THE MAKING OF A PHOTOGRAPHIC OBJECTIVE.

Being a Description of a Course in Applied Optics Offered at the Emerson McMillin Observatory of the Ohio State University.

H. C. LORD.

Photography, in its more serious phase, has taken an important place in almost every field of human activity while in its lighter mood, through the development of the "Kodak" and the roll film, is giving us one of our most delightful pastimes. As a condition for the best work, a high grade lens is a necessity and especially so for those extremely short exposures required in the photography of rapidly moving objects. It often happens that some of the most perfect and at the same time most difficult specimens of optical design are found on cameras so small that they can be easily carried in one's coat pocket. These so called anastigmats furnish to the optician a difficult and yet at the same time most fascinating problem for mathematical investigation. Thousands of photographic objectives are placed on the market every year, yet though almost every branch of engineering is covered by our technical schools, I know of no place outside of Germany where a student can be instructed in the design and construction of a simple photographic objective. Professor Silvanus P. Thompson in his inaugural address as President of the British Optical Convention held in London in 1912, states: "In the Universities and Colleges the only people who are learning Optics are merely taking it as a part of Physics for the sake of passing an examination for a degree, and care nothing for the application of Optics in the industries. They are being taught Optics by men who are not opticians, who never ground a lens or calculated even an achromatic doublet, who never worked an opthalmoscope or measured a cylindrical lens." Further on he speaks as follows: "What is wanted is an establishment where the whole atmosphere is one of optical interest; where theory and practice go hand in hand; where the mathematician will himself grind lenses and measure their performance on the test bench; where braincraft will be married to handcraft; where precision, whether in computation or workmanship, will be the dominating ambition."

Some four years before the above quotations were written, the author started to work up a course in Optics which should aim, not only to give to the student a knowledge of the fundamental theory of lenses, but should also apply those principles to the methods of optical design and thus enable him to compute the curves of the component lenses of a photographic objective. This has now been fairly well worked out and is given in the Arts college under the official titles "Astronomy, 107, 108, 109 and 110." The basis of this course is "A System of Applied Optics," by H. Dennis Taylor, the inventor of the Cooke lens. This splendid volume develops, from the standpoint of geometric optics, a complete discussion of the formation of an image by a combination of any number of lenses, but does not apply the methods and formulae there developed to the actual design of a photographic objective. The writer of this paper was, therefore, compelled to work out this part of the theory for himself and, as he had always felt that all mathematics should ultimately end in arithmetic and that all arithmetic should ultimately end in doing something, he resolved at the outset that the course should end in laboratory work in the actual computation, grinding and polishing of lenses. As to how well this has succeeded, I will let the illustrations which accompany this article speak for themselves. Suffice it to say that the half tone cuts were made from five by seven enlargements from negatives, one and three quarters by two and one-eighth inches, taken with a lens *designed* and *built* at this observatory and working at an aperture of F six. A peculiar feature of this lens is that it is composed of four lenses all cut from the same piece of crown glass. This lens beautifully illustrates the importance of adding to the theoretical side of the course, the practical work in the laboratory in construction and testing as this lens, though in the main satisfactory, has one serious defect and a defect which is very instructive in that it shows that at a certain point in the design, the theory was weak and needed to be extended and enlarged. It should be stated that this theoretical investigation is now completed and ready to be put to the test of practice.

This Observatory possesses a well equipped instrument shop, which was used for the practical side of this work and it has seemed to me that a description of how we used the ordinary tools of a machine shop, of what special appliances we were compelled to make, and how we finally ground and polished our lenses would be of general interest. These methods do not pretend to be the best, nor those actually employed by the manufacturer, but they do illustrate how a lens can be made and how a little ingenuity will enable one if he has the standard tools of a machine shop to carry out almost any kind of experimental work.

