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DESIGN CONSIDERATIONS FOR THE TRANSPARENT VISION AREAS IN ORBITAL GLIDE VEHICLES

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INTRODUCTION

This paper presents a summary of the characteristics of three high-temperature glasses and indicates the considerations required in applying these materials to the design of transparent vision areas for orbital glide vehicles. The three glasses discussed are Corning Glass Works 1723 alumino-silicate, 7900 96-percent silica, and 7940 fused silica.

DISCUSSION

General Characteristics of Glass

For almost 5,000 years men have been using glass. Soda-lime glass, which is widely used in automobiles, aircraft, and home windows, has been in use for 500 years. With such a background to draw upon, one might expect structural design with glass to be a highly developed science. Unfortunately, it is closer to a black art.

In order to understand a few of the idiosyncrasies peculiar to glass, some of its more interesting properties will be discussed.

The atomic structure of glass is random. It lacks the uniform lattice structure which is characteristic of the individual crystals in most solids. There is evidence of some tendency for glasses to form crystals at and below an experimentally determined crystallization temperature. However, the viscosity of the material is sufficiently high throughout this temperature range to preclude crystal formation. Glass is therefore called a high-viscosity liquid.

Because of its liquid-like structure, glass has no distinct melting point. Instead, its viscosity decreases continuously with increasing temperature. At ordinary temperatures, glass is so viscous that it may be considered an elastic material. Its modulus of elasticity, approximately 10 million psi, is comparable to that of aluminum. It obeys Hook's law and the theories of elastic solids to the point of failure.

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At elevated temperatures, its characteristics are quite different. Such plastic properties as creep under load, a phenomenon completely unknown at low temperatures, may be observed.

The transformation from elastic behavior to plastic behavior takes place slowly over a wide temperature range. Throughout this transformation range, the properties of glass are dependent upon both the temperature and the time of exposure. Thus, glass may be used at temperatures well into the transformation range, provided the time is sufficiently short and the load is sufficiently low to maintain elastic behavior.

In order to provide reference temperatures to which the transformation range and other properties may be related, a number of points on the smooth temperature-viscosity curve have been selected. Three of these points are of interest to engineers. These points are shown on the temperature-viscosity curve for soda-lime glass in figure 1.

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The softening point defines the temperature at which the glass will deform under its own weight. The viscosity at this temperature will range from $10^{7.5}$ to 10^{8} poises. Obviously, this establishes the absolute maximum exposure temperature for glass even for a short time and under no load.

The annealing point defines the center of the transformation range. The transformation range extends for about 250° F above and below this point. The viscosity at the annealing point is 10^{13} poises.

The most important point to engineers is the strain point. This point defines the maximum practical service temperature for annealed glass. The viscosity at this point is $10^{14.5}$ poises.

Failure in glass always occurs as a result of the tensile components rather than the compressive or shear components of a force. The stress at failure depends significantly upon the condition of the surface and edges. Incipient cracks and flaws in the surface may introduce stress concentration of 100 to 1,000 times the average. Since the glass structure does not permit stress relief through local yielding, the breaking stress is reduced by a proportionate factor. The average breaking stress for a severely sandblasted glass specimen may be 2,000 psi or below. However, if the surface is properly treated and protected, strengths above 250,000 psi are not uncommon. It is apparent that tests of glass specimens indicate relative quality of the surface rather than the actual strength of the glass.

Because of the wide scatter in breaking stresses for seemingly identical specimens, there has been considerable disagreement among engineers as to the design strength of glass. This problem has been

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resolved somewhat by the recent work of Matthew Kerper of the National Bureau of Standards. (See ref. 1.) Working under Wright Air Development Division contract, Kerper has obtained repeatable results by applying beam loading to sandblasted glass specimens. These results have provided excellent data upon which to base the design of glass for high-temperature applications. However, the difficulty of translating the characteristics of small specimens to full-scale designs still exists, and extensive testing of the final configuration is mandatory.

