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STUDY OF TECHNIQUES FOR THE FABRICATION AND TESTING OF LARGE OPTICS

by

William E. Webb
and
Victor Schutz

Final Report on Contract NAS8-25417

October 1970

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UNIVERSITY OF ALABAMA

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TECHNIQUES FOR THE MEASUREMENT AND FABRICATION OF LARGE OPTICS

Prepared by

William E. Webb, Project Director

and

Victor K. Schutz, Consultant

Final Report

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The personal contact made and the help received from them are too numerous to be mentioned here. However, here are some men I would like to mention because they have not only gone beyond what was normally expected of them but still are a source of continuous help and advise: Dr. A.B. Meinel, Mr. Don Loomis, University of Arizona; Mr. Ed Forkey, Itek Corp.; Mr. John L. Plummer, Plummer Precision Optics; Mr. Robert N. Chamberlain, Schott Optical Glass Inc.; Mr. Dieter Anders and Dr. Jurgen Petzoldt, Glaswerk Schott & Gen., Mainz; Mr. Christopher Kuhne, Carl Zeiss/Oberkochen; Prof. Dr. Hein Claussen and Prof. Dr. Franke, Erust Leitz, GmbH, Wetzlar.

Techniques for the Measurement and Fabrication of Large Optics

by

William E. Webb and Victor K. Schutz*

1.0 Introduction

The objectives of this research was to survey the current state-of-the-art in the production and testing of large optics such as will be required for orbital-astronomical telescopes and other aerospace applications and to make recommendations concerning the development of in-house optical fabrication facilities at Marshall Space Flight Center based on the results of this survey.

To accomplish the required survey two sources were used; literature search and on-site visitation of leading optical facilities both in this country and abroad. The literature search was preformed using the facilities of the Redstone Scientific Information Center, Redstone Arsenal, Alabama, and the Libraries of the Optical Institute of the University of Arizona. Much other valuable information was also obtained from the libraries of the various optical facilities visited. Unfortunately, much of the technique involved in the production of high quality optical surfaces depends upon the skill of individual opticians and have never been documented. We therefore found it necessary to collect most of the information for this study by on-site visitation of leading optical

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manufacture and person-to-person discussion with their staff. The installations visited were:

1. University of Arizona Optical Institute, Tucson, Arizona
2. Kitts Peak Observatory
3. Perkin Elmer Corp., Norward, Conn.
4. ITEK Corp., Lexington, Mass.
5. Schott Glass Co.
6. Strassburg and Tinsley Laboratories
7. Owens Illinois Corp.
8. Corning Glass Corp.
9. University of Rochester
10. Zeiss Optical Co.
11. Tuimco Corp.
12. Alfa American Corporation
13. Rodenstock Optical Works
14. Rawk and Co. (London England)
15. Grubb Parson Co. (Newcastle - on Thyme, England)
16. Evring and Co. (Germany)
17. Jenaer Glasswork of Schott General Corp.
18. Ernst Leitz

The information collected by these visits and from the literature search are numerized in this report. In preparing the report it was intended to produce a document which would be a useful reference for the personnel of the MSFC Optical Shops.

2.0 Optical Techniques

The fabrication of optical surfaces is still an art, as it was for centuries, rather than a science. In spite of the developments of new optical materials, abrasives, and machinery, the generation of precision optical surfaces depends upon the skills of the individually highly trained optician. There are times, neither the optician, nor anybody else, knows precisely which particular combination of techniques and materials will lead to the most efficient procedure.

Unlike the testing of optical surfaces and lens design which recently became rigourous, systematic, quantified processes, the fabrication of an optical surface is almost entirely based upon techniques developed by emperical methods.

Strange as it seems, there exists a sophisticated scientific state of development in optical testing and design, surpassing the ability to manufacture, on one hand - on the other, the fabrication and evaluation of a precision optical surface is soley dependent on the skill and intuition of the optical artisan. This apparent paradox suggests the urgent need for a program to develop a systematic, quantified approach to the fabrication of a precision optical surface. A possible approach was recently suggested by Robert R. Shannon (Reference 1 p.3)
In his words:

> "A consistent program in which the techniques developed in optimization of lens system designs are applied to optimization of the finished surface is distinctly appropriate at the present time. Such a program provides the only likely method of ensuring that very high quality surfaces of the nature required in large space telescopes can be made on a timely basis."

Implied here is a different approach from that of precision mass production which consists of the development of a repetitive process refined to attain a quality surface by some lengthy process control. A very few experimental machines exist in this country and West Germany with "automated" generation of precision surfaces, relating only a single variable to the improvement of the optical surface instead of a linear combination of variables. In lense design a merit function is used for a specific application which is a combination of the residual aberations that describe the state of correction. This system approach can be applied to the fabrication of precision optical surfaces in an analogous manner. Here, the optical engineer develops and selects the best linear combination of variables or polishing operations.

In order to construct an appropriate inert function for a particular problem the variables or the operations have to be defined and quantified. This ultimate objective must be used to guide the examination, definition and data collection of operation techniques, machine settings, tool preparations, abrasive actions, materials, and environmental effects.

2.1 Fabrication Techniques

2.1.1 The Classic Operations

Fundamentally they are the same in every optical shop, contrary to the impression given at times in the literature by practical opticians. They can be divided into the following steps:

(1) Rough grinding
(2) Medium grinding (truing)
(3) Fine grinding (smoothing)
(4) Polishing

Rough grinding is the process of removing unwanted material very rapidly. The coarse abrasive has grain diameters ranging from 50 to 500μ. It is here, where most of the progress has been attained recently by decreasing the operation time drastically: Grinding with loose grain has been replaced by grinding stones made of cast iron carrying a layer of sintered diamond bort. They exhibit long lifetimes, retain their forms, and are available with grain diameters down to 10μ, suitable for fine grinding. In loose grinding grain is pressed normal to the surface. It enters the surface causing glass particles to break out. In bound-grain grinding the forces are tangential to the surface while the grain remains completely external.

