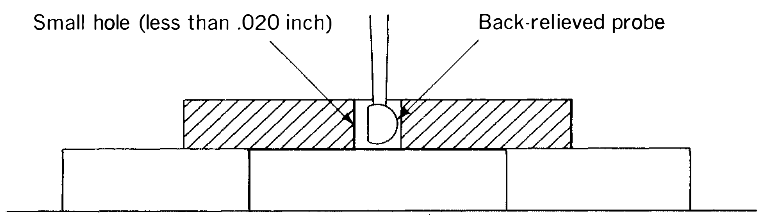


FIG. 483—*The advantage of the rotary table for part alignment with the measuring machine axes is that all adjustments are monitored. In contrast, hand-tapping the part into alignment depends more on operator technique and "feel." Both techniques are necessary at times.*

FIG. 484—*(top) Measurement of hole location by polar coordinates, still requires use of one machine axis to establish the center-distance at which radial values are to be determined.*

FIG. 485—*(center) To gain more working clearance for the measurement of small diameter holes, the back of the indicator probe (opposite the measuring direction) may be relieved.*





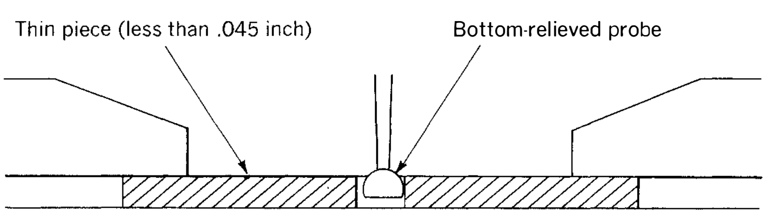


FIG. 486—*For the sake of convenience, small thin parts, such as die stampings, may be measured without clearance under the holes by relieving the bottom of the indicator probe. Care must be taken not to relieve the probe beyond its "equator."*

If the dimensions are specified from a center-hole in the part, initial line-up is greatly facilitated by using the reference hole in the center of the rotary table. The Measuring Machine spindle is aligned with the center hole of the rotary table prior to mounting of the workpiece. Once mounted, the workpiece is tapped to bring its center hole central to the machine spindle axis. The alignment of datum holes is now achieved simply by following previous procedures, except that the piece is rotated rather than tapped.

Accuracy of the rotary table in this application is not critical, since it is used only for orienting the workpiece, not for measuring.

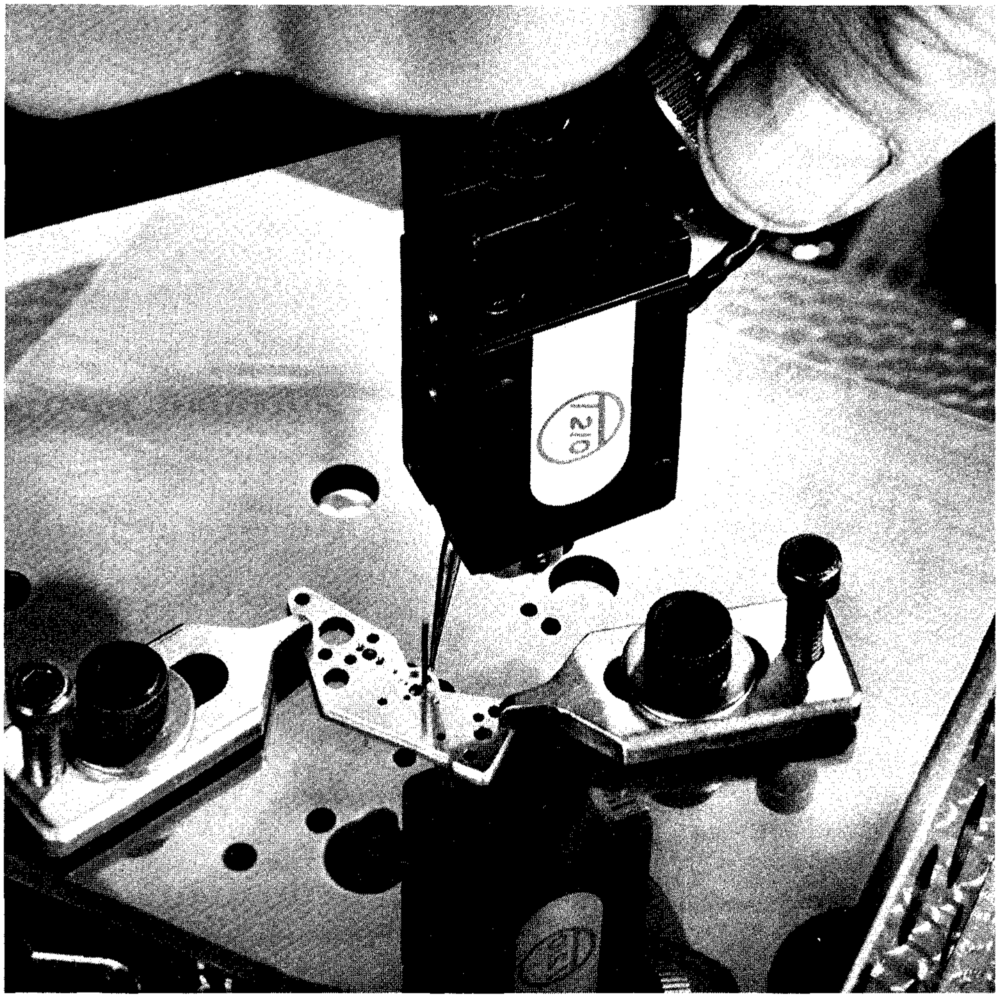
B. *To Measure by Polar Coordinates*

If the rotary table is to measure angles, such as of the holes of the part shown in Fig. 482, its accuracy must be commensurate with that which must be achieved on the part. Equipment is available to enable measurements to be performed in a range of accuracy from ± 12 seconds to ± 0.1 second of arc.

The Measuring Machine spindle is initially aligned with the center bushing of the rotary table. Then the piece is tapped central to the machine spindle, as in the previous example. However, the center hole of the rotary table is not absolutely concentric with the rotary table axis and may be in error by a few millionths of an inch [approximately 2 μm].

The center hole of the part must therefore always finally be adjusted concentric with the rotary table axis. Alignment of a hole with the rotary table axis is accomplished in the following manner. The probe is registered against one side of the center hole in the part. The rotary table is rotated through a full 360° and the misalignment of the hole is recorded at the 90° increments. Now, by rotating the machine spindle, the probe is oriented normal to

FIG. 487—*The location of a small hole may be determined by using a gage pin to represent its axis. The advantage is that probe-tips of a diameter greater than that of the hole may be employed.*



the 0° and 90° increments of the hole, and at each of these increments the piece is tapped to centralize the hole according to the deviations which had been recorded. This process should be repeated until the hole is aligned sufficiently close for the accuracy sought.

Once the center-hole of the part is aligned with the rotary table axis, the part is clamped. By moving the coordinate axes, the center hole of the part is located centrally with the machine spindle and a coordinate setting established.

The next step is to make an excursion equal to the radial distance from center to the holes to be measured, Fig. 484. Using the rotary table for rotation, the holes are then indexed one by one until located centrally with the measuring machine spindle. Angular spacings of the holes are read on the rotary table dial.

Unlike using a dividing-head and surface plate inspection, the Universal Measuring Machine is able to determine the center-distance of the holes, *as well as* the angular spacings.

Following this measurement, the piece may be double-checked by converting polar to rectilinear coordinates and measuring purely by the machine axes.*

Example No. 4—Measuring Coordinates of Small Holes

A. *With Relieved Probe-Tip*

Small holes may be measured through use of probe-tips as small as 0.010 inch in diameter [0.25 mm]. Additional working-clearance may be gained in small holes by back-relieving the probe, Fig. 485; however, the radius of the probe should always be smaller in size than that of the hole. If the part to be measured is very thin, and it is inconvenient to have through-clearance under the part, the probe may be relieved on the bottom, as in Fig. 486.

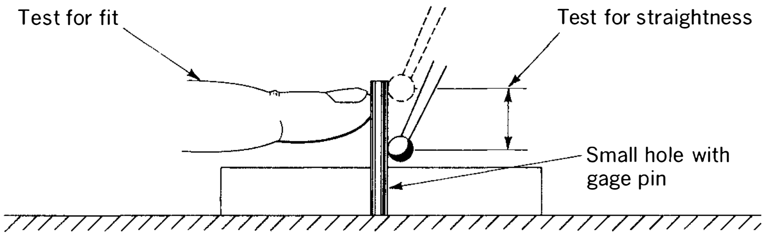
*Rectilinear coordinates may be calculated or found by referring to the "Woodworth Tables," *Holes, Contours and Surfaces* by Richard F. Moore and Frederick C. Victory, pp. 227–414.

The most accurate measurements of small holes are obtained through use of an electronic indicator, so this additional preparation, if necessary, is worthwhile.

B. *With Gage Pin Inserted Into Hole*

A gage pin may be used to represent the axis of the hole, as in Fig. 487. One advantage of this technique of measuring the location of small holes is that the probe-tip diameter may be larger than that of the hole to be measured. The probe should still

FIG. 488—*When using a gage pin to represent the axis of the hole, precautions must be taken to: (1) Check the fit of pin; (2) Check its straightness; (3) Indicate as near as possible to the hole.*



be of relatively small diameter, nonetheless, to minimize the error which may occur from the probe-tip not being exactly normal to the gage pin.

To be reliable, this method requires that the pin be straight, does not lean and fits the hole closely. Straightness and lean are checked by running the indicator probe along the length of the pin. Fit of the pin is checked by applying pressure, noting if the pin always returns to position after the deflecting force is removed, Fig. 488. It is good practice to measure as close to the hole as possible to minimize the introduction of erroneous readings from either condition.

C. *With Microscope*

The microscope is especially useful for measuring the location of small holes or shapes such as of the watch part shown in Fig. 489. A microscope is also necessary for measuring parts which might be damaged by physical contact. Some parts, for example, the micro-circuit component, Fig. 490, do not have any reference surfaces against which an indicator probe-tip may register, and also require the use of a microscope.

A rotary table is usually indispensable for all microscope work since the workpieces would otherwise be difficult to align. However, the rotary table need not be extremely accurate if used solely for orienting the piece.

The Standard Microscope

The convenience, versatility and range of magnification of the electronic indicator cannot be embodied into a single microscope. For this reason, the standard 30-power microscope shown in use in Figs. 489 and 490 is furnished as standard, and 30-power has been selected as the best compromise for all-around use. At less than 30× magnification, the field of vision would be greater but accuracy of resolution would

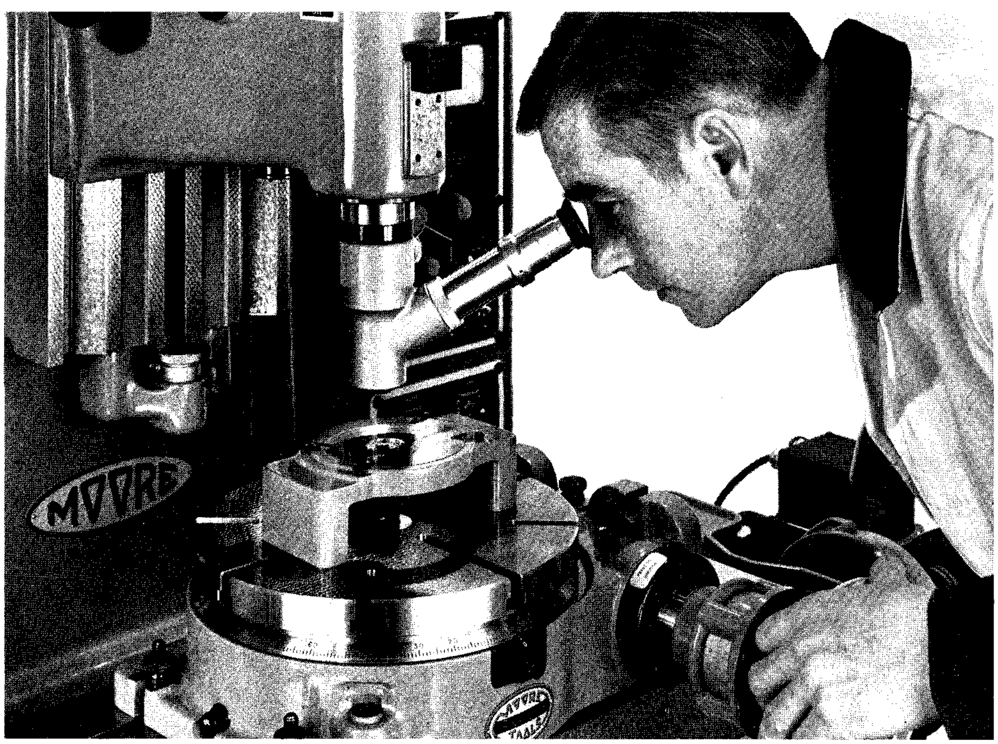


FIG. 489—*The measurement of location of small holes and surfaces, such as of the watch part shown, are sometimes more conveniently accomplished through use of the standard 30× microscope. The rotary table is indispensable to orient the part whether or not dimensions are specified by polar coordinates.*

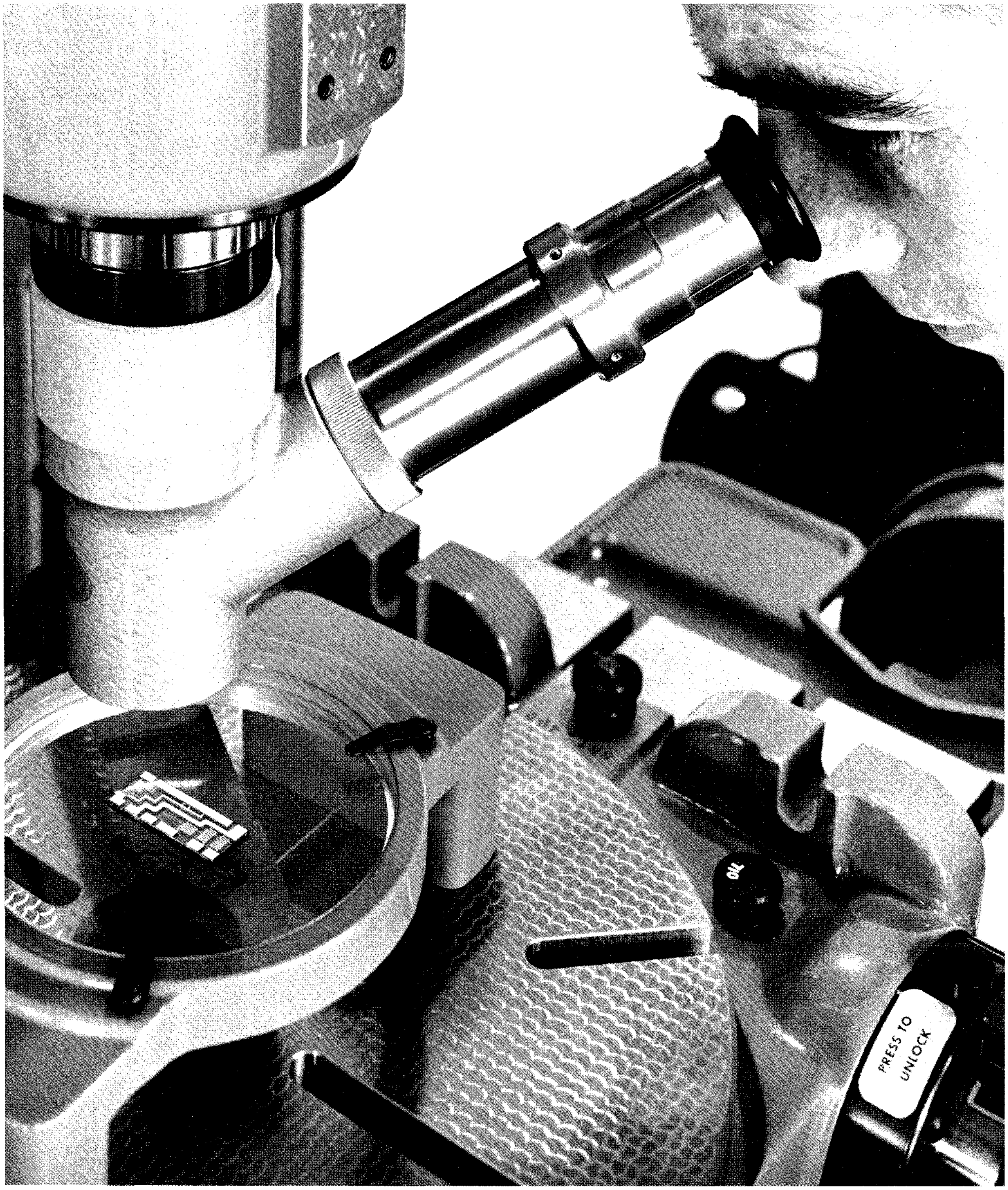
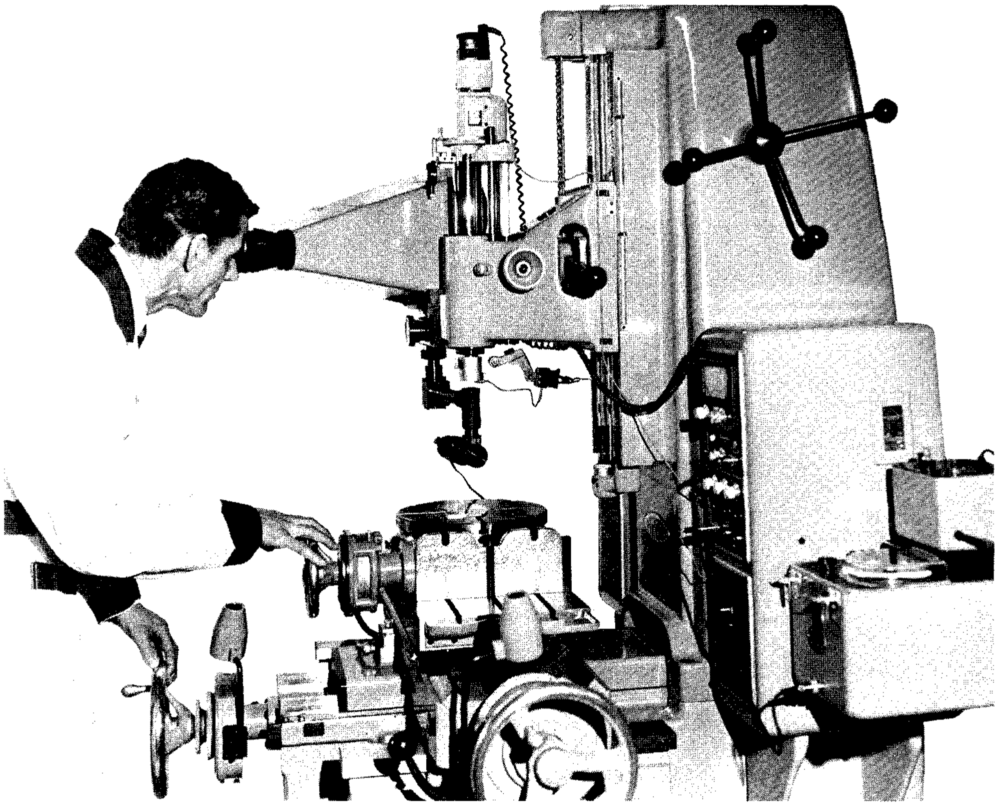


FIG. 490—*Inspection of the micro-circuit component, shown mounted on the optical stage, requires use of a microscope. A collimated light source located below helps to clearly define the functional surfaces.*

FIG. 491—A Stocker & Yale Visual Comparator was adapted to a No. 3 Measuring Machine as a "special" to enable one owner to use his machine for rapid inspection of production parts at a lesser accuracy. The optical arrangement may be swung clear to return to electronic indicator use for the measurement of precision parts and gages.



usually be inadequate. At more than 30× magnification, repeatability would be enhanced but the field of vision would be too narrow and focusing would be unduly critical.

The standard microscope has a field of vision of approximately 0.240 inch [6 mm] diameter.

The reticle aids in centering the axes of holes or in orienting other part features. It is made up of concentric circles which increase in value by 0.006 inch [0.1 mm in metric] diameter up to 0.036 inch [1.0 mm in metric] diameter of the reticle, and by 0.012 inch [0.2 mm in metric] diameter for the remainder of the 0.240 inch [6 mm in metric] field of vision.

Included with the standard microscope is a transparent stage for mounting of the part. A collimated light source is placed below the transparent stage so that when viewed through the microscope, part features are clearly defined.

Other Optical Arrangements

For the user with a specific type of work for which a nonstandard microscope seems in order, it is preferable to select a particular adaptation through engineering consultation.

For example, one user had the requirement of fast measurement for production-type work as would be achieved with a CMM, but also the requirement to measure gages to a high order of accuracy, as would be achieved with a Universal Measuring Machine. However, the workload in each category was insufficient to justify the expense of a machine for either category of inspection alone. The solution was to fit a Model No. 1½ Universal Measuring Machine with a Stocker & Yale visual comparator-type readout at a lower magnification of 20×, Fig. 491. This magnification was sufficient for the production-class of work. In this arrangement, the viewing screen can be quickly swung clear

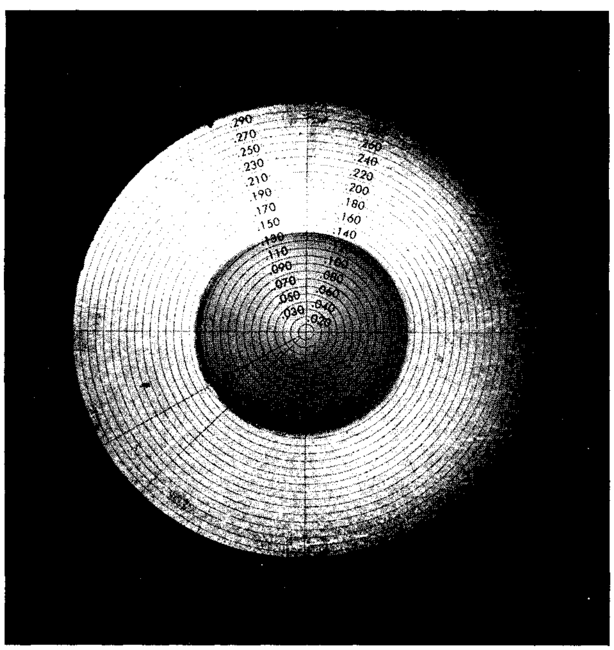


FIG. 492—Image of a hole viewed with the Visual Comparator. Production parts are easily related to their "true position tolerance" by using concentric circles as tolerance boundaries.

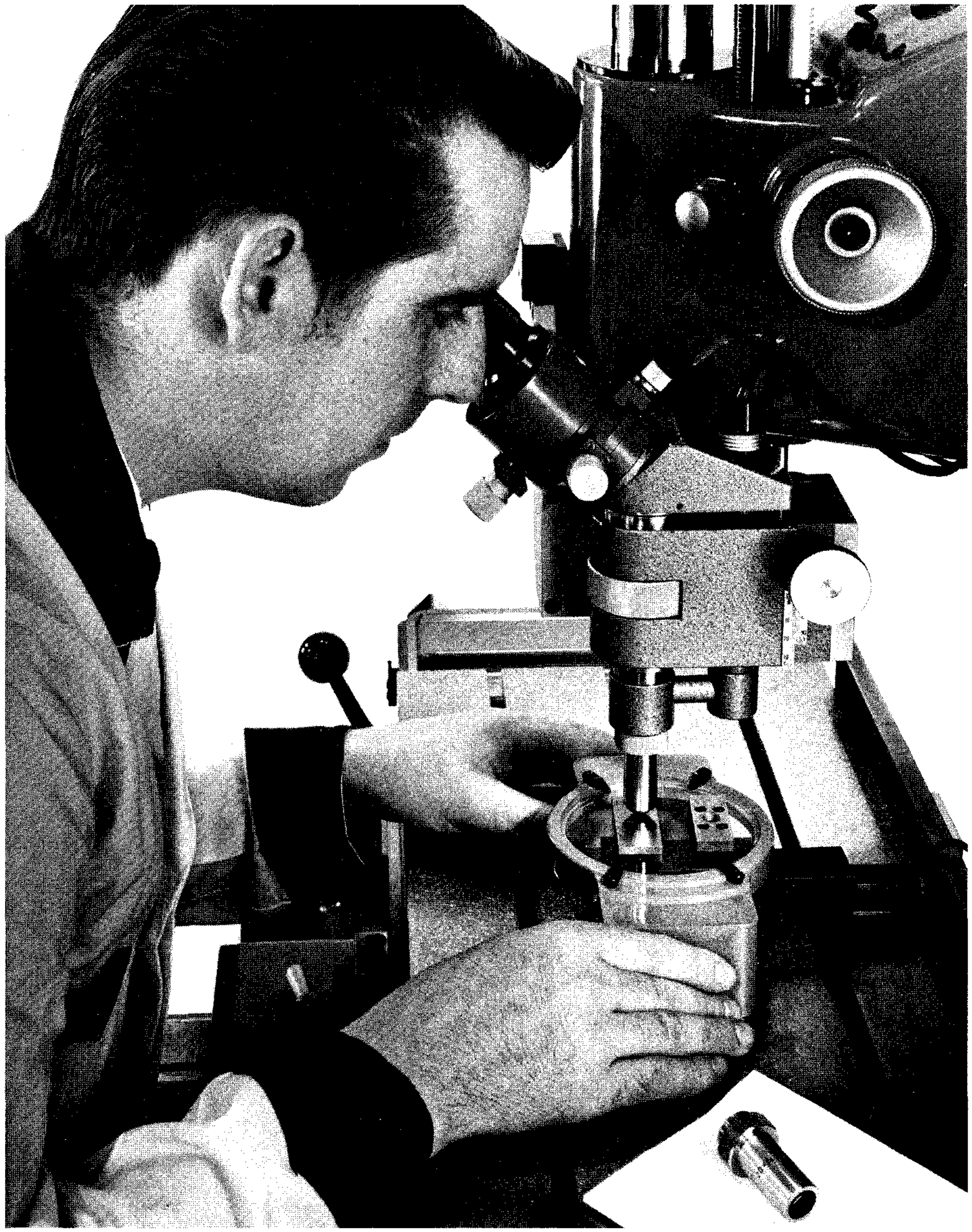


FIG. 493—*A 400× measuring microscope is used to inspect a pattern of holes of .0015 in. [0.038 mm] diameter, produced on a No. 3 Measuring Machine adapted to small hole drilling.*

to return to normal electronic indicator use for gage-type inspection. Fig. 492 shows the image of a hole projected on the viewing screen. Production-type inspection was performed particularly well with this design since quality control of this firm specified the use of "true position tolerancing."* The technique employed is interesting. Rather than orienting the holes concentric with the rings on the screen, and recording their *actual* location, the lead screw moves the axes to the *specified* location. Two concentric rings on the screen are selected (or drawn) as minimum and maximum diameter tolerance zones to determine immediately if the hole falls within true position tolerance.

In Fig. 493 is shown a 400-power measuring microscope. It is used to inspect size, location and other characteristics of a pattern of holes of 0.0015 inch [0.038 mm] diameter, which have been produced by means of a Moore small-hole drilling machine.

