Research and Development in Applied Optics and Optical Glass at the National Bureau of Standards

A Review and Bibliography



United States Department of Commerce

National Bureau of Standards

Miscellaneous Publication 194



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National Bureau of Standards Miscellaneous Publication 194 Issued July 15, 1949

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Price 15 cents

Contents

I.	Introduction
II.	Optical instruments and optical systems
	1. Refractometry
	2. Range finders
	3. Lens design
	4. Photographic lenses
	5. Optical shop
	6. Testing of optical instruments and systems
	7. Services as consultant
III.	Optical glass
	1. Slip-casting of clay melting pots
	2. Effect of composition on the optical properties of glass
	3. Annealing of optical glass
	4. Measurement of physical and optical properties of glasses
	5. Chemical analysis of glass
	6. Chemical durability of glasses
	7. Defects in glass
	8. Transmission of radiant energy
	9. Consulting and advisory services
	10. Testing and specifications
IV.	Bibliography of Bureau publications
	1. Optical instruments and optical systems
	(a) Photogrammetry
	(b) Photographic objectives
	(c) Design and construction of optical instruments
	(d) Testing and use of optical instruments
	(e) Miscellaneous papers on optical instruments
	(f) Refractometry
	2. Glass
	(a) Methods of manufacturing optical glass
	(b) Effect of composition on optical properties
	(c) Annealing
	(d) Measurement of physical and optical properties of glasses.
	(e) Chemical analysis of glass
	(f) Chemical durability of glasses
	(g) Transmission of radiant energy
	(h) Miscellaneous

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Development Optical Glass at the 1 of Standards

Bibliography and C. H. Hahner

relopment work in technological optics that i Standards. Noteworthy accomplishments i 70-inch optical disk (at the time of manu-Ohio Wesleyan University; a comprehensive tion and index of refraction of optical glass; erature and index; the design and construcfocal length which resolves railroad ties and miles; the design and construction of large poratory for testing range finders and similar ning to optical glass and optical instruments

is included.

I. Introduction

Optical instruments include not only those instruments developed for making observations or measurements within the field of optics but also numerous devices which serve as tools in other scientific work and for commercial and military applications. Within the first group, many of which have found important commercial uses, are spectrometers, polarimeters, interferometers, refractometers, and diffraction gratings. In the second and much larger group are astronomical telescopes, microscopes, binoculars, surveying instruments, motion picture projectors, airplane camera lenses, bomb sights, and range finders. An outstanding characteristic of optical instruments is the high precision necessary in their operation. This requires not only extremely accurate design and construction of all optical and mechanical parts but also the development of different types of optical glass each having a specified index of refraction within a very close tolerance while at the same time homogeneous and free from flaws, chemically and physically stable, highly transparent, and colorless.

The National Bureau of Standards, since its founding in 1901, has carried on a broad program of optical research and development which has led to the solution of many problems of interest to Government agencies and private industry. This work has included the development of technological processes for the production of optical glass, the study of the properties of optical materials, the maintenance of optical standards, the design of lenses and optical systems, the production of prototype optical instruments, the determination of performance characteristics, the devising of methods for testing and calibration, the preparation of specifications, and complete consultant service.

In both world wars, the requirements of the Armed Forces for optical fire-control instruments resulted in a tremendous expansion in domestic production of optical glass and optical instruments. Many new instruments, new optical glasses, and new processes for optical glass manufacture were developed. Indeed, the peacetime requirements for precision optical instruments are almost negligible in comparison with the need for military optical instruments in wartime. Moreover, the demands made on industry for the production of nonmilitary optical instruments are relatively stable, as the required characteristics of the various instruments do not change greatly within short periods of time. In military optical work the reverse is true, and the necessity for specialized laboratory research is correspondingly increased.

In view of the apparent need in this country for a continuing, integrated program of research and development in optical science, the National Bureau of Standards, with the cooperation of the Armed Services, has conducted a coordinated series of projects basic to the production of all types of optical instruments, with special emphasis on military fire-control devices. The National Bureau of Standards is particularly well fitted to render such service inasmuch as it is the only scientific institution in the world which has, entirely within its own organization, complete facilities for making an optical instrument beginning with the raw materials and producing in turn the glass, the optical design, the lenses and prisms, the mechanical parts, and finally the finished instrument. The greater part of this highly specialized work is done in the Bureau's Optical Instrument Laboratories, Optical Shop, Glass Technology Laboratories, and Optical Glass Plant. However, valuable assistance is frequently received from sections of the Bureau concerned with such diverse fields as chemical analysis, refractories, mechanical instruments, photographic technology, interferometry, spectroscopy, radiometry, photometry, colorimetry, automatic computing, and electron microscopy.