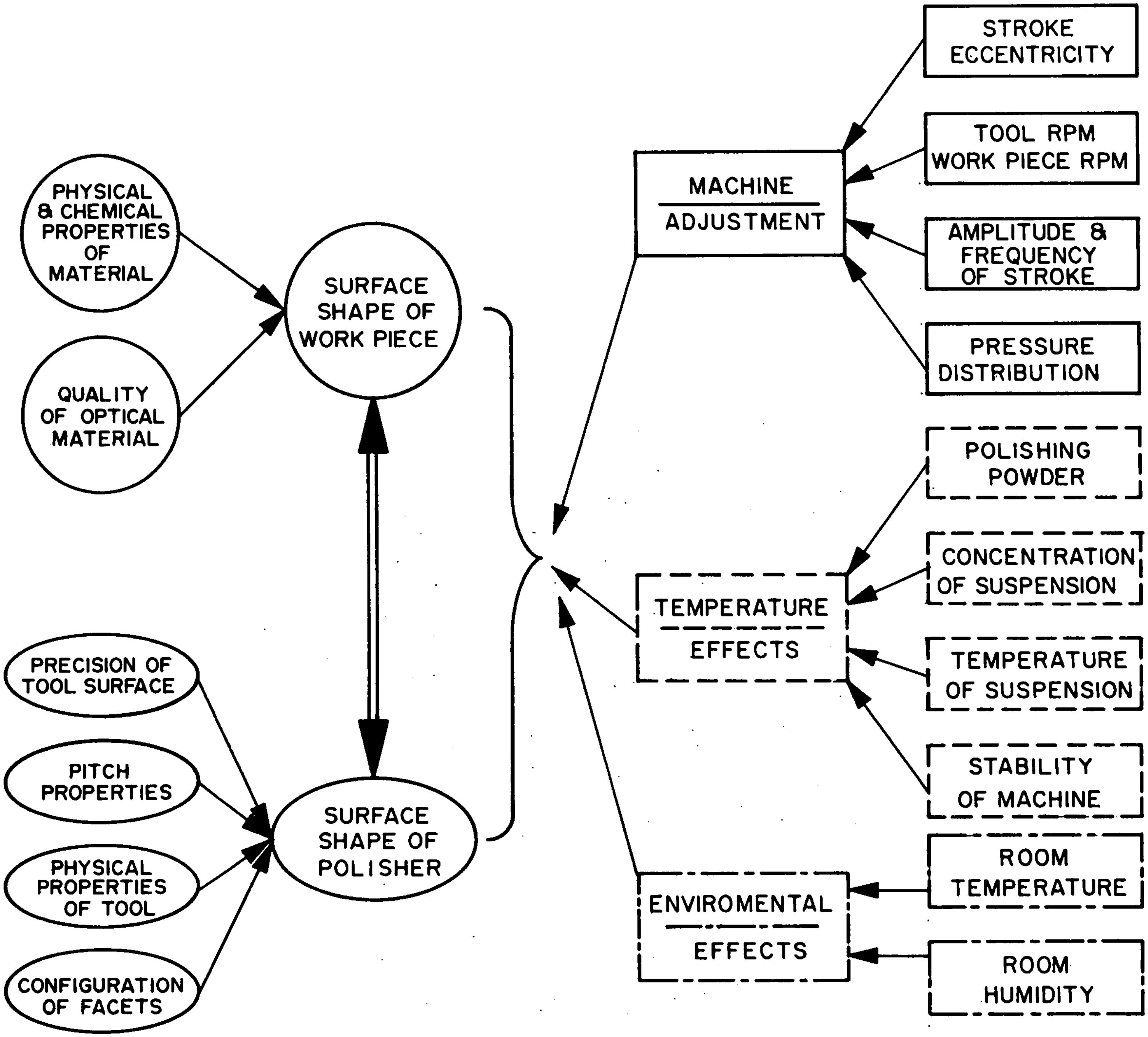
Medium grinding (truing) is the form-giving process. A spherical or paraboloidal mirror attains the required "figure" or curvature and lenses are given the proper thickness and form. The average grain diameter range from about 10 to 25µ and the abrasive used is usually synthetic or natural aluminum oxide (Al_2O_3). Natural Al_2O_3 is corundum. The grinding tool usually consists of either plain cast iron, or aluminum, brass or glass with ceramic or marble tiles attached to the grinding surface.

Fine Grinding (smoothing) prepares the surface for polishing. The average diameter of the abrasive (usually Al_2O_3) varies from 5 to 10µ, producing a silky-smooth surface. The modern trend is to work the surface with the faster grinding process, down to a few microns, in order to save on the time consuming polishing process.

Polishing generates a glossy surface with a micro roughness within 0.01 to 0.001µ without scratches and stains. The polishing compound is usually BARNESITE (cerium oxide). The polishing tool consists of a solid metal body covered with a relatively soft material such as felt, plastics, cloth, wax, and pitch. Pitch is universally used for polishing most precision surfaces. The polishing process is complicated and difficult to define; it will be discussed later.

2.1.2 Fine grinding and polishing

They are overlapping processes and are governed by many variables common to both. Fine grinding is still an abrasive action while polishing is only abrasive in its initial stages as will be discussed in another section. The polishing operation of a presision surface usually demands up to 80% of the optician's time. Sometimes the desired curvature or "figure" may be lost during this process because



THE OPTICAL POLISHING PROCESS
AND SOME OF THE PRINCIPLE VARIABLES

of the desire to attain a finer micro roughness or a "figure" closer to the specified, ideal curvature. In that case, a return to the fine-grind process is often imperative. A master optician, with proper tools, in a controlled environment, usually does not have to engage in such a time consuming, iterative process.

In fast production of fine photographic lenses the present trend is to cut down the time of the polishing process - for economic reasons. This is accomplished by rough-medium-fine grinding with bound diamond grain to within 5 to 12μ of the desired micro roughness. For ecstatic reasons (a better luster of the surface) this operation between 5 and 9μ is normally replaced with the usual fine grinding procedure.

The polishing process demands the highest skill, the most time, and the finest judgement of the master optician. The schematic outline, shown in Fig. 1, indicates the complication of this process. The circles describe the work piece and its direct variables; the ellipses the tool and its variables. The operation of the tool surface upon the surface of the work piece is governed by the machine adjustments (solid rectangular boxes) as well as temperature and environmental effects (rectangles with broken lines). From this consideration, with many possible combinations of variables, it's not surprising that each optical shop, or each optical artisan has adopted his own technique based on experience, intuition, and temperament. Obviously, any standardization of the polishing process demands the understanding and control of each variable, the proper weighing of its effect on the end product, and the optimum linear combination of variables or operations for the best resulting optical surface.

2.2 Loose Grinding and Polishing Compounds

Aluminum oxide (Al_2O_3) and silicon carbide (SiC) are the commonly used abrasive materials for the grinding process. The development of modern polishing compounds containing cerium oxide, a member of the rare earth or lanthanon series, as their active constituent have made the traditional ferric oxide (rouge) less important.