As a preliminary to this, a brief outline of the problem before the lens designer may be of interest. A simple lens consists of a piece of glass bounded by either plane or spherical surfaces as these, except in large reflecting surfaces, are the only kind that can be made with sufficient accuracy. Such a lens would have a great many defects or errors and would be unable to give a sharp image on the photographic plate unless stopped down to a very small aperture. By changing the radii of the surfaces, and the thickness of the lens, the designer can vary these errors, but after all is said and done he can do but little to improve the single lens. He then combines lenses of different forms and of different kinds of glass into a single objective, in this way making the positive errors of some of the lenses balance the negative errors of the others, until he arrives at a combination which is more or less perfect according to his skill as a designer. How this is accomplished is far beyond the limits of this paper, so I will now proceed to the mechanical side of the problem.

The first consideration is the glass; of course it must be what is known as optical glass and its selection is really part of the work of the designer. Optical glass is nothing more than a very perfect kind of glass which has been exquisitely annealed. You are all familiar with the intense green of window glass when seen edgewise; a piece of white paper will hardly be changed in color when seen through twelve inches of a good optical crown. The best optical glass is not made in this country, but must be purchased from either Schott & Gen. of Jena or Mantois of France. The Jena glass has become very celebrated and most of the lens makers state that their lenses are made out of it and as a consequence most people think that Jena glass means a certain kind, while, as a matter of fact, their catalogue for 1909 shows about seventy different varieties. These differ in optical qualities and chemical composition, and cost from about a dollar to five dollars a pound, with a few special varieties costing as much as fifteen dollars. This glass comes in slabs, but will be cut by the makers with either a diamond saw or a sand saw, the purchaser paying for the "saw dust."

The slabs that were used here were 2″ x 6″ x ½″ and the first operation was to cut from these round disks a little larger than the finished lens. This was accomplished in the following manner and is illustrated in Fig. 1. In the chuck of a drill speeder on a Barnes drill press was placed a ¼″ steel rod which carried at its lower end a copper tube, A, which was steadied at the bottom by a steel washer, bored to a loose fit to the tube, and clamped to the glass as shown. Number 40 Carborundum was used and lubricated with *plenty of water*. The tube must be lifted frequently to allow the abrasive to flow to the cutting edge. This is done so often that it seems almost a continuous motion of lifting and pressing down again, the tool resting on the glass hardly more than two or three seconds at a time. The cutting may be done at such a speed as to allow of a slight heating. As soon as the tube has cut itself about a sixteenth of an inch into the glass, the guiding washer may be removed and

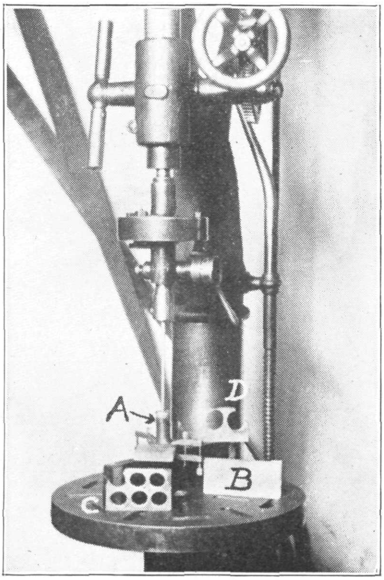

FIG. 1

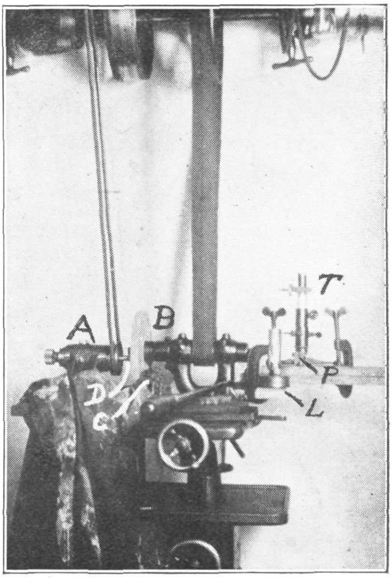

FIG. 2

the glass will then act as its own guide. A disk about one inch in diameter and a half of an inch thick could be cut out in a little over a half of an hour. At B Fig. 1 is shown one of the uncut slabs and at C and D two that are about used up. Though working rather slowly this proved quite satisfactory though wasteful of glass as it cut a rather wide scarf, copper must be used; brass was tried but the wear was so great as to render it almost useless while the copper shows almost none.