The scope of the optical program at the National Bureau of Standards may be indicated by examples of representative projects. Experience gained in basic research on the theory and methods of lens design has been applied in designing a large number of lenses required by other Government agencies. The Bureau has also established procedures for measuring and specifying the characteristics of photographic lenses, particularly those used in aerial photography. For the assistance of industrial and commercial laboratories, methods of high-precision refractometry were developed, and standards of refractivity set up. During the last war, a specially designed laboratory for the development and testing of range finders was completed, and other military optical fire-control instruments, as well as devices for testing them, have been designed and developed. Very large optical elements, required for supersonic wind

In the sections which follow, the more important phases of the work of the National Bureau of Standards in the fields of optical instrumentation and optical glass are listed and briefly discussed. These investigations have led to nearly 200 publications by members of the Bureau staff, which are given in a bibliography at the end of this paper. References to the bibliography are made in the text by means of numbers in parentheses.

II. Optical Instruments and Optical Systems

The work at the National Bureau of Standards on refractometers, range finders, lens design, and photogrammetry, because of its extent and importance, will be discussed in special sections which follow. Investigations of a general nature related to all optical instruments have involved a study of resolving power (45); the preparation of standard resolving-power charts with instructions for their use in testing camera lenses (12, 13); the publication of detailed instructions for the production of mirrors by chemical deposition of silver on glass (24); and the development of an interference method, based on the Hartmann test, for determining the aberrations of an optical system (47, 55).

A number of instruments have been developed for special purposes. Among these are an optical coincidence gage for measuring small distances (25, 57), an instrument for machining spherical surfaces of long radius such as are required for grinding and polishing lenses (27, 37), a camera for photographing the interior of a 30-caliber service rifle barrel (34, 56), an optical system for

indicating galvanometer deflection (35), spherometers, a camera lucida, a magnifying stereoscope (4), a field telemeter (32), an anallatic telescope, and an optical instrument for measuring the wall thickness of a compressed gas container (36). The Bureau has also built an interferometer with a 4-inch aperture for testing optical components or the homogeneity of optical materials, and construction of a much larger one is almost complete. Other instruments designed and built at the Bureau for its own testing needs include a special precision camera for testing airplane camera lenses and cameras (10), an instrument for testing 12-inch plane surfaces interferometrically over the entire surface at one time, optical benches (18), an optical spherometer, and many smaller instruments.

1. Refractometry

The growth of refractometry in the United States dates from the sudden demand for precise knowledge concerning the optical constants of the optical glass (77, 82, 83, 89, 114, 116, 119) that



FIGURE 1. Coincidence prism.—an important element in range-finder accuracy—constructed by cementing together a number of smaller prisms made from optical glass produced at the National Bureau of Standards.

The optical range finder, used by the Armed Forces to measure the distance from an observer to a target. is one of the most intricate and costly of optical instruments.

was manufactured in and after 1917. Instruments for measuring refractive index were soon being produced in this country; their use increased rapidly in chemical laboratories and spread to technical applications in the sugar, oil, soap, drug, paint, ink, food, and other industries. The National Bureau of Standards was then called upon to test refractometers (81, 85), to formulate standard performance requirements for these devices, and to measure refractive indices of transparent media.

To properly perform these services to industry and other Government departments, the Bureau has found it necessary to develop methods of highprecision refractometry (70, 77) in order to establish working standards of known refractivity (83). Use of water as a precise standard liquid in this work was made possible by measurement of its index of refraction over a broad range of temperature and wavelengths (74, 78, 79, 80).

Chemists engaged in petroleum research identify and determine the purity of hydrocarbons from measurements of refractive indices for several wavelengths. To aid in the attainment of higher precision and accuracy (81, 85) in such measurements, the Bureau has provided three standard samples of hydrocarbons—2,2,4-trimethylpentane, methylcyclohexane, and toluene—of known



FIGURE 2. A temperature-controlled test chamber at the Bureau makes possible the complete analysis of range-finder performance under conditions corresponding to a wide range of climate.

The operator, wearing an aviator's insulated suit for work at low temperature, is viewing a simulated target at 90-degree elevation through the oculars of a range finder under study. Targets at eight apparent ranges for elevations from 0 to 90 degrees are produced by a specially designed collimating system above and behind the range finder. The control hoard at the operator's right permits changes in range, elevation, and other settings.

high purity, for which the indices of refraction for seven wavelengths are certified to five decimals.

2. Range Finders

The range finder is one of the most complex optical instruments thus far developed. In this instrument, the number of residual errors which remain to be corrected is so large, and the individual errors so small and so nearly equal in magnitude, that it is quite impossible to separate and identify them from observations of terrestrial targets. Therefore, in development work for improvement of range-finder performance, these residual errors must be studied separately in the laboratory with adequate control of all environmental conditions such as temperature, exposure to directed radiation, and orientation with respect to the gravitational field.

