Transactions of the Indian Ceramic Society

ISSN: 0371-750X (Print) 2165-5456 (Online) Journal homepage: http://www.tandfonline.com/loi/tcer20

The Making of Optical Glass in India: Its Lessons for Industrial Development

Atma Ram

To cite this article: Atma Ram (1962) The Making of Optical Glass in India: Its Lessons for Industrial Development, Transactions of the Indian Ceramic Society, 21:1, 1-27, DOI: 10.1080/0371750X.1962.11011973

To link to this article: http://dx.doi.org/10.1080/0371750X.1962.11011973

Published online: 04 Nov 2014.

The Making of Optical Glass in India : Its Lessons for Industrial Development

ATMA RAM

Central Glass and Ceramic Research Institute,
Calcutta-32

This is the first Shanti Swarup Bhatnagar Memorial Lecture delivered by the author on October 6, 1961, before the National Institute of Sciences, India. The author has given a thoughtful account of the development of the optical glass industry and in this he discovers the fundamental prerequisite for industrial progress namely, the close co-ordination among scientific thoughts, technological actions and industrial growth. This happened in different countries in the past, happened again in India in producing optical glass, and is the right step towards our technological independence.

*In view of the special appeal of the lecture to the workers in the fields of glass and ceramics, it is being reproduced here from the Proceedings of the National Institute of Sciences of India [*27A *(6) 1961], with the permission of the Institute.*

—Editor

I am deeply grateful to the National Institute of Sciences of India for the high honour done to me by awarding the Shanti Swarup Bhatnagar Medal, recently instituted in memory of one of the eminent scientists of the country and a past President of the Institute. Dr. Bhatnagar's contributions to the progress of science and technology in India are unique and distinguished; and by wisely piloting the activities of the Board of Scientific and Industrial Research (B.S.I.R.), he brought dignity to the pursuit of applied sciences. Realistic in outlook and gifted with intuitive and persuasive powers, Dr. Bhatnagar possessed a remarkable organizing ability, and it was the blending of these qualities that made him a dominating figure in the scientific and technological activities of the country during the post-war period. For his brilliant contributions to science, he will rank among the eminent scientists of the country; and for his great rôle in founding a chain of National Laboratories, a parallel to which can be found in the establishment of the Kaiser Wilhelm Institutes in Germany, now known as the Max Planck Institutes, he will be remembered by his countrymen with admiration and gratitude.

Twenty-one years ago, at the time of the establishment of the Board of Scientific and Industrial Research in 1940, I was privileged to be taken as a member of the research team directed by him. As Director of Research, he believed in dealing with individual workers directly, and thus I came into intimate contact with him and was influenced by his methods of appraising problems and planning team work with an unerring eye on results. It was my good fortune to work with him till his premature death on New Year's Day in 1955, but I could hardly imagine during all these years that I would be honoured as the first recipient of the medal instituted by the premier learned society of the country in his memory.

Under the conditions of the award, the recipient is required to deliver a public lecture, and in discharging this obligation I find myself in considerable difficulty. I am not used to delivering public addresses; but obligations must be honoured and I find myself here today speaking to you on a subject which has been engaging my attention for some years past. Dr. Bhatnagar himself was keenly interested in the subject, and among the problems handled by the B.S.I.R. during the war period, the production of optical glass was one, and a major one at that, as its supply position at that time caused a good deal of anxiety. It is also a problem in which several Presidents of the National Institute of Sciences had taken keen interest.

Role of optical glass

'Knowledge is power' and the power that man has acquired in harnessing the resources of nature for ensuring better living conditions stems largely from science and its applications. In the acquisition of that knowledge perhaps no single substance has played a rôle worthier than that of optical glass. This remarkable material has become so much a part of modern civilization that it is difficult to imagine what progress could have been achieved without its services. As an essential material of the telescope, optical glass relieved science from the clutches of superstition and dogma and helped in the establishment of the laws of planetary motion. But for optical glass, which has provided that wonderful instrument, the microscope, many of the present-day sciences and industries would not have made such advance. Thus, the science of bacteriology, which has done so much for the alleviation of human suffering, would not have been born; fermentation industries which are amongst the major industries would have made but little progress; photography and cinematography would have been unknown and the development of astronomy would have remained stunted. Optical glass has extended human vision from the microscopic world to the macroscopic.

The use of optical instruments in military operations has made optical glass a vital strategic material. Modern weapons employ a wide variety of optical instruments, such as range finders, submarine periscopes, army and naval telescopes, binoculars, gun sights, cameras, etc. The high precision required for the effectiveness of operations is determined by the quality of the glass used in the manufacture of optical components. Indeed, optical glass has come to be known as the 'eye' of the Armed Forces.

It is desirable here to mention that spectacle lenses and signal lenses (used in the control of rail, road or air traffic), although used for transmission and refraction of light rays, are not optical glasses; they are 'ophthalmic' and 'signal' glasses respectively. Although required for aiding vision, ophthalmic glasses do not require the high degree of perfection demanded for optical glass. The term 'optical glass' is used for glasses employed in the manufacture of optical instruments of high precision.

Distinguishing features of optical glass

Optical glass is glass. What is then peculiar about it that makes it such a prized material?

The principal rôle of optical glass, whether it is used in the form of a lens or a prism, is to refract rays of light, and apart from refraction at the surfaces of incidence and emergence, the path of light should not deviate while passing through the body of the glass. To ensure this, the glass must be optically homogeneous; in other words, it should be isotropic. Ideal isotropicity has, of course, not been attained but a very high standard, almost approximating the ideal, has indeed been achieved. This is where optical glass differs fundamentally from other glasses.

Broadly speaking, the inhomogeneities in glass are of two types, chemical and physical. The former includes seeds, bubbles and blisters, stones, crystallization products, striae, cords, and the like. These inclusions not only, in themselves, block or deviate light in its passage through the glass, but they are surrounded by glass which differs in composition and refractive index from the main glass and consequently interfere with the performance of optical components. Even when chemical homogeneity has been attained, the presence of strains due to faulty annealing causes deviation of the light path, an effect known as Brewster Effect of double refraction. This constitutes perhaps the most serious physical inhomogeneity in glass.

Brightness of image is another important consideration in an optical system and, in order to achieve it, the glass must be highly transparent and should not be coloured. Since optical devices are often exposed to the atmosphere and the components are subjected to rough handling during grinding, polishing, etc., optical glass must be chemically durable, i.e. resistant to atmospheric and chemical attack; it must also possess good mechanical strength.

In short, optical glass must be:

1. Optically homogeneous.
2. Highly transparent and free from colour.
3. Chemically durable and physically stable.

The fundamental properties of optical glass, important from the point of view of the optical instrument designer, are the refractive index n_d, mean dispersion $n_F - n_C$, partial dispersion ratios $\frac{n_d - n_{A'}}{n_F - n_C}$, $\frac{n_g - n_F}{n_F - n_C}$ and dispersive power $\frac{n_F - n_C}{n_d - 1}$ or the reciprocal of dispersive power $\frac{n_d - 1}{n_F - n_C}$, ν-value, also known as the Abbe value. A', C, d, F, and g represent the wavelengths 7682 Å, 6563 Å, 5876 Å, 4861 Å and 4358 Å respectively. Optical glasses are designated by their n_d value and the Abbe value.

The lens manufacturer uses certain tools for grinding and polishing, and keeps to the radii of curvature calculated by the optical designer according to the constants of the optical glass used, namely the refractive index and the Abbe value. In this calculation he is mainly guided by the following well-known relation:

$$\frac{1}{f} = (M-1)\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{(M-1)t}{Mr_1r_2}\right)$$

where f, r_1 and r_2, and t represent the focal length, the radii of curvature and the thickness of lens, and M is the refractive index.

If the optical constants vary from supply to supply, the only alternative left to the lens maker is to change his tools according to the variation of refractive index—and obviously this is not a practical proposition. A supply may be good in regard to optical homogeneity and other properties, but if the optical constants vary beyond the standards laid down (cf. Table I), that glass is practically worthless to the lens maker.

TABLE I

*Limits of variation of n_d and ν value for optical glasses**

Type of glass	Tolerance	
	n_d ±	ν ±
Flour crown	0.001	0.5
Borosilicate crown	0.001	0.5
Light barium crown	0.001	0.5
Medium barium crown	0 0015	0.5
Dense barium crown	0.0015	0.4
Soft crown	0.001	0.5
Telescope flint	0.001	0.4
Light barium flint	0.0015	0.4
Barium flint	0.0015	0.3
Light flint	0.0015	0.3
Dense flint	0.0015	0.3
Extra dense flint	0.0015	0 3
Double extra dense flint ...	0.0015	0 3

* Indian Standard IS : 1400—1960.

It is thus the extreme purity, perfect optical homogeneity, uniformity and reproducibility of quality within very narrow limits that make the manufacture of optical glass a task of high precision, demanding rigorous control over every minute detail of operations. Exacting in requirements and difficult to produce, optical glasses form a hierarchy of their own in the realm of glasses. In view of their highly specialized uses and comparatively limited consumption, they have never been an item of mass production. The annual peace-time world production is stated to be of the order of 2,000 tons, and compared with the total production of glass, which is about 20 million tons a year, optical glass barely constitutes a fraction of one per cent. About half a dozen countries in the world produce optical glass and the methods of manufacture are closely preserved secrets.

