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Design of Viewing Windows for Controlled-Atmosphere Chambers

James N. Robinson

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ABSTRACT

This study presents a guide to the design of safe viewing windows. Design criteria, the properties of materials, the problems of structural design in unreliable materials such as glass, the mathematics of reliability and redundancy, and problems associated with testing windows are discussed, and formulas are presented for the design of windows. Criteria adopted at ORNL for controlled-atmosphere chambers are presented, a program for surveying and upgrading the safety of existing facilities is described, and the results of this program are reported.

I. INTRODUCTION

Many activities must be isolated from the surrounding atmosphere to prevent contamination of either the work or the operating area. The term controlled-atmosphere chamber is used here to describe the containment envelope employed to achieve this isolation. Most activities that require isolation also require viewing windows, installed in the containment boundary, so that the operation can be observed and controlled. It is to the design of these viewing windows that this study is directed.

Controlled-atmosphere chambers are necessary for many different kinds of work. The design of a chamber for a particular service must give consideration to (1) the reason that isolation is required, (2) the nature of the materials to be contained in the chamber, (3) the character of the operations to be performed in the chamber, and (4) the conditions of pressure and temperature that will be required in the chamber. This study considers the design of viewing windows after the parameters of the proposed operation have been established, all hazards have been considered, the service conditions to which the chamber will be exposed have been determined, the acceptable materials of construction have been identified, and any required quality assurance assessment has been completed. Although reference is made to the characteristics of materials which influence these prerequisite decisions, the intent here is to discuss the design of windows using known properties of predetermined materials. Specifically, this study is addressed to the solution of problems associated with the design of glass windows, although the discussion is of general applicability. In fact, window materials are referred to as "glass," even though the reference may be to some other window material.

This study is predicated on the thesis that a controlled-atmosphere chamber that is well designed in accordance with competent criteria, that is properly detailed, that is fabricated in conformity with the design, that is not subjected to service conditions more severe than those for which it was intended, and for which adherence to all of these requirements is affirmed by competent review and audit, will not fail in service. Because human error cannot always be eliminated, failures will occur, but with proper design the number of failures will be held to a minimum.

Design considerations

The degree of integrity necessary in a viewing window is dictated by the nature of the service to which the chamber is committed. For a competent design to be specified, the necessary integrity must be defined in specific, clear, and meaningful design criteria. The criteria should be realistic, not just conservative, for an extremely restrictive criterion — that failure must be impossible, for instance — might preclude the use of windows at all. A criterion that permits (even improbably) failure might need to restrict the mode of permissible failure to a less hazardous one — perhaps that, if a window fails, personnel must be protected from flying fragments by a protective shield.

The circumstances in which a postulated window failure might occur must be considered, for a window failure can occur either during routine operations or in consequence of the failure of some other component of the system. This possibility is particularly important with respect to personnel safety, because it may not always be possible to control the location or actions of personnel under emergency conditions.

In stipulating the design criteria for a chamber, it is important to consider the most extreme conditions that can be imposed on the chamber, not just the conditions that are intended to be imposed on the chamber. For instance, a chamber to be used at a slight vacuum should be designed for the greatest vacuum that a connected pump can pull, unless a "vacuum breaker" is provided, and then only if the vacuum breaker cannot be overpowered by the pump. Design criteria should recognize that test conditions may be more severe than anticipated extreme operating conditions — for instance, an overpressure test may be required to demonstrate the adequacy of a design.

Three specific hazards should be considered in establishing the criteria for any window. These are (1) fire, internal or external,

(2) explosion or impact by internal or external bodies, and (3) deterioration. Each of these hazards imposes special restrictions on the design, and there is no universal design philosophy that is optimal for all possible hazards.

If a chamber can be subjected to internal pressure, particular attention should be given to assuring that the frame assembly is adequate for the forces imposed by positive internal pressure as well as those imposed by vacuum.

II. WINDOW MATERIALS

This section describes some of the materials commonly used in construction of viewing windows and discusses some of their advantages and disadvantages. Mechanical properties used in design calculations at ORNL and approximate limiting service temperatures are presented.