The National Bureau of Standards has therefore built a special range-finder testing laboratory (fig. 2) under the sponsorship of the Army Ordnance Department (41). Equipped with a precision collimator system which optically simulates a target for eight different ranges at any desired elevation, this laboratory—the only one of its kind in this country—provides for testing under conditions corresponding to a wide range of climate and permits the complete analysis of the behavior of a range finder with a thoroughness and facility impossible with outdoor targets.

To obtain the necessary precision, the apparatus must produce two collimated beams separated by the base length of the range finder $(13\frac{1}{2}$ to 15 feet) and departing from parallelism by an angle differing from a preassigned value by not more than one-half second. This precision must be independent of large temperature variations and movements of the apparatus to vary the apparent elevations of the target. Such rigorous requirements have been met by mounting the collimator instrument in an insulated chamber which can be maintained at any fixed temperature between 0° and 100° F or subjected to a given rate of temperature change. Directed radiation comparable to that received from the sun under service conditions is simulated by a cylindrical mirror of paraboloid cross section extending the length of the range finder. Environmental conditions are thus under complete control at all times.

Range finders of foreign origin and improved prototype models, as well as those in use by the Army and Navy, have been tested in the new laboratory under a wide variety of conditions (53).



FIGURE 3. One of the first airplane camera lenses that permitted individual railroad ties to be distinguished at an altitude of 10,000 feet (fig 4).

This f/6.3 lens of 50-inch focal length was entirely a product of the National Bureau of Standards, from the manufacture of the glass to the design of the optical system and the construction of its component parts.

As a result of this work, it has been possible to clarify the many different types of error to which a range finder is subject (50, 51, 52). Quantitative studies of the errors have led to their correction or compensation. Individual components of range finders have been tested separately to determine their contribution to over-all performance, and improved components having reduced errors have been developed. Range-finder design has thus been placed on a sound engineering basis, and the paths along which future development should proceed have been clearly indicated.

3. Lens Design

Research on the theory and methods of lens design has been conducted at the National Bureau of Standards for many years (22, 28, 33). As early as 1927 the Bureau published a 125-page comprehensive treatment of the algebraic methods of applying the third-order aberration equations to lens design (23).

Lens designs required by other Government agencies have been provided on request (29, 31, 40). Notable designs completed at the Bureau include a telephoto lens system of 20-foot focal length and 9-inch aperture for photographing the solar corona (38, 39, 68, 69), an f/6.3 airplane camera lens (fig. 3) of 50-inch focal length, and an f/5 airplane camera lens of 40-inch focal length. The f/6.3 lens was one of the earliest airplane camera lenses of World War II which permitted individual railway ties to be distinguished from an altitude of 10,000 feet (fig. 4). Among other Bureau designs are sighting systems for airplane armament, refracting systems with aspheric surfaces, and Schmidt-type cameras with correcting plates consisting of a combination of spherical and aspheric surfaces (42).

4. Photographic Lenses

Immediately after World War I, the Army Air Corps submitted several captured German airplane camera lenses to the National Bureau of Standards for investigation (8, 9). Shortly thereafter, the Government mapping services and the military agencies became interested in photogrammetric methods, by means of which both cadastral and topographic maps can be made from airplane photographs. From this early beginning until the present, the importance of this branch of engineering and of the Bureau's participation in it have continuously increased.

An airplane camera lens, to be suitable for photogrammetric purposes, must have good resolving power and little or no distortion over the entire field. The Bureau therefore undertook the development of methods for measuring and specifying these characteristics (1, 2, 3, 5, 6, 11, 14, 15).

The measurement of distortion in a lens as the linear displacement of the image point from its distortion-free position—a value convenient for direct interpretation—was substituted for the older percentage method of designating distortion (18, 19). The Bureau also introduced the practice of measuring the resolving power of photographic



FIGURE 4. Photograph made at an altitude of nearly 2 miles with an airplane camera lens (fig. 3) designed and constructed at the Bureau.

On the original 9- by 9-inch print it is possible to distinguish individual railway ties as well as people crossing the street (within circle at upper right).

enses by a photographic method exclusively and egan expressing the result in terms of lines per nillimeter measured on the negative (5, 10). 'inally, the calibrated focal length was defined nd recommended for use, instead of the equivaent focal length, with airplane cameras for map naking (7). All of these practices have now come nto general use in the United States and have been widely accepted in many other countries.

The earlier measurements of distortion were nade on an optical bench, but this method became nadequate as the volume of work rapidly inreased. Furthermore, laboratory tests indicated hat the performance of a photographic lens must be studied by a photographic test in order to correlate results with performance in actual use. To meet this need, the precision testing camera was leveloped and constructed (10). Two negatives nade on this instrument, each containing a series of 19 exposures, enable distortion, resolving power, astigmatism, and curvature of field to be assessed at five-degree intervals across one diameter of the ield of view. At first, this testing camera was equipped with seven collimators, permitting a 60degree field to be investigated. Later, as wideangle lenses came into general use, three additional collimators were added so that a 90-degree field could be accommodated.