As these disks are cut out they are not only cone shaped but the edges are very rough so that the next operation was to grind these to smooth and true circular disks. This was done on a Wells tool grinder shown in Fig. 2, which was slowed way down by placing a large pulley on the counter shaft. The glass to be ground was held by cementing it with pitch onto a piece of brass rod which in turn was held in the drawing collet of the head A. A special wheel B, made by the Norton people for grinding the rims of spectacle lenses, was used and the machine slowed until the wheel would keep wet when running against a sponge, C, resting in water. The glass disk was in this way kept dripping and heating entirely prevented. The grinding was then carried out just as with any other material and the edge was made beautifully smooth and true in a few minutes. The beauty of pitch as a cement for holding the glass is that a slight heating will soften it so that the disk can be shifted to any position and then a dash of cold water clamps it in place and at the same time the pitch will slowly yield to the slightest pressure so that in a few minutes the glass is entirely free from strain. In manufacturing this sort of work is done with a diamond and is of course done much more quickly.

The disks were thick enough to make two lenses each so we sawed them into two as illustrated in Fig. 3. A is an old polishing head upon which was mounted a pulley at one end and a copper disk, B, at the other, the disk being held between large washers. C is a cast iron box fastened to an arm, D, hinged at E and kept pressed against the copper disk by a cord passing over two pulleys on the ceiling. This made a most excellent automatic feed. The glass to be split was fastened to a block of pine with pitch and the wood held in the iron box, C, with wedges. Number 40 Carborundum was used with plenty of water and the glass was cut through faster than a power hack saw would cut through steel. The glass should be cut half way through and then reversed so that the final break will come in the middle and thus prevent the edges from spawling off. The chief defect of this machine was the way it scattered emery.

The disks are now ready for the grinding which is done on the machine on the right of Fig. 3, which consists simply of a vertical spindle run by a quarter twist belt from the counter shaft against the wall. The end of this spindle is tapered at the upper end to receive the grinding tool or laps, shown on the table in Fig. 5 which also shows the spindle raised so that the grinding lap is seen above the tin box, C, which surrounds the spindle to catch the abrasive that is thrown off in grinding. The glass is first smoothed down on a flat lap until it is of equal thickness at all points as measured by a micrometer when it is ready to be ground to the proper curves. For this purpose the spherical laps, shown in Fig. 5, are turned in the special machine illustrated in Fig. 4. The compound rest of an old Seller's lathe was removed and in its place, on the cross slide of the

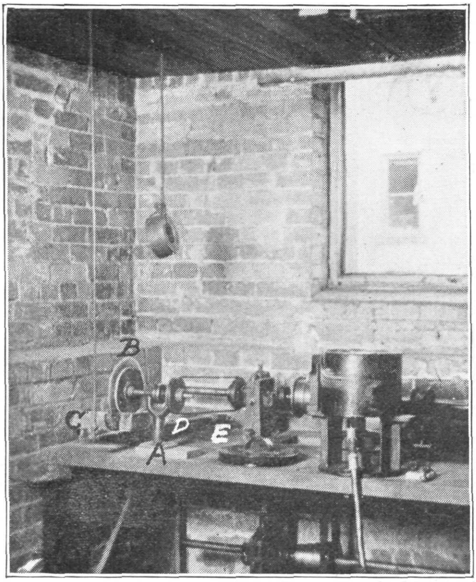

FIG. 3

carriage, was mounted the sphere turning rest. This consists of a base, A, in which the slide, B, is so mounted that it can be rotated about the center, C, by turning the milled head, D, which carries a worm at the opposite end. E is the tool post with the cutting tool T and L the lap to be turned. A hole was drilled at C into which was fitted a round piece of steel the upper end being pointed and then half cut away like a center reamer. This was used in finding the zero; the rod, pointed end up, was placed in the hole at C and the cutting tool adjusted against the flattened side. The zero position is then determined by measuring, with an inside micrometer, the distance from the tool post to a stop placed at the end of the slide B. By adding to or subtracting from the zero reading of the micrometer the length of the radius of the grinding lap, the tool post may be set to the proper position for either a convex or a concave surface. This, however, is only approximate, for these laps must be made with the highest possible accuracy. After sufficient cuts have been taken to give a spherical surface, the radius is carefully measured with a special spherometer and the error in the radius corrected by changing the position of the cutting tool by an amount calculated from the readings of the