Example No. 5—Measuring Radius Size (Edge-Finder-Method)

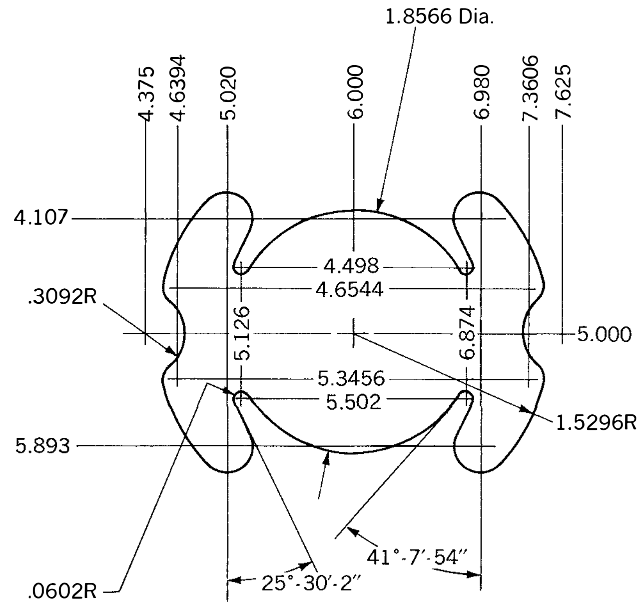
In generating holes and contours the jig grinder operator must continually make use of a technique called "indicator measuring," first described in *Holes, Contours and Surfaces.***

The procedure is to first give a coordinate location to each hole or contour as shown in the section of a motor lamination die, Fig. 494. This die section has a total of 21 holes and male and female radii, as well as several straight sections. It is readily apparent that while the coordinate locations may be determined in this manner,

*"Dimensioning and Tolerancing for Engineering Drawings," Bulletin USASI Y14.5-66, American Association of Mechanical Engineers, New York, pp. 41–84. See also R. F. Utter *et al.*, "Concepts of the True Position Dimensioning System," Sandia Corporation, Albuquerque, New Mexico, 1965, pp. 36–100.

**Richard F. Moore and Frederick C. Victory, *Holes, Contours and Surfaces*, p. 140.

FIG. 494—*This blanking station of a progressive die has 21 male and female radii, most of which the jig grinder operator must size by "indicator measuring" techniques. The same techniques are adaptable to the Universal Measuring Machine to perform a variety of measuring tasks.*



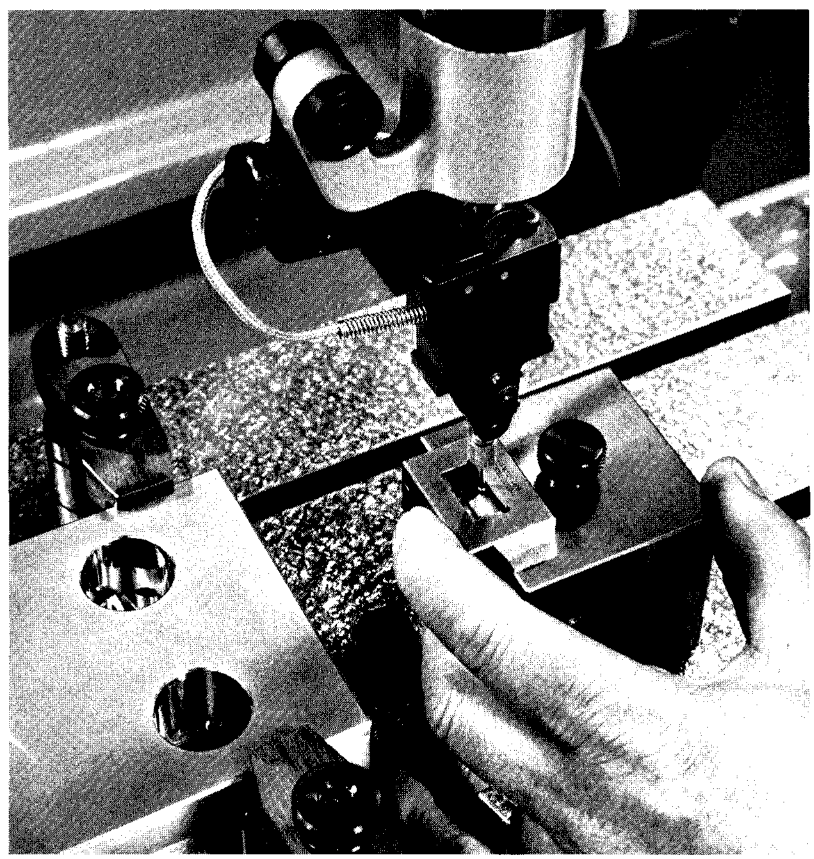
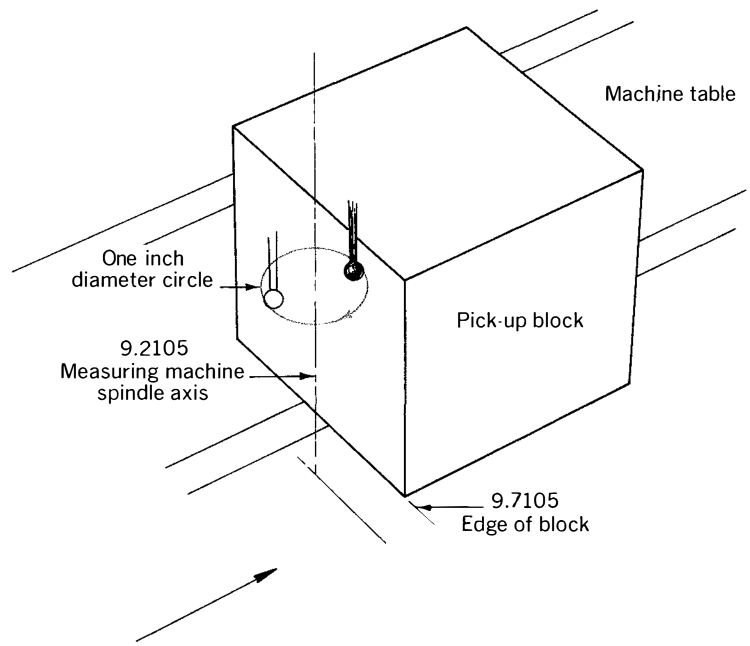


FIG. 495—*The "edge-finder" gage may be used as one method of locating an edge for indicator measuring.*

FIG. 496—*Demonstrated is how a located edge may be used as a reference to establish the size of a female radius.*



MEASURING FEMALE RADII

most of the recessed radii are not accessible for measurement of size by conventional tools such as bore gages, micrometers or gage pins.

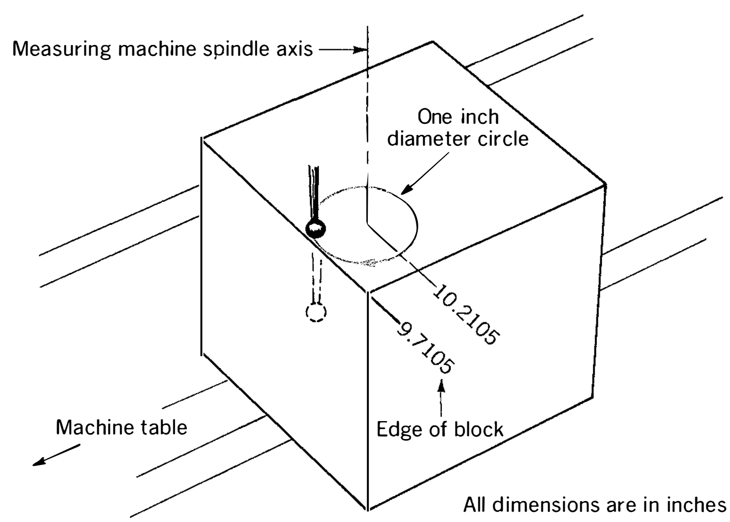
The lead screw has up till now been considered only as an element to establish location. Since the 35 millionths of an inch tolerance over 18 inches [0.0009 mm over 460 mm in metric machines] is often superior to that which can be obtained commercially in most length standards, it is logical that it be applied to measuring *size* as well.

The employment of the indicator measuring technique is an absolute necessity for the jig grinder operator. Once these same techniques are understood and applied to the Universal Measuring Machine, not only can size be measured, but a wide range of other measuring applications is possible.

The Edge-Finder Method

The measurement of size through use of the Universal Measuring Machine requires a very few simple but accurate accessories. In one method, an accurate, convenient reference edge (it may even be that of the workpiece) is aligned parallel to one of the axes. The location of this edge is found by using an "edge-finder." The body of this gage has a 0.400 inch [10 mm in metric] wide slot at the top. A lower edge of the gage is exactly central to this slot, and is used to register against the given reference edge, Fig. 495. Once the spindle is centralized with the slot (see Example No. 1, Step 11, page 291), its axis is automatically in line with the reference edge at a location which can be read on the reference scale and lead screw dial. Note also that when the indicator is set to zero at the high point of its contact with the edge of the slot, it is in effect describing an exact 0.400-inch [10 mm] diameter circle.

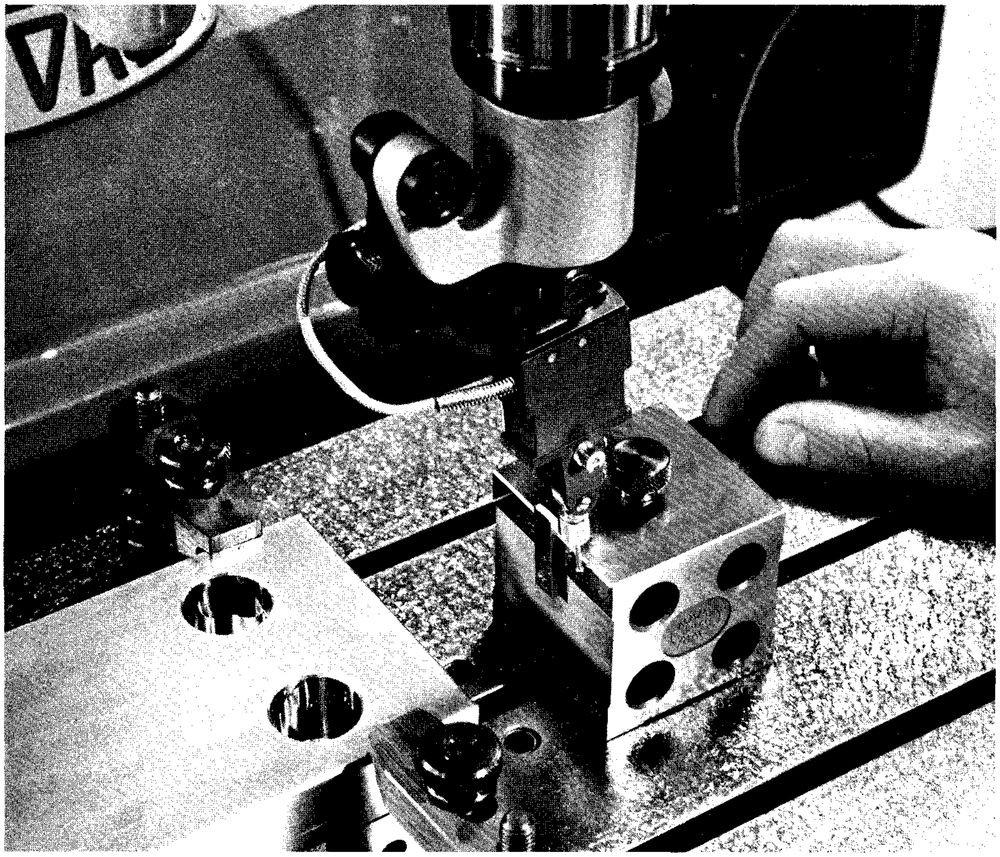
Assume that when the reference edge has been located in reference to the spindle,



MEASURING MALE RADII

FIG. 497—*Shown is how the indicator is set as a reference to accurately size a male radius.*

FIG. 498—*A gage block wrung onto an accurate lapped surface (the pick-up block) provides the most accurate method of locating an edge for use in measuring size with the indicator.*



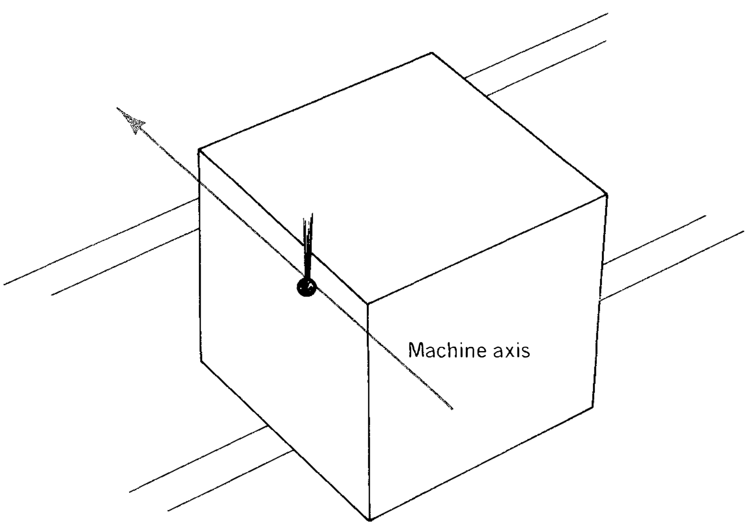


FIG. 499—*The edge of the pick-up block is first tapped into alignment with one of the machine axes, then the block is clamped firmly in place.*

that the position recorded on this axis happens to be 9.7105 inches [246.647 mm], for example. Proof of this location and the accuracy of the edge-finder are accomplished by moving the reference edge 0.200 inch [5 mm in metric] away from the spindle centerline. The spindle centerline is then at coordinate reading 9.7105—0.200 or 9.5105 inches [246.647 mm — 5 mm or 241.647 mm]. The indicator should now read zero at the high point of its contact with the reference edge as the spindle is swung through an arc.

The reference edge may be given a more convenient nominal setting, such as 9.0000 inches [or 200 mm] if desired, by locking the axis and adjusting the reference scale and dial to this figure, as shown previously in Fig. 477.

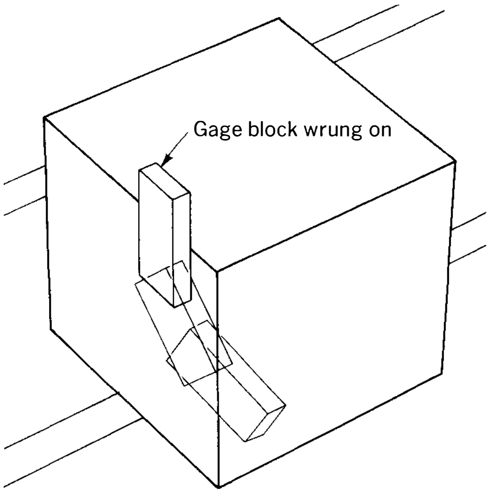
Once the location of the edge is recorded, it may be moved any specified distance from the spindle and the indicator linkage extended manually until a zero is once again set. *The indicator can thus be made to describe an arc the equivalent of a highly accurate gage of any chosen radius.* For example, suppose that the hole sizes of the test piece shown in Fig. 474 are to be determined. The nominal size of the hole is 1 inch [or 25 mm]. An arc of 0.500 inch radius is set by moving to the coordinate 9.7105 inches [12.5 mm radius at 234.147 mm] and striking a zero at the *high* point of the arc of the indicator probe against the reference edge, as in Fig. 496. Leaving the indicator fixed, each hole is next compared to this setting at its respective coordinates. If "minus," the hole is oversize; if "plus," the hole is undersize—by twice the amount shown on the indicator meter.

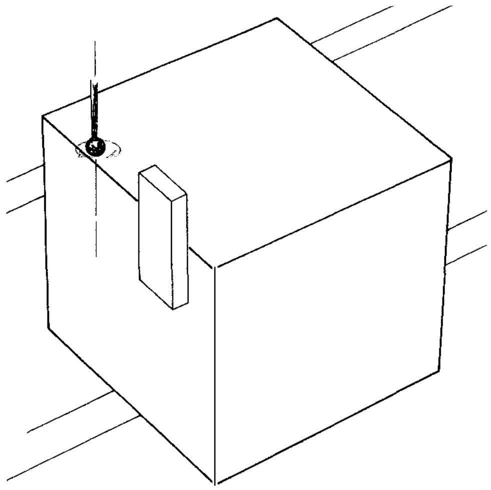
The sizes of male radii are measured as in Fig. 497. The reference edge is moved to the opposite side of the spindle and a zero is struck at the *low* reading of the indicator as it is swung through an arc. Note that only a small portion of the male arc may

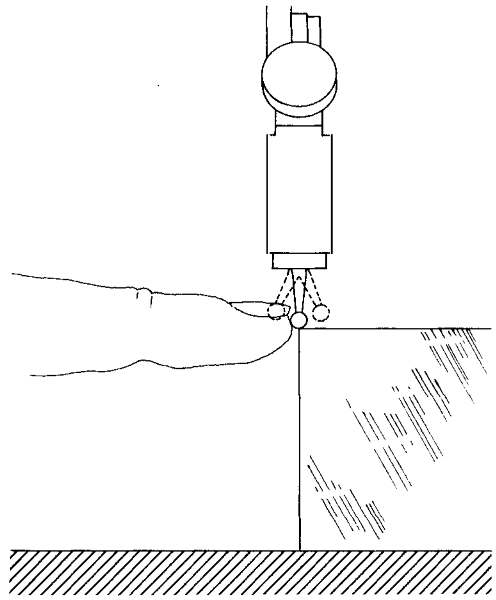
FIG. 500—*The gage block is carefully wrung with a rotating motion to the pick-up block.*

FIG. 501—*The axis is moved until by eye assessment the edge appears to coincide with the spindle axis.*

FIG. 502—*The indicator probe is adjusted at right angle to its measuring direction through a clutch arrangement until by eye assessment the probe-tip appears to have no run-out. The edge of the block is a convenient visual reference to which the probe-tip may be compared when swung through 180°.*







be used, since the indicator probe is restricted in rotation by the reference surface.

Through use of this technique, it is possible to measure the size of all radii, both male and female, of the piece shown in Fig. 494. The advantage of the Universal Measuring Machine for such measurement tasks is that location, hole size, roundness, lean and taper may all be measured and thus interrelated simultaneously.

Although the "edge-finder" method is the most convenient for jig grinder or jig borer use, it is not the most accurate. The following method, using a "pick-up-block" (a standard accessory) is preferred.

Example No. 6—Pick-Up Block Method

The technique described here may also be used to locate a reference edge for the purpose of setting an arc of known size. However, it is most useful as a means of adjusting the indicator so that a null or zero is set with the indicator under the spindle axis. This relation of the probe to the spindle can be established in a matter of minutes once the method is understood, Fig. 498. However, an undue amount of time may be consumed if the proper system is not followed.

Therefore, even though most of the steps are taken in a matter of seconds, the method is broken down step-by-step for completeness and clarity.

1. Align the pick-up block with one axis of the machine, then clamp it, Fig. 499.
2. Wring the gage block on carefully so that it protrudes slightly over the reference edge, Fig. 500. In so doing, take care not to misalign the pick-up block.
3. Verify that the pick-up block is still aligned.
4. Move the X axis while revolving the spindle until by eye the probe is centered over the reference edge, Fig. 501.
5. Adjust the indicator probe tip at right angles to its measuring direction until visually it appears to have no run-out when revolving the spindle, Fig. 502.
6. Without altering the lead screw, face the probe in its measuring direction toward the pick-up block. Rotate the spindle while adjusting the probe until a zero is struck when the high point of the arc registers against the pick-up block, Fig. 503.

   The fine adjustment on the gage head and the zeroing feature of the meter will facilitate setting this null. *Record the lead screw reading at this position.*
7. Raise the spindle to clear the probe; make a short movement with the cross axis to a point opposite the gage block, and rotate the spindle through 180° to register against the gage block face. The zero or null which had previously been set on the meter against the pick-up block is not altered. Instead, the lead screw is employed to bring the face of the gage block to the exact same null obtained on the face of the pick-up block, Fig. 504. *The new lead screw reading is recorded.*
8. The location of the reference edge in reference to the spindle axis is at a location half way between the two recorded lead screw readings. This

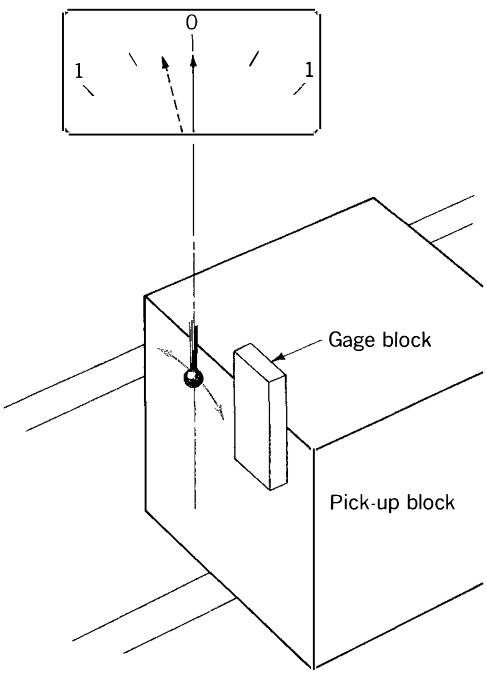


FIG. 503—*A "zero" is struck on the edge of the pick-up block at the high point of the indicator arc.*

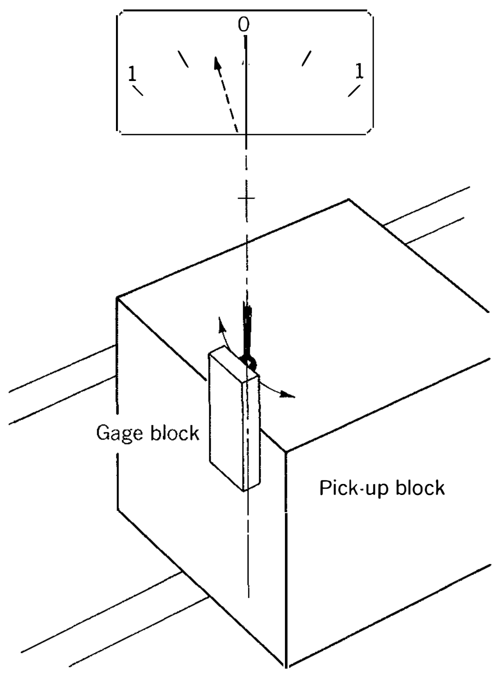


FIG. 504—*The indicator is not adjusted and the axis traversed until a zero is struck on the back face of the gage block—the same reference line in space as the edge of the pick-up block.*

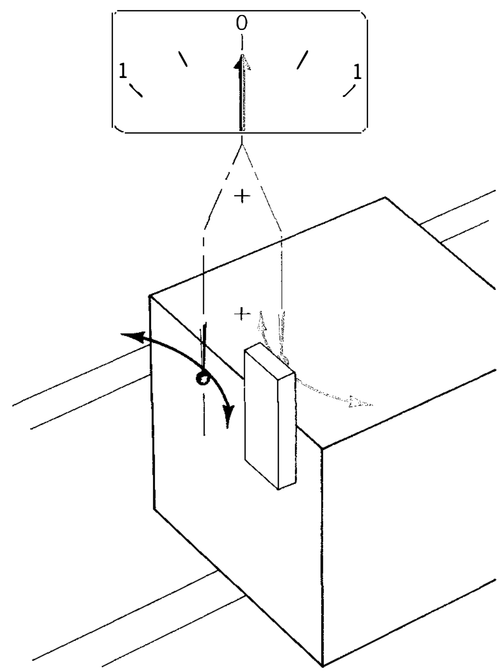


FIG. 505—*Once the edge of the pick-up block exactly coincides with the Measuring Machine spindle axis, a zero can be struck on the edge of the pick-up block and the wrung-on face of the gage block without moving the machine axis.*

location is determined by adding the two lead screw readings and dividing the sum by 2.

The lead screw is set to the location thus determined and the axis clamped. The location is proved by registering against the faces of the pick-up block and gage block as before, but without adjusting the lead screw, Fig. 505.

The reference edge may still be slightly away from the spindle axis, as shown on the meter. However, final precise location is accomplished very simply. The probe is registered against either the pick-up block or the gage block. The reference edge is brought by means of the lead screw to the mid-point of the two meter readings obtained on both faces, Fig. 506.

Final approach to position should always be made by turning the lead screw in the direction shown by the arrows on the lead screw dials to take out backlash.

The procedure of locating a reference edge under the spindle has been described in detail because it is a useful technique to understand for anyone interested in measurement. In actual practice, an edge of the pick-up block can be initially centered beneath the spindle closely enough by eye so that the deviation is within the full meter range at its lowest magnification, which is ± 0.010 inch [± 0.2 mm in metric]. In this case, the setting of the lead screw is established as simply the mid-point of the deviation of the pick-up block and gage block as shown on the meter. Final setting is then accomplished by switching the electronic indicator to a higher magnification, such as 20,000$\times$, and setting to the mid-point once again.

A special attachment which fastens to the front of the housing, Fig. 507, enables the probe to be automatically positioned in line with the spindle to within 0.0001 inch [0.0025 mm]. Once "on the meter," final precise zeroing of the indicator is accomplished with the pick-up block and wrung-on gage block.

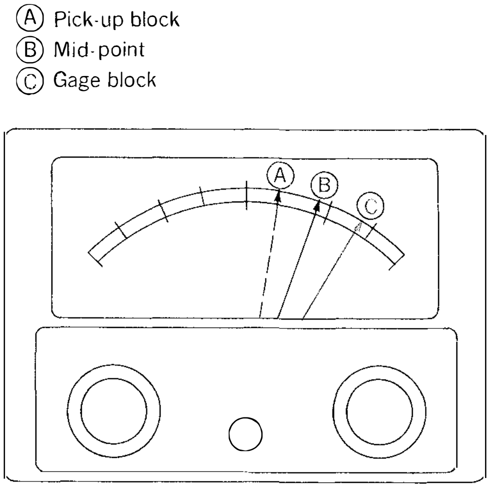
Absolute Measurements

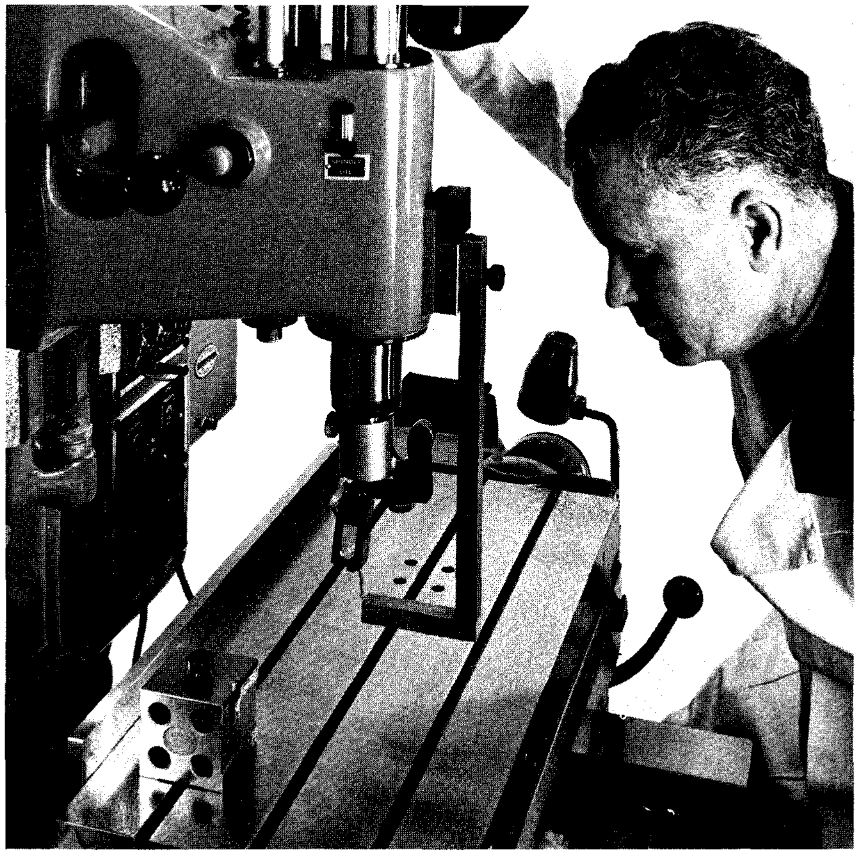
Once the reference edge has been located under the spindle centerline and a zero set against this edge, a variety of absolute measurements may be performed. Examples may be shown by referring once again to the demonstration piece of Fig. 474. The length of the piece is measured by striking a zero indicator reading at one end and recording the lead screw setting. The spindle is rotated 180° and the table is traversed until the other end registers a zero on the indicator probe. The length of the demonstration piece is equivalent to the difference in lead screw readings recorded at either end, Fig. 508. The 4-inch width [100 mm in metric] of this piece is measured in the same manner.