The increasing interest in photogrammetric methods has been largely due to the strategic value of airplane mapping for military defense. However, the requirements of the Agricultural Adjustment Administration and of the Soil Conservation Service for prompt delivery of maps of large areas have also greatly stimulated the establishment of civilian engineering firms specializing in airplane photography and map preparation. This has resulted in a need for standard specifications to be used by Government procurement offices in contracts with civilian airplane-mapping agencies. Such standard specifications, prepared under the guidance of the Photogrammetric Society of America, require that bids for Government contracts be accompanied by a National Bureau of Standards certificate applying to the lens and camera which the contractor proposes to use (6). During 1947, 326 cameras and photographic lenses for photogrammetric work were tested or certified at the Bureau. Publications have also been issued dealing with lens testing, lens design, performance of typical camera lenses, and tolerances in lens and camera performance for mapping purposes (11, 14, 15, 21).

The work just described has been restricted almost entirely to lenses for photogrammetric work. In addition, at the request of the Society of Motion Picture Engineers, the Bureau has developed a method of calibrating the aperture openings of a photographic lens in such a way as to compensate for the loss of light by reflection and absorption within the lens (16, 20). It appears probable that this system of lens marking will be extended to all photographic lenses. The departure of the illumination over the field from the cosine-fourthpower law has also been derived (17), and measurements of the variation in illumination introduced by vignetting have been measured (14, 21).

5. Optical Shop

To aid in the work on optical instruments and lens design, the National Bureau of Standards maintains a thoroughly modern Optical Shop (fig. 5). In general, this shop does not attempt to utilize production methods but specializes in making very precise optical components or custom-made optical systems in accordance with the Bureau's own designs. Lens systems produced by the Optical Shop include the 20-foot focal length eclipse lens (38) and the f/6.3 airplane camera lens of 50-inch focal length (fig. 3) mentioned in the discussion of lens design.

Recently the requirements of wind-tunnel optics—a new field concerned with wind-tunnel instrumentation for supersonic velocities—have created a need for large optical components of extreme precision for use in the interferometers and schlieren apparatus employed. Glass disks 36 inches in diameter are often required, and even larger constructions have been contemplated. The Optical Shop has been called upon to make large interferometer plates, beam splitters, and aspheric lenses for this purpose. Off-axis parabolic mirrors, another type of aspheric surface now important in infrared spectrometry, have also been constructed with diameters up to 8 inches.

As interferometric methods of testing surfaces and measuring lengths are in general use throughout the Bureau, a large part of the work of the Optical Shop consists in supplying optical planes of various sizes and their restoration when they become badly scratched through use. These planes are produced with remarkably high precision (67). The graphs in figure 8 show the departure from planeness of three 11-inch optical planes of fused quartz which were being worked at the same time and tested against each other. Plane No. 12 departs from planeness by not more than one-hundredth of a wavelength (two tenmillionths of an inch). If this plane were magnified equally in all dimensions so that the diameter were one mile, the departure from planeness would still be only about one-thousandth of an inch.

The production of optically plane surfaces on metal requires a technique considerably different from that used with glass. In making a first-order transit theodolite, an optically plane metal blank is necessary for the graduated circle if the graduations are to be sufficiently accurate. (Errors should be no greater than one or two seconds of arc.) The Optical Shop has devised methods for producing such surfaces and also for bringing the

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FIGURE 5. Polishing room in the Bureau's Optical Shop.

This shop does not attempt to use production methods but specializes in making very precise optical components or custom-made optical systems in accordance with the Bureau's own design.



FIGURE 6. Centering and edging lens components in the National Burcau of Standards Optical Shop.

After the lens is correctly centered on the rotating spindle in the lcft foreground, the two spindles will be interchanged so that the edge of this lens may be ground true on the large diamond-charged wheel at the operator's right. Meanwhile, the lens attached to the second spindle, which has already been centered, is undergoing the edging operation. Accuracy of centering is tested by observation of images reflected from the two surfaces of the lens.



FIGURE 7. A telescope objective must be polished so precisely that the finished surface does not depart from regularity by more than six-millionths of an inch.

This is done in the Bureau's Optical Shop hy means of a rotating pitch surface pressed into the proper curvature and charged with rouge and water. The lens, cemented to a small metal disk, is pressed down against the pitchcovered tool by a pin that fits in a depression in the center of the metal disk. Lateral motion of the pin support swings the lens back and forth across the tool as it rotates. Rouge and water are applied with a brush between the two surfaces at intervals. Note that the surface of the pitch is marked off into squares by grooves which receive excess polishing materials. locating shoulders of a graduated circle into optical parallelism with the surface to be graduated. During World War II the Army Engineer Board undertook the development of a precision transit of the European type with graduated circles not more than 4 inches in diameter. The Optical Shop produced the metal blanks for the circles used in the earlier instruments and also made the glass blanks required for the later models.