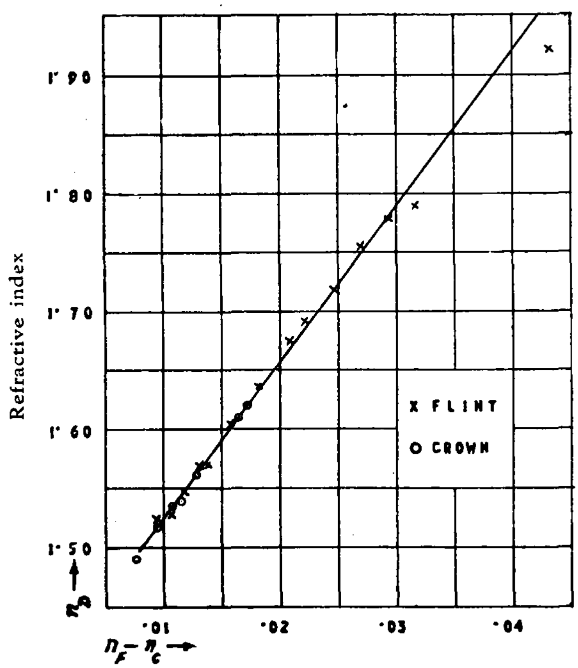
The beginnings of optical glass

Optical glass is the essential raw material of the optical instrument industry and the progress of its manufacture is the result of efforts to produce a material which satisfies the exacting requirements of geometrical optics based on the laws of refraction of light, and to obtain with the help of the optical system an image free from defects, such as chromatic aberration, spherical aberration, curvature of surfaces, coma and distortion.

Prior to the nineteenth century, optical components were made from a selection of the best available crystal glasses of the ancient alkali-lime-silica (the crown glass) and alkali-lead oxide-silica (the flint glass) types. The glasses were defective in one way or another from the optical point of view and it was often difficult to find a piece good enough to make a satisfactory lens. In the latter part of the eighteenth century, Pierre L. Guinand, a Swiss woodworker engaged in making clock cases and bells, got interested in producing telescopes. He started melting glasses for his business, and succeeded, after several disappointments and serious financial losses, in obtaining a fairly homogeneous glass by stirring the molten mass with a fireclay rod. This was a great advance, and even after one and a half centuries, stirring continues to be the principal operation for ensuring homogeneity, although the operation is now performed with great precision. Guinand started making homogeneous glasses both in his own workshop at Les Brenets (Switzerland) and at Benediktbeurn (Germany) as an associate of Utzschneider, a manufacturer, and Fraunhofer, an early pioneer in optics. After Guinand's death in 1824, optical glass making was taken up in France by two small firms in collaboration with the successors of Guinand. One of the firms soon closed down, and the other, after passing through several vicissitudes, ultimately developed into the now well-known firm of Parra-Mantois et Cie of Paris. In England, optical glass making was started in 1848 by Chance Bros. at Birmingham with the association of Georges Bontemps, a skilled French technician, at one time an associate of Guinand's descendants, who had very much improved the technique of stirring. Thus, till about 1880, there were three works producing optical glass, one each in England (Chance Bros., Birmingham), France (Parra-Mantois, Paris) and Germany (at Benediktbeurn), all employing Guinand's technique of stirring for homogenising the glass. Guinand may thus be legitimately called the founder of optical glass making.

Secondary spectrum—A great drawback

At that time, the available optical glasses which were more or less variants of the crown-flint series were characterized by a linear relation between dispersion and refractive index (cf. Fig. 1); the dispersion increased progressively with refractive index. Due to this relation, achromatic combinations made by using low dispersion crown glasses for the positive element and high dispersion flint glasses for the negative element had an appreciable secondary spectrum, as also spherical aberration and other defects, For nearly three quarters of a century after Guinand's invention, attempts were made to produce glasses which would minimize this secondary spectrum, some of them by leading men of science. Premier scientific organizations, like the Royal Society in England and the Academy of Sciences in France, sponsored investigations on this subject and the latter instituted a prize for the development of optical glass free from defects.



Mean dispersion.

FIG. 1—(Wright 1921).

Fraunhofer is stated to have obtained flint and crown pieces with reduced secondary spectrum, but no attempt appears to have been made to produce the glasses on a large scale. Since he had facilities at his disposal at Benediktbeurn to produce the glasses on a commercial scale, it may be presumed that the glasses were unsuitable in other respects. However, in collaboration with Guinand he succeeded in making the great Dorpat refracting telescope with a 9-inch diameter objective, which was decidedly superior to anything previously achieved. Incidentally, the improvement in the telescope helped in the better utilization of the spectrometer.

Deeply impressed by this achievement and keen on promoting researches in practical astronomy, the Royal Society took the initiative in 1824 for encouraging production of optical glass of high quality. At its instance, Michael Faraday, in collaboration with Sir John Herschel and G. Dollond, succeeded, after several years of intensive study, in producing some good glasses by melting glass batches in platinum trays and using platinum rakes for stirring; the resulting glasses gave objectives which were fairly achromatic. But being more interested in other problems, Faraday discontinued the work in 1831 and even declined the request of the Royal Society to produce larger pieces. It may be stated in passing that seven weeks after declining the request of the Royal Society, Faraday announced the great discovery of electromagnetic induction which has immortalized his name.

In 1834, Rev. William Vernon Harcourt, founder of the British Association for the Advancement of Science, started investigations on the relationship between the chemical composition of glasses and their optical properties, in collaboration with Sir George Stokes. He conducted numerous meltings in platinum crucibles, particularly of phosphate glasses containing oxides of potassium, sodium, lithium, aluminium, calcium, strontium, barium, titanium, molybdenum and tungsten. Harcourt and Stokes succeeded, as a result of these studies extending over a period of about a quarter of a century, in obtaining phosphate glasses containing titanium which showed better achromatization. Due possibly to limitations of equipment and manufacturing facilities, the practical value of these investigations was not realized and the results did not perceptibly influence the practice of making optical glasses. Due mainly to the failure of obtaining, in small meltings, glass pieces large enough for measuring optical properties, the investigations suffered from uncertainty and the conclusions reached were indefinite.

New era in optical glass making

This was the position in 1870 when Ernst Abbe, then Professor of Physics and Director of the Observatory at Jena, began to interest himself in optical instruments, particularly the microscope, at the persuasion of the instrument maker, Carl Zeiss. In spite of elaborate computations based on the principles of geometrical optics, first introduced by him in optical designing, and using practically all the glasses then available, he failed to effect any noticeable improvement in the optical system of the microscope. Abbe enunciated the problem with remarkable clarity and even indicated the lines of attacking it. This was a great advance, as knowing the problem, as the great Rutherford once remarked, is half-solving it. Abbe said:

> 'It is not difficult to state definitely the source from which this shortcoming originates. The inadequacy in removing those chromatic differences of spherical aberration is caused by the fact that with the types of glass available at present, with crown glasses and flint glasses, dispersion is always co-ordinated with the mean refractive index in such a manner that the higher index (with very few exceptions) is always accompanied by a higher dispersion and vice versa. The aberrations mentioned could be entirely, or at least partly, compensated if optical materials were available which would combine a relatively low refractive index with a high dispersion, or else a high refractive index with a relatively low dispersion. It would then be possible, by suitably combining such material with the ordinary crown and flint, to compensate the chromatic and spherical aberrations to a certain extent independently of each other, thus providing the prerequisite on which the removal of the chromatic difference depends' (Moritz 1957).

Even though devoid of practical utility, the findings of Harcourt and Stokes, particularly those relating to new oxides, did apparently provide Abbe a fair indication of the lines of approach as also confidence in the correctness of the step so helpful in tackling a new problem. Abbe mentioned:

> 'Some experiments in the production of glasses with small secondary dispersion conducted by Stokes in England a few years ago, though barren of direct practical result, gave useful hints as to the specific effects of certain bases and acids on refraction of light. The uniformity shown by existing glasses in their optical qualities is probably chiefly due to the very limited number of materials hitherto used in their manufacture. Beyond silicic acid, alkali, lime and lead, scarcely any substances have been tried, except perhaps alumina and thallium. *When this narrow groove is left, and a methodical study on an extended scale is made of the optical qualities of chemical elements in combination, we may anticipate with some confidence a greater variety in the products*' (Hovestadt 1902, p. 3).

It would be a mistake to presume that only Abbe was aware of these results. Attempts had been made by Chance Bros. to utilize Harcourt and Stokes' findings soon after their publication.* Also, C. Feil, great-grandson of Guinand, in association with the French chemist Frémy, conducted extensive experimental meltings on the use of barytes in glass. What was perhaps lacking was not so much an indication of what new oxides could be used as the exact proportions and combinations which should be employed to ensure the desired properties in the resulting glasses. With penetrating insight, Abbe concluded that the problem was not merely of melting glasses but of systematic scientific study of the chemico-optical behaviour of the new oxides and he pointed out that success would come through the laboratory, not from the fac-

* Report of The British Association, 1875.

tory by following arbitrary and traditional lines. Realizing fully the magnitude of the work and also the reluctance of the manufacturers to undertake it, he made an appeal to learned societies and other organizations for assistance—scientific and financial. He said:

'This is a field in which learned societies in a position to furnish material help for scientific requirements could discharge a peculiarly useful and grateful office; for very important and diversified interests are dependent on the glass making industry, its continued efficiency and its further improvement. It is not the microscope alone that is here affected, but all sciences and arts that need optical appliances' (Hovestadt 1902, p. 4).

Otto Schott, a young German chemist who had carried out researches on the chemical reactions involved in glass melting, and who had also practical experience of glass making as a family business, read Abbe's report. In the hope that the lithium glasses he had prepared might provide the answer, he sent a few samples to Abbe for examination. These glasses did not meet the requirements, but Abbe was able to perceive in Schott the right person, with knowledge of chemistry and acquaintance with glass making, who could possibly help in achieving the desired results. He accordingly wrote a very encouraging letter to Otto Schott on his equally discouraging samples:

'I regard it as a great achievement that you have succeeded in producing, from meltings in tiny crucibles, specimens good enough to admit of perfect optical investigation. Feil, though an eminent and experienced glass maker, has never sent me any such which would allow of anything like an approximate estimate of the mean dispersion, much less a reliable determination of the partial dispersions. The most important condition for improvement in the manufacture of optical glass seems to me to be the practicability of making good (i.e. spectroscopically measurable) trial meltings, since in this way only is a course of methodical investigation possible. So long as one must make every trial with a quantity of 60 to 80 lb. in order to get one small prism to examine, any systematic testing of new combinations will be out of the question. Hence in spite of the negative result, *I regard these researches as of more value than if they had led by a lucky chance to the discovery of a useful new glass*' (Hovestadt 1902, p. 14).