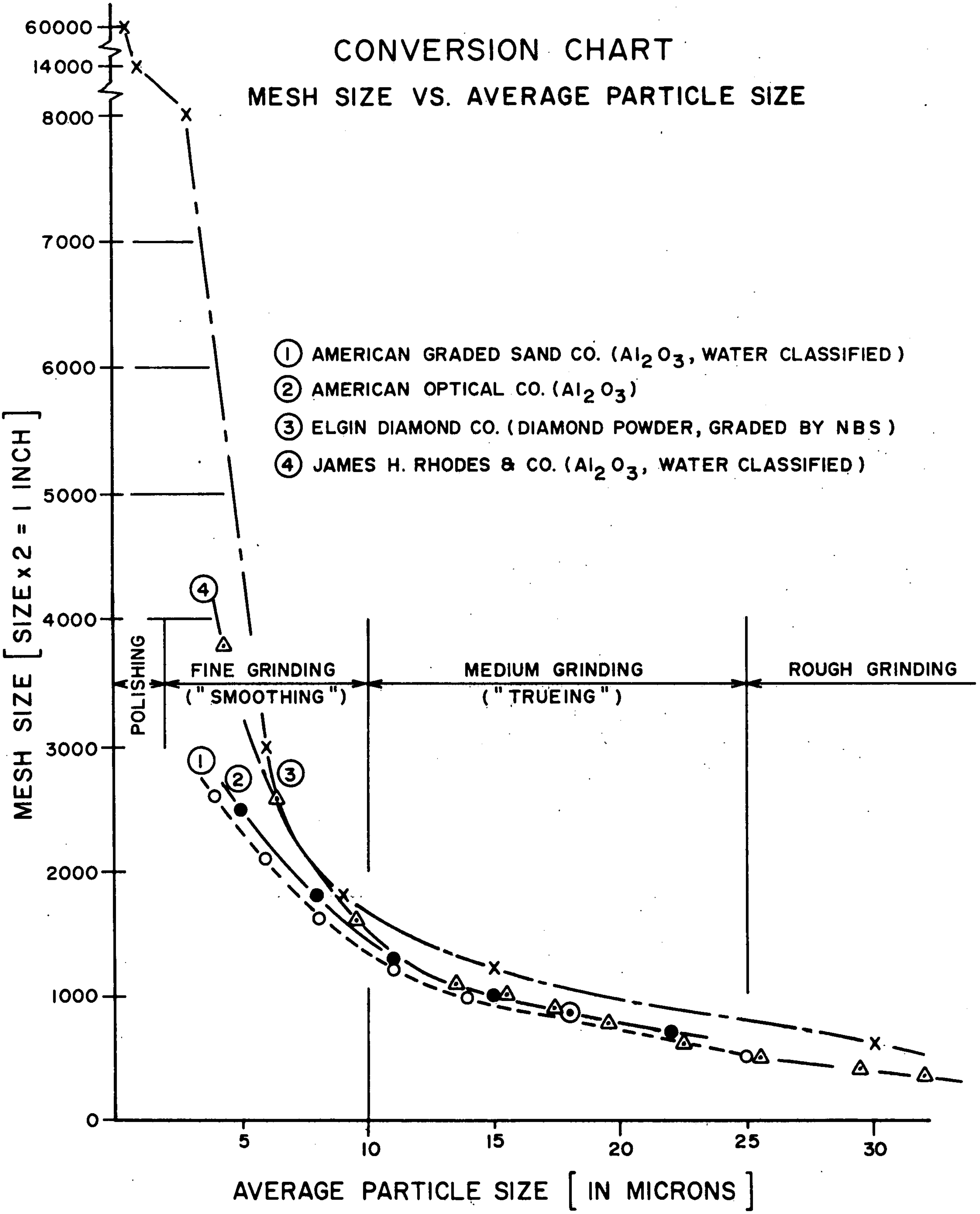
Rare earth compounds. Rare earth elements range from atomic number 57 (lanthanum) through 71 lutenum. They can be separated only with difficulty because of their similar chemical and properties. An exception is cerium (58) which constitutes about 50% of the rare earths in a naturally mixture. BARNESITE is a rare earth oxide type polish in which the rare earths are present in their natural ratio of abundance. It is processed by a proprietary, lengthy technique which makes it very effective for high precision, quality, optical surfaces. The powder particles of BARNESITE are thin, flat hexagonal shaped agglomerates, and fractures thereof, with an approximate diameter ranging from 5 to 15μ and from 0.1 to 0.01μ in thickness. These in turn are composed of small crystallites measuring from about 0.1 to 0.01μ in diameter. It is believed that the honeycomb type structure of the larger agglomerates aids in the polishing process.

"High cerium" polishes are manufactured by increasing the concentration of cerium oxide in the natural mixture. This material generally is less expensive and generates good polished optical surfaces in mass production application faster than it can be obtained with BARNSITE.

Aluminum Oxide (Al_2O_3) is used in two forms one synthetic the other natural. The synthetic form is manufactured by fusing bauxite (hydrated aluminum oxide) in the presence of coke and iron in an electric furnace and is also referred to as Emery. The second type of aluminum oxide is naturally mined in South Africa and is called (natural) corundum. It is preferred because of its crystal structure (rhombohedral hexagonal barrel-shaped crystals with basal cleavage at right angles to the long axis) for the production of optical grinding powders.

Silicon carbide (SiC), referred to in general usage as carborundum, is used primarily for rough grinding; thus average diameters of particles normally used are from 30μ to several hundred. It is harder than aluminum oxide and therefore hardly used for medium grinding (Note that carundum, when capitalized, is a trade name used for silicon carbide abrasives manufactured by the Corborundum Company).

Dimensions of abrasive particles are usually given by mesh size, average size in microns, or by a manufacturers code designation. Mesh size refers to the number of wires per inch in a grit. The spacing between wires equals the diameter of the wire used. For example a mesh size number 1000 refers to 1000 wires per inch with a diameter of 1/1000 inch and a wire spacing of 1/1000 in. Average particle size is the approximate average diameter of the particle in microns (10^{-6} meters). The relationship between the two dimensions is given in Fig. 2. The data was supplied by various manufacturers. Two observations are made. First, there exists a quasi hyperbolic relationship between mesh size and average particle. Second, the average particle for a particular mesh size varies with the manufacturer and is only a rough approximation. Also, it should be relaized that a typical abrasive powder with an "average" size of 9.5μ consists of particles ranging from 4μ to 25μ.



CONVERSION CHART

MESH SIZE VS. AVERAGE PARTICLE SIZE

Three processes are used for the classification of abrasive particle size. One is by shaking the material through a series of grits with different mesh sizes starting with the widest mesh. A second is based on the gravity principle. The material is dropped into a slow-moving water stream at one location and collected at the bottom of the stream in a series of boxes with the heavier (and bigger) particles falling into the box nearest the dropping zone of the undivided material and the lighter (and smaller) particles being carried by the water to a more distant box. A third technique uses the centrifugal force. The material is fed onto a revolving disk surrounded by concentric boxes with the largest particles being forced into most distant box. This technique seems to be the least accurate. Both techniques, the water classification and the centrifugal separation are calibrated in terms of the hopper-grid technique with units of mesh size.