The making of graduated circles is an instance where the precision obtained in optical tests and methods of working optical surfaces is utilized to produce parts for other than optical applications. Other examples from the work of the Optical Shop are high-precision decimeters and other length standards of fused quartz, accurate cores for inductances, and precise spheres to serve as standards of curvature.

Each different crystalline material requires a special technique for the production of an optically regular surface and a good optical polish. At present a large number of new synthetic crystals are becoming increasingly important because of their refraction or transmission characteristics, and the development of suitable techniques for polishing them is a matter of special study at the Bureau.



FIGURE 8. Profiles of three standard planes of fused quartz that were made in the Bureau's Optical Shop.

Interference methods show the departure from planeness of plane 12 to be less than two one-hundredths of a wavelength of light, i e., less than onehalf of a millionth of an inch. The planes are 10% inches in diameter and 2 inches thick.

6. Testing of Optical Instruments and Systems

Military Optical Fire-Control Instruments. In addition to the range finder program (30, 41, 53), the National Bureau of Standards has done much work on optical fire-control instruments (66). This has included investigations of the Sperry and Norden bomb sights and the development of instruments for testing gun sights to be used on



FIGURE 9. An optical instrument designed at the Bureau to test the accuracy of gun sights for the Air Force.

airplane-mounted machine guns (fig. 9), as well as the actual design and development of sights for aircraft armament.

General Testing. The National Bureau of Standards also does a large amount of general testing of optical instruments for the public and for other Government agencies (43). Examples are: determinations of focal length for all types of lenses, measurements of the power and freedom from defects of spectacle lenses, and determinations of the optical characteristics of surveying instruments. The results often serve as criteria for acceptance or rejection of instruments being purchased by Government agencies. In other instances calibration curves are provided for use in obtaining corrections to indicated readings. Occasionally, data for special types of apparatus are of sufficiently general interest to justify their separate publication (48, 49).

Specifications for Optical Instruments. The Federal Specifications Board, the American Standards Association, the National Military Establishment, the Society of Motion Picture Engineers, the International Commission on Illumination, and the International Commission on Optics are among those organizations which have a continuing interest in the standardization of optical nomenclature and units and in the preparation of specifications to govern the purchase of optical products and optical instruments. The National Bureau of Standards is represented in all such committee work, and its staff members devote a considerable portion of their time to obtaining the necessary information and formulating it into the proper form for the reports of these organizations.

7. Services as Consultant

The National Bureau of Standards provides general consulting services to other Government agencies on matters relating to the use and design of optical instruments. Consultations cover a wide range of subjects, including high-speed cameras for the National Advisory Committee for Aeronautics; large interferometers for the Air Force, the Navy, and the Army Ordnance Department; precise mapping cameras for the Geological Survey, photographic lenses and surveying instruments for the Coast and Geodetic Survey; motion picture projectors for the Bureau of Federal Supply, Treasury

Optical glass, an indispensable raw material for precision optical instruments, has been developed and produced by the National Bureau of Standards ever since World War I, when the lack of available manufacturing facilities and scientific knowledge in this field combined to expand the Bureau's newly established experimental glass plant into a manufacturing unit. With the production of optical glass in large quantities, it became necessary to provide for the prompt measurement of samples of glass from the large melts and also from the numerous experimental melts that were made. Tolerances for the quality of optical glass were formulated, and methods of test were worked out for determination of strain, striae, and other defects. During this period the immersion tests were devised which permit testing of glass for striae without preliminary grinding and polishing. This method greatly simplified control and was of material aid in development and production of new glasses. It was followed by a procedure for measuring the index of refraction of glass in irregularly shaped pieces.

At the end of World War I the American optical glass industry was allowed to decline, most manufacturers ceasing production entirely. However, from 1919 to 1939 the Bureau's optical glass laboratories were maintained for research and small-scale production. This, along with the output of the Bausch & Lomb Optical Co., was the extent of optical glass manufacture in the United States over that period. Probably the best known achievement during these years was a 70-inch optical disk successfully completed at the Bureau in 1928 for the telescope of the Perkins Laboratory, Ohio Wesleyan University. At that time the disk represented the largest optical element ever made in this country. No American commercial manufacturer was then willing to undertake the casting and annealing of so large a blank for astronomical purposes.

World War II brought greater demand for optical instruments than ever before, with consequent heavy requirements for optical glass, and Department; and microfilm readers for the Army. As these agencies do not, in general, have sufficient optical work to maintain a permanent staff of optical specialists, they find the services of the Bureau most convenient.