Size of the holes may also be measured with this technique. Once the location of

FIG. 506—*Final precise alignment of the edge of the pick-up block with the machine spindle is accomplished by noting the reading obtained against the pick-up block and the gage block without having moved the axis. Exact location of the edge is the mid-point of the two readings.*

FIG. 507—*A special attachment which fastens to the front of the quill housing allows the indicator probe to be set on the spindle axis within .0001 inch [0.0025 mm] for faster alignment.*





the holes is determined, their centerlines are also known for the purpose of measuring size.

It should now be apparent that with this method it is possible to measure to any point in the 11 by 18 inch [280 mm by 460 mm] plane of travel of the machine.

Measure Diameter of Ring Gage—3 Methods

In order to measure the diameter of a ring gage, or any hole, its centerline must first be determined, and is accomplished by any one of three different methods.* The first

*At the time of writing, a new "sizing" probe has become available. The design was arrived at by cooperation of engineers at Federal Products Corp. and the Moore Company, specifically for use with the Moore Universal Measuring Machine. The use of this probe will allow sizes to be measured without first zeroing on the pick-up block and without rotating the spindle. Most importantly, *probe-tip size still does not enter into consideration.*

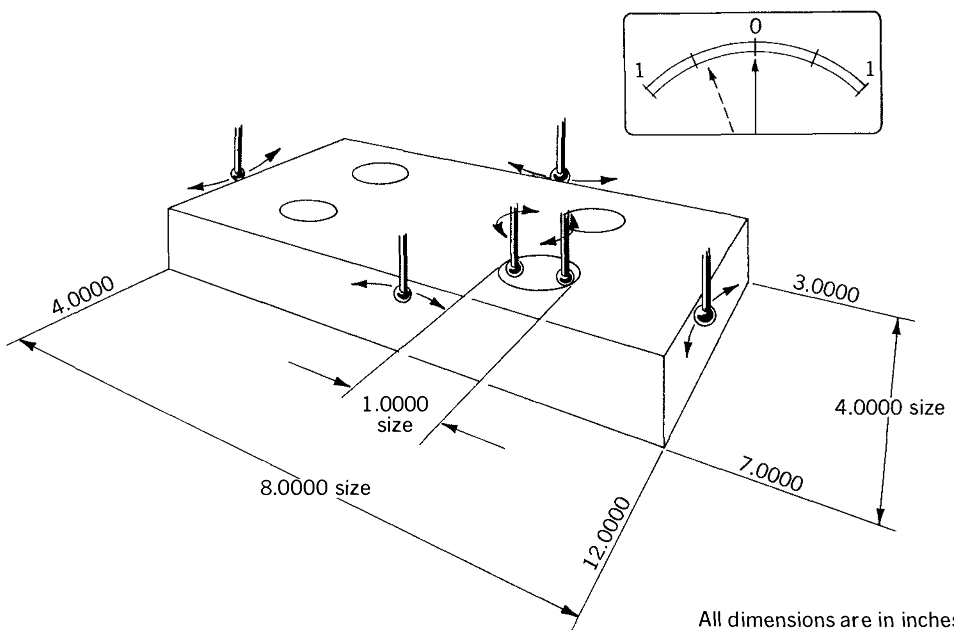
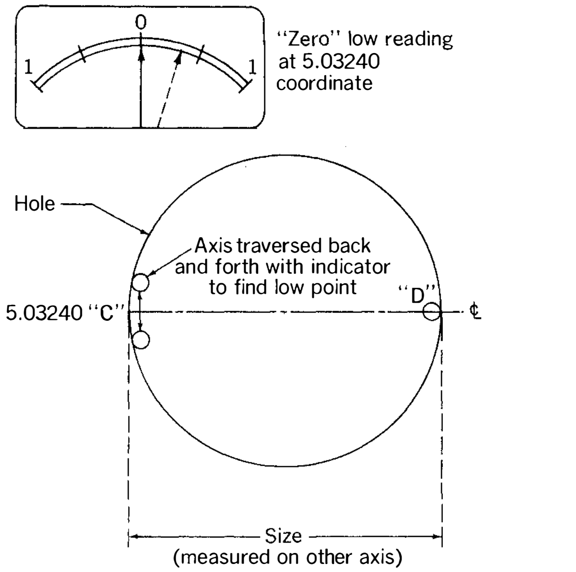
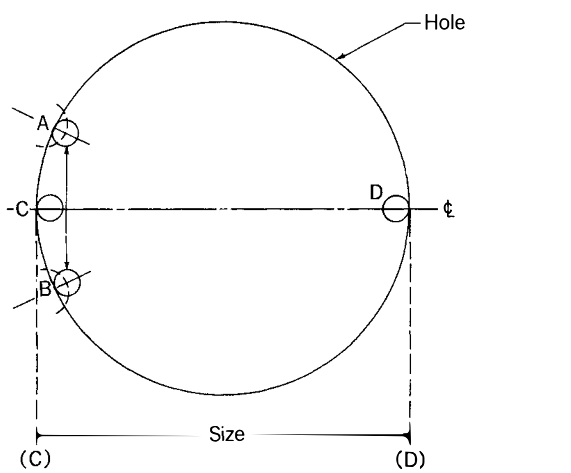


FIG. 508—*The demonstration piece is used here to show how the Universal Measuring Machine may be used to perform a variety of absolute measurements. All these measurements may be accomplished once a "zero" is set with the indicator on an edge directly on the spindle axis.*

FIG. 509—(top) One method of measuring the size of a hole is to tram one axis back and forth with the indicator registered in the hole so as to find the "low" point which is its centerline. Size of the hole is then measured on this centerline with the other machine axis.

FIG. 510—(center) A more exact method of determining the centerline of the hole for purposes of measuring size with a set probe is to strike a "zero" by rotating the spindle at locations A and B using one machine axis. The centerline is exactly between the two lead screw readings obtained.





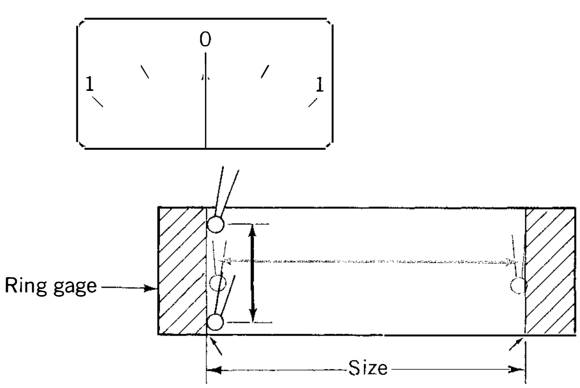


FIG. 511—Size of a hole, such as a ring gage, may be measured at any depth simply by employing the vertical adjustment of the measuring machine quill.

method, in which the probe is extended to register against the sides and the lead screw is used to center the piece under the spindle, has already been described in Example No. 1, Step 11, page 290. This method is the most accurate way to find the center of the hole but this accuracy is unnecessary and moreover time consuming when only size is to be determined. Also it is more convenient to be able to determine the centerline of the hole without having to alter the probe, once a zero has been set against the pick-up block.

The second method, illustrated in Fig. 509, does not require altering the probe. One axis of the machine is traversed back and forth while the indicator is registered normal to one side of the hole. The centerline of the hole is at that point of the axis where the lowest indicator reading is recorded. The hole is then measured with the other axis along this centerline from C to D. This is by far the fastest method. While it does not establish the centerline of the hole as precisely as the previous method, the error which may be introduced through its use is negligible except for small holes.

A third method, illustrated in Fig. 510, is the most precise for determining the centerline of the hole, while still leaving the probe set to zero under the spindle axis. This method is preferred for orienting single small holes. The steps are:

1. Strike a zero by rotating the spindle, with probe contact at a point such as A. Record the lead screw reading.
2. Similarly, strike a zero at point B directly opposite, moving only the cross axis.
3. Halfway between A and B is the centerline of the hole. Its diameter may be measured with the long axis in the manner previously described.

Since the centerline of the hole in the other direction is halfway between the coordinates at C and D, a second measurement of the hole may be made across its diameter using the cross lead screw. This second check is valuable since it provides a measurement of the hole across two diameters, and to some extent double-checks the first measurement by comparing the two lead screw measurements.

The diameter of the ring gage at the bottom is measured by simply lowering the spindle and traversing from C to D as in Fig. 511.

All the sides of the ring gage may now be probed to determine straightness, lean and other geometric aspects of the hole, Fig. 512.

While the ring gage is in the same position, a polar recording of roundness may be made. The concentricity of the top and bottom of the hole can also be determined, Fig. 513. The reader should also refer to the previous section (see pages 268-272) for further information on using the Universal Measuring Machine for measuring roundness.

Internal comparators are the usual instruments for the measurement of hole size. These instruments usually consist of two probes which project vertically from a platen which supports the piece to be measured. The two probes may be set to read differentially, as in Fig. 514. In this case, the reference size is a stack of gage blocks or a master ring gage to which the hole size is compared. This design usually allows greater accuracy in determining hole size than other instruments which have built-in length-measuring systems. The latter instruments, however, avoid the need for masters or stacks of gage blocks.

It is not meant to imply that the Universal Measuring Machine surpasses such comparators. Internal comparators, especially the differential type, can hardly be excelled for speed and accuracy in repetitive-type measurements. The advantage of the Measuring Machine for such applications is that it allows the

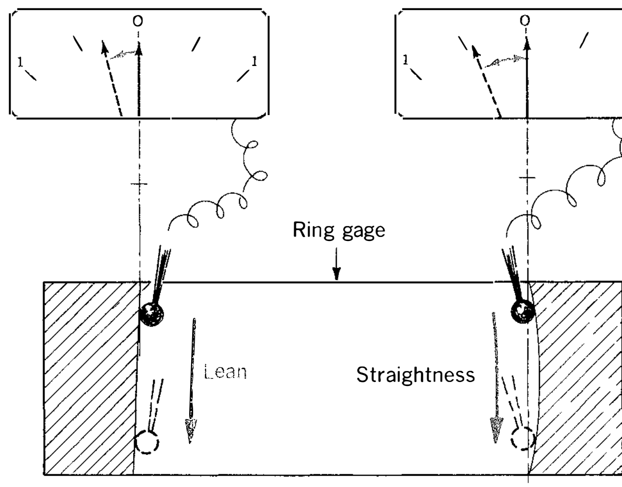


FIG. 512—(*top*) *All aspects of hole geometry, as with this ring gage, may be determined through use of the accurate movements built into the Universal Measuring Machine.*

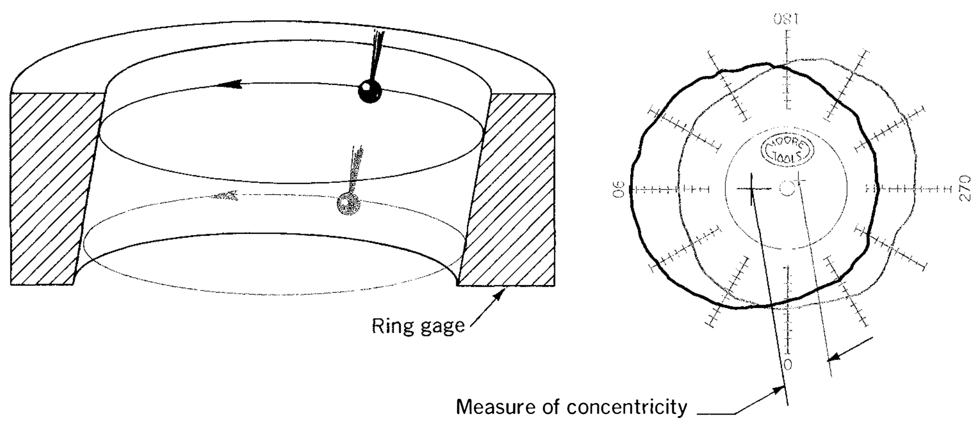


FIG. 513—(*center*) *Concentricity of top to bottom of a hole is determined by making a polar tracing, adjusting the quill to a new depth and then comparing the two tracings.*

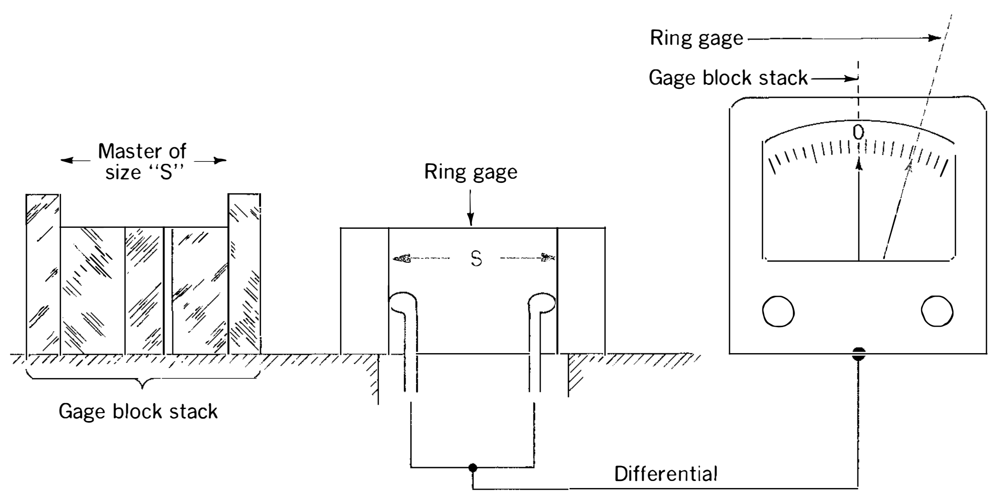
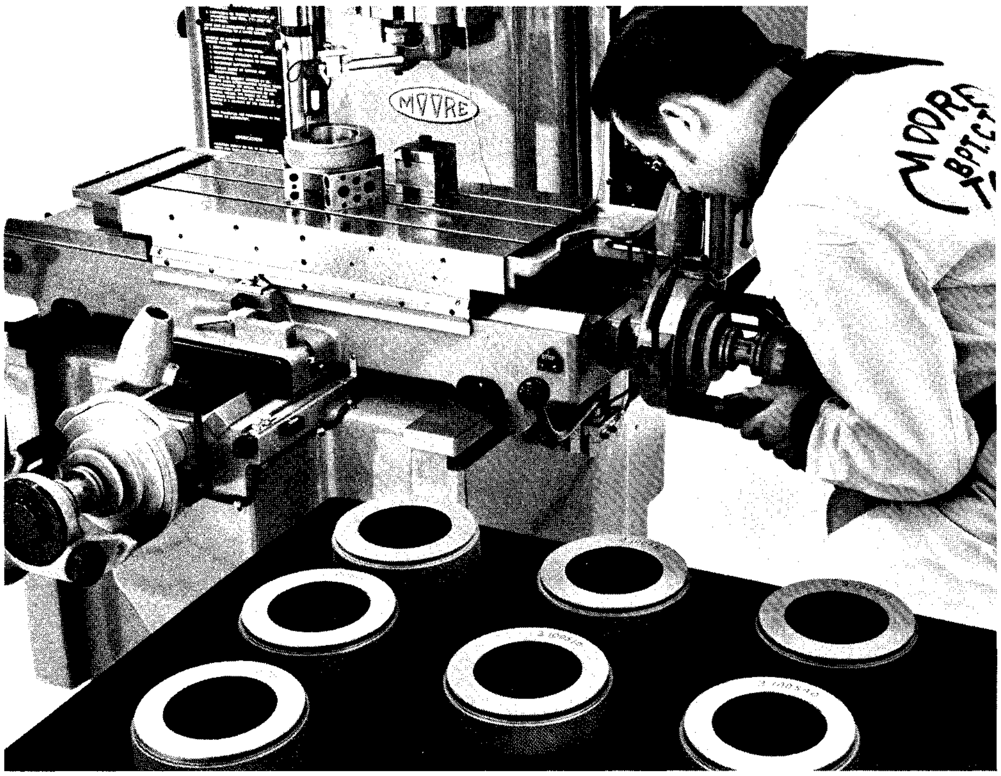


FIG. 514—*Very accurate determinations of ring gage size are made by internal comparators which have been set against gage blocks.*

FIG. 515—*The ten ring gages shown are in 10 millionths of an inch increments [0.00025 mm] and are used as a physical test of size of the rotary table spindle assembly. The Universal Measuring Machine allows size, roundness and other geometric characteristics of the holes to be inspected in one set-up.*



measurement of "specials," especially large, odd size holes when there is no available master to which the hole may be compared, or when there is doubt as to the accumulated accuracy of a number of gage blocks that have been wrung together. It has been the author's experience that the wringing films may vary surprisingly in thickness, in actual workshop practice. It is therefore standard practice at Moore to measure master ring gages with the Universal Measuring Machine.

An example of th use of the Universal Measuring Machine for calibrating the hole size of masters is shown in Fig. 515. The ten ring gages being measured differ in size by increments of 10 millionths of an inch [0.00025 mm] for a total spread of 0.0001 inch [0.0025 mm]. These gages are used as a final physical test of the assembly size of the rotary table spindle. Since they are used in production and are subject to wear, the ring gages are calibrated on a calendar basis as shown for size, roundness and straightness.

THE MODEL No. 1½ UNIVERSAL MEASURING MACHINE

The No. 1½ Universal Measuring Machine, which is shown in Fig. 516, has virtually the same principles of construction and measurement capabilities as the No. 3 model. The essential differences are the lesser capacity of 9 by 14 inch travel [230 by 355 mm] and the use of scraped cast-iron V-ways, rather than the hardened, ground and lapped ways of the No. 3 model. Although initially made to the same accuracies, the wear-life of the No. 1½ model is therefore much less than that of the No. 3 model.

The smaller model has been made available to allow small workpieces to be measured with a lesser investment by the owner. For this reason, this model is an

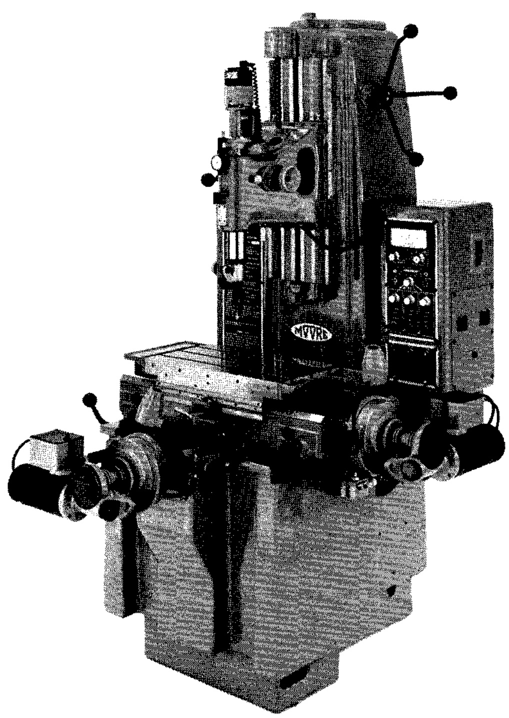
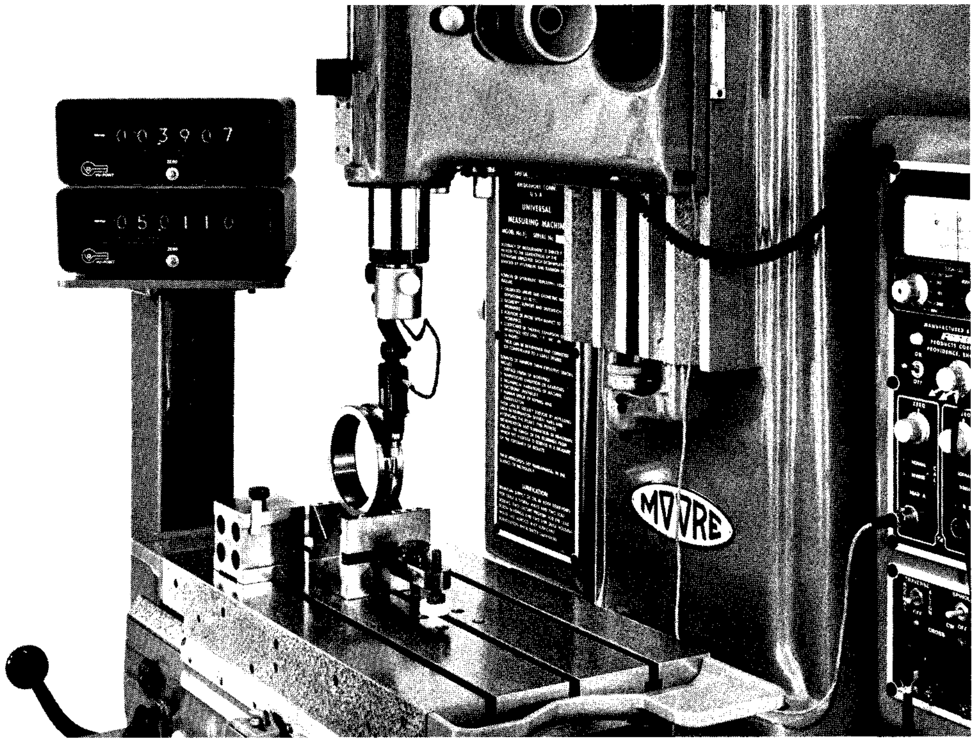


FIG. 516—*The No. 1½ Universal Measuring Machine employs the same design characteristics as in the No. 3 Universal Measuring Machine, but has a lesser travel of 9 in. by 14 in. [230 x 355 mm in metric machines]. Also, mating way surfaces are of scraped cast iron and are not hardened, ground and lapped as in the No. 3 model.*

FIG. 517—*This model No. 1½ Measuring Machine is shown with a built-in readout whose accuracy still derives from the lead screw. The readout may be used to record radius size of the ball track (shown), and the lead screw dials to record simultaneously other part dimensions. The readout may be switched on and off as often as desired without accumulated loss of accuracy, since the lead screw dials, once set, provide a permanent reference.*



ideal selection when the essential application is to be the measurement of roundness of small parts.

READOUT ON THE UNIVERSAL MEASURING MACHINE

An example of the measurement of small parts on the Model No. 1½ Measuring Machine is shown in Fig. 517. This particular machine has been fitted with a "Vu-point readout."* Virtually all of the accuracy of the lead screw is retained when a readout is adapted to any model of the Universal Measuring Machine, since engineering practice is to use only rotary transducers to monitor the indexing of the lead screw.

A great advantage of the readout, as used on a Universal Measuring Machine which measures displacement by means of an accurate lead screw, is that two separate types of dimensions may be recorded simultaneously with only one measuring element. For example, the reference scale and dials may be used to record coordinate locations, while the readout is used to record individual hole size, (or vice versa). In Fig. 517, the readout records the cross-section size of the ball track, using the pick-up block to the left to set the indicator to the given radius. The reference scales and dial may be used simultaneously to record the circular diameter of the ball race from the center of its track radius as in Fig. 518.

The readout may be switched on and off or re-set to new figures as often as desired during the measurement process with no loss of accuracy, since the lead screw dial settings provide a permanent reference.

The readout package may also be fur-

*Vu-point readout manufactured by Remex Electronics, Division of Ex-Cell-O Corporation.

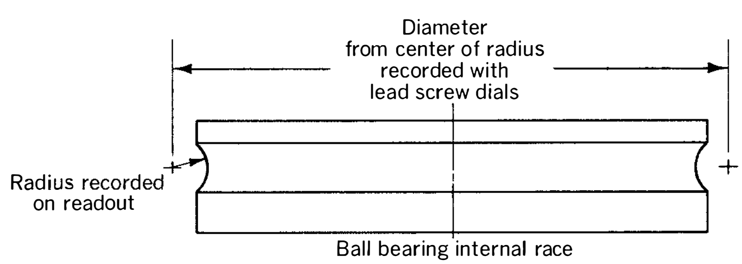


FIG. 518—*Drawing of the internal race shown in Fig. 517 demonstrates the convenience of using the readout and the lead screw dials simultaneously.*

FIG. 519—*The ability of the Universal Measuring Machine to perform "absolute measurements" is particularly essential in the measurement of cam shapes, as with this master for an automotive cam shaft.*

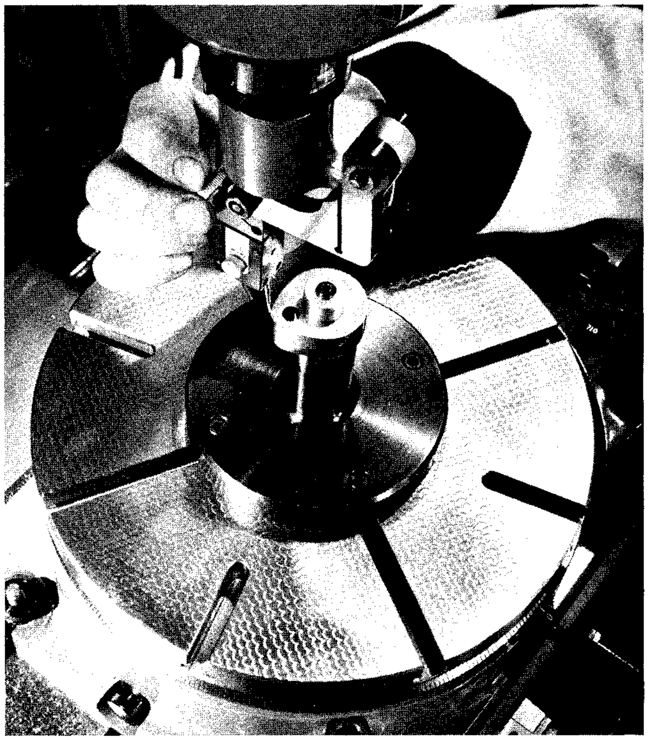


FIG. 520—*Angular spacing of gear teeth is most truthfully inspected when the Rotary Table is used in conjunction with a Universal Measuring Machine rather than by surface plate methods. Use of a gage pin allows both flanks of the gear tooth as well as center-distance to be included in the measurement. Two gage pins aid in initial aligning of the gear.*

nished with a printout in order to record all dimensional values.

Cam Shapes

Fig. 519 shows an automotive master cam mounted on the Measuring Machine and rotary table. The cam has been generated by a tape-controlled jig grinder.

The value of being able to measure absolutely, once the probe is centered with the Measuring Machine spindle, is particularly apparent for such applications. Cam shapes may be measured at as many tens or hundreds of points as is feasible or practical. Measurement may be performed entirely by rectilinear coordinates or by a combination of angular rotation and linear movement as shown here.

3. Applications of the Universal Measuring Machine

The basic techniques of measuring size, roundness, and rectilinear and polar coordinates through use of the Universal Measuring Machine have now been described. With a little imagination, these same techniques may be applied to solve an extremely wide range of measuring tasks. It is instructive to present some typical measuring applications which demonstrate the machine's even greater versatility when used in conjunction with other available instruments.

USE OF ANGULAR-MEASURING INSTRUMENTS ON THE UNIVERSAL MEASURING MACHINE

The Rotary Table

The rotary table is the most versatile instrument for a wide range of measuring applications where angle is the essential consideration.

FIG. 521—*The rotary table is shown mounted on the Universal Measuring Machine, utilizing its built-in right angle feature. The thin walled aluminum part has been permanently fixtured until all precise machining and inspection are completed. Holes in this part must be positioned and aligned within .0001 inch [0.0025 mm].*

Used Flat

In Fig. 520, the tooth-to-tooth spacing of a gear is inspected through use of the rotary table. The gage pin is of a specific size to establish its axis on the pitch line of the gear, and is placed in each consecutive notch as the rotary table indexes to the specified angle.