One conclusion may be drawn from the considerations above. The material graded by the individual manufacturer has too wide a latitude in the systematic application of precision optical surfaces. It must be regraded in the optical shop by a statistical microscopic analysis. It seems also reasonable that during the last stages of the fine grinding operation with an average particle size of 5μ the typical 10% presence of 10 to 15μ particles cause scratches on the "smoothed" surface and hence have to be separated.

2.3 Present Theory of Optical Polishing

There is no universal agreement as to the specific behavior of a glass surface during the polishing operation. There are essentially three theories. References 3, 4 (Chapter 1), 5 and 6 discuss these in various depths and cite the literature and investigators. One has to draw his own conclusions from them. One theory of polishing regards it as a thermo-plastic effect smearing out over the whole surface, leveling the micro roughness. Another theory is purely mechanical, removing material by a cutting and planning action. A third theory proposes a complicated super imposition of chemical reactions between the glass surface, the water, the polishing pitch, with physical processes participating only indirectly.

The polishing is most likely a combination of the three theories - with the mechanical especially in its initial stages, dominated by the chemical reactions throughout the polishing action. The thermo plastic effect seems to be the best plausible at the present time as far as glass surfaces are concerned because of the absence of the required large pressures. (Investigations with nonglass optical materials, such as ceramics, have so far been almost non existent).

The polishing process may be described as follows: (1) At the outset the peaks of the rough surface are broken down mechanically leaving the surface with low elevations and the grinding cavities and cracks which extend below the surface. It was shown by multiple beam interferometry that only small shavings, approximately 0.0100μ in diameter, are removed at the time, rather than a rough breakdown as it occurs in grinding. (2) Chemical reactions begin to occur. Glass is hydrolized by water. The alkalines (primarily of sodium or potassium are dissolved by the water and replaced by hydrogen. Thus a layer of silica-gel is formed protecting the surface of the glass against further attack by the water. At first small areas are involved indicated by the small glossy areas which are generated. These areas increasingly are expended until they grow together covering the whole surface. The individual cavities still remaining collect the microshavings which may be hydrolized and other waste from the polishing process. (3) The effectiveness of the polishing compound is not due to the hardness alone but also due to its brittleness and chemical reaction. As the particles of the polishing material break down the fresh fractures exhibit a high level of activity, pushing the silica-gel aside so that water can again attack the fresh glass. (4) As the cavities become progressively smaller they apparently are filled with polishing products consisting mainly of silica-gel. At this stage the surface appears almost perfect but it hides beneath its glossy surface skin all the remaining impurities and cracks in the cavities which can break open upon cleaning. (5) The last stage of the polishing process, consisting of leveling down the cavities with the sound surface to beneath the cracks, requires most of the time with the polishing process getting progressively slower as the desired polishing state is approached.

As in the case of grinding a general statement with regards to the microroughness of the optical surface can be made. The microstructure of the polished surface becomes coarser with increasing hardness of the pitch and finer with increasing hardness of the glass surface.

2.4 Optical Surface Measuring Techniques

The classical tests are described in the literature in detail such as Reference 7 (Section 25). They are straight forward and nothing further has to be said. Those tests which are of interest to the Optical Research Shop at Marshall are mentioned in Chapter 3 of this report. Attention should be called upon a recently developed electronic spherometer (available from the Howard Strassbaugh Co.) because of its accuracy (to 0.25μ) and simplicity.

Modern tests with high accuracies such as the scatter plate, laser unequal path, multipath, phase and hologram interferometers are discussed in detail in Reference 8. Of immediate interest is the scatter plate and laser unequal path interferometer. The first because it can be used conveniently by the optician during the polishing process and does not require a standard optical surface. The latter is suitable for final or acceptance testing, or near the end of the polishing operation because of its sensitivity and accuracy.

Both tests are easily used for testing spherical surface. On aspheric surfaces the required fringe pattern has to be either generated by the aid of the computer and then compared with the test result or a mill lense is fabricated in order to "spherize" the aspheric surface under test.

It is known that measurements of $\lambda/10$ rms and less become more and more subjective in interpretation. The test procedure may be "automated" and make interpretations of fringe pattern more objective with the aid of the computer. The observed fringe patterns is photographed and the interferogram measured with a microdensitometer. A comparator registers the X and Y data on preprogrammed punch cards or are fed directly into the programmed computer. The output data from the computer may be fed into an X-Y recorder resulting in a contour type pattern which represents the actual surface under test.

2.5 Environment for Optical Fabrication and Testing

Fabrication. During the grinding and especially during the polishing operation a constant atmospheric condition is desired. The temperature should be about 75° C and held within 2 degrees, and a humidity of 75%. This seems to give excellent polishing results and prevents the drying out of the abrasive suspension towards the outside of the work piece causing "roll-off". The air surrounding the fine-grinding and polishing operation must be clean. The accidental drop of a dirt particle on a surface being polished can scratch it and fine-grinding has to be re-initiated. Itek Corporation (Reference 10) solved the problem of keeping clean conditions in a large room using an air plenum ceiling in a laminar flow through floor gratings.

Testing. Interferometric tests for accuracies $\lambda/10$ or better require a fixed, static interferogram. Hence the requirements are a vibration-free mounting bench and still air in the optical path. The surest method to achieve this is with a slightly evacuated thermally insulated tank mounted on a concrete block which rests upon Barry mounts. Such test facilities can be found at Perkin-Elmer Corporation and especially at Itek Corporation (References 9 and 10, respectively). Depending on the environmental disturbance, the tests are often performed without vacuum in the vertically erected, cylindrical vacuum steel chambers. Itek and Perkin-Elmer pioneered certain isolation techniques from local vibrations. Low-frequency vibrations are damped by use of springs, and high-frequency vibrations by use of fiberglass mattes molded in plastic. This is less expensive and almost as good as using pneumatic isolators.

For testing massive optics (from 60 inches to 150 inches in diameter) test facilities of the nature described approach 1 million dollars in in cost. To reduce this cost several laboratories (University of Arizona, Kitt Peak National Laboratory, Zeiss-Oberhochen) have recently built test towers with thermal controls (References 11, 12, 13). It will be interesting to study the results of the tests as soon as they become available. One laboratory (Foecker Division of Owens Illinois, Inc.) reports good stability from the utilization of an abandoned mine shaft.

In general, vertical testing is preferred over a horizontal arrangement in massive optics. For a vertical test the mirror with the polishing machine can be moved underneath the test tower; it does not have to be turned. In the absence of vacuum, the horizontal, laminar flow of air in a vertical test tower, vertical cylinder, or mine shaft, being normal to the optical axis, is less disturbing to the observations of test interferomgrams than the air-flow parallel to the optical axis in the horizontal arrangement.

