PHYSICS IN THE GLASS INDUSTRY

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IT is in keeping with the transparent nature of the substance that the first physical properties of glass to receive conscious study in comparatively modern times should be the optical properties. The problem of dispersion in the simple telescope lens found a partial solution in the achromatic lens combination of John Dollond in 1758, and the subsequent development of lens systems, in which the correction of chromatic aberration is still more complete, has involved the utilization of glasses of different and precisely known refractive indexes and dispersions. The work of Guinand, of Faraday, of Harcourt and of Schott was in all cases concerned with the production of better glasses of constant optical properties, or of new glasses permitting a wider range of optical properties for use in combinations.

With the work of Schott, however, there was opened up the possibility of exploiting some of the new glasses experimented with, for purposes other than components of optical instruments. Thermometer glasses of low after-contraction were one development. The accumulation of general physical data about glass had set in at Jena, so that, between about 1883 and 1895, many data were compiled about density, thermal expansion, thermal conductivity, tensile, compression and other aspects of mechanical strength; and although in recent times some of these data have had to be drastically revised, they led to the manufacture of a variety of new glasses for heat resistant and other purposes, and pointed to the usefulness of certain compound glasses.

For the next twenty years, the impact of physics on the industry was less exciting and dramatic, but some of the results at least contained the seeds of later important developments. Then began an altogether new period in which striking individual results of physical studies led to new types such as Pyrex and other low thermal expansion glasses; R. W. Wood's glass; the Corex glasses, etc., side by side with the development of revolutionary processes in which highly productive automatic machinery began rapidly to displace the hand worker. The manufacture of glass bottles and containers in thousands of types; of sheet and plate glass; of electric light bulbs; of glass tubing and rod and of some types of domestic glassware has within the past twenty to twenty-five years been transferred almost entirely to highly productive automatic machines, the efficient function-

ing of which was, in a number of cases, achieved only after many years of development.

It is in these fields of manufacture that the bulk of the capital of the industry is locked up. That represented by optical and scientific glassware of all types is relatively insignificant. The development of several of these automatic machines was in the early years in the hands of the clever mechanic, with no background of systematic knowledge of physics and chemistry, or even of the fundamental principles of engineering. It has been the service of the physicist to work out processes of control so as to maintain constant conditions under which the machine can operate favourably. As an illustration, it may be mentioned that with one automatic machine, the temperature of the molten glass (at 1140–1160° C., according to size of article to be made) in the bath from which the machine takes its own supply many times per minute, must be kept constant to $\pm 5^\circ \text{C.}$; and high-temperature pyrometry, glass-level control in furnaces holding huge quantities of the molten material, and various other problems have had to be worked out suitable for each set of conditions of operation. At every stage of mass manufacture, speed and efficiency involve fundamental knowledge, and it is not surprising, therefore, that the widespread employment of physicists and chemists has really only begun with the introduction of mass manufacture.

Some conception of the part which the physicist plays both in the development of new types of glass and in the manufacturing control of others was clearly brought out during a discussion on February 15 on the subject of "Physics in the Glass Industry", held at the Royal Institution under the auspices of the London Branch of the Institute of Physics. The contributors of papers to the symposium were Dr. Harry Moore on "Strains intentionally introduced during Glass Manufacture", Dr. W. M. Hampton on "The Spectacle and Optical Glass Industry", Dr. Eric Seddon on "Physics in the Manufacture of Glass Bottles", Dr. B. P. Dudding on "Glass for Lamps and Electronic Devices", and Dr. J. H. Partridge on "Refractories used in the Glass Industry".