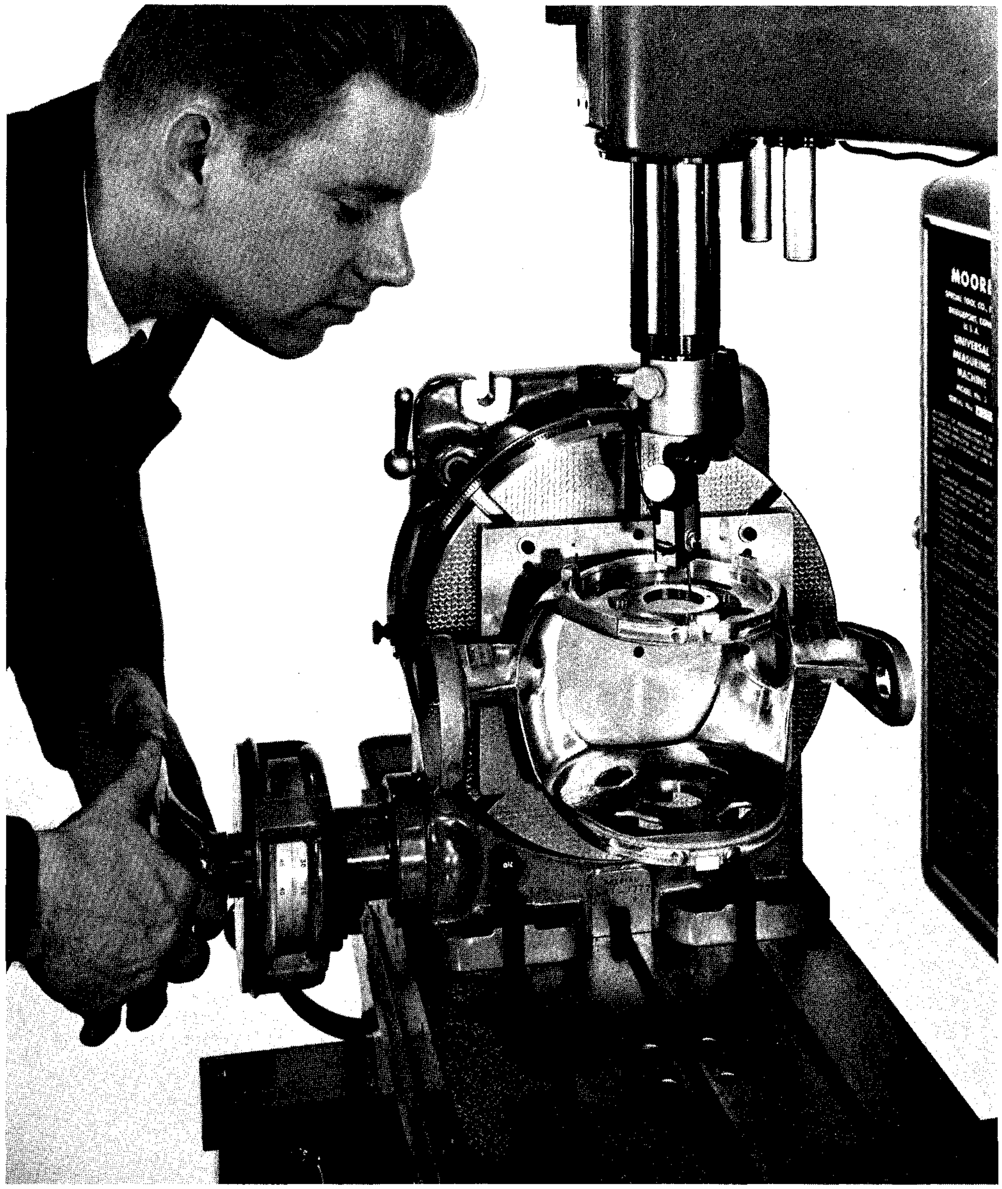
Such an inspection is usually performed on a surface plate, the gear being mounted with its axis horizontal on some form of indexing head. Angular spacing of the teeth is then determined with an indicator and stand, using the high point of the pin as a reference.

However, the angular spacing of the teeth is more truthfully represented by picking up the axis of the pin, Fig. 520, rather than its high point. The center-distance of the teeth, an important dimension, can also be determined simultaneously.

The use of two pins at opposite diameters as shown insures the most accurate orientation of the gear to the measuring system. The technique is to first align both pins with the measuring machine axis, while intersecting the rotary table rotation axis (if the gear has an even number of teeth). Re-checking the alignment of the pins after turning the rotary table through 180° provides a sensitive proof, since any set-up error is doubled.

Used Horizontally

In Fig. 521, the rotary table is mounted with its axis horizontal, utilizing its built-in right angle feature. Shown is a fragile, thin-section aluminum part. To establish an adequate reference and clamping surface, the part is permanently fixtured on the flat plate shown until final machining and inspection are completed. The alignment of the holes in this part, which is particularly critical, may be accurately measured because of the exceptional angular and rotational accuracy of the Ultra-Precise Rotary Table.



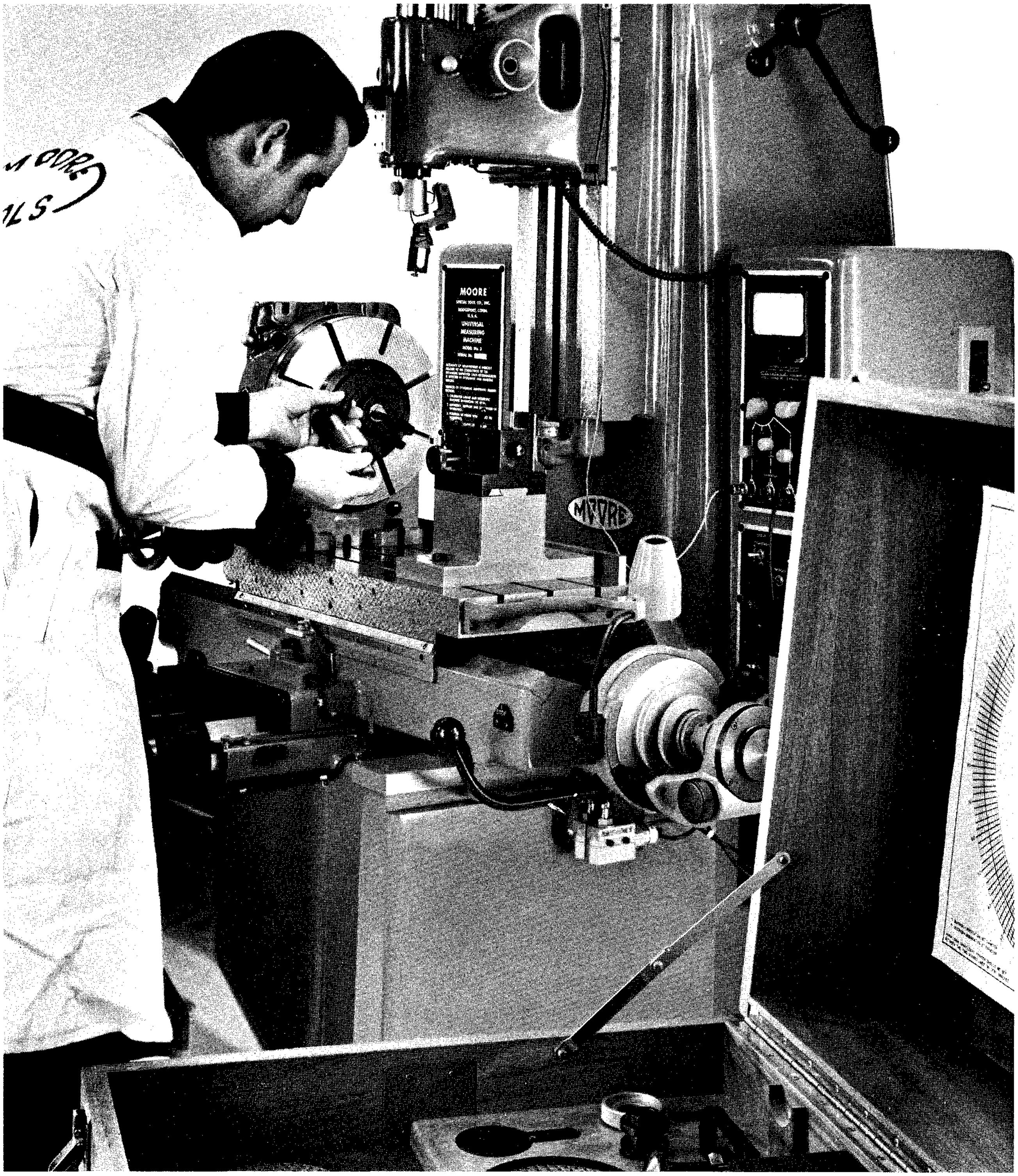


FIG. 522—*A special accessory for the Rotary Table is the Tailstock Unit; shown here, it is used to make possible an inspection of lead and periodic error of a thread-ground worm.*

Used With Tailstock Unit

A tailstock unit is available for use with the rotary table to allow the measurement of features of a part when held between centers. In addition to the tailstock itself, this unit consists of an adjustable center which mounts on the face of the rotary table. When thus equipped, the rotary table may perform the functions of an indexing head, but with the additional advantages of a large swing of 15½ inches [393.7 mm], accuracy to ±2 seconds, and the option of either reading angles on the dial or using an index plate (see "Dividing the Circle," p. 218).

In Fig. 522, the tailstock has been removed from its storage nest in the mahogany rolling cabinet (foreground) and mounted on the machine table. The part which is being mounted will be inspected for overall thread lead, and indexed by use of the rotary table to measure periodic error.

In Fig. 523, a turbine has been arbor-mounted between centers. As each blade is indexed over center, its size, geometry and angular spacing are compared.

In Fig. 524, a 500-line dial is mounted on an arbor and inspected with the standard 30-power microscope.

The Precision Index Center

The Index Center shown mounted on the Universal Measuring Machine in Fig. 525 also allows the inspection of parts held between centers. Spindle accuracy of this instrument is better than 15 millionths of an inch [0.00038 mm] T.I.R. Indexed position is governed by hardened, jig-ground index plates, accurate to ±6 seconds, which are fastened to rotate integral with the Index Center spindle. The knurled knob in the inspector's right hand rotates the spindle, and the carbide pin in his left

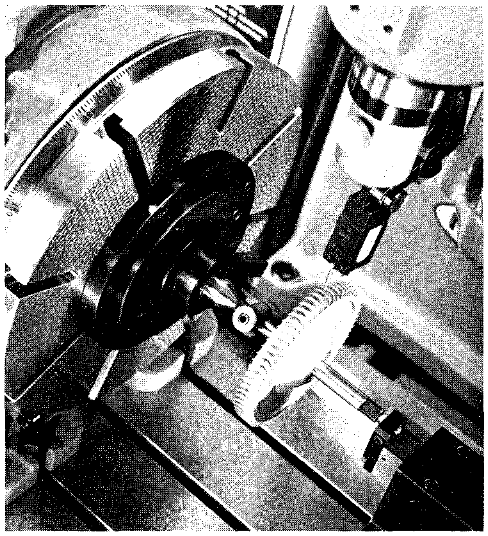


FIG. 523—*An air turbine is arbor-mounted between centers of the Rotary Table and Tailstock. Geometry, radial size and angular spacing of the blades may be inspected in this manner.*

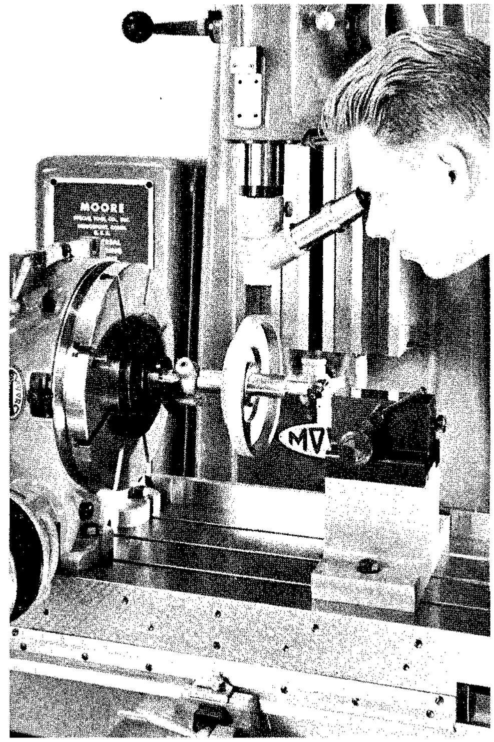


FIG. 524—*A precision dial having 500 lines is mounted on an arbor between centers on the Rotary Table and Tailstock. A graticule in the 30× Standard Microscope is used to position each line to a reference line, included angle being determined with the rotary table.*

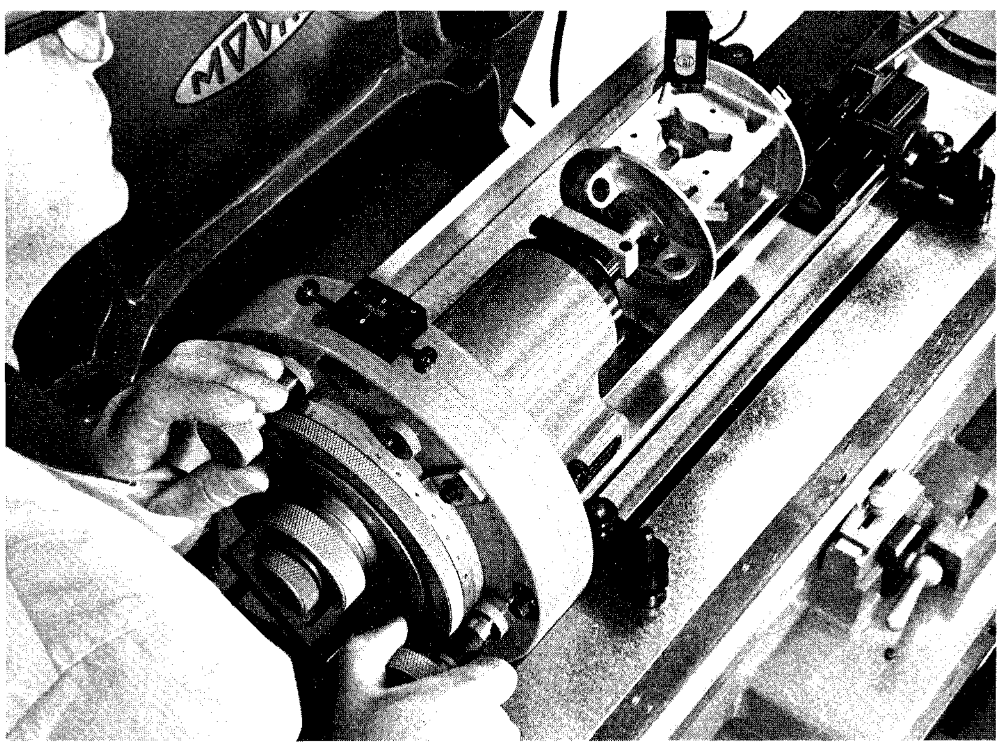
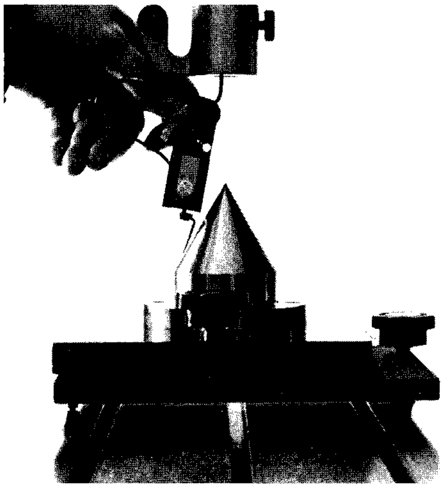
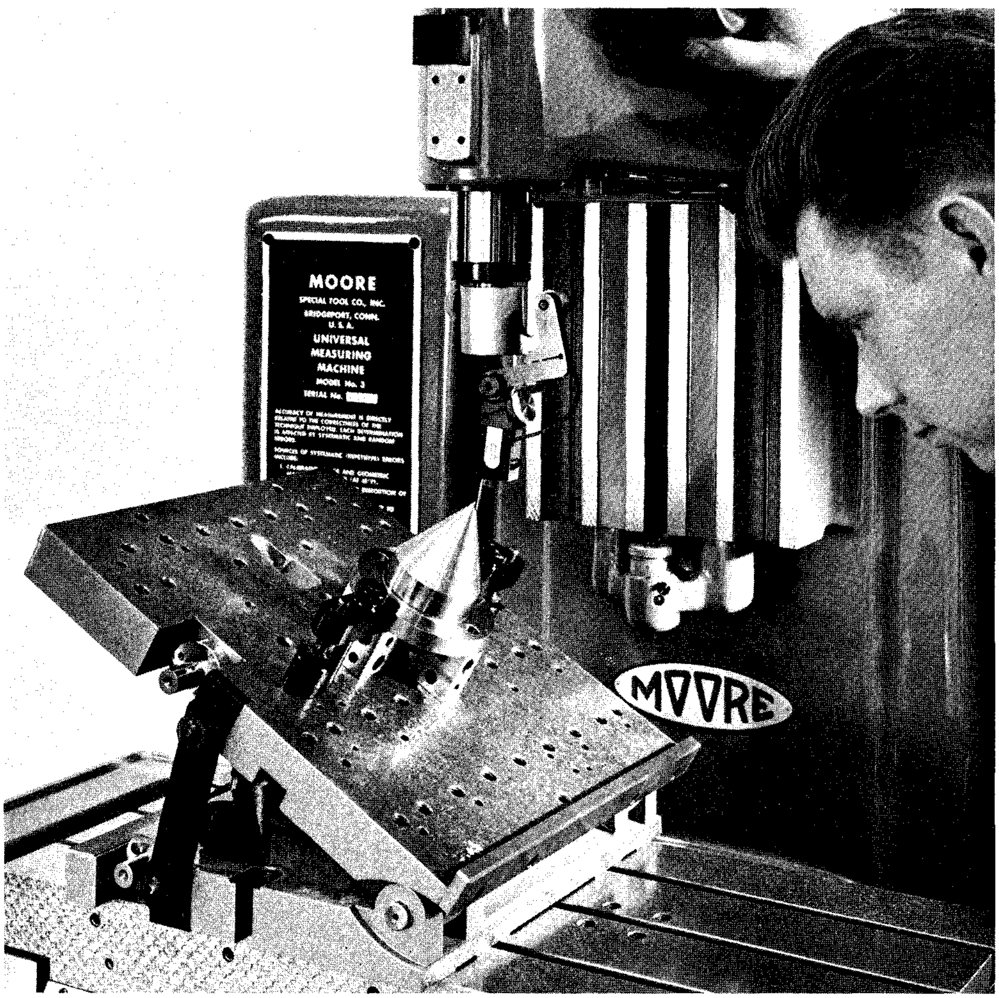


FIG. 525—*The Precision Index Center provides a rapid method of angular indexing of parts. It is designed with a low profile for convenience in inspecting smaller parts.*

FIG. 526—*When roundness of a conical part is inspected using a leveling plate, the axis of the cone may unknowingly be shifted to obtain the best circular trace.*





is used to locate from a lapped carbide hole to the index plate hole.

Because of its fast indexing capability and its low profile, the Index Center is ideal for repetitive-type indexing and for the inspection of small gears and gear dies. This instrument is also designed to allow through-grinding on the surface grinder, and is sealed to make wet-grinding applications possible.

The Micro-Sine Table

The No. 3 Micro-Sine Table is particularly adaptable to measuring machine use since it is capable of great accuracy when set with care by the inspector (see page 214).

One of its unique advantages when used with the Universal Measuring Machine is illustrated in Figs. 526 and 527. Conical parts are typically inspected for roundness as in Fig. 526, using the leveling table to obtain the best circular trace if the piece has no reference surface to use in alignment. However, in doing so, the axis of the cone may be unknowingly adjusted out of alignment to compensate for its roundness condition. When the conical part is mounted on the Micro-Sine Table instead, its angle and roundness may be inter-related. Roundness is inspected while the Micro-Sine is at 0°, and the angle is inspected as shown in Fig. 527.

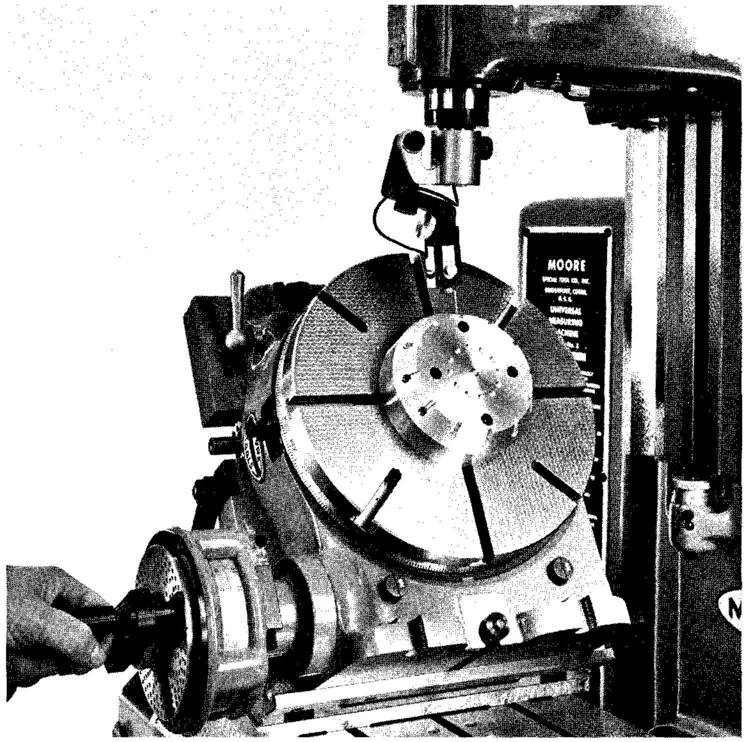
Rotary Table Mounted on the Micro-Sine Table

The No. 3 Micro-Sine Table has been designed especially for use with the rotary table for the inspection or generation of compound angles. In Fig. 528, the rotary table and Micro-Sine Table are used to inspect the angular spacing of thirteen holes which have been bored at a 45° angle to the axis of the part. Note the use of the index plate, which facilitates the measurement of inconvenient angular spacings (such as thirteen).

The twelve holes about the center of the

FIG. 527—*The roundness and included angle of conical parts should, if possible, be inter-related in an inspection. This can be accomplished through use of the roundness inspection features of the Universal Measuring Machine and the Micro-Sine Table. Included angle (and orientation of the axis) is being determined here prior to performing a roundness trace.*

FIG. 528—The rotary table is mounted on the Micro-Sine Table for the inspection of 13-hole spacing. The index plate aids in the setting of such inconvenient angular spacings. The 12 holes about the center of the part are inspected by reading the dials while the Micro-Sine Table is horizontal (0°).



part are inspected while the Micro-Sine is at 0°, and their angle-spacing read on the rotary table dial.

1440 Small Angle Divider

The highest grade of rotary table offered by Moore is accurate within ±2 seconds. Although this accuracy is certainly sufficient for even the finest class of laboratory-type use, it is not truly consonant with the accuracy of the Universal Measuring Machine. To illustrate, on an 8-inch [203 mm] diameter workpiece, a 2-second error is equivalent to approximately 40 millionths of an inch [1 μm]. In contrast, the Measuring Machine would have no more than 20 millionths of an inch [0.5 μm] error in this distance. Moreover, circle-dividing instruments in use have the unfortunate characteristic of doubling small errors in alignment or in centering of the workpiece.

The 1440 Index by itself is not convenient for general use with the Universal Measuring Machine, since it does not allow for fine increments of angular movements, which are necessary to orient holes central to the Measuring Machine spindle. Also, this instrument is restricted to only 1440 positions. In order to overcome the discrepancy in the accuracy attainable with linear as compared to angular measurements, the 1440 Small Angle Divider has been adapted for use with the Universal Measuring Machine. This instrument will discriminate angular values as fine as 0.1 second.

In Fig. 529, an index plate for use with the Precision Index Center is inspected through use of the 1440 Small Angle Divider. In such applications, if the number of holes in the piece is a factor of 1440, only the 1440 index component is indexed, and the accuracy of angle-setting is ±0.1 second. At all other numbers of hole-spacings, accuracy is within ±0.5 second.

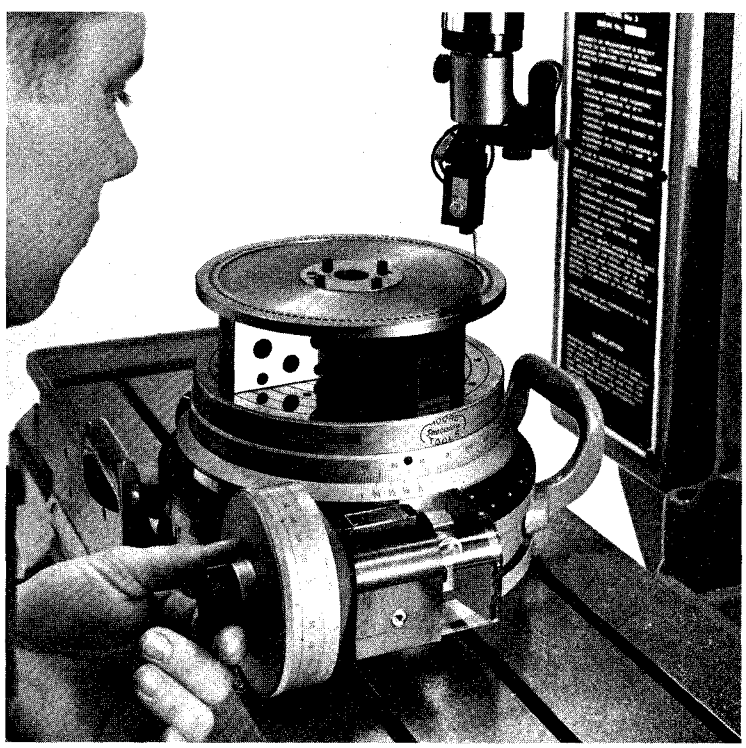
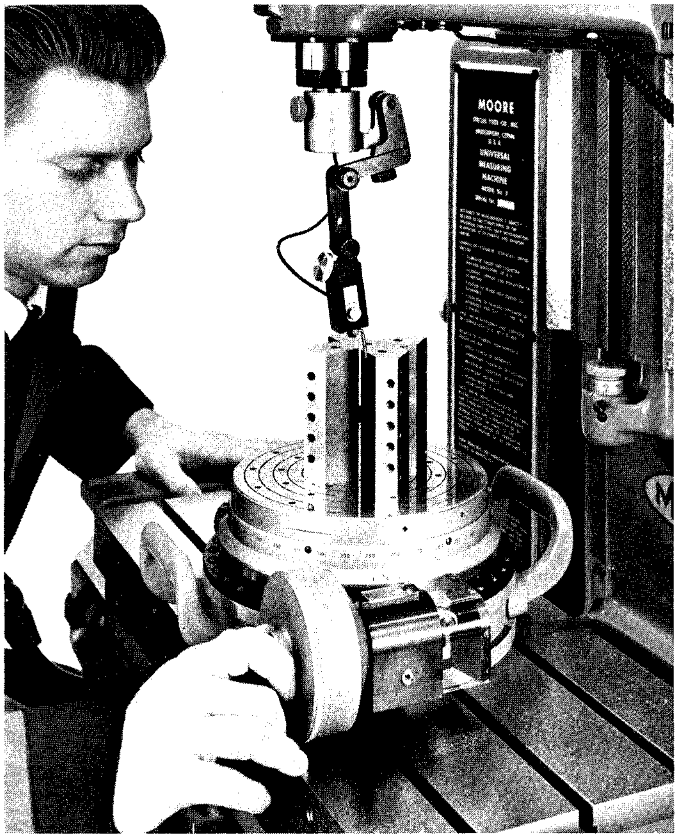


FIG. 529—The most accurate instrument for resolving angular errors with the Universal Measuring Machine is the 1440 Small Angle Divider. One thousand, four hundred and forty increments are inspected within ±0.1 second. This instrument will set to increments as fine as 0.1 second with an accuracy of ±0.5 seconds over the full 12,960,000 increments. Under inspection is a jig ground index plate used with the Precision Index Center.