The National Bureau of Standards is also required "to supply available information to the public upon request, in the fields of physics, chemistry, and engineering." Individuals and business firms constantly are asking for assistance. They are furnished information on specific optical subjects or given reference to other sources of information.

III. Optical Glass

the Bureau's experimental glass plant was put into full-scale operation. From this nucleus, with greatly expanded facilities and increased personnel, it became one of the small group of plants supplying this country's optical glass needs. Production of optical glass at the Bureau increased from 8,000 pounds in 1938 to a peak of 236,000 pounds in 1943.

At the beginning of the war six kinds of optical glass were being made at the Bureau; during the war this was increased to 28 types. For some of these which had been made previously, published information was available on compositions, annealing temperatures, and other physical properties so that little experimental work was necessary before satisfactory glasses could be produced. In other cases entirely new types, on which little or no data previously existed, were developed in the laboratory and then put into full-scale production. Early in the war, representatives of the Canadian and Australian governments visited the Bureau's glass laboratories to study methods and equipment. As a result, plants were established and producing optical glass in each of these countries by 1941. Technical assistance was also given to several manufacturers in the United States who were thus able to begin production in a remarkably short time, although they had had no previous experience in optical glass manufacture. With the end of the emergency, the optical glass program at the Bureau again returned to pilot plant-scale operations and to research on new glass compositions, methods of making glass, and measurement of its physical and chemical properties.

1. Slip-Casting of Clay Melting Pots

One of the major problems in manufacturing optical glass is the making of the melting pots (fig. 10). Good-quality glass requires pots that will not introduce impurities through reaction with molten glass.



FIGURE 10. Clay pots and stirring thimbles used in melting optical glass.

These pots are produced by means of a slip-casting process developed at the Bureau to meet the need for pots that would not react with molten glass. This process replaced the hand-molding methods previously used in making clay pots.

To meet this need, the Bureau's Refractories Laboratory developed a process for making pots by slip-casting to replace laborious hand-forming methods (88). This process has been widely used, and cast pots have now largely supplanted handmade pots, not only in optical glass plants but in plants manufacturing glass for other purposes. At the same time it was found that the pots could be produced entirely from domestic ball clays and kaolins. A number of improvements were later introduced, such as lining the pot with less permeable material. Although there have been some changes in composition, the basic process has remained the same (91, 92, 95, 96, 99, 100).

2. Effects of Composition on the Optical Properties of Glass

An important phase of optical glass rescarch at the National Bureau of Standards has been the development of new glasses with unusual optical properties. Optical designers particularly desire glasses having a ratio of index of refraction to dispersion different from that for standard types. Although a number of glasses of this sort have been made available within recent years, many more are needed. However, their development will require extensive research since they must not only have the desired optical properties but must be adaptable to large-scale manufacture.

When a new type of glass is required, its tentative composition is first formulated on the basis of the known effects of the various constituents on optical properties, such as index of refraction and dispersion. A trial melt of about 50 grams is made, and measurements are taken of index of refraction, dispersion, liquidus temperature (Fig. 11), softening point, stability of the glass, and other characteristics. Melts on a pilot-plant scale may then be undertaken. However, on this scale such factors as volatilization rate and pot solution become important. As a result, the first large-scale melt is seldom satisfactory, and often several trials are necessary before appreciable quantities of suitable glass are obtained.

In this work the glass technologist must cooperate closely with the instrument designer. It is also essential that he know the effect of each chemical element on the index of refraction and on dispersion. These relations have been the subject of numerous investigations at the National Bureau of Standards (104 to 108). While several theorics have been advanced which permit calculation of the index of refraction and dispersion from composition, the results are not always accurate if extrapolations are made into fields of compositions that differ widely from those in which the data were taken. For this reason, new fields of compositions must be explored thoroughly before accurate predictions can be made as to the



FIGURE 11. A sample of optical glass produced in the Bureau's experimental glass plant is introduced into a tubular electric furnace designed for study of the liquidus temperature and crystallization rate of the glass.

In the new fields of glass composition now under study at the Bureau, data on these properties are highly important, since glasses that crystallize readily cannot be made in large pieces. compositions which will give the desired optical constants.

Optical glass must also have satisfactory durability if it is to be used widely either in military or in scientific instruments. Moreover, glasses that devitrify readily cannot be made in large pieces since crystals would form before the piece could be cooled. Thus, in new fields of glass compositions now under study at the Bureau (108) data on liquidus temperature and rate of crystal growth are important.