The "notch sensitivity" and tensile weakness of glass can be mitigated somewhat by a strengthening process known as tempering. Tempering is accomplished by heating glass to the neighborhood of the softening point and then rapidly chilling the surface. The surface contracts and becomes rigid, leaving the interior semimolten. As the interior cools and shrinks, compressive stresses are induced at the surface. The resulting stress distribution is shown in figure 2. The tempering process may increase the average breaking strength by a factor of $2\frac{1}{2}$ to $3\frac{1}{2}$.

Unfortunately, the maximum long-time temperature exposure for tempered glass is considerably below that of annealed glass. At the strain point, the tempering stresses will be essentially relieved in a period of 4 hours. Due to this slow stress release at temperatures approaching the strain point, the maximum long-time temperature exposure for tempered glass must be reduced to about 400° F below the strain point.

In selecting a glass for the high-temperature applications of orbital glide vehicles, two factors are prime requisites. First, a low coefficient of expansion is required to provide resistance to thermal shock and, second, a high strain point is required to provide strength at elevated temperatures.

Thermomechanical Properties of High-Temperature Glasses

Figure 3 compares the expansion coefficients of three high-temperature glasses with that of soda-lime glass. The 96-percent-silica and fused-silica glasses have extremely low expansion coefficients and exhibit excellent thermal shock resistance. However, there is a paradox here. The expansion coefficient of these glasses is so low that it is almost impossible to strengthen them by tempering. This paradox is one of the reasons why the alumino-silicate glass is of interest. Its expansion coefficient is sufficiently high to allow tempering yet is low enough to provide considerable resistance to thermal shock.

The temperature limits of the four glasses are shown in figure 4. Since tempering of the high-silica glasses is not presently feasible, the tempered use range has been excluded for these glasses. The maximum long-time temperature of the annealed glasses is defined by the strain point. Use of the glass above the strain point will depend upon the loading, temperature, and time of exposure.

Figure 5 illustrates the effect of temperature and time on the breaking strength of tempered and annealed alumino-silicate glass (ref. 1). In the annealed state, alumino-silicate glass reaches its maximum strength at approximately 50° C below the strain point. The increased strength elevated temperature is the result of some stress reduction through local yielding permitted by the reduced viscosity. The drop in strength in the 400° F to 700° F range may be attributed to the deleterious effects of surface chemical attach which are more influential than the healing effects of annealing.

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The curves for tempered alumino-silicate glass in figure 5 illustrate the influence of time and temperature on the loss of temper. A short time exposure of 1 hour at 1,150° F causes only a 25-percent loss in temper. A 500-hour exposure at 1,150° F results in almost complete loss of temper.

The center curves in figure 5 provide a comparison of the temperature-strength properties of fused silica with alumino-silicate. Fused silica is extremely resistant to atmospheric chemical attack. Consequently, its strength increases continuously with increasing temperature to above 1,700° F. The 500-hour exposure at temperature has little influence on the strength of this glass below 1,700° F.

Design Applications

At this point, the application of each high-temperature glass becomes apparent. Window designs for orbital glide vehicles will probably require a composite of several glasses to utilize the best properties of each material. The superior strength of tempered alumino-silicate may be used for the cooler interior layers to withstand pressurization and structural loads. The high-silica glasses may be used for the outer layers which require resistance to high temperature and thermal shock.

The problem of attaching these materials to the vehicle frame now arises. Figure 6 compares the expansion coefficients of some metals proposed for orbital glide vehicles with those of the glasses. It may be noted that a frame of either 0.5-percent titanium molybdenum, kovar, or tungsten would be reasonably compatible with alumino-silicate glass. However, these metals have an expansion coefficient 10 times that of the high-silica glasses. Any edge attachment for the high-silica materials must be designed to compensate for differential thermal expansion. Since relative movement and low clamping pressures are required, sealing between the glass and frame at high temperatures will be difficult.

Figure 7 illustrates the type of glass configuration which might be used in orbital glide vehicles. The maximum long-time temperature limit of the configuration is around 1,800° F, the strain point of fused silica. Short time exposures to 2,400° F may be tolerated. However, at these temperatures, the material exhibits properties which vary with time, loading, and size of specimen. The maximum thermal limits can be determined only through testing the design configuration. If, as in the Dyna-Soar windshield, the maximum temperature is above the limits of fused silica, a removable external heat shield is mandatory.