Plastics. A large number of plastic materials are available, of which methyl methacrylate (Plexiglas and Lucite) and polycarbonate (Lexan) appear to be the leading contenders. Because most plastics are subject to either flammability or heat softening, they do not seem to be preferred as window materials, and are considered here as a group.

Advantages:

a. Not as brittle as or as prone to shatter as glass (methacrylate is more brittle than polycarbonate).

b. Not as likely to break spontaneously or as the result of a scratch as glass.

Disadvantages:

a. Frequently flammable, constituting a fire hazard.

b. Not impervious to water vapor and other gases.

c. Subject to outgassing in a vacuum.

d. Can react with chamber contents.

e. Subject to checking with age.

f. Scratches easily, impairing vision.

Properties:

a. Modulus of rupture: 9000 psi

b. Poisson's ratio: 0.40

c. Service temperature: 160°F (methacrylate)
250°F (polycarbonate)

Annealed plate glass. Plate glass is a soda-lime glass, and annealed plate, being inexpensive and readily available, is frequently supplied when nothing else is specified.

Advantages:

a. Less sensitive to scratches than strengthened glass.

Disadvantages: a. Breaks into sharp-edged shards.
b. Weaker than strengthened (semitempered or tempered) glass.

Properties: a. Modulus of rupture: 3000 psi (long-term loading)
b. Poisson's ratio: 0.20
c. Service temperature: 800°F

Semitempered plate glass. This is a plate glass that has been subjected to a mild tempering treatment. It has characteristics that fall between those of annealed and fully tempered glasses, sharing the advantages and disadvantages of each. It is not easy to determine how much temper a semitempered piece of glass has received, and its use is generally not recommended. It is preferred, however, to annealed glass when fully tempered glass is not obtainable.

Tempered plate glass. This is a plate glass that has been heated almost to the softening point and then cooled quickly by blowing air on its surfaces. It contains residual stresses, having large compressive stresses at the exposed surface (30,000 psi) and tensile stresses at the midthickness (15,000 psi).

Advantages: a. Greater strength (5×) than annealed plate.
b. On failure, breaks into small cubes.[1]
c. More resistant to mechanical impact than annealed glass.
d. Edges are partially fused, relieving stress concentrations.
e. More resistant to thermal shock than annealed glass.

Disadvantages: a. More sensitive to scratches than annealed glass.
b. On failure, entire pane disintegrates.

Properties: a. Modulus of rupture: 15,000 psi
b. Poisson's ratio: 0.20
c. Service temperature: 450°F

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1. The size of the break pattern becomes smaller as greater potential energy is stored in the glass by the tempering treatment.

Chemically tempered glass. This is a glass which is tempered by a process that substitutes large ions for small ones on the glass surface and which, on cooling, achieves a much higher surface compression (70,000 psi). This glass is commonly available only in 0.085-in. thickness, but its special characteristics may be useful in special circumstances. The service temperature is limited to 435°F.

Laminated plate glass. Any combination of panes of glass may be laminated, using a thin (0.015- to 0.060-in.) layer of polyvinyl butyral as a bonding agent.

Advantages: a. Failure of one pane will not propagate across the plastic.

Disadvantages: a. Composite is weaker than a single piece of glass having the same total thickness.
b. Plastic may flow at room temperature.

Properties: a. Service temperature: 140°F

Quartz (100% silica).

Advantages: a. High service temperature.

Properties: a. Modulus of rupture: 7000 psi
b. Poisson's ratio: 0.16
c. Service temperature: 1000°C

Sapphire.

Advantages: a. Chemical inertness.
b. High strength.
c. High service temperature.

Properties: a. Modulus of rupture: 40,000 psi
b. Poisson's ratio: 0.16
c. Service temperature: 1000°C

96% Silica (Corning trade name is Vycor).

Advantages: a. High service temperature.

Properties: a. Modulus of rupture: 2250 psi
b. Poisson's ratio: 0.17
c. Service temperature: 1600°F

Aluminosilicate glass.

Properties:	a.	Modulus of rupture:	3000 psi (annealed) 9000 psi (tempered)
	b.	Service temperature:	410°F (annealed) 750°F (tempered)

Borosilicate glass (Pyrex).