FIG. 530—*A master V-block is inspected using the 1440 Small Angle Divider on the Measuring Machine. The former establishes the angle and the latter the datum straight line. The angle may be measured along the full length of the V-block by extending the quill.*



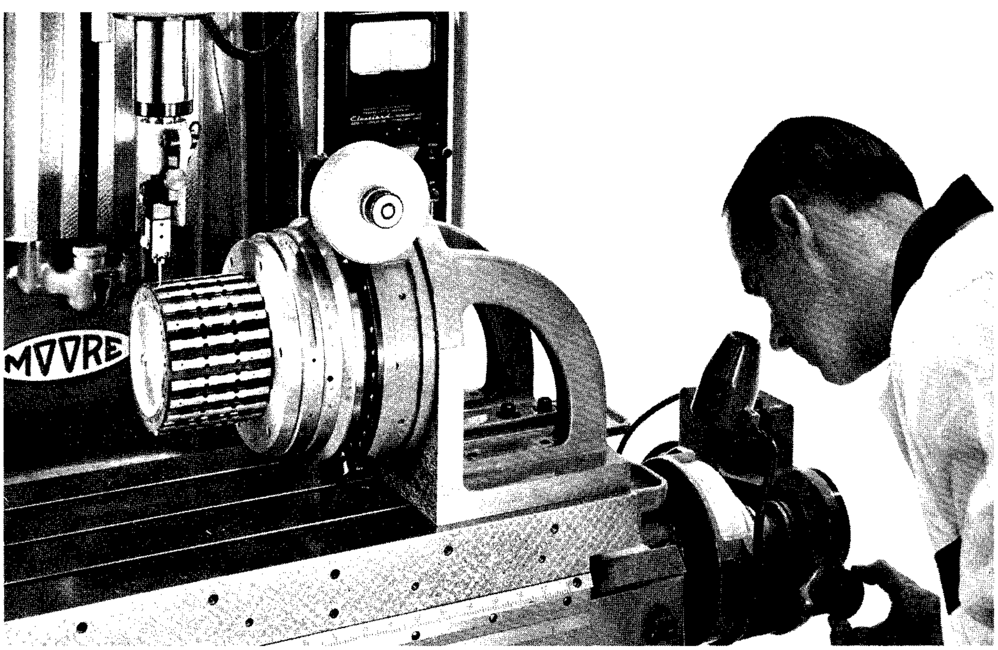


FIG. 531—*The 1440 Small Angle Divider is mounted on a special angle iron when angular values are to be inspected while the part is in such an attitude, as shown here. The part is an element of a high-speed film-cutting die.*

The inspection of geometric forms to a high degree of accuracy is possible when the 1440 Small Angle Divider is mounted on the Measuring Machine. In Fig. 530, the 90° included angle of a master V-block is measured. The procedure is to first align one side of the V with the machine axis while the 1440 Small Angle Divider is at 0°. Next the other side of the V is rotated into alignment with the machine axis by use of the 1440 Small Angle Divider. The included angle is read directly. By extending the quill, the included angle and the shape of each side is inspected along the full length of the V-block.

Angular relationships in another attitude are inspected by mounting the 1440 Small Angle Divider on a special angle iron, as shown in Fig. 531. The slots and holes of a component of a film-cutting die are inspected by mounting the 1440 Small Angle Divider with its axis horizontal.

Use of the Strip Recorder

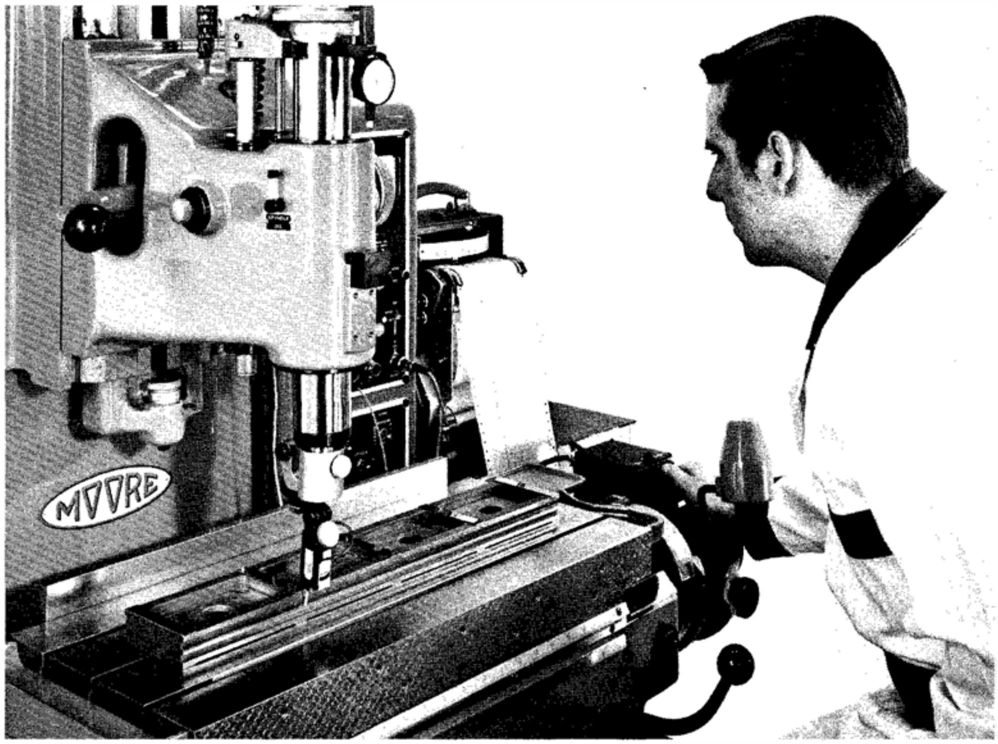
A linear recorder, Fig. 532, may be used to record indicator values. Vertical magnifications of the trace are set on the meter panel.

This accessory has many possible applications such as the recording of roundness, straightness, angular deviations or errors of surfaces of a workpiece from their specified coordinates. The method of calibrating the master straightedge against the machine axis shown in Fig. 532 is ideal, since any deflection of the straightedge in this attitude is in a neutral direction to the surface being measured. Deviations from straightness are shown on the graph (right).

Straightness of the machine axis is self-proved upon turning the straightedge over and making a second tracing of the same side.

Fig. 533 shows the same principle extended for an even more comprehensive calibration. Attached to the housing on a

FIG. 532—*The Strip Recorder allows indicator values to be recorded on a strip chart. This instrument has many applications, one of which, the recording of straightness of a master straightedge, is shown. The straightedge is rested in a neutral direction to bending, and may be reversed to self-prove the machine.*



common bracket are two indicator gage heads. Switching facilities built into the meter-panel allow the readings of either probe (or even a third probe) to be viewed on the meter, or to be recorded. The upper trace on the chart is a recording of the straightness of the far edge of the straightedge using probe No. 1. The lower trace is of the front edge of the straightedge using probe No. 2. The center trace of the chart records the variation of thickness of the straightedge, obtained by operating the two probes differentially.

SPECIAL MACHINES EMPLOYING THE No. 3 OR No. 1½ BASE CONSTRUCTION

The coordinate-system is a fundamental mechanical principle which is applied to a countless number of tasks in science and industry. The No. 3 base construction is a coordinate-system which has been proven to be capable of the ultimate in accuracy. Yet it is made in sufficient quantities (several hundred a year) to enable economical production. It is therefore a logical choice for other applications requiring slide-way movements, but to jig borer or measuring machine accuracies. In addition to those uses already described (see pages 223 and 235), the No. 3 base has been applied as the coordinate system for such diverse applications as electrical discharge machining (Keystone Carbon, Eltee Manufacturing), micro-circuit analysis (CENG, Grenoble, France), fresnel lenses (Alliance Tool and Mold Corp.) and a ruling engine for diffraction gratings (Massachusetts Institute of Technology).*

Recently, the No. 3 base slide-way has been applied with a roller way construction, Fig. 534. The advantage of this design

*For more detailed information see: George R. Harrison & Stephen W. Thompson, "Large Diffraction Gratings Ruled on a Commercial Measuring Machine Controlled Interferometrically," *JOSA*, Vol. 60, No. 5, 1970.

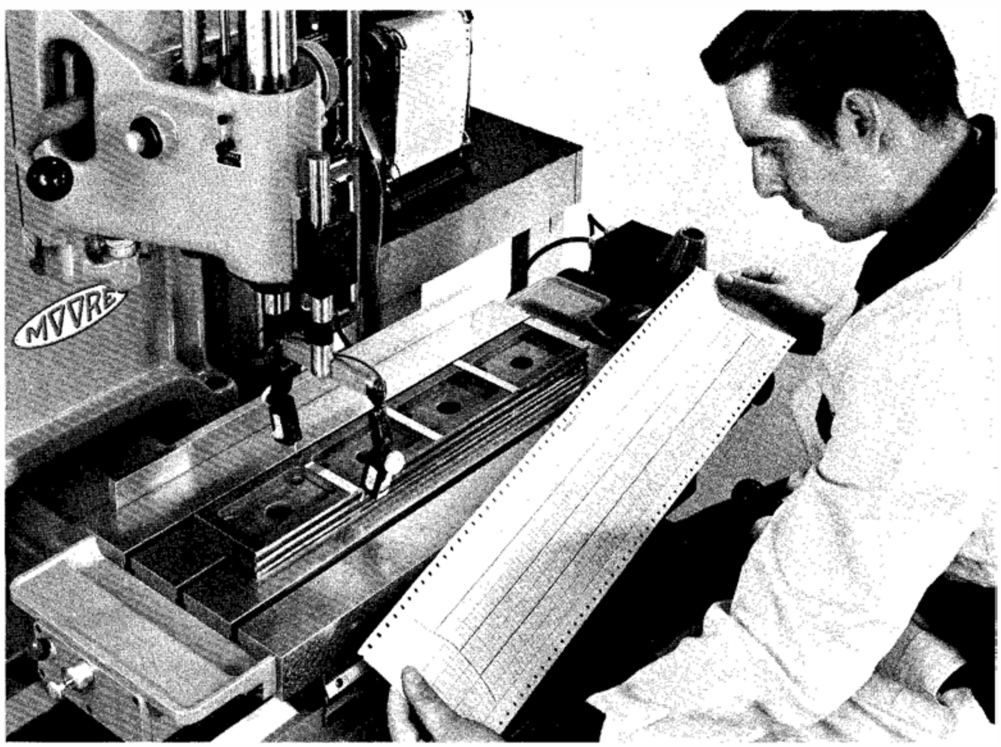


FIG. 533—*Three features of the master straightedge are recorded on the strip chart. The top line shows straightness of the far side of the straightedge, the bottom that of the near side. The middle line records variation in straightedge thickness, using the indicators set up differentially.*

FIG. 534—A roller-way construction applied to the No. 3 base slide-ways has certain advantages for special purpose applications, notably repeatability to a fraction of a millionth of an inch [hundredth of a μm]. Important applications are listed.

is that the limitation imposed on accuracy by the accumulated effect of friction, oil-film, and "wind-up" of machine members is virtually eliminated. Repeatability and sensitivity of movement to fractions of a millionth of an inch [hundredths of a μm] are possible with this design (see page 320). Examples of applications of this design are as a micro-densitometer (Ansco), Continuous Path Jig Grinder,* fabrication of integrated circuits (Stewart-Warner Company), grinding of aspheric lenses (Bell and Howell Company, Canon Camera Co.) diamond-tool facing lathe (Lawrence Radiation Laboratory, University of California), optical scanning machine (U.S. Geological Survey), artwork generator (Concord Control, Inc.).**

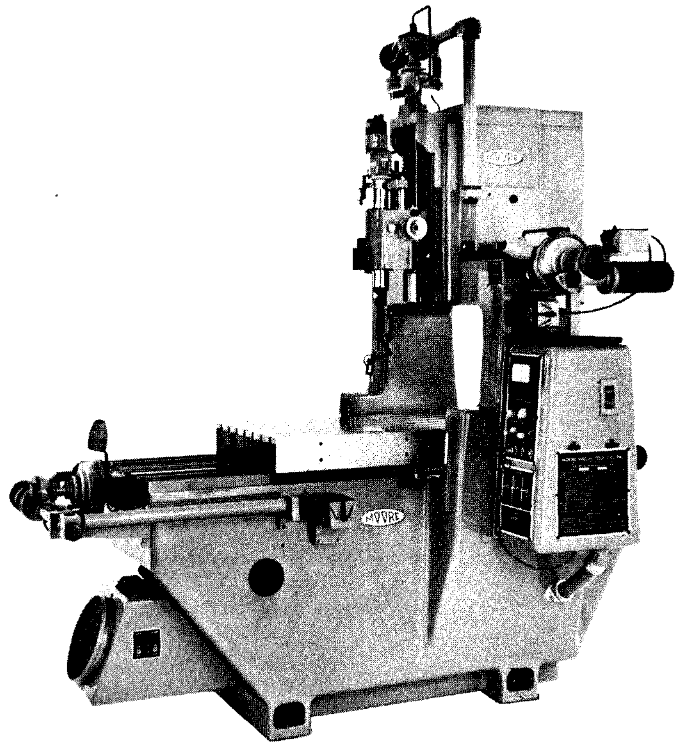
4. The No. 4 and No. 5 Universal Measuring Machines

The No. 4 Universal Measuring Machine has an 18 by 32 inch travel [460 by 800 mm], and the No. 5 Universal Measuring Machine has a 24 by 48 inch travel [600 by 1200 mm.] Both are of a planer-type construction. A third Z axis is available in either model and is demonstrated in the model 4Z Universal Measuring Machine in Fig. 535. The No. 5 Universal Measuring Machine shown in Fig. 536 has been adapted for automatic measurement by numerical control (Union Carbide Nuclear Company).

*For more detailed information see: Rupert LeGrand, "N/C Jig Grinder Makes Molds," *American Machinist*, January 29, 1968; Richard C. Ferguson, N/C Jig Grinder Joins the Ranks," *Modern Machine Shop*, February, 1968; William Hoffman, "Diemakers Big Step—N/C Contour Jig Grinding," *Tooling & Production*, March, 1970; "Numerisch gesteuerte Koordinaten-Schleifmaschine, *Werkstatt und Betrieb*, 1968.

**"The Concord Artwork Generator: A High-Precision Automated System for the Production of Integrated Circuit Artwork Masters," Publication of Concord Control, Inc., Boston, Massachusetts.

FIG. 535—*The model No. 4 Measuring Machine has an 18 in. by 32 in. travel [460 mm x 800 mm]. A vertical Z axis shown on this machine, can be fitted to any model of Universal Measuring Machine.*



Considerations of size, weight and intended function have dictated the selection of the planer-type design for these machines. A compound-type design as used in the No. 3 model would be unnecessarily huge and cumbersome to attain this capacity for purely measurement purposes.

For maximum accuracy, the rail of these larger measuring machines does not have a means of elevation, normally provided in the planer-type jig borer. Instead, uprights are cast integral to the base for maximum strength, and to eliminate stresses when the bridge is bolted to the base. Riser blocks are used between the base and bridge in order to meet the user's specifications as to clearance under the bridge.

The base carries the table, or X axis only, the Y axis traveling on the bridge overhead. Because of the greater masses to be moved (the table of the No. 5 model weighs 1000 pounds [453.6 kg], the movable members are supported on rollers. This design virtually eliminates loss of accuracy which may occur from frictional heat and "stiction."

The planer-type jig borer normally uses as guide ways a V at the top of the rail, and a flat guide at the lower front face of the rail, which is the proper design when there is metal-cutting to be performed. However, the design of the No. 4 and No. 5 models, not having to consider the stress of cutting, or of machine wear, or friction, can employ a double-V construction for maximum accuracy.

All machine members are of close-grained Meehanite iron for stability and are strongly ribbed for rigidity.

As in all Moore Universal Measuring Machines, a 1/10th inch pitch modified acme thread lead screw is employed [3 mm pitch in metric models]. Because of the greater lengths of the lead screws in these models, precision rollers are used to support and align them as shown previously

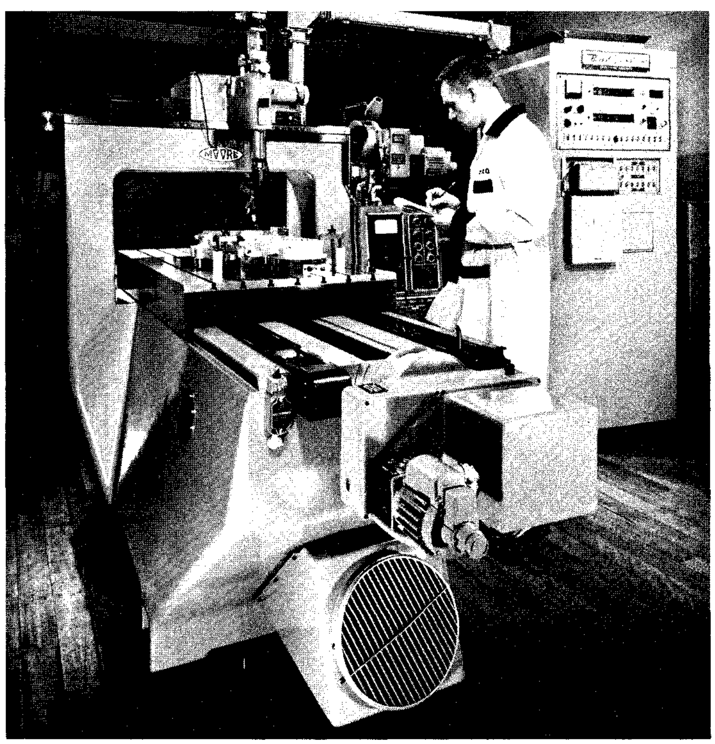


FIG. 536—*The No. 5 Universal Measuring Machine with Numerical Control. Numerical Control is readily adaptable with many possible combinations to a coordinate machine whose accuracy derives from a precision lead screw. Numerical Control is especially suited for the inspection of templates or cams wherein many minute incremental movements are to be made and recorded.*

FIG. 537—*A large Universal Measuring Machine has been seen to be capable of repeat settings and discrete movements as fine as 0.1 millionth of an inch [1/400th μm], when tested against a "fiber-optic probe."*

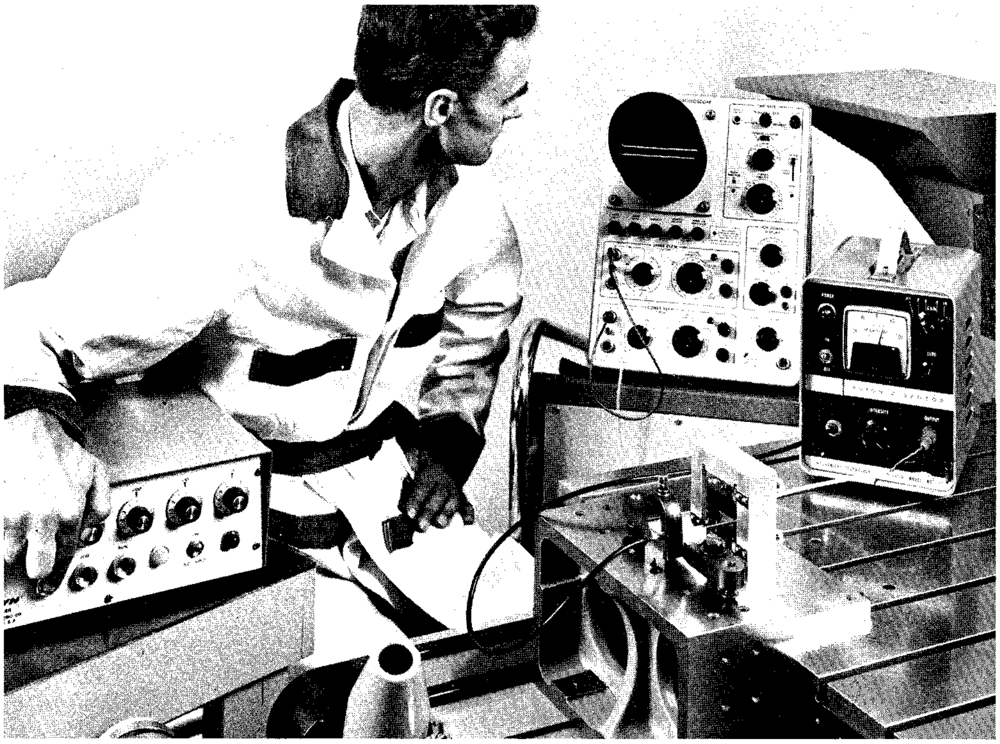


FIG. 538—*The light-gap of the fiber-optic probe to the reflecting surface is made to act on a photo-cell, then is electronically amplified to appear on an oscilloscope screen. Separation of the lines is .400 inch [10 mm] and represents a machine movement of 1 millionth of an inch [1/40th μm]. Roller-way measuring machines have been seen to make ten distinct movements within this 1 millionth inch [1/40th μm].*

in Fig. 329. This design also minimizes frictional heat of the lead screw in use. To further maintain the temperature of the lead screw, it is made to operate in a reservoir of oil. The oil in this reservoir continually flows down into the base of the machine, where any slight build-up of heat is transferred to the large mass of the base. The oil is next pumped back into the lead screw trough.

To avoid a dead air space in the cavity of the base, a fan is used to cause through-flow of air, which helps to maintain the ambient temperature of the casting as well as the circulating oil.

Although on the one hand there is a considerable overall gain in accuracy by separating the axes through a bridge-type construction, this design has the unfortunate effect of making the temperature problem more acute. It is now more essential that temperature be exact and that stratification be prevented. Since it is virtually impossible to completely eliminate errors due to temperature stratification (vertical gradations in ambient temperature) within a room environment, the bridge axis is specified to no closer tolerance than that of the base axis, despite the fact that it is of a shorter travel.

In addition, when more clearance is given under the bridge by means of a riser block, the tolerance must be broadened. The need for this is attributable not so much to difficulty of construction but more to the increased problem of stratification as the axes are further separated.

Despite the large masses to be moved, the repeatability attained by this design is exceptional. In an experiment employing a non-contact "fiber-optic probe," it was seen that the machine could make repeat settings within 1/5 millionths of an inch [0.005 μm], and could also move in discrete increments of that small an amount when the eye was aided by a microscope in reading the lead screw dials.*

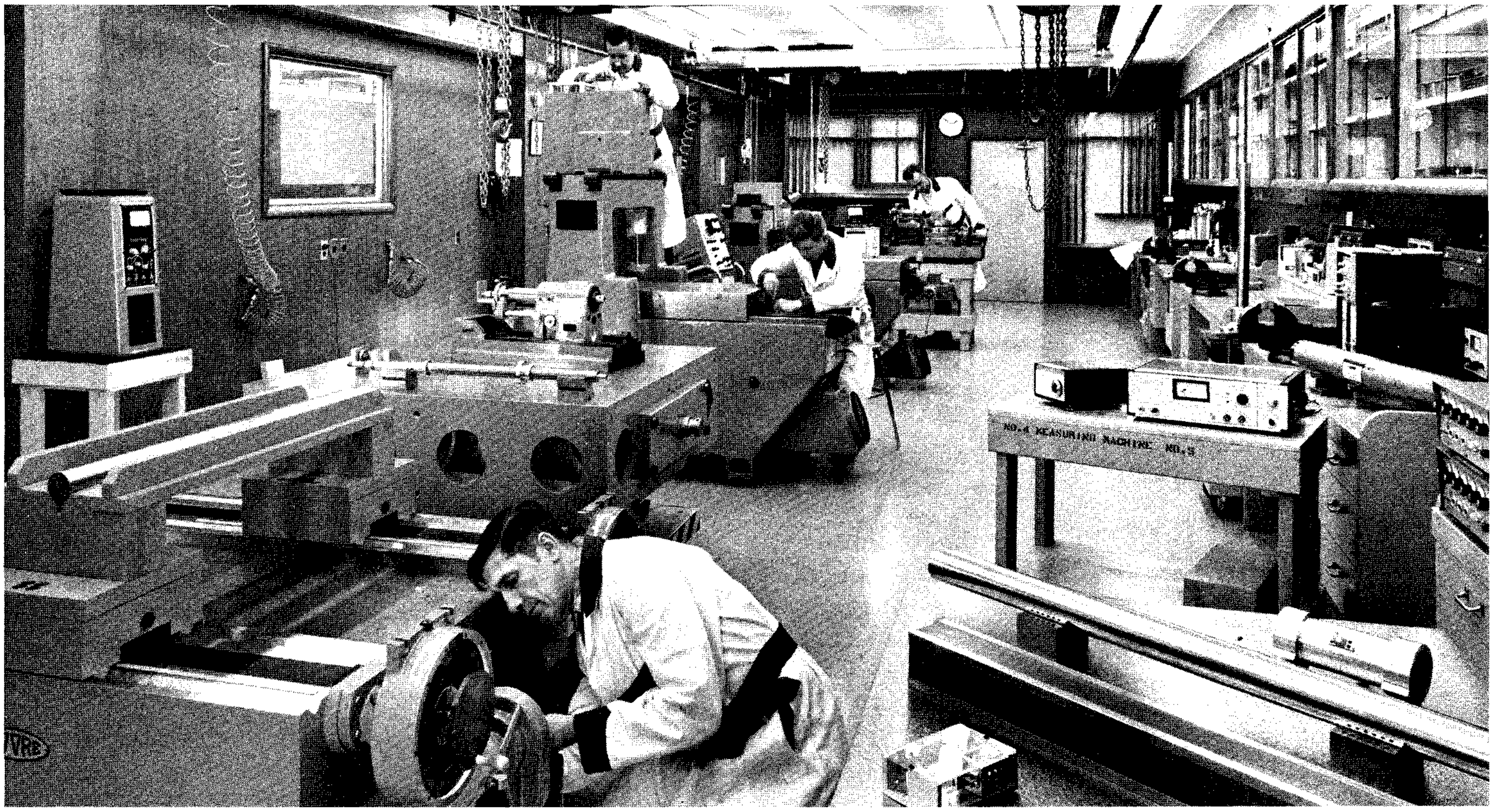
In later models of No. 4 and No. 5 Measuring Machines, adapted for special purposes, a master rotary table gear and worm have been fitted to the end of the lead screw shaft, together with other reduction gearing to provide tremendous reductions of up to 100,000 to 1.** When a relatively simple stepping motor is placed at the end of the gear train, it is found that the machine table can be *pulsed automatically* through such small increments.

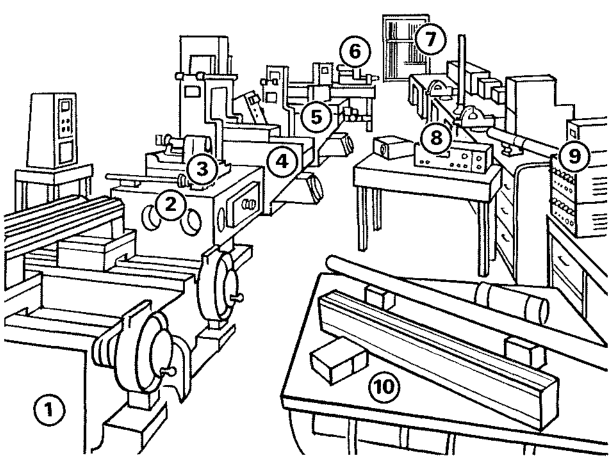
The means by which such small displacements are measured is shown in Fig. 537. To the left are the controls which determine the particular number of pulse increments of the stepping motor. In the fore-

*Wayne R. Moore, "Repeatability to 0.2 millionths!", *American Machinist*, August 29, 1966.

**To arrive at this figure, the author used a somewhat loose interpretation of reduction, but nevertheless a fair one: a 0.050 inch movement of a 3 inch dial used in place of the stepping motor would displace the table only 0.0000001 inch.