In the manufacture of spectacle and optical glasses, physical methods continue in the line of traditions of fifty or sixty years ago, though with some important developments. Both types of glasses must be controlled in respect of refractive

index so that repeat meltings are kept within ± 0.001 of the desired value for well-annealed samples. The Pulfrich refractometer is normally employed for this control and has an accuracy of one in the fourth place of decimals on refractive index and two in the fifth on dispersion; but master standard prisms of optical glasses of refractive indexes and dispersions measured to a few units in the sixth place of decimals are used to control the Pulfrich observations. Modern optical glasses must also have a light absorption of not more than a fraction of 1 per cent per inch thickness, and the amount which occurs in the visible, ultra-violet and the infra-red has been the subject of close study and control, the main cause of absorption being the presence of very small amounts of iron oxide in solution. Spectacle glasses, on the other hand, may have colour dependent on the purpose for which they are intended, such as protective goggles for use by welders, and in all such cases the transmission in the three spectral regions must be determined as a routine control measurement.

The annealing of glass has received much detailed scientific and practical study during the past twenty years, in particular by Twyman and by Hampton in England, and by Adams and Williamson in the United States, in regard to general theory, and by English and Turner in regard to the relation of composition to the annealing temperature. The latter quantity is usually related to the viscosity, on which property of glass much work has been done in recent years. At the highest temperatures used in melting a glass, the viscosity is usually reduced to not more than 100 poises, but with fall of temperature the increase of viscosity is such that at room temperature it should be of the order of 10^{20} . The viscosity corresponding to annealing temperature conditions lies between 10^{12} and 10^{13} poises, rapid removal of strains, that is, rapid annealing, being possible at the lower viscosity figure or higher temperature, slow annealing resulting at the higher viscosity.

The annealing temperature chosen depends on the character of the glass, on its size and thickness and the degree of strain permissible. In mass-produced glass the object is to anneal as speedily as possible, and the higher annealing temperature is accordingly chosen. In modern glass bottle annealing, as illustrated by Dr. Seddon, the glassware is annealed and cooled nearly to room temperature in less than two hours. In the case of the Fourcault sheet glass process, producing an article of simple shape and uniform thickness, it is a matter of only a few minutes before the flat sheet, drawn out of a bath of molten glass at approximately 1000° , emerges from the annealing shaft at a temperature cool enough to enable it to be

carried safely in the open air. On the other hand, in the case of large slabs of optical glass, it is not unusual, as Dr. Hampton pointed out, for the annealing process to involve heating them slowly from room temperature up to the annealing temperature in five to six days, to maintain them for 24–70 hours at that temperature and then to cool them during the first 150° below the annealing temperature at a rate of perhaps only 10° per day. In the case of a large telescope disk, such as the famous 200 in. disk, the cooling must be spread over several or many months.

Control of the distribution of strains in the flat-drawn sheet glass prepared either according to the original Fourcault process or its modification the Pittsburgh process, is important if excessive breakage is to be avoided. In either method, there is some contrivance whereby the edges of the sheet, which may be more than 100 in. wide and up to $\frac{1}{4}$ in. thick, are chilled and maintained rigid so soon as it is raised above the molten glass. This results in these edges being put into compression vertically as the temperature becomes uniform, whilst the centre develops tensile strain vertically, there being other tensions and compressions across and through the sheet. The tensile strains must not reach the breaking limit and must be so distributed as to leave the sheet substantially free from strain when, as is part of the normal operation, the edges are cut off. Dr. Moore described an elegant method now under trial of using Babinet compensators to maintain routine observations on the edges and centre of the sheet as it emerges from the drawing tower.

The physicist has also been set a problem by no means easy in the testing and control of 'toughened' glass produced by heating plate or sheet glass to a temperature some 50° C. above the annealing point and chilling it rapidly by a blast of cold air from many small orifices, the result being to multiply several-fold the forces which it will withstand before fracture. The compressive forces thus introduced into the surfaces are such that the glass sheet can be bent or otherwise deformed considerably before these compression strains are removed and replaced by tensile strains under which glass almost invariably breaks, since the tensile strength is only one eighth to one tenth of that of the compression strength. Here control may be exercised by a combination of mechanical testing methods and of the tensile strains measured optically either on pieces cut from lightly 'toughened' plate or on 'toughened' thick plates of glass convenient for edgewise examination.