Thus, Schott had already overcome one of the chief obstacles which had largely hampered the studies of previous investigators. A regular correspondence between Abbe and Schott ensued, and this resulted in 1880 in the historic collaboration between the forty-years-old brilliant physicist and the twenty-nine-years-old painstaking chemist. It is well to remember that when they started work, glass batches were secret empirical recipes without adequate knowledge of the effect of the ingredients on the properties of the resulting glass, and against this background the undertaking was indeed a bold research adventure. As a first step, a systematic study of the chemico-optical effect of new oxides, such as boric oxide, phosphoric oxide, barium oxide, titanium dioxide and zinc oxide, was undertaken. Schott melted the glasses at Witten and Abbe examined them at Jena. In about two years' time they obtained results which indicated the need for carrying out meltings in large quantities. And for this purpose a glass laboratory, for which money was collected by Abbe and Schott, was erected in Jena to which place Schott had moved.

The results of melting promising compositions in somewhat larger quantities were impressive enough to warrant commercial production and this decision was fully justified by later developments:

'We will now only remark that these results were in the main established before the autumn of 1883, and that the whole investigation as a scientific preparation for the rational manufacture of optical glass would then have been brought to a conclusion, had we not received at this time, from several eminent scientists, the suggestion that we should ourselves take in hand the introduction of our results into practice and follow up our laboratory work by undertaking the commercial production of optical glass' (Hovestadt 1902, p. 7).

With the collaboration of the optical instrument firm of Carl Zeiss, in which Abbe was a partner, and a grant of 60,000 D.M. from the Prussian Government, generously made at the instance of Dr. W. Förster, Director of the Physikalisch-Technischen Reichsanstalt (then known as Kaiserlichen Normal-Eichungskommission), also Director of the Royal Observatory, Berlin, the small laboratory was enlarged to a production laboratory, the 'Glastechnisches Laboratorium Schott u. Genossen', Jena. In course of time, Glastechnisches Laboratorium gradually dropped off, leaving the name Schott & Genossen, by which it became famous all over the world. The establishment of this laboratory for the production of optical and other glasses has been described by that doyen of glass technologists, Prof. W. E. S. Turner (1936), in the following words:

> 'The founding of the Glass Technical Laboratory *Schott und Genossen* was an event which was without real parallel in the history of glass making. ... There may, at rare intervals, have been some other parallel during the history of glass making, but it must indeed have been rare. In the case of Schott, the new works were not merely to make glass of good quality in the sense of homogeneity and clarity, but also to introduce a whole new world of glasses. There was no intention in the factory to make glasses of existing types.'

Production of new optical glasses, such as the borosilicate crowns, barium crowns, barium flints and borate and phosphate glasses, began about 1884, but very soon the laboratory's activities spread to several fields arising mainly out of its own researches, particularly heat-resisting glass, boiler gauge glass and thermometer glass. The optical designers, who were used to glasses characterized by the undesirable linear relation between refractive index and dispersion, had the exciting experience of having at their disposal glasses in which these properties were independently variable. For instance, the ν -value of a dense barium crown of n_d 1·61 is 55·4, whereas for a flint of the same index it is 39·7—what a difference indeed! By using the new glasses, pairs could be so selected as to have their dispersion ratios more in accord than in the older ones and better colour correction could be secured in the lens system, leading ultimately to the production of anastigmatic lenses and apochromatic objectives. The results were so spectacular in improving microscopes and photographic lenses that within a few years Germany, which had been importing 90 per cent of her requirements of optical glass from England and France, not only stopped import but commenced export to these countries.

The existing manufacturers gradually resigned themselves to a situation of virtual elimination from the optical glass field. The Jena organization enjoyed almost a world monopoly for about thirty years, up to the outbreak of the First World War. Thus, the little town of Jena became inseparably associated with glass in the world of science, and 'Jena glass' has enjoyed a reputation and popularity almost unique in the history of glass manufacture, equalled perhaps only by Corning in more recent years.

Although after the war optical glass manufacture became well established, particularly in Great Britain and the U.S.A., German optical glass and optical instruments continued to be considered superior, and it was hard to overcome the prejudice against similar products even in the countries of origin, so much so that in England, Sir Frank Smith, Director of

Scientific Research, Admiralty, and later Secretary of the Department of Scientific and Industrial Research, had to issue a public statement in this regard (Chance 1947).

> 'It is a commonly held belief that optical instruments and optical glass of British manufacture are inferior to the instruments and glass produced by certain well-advertised Continental firms. I wish to state that this belief is erroneous and that it is based on prejudice rather than a knowledge of the facts. Comparative tests made with rigid accuracy in the laboratory and trials under stringent service conditions prove that British optical glass and instruments are inferior to none.'

Being the chief factor responsible for the commercial success of the Jena venture, the results of the investigations of Abbe and Schott, particularly those dealing with chemical composition and optical properties, were obviously never published in detail. However, a summary of these and other results obtained later with other collaborators appeared in a few papers and also in the delightful book of Hovestadt, 'Jena Glass', in which was indicated the approximate additive relation between chemical composition and physical properties, such as density, thermal expansion, specific heat and Young's modulus, for which even factors were worked out. In addition to opening a new era in optical glass making, the results provided, in later years, a sound basis for modern glass technology.

German supremacy in optical glass making

It is pertinent to ask why France and Britain, particularly the latter, with all the lead in optical glass manufacture, a sizeable instrument industry and the promising results of scientific investigations, could not achieve a measure of success comparable to that of the Jena pioneers. The British optical instrument industry was at that time piloted by master craftsmen who, with their faith pinned to hereditary art and skill were, unlike Abbe, unable to comprehend the importance of scientific designing on the principles of geometrical optics. The optical glass makers, who earned the bulk of their profits from other lines of glass manufacture, remained unconcerned about developments in the instruments industry, and the scientists tackled the problem somewhat isolated from production considerations. The conspicuous absence of collaboration between these three groups, each working independently in its own sphere, failed to create an atmosphere conducive to practical developments. Thus,, the results of the apparently unfruitful scientific investigations on the rôle of some oxides in overcoming secondary spectrum, carried out in Great Britain by some of the outstanding men of science, such as Faraday, Harcourt and Stokes, inspired Abbe, who found in them a clue to the solution of the most pressing problem of the optical instrument industry. Already assured of the association of the instrument maker, Carl Zeiss, as a partner in the firm and securing Schott's collaboration, Abbe became instrumental in creating, so to say, a revolution in the optical glass and optical instrument industry. The happy combination of the physicist designer, the chemist glass maker and the instrument manufacturer, backed by highly skilled technicians is thus the secret of the overwhelming success of the Jena venture. These efforts were generously backed by the Government, but without the atmosphere of collaboration between the different disciplines it is doubtful if State aid alone could bring about such phenomenal developments.

First World War : Optical glass a strategic material

When the war broke out in 1914, Great Britain was importing about 90 per cent of her requirements of optical glass principally from Germany; the U.S.A. was almost wholly dependent on Germany for supplies and France was also importing substantial quantities. On the declaration of hostilities, supplies to these countries from Germany were completely cut off and the Allies were exposed to great difficulties. Never before was the importance of optical glass as a strategic material realized more than during this critical period and its production received, necessarily, top priority. But production of optical glass is not just digging a few trenches here and putting up a few barricades there. It was a question of producing a very precise material for the exacting requirements of military optical instruments likely to affect the course of war. One of the belated realizations that went home was that although on the Allies' side there were two works in existence, namely Chance Bros. in England and Parra-Mantois in France, enjoying long seniority in establishment over the firm of Schott, quantity production of the desired quality could not be achieved without associating physicists and chemists with its manufacture. That being provided, the production of Chance's Works, which had stuck to optical glass making in spite of adverse market conditions, increased steadily, but to meet the unusually large war demands, manufacture was initiated in one more plant at Derby with the association of scientists; and these two factories were able to supply the war requirements in Britain. This success was really very praiseworthy.

> 'In the face of unparalleled difficulties, we have accomplished in three short years practically as much as it took our late enemies across the Rhine thirty years to do' (Peddle 1920).

America, today the land of plenty and a pioneer in many technologies, though not a belligerent in the beginning of the war, had her supplies of optical glass cut off rather abruptly and was even in a worse position. Although some attempts had been made to produce optical glass and some success had been achieved, particularly by Bausch & Lomb Optical Co., there was hardly any worthwhile production to meet war demands. The situation is well described by Lieut.-Col. Dr. F. E. Wright (1921), Chairman of the Army Commodity Committee on Optical Glass and Instruments, U.S. Ordnance Reserve Corps:

> 'When we entered the war we not only lacked a supply of optical glass, but we lacked information regarding the processes of its manufacture. We had little knowledge of the quality and sources of supply of the raw materials required. We lacked manufacturing capacity and a trained personnel to handle the problems.'

The secrecy regarding the manufacturing operations was so complete that, even under the emergency of war, America failed to receive assistance from her Allies. To quote Dr. A. L. Day (1920), Director of the Geophysical Laboratory of the Carnegie Institution of Washington and in charge of optical glass production, War Industries Board, U.S.A.:

> 'It is perhaps interesting to remark parenthetically that at the time when the French Liaison Commission visited this country after our entry into the war, to aid us with their experience in the production of war material, it was not permitted to divulge any details regarding the manufacture of optical glass upon the ground that the integrity of the existing glass monopoly in France had always been respected by the Government and must be so still, in spite of the war pressure. England adopted a similar attitude, and so in this one branch of the service, the United States was left to proceed unaided to endeavour as best it might to reproduce within the period of a few months all of the experience which had been attained in optical glass manufacture since the days of Abbe and Schott in the early eighties.'

The reference to England is somewhat surprising since it is on record that during the First World War, Messrs. Chance Bros. helped the Russian Government in starting the manufacture of optical glass at the Imperial Porcelain Works, Petrograd. This, it is claimed, provided the foundation of Soviet optical glass industry.