Properties:	a.	Modulus of rupture:	3000 psi (annealed) 9000 psi (tempered)
	b.	Service temperature:	450°F (annealed) 550°F (tempered)

Leaded glasses. Because of their low strength, use of these glasses as pressure boundaries is not recommended.

Properties:	3.3 density:	Modulus of rupture: 2250 psi
		Poisson's ratio: 0.23
	6.2 density:	Modulus of rupture: 1200 psi
		Poisson's ratio: 0.29

III. STRUCTURAL DESIGN OF GLASS

Nearly all commercial glasses are silicates — combinations of silica (silicon dioxide) with one or more alkali oxides. The alkali oxides act as fluxing agents and form, with the silica, a mixture that softens and flows at a lower temperature than pure silica. The higher the proportion of silica in a glass, the higher its softening temperature and the lower its thermal expansion coefficient.

Glass does not have a melting point. As it cools from the temperature range wherein it is a true fluid, viscosity increases rapidly. The resultant decrease in atomic mobility is sufficient to prevent the atomic structure from assuming the regular lattice characteristic of crystalline solids. Instead, a random network is frozen in; this network is characteristic of the glassy state. As a result, glass does not change state as it cools and does not exhibit a sharp melting point. Instead, the term "softening point" is used and is defined as that temperature at which glass has a viscosity of $10^{7.6}$ to 10^{8} poise.

Glass does not exhibit the property of plastic flow. It is a perfectly brittle material and fails only in tension. The initiation of failure is not limited to the surface of the material, where stresses are maximum, however, because a subsurface imperfection may produce a stress concentration sufficient to initiate failure in a lower internal stress field.

Although stress distributions in brittle materials are calculated using the conventional elastic-stress formulas, the calculated stress that coincides with failure (modulus of rupture) is not the true stress in the material. The ratio of ultimate tensile strength to computed maximum stress at rupture is called the rupture factor, and its value varies from about 1.60 to 1.75 for rectangular and circular flat plates loaded in flexure. It is convenient to design brittle structures by dividing the tensile strength (10,400 psi for annealed glass subjected to short-term loading) by a conservative rupture factor (1.75) and performing all calculations on a modulus of rupture basis, as if the tensile strength were 10,400/1.75 = 6000 psi.

The strength of glass can only have meaning when it is considered in a statistical sense, for the breaking strength of glass has a coefficient of variation of about 0.25.

Poisson's ratio for glass ranges from 0.15 to 0.25, in contrast to the 0.30 characteristic for most steels.

The breaking strength of glass is influenced by the time duration of loading, experiencing a reduction with time whether the loading is sustained or cyclic. This loss of strength with time results from the propagation of microcracks, which are always present. Annealed glass, tested in air, loses about half its strength over a period of years. The following table gives the recommended breaking strengths (on the modulus of rupture basis) for loads of different duration:

	Breaking stress[2] (modulus of rupture, psi)		
Load duration	Annealed plate	Semitempered	Fully tempered
0.1 sec	6000	15,000	30,000
5-10 sec	5500	13,750	27,500
1 min	4000	10,000	20,000
2 hr or more	3000	7,500	15,000

Large windows and windows that must contain a large pressure differential demand strength so great that necessary thicknesses of annealed plate glass become intolerably large. Although the use of tempered glass can reduce the required thickness of the window, the highly stressed condition of the tempered surface makes it more subject to spontaneous and complete failure if the surface is scratched. To permit use of tempered glass, and to reduce the hazard of such a catastrophic failure, a design is sometimes used wherein a piece of tempered glass, which provides the requisite strength, is laminated between two relatively thin pieces of annealed glass, which protect the surfaces of the

2. PPG Industries, *Glass Product Recommendations, Structural*, Technical Service Report No. 101, p. 22.

tempered glass from damage. The question has been raised, if the edge of the glass is exposed to the higher pressure, whether plastic flow of the laminating material might not result in the full pressure being imposed on the inner protective piece of annealed glass and in the resultant failure of this inner piece. This would obstruct vision through the window without violating the integrity of the containment.

A double-containment design philosophy has been proposed by Sloan Bomar[3] which utilizes two layers of glass laminated together, each layer being designed to separately carry the pressure differential. If either layer is damaged and fails, the failure will not propagate across the laminating plastic, and the remaining layer will provide containment.