3. Annealing of Optical Glass

As glass passes from the liquid to the vitreous solid state, strains are set up within the body of the glass. These strains, which seriously affect its physical as well as optical properties, are removed by annealing. In the process of annealing, the glass is heated to a temperature just short of its softening point, held at this temperature long enough to remove the strains, and then cooled gradually. The annealing of optical glass is one of the most important, and at the same time one of the most critical, processes in its production. When properly annealed, an optical element should be free from strain and of uniform refractive index throughout, and the final polished surfaces should not distort with time. As the index of refraction of glass is affected by its annealing temperature, an exact knowledge of the relation between these two quantities is necessary. Valuable contributions to the knowledge of the changes that take place in glass when it is annealed have been made by A. Q. Tool and other members of the staff of the National Bureau of Standards (109 to 117, 120 to 127).

4. Measurement of Physical and Optical Properties of Glasses

Measurement of the physical and optical properties of glasses has been an important part of the work of the National Bureau of Standards. These properties are of interest because they con-



FIGURE 12. A pot of molten glass is removed from one of the melting furnaces in the Bureau's Optical Glass Plant. Temperatures in the neighborhood of 1,400° C are required for fusion of the sand and other ingredients into a homogeneous transparent material.



FIGURE 13. Slow cooling of molten optical glass produces large chunks, which are removed by breaking open the melting pot.

These chunks are then cut into smaller pieces from which lenses and prisms are made.

tribute to an understanding of the basic nature and structure of glass, and because they provide information for the manufacture and intelligent utilization of this important substance. One of the earliest reports on this work was that of Peters and Cragoe (130) on the thermal dilatation of glass. The interferometer method which they used has proved to be one of the most satisfactory procedures for measuring the thermal expansion of glass at high temperatures. The method has been further refined by Saunders (139, 142), and an instrument for continuous recording of the data on a photographic film has been developed. Studies of the effect of various glass-making oxides on expansion, annealing point, and softening point have also been made by a number of investigators.

The viscosity and surface tension of glass, as modified by composition and other variables, are of great interest since these properties affect the melting and forming of hot glass. Significant work in this field has been done by members of the Bureau staff (136, 143, 145).

5. Chemical Analysis of Glass

Because the chemical analysis of glasses has been a time-consuming operation, it has often been avoided. Much of the literature on glass is thus of limited value because the exact compositions of the glasses studied are unknown. In many cases manufacturers have not had an exact knowledge either of the chemical composition of the raw material they were using or of the finished glass. Rapid and accurate methods of chemical analysis are therefore of great interest to glassmakers. A number of improved analytical methods developed at the National Bureau of Standards (146 to 153) have found widespread use in the industry.

Another important aid to analytical chemistry has been the maintenance of standard samples of glasses, of sand and other raw materials, and of a number of refractory bodies. These samples have been prepared for checking the accuracy of methods of analysis and may be purchased at a nominal fee.

As even the more rapid analytical methods require an excessive amount of time, glass compositions are often calculated from measurements of density or index of refraction. While such methods cannot accurately determine composition without other background information, they can be very useful tools in process control. In fact, if conditions are such that only one or two ingredients in a glass batch are subject to variation (as by volatilization or solution of refractory), calculation of quantities of major constituents from physical measurements may give more accurate results than chemical analysis.

The Bureau's work on variations of density and index of refraction with composition (104 to 108) gives much of the information necessary to make such calculations. However, since these properties depend upon the heat treatment received, the glasses must be annealed to prescribed conditions before they can be properly measured. A number of papers (110, 112, 113, 114, 115, 117, 120, 121, 123, 124, 125, 126, 127) deal with the variation of physical properties of glasses with heat treatment.

6. Chemical Durability of Glasses

While glass is usually highly resistant to chemical attack, yet glasses do undergo chemical changes which may be very slow or quite rapid, depending upon composition and conditions of exposure (154 to 168). Optical glasses, especially those used in military instruments, must withstand moisture, carbon dioxide and other gases, and fungus growth. Resistance to chemical action is also important in laboratory glassware and in glass containers for pharmaceutical preparations.

Because of the widespread interest in methods of measuring the chemical durability of glasses, the National Bureau of Standards has been active for many years in developing such tests. This program has involved not only practical procedures for measuring durability (154, 155, 156, 157, 158, 160, 162, 164, 165), but also more fundamental work on the mechanism of chemical attack and the nature of the chemical reactions that take place at glass-liquid or glass-air interfaces (161, 165, 166, 167, 168).



FIGURE 14. Large pieces of optical glass produced in the Bureau's Optical Glass Plant. The glass is sawed with a diamond saw into sizes convenient for molding into blanks from which lenses, prisms, and optical flats can be made.



FIGURE 15. A step in the preparation of an optical blank in the Bureau's Optical Glass Plant.

The rough glass chunk is heated on the end of a punty rod in the furnace (background), then rolled into cylindrical form. In the next operation it is cut off into a metal mold, and pressed to shape.