FIG. 539—*Laboratory is used to assemble and calibrate large standard and special measuring machines and ruling engines.*





1. Left foreground—Ruling Engine built for Professor George W. Stroke of the State University of New York—to produce diffraction gratings.
2. 48-inch square master surface plate.
3. 3rd axis assembly of the Moore No. 4Z Universal Measuring Machine.
4. Model No. 4Z (3 axis) Universal Measuring Machine built for International Business Machines (IBM).
5. Universal Grid and Scale Calibration Machine, built for Bausch & Lomb. Calibrations are based on direct laser measurements.
6. Test set-up for automatic calibration of Rotary Tables.
7. In glass cabinets—Moore Master Lead Screws of various lengths to be used in Measuring Machines.
8. Part of laser system (Spectrophysics) to be used with Ruling Engine for Professor George W. Stroke.
9. Slo-Syn Controls for automatic stepping of Lead Screw to as small as 0.2 millionths movement (used on Professor George W. Stroke's Ruling Engine).
10. 42-in. Surface Plate on which rests various elements that make up diamond-ruling mechanism, including diamond-lifter, straight-edge, monorail and diamond carriage.

FIG. 540—*Variety of projects, underway in the Measuring Machine Laboratory.*

FIG. 541—*The 48 inch [1219 mm] box-type surface plate, used as a master, is also convenient as a datum to inspect heavy machine parts and assemblies. Shown is the inspection of a Z axis assembly of the No. 4Z Universal Measuring Machine (background).*

FIG. 542—*The No. 5 Universal Measuring Machine has ample capacity to perform calibrations of end standards and line standards of considerable length. Shown is the inspection of a line standard using a 30× microscope mounted in the Measuring Machine spindle.*

ground, the fiber-optic probe is mounted on a box parallel with the light-discharge end held in proximity to a reflecting surface fastened to the machine table. The intensity of the reflected, returning light varies with the distance of the light probe to the reflecting mirror. The varying light intensity acts on a photocell contained in a meter (to the rear of the machine table). The varying voltage is amplified to be viewed on the oscilloscope screen to the rear.

A close-up of the oscilloscope screen is seen in Fig. 538. The separation of the lines shown is a distance of 0.400 inch [10 mm] and represents a machine movement of 1 millionth of an inch [1/40th μm]. The lead screw, when pulsed, can be seen to displace the machine table in ten distinct movements within this 1 millionth of an inch [1/40th μm].

The ability of these larger Measuring Machines to move in such fine increments, together with their geometric accuracy, has led to their being adapted to many different uses, apart from that of purely a measuring function.

To fulfill these expanding requirements, a separate laboratory has been constructed expressly for the purpose of calibrating and assembling the larger measuring machines, Fig. 539. Some of the projects undertaken and equipment shown in use in Fig. 539 are illustrated in Fig. 540.

In Fig. 541, a Z axis of the No. 4 Model Measuring Machine is being assembled and inspected while mounted on a master 48 inch [1219 mm] surface plate within this laboratory.

APPLICATIONS OF LARGE UNIVERSAL MEASURING MACHINES

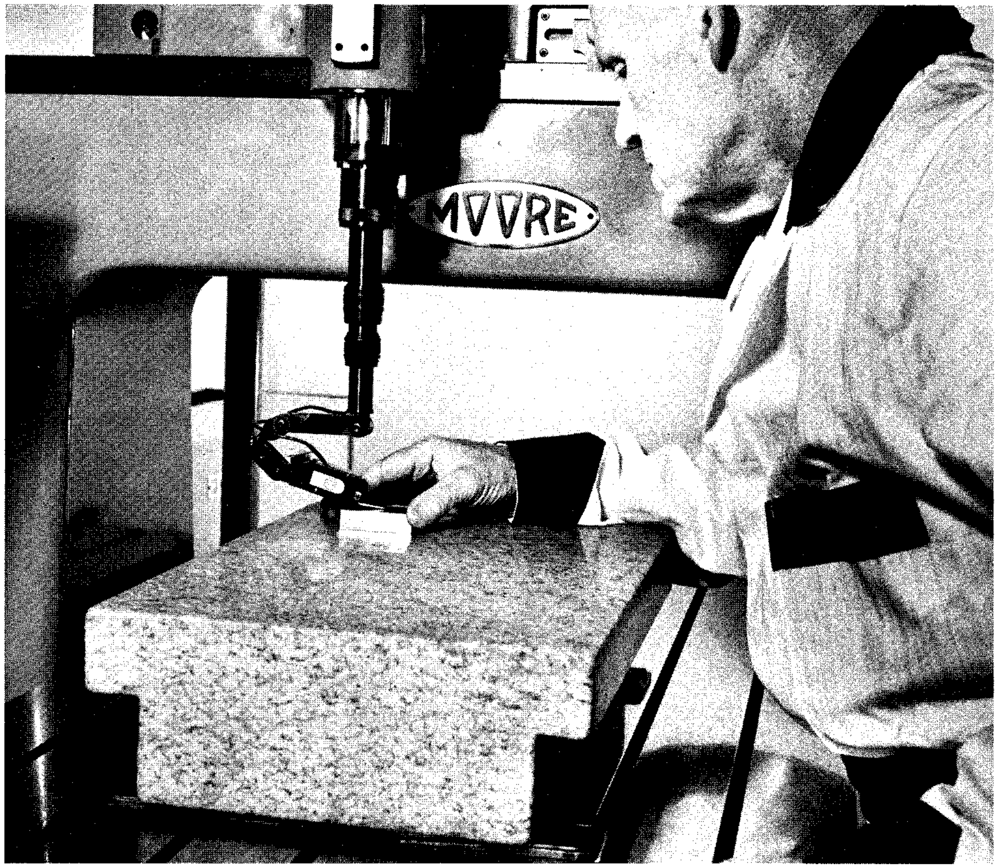
Measuring techniques and applications of the standard No. 4 and No. 5 Universal Measuring Machines are virtually identical to that of the No. 3 model. A few applications are included here to indicate the greater capacity and versatility of these machines.

In Fig. 542, a master precision scale is inspected while mounted on a No. 5 Universal Measuring Machine.

A granite surface plate has been leveled by means of steel wedges in Fig. 543, so that its top surface is parallel to the plane of travel of the Measuring Machine. Measurement of flatness of the granite surface plate may now proceed in a direct fashion and is accomplished in a matter of a few minutes. The readings recorded are direct errors of flatness, and require no calculations nor use of tie-down points as in the usual autocollimator-type calibration.

A master box-type straightedge 46 inches in length [1168 mm] is inspected for straightness while mounted on the No. 5 Universal Measuring Machine, Fig. 544. The advantage of this type of inspection over that where a surface plate is used is that the edge being measured is in a neutral direction to any elastic deflection which may occur in the straightedge due to its own weight.

FIG. 543—*The granite surface plate has been adjusted parallel to the plane of travel of the Universal Measuring Machine axes through the use of steel wedges. Calibration readings may be taken directly and require no calculations, as is normally the case with an autocollimator-type inspection of a surface plate.*



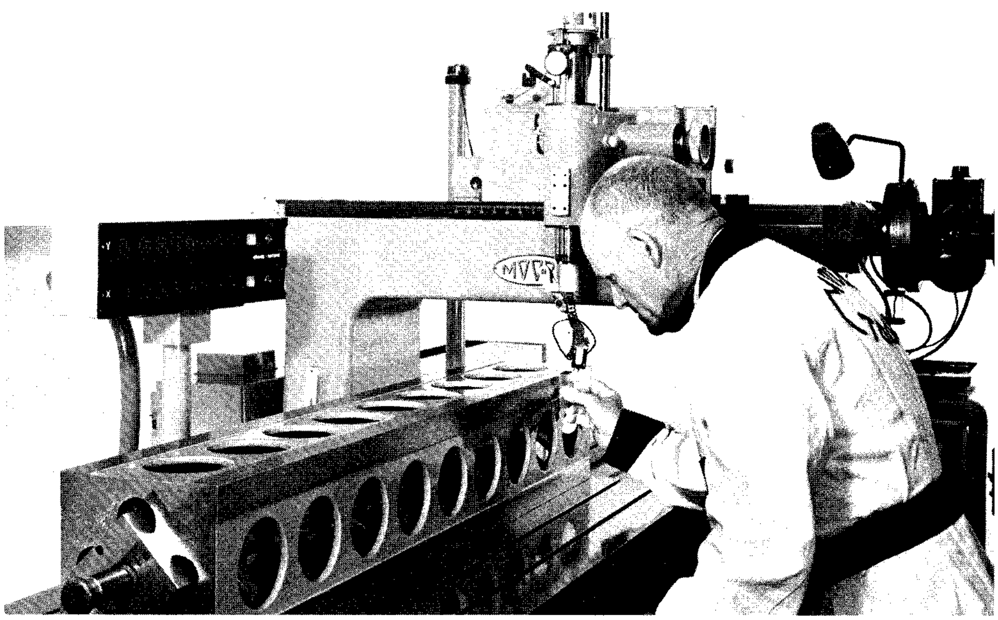
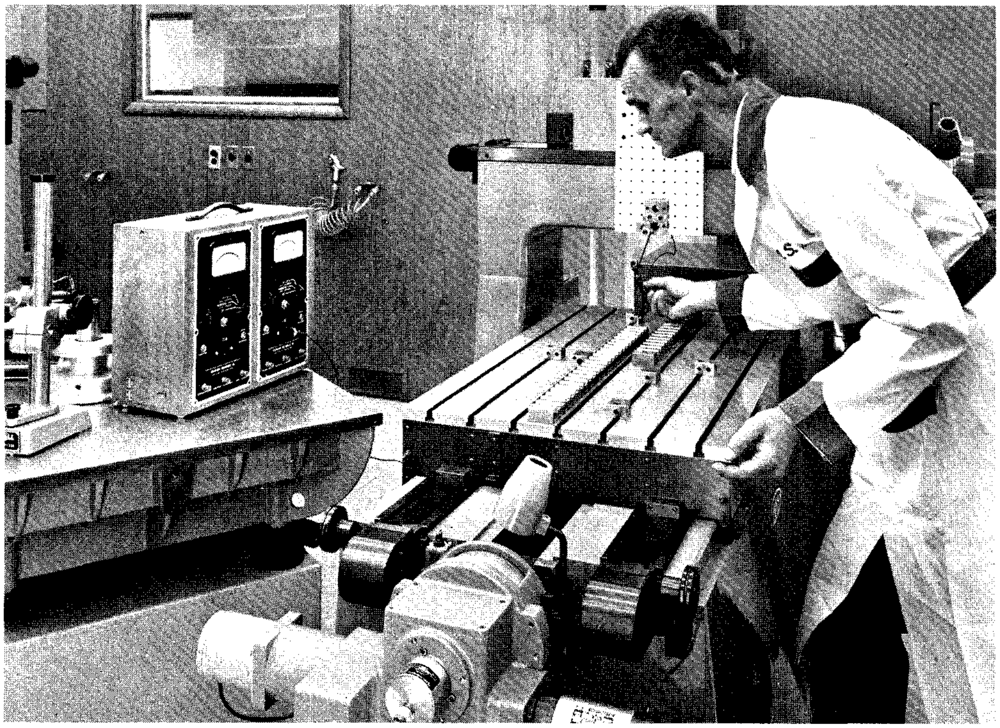


FIG. 544—*The unusual capacity of the No. 5 Universal Measuring Machine is demonstrated. Straightness of a 46-inch long [1168 mm] master box-type straightedge is being inspected. The edge under inspection is in a neutral direction to any deflection which may occur.*

FIG. 545—*A No. 4 Universal Measuring Machine has been modified for special applications for the Bausch & Lomb Optical Company. A mounting plate is fastened to the front of the cross-carriage in place of the spindle. Special driving elements and clutch allow the machine to be traversed either rapidly or in fine increments.*



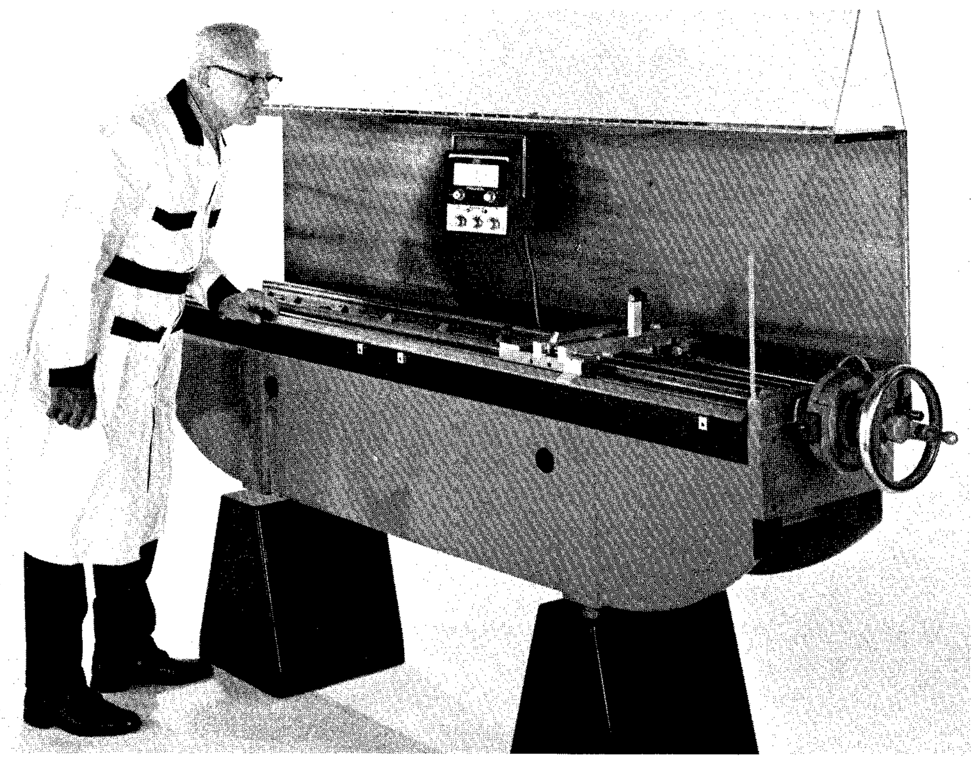


FIG. 546—*The 72-inch Single Axis Measuring Machine has the capacity to measure lead screws, end standards, and line standards up to 72 inches in length [in metric 1830 mm]. A unique disengageable "nut" allows the carriage to be moved rapidly along on rollers and cylindrical ways to the nearest .100 inch [in metric 3 mm]. Finer increments are established by engaging the nut and setting as with a standard machine.*

SPECIAL DESIGNS

The skills, techniques, masters and gages which are employed to make standard machines are also adaptable to modified or special-purpose machines.

A No. 4 Universal Measuring Machine, modified for special application for the Bausch & Lomb Optical Company, is shown in Fig. 545 undergoing final calibration by comparison to Step Gages. Mounted on the cross-carriage (no spindle used) is a scraped flat plate containing a pattern of tapped holes to facilitate the mounting of various measuring fixtures. To the right in the foreground is a slewing motor attached directly to the lead screw and used to transport the machine table rapidly. To the left, foreground, is a stepping motor which drives the lead screw through 20 to 1 gearing when fine resolutions of movement are needed. The stepping motor is disengaged by a clutch arrangement when the slewing motor is used to drive the table. At the end of the lead screw is a coarse encoder for establishing rough location.

72-Inch Measuring Machine

The 72-inch Measuring Machine shown in Fig. 546, unlike other Moore Measuring Machines, is a single-axis design. Its function is to calibrate lengths up to 72 inches [in metric 1830 mm] swiftly and accurately. Cylindrical guide ways are used rather than V-ways. The carriage is lightly constructed and non-friction rollers are used to allow movement with only feather force.

In place of the standard lead screw nut, a single-tooth nut (or wedge) is used to contact the thread flank of the lead screw. The "nut" may be disengaged from the screw, which frees the carriage to be moved with great speed by hand. The nut, when re-engaged, is done so very accurately with a near-perfect double-cone and ball pivot, pulling the carriage into position repeatably to within 1 or 2 millionths of an inch

[1/20 μm or less]. By this means, every 0.100 inch [3 mm in metric machines] is established by using the lead screw as a length standard, and without rotating the lead screw. Increments within 0.100 inch [3 mm in metric machines] are secured by re-engaging the nut and rotating the screw, displacements being read on the lead screw dial.

The advantage of this design is the virtually instantaneous measurements which may be taken of any length within its range, without heat built-up in the lead screw. The master and the part to be checked both rest on the base of the machine, which acts as a heat stabilizer to asssure equalization of their temperatures.

The 72 inch [in metric 1830 mm] Measuring Machine is presently being employed to calibrate the longer lead screws used in large Measuring Machines in the course of thread-grinding and corrective lapping. It is also suitable for calibrating end standards and line standards.

Numerical Control of Measuring Machines

The lead screw is ideally suited to numerical control, since the control system must only, in effect, accurately index the lead screw by use of resolvers or transducers through the correct number of whole turns or fractional turns.

Basically there are two approaches which may be considered for numerical control of a Measuring Machine. In the first approach, the Measuring Machine is commanded to traverse to an intended position. The deviation from true position is read on the electronic indicator, or may be registered on a strip recorder, or even printed out.

In the second approach, the Measuring Machine is made to "hunt" for position (for example, the location of a hole) with a special type of comparator* through a servo feedback system, perhaps through a computer to the lead screws. The first approach is relatively simple and has already been applied successfully on many Moore Jig Borers, Jig Grinders and Measuring Machines. The second approach has not yet been used, although it has been seriously discussed by some firms. The second approach will almost certainly be more complex and more costly, although within present capabilities.

The author is inclined to think that the first approach is more realistic since it allows the use of standard components, and cost will be less. Also, although the second approach gives actual coordinates of the part, present availability of computers allows such information as obtained in the first approach (deviations from nominal) to be readily converted to coordinate values, at much less investment.

Numerical Control may be adapted to Measuring Machines in so many various arrangements and combinations, that the particular design arrived at by the user is normally decided upon only after engineering consultation. The two basic control systems used, however, are "point-to-point", when the number of positions is relatively few (as in hole-location), or "continuous path," when many coordinate positions are to be recorded, as in a cam or template.**

*The Sperry Gyroscope Company makes a comparator of this type called a "Sperry Powered Inspection Probe." See "Industrial Controls and Instrumentation," Publication of Sperry Gyroscope Company, Ltd., Canada, June, 1966.

**For more detailed information see: "Moore Numerically Controlled Continuous Path Jig Grinder with General Electric Mark Century Numerical Control, Pamphlet No. GEA-8701, General Electric Company, Schenectady, New York, 1969; "Adaptation de l'outillage à la commande numérique," *Usine Automation*, May, 1967.

See also articles listed in footnote No. 1, page 318.

5. Ruling Engines—Diffraction Gratings

DIFFRACTION GRATINGS

"No single tool," observes George R. Harrison, "has contributed more to the progress of modern physics than the diffraction grating, especially in its reflecting form."*

Gratings are applied to a wide variety of scientific and industrial tasks such as metrology (moiré fringes), radioastronomy (microwave gratings) and optical image-forming (fresnel lenses). Optical gratings, depending on their intended purpose, may be of different types, such as concave or flat, and may be used either in transmission or reflection. George W. Stroke notes in "Diffraction Gratings": "When gratings are used for spectroscopic purposes, their function is to separate the diffracted wave fronts of different frequencies (or wavelengths) by angles which are sufficiently large to permit easy resolution by an appropriate optical system and receptor."**

Spectrographs utilizing diffraction gratings have provided most of the information we now have on the structure of atoms and molecules. The diffraction grating, it would appear, has been aptly termed by Henry Norris Russell "the master key of science."***

*George R. Harrison, "The Production of Diffraction Gratings—1. The Development of the Ruling Art," *JOSA*, June, 1949, p. 413.

**George W. Stroke, "Diffraction Gratings," *Handbuch der Physik*, p. 432.

***George R. Harrison, "The Controlled Ruling of Diffraction Gratings," *Proceedings of the American Philosophical Society*, October, 1958, p. 483.

An important category of diffraction grating is the flat, reflective type. It consists of a blank of optically-flat quartz, glass, pyrex, or other ceramic material such as the new composition Cer-Vit.* On the functional surface of the blank is a thin metallic coating. While Speculum metal was used most extensively in the past, today a layer of aluminum, deposited by vaporization is usually used. Thickness of the deposit is no more than a few μm [1/10,000 inch or so].

As many as 30,000 grooves per inch [1181 per mm] are furrowed (not cut) by a diamond tool into the aluminum strata. The diamond tool, as shown by J. Robert Moore, may vary in shape depending on the characteristics which are sought.** In most gratings, metal is displaced or burnished, but not removed.

Ruling of the grating is performed by "ruling engines," designed and constructed to near mechanical perfection. The level of this accuracy may be appreciated when one considers that for ruling a 10-inch grating at 300 per millimeter spacing [7620 per inch], the ruling engine must traverse the equivalent of 15 miles [24.140 kilometers], and yet maintain prescribed spacing and parallelism within a small fraction of a light fringe.*** A 6-inch grating of 30,000 lines per inch [1181 per mm] produced at Jarrel-Ash is said to require 12 days of continuous ruling.****

For a grating to be classified "excellent," it must be accurate to within at least 1 millionth of an inch [0.000025 mm], according to Harrison. Special gratings having up to 270,000 grooves per inch [10630 per mm] have been produced—a fact which may impress the reader, but not the spectroscopist who is concerned mainly with the quality, spacing and parallelism of the lines.* As Harrison states: "As many as 100,000 grooves to the inch [3937 per mm] have been ruled on inferior engraving engines."**

For some period of time it was falsely assumed that resolving power of a grating could be enhanced only by increasing its number of grooves. Spectroscopists now acknowledge that the ruled width of the grating is the more critical factor in resolution. The perfection of gratings in greater widths is perhaps their greatest goal.

In order for the engine to perform to its full potential, the environment in which it operates must receive elaborate attention. The operation of an early engine by Blythswood was reputed to have been ruined by the natural movement of trees in the vicinity during a heavy wind; R. W. Wood refers to the effect of passing streetcars.*** In order to negate these vibration effects, the engine is supported on huge concrete structures and piers, some floated on compressed air. Still further damping of vibration is obtained through the use of alternate layers of cork, sand and other materials. Even with these precautions, natural phenomena still dictate design. Harrison reports that even in a controlled environment, earth tides caused slow drifts in diamond position when the diamond monorail was at first separately supported from his engine.

Temperature of the air surrounding the engine is held as close as 0.01° C [0.018° F]. In the Spectroscopy Laboratory at Massachusetts Institute of Technology, however, one engine is further temperature-stabilized by immersion in an oil bath, controlled to an order of 0.001° C [0.0018° F].

Even so, an excellent grating is produced only with scientific perspective, devotion, ingenuity and instinct compounded with luck. Endorsing this thinking, Harrison quotes similar sentiments expressed by Michelson, the American scientist who wrote in *Nature:*

> "When the accumulation of difficulties seems to be insurmountable, a perfect grating is produced, the problem is considered solved, and the event celebrated with much rejoicing only to find the next trial a failure . . . one comes to regard the machine as having a personality . . . requiring humoring, coaxing, cajoling, even threatening!"*

Dr. Harrison cogently positions the diffraction grating as to its significance to science:

> "It is difficult to point to another single device that has brought more important experimental information to every field of science than the diffraction grating. The physicist, the astronomer, the chemist, the biologist, the metallurgist, all use it as a routine tool of unsurpassed accuracy and precision, as a detector of atomic species to determine the characteristics of the heavenly bodies and the presence of atmospheres in the planets,

*Trade name of a material manufactured by Owens-Illinois Inc., Toledo, Ohio.

**J. Robert Moore, "Precision Diamond Tools for Ruling Diffraction Gratings, etc.," Petersham, Massachusetts, August 1, 1968.

***George W. Stroke, "Diffraction Gratings," *Handbuch der Physik*, 1967, p. 702.

****Ibid., pp. 705–706.

*Erwin G. Loewen, "Positioning System Spaces Lines to Within 1/10 Micro-Inch," *Control Engineering*, May, 1963.

**George R. Harrison, "The Controlled Ruling of Diffraction Gratings," *Prooceedings of the American Philosophical Society*, October, 1958, p. 483.

***George R. Harrison, "The Production of Diffraction Gratings—1. The Development of the Ruling Art," *JOSA*, June, 1949, p. 424.

**Ibid.*, p. 416.

to study the structures of molecules and atoms, and to obtain a thousand and one items of information without which modern science would be greatly handicapped. The history [of gratings] is of special importance in emphasizing the basic role of the experimenter, and particularly that of the perfector of new instruments, the availability of whose product is all too often taken for granted by other scientists."*

A master grating may command a price as high as $50,000.00. By carefully controlled processes, replicas are made to such perfection as to be almost indistinguishable from the original. Indeed, in some ways they may even be superior.**

A plane reflection replica grating, ruled over an area of 2.5 by 2.5 inches [63.5 by 63.5mm], having 91,500 grooves per inch [3602 per mm] may sell for $1,200.00.***

RULING ENGINES FOR DIFFRACTION GRATINGS

(Historical)

Light that contains a mixture of wave lengths, such as sunlight or starlight, is broken into its spectrum of individual colors when passing through a prism (see "Standards of Length," Fig. 163).

David Rittenhouse, the American astronomer, noted in 1786 the diffraction effects when light from a distant lamp was viewed through a silk handkerchief. This observation led him to construct what was perhaps the first grating by laying hairs across two fine-pitch screws.

By 1821, Joseph von Fraunhofer had produced diffraction gratings by ruling gold film deposited on glass. One grating thus ruled was ½ inch [12.7 mm] wide with 4,000 grooves. It was not until 1870, however, that a grating was made which surpassed the prism in resolving power. This grating, constructed by L. M. Rutherfurd, a New York amateur astronomer, was 2 inches wide [50.8 mm] and had 35,000 grooves.

The goal has always been to produce wider gratings, for the larger the grating, the higher can its resolving power be. George R. Harrison observes: "The greater the width of ruled surface on a grating, the greater is its power to separate close-lying wave lengths which may otherwise be indistinguishable."* To separate properly the lines of complex spectra such as those emitted by uranium or thorium calls for gratings ruled at least 12 inches wide [304.8 mm].

The wider the grating, however, the more complex and exacting must be the ruling engine and the total environment in which it operates. Early physicists and technicians did not have available the technologies necessary to construct accurate large gratings. Ingalls describes what he calls the "seven demons" of *friction*, *wear*, *warpage of the engine ways*, *creep* (*or instability*), *vibration*, *dust*, and *changing temperature* which conspire against those attempting to rule gratings only a few inches [75 mm or more] in width.** In fact, an Australian, H. J. Grayson, (*circa* 1893) was so consumed with the ruling engine "fever" in life, that his widow burned all his papers relating to ruling engines on his death.

Scientists from all over the world contributed to the advancement of the ruling art. In England, for example, a ruling engine was constructed by Lord Blythswood in 1880, and was the only source of British-made gratings until 1950. The machine, which employed a 2 foot [610 mm] diameter, 720 tooth wheel attached to the lead screw, was used at the N.P.L. Later it was used by Hilger-Watts, Ltd. (now a Division of Rank Industries) and is today at the Science Museum at Kensington.

Henry A. Rowland —Johns Hopkins University, 1882

For decades, attempts to rule larger gratings were unsuccessful. Not until 1882, when the first of three ruling engines was constructed at Johns Hopkins University by Henry A. Rowland, a physicist, were high quality gratings up to 6 inches [152.4 mm] in width generated. Rowland's success was to a great measure attributable to improved mechanical design, especially to his perfection of lead screws through laborious lapping.

John A. Anderson —Johns Hopkins University, 1901

In 1901, on Rowland's death, his engines were rebuilt and improved twofold by John A. Anderson of Johns Hopkins. Anderson's greatest improvement was in the perfection and alignment of Rowland's already superb lead screws. For many years, the most precise gratings were produced by Rowland, Anderson and then Remsen W. Wood at this university.