2.6 Optical Machinery and Techniques

Machines. Traditionally, the procured optical machinery is modified by the customer in his optical shop to meet local specifications which have been evolved from past experience and tradition. Consequently, the builders of optical machines have generally not an intimate knowledge of optical surface fabrications. They neither are familiar with the specific, specialized applications of their machines in optical practice because of the largely proprietary nature of optical fabrications. The typical company manufacturing optical machinery is generally small (20 to 200 employees) and dominated by the owner-designer-founder and his family. Among the best known firms are R. Howard

Strasbaugh, Inc. (Reference 14) in the U.S.A. and Wilhelm Loh, Wilhelm Bothner, and Dama Optik, in West Germany (References 15, 16, 17). The optical machine manufacturers generally furnish equipment to fabricate optical surface up to approximately 12 inches. An exception is R. Howard Strasbaugh, Inc., which supplies Draper type polishing machines up to 100 inches in diameter (for about $40,000.00). Large machines are normally designed by the optical surface fabricator and constructed by a competent precision machine shop. That was the method used for the 160-inch diameter Kitt Peak Polisher (Reference 12) and more recently for various large machines by the Astro Division of Zeiss (Reference 13), the latter machines being massive, overdesigned, and stable -- a characteristic of most German machines.

Three main trends in the optical machine industry. First, the emphasis on "automatic" feeder machines; second, the trend to grind fast and precise with fixed diamond abrasives in the form of a cylindrical tool or an assembly of diamond pellets mounted onto a smoothing tool. A third trend gaining momentum and interest is the development of aspheric machines. Although Dama Optik (Reference 17) produced such machines for the last several years, they have not found acceptance in this country. A discussion with Messrs. Spira and Schafer, co-owners and designers, seems to indicate that too high a precision work is asked from their aspheric generator in the U.S., since intrinsically an aspheric machine will be less precise than a spherical generator.

A large, 16 inch diameter, polishing machine for flat optics, with an arrangement of simultaneously sharpening of the polishing tool which is now available from Strasbaugh (Reference 14) may be worth mentioning.

Also the loading of the polishing tool with weights is giving way to pneumatic pressure control in the modern machines, avoiding the "jumping" of the tool if seizure occurs between tool and optical surface, frequently causing damage to the polished surface.

The next major improvement in optical machine design will undoubtedly be in the computer control of the machines. It is doubtful that the traditional manufacturers of optical machinery will initiate this trend because of their technical and financial limitations. While fabricators of high-precision optical surfaces may have the capability of developing such a system, the financial investment does not permit it at the present time. With an average age of the master opticians in the mid-fifties for most large precision optical surface fabricators and a lack of interest in the young for this demanding profession, government support in the development of automatic precision systems may be an answer in the interest of national capability.

2.7 Large Mirrors: Materials, Fabrication and Testing

The principal element of large space telescopes in the future will be mirrors. The surface shape, or the "figure", of these mirrors may be that of a simple sphere, paraboloid, or a curve of higher order. The quality and stability requirements for a telescope mirror in space exceeds at least one order of magnitude those which are presently set for large terrestial telescopes. In space, there is no atmosphere which distorts the wave front before it strikes the mirror and thus obscures the mirror's own imperfection or absorbs the shorter wave lengths that could provide increased resolution for a limited aperture. Hence it is of considerable importance that the shape of the reflected wave front compares with the incident wave front to a very high accuracy. A "figure" accuracy of the mirror surface of 1/40λ is a reasonable goal but applicable fabrication techniques need to be developed. A material of the mirror must be chosen that is dimensionally stable during thermal cycling, vibration, and aging, at least an order of magnitude better than found in any large telescope presently in existence. The future demand of a 120-inch mirror for a space telescope still requires the demonstration of critical areas in optical technology such as precision figuring to λ/40 rms and long-term substrata stability to λ/40 rms for mirrors of that size.

2.7.1. Materials

Instability of mirror dimensions may be thermally induced (by thermal gradients and inhomogeneous coefficients of thermal expansion), and by the spontaneous release of stored (chemical and mechanical) energy. Hence, low thermal expansion and/or high thermal conductivity as well as homogeneity is required for the first cause, and control of phase changes, processing procedures, and mechanical work for the latter. A high stiffness-to-weight ratio is also of primary importance for orbiting space telecsopes, as well as the availability of large-diameter mirror blanks.

The material for the largest known mirror, 160 inches in diameter, which is presently being completed by Kitt Peak National Laboratory, is fused quartz. The fused quartz blank, supplied by the General Electric Company, is constructed by fusing small hexagonal segments (ingots) of Brazillian quartz together. This material is becoming obsolete now with the introduction of "zero coefficient of expansion materials": In the U.S.A. Owens-Illinois, Inc. developed "Cer-Vit" and Corning Glass Works "ULE" (Reference 1. p. 195 and p. 241; Reference 18). In West Germany Schott contributed its "ZERODUR" (Reference 19). Ohara from Japan is also marketing a similar mirror material (Reference 20). The materials are all ceramics (polycrystalline) with the exception of ULE which is glass containing titanium silicate.

Besides the obvious advantage of retaining the shape of the surface over a wide range of temperature, "zero coefficient of expansion" material is efficient from the optician's point of view; it does not require stabilization time between polishing and testing. From the material manufacturer's point of view, it is highly desirable because the cooling or annealing time is drastically reduced from "non-zero coefficient of expansion" glasses. For example, it took 11 long months of careful slow cooling for the Palomar 200-inch Pyrex blank to relieve the internal stresses that could fracture the blank or make it very unstable.

Stiffness-to-weight ratio of the ceramic materials can be increased by the removal of approximately 80% of the material from the solid mirror blank with machine coring operations. ULE light-weight blanks, being glass, can be constructed by fusing ribs and spacers onto a thin optical surface.

Perhaps the most complete and up-to-date information on traditional, new, and possible future mirror blank materials is given in Reference 21. In the traditional category are Pyrex, Fused Silica, Beryllium, Aluminum and Invar. New materials are ULE glass and the ceramic Cer-Vit. A possible future material may be Silicon which exhibits the best compromise for meeting the ideal physical requirements.

2.7.2 Fabrication

Special techniques are required for fabricating mirror blanks above 90 inches in diameter. A simple extrapolation of procedures and techniques from smaller work pieces (say 6-12 inches in diameter) is usually not applicable. Gravitational forces and size require special handling procedures, and massive machinery. Mistakes can be costly in manpower and material.

Perhaps the most detailed account of figuring large mirrors is described by the Optical Sciences Newsletters of the University of Arizona in Tucson during 1967-1969. Of particular interest is the "diary" given in figuring the 90-inch primary mirror of the Steward Observatory. This mirror was fabricated in the Optical Sciences Center by Don Loomis, Chief Optician, and his colleagues under the direction of Dr. A.B. Meinel (Reference 22).