The outer panels of high-silica glass will be isolated as much as possible from structural loads and vibrations. An inorganic cushion between the glass edges and the frame will be required to permit relative movement and to provide some measure of sealing.

Absolute sealing of the inner alumino-silicate panel may be accomplished by bonding a metallic foil directly to the glass. Compartment pressure loads may be transmitted through a heavier framing member which would back up the foil. This attachment has been developed by Narmco, Inc., under Wright Air Development Division contract. (See refs. 2 and 3.) Its temperature is limited by the bonding material to 600° F.

A second higher temperature seal is presently under investigation. This seal consists of a fused bond between alumino-silicate glass and siliconized 0.5-percent titanium molybdenum. No deleterious effects on this seal have been noted over the -90° F to +900° F range. Investigation of the upper temperature limit is now underway. An upper temperature of 1,200° F is anticipated.

A third type of seal for the inner panel might be accomplished through the use of an interlayer. This seal would be similar to the type used in current aircraft and would be limited by the interlayer to a temperature of approximately 350° F.

No discussion of transparency design would be complete without a word about optics. Two definitions relative to optical properties are illustrated in figure 8. The angle of incidence is the angle between the line of sight and a perpendicular to the glass surface. The deviation is the distance between the image and the point where the image appears when viewed through the glass.

As the angle of incidence increases above 60°, the optical qualities of a panel deteriorate rapidly. This point is illustrated in figure 9 (ref. 4). It may be noted that the deviation increases and the light

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transmission decreases rapidly above 60°. The increase in deviation gives an indication of the relative difficulty of maintaining optical quality at large angles of incidence. The decrease in light transmission points up another problem - that of maintaining visibility. Additional glass panels separated by air spaces will reduce the light transmission by a proportionate amount. Three panels each with 70-percent transmission would reduce the overall transmission to around 34 percent.

The light transmission at large angles of incidence may be increased by the use of reflection-reducing coatings. However, a coating is not a panacea. Light transmission at nonoptimum angles of incidence and of nonoptimum wavelengths will be reduced. Also, these coatings may reduce the temperature limit of the high-silica glass or may tend to glow at elevated temperatures. In view of the optical difficulties which arise, the angle of incidence should be kept below 60°, if possible.

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The need for transparent materials having higher temperature ranges is illustrated by the requirements for a shield on the Dyna-Soar windshield. There is a good possibility that future materials will extend the temperature range past the present limitations of fused silica. The most promising materials appear to be single crystals grown from metallic oxides. Aluminum oxide crystals, known as synthetic sapphire, are available in small sizes. The materials laboratory at the Wright Air Development Division is currently evaluating this material. A temperature extension into the 2,000° F range appears feasible. As crystal-growing techniques improve, larger and higher temperature transparent materials may be expected.

CONCLUDING REMARKS

Transparent areas for orbital glide vehicles will require a composite structure of several different glasses. The low-expansion high-silica glasses will provide heat shields for the alumino-silicate structural glasses. Edge attachments must be designed to isolate the glazing, compensate for differential expansion, and provide a seal between the glazing and the frame. The angle of incidence, number of glass panes, and type of glass coating must be chosen so that the optical quality of the overall transparency is maintained. The work of Kerper and Partain provides background data upon which to base the design of glass and edge attachments at elevated temperatures. However, due to the pecularities of the material, extensive testing of the design configuration is required.