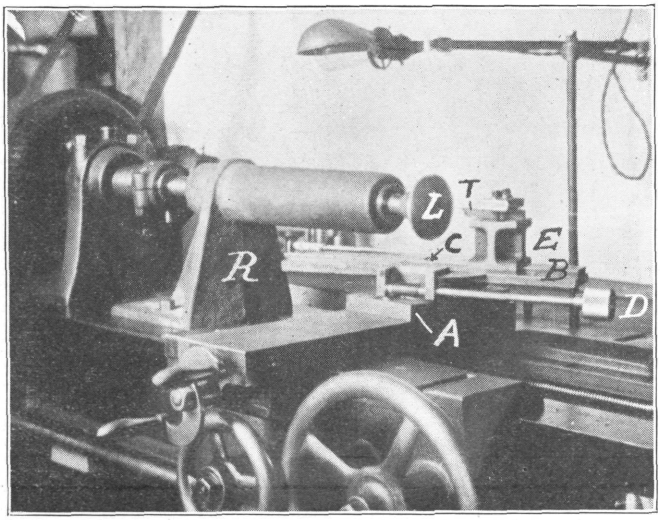

FIG. 4

spherometer. This spherometer we were compelled to build as we could find none of sufficient accuracy on the market and it is described in a note at the end of this article.

In Fig. 4, R is simply a steady rest made with the large overhang to allow the slide B to swing under it in turning a convex surface. Two master laps, male and female, must be made and carefully ground together. Every effort should be taken to make these as accurate as possible since upon these depends the goodness of our lens. This special tool is easy to make and leaves nothing to be desired in its operation. Detail drawings and directions for making it are given in a note at the end.

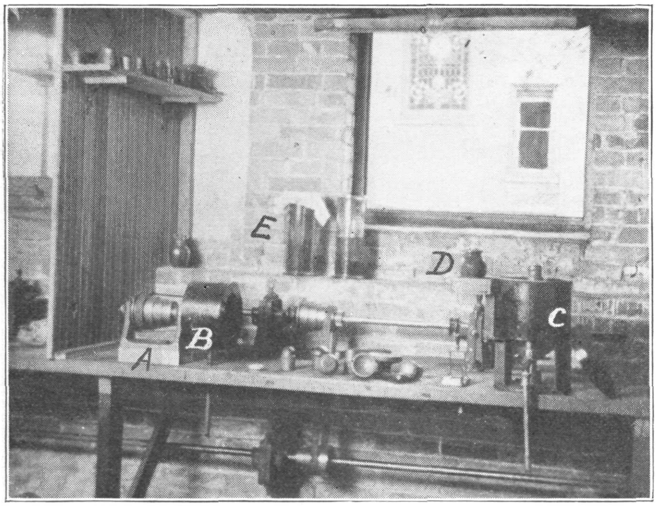

FIG. 5

We now come to the grinding or lapping of the lenses themselves. This is done in a lap turned as above and carefully fitted to the master laps and which must be trued from time to time as the work progresses. This lapping of glass is entirely different from the lapping of metals in that, while in metals the lap is to be kept almost free from the abrasive, in glass the lap must be freely supplied with emery and water or deep scratches will result. The best way to apply the emery is with a paint brush; the brush, saturated with emery, being held in front of the lens as it is ground. The lens may be held in the hand or cemented to a disk of brass having a center hole drilled in the back in which is placed a pointed piece of steel held in the hand, the lens being free to rotate about the pointed steel holder. Of course where the lens has to be ground to a definite thickness it must be held by hand. Flour of emery was used to rough grind though coarser grades would have worked faster. The final smooth grinding was done with a special fine emery made for this purpose by Bausch and Lomb. Great care must be taken in the grinding to keep the lens as nearly centered as possible. A lens is said to be centered when the line which joins the centers of curvature of the surfaces passes through the center of figure. Obviously if a double convex lens could be ground to a knife edge it would be centered but if this were done the edge would be almost certain to crumble in the final polishing and deep scratches result. The centering of a convex lens can be watched by keeping the edge as nearly uniform of thickness as possible with a concave lens, if the original blank is made larger than necessary and care is taken to make the sides parallel, the centering can be watched by keeping a flat edge of *equal width* around the concave portion, the lens being placed back on the flat tool, from time to time, as the work progresses. If care is used the lens need be made but little larger than the finished size to allow for the final accurate centering to be described later.