The mirror blank was fused quartz aupplied by the General Electric Co. (While this material is now becoming obsolete, most techniques described are applicable to the currently favored ceramic materials described elsewhere). It had a diameter of 90 inches and a thickness of 13 inches and a weight of 5000 lbs. A 100-inch Strasbaugh type Draper machine (Reference 14) was used for cutting of the central hole (78 inches in diameter), for generating the outer edge and for shaping the front and back surfaces. The polishing process took approximately one year, with another year for preparation, rough and fine grinding operations. Further details are given in the Appendix.

Techniques for mounting the 150-inch mirror blanks (one for Kitt Peak, the other for Cerro Tololo) onto the surface of a grinding table via piston pads are described by Norman Cole, Chief Optician, Kitt Peak National Observatory, on page 20 in Reference 1 (also Reference 23). Others are described on page 20, Reference 1. This reference also discusses large ring-shaped tools for polishing out "zones." Another technique is employed by Don Loomis using a small conventional polishing tool with almost zero eccentric stroke and rapid table motion (Reference 22).

2.7.3. Testing

The optical surface is tested by interferometry with the scatterplate and the laser unequal path interferometry (LUPI) technique mentioned previously.

2.8. Principal References

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   A workshop held at Marshall Space Flight Center, Huntsville, Alabama, April 29-May 1, 1970; NASA Report SP-233, Library of Congress Cat. No. 79-605809. This is a comprehensive discussion on the use of space telescopes in observational astronomy, a review of current technical status, on materials, figuring and optical design, and instrumentation.

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9. The Perkin-Elmer Corp., Optical Systems, Norwalk, Connecticut.
10. Itek Corporation, Optical Systems Division, Lexington, Massachusetts 02173.
11. The Optical Sciences Center, Univeristy of Arizona, Tucson, Arizona 85721.
12. Kitt Peak National Laboratory, Tucson, Arizona 85721.
13. Carl Zeiss, 7082 Oberkochen/Wurtt., West Germany.
14. R. Howard Strasbaugh, Inc., 3400 Airport Way, Long Beach, California 90806.
15. Wilhelm Loh, H.G., Friedenstrasse 16, 633 Wetzlar/Lahn, West Germany.
16. Wilhelm Bothner, Maschinen und Zahnradfabrik,* 3301 Stockheim bei Braunschweig, West Germany.
17. Dama Optik*, Riedstrasse 10, 61 Darmstadt, West Germany.
18. Dr. George A. Simmons, Owens-Illinois, Inc., Toledo, Ohio. Private communications and on-site inspection of facilities.
19. Dr. Jurgen Betzold, Mr. Dieter Anders, Jenaer Glaswerk Schott Gen., Mainz, West Germany. Represented by Schott Optical Glass, Inc., Duryea, Pa.
20. OHARA (Japan), represented by Bourns, 2424 Morris Ave., Union, N.J. 07085
21. LARGE TELESCOPE EXPERIMENT PROGRAM (LTEP), Perkin-Elmer Engineering Report No. 9800, Vol. I, Part 2, pp. 587-600, prepared for NASA under Contract NAS 8-21497, by the Optical Group, Norwalk, Connecticut, April 24, 1970.

22. Dr. A.B. Meinel, Director; Mr. Don A. Loomin, Chief Optician, The Optical Sciences Center, Univeristy of Arizona, Tucson, Arizona.
Private communications and inspection of facilities.

23. Mr. Norman Cole, Chief Optician, Kitt Peak National Observatory, Tucson, Arizona.
Private communications and inspection of facilities.

APPENDIX TO CHAPTER 2

Fabrication Procedures of a 90-inch Mirror

The inner core of a 90-inch diameter, fused silica blank was removed with a biscuit-cutter shaped rolled sheet steel tool (and took 35 continuous hours). For inspecting the inner-face fusion of the hexagonal cores, the outer edge of the mirror was ground with a perforated metal band and fine ground (smoothed) with #220 carborundum #F aluminum oxide, and #12 microgrit. It was polished with 4-inch Pellon disk, waxed on two-sided backing tape onto the metal grinding band. Unmilled Barnesite which was thoroughly wetted down was the polishing compound.

The surface of the 90-inch mirror was now rough-ground on the same 100-inch Strasbaugh machine to a radius of roughly 500 inches. In preparation for fine-grinding and polishing the machine table of the 100-inch machine was ground concave (to compensate for a calculated 0.0037 inch sag) with a tool using 9-inch-square clay tile. The mirror was placed upon the table with its backside up and ground with the same tool to 30 micron abrasive in order to match the table surface with the back surface of the mirror.

The mirror was turned face up resting on doughnut-shaped rubber pads positioned for equal weight distribution on the machine table. The grinding process was accomplished with a full-sized (90-inch diameter) tool consisting of 4-inch-square beveled clay tiles which were secured with a beeswax-and-rosin combination. The tool had initially no eccentric motion. When approximately 40% of the tool surface made contact with the blank, a stroke of 2 inches was used. A pneumatic airlifting device relieved 1200 lbs. of the downward force of the tool weighing 2300 lbs.

Grinding was started with 100 mesh silicon carbide. The fine grinding technique consisted of using Aluminum Oxide 30μ and 12μ consecutively, the 30μ to seat the tool onto the glass followed by flushing 12μ abrasives between the tool and the glass (without cleaning up or taking the tool off). The 30μ material was then washed toward the center hole and collected, leaving the 12μ material uncontaminated. The grinding operation was stopped when the figure was within 1/16 inch of the desired value. The longer a full-sized tool is used for polishing, the more symmetric and smooth the mirror surface will be and the fewer ring zones are found.

The 90-inch polishing tool was similar to the grinding tool. Squares 4 x 4 x 5/8 inch were fabricated from a hard pitch substance (a formula similar to that used on the 200-inch Mt. Polmar mirror and supplied by D.O. Hendricks of Mt. Wilson Observatory) and mounted singly on the 90-inch tool with a mixture of zylene and asphalt and a small hand torch. The polishing compound was a combination of cerium oxide and barnesite. After each polishing run the mirror was rotated 92° with respect to the table to avoid astigmatism. The mirror was aspherized by using a short stroke and a considerable overhang of the tool while the mirror blank was rotated rapidly.

3.0 THE OPTICAL RESEARCH SHOP

3.1 Present Status

The distinguishing characteristic of the Optical Research Shop at MSFC over similar facilities elsewhere is the extraordinary skill and the unusual background of the personnel with a unique sense for improvisations. This is mandatory for a wide variety of precision optical work. Improvisations may be taken too far, however, when they are applied to ordinary standard procedures.