In the absence of assistance from the Allies, the U.S. Council of National Defence approached two of the country's premier research organizations, namely the Geophysical Laboratory of the Carnegie Institution of Washington, then engaged in phase equilibrium studies on silicate systems, and the National Bureau of Standards where researches on glass and ceramics had recently been undertaken. With the co-operation of some of the optical instruments manufacturing firms and others, such as Bausch & Lomb Optical Co., Spencer Lens Co. and Pittsburgh Plate Glass Co., the scientists from the laboratories set themselves to work out the details of operation schedules and scientific methods of control, and succeeded in modifying the existing processes to produce satisfactory optical glass. Practically all the optical glass was produced during that period mainly through the combined efforts of the physicists and chemists of the two institutions. Their contribution was not confined merely to laboratory and advisory work but extended to commercial production, and so unique was their success that they were even able to reduce the conventional melting schedule substantially from three days to about 24 hours. At some places they even took over charge of the entire plant. This remarkable success in the production of an essential munition material during a national emergency, without any external aid, is unquestionably a great tribute to the ability of scientists to tackle problems and even make great advances in highly technical and closely preserved fields.

One of the noteworthy features of developments in the U.S.A. and at the Government plant in Derby in the U.K. was the publication of the results, which highlighted particularly the contribution of various oxides used in glass making to the optical properties of glass; the need for controlling the additions to avoid devitrification and poor durability of the resulting glass was emphasized. Some of the publications, e.g. those of C. J. Peddle, are now classics on the subject; they helped to remove a good deal of secrecy which surrounded the composition of optical glasses. No doubt, chemical analyses of a number of common optical glasses were available, but that information alone was not enough to produce optical glasses required by instrument makers.

The emergence of optical glass as a strategic material during the First World War led various Governments to take steps to encourage its production and the development of instruments industries in their countries. In Great Britain, an Optical Glass Committee was set up with the Director of Scientific Research of the Admiralty as Chairman to co-ordinate the activities of various organizations, such as Chance Bros., the British Instruments Research Association and the optical instrument makers. In the U.S.A., Government interest was more direct and the production of optical glass became a regular feature at the National Bureau of Standards. This ensured an uninterrupted supply of high quality optical glass to Government; not only that, it enabled continuous research and development and the maintenance of a viable production organization which could be expanded should an emergency arise. The foresight and correctness of this decision was demonstrated in the Second War when the Bureau's plant stepped up its production from 18 tons in 1941, when America was not a belligerent, to 68 tons in 1942 and to 120 tons in 1943.

In view of the steps taken by different countries, supported in many cases by their respective Governments, the production of optical glass was not much of an anxiety at the outbreak of the Second War. Production was stepped up in the then existing plants, and two other countries, namely Canada and Australia, entered the field, the former in collaboration with Messrs. Chance Bros. and the latter with the technical assistance from the National Bureau of Standards.

Beginning of glass technology

The war years of 1914-18 and the post-war period witnessed the very welcome move, encouraged in some of the industrially advanced countries, towards the scientific study of manufacturing operations, the designing of equipment and furnaces and the fuller understanding of the physico-chemical principles underlying the composition of glass. New research organizations were established; empiricism began to make way for scientific understanding and the veil of mystery which had shrouded glass making began to be gradually lifted. These developments transformed glass, hitherto regarded mostly as a medium for the expression of art, into the material of versatile utility that it is today. The accumulation of knowledge is a painstaking and necessarily a slow process, and in this, although many persons from several countries have made substantial contributions, the work of Prof. W. E. S. Turner and his skilled collaborations stands out; the contributions of Prof. Turner and his school are remarkable both for the diversity of fields investigated and for the usefulness of results obtained.

New developments—Rare earth and other glasses

Although the introduction of barium crowns, barium flints and borosilicate crowns by Abbe and Schott produced remarkable results, particularly for photographic and microscope lenses, it did not provide a complete solution of the problem of glasses of different dispersions for the same refractive index and of the same dispersion with variable indexes. There still remained the question of making flints with high dispersions but of low refractive index. In addition, the optical designers became more and more interested in glasses of higher refractive index and lower dispersion than those attained hitherto.

During the period between the two World Wars, a significant advance was made by George W. Morey (who had done valuable work on the production of optical glass during the war) in the U.S.A. and by Korde in Germany, by the discovery of what are known as *rare earth optical glasses* possessing very high refractive index and low dispersion. By painstaking researches on the chemico-optical behaviour of various oxides with the specific object of producing crown glasses of high refractive index, Morey was able to establish that the traditional conceptions based on silicon or phosphorus as the essential elements of optical glass must be modified. By using boric oxide alone as the glass former in combination with rare earth oxides, such as lanthana and thoria, and other oxides like titania and tantalum and tungsten oxides, optical glasses with very high index but low dispersion could be obtained. Thus started another landmark in optical glass making as significant, though not as exciting, as the development of barium glasses by Abbe and Schott.

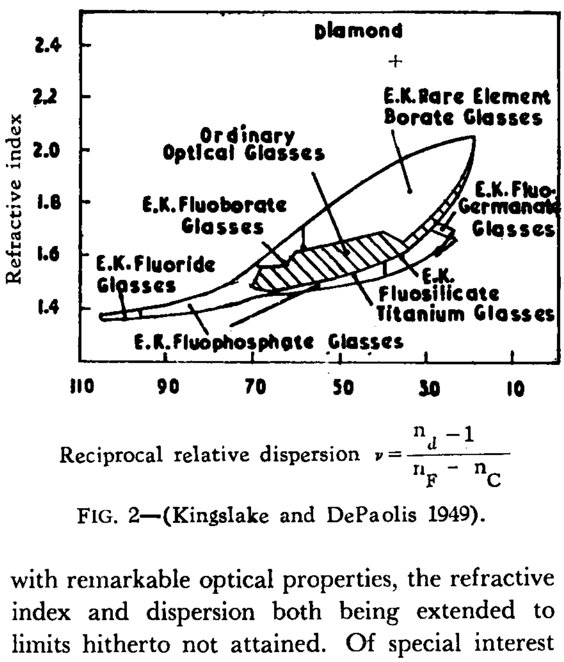
This pioneering work received considerable stimulus by the brilliant contribution of Zachariasen, a pupil of V. M. Goldsmith, in 1932, on the extension to glass structure of the principles of crystal chemistry based on size and electric charge of participating ions. Researches on the composition and physical properties of glass were handicapped by the lack of knowledge of the structure of glass and Zachariasen's views, postulating continuous three-dimensional random structure, supported by Warren and his collaborators by X-ray analysis, provided a great lift to investigations on the interpretation and correlation of the properties of glass with composition, and even helped in predicting new fields of glass formation.*

The extremely corrosive nature of rare earth glasses to even the most resistant refractories presented a serious production problem, and this was solved by resorting to melting in mode-

* Prof. W. A. Weyl (1960) has recently discussed in detail Zachariasen's hypothesis *vis-à-vis* the conditions of glass formation.

rate sized platinum crucibles in electrically heated furnaces—a practice which Faraday, Harcourt and Stokes, and also Abbe and Schott, had adopted in some of their experimental work. The production of these glasses was begun in the U.S.A. just before the Second War and during the war period several tons were produced. In view of their superiority and versatility for photographic lenses, they are now being liberally used in sensitive and special cameras.

Inspired by the work of Morey and assisted by the new approach provided by Zachariasen, the development of new optical glasses became a favourite subject in many laboratories, and the labours of the Kodak group of investigators met with conspicuous success in obtaining glasses



Reciprocal relative dispersion $\nu = \dfrac{n_d - 1}{n_F - n_C}$

FIG. 2—(Kingslake and DePaolis 1949).

with remarkable optical properties, the refractive index and dispersion both being extended to limits hitherto not attained. Of special interest among them are the fluosilicate flints or super flints, i.e. glasses with dispersion higher than flints of corresponding refractive index and the all-fluoride glasses without the traditional silicon, phosphorus or boron glass formers. Super flints have been produced commercially and have proved to be of great assistance to instrument designers. Fluoride types are difficult to produce, but in view of their very low refractive index (1.4) and high ν-value (about 100), they are of special merit in extending light transmission both towards ultraviolet and infra-red—a very desirable feature for optical instruments; it has established the possibility of replacing the use of fluoride minerals, particularly in microscopes. Another group of non-silica optical glasses possessing high transmission in the ultraviolet but high absorption in the infra-red are the phosphate glasses made by incorporating aluminium phosphate, a material similar in some properties to silica. Thus, during the period of about a decade, the field of optical glasses has widened remarkably and a much larger number of elements is now available for incorporation in them. The successive stages of these developments are illustrated in the refractive index and reciprocal relative dispersion diagram (cf. Fig. 2).

Plastics and optical systems

There has recently been some curiosity about the possible use of transparent, colourless plastic materials in place of optical glass, since some of them have refractive index and Abbe values very similar to the crowns; some of them, it is claimed, possess partial dispersion ratios similar to the extra dense flints and also extended transmission farther into the ultraviolet. In view of these optical advantages, reinforced by their unbreakable character, they should be very useful in obtaining complete colour correction in lenses. The ease of varying their refractive index and dispersion by adding various ingredients provides additional flexibility. They have, however, the very serious drawback of getting scratched easily and many of them get discoloured when exposed to light and atmosphere. An optical instrument cannot be expected to be operated in the absence of light and the atmosphere, and hence, in spite of the apparent advantages, the appearance of plastic substitutes has not enthused the optical instrument maker.