The Babinet compensator has also been a valuable tool in the study and control of permissible stresses in vacuum-tight glass-to-metal seals in electric lamps and valves; and of flashed opal

glasses, Dr. Dudding having some excellent coloured slides to show of strain patterns; whilst Dr. Hampton illustrated its use in the manufacture of bifocal lenses. In such a lens the major part consists of spectacle crown glass, into a depression of which a button of glass of higher refractive index is fused, and the whole then ground down to the required curvature. Satisfactory welding is found to require, for similarity of thermal expansion, coefficients of the two glasses to within $\pm 2 \times 10^{-7}$. Since 1920, many investigations of this property have shown that the thermal expansion-temperature curve deviates considerably from a straight line and at a transformation temperature the coefficient increases several-fold. The successful solution of the problem of obtaining two glasses, or a metallic wire and a glass, of thermal expansion curves closely agreeing with one another, is a testimony to the thoroughgoing nature of the study of this subject.

Researches on the electrical properties of glasses have had various practical applications, nowhere perhaps more vitally than in the electric lamp industry. By systematic researches on the relation of composition to electrical resistance, glasses have

been made available for mercury vapour discharge lamps which will permit of their operation at temperatures of 600° and yet have a resistance 300,000 times that of the simple soda-lime-silica glasses used in 1916*, and offering prolonged resistance to blackening.

Not merely in the operations of glass fabrication and manipulation but also in auxiliary processes in its melting, modern physical methods have received valuable application. In the study of the performance of refractory articles in which glasses are melted, X-ray methods of examining structure have often led to vital knowledge; and tensile strength and creep tests at high temperatures, as Dr. Partridge showed, have been of great value.

Some fields of investigation have been but little explored by the physicist. Thus, Dr. Seddon emphasized the lack of systematic information available about certain thermal properties at high temperatures, namely, specific heat, thermal conductivity and emissivity. But sufficient has been said to demonstrate how physics has assisted in transforming glass-making into an enterprising and efficient industry.

* See, for example, Dudding, B. P., *Proc. J. Soc. Glass Tech.*, **22**, 43 (1938).

THE FLORA OF MADAGASCAR

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FEW naturalists will need reminding that Madagascar, the third largest island in the world, possesses a fauna and flora of exceptional interest. Although only 260 miles distant from the nearest point on the East African coast, its flora bears an almost equal relationship with that of the great continent and that of Ceylon, Malaya and even Australia, whilst its fauna, as pointed out long ago by Alfred Russel Wallace¹, is almost exclusively related to that of Eastern Asia. Of equal interest is the fact that the language of the natives is closely related to those of Malay-Polynesia, whilst another remarkable feature is that they do not employ skins for clothing their bodies as do the natives in Africa, but make use of vegetable fibres as do the eastern peoples.

The distribution and affinities of the animal life, therefore, and of the plants in part, indicate that Madagascar was in former times connected much more closely with the continent of Asia than it is at the present day. As is well known, there are two rival hypotheses which might account for these interesting facts, either the mythical

Gondwanaland of Suess, or the continental drift of Alfred Wegener. With respect to its organic life, therefore, Madagascar ranks equally with other oceanic islands such as New Guinea, New Caledonia, St. Helena and the Galapagos in being a 'museum of antiquity'.

Madagascar is nearly a thousand miles long, has an average of 250 miles in breadth and an extreme width of 360 miles. Its area is nearly four times that of England and Wales.

The main features of the island are the great central ridge of elevated ground, the encircling tropical plains, broad on the west side, narrow on the east of the ridge, and with a long girdle of primeval forest nearly 2,000 miles in length. There is fine mountain scenery in the Betsileo country in the southern portion of the island, and in the centre the Ankaratra mountains rise to a height of 9,000 ft. within a short distance of the capital, which stands at 4,000 ft. This central portion consists of rolling moor-like hills covered principally with long grass which becomes very brown and dry by the end of summer.