3.1.1 Qualification of Personnel

There are trends, at the present time, to define the master optician in terms of the quality of the product he creates. A qualitative definition of the skilled optical technician contains various intangibles. Patience, experience, analysis and an active intuitive mind are perhaps the salient prerequisites for precision optical fabrication. Patience is required because most of the work requires detailed attention to tedious and dull tasks often compounded with recurrent disappointments. Experience, analysis, and intuition will permit the master optician to continually adapt and improvise techniques to cope with the variables as outlined in Figure 1. For example, small changes in atmospheric conditions may severely change the characteristics of the polishing tool, the polishing compounds, and surface conditions of the optical work piece.

Each man in the Optical Research Shop at MSFC has demonstrated the salient prerequisites for precision optical fabrication. Patience, analysis and an active intuitive mind were fundamental to their past accomplishments. The diverse professional experience of the personnel in the Optical Research Shop is unusual when compared to similar facilities elsewhere. Most men average 8 to 10 years experience in related specialized lapping and finishing work and 10 years as precision tool and instrument makers; others have 6 to 12 years experience in vacuum deposition with various materials. All of them have been engaged in the fabrication and measurements of unusual optics of the highest precision for the last 4 years.

Conspicuously absent is an apprentice position. In view of the vast experience present and the fact that the youngest man is in his forties, a talented young man (or two) could profit professionally as well as transfer the present knowledge to future demands at MSFC.

3.1.2 Optical Procedures

Unusual and difficult optical procedures are generally not discussed in the literature. It is here where the master artisan has to rely on his own resources -- intuition, common sense, improvisation -- because each task demands either a new technique or a variation of a previous one. The men in the Optical Research Shop are comfortable in such demanding situations because there qualities have been fundamental to their professional history. Their tasks have often been almost impossible. Usually the proper tooling and equipment was either not available or was not made available to them, and the lack or required environmental facilities did not and still do not exist for them to perform their demanding tasks. In spite of these difficulties, many unusual projects were successfully completed due to their patience, intuition, common sense, and especially because of their talent of improvisation.

It is natural that the same painstaking and demanding attention is

also given by these men to *conventional* and *less difficult* optical procedures where it is not necessary. The standard procedures *are* available from the literature as shown in the Reference Section of the previous chapter and can be adopted with minor modifications. The precision to non-precision work is uneconomical with respect to their valuable time and leads to gross inefficiencies. For example, efforts should be made to routinely fine-grind down to about 5μ to complete the "figure", and then polish the optical surface. Yet because of inadequate environmental facilities, tools, abrasives and/or procedures, the fine-grinding operation is stopped with 11μ diameter abrasives, followed immediately by the polishing process which is long and slow and is directed primarily towards *polishing* the optical surface, and not the *"figuring"* of the surface.

If the techniques applied to the fabrication of unusual and difficult optical pieces, which vary from man to man, should ever be resolved in terms of "standard" procedures -- procedures for conventional and less demanding optics must be established first in the Optical Research Shop at MSFC.

3.1.3 Equipment, Tools, and Measuring Instruments

The optical machinery is the same found in most optical shops up to 12 inch diameter work and perhaps even up to 36 inch. In optical research however it is desirable to have additional accessories to the machines such as an independently driven tool with variable speed and a pneumatically applied variable pressure between the tool and the work piece.

The tools available are not even sufficient for an ordinary optical shop. For example, cast iron tools with proper diameters and face patterns for fabricating optical flats are urgently needed.

The additions of the recently acquired LUPI instrument and the in-house designed and constructed scatterplate interferometer establish measurement capabilities beyond those normally found in optical shops; although accessories need to be added in order to extend their usefulness, such as a spherical test mirror for testing large flats, corrector plates for simplifying aspheric surface measurements, as well as automation techniques for reducing the data of the interferogram.

The usual complement of instruments for measuring spherical surfaces, smaller flats (up to 10 inches in diameter), radii (up to 24 inches in diameter), and lenses (up to 5 inches in diameter) are available.

3.1.4 Optical Supply

Very little is known about the quality, the calibration, and the consistency of the optical abrasive compounds presently used. There are indications that MICROGRIT (aluminum oxide manufactured by the Micro Abrasive Company, Westfield, Mass.) is a superior quality to the aluminum oxide presently used.

3.1.5 Environmental Facilities

Environmental control is substandard and would be inadequate for most ordinary optical operations. There is no temperature control, humidity regulation, nor is there a dust filtration system. (Wastebaskets are regularly cleaned by the custodian 3 feet from the polishing operation!). While some initial efforts have been made recently along these lines, much more has to be done to create desirable laboratory conditions.

The measurement environmental controls being built presently for interferometric measurements are as good or superior to similar facilities elsewhere (a vacuum tank 30 inches in diameter and 30 feet in length, thermally insulated, mounted on a heavy concrete block which is vibrationally isolated with pneumatic cylinders (Barry mounts)). The existing tower for measurements can easily be modified and may serve for testing larger optics to perhaps λ/10 or better.

3.1.6 Technical and Management Support

Up to now there has been sporadic direct support from within the optical research section and contractors; a more consistent program is being worked out. A major weakness seems to be the lack of opportunity the men have to make on-site visits and to discuss technical problems with colleagues from other institutions due to a lack of travel funds. The nature of their work and responsibility demands frequent exchange of ideas.

While the overall direction and planning from the branch and division levels are excellent, the fact that there is no section chief who is the direct leader of the Optical Research Section leads often to unnecessary misunderstandings, inefficiencies, and confusions.

3.1.7 Accomplishments

The accomplishments ranging from fabricaiton of a precision x-ray lens to a standard optical sphere for the National Bureau of Standards, in spite of the lack of desirable facilities, tools and materials, speaks for the unusual skill, experience and intuition of the optical technicians at MSFC. The quality of the completed products may serve as a quantitative definition of the skill of the men. How many more projects could be accomplished, at a fraction of the time spent, with the help of these unique men if they could work in more favorable conditions?

3.2 Recommendations and Implementations

No major problems exist to implement basic procedures, environmental facilities, equipment and tools to define those variables which can and should be controlled -- and constrain others which are less tangible. Only then real laboratory conditions can be established to perform significant R & D work in the Optical Research Shop.

The problem of implementation is not a major one, primarily because of the unusually skilled manpower, the available technical support, and the management support discussed previously.

3.2.1 Objectives - Immediate and Long-Range

The immediate objectives should be the improvement of the environmental conditions, procurement of essential equipment and tools, quality control of optical supply and the establishment of basic shop procedures. These areas are discussed in more detail below.

The intermediate objectives are the automation of the polishing and measuring operations as delimeated in the first chapter.

The long-range objectives are to apply the above to massive diffraction-limited optics - up to 10 feet in diameter.