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TEMPERATURE-VISCOSITY CURVE FOR SODA-LIME GLASS

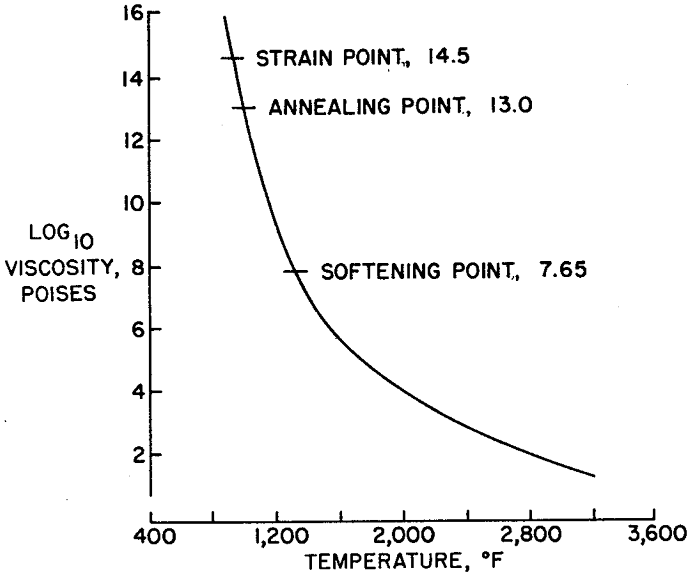

Figure 1

RESIDUAL STRESSES IN A PLATE OF TEMPERED GLASS

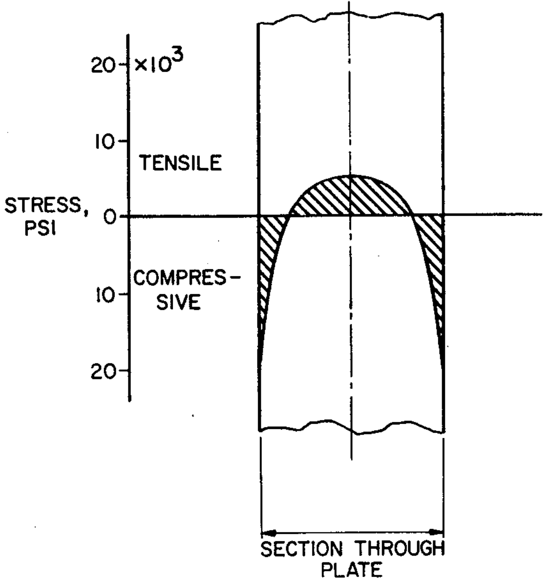

Figure 2

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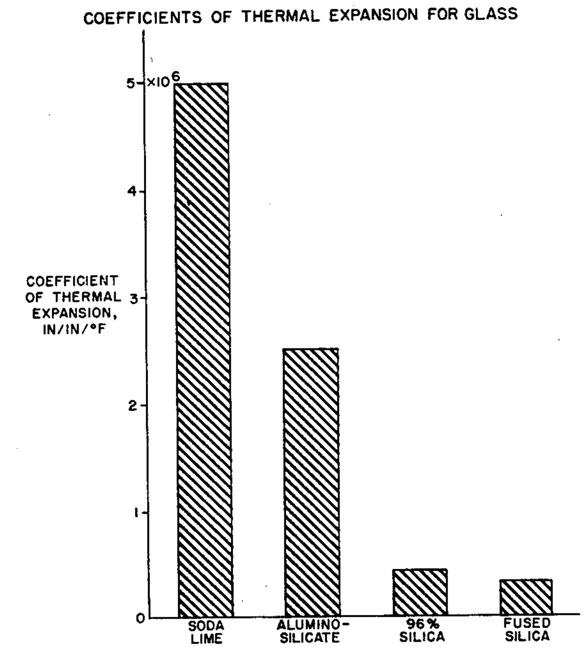