It is recommended that, whenever possible, windows be designed using this double-containment philosophy. The design should utilize an appropriate factor of safety relative to the long-term modulus of rupture. A factor of safety of 10, for instance, can be achieved by applying half of the load to each layer of glass and designing that layer with a factor of safety of 10, or by applying all of the load to one layer of glass and designing that layer with a factor of safety of 5 — the result is the same.

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3. Presented at a meeting of the Metals and Ceramics Division Vacuum Safety Hazards Committee in August 1970.

IV. DESIGN OF WINDOWS

Most windows in controlled-atmosphere chambers are of simple geometry — either circles or rectangles — and contain no penetrations. Formulas for these simple shapes are presented here, and then some generalizations are proposed for dealing with complex shapes and with windows containing penetrations.

In the analysis of flat plates, the condition of edge restraint — how much the edge is free to rotate under an imposed load — is important. Because it is difficult to envision a gasketing arrangement that can impose significant restraint on a relatively thick glass window, it seems reasonable to arbitrarily design all windows as if they are simply supported — free to rotate at the edges. This assumption results in higher stresses than would result if the edges were restrained; so any error introduced is in the direction of being more conservative.

The formulas presented here are developed from the conventional elastic-stress formulas for uniformly loaded simply supported flat plates.

For a circular plate,[4]

$$\max s_r = s_t = -\frac{3W}{8\pi m t^2}(3m + 1) \ ,$$

where

s_r = radial stress at center, psi,

s_t = tangential stress at center, psi,

W = total load on plate, lb,

m = reciprocal of Poisson's ratio,

t = thickness of plate, in.

Changing nomenclature to be consistent with the later formula for a rectangular plate, we have

4. Raymond J. Roark, *Formulas for Stress and Strain*, 4th ed., McGraw-Hill, New York, 1965, p. 216.

$$\sigma_{max} = \frac{3qd^2}{32mt^2}(3m + 1) = \frac{\sigma}{F/S} ,$$

where

σ_{max} = maximum stress, psi,

q = unit load on plate, psi,

d = diameter of plate, in. (more will be said about how diameter is measured later),

σ = breaking strength, psi,

F/S = factor of safety,

and m and t are unchanged. Rearranging yields

$$t = d\sqrt{\frac{3q\ F/S\ (3m + 1)}{32m\sigma}} .$$

For materials of interest, this can be simplified to

$$t = dk\sqrt{q\ F/S} ,$$

where $k = \sqrt{\frac{3(3m + 1)}{32m\sigma}}$,

and values of k can be calculated:

	Poisson's ratio, V	$m = \frac{1}{V}$	σ	k
Single thickness annealed glass	0.20	5.0	3,000	0.01
Single thickness tempered glass	0.20	5.0	15,000	0.0045
Single thickness plastic	0.40	2.5	9,000	0.0060
Single thickness quartz	0.16	6.25	7,000	0.0065
Single thickness sapphire	0.16	6.25	40,000	0.0027
Single thickness 96% silica	0.17	5.88	2,250	0.0115
Single thickness leaded glass	0.23	4.35	1,200	0.0159

For windows laminated with two layers of glass, each layer carries half of the imposed load, and

$$t = d\sqrt{\frac{3q\ F/S\ (3m + 1)}{64m\sigma}}$$

$$= dk\ \sqrt{q\ F/S}\ ,$$

where t = thickness of each layer of glass,

$$k = \sqrt{\frac{3(3m + 1)}{64m\sigma}}\ ,$$

and values of k can be calculated:

	Poisson's ratio, V	$m = \frac{1}{V}$	σ	k
Laminated annealed glass	0.2	5.0	3,000	0.00707
Laminated tempered glass	0.2	5.0	15,000	0.00316

For a rectangular plate,[5]

$$M = \beta qa^2\ ,$$

where

M = bending moment at center of plate per unit width, in.#/in.,

β = factor related to the ratio of the long side to the short side of the rectangle and to Poisson's ratio,

q = unit load, psi,

a = length of short side of the rectangle, in.