3.2.2 Improvement of the Environmental Conditions

Separation. The present separation of the facilities for rough grinding from the medium, fine-grinding, and polishing operations should be divided further in order to separate the medium-grinding from the fine-grinding and polishing facilities. The latter operations demanding more stringent environmental requirements are extremely sensitive towards contaminations due to rough abrasive particles.

Temperature control for the fine-grinding and polishing room require a temperature of 75° ± 30 F. This level is held in most precision optical shops.

Humidity should be at approximately 75% for fine-grinding and polishing.

Dirt particles should be controlled with a filter system, the optical technicians should wear "fine-grinding and polishing" coats, and under no circumstances should it be tolerated to transfer trash from wastebaskets to collective trash containers in the "clean room" where polishing and fine-grinding take place.

Modifications. Less stringent environmental conditions may be achieved by providing the separate machine(s) with an individually controlled atmosphere.

3.2.3 Desirable Equipment, Tools and Instruments

Equipment. For the control of certain polishing variables the optical machines should be equipped with an independent speed-controlled drive for the tool as well as a pneumatic pressure control device, or something similar, to guarantee an equal and constant pressure distribution upon the optical surface of the work piece.

Tools. Separate tools for rough-, medium- and fine-grinding are mandatory in order to be able to fine-grind down to 5μ. For example, in order to fabricate precision flats three cast iron tools are required for each of the sizes from 6 inches to 18 inches in diameter: one for rough grinding (22μ abrasive), another one for medium-grinding (11μ to 8μ abrasive), and a third for fine-grinding (5μ abrasive). This is suggested to prevent contamination of the finer grains with coarse ones from the previous operation.

Instruments for measuring spherical surfaces may be supplemented with a recently developed electronic spherometer (R. Howard Strasbaugh, Inc.), measuring down to 10^{-5} inches, because of its versatility, accuracy, and ease of use.

For measuring paraboloidal surfaces, correction plates are required for the Focault and Ronchi tests, and the scatterplate and laser unequal path interferometers. For measuring optical flats to 40 inches in diameter, a Hindel sphere is required. Once these additions are made, attention should be given to automatic data reduction so that the interpretation of the interferograms by the measuremtnt experts which can often be subjective, can be replaced by routine measurements taken by less qualified people.

3.2.4 Quality Control of Optical Supply

It is necessary to control the quality of the abrasive powders. First, the present source of aluminum oxide should be replaced with the Micro Abrasive Company, Westfield, Mass., which manufactures a better grade under the trade name of MICROGRIT. Second, the abrasive powders should be regraded in house. A simple traditional method is letting the suspension in a beaker settle for a fixed duration of time. The heavier particles gravitate towards the bottom and the lighter ones, still in suspension, can be poured off. Third, the fine abrasives (8μ and less) should be applied with a fine brush instead of a squirt bottle, again reducing the probability of using a stray, coarser grain during the finer and more critical operations. Fourth, it may be necessary to photograph samples of the abrasive powders and make a microscopic statistical analysis to constrain fabrication variables which are introduced by the quality of the optical abrasive powders.

3.2.5 Education Program

Individual Growth. It is wasteful and unsatisfying to attempt to train each of the skilled men to become an expert in every far-out specialty of precision fabrication. It is desirable for each worker to have a broad background, but also a specialty, which is then his professional responsibility for growth in depth and width. For example, every optical technician should be able to fabricate and test an optical flat say to λ/4 accuracy. But only one or two should concentrate on producing flats to accuracies of λ/40 and better and maintain that specialty and grow professionally in it.

Professional Exposure. A profession which is still primarily based on individual techniques and experience with changing demands and with little or no recording in the literature requires a constant transfer of knowledge. This may be accomplished in three ways. First, by periodic (monthly) internal discussions and reports. Second, by inviting appropriate experts to a workshop symposium at MSFC, such as personnel from the optical research shops at Frankford Arsenal, Kitt Peak National Laboratory, and the Optical Sciences Center of the University of Arizona (whose opticians are Ed Tumasz, Norman Cole, and Don Loomis, respectively). Such sessions may be organized via the NASA Training Branch, the University of Alabama in Huntsville, or internally. Thirdly, opportunities should be provided for the optical technicians to visit their counterparts in other optical facilities for mutual exchange of ideas as well as follow the progress of unique optical projects. These areas of activity are important for the maintenance of professional growth and leadership.

3.2.6 Fabrication and Test Procedures

Procedures for fabrication and test operations must be established for the sake of efficiency, transfer of knowledge, management guidance, and for providing the necessary base from which to expand into areas of more difficulty and sophistication. These procedures should represent a common denominator among the experts in the Optical Research Shop and from established techniques elsewhere. This may be accomplished as a result of the previous section or by a topic-oriented discussion among the workers, with inputs from other optical laboratory facilities. A "base line" for a particular operation can then be determined and recorded by the men themselves. This would assure the adherence to such "basic" procedures. At no time, of course, is it suggested that the "rules" do not permit deviation. They would furnish, however, much needed guidelines.

3.2.7 Recommended Experiments

Efficient and systematic techniques are required for the generation of optical surfaces which are of high geometric precision and excellent microstructure quality (for low scattering). The following should be examined with respect to the above objectives:

Tools. Examine the design and effectiveness of medium- and fine-grinding tools made of diamond pellets, cast iron, glass, zero-expansion ceramics, ceramic tiles, and marble. Test conventional polishing tools with various pitch formulas, investigate the possibility of using polishing compounds frozen in ice as a polishing surface as suggested by the chief of the Optical Research Shop.

Techniques. Investigate the effect of facettes, ratio of tool size to size of work piece, tool motion and pressure. Develop techniques for generating precision flats similar to the aspheric techniques at the University of Arizona.

For "figuring" large ashperic surfaces comparisons should be made between "the no-stroke technique" used by the Optical Sciences Center (University of Arizona) and the ring tool technique" proposed by the Foeker Division of Owens Illinois Inc. (p. 149, Reference 1). The no-stroke technique incorporates a small (6 inches in diameter mirror blank being rotated at 140 rpm. The stroke length varied between 1/4 to 1/2 inch and made ponted zones 2 inches wide, especially at low f-ratios. The latter technique apparently accomplishes the same but with ring-size tools coinciding with the diameter of the selected zone.

Another area of investigation is the desired degree of concavity of a "flat" (3λ?) prior to fine-grinding and polishing to compensate for roll-off effects.

Materials. Determine the sensitivity of the variables if identical polishing procedures are followed on Cer-Vit and Zerodur ceramics, fused silica, and Pyrex; observe the effects of environmental variations.

Conclusion

The principle asset of the Optical Research Shop at MSFC is the unique qualification of the personnel. While additional equipment, improvement of environmental conditions, and the introduction of professional procedures, it should be second to none. The unoccupied position of the section chief in the Optical Research Section may be the only obstacle for reaching the desired objectives.