Figure 3

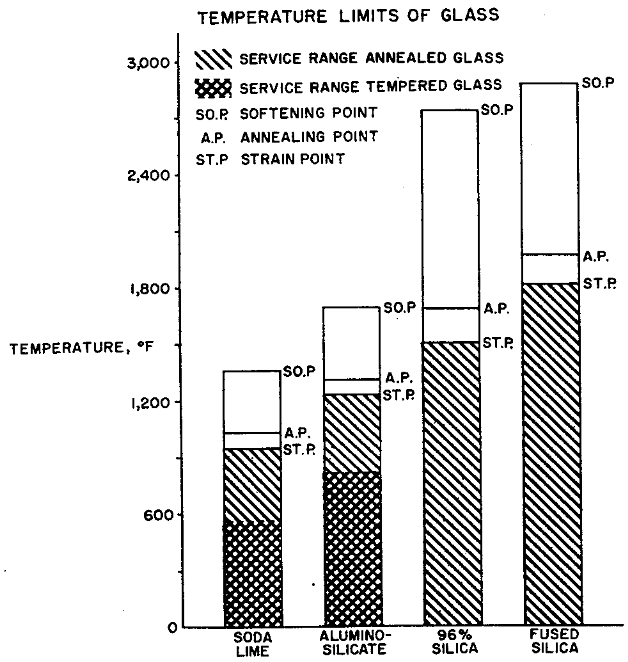

Figure 4

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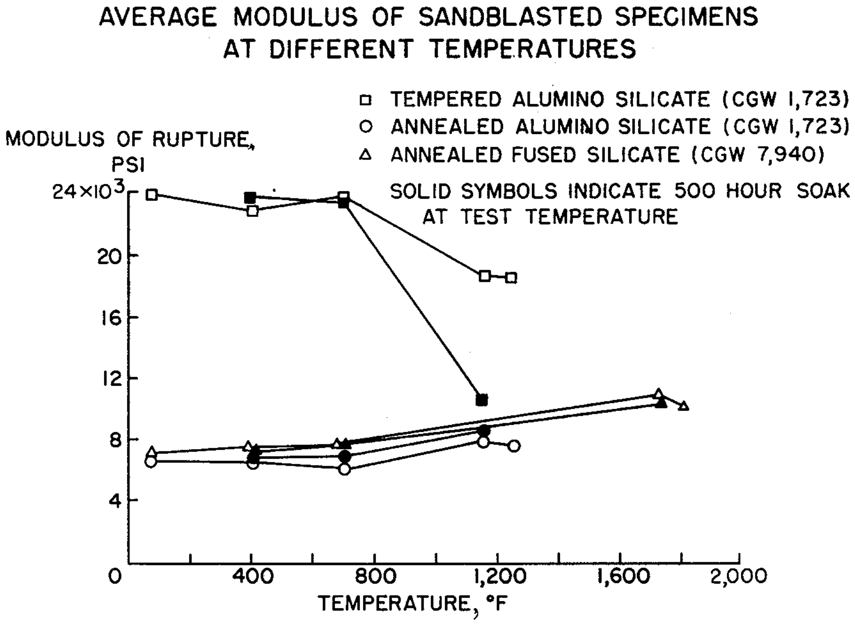