Development in production technology

Although soon after the First World War, several branches of the glass industry witnessed a rapid transformation from a hand-operated to a highly mechanized industry, the practice of optical glass making did not, barring a few exceptions, undergo any comparable change and the manufacturing operations continued to remain more or less similar to those introduced by Guinand more than a century ago. One advance, however, was the introduction of the stirring machine in place of hand stirring. Another of importance has been the casting of molten glass after homogeneization in a rectangular iron container in which it is slowly cooled and annealed to produce a large block from which smaller blocks or plates may be cut with a diamond saw; from the small blocks or plates, pieces of any given weight can be taken, resoftened in a mould and pressed into lens blanks. The latter, namely, lens blanks, are advantageous when the demand for a particular shape is quite large. The quality of the refractory pot and the stirrer, which is a determining factor both in regard to quality and yield of usable glass, has been much improved by using better clays and by adjusting the composition of the refractory according to the acidic or basic nature of the glass composition. Also contributing to an increase in output and to a much better pot has been the process of making pots by slip casting developed by A. V. Bleininger of the National Bureau of Standards. With these developments and with the gradually increasing understanding of the physical and chemical principles underlying glass making, efforts have been concentrated mainly on improving the quality of glass in respect of homogeneity and light transmission, on ensuring better reproducibility of glass within still narrower limits of tolerance of refractive index and dispersion, and on increasing processing efficiency in regard to yield and utilization factor of the glass obtained. The availability of raw materials and chemicals of much higher purity than previously used has materially contributed to success. These developments have made available to the instrument maker optical glasses of more varied properties, and have ushered in optical instruments of improved performance and utility.

A daring advance in the technique of production was made by Corning Glass Works during the Second War at the instance of the U.S. Government to meet increasing war demands; and this is the development of a *continuous process* of melting optical glass, which had hitherto been made by the *intermittent process* in platinum-lined tanks—a practice similar in principle to the melting of commercial glasses in tank furnaces. The platinum-lined tank is heated electrically and a platinum stirrer is used for homogeneization. The glass comes out of the tank in the form of a thick ribbon or bar from which prisms and other shapes can be made. Also, mouldings can be made by discharging the glass in the molten condition through a special feeder into the moulds of an automatic pressing machine. Thus, a century-old conception that optical glasses can only be melted in pots has had to give way. The process has been very much improved in post-war years. The yield is much higher than that obtained with the intermittent process and platinum being practically non-corrosive to glass, the quality of glass is much better; the loss of precious metal is negligible. This entails, obviously, very heavy investment and consequently the process is suitable only for the large production of particular shapes. It is eminently suited for the production of ophthalmic glass which is required in large quantities and in very few shapes and sizes.

Thus, within a period of 25 years, through daring steps and spectacular developments, America, which was denied, even under the emergency of war, technical assistance by those controlling the know-how, has become the leading country in optical glass making.

Varieties of optical glass

A welcome move during the post-war period was the rationalization of optical computations resulting in a substantial reduction in the number of glass varieties required by the designers. Whereas until the beginning of the Second War, the number of varieties in actual use was unduly large (about 200), it has, in spite of the much wider range of refractive index and dispersion now available, been reduced to about thirty. This number seems to cover most of the requirements.

'The number of varieties of glass available is very large, probably larger than is necessary .... Some of these are so close to others that they are obviously accidental variants rather than the result of deliberate attempts to produce them .... Since the designer's employer is not ordinarily able to take issue with his statements as to how many kinds of glass he must have to produce results, he is naturally tempted to shift as much as he can of his burdens on to the shoulders of the glass maker' (Rayton 1938).

'The Chance Catalogue and a supplement give the optical data for ninety-four types of optical glass; some of these are rarely in demand and in consequence cannot be produced economically. This handicap is recognized by the industry and in 1949 it was generally agreed among users that many of the glasses usually intermediate between other closely related types are not essential. These intermediates had been created in past years, sometimes as off-index variants of former standard types, sometimes to meet the particular requirements of individual computers. Collaboration between the various interests concerned resulted in agreement on thirty standard types, apart from the rare earth and other special glasses, and these now meet 96 per cent of the total demand' (Wheat 1954).

In India, at present about twenty varieties of optical glass are used, and some of these might be due to supplies having, at times, been imported from different sources. In view of the very small demand, the suppliers naturally prefer to supply whatever they have in stock. In some cases, the total annual consumption is not enough to use up the glass from a single melting, and the surplus has to be stocked over several years and thus adds to the cost. There is considerable room for reducing the number and it would be more economical to compute and make tools on the basis of varieties common to most consumers, rather than demand small quantities of many closely related varieties.

Position in India

Hitherto, India has depended for her requirements of optical instruments on other countries, particularly Germany, and an atmosphere favourable to the growth of a sizeable instruments industry was almost non-existent. The Mathematical Instruments Office, established in Calcutta in 1930 as an instrument repair shop (now the National Instruments Ltd.), the Technical Development Establishment, Dehra Dun, of the Ministry of Defence, started during the Second War, and the few optical instrument makers carried out only grinding and polishing of optical components made from imported glass. The total output was small. It was possibly the smallness of the total demand for optical glass (two to three tons per annum) and the ease of importing it that overshadowed its importance as a strategic material. This importance was realized during the Second War, mainly on account of the difficulty of getting supplies from abroad, and in order to start its production in the country the Government approached the British Government for technical assistance from Messrs. Chance Bros. Ltd. Simultaneously, the Council of Scientific and Industrial Research financed research schemes for working out processes for its production, but the results obtained were not particularly useful. In a report on the post-war development of the Indian glass industry, the Glass Panel of the Government of India pointed out (1947) that on account of the specialized and limited demand for optical glass it was doubtful if private parties would be willing to undertake its manufacture; the Panel recommended that in view of its strategic importance, the Government should take early steps for its production.

During his visits to Europe and the U.K. soon after the termination of hostilities in 1946 and 1947, the speaker got the impression, during his discussions with optical glass manufacturers, that it would not be easy to obtain technical collaboration with manufacturing firms. When, therefore, he was a guest worker at the National Bureau of Standards, Washington, in 1948, he welcomed, through the goodwill of the U.S. Government, the opportunity of seeing the methods adopted in producing optical glass in the experimental plant attached to the Bureau. After his return to India, he submitted proposals for the production of optical glass in the country, but emphasized that in considering a scheme of this nature the strategic value should outweigh the commercial aspect and that even though it might be cheaper for some of the manufacturing countries to import optical glass, they made it and the Governments encouraged its production in various ways. This view was later corroborated by different teams of experts visiting the country.

The Government of India conducted negotiations for technical collaboration with almost all optical glass manufacturing firms, particularly in the U.K., the U.S.A., East and West Germany, France and Japan. Technical teams from some of these countries visited India, but no satisfactory basis for collaboration could be worked out. Optical glass continued to remain a matter of anxiety for the Government, and the Prime Minister even felt that under the circumstances the best course would be to ask the Central Glass and Ceramic Research Institute to take up the work. In the meantime, two senior officers of the Institute also had the opportunity of acquainting themselves with the methods of production adopted at the Glass Division of the National Bureau of Standards. Finding that negotiations with foreign firms were not leading to any practical result, the Planning Commission, towards the middle of 1956, assigned the task of producing optical glass to the Institute. In the meanwhile, the Government of the U.S.S.R. agreed to offer assistance in putting up a factory for the production of optical and ophthalmic glasses in India.

Complexities of optical glass making

If it were possible to obtain the final product precisely as computed from the ingredients of the glass batch put into the pot, the manufacture of optical glass would be a comparatively simple operation. But glass melting is a process in which some constituents are being continually lost on account of volatilization and some others are being added to due to the corrosion of the pot; and both factors, the latter more effectively, affect the homogeneity and clarity of glass. In fact, glass is never in equilibrium; its composition is continuously changing during melting. The intricacies of optical glass making arise from this inherent peculiarity of the manufacturing operations to obtain a product possessing the highest standards of homogeneity and transparency, and values of refractive index and dispersive power which should vary within narrow limits of tolerance.

Precision industries necessarily have precision tools of production, but the optical glass maker, although assigned the task of producing a very precise material, has no such tools and he has to face an array of fluctuating conditions at very high temperatures. *The secret of success of optical glass making—call it an art or technology—lies, not in melting a secret batch which can be worked out after some experience, but in the scientific mastery of the minutest detail of the entire range of operations and rigorously controlling every one of them.* It is for this reason that every optical glass manufacturer maintains an up-to-date research laboratory manned by able and experienced staff. This explains the conspicuous success achieved by the scientists of the Geophysical Laboratory and the National Bureau of Standards during the First World War. Neither had any previous experience in optical glass making but both were well versed in the fundamental sciences bearing on glass, particularly the chemistry of silicates. In view of the very decisive rôle of the laboratory and the limited demand for the product, optical glass manufacture has often been called 'laboratory production on a commercial scale'. It is, in fact, *a research-cum-production business*. It is worth mentioning that every team of experts which visited this country included provision for either a well-equipped laboratory attached to the works or, in the case of the factory being located in Calcutta, its association with the Central Glass and Ceramic Research Institute.

Selection of technology

Being a supremely important strategic material, not much has been published on the technology and operations of optical glass manufacture. Some information is available from the publications of the Geophysical Laboratory and the National Bureau of Standards, Washington. There are at present three processes by which optical glass is made: the *classical process* in which a refractory pot is used for melting the glass, the process of *melting in platinum crucibles* and the *continuous process* of melting in platinum-lined tanks. In all the three processes, homogeneization is achieved by stirring; a refractory stirrer is employed in the first, and platinum stirrers in the other two. The first two are intermittent in operation, whereas the third is continuous.

The quality of the more common types of optical glass produced by the first process, even though employing a refractory pot susceptible to corrosion by glass, is remarkably good, but the yield is small. In the other two, corrosion is almost negligible and the molten glass after homogeneization is fairly free from striae. The first is suitable for producing moderate quantities of a given type of glass, the second for making only small quantities, and the third, on account of its high rate of production, is suitable for meeting large demands of a particular type and shape. The last process is stated to be unsuitable for melting high lead glasses and also phosphate glasses. The change from one type of glass to another involves emptying and cleaning the tank before receiving the other batch and this makes the process relatively inflexible; for economic operation, the minimum daily production should be about one ton.

When the Institute undertook work on optical glass, one of the first decisions to be made was the selection of the technique appropriate for production, taking into consideration the present demand and also the demand to be anticipated in the near future. It was apparent that the continuous process with the heavy capital investment it obviously entails, was out of the question. Added to this, was the need for importing every bit of platinum equipment. Moreover, even with all the care, the use of platinum is not without risk; in the case of damage during melting, the repair of equipment will have to be carried out in a foreign country and this would make the process more intermittent than the intermittent processes themselves. The demand even in the next ten years is not likely to be large enough to warrant adoption of the continuous process. It has not so far been adopted in several optical glass making plants, and the bulk of optical glass is still made by the intermittent processes.