John A. Anderson, Harold D. Babcock, and Harold W. Babcock —Mount Wilson Observatory, 1916

John A. Anderson, on leaving Johns Hopkins in 1916, went to the Mount Wilson Observatory at Pasadena to work on a

*John Strong, "The Johns Hopkins University and Diffraction Gratings," *JOSA*, 1960, p. 1152.

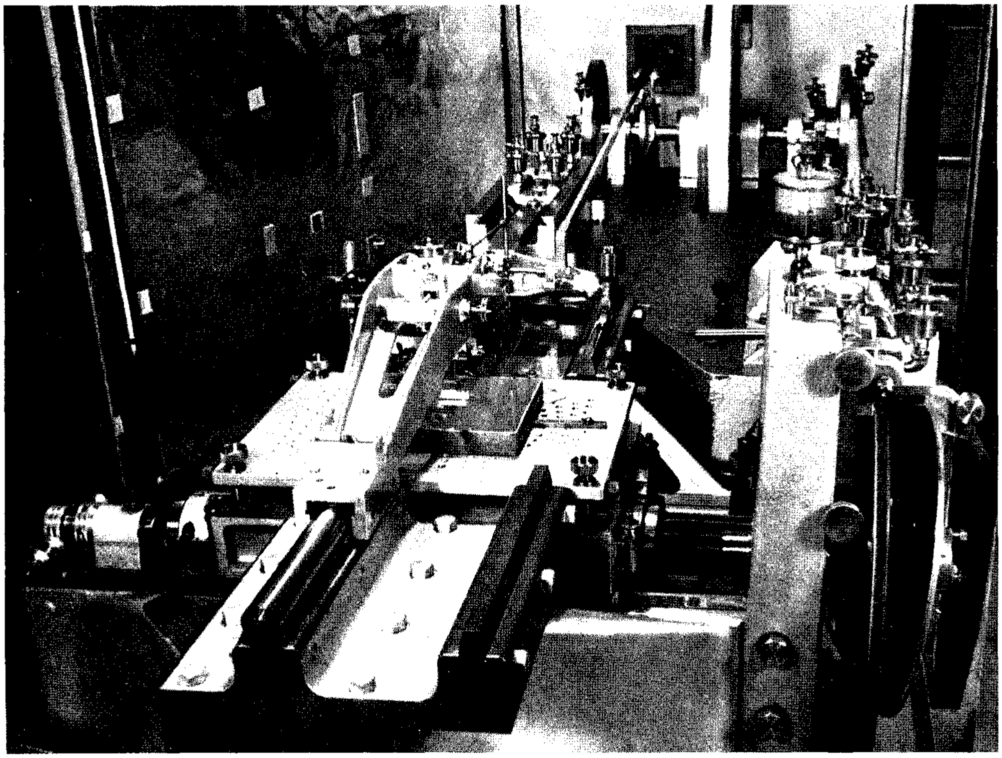
**Erwin G. Loewen, "Positioning System Spaces Lines to Within 1/10 Micro-Inch," *Control Engineering*, May, 1963.

****Idem.*

*George R. Harrison, "The Challenge of the Ruled Grating," *Physics Today*, September, 1950.

**Albert G. Ingalls, "Ruling Engine," *Scientific American*, June, 1952, p. 47.

FIG. 547—*Diffraction gratings are used in spectrographs for astronomical purposes. The ruling engine art has been advanced especially by astronomists, interested in refining their own technology. View is of Babcock's ruling engine at the Mt. Wilson Observatory Laboratory.*
Photograph from the Hale Observatories.



huge Rowland-type of design, already several years in construction. This machine was intended to rule gratings up to 18 inches by 24 inches [457 x 610 mm]. After 30 years of effort on this engine, it was abandoned. A 10-inch [254 mm] engine undertaken by H. D. Babcock in 1930, and at a later date continued by son Harold W. Babcock produced some excellent gratings up to 7.5 inches [190.5 mm] in width. See Fig. 547.

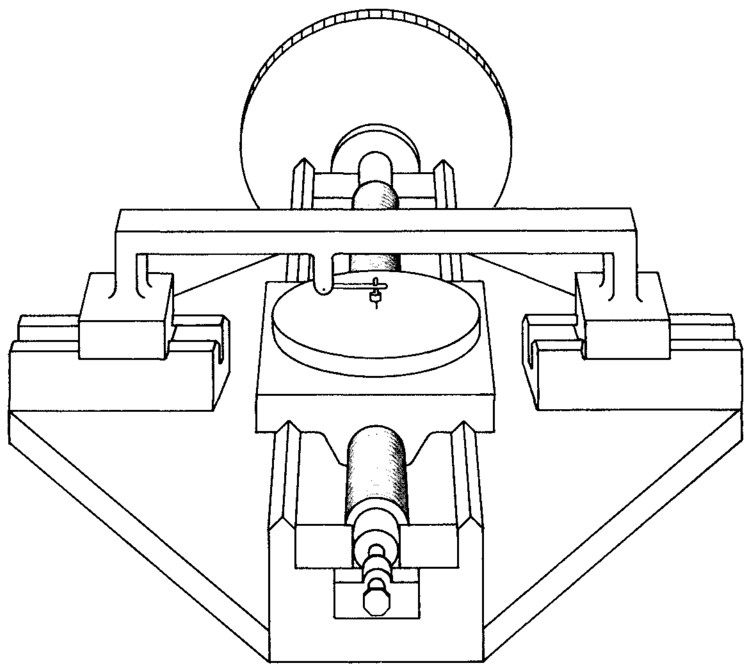
Albert A. Michelson, Early 1900's

A ruling engine was constructed by A. A. Michelson at the University of Chicago in the early 1900's. Though he attempted to produce gratings up to 14 inches [355.6 mm] wide, he was largely unsuccessful. A second engine was built by Michelson, however, and he set his sights a little lower, striving instead for 12 inch [304.8 mm] gratings. A ball-bearing carriage was employed to reduce frictional movement.

The idea of interferometric control of ruling engines can be traced to Michelson, although he limited its application to improve his screws, or to test the engine prior to ruling. A 9.4 inch [238.76 mm] grating was produced with the second engine, the largest to that date, but not of a quality to match those made on the Rowland engines. The second engine, started around 1910, was still not functioning to expectation when taken over and completely rebuilt in 1930 by Henry G. Gale, another physicist at the University of Chicago. Gratings produced on this engine still did not match the quality of those produced on the Rowland engines.

In 1947 the Michelson-Gale engine was given to the Bausch & Lomb Optical Company, Rochester, New York where it was again rebuilt, on this occasion by David Richardson and Robert S. Wiley. This engine has since been operated successfully at Bausch & Lomb, and has helped to make this company the world's prime supplier

FIG. 548—*The success of Rowland's ruling engine is attributable to his perfection of mechanical design and to his attention to the construction, mounting and lapping of the lead screw. This engine resembles a shaper in operation.*



of commercial gratings up to 8 inches [203.2 mm] in width.

The principle by which the Rowland and Michelson-Gale engine operated was to support the grating blank on the engine carriage of a double-V design. The carriage was displaced by a single screw, the diamond point being traversed over the grating at each position.

John Strong —Johns Hopkins University, 1950

A major contribution to diffraction gratings and ruling engine design was made by John Strong of Johns Hopkins University in 1950. Strong showed great mechanical insight and ingenuity in its construction and in aligning and lapping components such as the guideways and the lead screws. He was especially successful in tackling the problem of "Rowland ghosts," spurious spectral lines usually caused by periodic error attributable to the screw or its mounting. Strong followed Rowland's principle of design as he expressed it in an article for *Encyclopedia Brittanica* entitled "The Screw" (Vol. XI): "... no workmanship is perfect; the design must make up for its imperfections." * This led him to his own principle of "... *overconstraint and elastic averaging*—a principle which contrasts with that of kinematic design—instruments of the very highest order are not attainable after the teachings of the latter."** Strong seemed to reinforce the philosophy of this text when he stated: "I find that the construction methods of greatest precision are all primitive methods."*** As examples, he cites Whitworth's three-plate method and the generation of a 360 tooth dividing head to index the screw with "unmeasurable errors" (a principle not unlike that of the 1440 Index; see pages 233–235).

The Rowland-type of engine resembled a shaper (Figs. 548, 549), whereas the design showed by Strong in 1951 resembled a planer (Figs. 550, 551). The principle of operation of both the Rowland and Michelson-Gale engines was to support the grating blank on the engine carriage as it was displaced by a single screw while the diamond point traversed the grating at each position. In the Strong engine, the diamond carriage is advanced instead by two oppositely placed, counter-rotating screws. The purpose of this design is to nullify the effect of heat on the screws, since they expand in opposite directions. The interconnection of the nuts is used to carry the ruling diamond. In marked contrast to the Rowland design, the grating blank itself is reciprocated, controlled by the guide-ways under the diamond carriage after the latter is stopped.

This design removes the weight of the grating blank from the displacing member, and makes "fan errors" of the grating due to way curvature impossible, although the lines still may not be straight.

At first, gratings were scribed on hard speculum mirrors which deteriorated the diamond rapidly. Strong made an important contribution to the grating itself by introducing the still accepted process of vaporizing a thin layer of soft aluminum on the blank to be ruled.

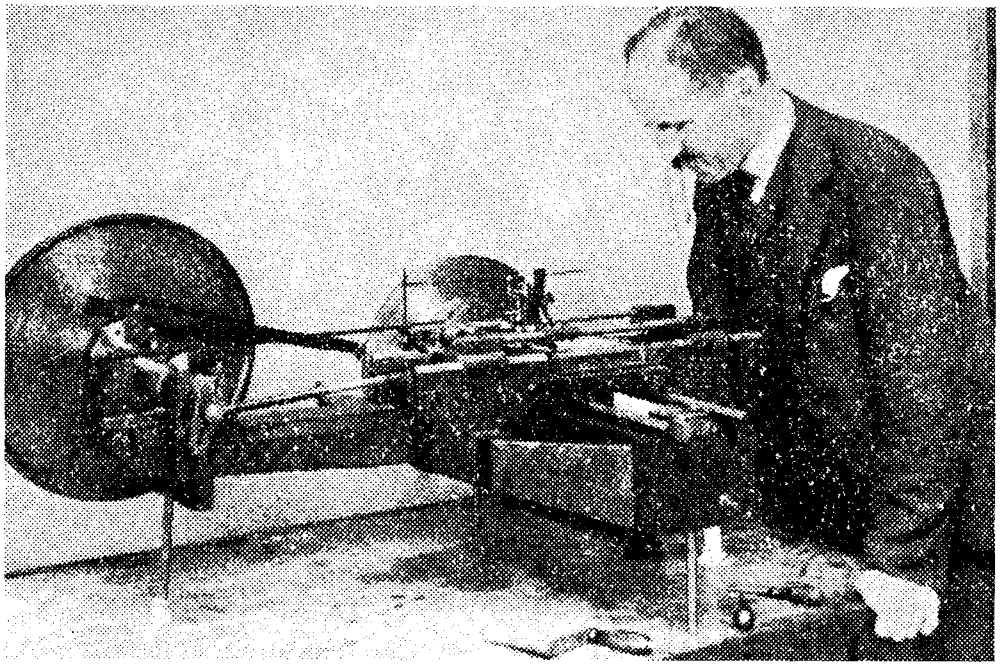
*John Strong, "New Johns Hopkins Ruling Engine," *JOSA*, January, 1951, p. 5.

***Idem.*

****Ibid.*, p. 7.

FIG. 549—*H. A. Rowland can be credited with fathering the ruling engine art for diffraction gratings. He is shown with one of his ruling engines at Johns Hopkins University.*

Courtesy Journal of the Optical Society of America.



George R. Harrison—Massachusetts Institute of Technology, 1948.

The first Michelson engine was sent from the University of Chicago to M.I.T. in 1948, where it was rebuilt by George R. Harrison, a spectroscopist (see "Introductory"). Although O'Donnell of the University of Chicago noted that the buttress screw of 2mm [.079 in.] lead of this engine was originally corrected to ± 0.1 fringe periodic error and 0.7 fringe cumulative error, Harrison found an increased error because the screw was bent—a consequence of prolonged support on its ends while the machine lay idle during the years of World War II.

The method introduced by Harrison was to revolutionize the art of controlling ruling engines. He used a Michelson-type interferometer and the green line of an isotope of mercury (Hg 198) as a light source to measure carriage displacement. Through a servo feedback, the engine was controlled continuously. This "Commensurator," as it was called, enabled improvements in gratings beyond the pure mechanical precision of the lead screw and the engine, Figs. 552 and 553. In addition, Harrison recognized early that variations in atmospheric pressure could alter the wavelength; he therefore compensated for this natural variable in his design.

By 1949, Harrison had made appreciable progress with this technique, but reported that 8-inch [203.2 mm] gratings with a resolving power of 400,000 were not yet within the capability of ruling engines.*

In 1955, Harrison and Stroke reported significant advances with the ruling engine at M.I.T. through interferometric control and continuous carriage advance. In this technique, the blank moves forward at a constant speed while the diamond rules

*George R. Harrison, "The Production of Diffraction Gratings—1. The Development of the Ruling Art," *JOSA*, June, 1949, p. 416.

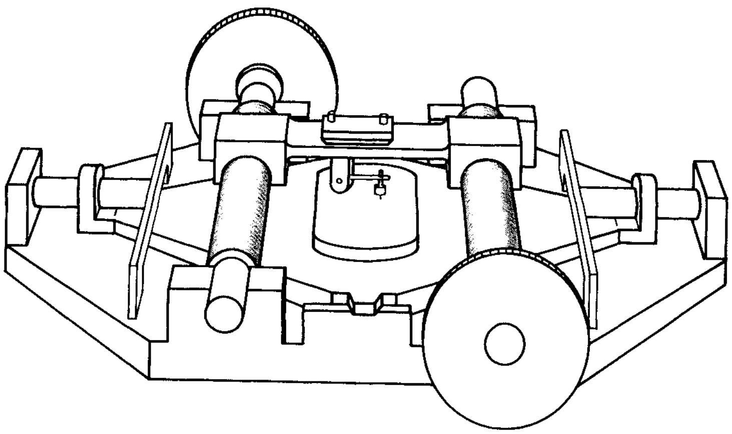


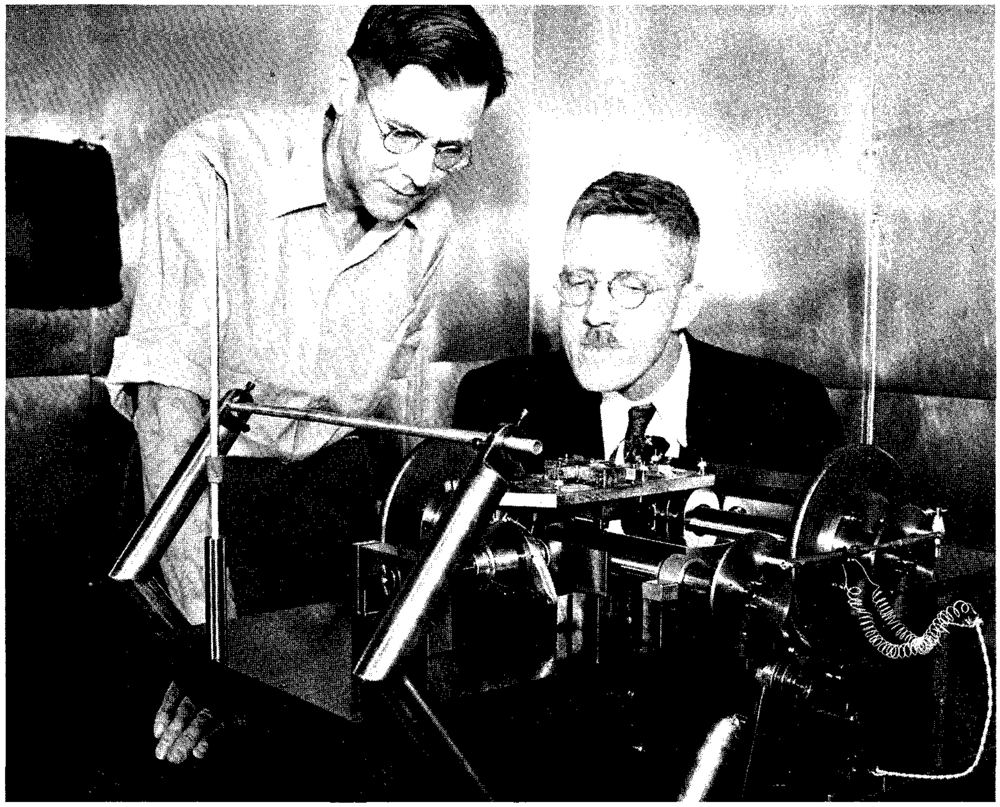
FIG. 550—*John Strong followed the principle of Henry Rowland that design must compensate for mechanical imperfection. To this principle he added his own precept of "elastic averaging." The result was a ruling engine that differed substantially from that of Rowland, resembling a planer in design. Both the Rowland and Strong engines, however, achieved success.*

FIG. 551—*John Strong of Johns Hopkins University made many important contributions to ruling engine design and diffraction gratings. The success of his engines can be attributed to mechanical insight and devotion to accuracy. He is shown with W. H. Perry (left) looking at the ruling engine he designed while at Johns Hopkins.*
Courtesy Johns Hopkins University.

the grooves. They reported excellent gratings of 8-inch [203.2 mm] ruled width and 5-inch [127 mm] groove length. In addition, problems relating to inertia and stopping "stiction" were virtually eliminated, with no apparent deleterious effect on the grating.*

Interferometric control, it should be noted, did not rule out the need for mechanical perfection, but extended its limits. The choice still had to be made as to whether servo-control or mechanical means were best to apply corrections. Interferometry and servo-control could more easily correct for overall groove spacing than for rapid errors.

By 1959 Harrison and his associates at the M.I.T.'s Spectroscopy Laboratory had ruled more than 100 test plane gratings by interferometric control, seven of these in excess of 10 inches in width [254 mm]. Harrison comments on these gratings: ". . . these [specimens] show the weakest Rowland ghost and satellite intensities yet reported for ruled gratings."** Periodic error of the screw was reduced to less than 1/10th fringe. The slow progress that has been made in making grating blanks more readily available is reflected in Harrison's report when he notes that of seven 10-inch [254 mm] blanks, two of the poorly ruled specimens had to be stripped to continue the tests. Recent reports indicate that this problem is being solved in various laboratories.***



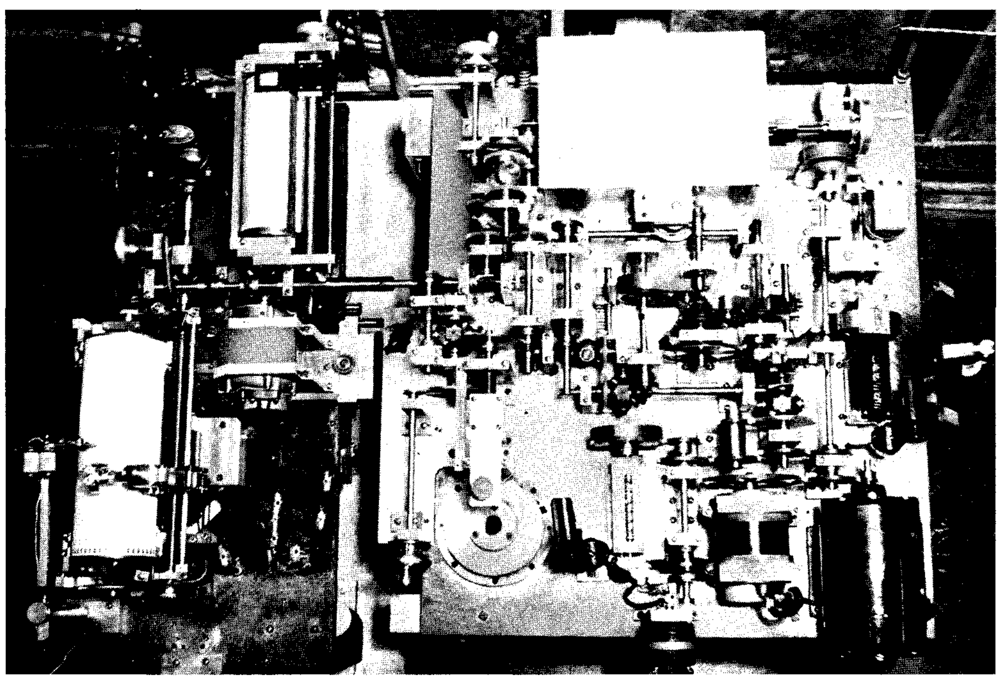


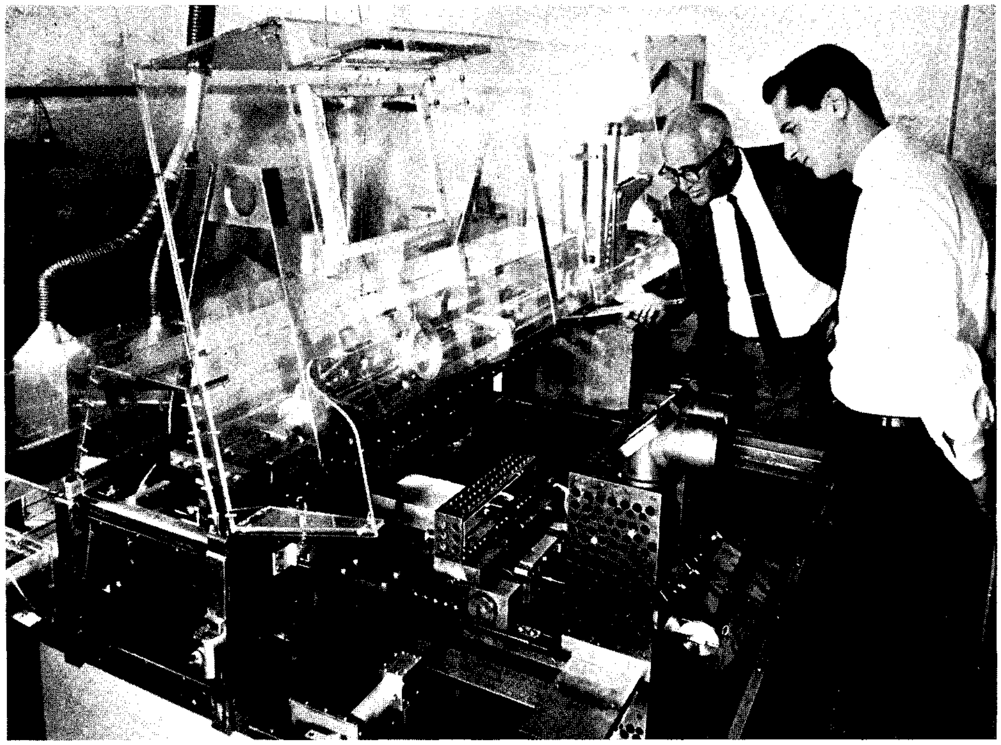
FIG. 552—*The "Commensurator" of George Harrison of Massachusetts Institute of Technology represents an important historical development, since it was the first successful application of interferometric control of ruling engines.*
Courtesy George Harrison, M.I.T.

*George R. Harrison and George W. Stroke, "Interferometric Control of Grating Ruling with Continuous Carriage Advance," *JOSA*, February, 1955, p. 113.

**George R. Harrison *et al.*, "Interferometrically Controlled Ruling of 10-Inch Diffraction Gratings," *JOSA*, March, 1959, p. 205.

***George R. Harrison and Stephen W. Thompson, "Large Diffraction Gratings Ruled on a Commercial Measuring Machine Controlled Interferometrically," *JOSA*, Vol. 60, No. 5, 1970. p. 4.

FIG. 553—*George Harrison (left) with Stephen W. Thompson at the M.I.T. Spectroscopy Laboratory, 1965. The "A" engine shown was originally built by Michelson, and was completely re-built and adapted to interferometric control at M.I.T. by Harrison.*
Courtesy George Harrison, M.I.T.



In the years since, most of the outstanding ruling engines have been adapted to interferometric control, as at Jarrell-Ash by Stroke and associates* and also at Bausch & Lomb and the Mount Wilson Observatory. Interferometric control has in each case improved the performance in comparison with that attained by purely mechanical means.

The Ruling Engine and the Lead Screw

There is an apparent disagreement as to the importance of the lead screw. Bausch & Lomb stated in 1957: "... the precision screw ... is the heart of any ruling engine. . . ."** From his study of existing systems up to 1952, Ingalls remarks: "If the lead screw did not exist, it would be necessary to invent it for the ruling engine."*** On the same topic, Harrison stated in 1949: "A popular misconception exists that the critical portion of a ruling engine is its screw; a screw that will produce translations precise to one micro-inch [1/40th μm] without need of correcting mechanism can be made readily by the lapping method of Rowland."**** He goes on to say that Michelson, perhaps to emphasize its importance, claimed 15 years' time to produce his screw. O'Donnell, on the other hand, observes that the 20-inch [508 mm] screw for the M.I.T. engine required only 3 months working time spread over 1 year. Harrison concluded in

*George W. Stroke, "Diffraction Gratings," *Handbuch der Physik*, p. 703.

***Ibid.*, p. 706.

***Albert G. Ingalls, "Ruling Engines," *Scientific American*, June 1952, p. 51.

****George R. Harrison, "Production of Diffraction Gratings—1. The Development of the Ruling Art," *JOSA*, June, 1949, p. 418.

the same paper, nevertheless, that there was no more superior element for displacement than the screw.*

Stroke mentions "... the successful substitution of a hydraulic drive for the screw in an interferometric velocity of light experiment...,"** and W. R. Horsfield of Bermuda has built a successful controlled ruling engine with hydraulic blank advance.

The apparent disagreement as to the relative importance of the lead screw is probably one of emphasis rather than substance. The most sophisticated ruling engines will undoubtedly encompass some form of interferometric-control in their designs. Yet almost every successful ruling engine in the past and those under construction or on the drawing board now rely on a lead screw for basic translation of carriage movement. Careful attention is given the lead screw's design and accuracy, and greater perfection is continually being sought.

Even if the engine is interferometrically controlled, the lead screw must respond sensitively to command and permit extremely fine displacements of the carriage. The more perfect the mechanics, the less compensation on the part of the interferometer, leading to ever-higher accuracy.

Modern ruling engines for diffraction gratings must be a synthesis of the ultimate in mechanics and the ultimate in optics and electronics.

M.I.T. "B" Engine with the No. 3 Measuring Machine Base

In the early 1960's, the potential of the No. 3 Measuring Machine base design for use as a ruling engine became apparent to Harrison of M.I.T. Accordingly, arrangements were made to modify a base for this express purpose. To the base was added a monorail diamond carriage as designed previously by Harrison for the rebuilt Michelson engine. Oil-film ways were employed, rather than roller-ways, since the slight "flutter" caused by the rollers was objectionable. The machine was transported to M.I.T. where it was adapted to interferometric control by Harrison and his associates in the Spectroscopy Laboratory. Construction of this engine had been financed by the Bausch & Lomb Company, and the engine was considered to be loaned to M.I.T. by that company. Corwin Brumley, Erwin Loewen and Robert S. Wiley of Bausch & Lomb gave technical assistance, and supplied blanks, coatings, ruling diamonds and grating replicas for testing. Much experimentation took place with this engine while the first M.I.T. engine was ruling gratings. By September 4, 1963, the first 5 by 10 inch [127 by 254 mm] high quality grating was produced on this engine.

At a later date, graphitar* was substituted for the more usual ball construction in the lead screw thrust bearing. Since the engine was to operate under continuous carriage advance, the slight added "stiction" was considered less deleterious to performance than the slight "noise" of the balls, and accidentally brinelled thrusts were avoided. Since that time this engine has produced "... many excellent gratings of previously unattained dimensions and quality."**

Several gratings, as large as 8¼ by 16¼ inches [209.55 by 412.75 mm] have been ruled on this engine.