Stress is moment divided by section modulus ($S = \frac{bt^2}{6}$), so

5. S. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells*, 2d ed., McGraw-Hill, New York, 1959, p. 120.

$$\sigma_{max} = \frac{M}{S} = \frac{\beta q a^2 6}{bt^2} = \frac{\sigma}{F/S} ,$$

where

$b = 1$ = width of section (here a unit width), in.,

t = thickness of plate, in.,

σ_{max} = maximum stress, psi,

σ = breaking strength, psi,

F/S = factor of safety.

Letting $\gamma = \sqrt{\beta}$ and rearranging (values of γ for different dimensional ratios for glass and for plastic are presented in Fig. 1),

$$t = a\gamma\sqrt{\frac{6q\ F/S}{\sigma}} .$$

This can be simplified to

$$t = a\gamma k \sqrt{q\ F/S} ,$$

where $k = \sqrt{\frac{6}{\sigma}}$,

and values of k can be calculated:

	σ	k
Single thickness annealed glass	3,000	0.0447
Single thickness tempered glass	15,000	0.02
Single thickness plastic	9,000	0.0258
Single thickness quartz	7,000	0.0293
Single thickness sapphire	40,000	0.0122
Single thickness 96% silica	2,250	0.0516
Single thickness leaded glass	1,200	0.0707
and for laminated windows, where $k = \sqrt{\frac{6}{2\sigma}}$		
Laminated annealed glass	3,000	0.0316
Laminated tempered glass	15,000	0.0141