7. Defects in Glass

Because of its intimate contact with glass manufacturers and other branches of the ceramic industry, the National Bureau of Standards has been able to add much to the knowledge of the reactions that take place between molten glass and refractory melting pots (183, 184, 186, 189). Closely allied to these investigations has been a study of the crystalline material which may form either by reaction of the glass with the refractory or within the molten glass itself (181, 182, 185, 188, 190, 192).⁴

8. Transmission of Radiant Energy

The National Bureau of Standards has made transmission measurements of a number of glasses used for protecting the eyes from injurious radiation (169, 176). The effects of many different ingredients on transmittance of the glass have also been investigated. Of particular importance has been the transmittance in the ultraviolet and infrared region of the spectrum (169 to 176 and 178).

9. Consulting and Advisory Services

Another important part of the Bureau's work on glass is the consulting service furnished to other Government departments. Many requests are received for technical information on optical glass. safety glass, chemical durability of glass, and specifications and tests. Information on specific topics relating to glass is also given to the general public upon request.

10. Testing and Specifications

The National Bureau of Standards has been active in the development of methods for testing

glass and glassware, and in preparing specifications for a number of glass products. Much of this work has been done in cooperation with manufacturers and users through organizations such as the American Society for Testing Materials and the American Standards Association. The Bureau has also been represented on the committees that have prepared Federal Specifications for glass items of interest to the Government.



FIGURE 16. Three stages in the production of an optical prism at the National Bureau of Standards.

The blank is cast (left) of size larger than required in order to permit the removal of all irregularities. It is then ground to very nearly the desired dimensions (center) before final polishing to produce the finished optical element (right).

IV. Bibliography of Bureau Publications

The publications of the National Bureau of Standards are intended to record those phases of an activity that are of general interest and permanent value. Listed below are 195 publications by members of the Bureau staff in the fields of optical instrumentation and glass technology; however, a large number of reports on these subjects, which were circulated as classified material during the last war, are not included.

Where prices are shown for publications issued by the Bureau, they may be purchased from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Where prices are omitted for Bureau publications they are out of print, but may be consulted in libraries maintaining reference sets of Bureau publications.

A complete catalog of Bureau publications, 1901 to June 30, 1947, with author and subject indexes, NBS Circular C460, is available from the Superintendent of Documents for 75 cents.

Copies of articles published in the technical

journals referred to are not obtainable from the Government. They may be consulted in technical libraries maintaining reference sets of such periodicals, or requests should be sent direct to the publisher.

The following letter-symbol designations are used in this paper for Bureau publications, and these letters should be included with the serial number in all references to Bureau publications.

- S, Scientific Papers. T, Technologic Papers.
- RP, Research Papers.
- C, Circulars.
- H, Handbooks.
- M. Miscellaneous Publications.
- CS, Commercial Standards.
- LC refers to mimeographed pamphlets designated "Letter Circulars," single copies of which may be obtained free from the Bureau so far as copies are still available.

1. Optical Instruments and Optical Systems

(a) Photogrammetry

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- (3) Locating the principal point of precision airplane mapping cameras. F. E. Washer. J. Research NBS 27, 405 (1941) RP1428. 10¢
- (4) A magnifying stereoscope and camera lucida; two instruments for airplane mapping. I. C. Gardner, J. Opt. Soc. Am. & Rev. Sci. Instr. 11, No. 2, 195 (1925).
- (5) The interpretation of lens tests and camera calibra-tions. I. C. Gardner. Photogrammetric Engi-neering 3, No. 1, 13 (1937).
- (6) Specifications for a precision mapping camera. I. C. Gardner. Photogrammetric Engineering 4, No. 3, 173 (1938).
- (7) The significance of the calibrated focal length. I. C. Gardner. Photogrammetric Engineering 10, No. 1, 22 (1944).

(b) Photographic Objectives

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- (9) Aberrations of long focus anastigmatic photographic objectives. A. H. Bennett. Sci. Pap. BS 19, 587 (1923-24) S494.
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- (16) Compensation of the aperture ratio markings of a photographic lens for absorption, reflection, and vignetting losses. I. C. Gardner. J. Research NBS 38, 643 (1947) RP1803. 10¢
- (17) Validity of the cosine-fourth-power law of illumina-tion. I. C. Gardner. J. Research NBS 39, 213 (1947) RP1824. 10¢
- (18) The distortion of some typical photographic objectives. A. H. Bennett. J. Opt. Soc. Am. & Rev. Sci. Instr. 14, No. 3, 235 (1927).
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 I. C. Gardner and F. E. Washer, J. Research NBS 40, 93 (1948) RP1858, 10¢; J. Opt. Soc. Am. 38, No. 5, 421 (1948).

(c) Design and Construction of Optical Instruments

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- (23) Application of the algebraic aberration equations to optical design. I. C. Gardner. Sci. Pap. BS 22, 73 (1927-28) S550.
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WASHINGTON, March 1, 1949.

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