After being smooth ground the lens is beautifully smooth and velvety to the touch but is just as much ground glass as ever, that is, it is absolutely opaque. We now come to the polishing. This is done with specially prepared rouge and only an excessively small amount of glass is taken off. Lord Rayleigh in a paper on "Polishing of Glass Surfaces" read before the British Optical Convention held in 1905, states: "I started with a finely ground surface, rather more finely ground I think than is used in practice, and I found that in order to obtain a pretty good polish it was necessary to remove a weight of glass, corresponding to a depth of about 6 wave-lengths. I do not pretend that such a polish would satisfy the requirements of commerce; probably the 6 would have to be raised to 10 or 12 in order to get to the bottom of the deepest pits." When it is remembered that a wave length is about the fifty thousandth part of an inch we realize how very delicate such lapping must be. For this work the lap is covered with pitch which has been brought to the proper degree of hardness either by boiling, to harden it or by adding asfalt varnish to soften it. The proper degree of hardness is very important and must be adjusted to the temperature of the room. Obviously if the pitch is too soft it will not hold its shape and it will be impossible to hold the polishing tool to the proper radius. I have put three different curves on a lens about an inch in diameter in a few minutes and it had to go back on the grinding machine before it could be finished.

The polishing tool is prepared as follows: A disk of pitch, about ¼″ thick, is cast by pouring it in a mold made by a strip of brass bent to a circle, the ends clamped with a tool maker's clamp, and rested on a piece of cold cast iron which has been planed smooth. This should be of such size that when bent to the proper shape it can be molded over a tool similar to the grinding tool but with a radius changed by about the thickness of the pitch. This tool is then heated and painted with a stick of pitch, the disk is warmed, and the two pressed together, when cooled the pitch will stick tight to the iron but will be far from a smooth surface. This and the master tool of the opposite curvature are placed in warm water and pressed together and at the same time one slowly rotated, one about the other. When a good fit is secured they are cooled and a number of small holes, about 1–8″ in diameter, are drilled all over the pitch to distribute the abrasive, which of course spoils the surface and the tool must be again pressed. This pressing to shape must be done repeatedly and requires great care and some practice in order to have the pitch come to the exact opposite of the pressing tool. The most important thing is to do the pressing slowly and in fact in the whole process of this work one must never get in a hurry. Ritchey, in his memoir on the construction of the great 60″ at Mt. Wilson, recommends covering the pitch with beeswax, and for quicker and poorer work a cloth polisher may be used, the cloth being a special felt and cemented to the cast iron tool with a thin layer of pitch.

The abrasive is rouge or red oxide of iron and its preparation is fully described in the above mentioned work by Ritchey. We purchased the anhydrous red oxide of iron from Merck & Co. This was mixed with plenty of water in the jars shown at E, Fig. 5. The rouge will rapidly precipitate, the coarse particles falling to the bottom, and leaving clear water above the precipitated rouge. The upper two-thirds of the rouge will be almost perfect and will give a beautiful polish when carefully siphoned off. This should be kept in tightly corked bottles, one of the best things is a horse radish jar as this has a place for the handle of the brush in the glass stopper, and all dust and grit can be easily washed off before the jar is opened. For polishing, the lens is cemented to a handle at whose end is a piece of brass turned to fit the lens in the sphere turning machine already described. Even in a small lens the polishing tool must be run slowly, the speeds of our machines run from 170 to 300 revolutions per minute and the fastest can seldom be used. The reason of this is that the lens fits the polisher so perfectly that almost a perfect vacuum is formed and the lens hugs the polished so closely that it is impossible to hold it in small sizes by hand alone and in the case of a convex surface, if the cavity is carried clear out to the edge of the glass disk, this may be broken simply by the friction due to this grip of the glass and pitch. Fig. 5 shows a horizontal polishing head at B and a vertical one at C. There is little choice except that for convex surfaces B seems the best, as it can be run faster, while for concave C seems better.