One particular grating, "B-033", of 5 by 10 inches size [127 by 254 mm], having 316 per mm [8,026.4 per inch] groove spacing, is described by its user as "the best ever produced."*

The performance of this engine was summarized in 1969: "Several dozen gratings in sizes from 125 x 260 mm to 210 x 410 mm (4.92 x 10.24 inches to 8.27 x 16.14 inches) have been ruled on the "B" engine, during the past three years, of which a dozen or more have not only exceeded previously available gratings in size, but in quality as well."**

M.I.T. "C" Engine with the No. 4 Measuring Machine Base

Since the early 1960's, technology has progressed significantly. Laser interferometry, for example, has made possible light beams of great strength, maintaining light wave stability and coherency over long optical paths.

Use of the Mercury 198 light source at M.I.T. was replaced by a "Spectra-Physics 119 controlled laser" in 1966. When the last grating (A-200) was produced on the A engine in 1966, the engine was transported to the Bausch & Lomb Company. According to plan the No. 3 base engine ("B") is also slated to go to the Bausch & Lomb Company.

At Moore, improvements were made in lead screw accuracy and design. Techniques of roller-way construction were perfected. In 1966, a demonstration of re-

*Ibid., p. 419.

**George W. Stroke, "Diffraction Gratings," *Handbuch der Physik*, p. 671.

*Graphitar is a product of the U.S. Graphite Company.

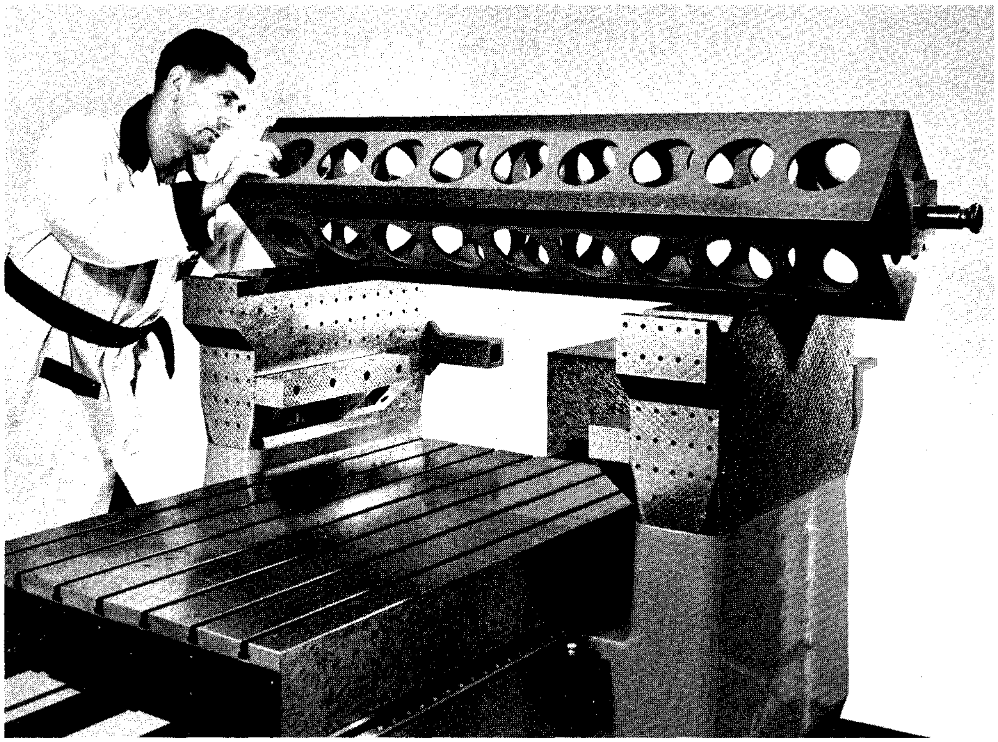
**George R. Harrison and Stephen W. Thompson, "Large Diffraction Gratings Ruled on a Commercial Measuring Machine Controlled Interferometrically," *JOSA*, Vol. 60, No. 5, 1970, p. 1.

*Unpublished letter to George Harrison from Dr. John Evans, Superintendent of Sacramento Peak Observatory, December 29, 1969.

**George R. Harrison and Stephen W. Thompson, "Large Diffraction Gratings Ruled on a Commercial Measuring Machine Controlled Interferometrically," *JOSA*, Vol. 60, No. 5, 1970, p. 3.

The original engine at M.I.T. is designated "A", the modified No. 3 base "B", and the modified No. 4 Measuring Machine as "C".

FIG. 554—The master box straightedge is used to establish the V-mounting surfaces for the two monorails of the M.I.T. "C" ruling engine.



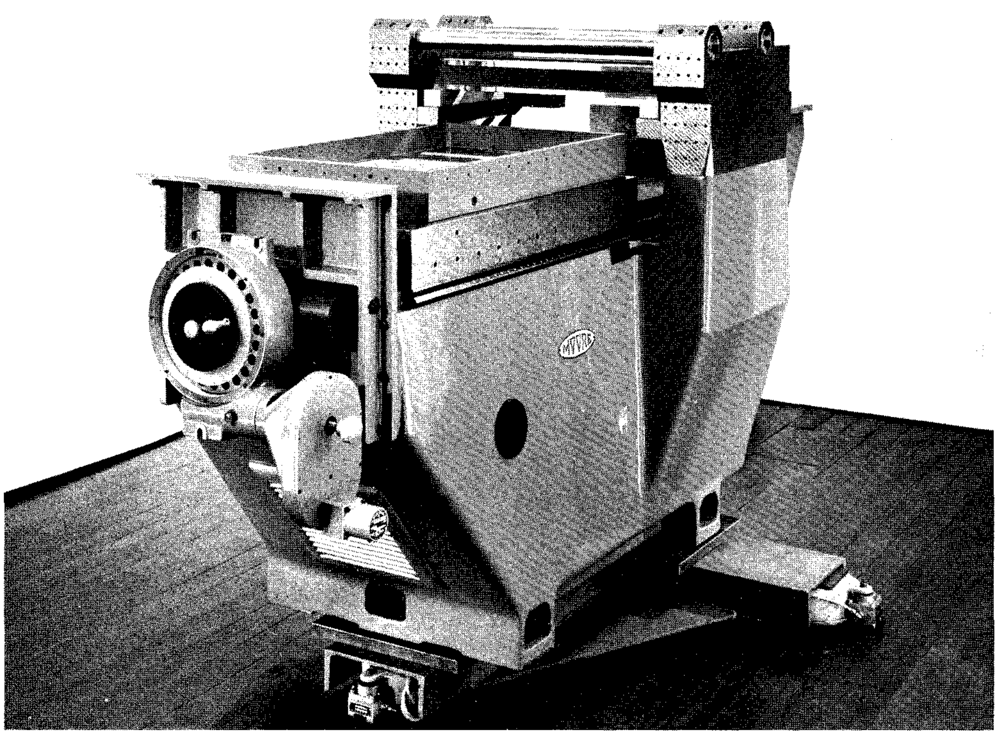


FIG. 555—A Moore Model No. 4 Measuring Machine, with monorail to guide the diamond element and master worm and gear to control lead screw displacements, is shown as modified for use as a ruling engine for large diffraction gratings. The machine was built for the Massachusetts Institute of Technology where it was brought and adapted to laser-interferometric control by Harrison.

peatability of a No. 4 Measuring Machine using fiber-optics* was performed for Harrison. The repeatability and sensitivity of the lead screw using a roller-way design shown in this experiment, plus Harrison's further tests of the machine at Moore by laser interferometry, convinced him that this design was essentially correct for the basis of a ruling engine capable of producing unusually large diffraction gratings. A No. 4 Measuring Machine was then modified for introduction of interferometric control according to Harrison's design, by Albert E. Johnson, Chief Project Engineer at Moore, aided by engineer Vilmars Fimbers and various technicians.

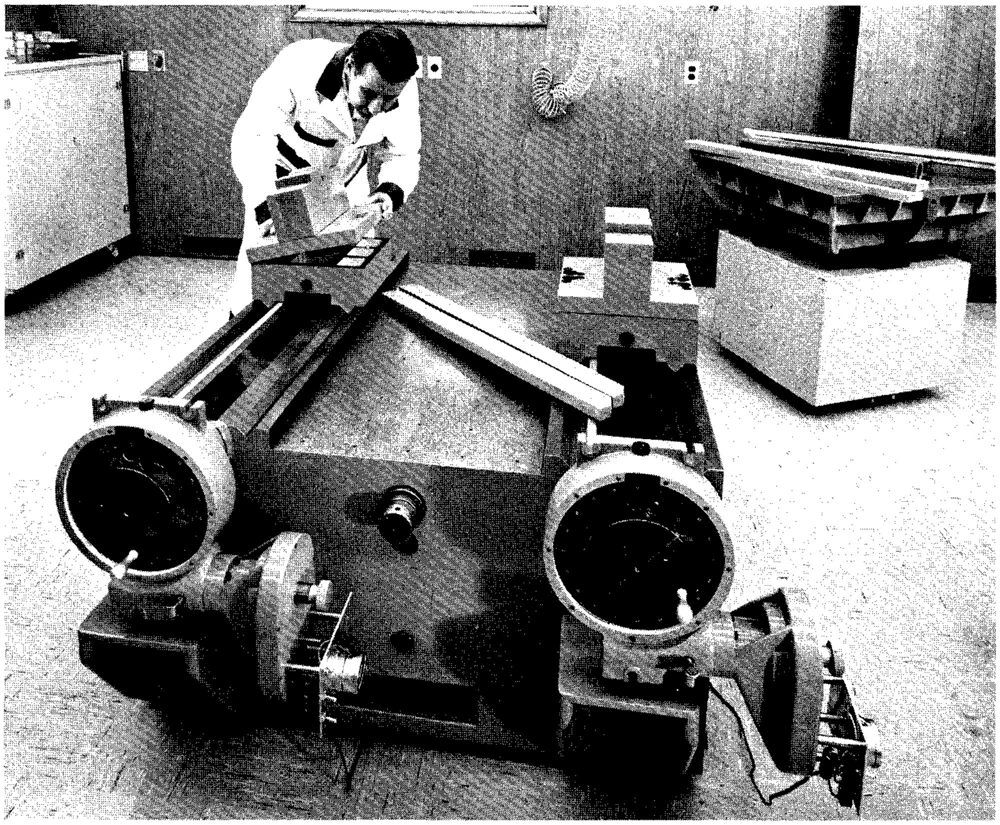
In place of the cross rail member, a lapped Nitralloy cylinder held to close tolerance of roundness and straightness is used as a monorail to guide the diamond element. Closer to the grating, the diamond is guided by a master Nitralloy straight-edge. Shown in Fig. 554 is the master box-type straightedge as it is used to establish the V-mounting surfaces for the monorail. Fig. 555 shows the nearly completed machine.

Mounted on the main carriage is a "yaw table," or compensating plate, used to eliminate the approximately ¼ second of arc error of carriage curvature of travel.

Aside from greater size and accuracy, this engine has many practical improvements over the previous engines at M.I.T. The "A" engine could operate with a diamond stroke speed of 2 inches per second [50.8 mm/second]; the "B" engine (No. 3 Moore base) operated at 3 inches per second [76.2 mm/second]. The "C" engine (No. 4 Measuring Machine) strokes at rates up to 6 inches per second [152.4 mm/second] without undue vibration. As shown, this engine has two sets of monorails, diamond carriages and diamond drives, running in opposite phase and

*Wayne R. Moore, "Repeatability to 0.2 millionth!" *American Machinist*, August 29, 1966.

FIG. 556—*Overall proportion of the carriage members is tested against the completed base of a ruling engine for Professor George W. Stroke of the State University of New York, Stony Brook. Wooden models are often used to obtain correct configurations prior to actual construction.*



spaced 200 mm [7.874 inches] apart to allow simultaneous ruling of two blanks. In this manner, whether the error is attributable to either the interferometer, the carriage, or the diamond position can be differentiated.

George W. Stroke

George W. Stroke made significant contributions to the ruling engine while at M.I.T., and was an early disciple of and later a strong advocate of interferometric control. After M.I.T., Stroke went to the University of Michigan and together with O. C. Mohler, F. Denton and T. Harada conceived a different design of ruling engine intended to make gratings 32 by 20 inches [813 x 508 mm]. The blank itself was kept stationary; the diamond carriage was transported by two lead screws, each interferometrically controlled. Its base and carriage were built at Moore, using standard equipment, masters and techniques.

Stroke then transferred the ruling engine along with most of his equipment to the State University of New York, Stony Brook,* where it was decided to complete the mechanics of the engine at the Moore company. There it is still undergoing construction and design changes. Overall configuration of the diamond carriage element is shown being tested using wooden models, Fig. 556. The diamond-lifting mechanism is shown under assembly in Fig. 557. Its function is to feed the diamond gently onto the grating (controlled by a ramp), lifting it to clear on the return stroke.

*"New Holography Lab for Stroke," *Scientific Research,* January 22, 1968.

FIG. 557—*The function of the diamond-lifting element under assembly is to feed the ruling diamond accurately and gently onto the grating blank, and to retract it on the return stroke.*

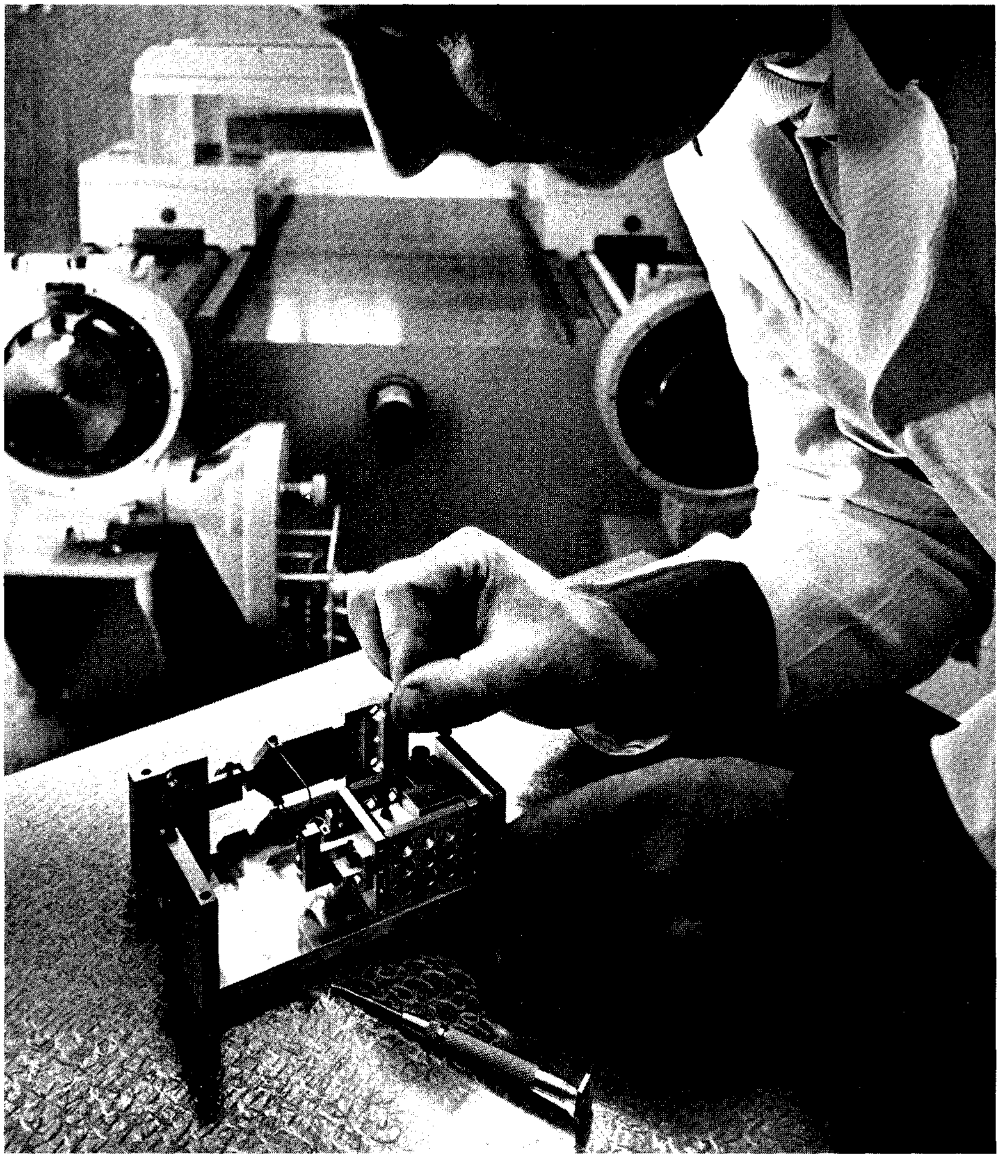


Fig. 558 shows the main elements of the ruling engine assembled. The system of the ruling engine can be considered to have two main structures. In the foreground is the first structure—the engine proper. Twin carriages are used to carry the monorail, which guides the diamond carriage and diamond-scribing element. Attached to the lead screws which displace each table is a master worm and gear along with further reduction gearing to a stepping motor. After scraping and lapping of the carriage ways, Rulon is applied to the table to reduce friction.

A reflecting mirror is attached to each table as part of a laser-interferometer arrangement. By means of a fringe-counting and electronic feedback system, the stepping motors attached to each screw are pulsed to maintain uniform spacing and parallelism of the grooves.

The monorail consists of mechanical elements similar to those in the M.I.T. engines. Both tables of the ruling engine move continuously while the grating blank is being scribed. This procedure is followed to avoid errors resulting from starting "stiction" and non-uniform oil film as well as errors from starting and stopping inertia. In effect, the grating is ruled while the monorail is being displaced; but since the ruling stroke is performed thousands of times faster than the carriage movement, groove inclination is negligible.

To the rear is the second main structure of the engine, containing the driving element. Its accuracy is not nearly as critical as that of the engine proper. Its function, nonetheless, is very important. It also contains a movable carriage which is constructed to move synchronously with the ruling engine by means of a lead screw, worm and gear and timing belt. A unique design is employed to drive the diamond

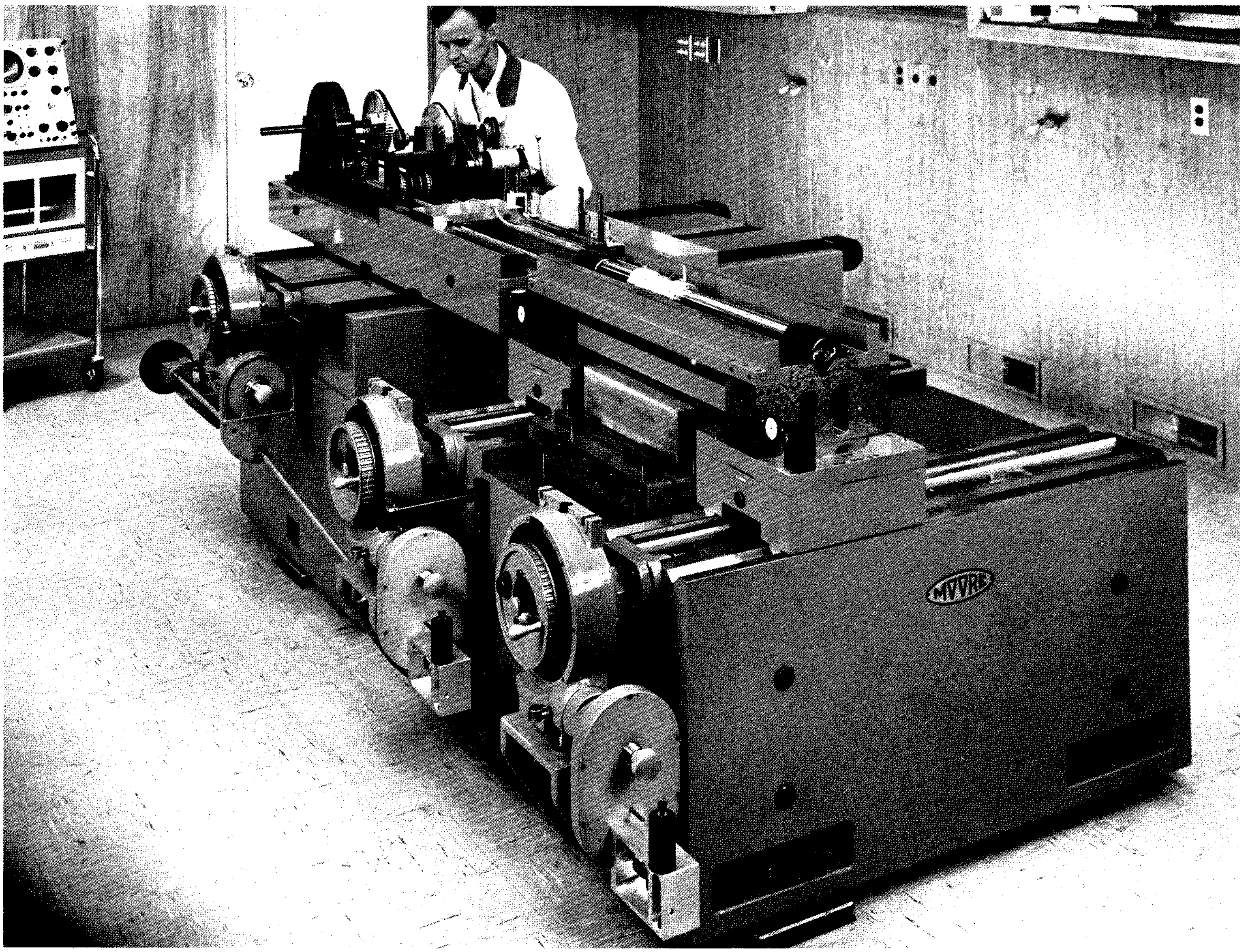


FIG. 558—*The ruling engine for the State University of New York, Stony Brook, is composed of two structures: (1) The ruling engine proper which must accurately displace the grating (foreground); (2) The driving element used to traverse the diamond across the blank in prescribed increments (background).*

element at a constant feed rate across the grating—an essential condition to good gratings.

Expectations of the No. 4 Measuring Machine ("C") Engine

The No. 4 Measuring Machine ruling engine was shipped to M.I.T. on December 7, 1966. It has since been adapted to interferometric control, and has ruled several excellent gratings of 12 x 15 inches size [304.8 x 381 mm]. Further improvements in the performance of this ruling engine are projected by Harrison:

"We are now testing and improving a larger controlled ruling engine, the C engine, based on a Moore No. 4 Measuring Machine with 30 in. [762 mm] travel. Blanks up to 450 x 635 x 130 mm [17.7 x 25 x 5.1 inches], weighing as much as several hundred kg (close to 1000 lbs.) can be ruled on this engine. Several 300 x 390 mm [11.81 x 15.35 inches] gratings produced on it show high speed and excellent grating quality at angles less than 45°. A further fivefold improvement is hoped for to make possible the ruling of very large echelles of quality equal to those produced on the B engine."*

Conclusion

It is fitting that this text should conclude with a description of a tool which is perhaps the most exacting which man has ever constructed to date. This tool will increase not only our knowledge of the minute atomic structure of elements, but when mounted on telescopes, will help analyze the light spectra of the most distant stars. Thus, such mysteries as stellar composition and the age of the universe will be explored. The information barriers imposed by man's physical limitations of traveling in space may then be overcome, Fig. 559.

The ruling engine—the most reaching development of our mechanical and metrological skill—will contribute in a substantial way to the furthest extension of man's probing. As Ingalls summarized: "If the spectrograph is man's most potent tool, the diffraction grating is his highest achievement in mechanical precision."*

We at the Moore Special Tool Company have been pleased to contribute in some way to this scientific advancement. Four distinct mechanical arts—geometry, length, dividing the circle and roundness—have been separately perfected, then combined to create the mechanical basis of a ruling engine. Each one is vital to performance; each mechanical art, in turn, derives from the foundations of mechanical accuracy.

*George R. Harrison and Stephen W. Thompson, "Large Diffraction Gratings Ruled on a Commercial Measuring Machine Controlled Interferometrically," *JOSA*, Vol. 60, No. 5, 1970.

*Albert G. Ingalls, "Ruling Engines," *Scientific American*, June, 1952, p. 45.

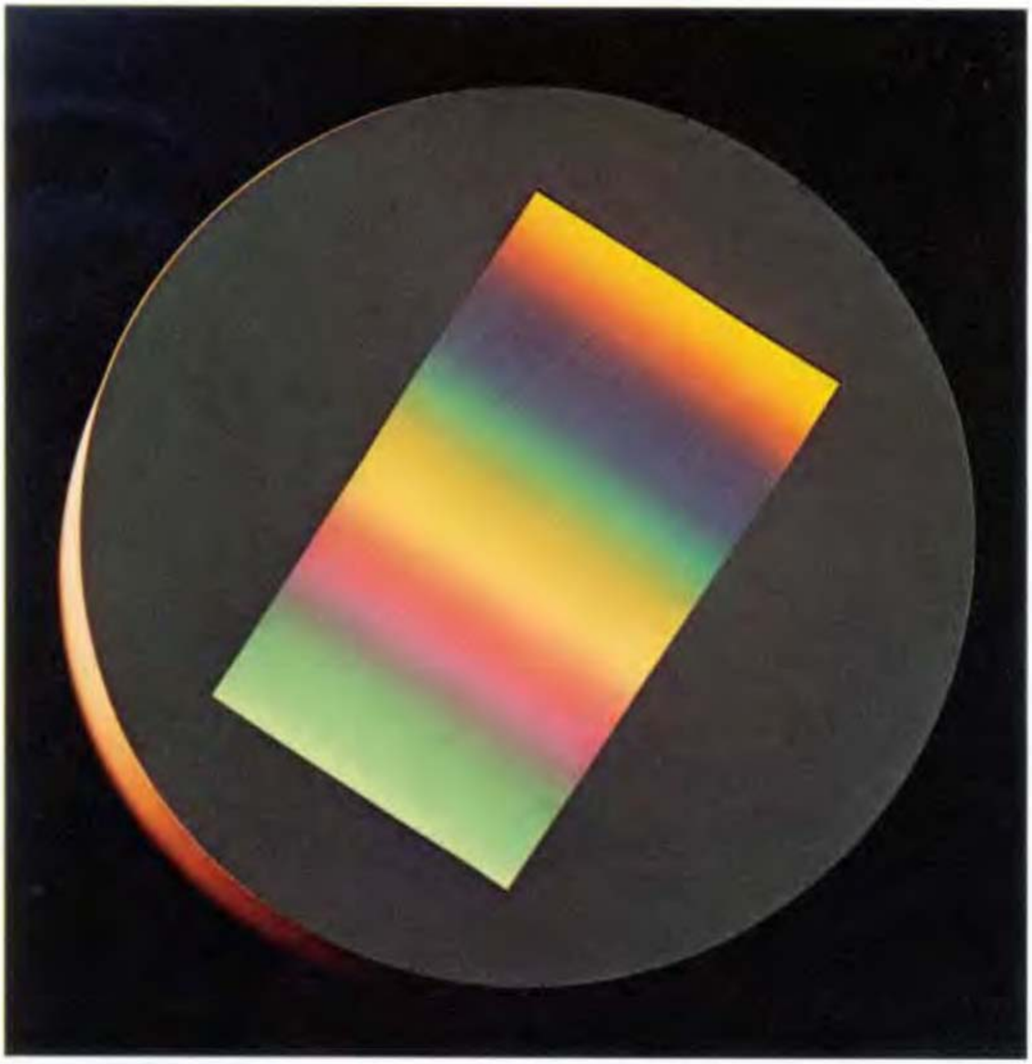


FIG. 559—*Rainbow effect demonstrates the ability of a diffraction grating to sort out complex and close-lying wave lengths and electromagnetic radiation. Much of our understanding of the universe, from the minutest atomic nucleii to the far reaches of the universe is owing to spectrographs, the heart of which is the diffraction grating. So vital an element is the diffraction grating to experimental physics that it has been described as the "master key of science."*

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