Figure 5

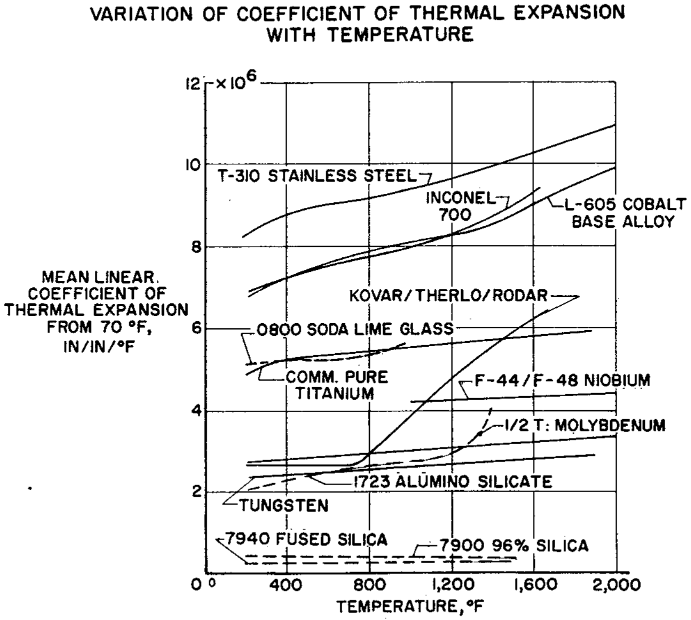

Figure 6

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GLASS CONFIGURATION FOR ORBITAL GLIDE VEHICLES

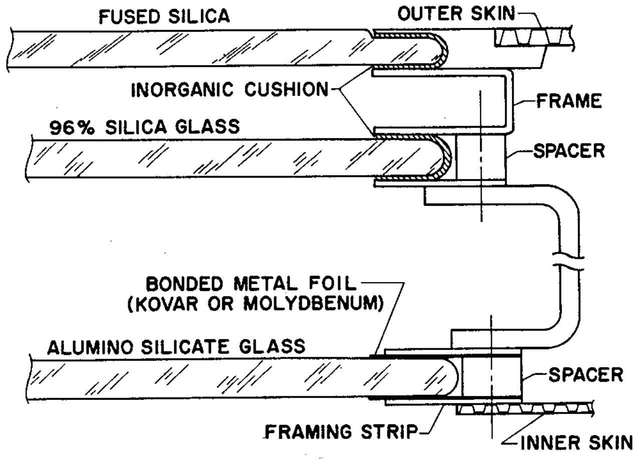

Figure 7

ILLUSTRATION OF ANGLE OF INCIDENCE AND DEVIATION

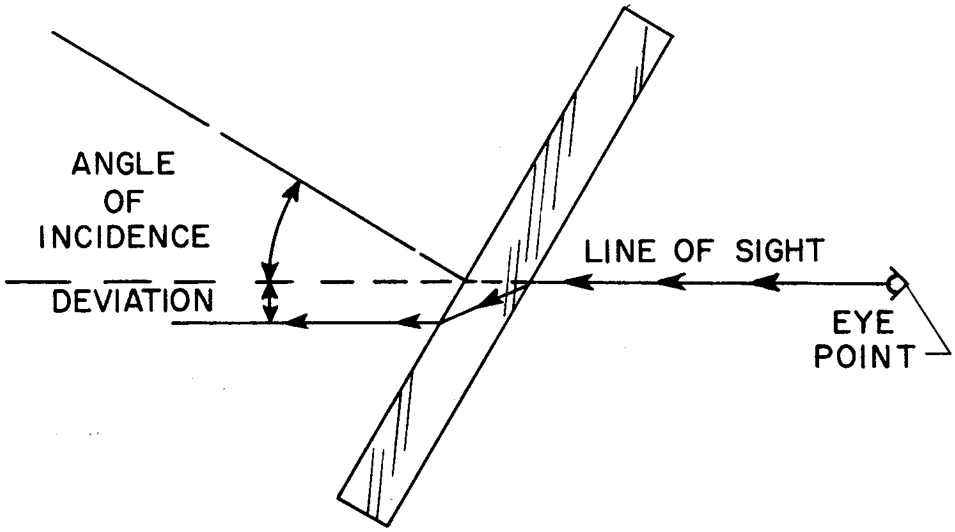

Figure 8

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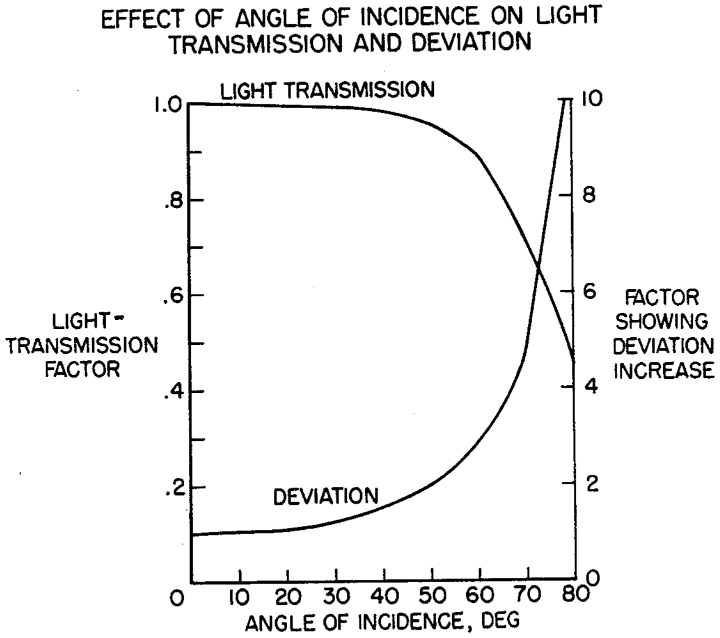

Figure 9

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