The lenses are now ready to be centered, that is, the circumference so turned that the line which joins the centers of curvature of the two spherical surfaces shall pass through the center of figure. In order to accomplish this, the lens is first cleaned from the pitch used to cement it to the handle used in holding the lens for polishing. For a long time I could find no way of doing this satisfactorily when pitch was the cement; finally, I laid my troubles before Dr. A. M. Bleile, Head of the Department of Physiology, and he suggested to first soak the lens in lard and then wash it in benzol (C_6H_6). This worked like magic though the first time I tried it I used some lard that had been heated with some pitch in it which made the lard very soft in fact almost as soft as it could be and yet not be an oil, and this same lard was used over and over again. The action is rather peculiar; the lard does not apparently effect the pitch at all but after a few minutes in the benzene it all flakes off and leaves the lens perfectly clean. The actual centering is then carried out on the grinding machine shown in Fig. 2; A holder, D, whose front face has been turned in the spherical turning machine to fit one of the surfaces of the lens, is held in the head A. If the lens be cemented to this with a thin coat of pitch, it is obvious that the surface of the lens next to the holder will have its center of curvature coincide with the axis of rotation of the spindle of the head A, but the center of curvature of the other lens surface will probably fall outside of this axis. A lamp, L, has a tin chimney with a pin hole in it turned towards the lens, this pin hole forming a brilliant point of light, an image of which is formed by each surface and reflected by the total reflecting prism, P, into the telescope, T, where it is seen through the eyepiece. If the centers of curvature of both surfaces do not accurately coincide with the axis of rotation of the head, A, the images of the pin hole will describe circles as this axis is rotated. The back surface will of course be centered if the layer of the pitch used as cement is of uniform thickness which will generally be the case if the work has been carefully done; but in any case the image formed by it should be examined. If the front surface is out of center, as it generally will be, the holder should be warmed and the lens shifted, care being used to keep it tight against the surface of the holder as it is being shifted. As soon as both images remain stationary as the head, A, is rotated, the lens is fed against the wheel, B, and ground true and to size. This worked beautifully and the tests were wonderfully sensitive. As soon as the component lenses of the objective have all been thus centered, they are ready to be assembled in the cell or shutter in which they are to be used; but as this is simply a matter of careful machine work, I need not describe it further.

I know of no literature on the grinding of small lenses though the following memoirs on the making of large reflecting telescopes should be in the hands of any one interested in this work:

On the Construction of a Five-foot Equatorial Reflecting Telescope. By A. A. Common, LL. D., F. R. S. Memoirs of the Royal Astronomical Society, Vol. L., 1890-91.

On the Construction of a Silvered Glass Telescope, Fifteen and a Half Inches in Aperture, and its Use in Celestial Photography. By Henry Draper, M. D., Smithsonian Contributions to Knowledge, Vol. 34.

On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors. By George W. Ritchey. Smithsonian Contributions to Knowledge, Vol. 34.

NOTE 1—A SPHEROMETER FOR SHORT RADII.

In Fig. 6, A is a regular Brown & Sharpe Micrometer Head with the measuring point ground to an angle of 60° and slightly rounded; B is a round steel base all machined at one setting in which the micrometer head is clamped by a set screw not shown.