Taking into consideration all the factors, it was decided to concentrate on working out the details of the intermittent process, using both the refractory pot and the platinum crucible for melting. General acquaintance with the operations at the National Bureau of Standards of melting glass in refractory pots also favoured this decision. It may be interesting to mention here that almost every team of optical glass experts that visited the country for negotiating technical collaboration suggested the adoption of the intermittent refractory pot technology. Again, in view of the small demand of any one type of optical glass, the choice was restricted to the pot cooling operation rather than casting the glass into slabs or rolling it into plates. The annual requirement of some types of glass is no more than one hundred pounds and the adoption of the continuous process was, obviously, not feasible.

Raw materials and equipment

The precise properties expected of optical glass, referred to earlier, demand the use of raw materials of high purity and uniform quality. The presence of colouring oxides, such as those of iron, chromium, cobalt, copper, titanium, nickel, manganese, etc., even to the extent of one-thousandth of one per cent, has a deleterious effect on the transmission of glass. Decolourization, i.e. neutralizing the colour of iron by suitable additions of manganese or selenium, is not desirable on account of the reduction in overall transmission, although some of the early optical glass makers are known to have used them. Moreover, on account of solarization of the resulting glasses and the consequent deterioration of the optical instrument when used in light containing an appreciable proportion of ultraviolet radiation, the use of decolourizers, particularly of manganese, is inadvisable. Clays, felspars, etc., used in making the refractory pot and the stirrer should be sufficiently free from colouring oxides so that contamination of glass due to the corrosion of the refractory is reduced to the minimum; chlorides and sulphates tend to produce opalescence in lead glasses and should not be present in the chemicals and other raw materials.

The first step, therefore, was to study the raw materials, their beneficiation and processing in order to render them suitable for use in optical glass manufacture. The survey of raw materials undertaken by the Institute some years ago proved to be of great help. After extensive studies, involving trials on refractories and experimental melting, it was established that except for some chemicals, such as soda ash, potassium carbonate, borax, boric acid and barium carbonate, which are being imported to meet the requirements of various other industries, the chemicals and raw materials required for optical glass making were available in the country, and the erroneous impression that India lacked such raw materials was finally dispelled. Table II indicates the standard of purity of raw materials maintained in the optical glass plant at the Institute.

To make a start, the main problem was the procurement of special equipment. Such equipment is not available for import as the items are specially designed and fabricated for the firms, which maintain rigid secrecy for their manufacturing techniques and processes. All equipment, such as stirring machine, pot lifting carriage and various other gadgets, including plaster moulds, were designed and fabricated at the Institute. So also the furnaces and kilns required for firing the pots, for melting, slumping, moulding, annealing, etc., were designed and constructed at the Institute. Needless to add, the several special refractory parts and fittings required for the furnaces were also made.

Some typical problems of production

Homogeneity and reproducibility of refractive index and dispersive power are requirements insisted upon for all types of optical glass. To attain these, constancy of chemical composition is the first essential. Even when every attention has been paid to the analyses and to the weighing and mixing of raw materials, there are two factors which give rise to a composition different from the one calculated on the basis of input of raw materials. There are losses due to volatilization during melting and there is absorption into glass of alumina, silica, iron oxide, etc., from the melting pot. These losses and gains vary with temperature and operating proce-

TABLE II

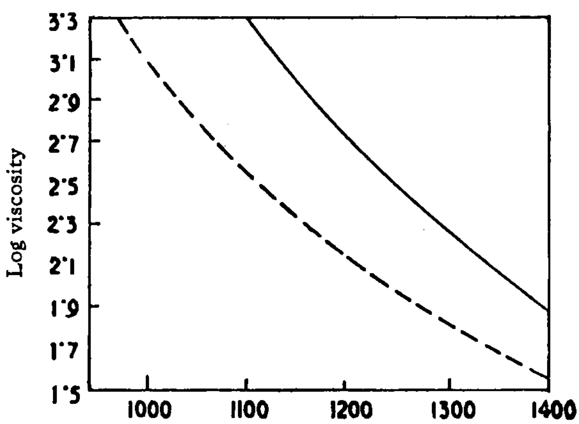
Standards of purity of important raw materials used in the production of optical glass

Raw materials	Purity standard (per cent)	Raw materials	Purity standard (per cent)
Sand SiO_2	Fe_2O_3 < 0.003, no Mn, Co, Ni, Cr.	Red lead Pb_3O_4	Fe_2O_3 < 0.001 CuO < 0.0005 Pb < 0.1
Boric acid H_3BO_3	Fe_2O_3 < 0.001	Soda ash Na_2CO_3	Na_2CO_3 > 98.0 Fe_2O_3 < 0.002 NaCl < 0.50 Na_2SO_4 < 0.20
Borax, anhydrous $Na_2O.2B_2O_3$	Fe_2O_3 < 0.001	Potash K_2CO_3	K_2CO_3 > 98.0 Fe_2O_3 < 0.001 KCl < 0.10 K_2SO_4 < 0.10
Barium carbonate $BaCO_3$	$BaCO_3$ > 99.0 Fe_2O_3 < 0.005 $BaSO_4$ < 0.25 BaS < 0.25 CuO < 0.0005	Aluminium hydrate $Al_2O_3.3H_2O$	Al_2O_3 > 64.4 Fe_2O_3 < 0.005
Barium nitrate $Ba(NO_3)_2$	$Ba(NO_3)_2$ > 99.0 Fe_2O_3 < 0.001 $BaSO_4$ < 0.10	Zinc oxide ZnO	ZnO > 99.0 Fe_2O_3 < 0.001 PbO < 0.10 CuO < 0.0005
Calcium carbonate $CaCO_3$	CaO > 98.5 MgO < 0.5 Fe_2O_3 < 0.010 $CaCl_2$ < 0.10	Arsenic trioxide As_2O_3	As_2O_3 > 99.0 Fe_2O_3 < 0.01
		Antimony oxide Sb_2O_3	Sb_2O_3 > 99.5 Fe_2O_3 < 0.01 As_2O_3 < 0.20

dures, and have to be carefully worked out in advance. High temperatures and long melting periods increase the extent of volatilization and corrosion, and both tend to produce striae in glass. Pot corrosion has, in addition, two other adverse effects: firstly, the introduction of undesirable iron into the glass and, secondly, production of bubbles. The latter can often be so serious that an otherwise good melt may be completely ruined in the very last stage of melting.

In the course of pilot meltings designed to work out the precise conditions for ensuring reproducibility of melts, it became apparent that the chief hurdle in optical glass making was the performance of the refractory pot; and the production of a satisfactory pot became a major essential step. It was fortunate that the Institute had an experienced refractories research group. Pots were made by slip casting and although the various steps of the process are fairly well known, the production of a satisfactory pot with the clays available proved to be very difficult. Failure to reproduce results, particularly in regard to making the glass bubble-free, although conditions of making and firing the pot remained apparently the same, proved baffling. The causes were tracked down and all difficulties were overcome.

One of the critical operations in optical glass making is the stirring of the molten glass mass for ensuring homogeneity. The working out of an appropriate stirring schedule in regard to speed, radius of sweep, duration of stirring, rate of drop in temperature and temperature of the furnace at the time of removing the pot is important and for this a precise knowledge of the viscosity of molten glass at various temperatures is a prerequisite. Viscosity measurement at high temperatures demands particular care; the operation of the furnace is specially important, as even a slight change in temperature in the range of operation markedly affects the viscosity. Viscosity values are determined at the Institute by the N.B.S. platinum ball-moving method in a controlled Pt-Rh wire-wound furnace and a large number of curves indicating the variation in viscosity with temperature for various optical glasses have been prepared (cf. Fig. 3) to provide the basis on which appropriate stirring schedules can be formulated.



- - - - Dense flint . . . . n_d = 1.623

——— Borosilicate crown n_d = 1 610

FIG. 3—Variation in viscosity with temperature

After stirring, the pot containing the molten glass is removed from the furnace and is cooled under controlled conditions. The cooled pot is broken and the chunks are inspected for imperfections, which are trimmed off, and the good pieces free from striae are selected for moulding into blanks or for converting into slabs. Inspection and trimming need great care and skill, as slight negligence may result in bad glass remaining embedded in good pieces or in trimming away good glass from acceptable pieces.

Selected pieces, even though chemically homogeneous, contain an appreciable amount of residual strains and these are removed by annealing, an operation which demands meticulous care and control. In annealing optical glass, in addition to composition, shape and size of the piece influencing the annealing schedule, there is one other factor which has to be taken into consideration, and that is the increase in refractive index during annealing. In order that the increase in refractive index is the same throughout the piece, the temperature distribution in the piece should be uniform. A difference of about 10°C. at two different points in the same piece may not cause an objectionable strain, but it causes sufficient difference in refractive index to render the glass worthless for optical purposes. The annealing kilns have, therefore, to be constructed with precise temperature control. Properly annealed optical glass slabs should not show a deviation of more than 5μ per centimetre length when viewed in a polarimeter.

In this lecture, it is obviously difficult to refer to all the intricate operations of optical glass manufacture; I have, however, said enough to indicate the nature of the tasks confronting the optical glass maker. Perhaps it is not surprising that the glass maker should jealously safeguard the results achieved and the experience gained after so much sustained effort. It is remarkable how, in spite of all the intricacies in the various operations, it is possible to obtain a product of unusual purity and reproducibility. *There is no mystery about optical glass making which only the specially gifted are required to unravel. A scientific approach is what is needed, and the secret of success lies in scientific understanding as opposed to empiricism.*

After about eighteen months of systematic work on raw materials and on designing and fabricating of equipment and furnaces, studying details of pot making, working out different schedules, such as stirring and annealing, and fixing up suitable compositions, the Institute was able to produce optical glass on a pilot scale in 600-lb meltings. The samples were examined by Prof. P. K. Kichlu, Professor of Experimental Physics, University of Delhi; by the National Physical Laboratory of India, New Delhi; and by the Technical Development Establishment of the Ministry of Defence, Dehra Dun, and were found to be satisfactory. The last-named establishment, which is the biggest consumer of optical glass in the country, declared them *A Grade*. In the preparation of some of the schedules, we were considerably assisted by some of the recent publications of the Bureau of Standards.