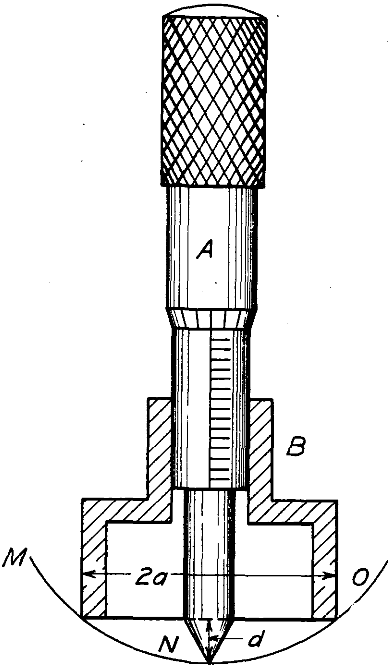

FIG. 6

Let r be the radius of the spherical surface, MNO, and we will have at once $r = (a^2 + d^2) / 2d$. The advantage of this form of spherometer is that it is very easy to make the point of the micrometer exactly central with the base and the value of 2a can be accurately determined by means of an ordinary micrometer calliper. For a convex surface, 2a should obviously be the inside diameter of the base, B.

In using the instrument, two tables, one for concave and one for convex surfaces, should be prepared; these tables to give the power in dioptres for each one thousandth of an inch in the value of d. Using the American Optical Co.'s Standard Index, namely, μ equal to 1.5000 and one dioptre as being the power of a lens of 40 inches focus, we have, for a plano lens, $p = 40/f = 40d/(a^2+d^2)$ since $f = r/(\mu-1)$.

The advantage of forming the table in dioptres in place of radii directly is that the tabular differences are small at all parts of the table so that interpolation can be readily done and this is not the case in tables which give the radii directly.

If upon measuring the radius of the tool or lap being turned in the sphere turning machine, Fig. 4, with this spherometer, the tool is found to be in error by an amount $\triangle p$ this may be corrected by changing the position of the cutting tool by an amount $20\triangle p/p^2$.

NOTE 2—CROSS SECTION OF THE SPHERE TURNING REST.

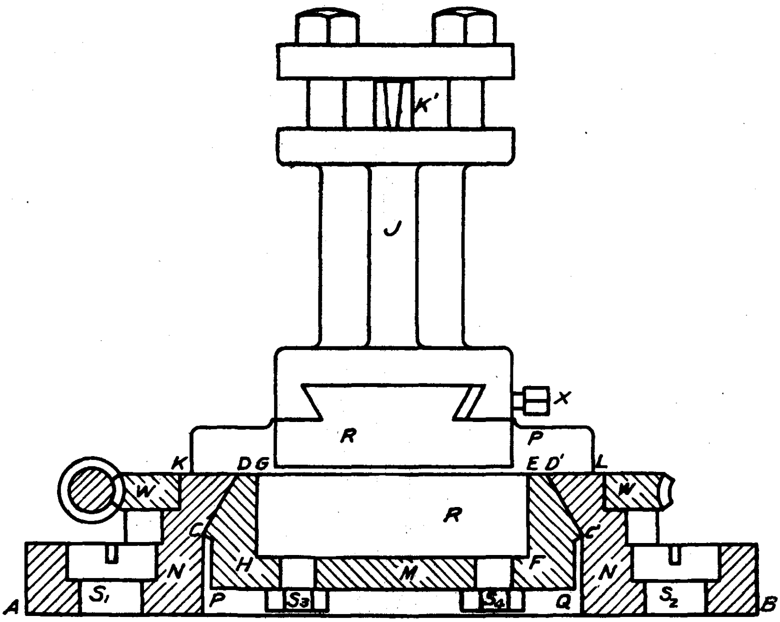

FIG. 7

In Fig. 7 is shown a cross section of the sphere turning rest further illustrated in Fig. 4. In machining this the following suggestions should be followed. The piece M should be cast with a lug projecting from the face PQ to chuck it by and all the turning done at one chucking. It should be made a close fit to R and bolted tight against DG and ED' with the bolts S_3 and S_4, clearance being given along the line HF. To compensate for ware the face DG and ED' can be releaved from time to time with a file. The base N, should be planed along AB, where it fastens to the cross slide of the carriage, then bolted to a face plate of the lathe and finished, care being used to leave the setting of the compound rest unchanged between machining the faces CD and C'D' of the pieces M and N. The dove tail on R should be first planed and then this bolted to a face plate and the boss GHFE and the faces KG and EL turned at one setting. If these directions are followed almost no hand work will be needed. W is a brass worm wheel held by screws not shown and J is the sliding tool post clamped at X with the tool at K'.