On the completion of pilot trials, the Government of India and the Planning Commission reviewed the position with respect to the manufacture of optical glass and early last year entrusted its production to the Institute. A plant with sufficient capacity to meet the requirements of the country has been fabricated and erected in the Institute premises. It went into production in the latter part of 1960.

Yield and cost of production

The yield of usable optical glass by the refractory pot process is, as already mentioned, rather low due mainly to pot corrosion. It depends very much on the form in which the glass is ultimately shaped for delivery to the instrument maker. Experience of the last few months of actual production of some major types of glass in the Institute's plant indicates that with the methods adopted and equipment made at the Institute, the yield is not lower than that mentioned in the proposals of the various expert teams that visited the country. A few transmission curves of and values of light absorption by glasses now in production at the Institute, compared with those of the best imported samples, are given in Figs. 4—9 and Table III. It will be observed that the optical quality of the glasses produced at the Institute is highly satisfactory.

The question has sometimes been raised as to how far, with such a small demand, the production of optical glass is a commercial proposition. It is a difficult question and the answer requires an appreciation of the relative importance of cost *vis-à-vis* the material itself. As already pointed out, optical glass is a strategic material; it is not an item of mass production. It is not generally appreciated that optical glass manufacture by itself is not a fortune-making business and without reflecting on the business acumen of optical glass makers, it would not be far from truth to say that they earn their profits from other items of manufacture and not from optical glass. Some of them are also consumers of optical glass as instrument makers, while some produce the glass as one of several other items because it bestows a special and enviable prestige on the manufacturer. Ever since the First World War, the manufacture of

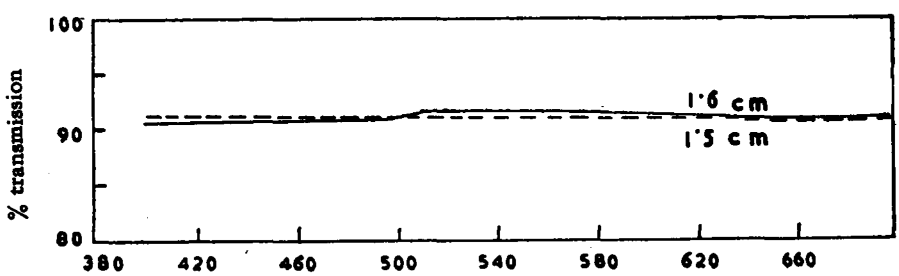
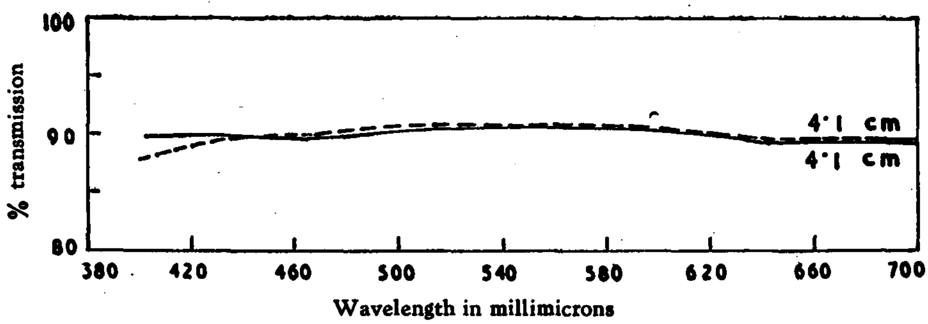


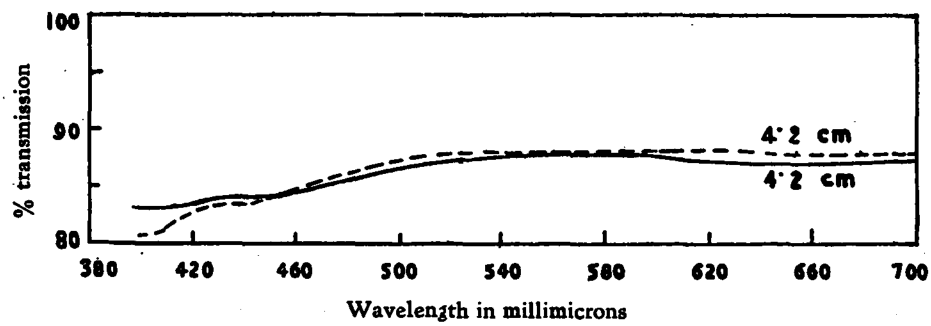
FIG. 4—Borosilicate crown



----- Imported ; ... ... n_d = 1.5720

——— C.G. & C.R.I. ... n_d = 1.5721

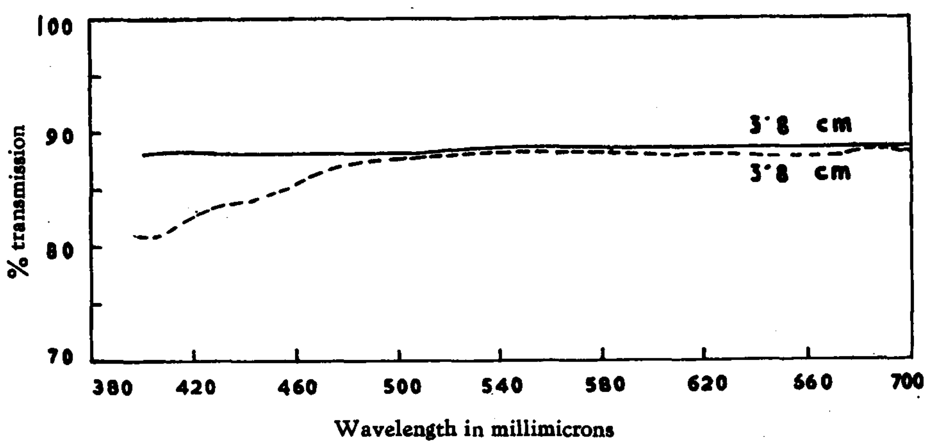
FIG. 5—Medium barium crown



----- Imported ; ... ... n_d = 1.6100

——— C.G. & C.R.I. ... n_d = 1.6122

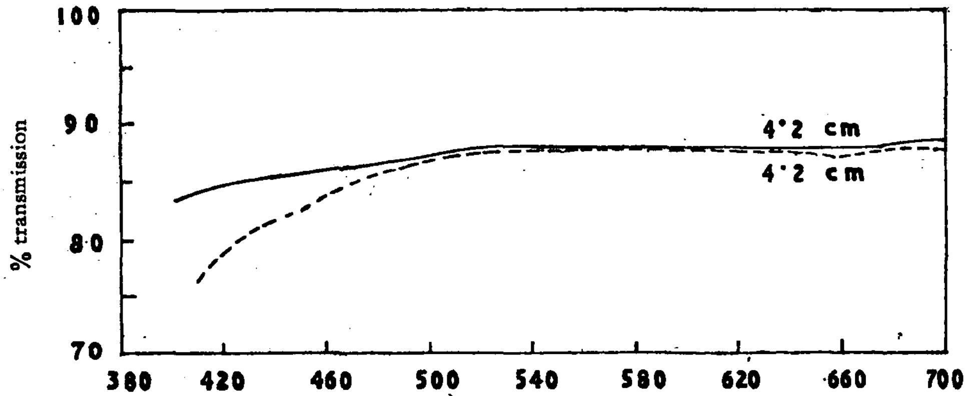
FIG. 6—Dense barium crown



----- Imported ; ... ... n_d = 1.6234

——— C. G. & C.R.I. .... n_d = 1.6217

FIG. 7—Dense flint



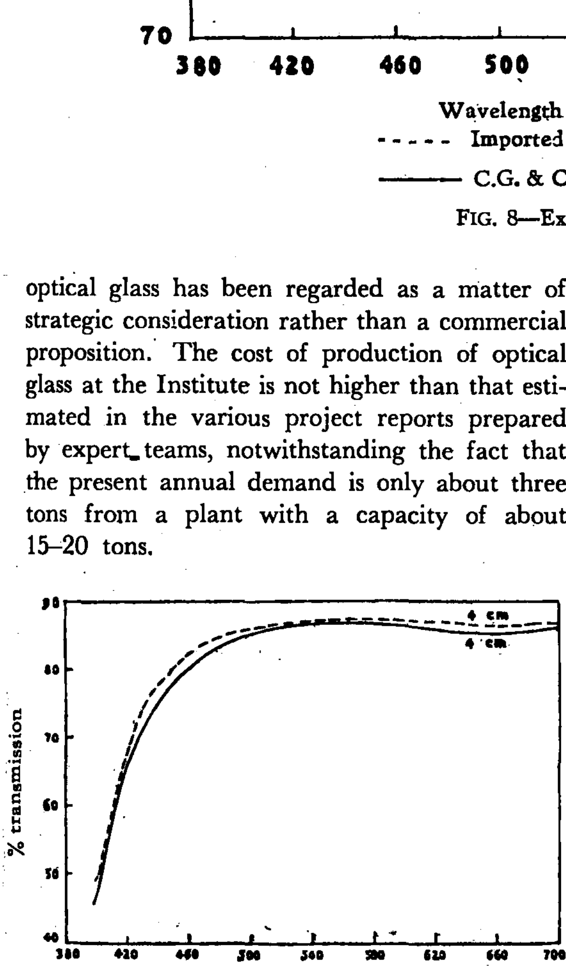
Wavelength in millimicrons

- - - - - Imported; ... ... n_d = 1.6510

——— C.G. & C.R.I. ... n_d = 1.6489

FIG. 8—Extra dense flint

optical glass has been regarded as a matter of strategic consideration rather than a commercial proposition. The cost of production of optical glass at the Institute is not higher than that estimated in the various project reports prepared by expert teams, notwithstanding the fact that the present annual demand is only about three tons from a plant with a capacity of about 15–20 tons.



Wavelength in millimicrons

- - - - - Imported; ... ... n_d = 1.717

——— C.G. & C.R.I. ... n_d = 1.7162

FIG. 9—Double extra dense flint

In presenting the account of the efforts of the Institute for relieving the country's dependence for a vital strategic material, I should like to pay a tribute to my colleagues at the Institute who helped in solving the many problems that arose during the course of this work with great devotion and enthusiasm.

Industrialization in India

I chose to speak today on optical glass not merely because it has absorbed my attention for some years now, but also because the history of optical glass production has some lessons by which we can profit in the present context of industrialization of the country.

The supremacy in optical glass manufacture achieved by Germany in the eighties of the last century was due solely to the fact that while in other countries the producers were content with empirical methods of production, in Germany, scientists and manufacturers collaborated in gaining a full scientific understanding of the various processes and in developing appropriate manufacturing techniques. Although one might succeed in starting industries by importing know-how, plant and equipment from others, that

TABLE III

Light absorption by optical glasses

Type of glass	Light absorption (%) per centimetre		
	CGCRI sample	Imported sample	Permissible limit* (maximum)
Borosilicate crown 510/645 ..	0.30	0.30	1.0
Dense flint 623/360 ..	0.33	0.45	2.0
Extra dense flint 651/337 ..	0.38	0.35	2.0
Double extra dense flint 717/295 ..	0.73	0.60	—
Hard crown 519/603 ..	0.80	0 80	1.0
Light barium crown 541/597 ..	0.30	0.80	1.0
Medium barium crown 572/576 ..	0.51	0.40	1.0
Dense barium crown 610/560 ..	0.60	0.55	2 0

* Indian Standard IS : 1400-1960.

alone is not enough to ensure advancement. Far more important is the scientific understanding of the manufacturing operations. For lack of a suitabe term, I may call it the 'know-why'. It is not enough to acquire the 'know-how', we must develop the 'know-why' through our own efforts.

The second lesson to learn is that mere availability of facilities for scientific research and of opportunities for industrial development are not enough to ensure economic progress. England and France were both ahead of Germany in having an established optical glass industry, and some of their outstanding men of science were also busy in optical glass research. A proper co-ordination of science, technology and industry is what is required. It is this co-operation which led to the pre-eminence of Germany in the optical glass field. Co-ordinated effort is much more productive of practical results than isolated brilliance in science or technology.

Let me elaborate this point a little. The Jena pioneers, even though utilizing the know-how long established in other countries, not only succeeded in stopping imports of optical glass from France and England but, what is even more telling, they even started exporting optical glass to these very countries; not only that, they succeeded, because of their co-ordinated efforts, in establishing a world monopoly in optical glass. Towards the close of the last century, Germany was systematically adding science as an additional dimension to industry, and by developing a new conception of technology based on the integration of science with manufacture, she achieved industrial supremacy in several fields pioneered by others, such as dyestuffs and, no doubt, optical glass. A tradition of applying science to industry grew in that country and a climate conducive to the effective co-ordination of science and industry soon developed. This has provided Germany with that infallible capital, the technological skill, in the industrial field and its effectiveness has been confirmed by the astonishing success, often called 'economic miracle', which Germany has achieved in recent years in rehabilitating her war-shattered economy. No doubt in these efforts she has received liberal financial assistance through the Marshall Plan, but that alone without the technological skill could not have produced, within a decade, these prodigious results and raised her to a position from where she could help America in her difficulty of balance of payments. What can be achieved by a proper co-ordination of science, technology and industry has been demonstrated by the most spectacular achievements of space travel just achieved by the Soviet Union and the United States; the former, before the Revolution, was not much of a scientifically developed country.

India is now engaged in the mighty effort of rapidly industrializing the country for raising the standard of living of the masses. The results of these efforts will be largely determined by the speed of technological progress and the quickness with which the country becomes technologically independent. In order to make up the long leeway and catch up with industrialized countries, she has been getting welcome assistance—technical and financial—from friendly nations. But economic progress cannot be assured by drawing on others' goodwill only. Those in charge of economic affairs have appreciated the situation; it was recently stated, for instance, that:

> 'We in India regard its (external assistance) indefinite continuance as inimical to our sense of national resolve and purpose. That is why we have adopted as our objective that we should be independent of extraordinary forms of external assistance in as short a time as possible.'
>
> (Speech delivered in Chicago by B. K. Nehru, Commissioner-General for Economic Affairs, *Amrita Bazar Patrika*, November 20, 1960.)

and

> 'The earlier we rely less and less on technical know-how from abroad the better for us.'
>
> (Shri Manubhai Shah, Union Minister of Industry, *Hindusthan Standard*, January 25, 1960.)

While the country is procuring know-how, plants and equipment from other countries, we should simultaneously and without loss of time initiate studies on the 'know-why' of operations which will help not only in running industries more efficiently but also in developing new and better machines and equipment and making the nation technologically independent. Merely copying the know-how, without adequate scientific understanding, will not help us to achieve productive efficiency and high quality manufactures. Complaints are often being heard about the quality of our exports and this is understandable. Several manufactures which are now being exported have been established on the basis of imported know-how and imported machines, without much regard for integrating scientific understanding with production. It should be emphasized that although individual genius has proved helpful in developing novel processes and machines, the success of commercial enterprise has been achieved mainly through the integrated efforts of scientists, technologists, engineers, economists and industrialists, by first understanding the conditions conducive to maximum efficiency, then developing suitable processes, plant and machinery and techniques in carrying out operations to achieve the desired results.

Appreciating the essential role of science in the progress of industries and as a first step towards technological independence, a large number of scientific and technological institutions devoted to research and development have been established in the post-independence period, and facilities in existing institutions have been very considerably augmented. Never before in India, and perhaps in few countries elsewhere, has science received such massive support from Government. The Prime Minister has an unflinching faith in science; he is convinced that:

> '... It is science alone that can solve the problems of hunger and poverty, of insanitation and illiteracy, of superstition and deadening custom and tradition, of vast resources running to waste, of a rich country inhabited by starving people ... Who indeed could afford to ignore science today? At every turn we have to seek its aid ... The future belongs to science and to those who make friends with science ...'

In securing beneficent possibilities which science holds for economic and welfare activities, particularly the development of industries, the German optical glass industry offers useful guidance.

Much progress has been made since independence and valuable results have been produced. There is, nevertheless, a feeling, more or less undisguised, that the results achieved in Indian laboratories and institutions are too few and rather insignificant in comparison with the great achievements in advanced countries. Comparisons are always odious; whatever the justification for the feeling, the fact remains that even the few results achieved are not always utilized. Apart from the waste of effort and resources, the neglect of results of proved value creates a sense of frustration in the minds of scientists and exposes the institutions to criticism for no fault of theirs. Also, viewed against the background of foreign collaboration and the publicity such collaboration is receiving, a conviction is rapidly growing in the mind of the average person that technology is foreign to Indian talent. Collaboration in new and special fields should be welcomed, but collaboration even for minor expansion programmes of well-established and even exporting industries is indicative of chronic technological dependence. This is developing into an undesirable situation in which research and industry tend to remain apart from each other. If the lessons of the German optical glass industry are any guide, it is of the utmost importance that an atmosphere conducive to the integration of science, technology and industry should be developed. In addition to establishing research laboratories, effort should be made to ensure the utilization of the results of research. This is a task to which we must address ourselves with a sense of urgency and dedication.

In the face of unprecedented State patronage, public expectations from science and technology have soared high. The yardstick for public appraisal of the utility of technological institutions is the achievement of beneficial results in measurable terms, here and now. The public are not much interested in reports, statements, etc. Utilization of research results for the advancement of industry and substantial increase in economic productivity are what the public expect.

Scientific criticism has helped the growth of science and the creation of a scientific atmosphere everywhere. One of the Presidents of the National Institute, Prof. P. C. Mahalanobis, has, in a recent note on Scientific Man-power, drawn attention to Prof. Haldane's remark about the lack of sound and informed scientific criticism in India. The history of science is full of instances of discoveries being inspired by criticism of competent scientists. There is no dearth of criticism in India, but much of it has unfortunately tended to be personal rather than scientific. Criticism of this type stifles progress and vitiates the atmosphere for creative work. Criticisms to be of value should be based on informed understanding of facts.

Science and technology in India are on the march. The efforts that are now being made to offer inducements to talented youth to take to science as a career are most welcome. An atmosphere which would encourage adventure in science and technology is essential to attract and retain enterprising men and women. In the absence of such an atmosphere there would be migration of scientific talents to professions which place no premium on adventure but demand only adherence to rules, procedures and precedences. The climate is more important for scientific endeavour than the material means, like apparatus, buildings, etc.—no doubt essential—and it is to the creation of that atmosphere that the National Institute of Sciences, with its great prestige as the leading learned society of the country, should devote some of its attention and effort.

References

1. CHANCE, H., *Chem. & Ind.* (*Rev.*), 800 (1947).
2. DAY, A. L., *J. Frank. Inst.*, **190**, 46 (1920).
3. HOVESTADT, H., Jena Glass and its Scientific and Industrial Applications, pp. 3, 4, 7, 14. Macmillan and Co. (1902).
4. KINGSLAKE, R. AND DEPAOLIS, P. F.; *Nature*. **163**, 413 (1949).
5. MORITZ, HEINZ., *Jenaer Rundshau*, **4**, 104 (1957).
6. PEDDLE, C. J., *J. Soc. Glass Tech.*, **4**, 226T (1920).
7. RAYTON, W. B, *J. opt. Soc. Amer.*, **28**, 11 (1938).
8. TURNER, W. E. S., *Ibid.*, **20**, 91T. (1936).
9. WEYL, W. A., *Glass Ind.*, **41**, 430 (1960).
10. WHEAT, W. N., *Research, Lond.*, **7**, 22 (1954).
11. WRIGHT, F. E., The Manufacture of Optical Glass and of Optical System, U. S. Ordnance Department, Document 2037, 13 (1921).