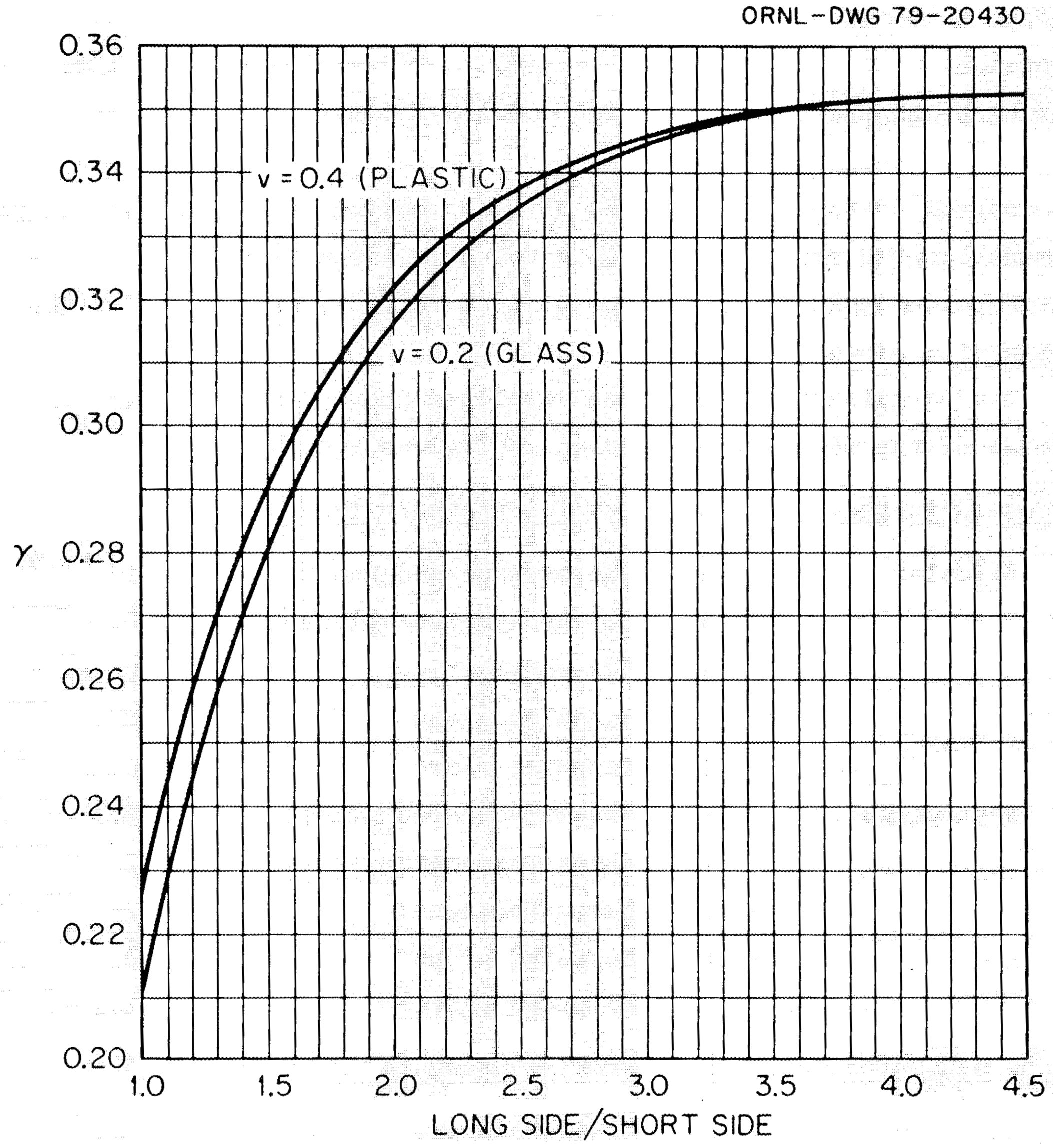

Fig. 1. Values of the factor γ for different geometrical ratios.

The following thickness tolerances are applicable to plate glass:

Nominal thickness	1/8	3/16	1/4	3/8	1/2	3/4	1
Tolerance	←		±1/32		→	±1/16	±1/8
Minimum thickness	0.094	0.156	0.219	0.344	0.469	0.688	0.875

The control of the float process of glass making is very good, and glass so manufactured tends to run close to the minimum tolerance. It is therefore recommended that these minimum thicknesses be used in the design of windows.

The formulas that have been developed above can be summarized for several of the more common loading conditions encountered:

<u>Window subjected to any differential pressure (any F/S)</u>

Circular,	Single thickness annealed glass:	$t = 0.01d\sqrt{q\ F/S}$
	Single thickness tempered glass:	$t = 0.0045d\sqrt{q\ F/S}$
	Single thickness plastic:	$t = 0.006d\sqrt{q\ F/S}$
	Laminated annealed glass:	$t = 0.0071d\sqrt{q\ F/S}$
	Laminated tempered glass:	$t = 0.0032d\sqrt{q\ F/S}$
Rectangular,	Single thickness annealed glass:	$t = 0.045a\gamma\sqrt{q\ F/S}$
	Single thickness tempered glass:	$t = 0.02a\gamma\sqrt{q\ F/S}$
	Single thickness plastic:	$t = 0.026a\gamma\sqrt{q\ F/S}$
	Laminated annealed glass:	$t = 0.032a\gamma\sqrt{q\ F/S}$
	Laminated tempered glass:	$t = 0.014a\gamma\sqrt{q\ F/S}$

<u>Window subjected to any differential pressure (F/S = 10)</u>

Circular,	Single thickness annealed glass:	$t = 0.032d\sqrt{q}$
	Single thickness tempered glass:	$t = 0.014d\sqrt{q}$
	Single thickness plastic:	$t = 0.019d\sqrt{q}$
	Laminated annealed glass:	$t = 0.022d\sqrt{q}$
	Laminated tempered glass:	$t = 0.010d\sqrt{q}$
Rectangular,	Single thickness annealed glass:	$t = 0.142a\gamma\sqrt{q}$
	Single thickness tempered glass:	$t = 0.063a\gamma\sqrt{q}$
	Single thickness plastic:	$t = 0.082a\gamma\sqrt{q}$
	Laminated annealed glass:	$t = 0.101a\gamma\sqrt{q}$
	Laminated tempered glass:	$t = 0.044a\gamma\sqrt{q}$

Window subjected to full vacuum (any F/S)

Circular,	Single thickness annealed glass:	$t = 0.038d\sqrt{F/S}$
	Single thickness tempered glass:	$t = 0.017d\sqrt{F/S}$
	Single thickness plastic:	$t = 0.023d\sqrt{F/S}$
	Laminated annealed glass:	$t = 0.027d\sqrt{F/S}$
	Laminated tempered glass:	$t = 0.012d\sqrt{F/S}$
Rectangular,	Single thickness annealed glass:	$t = 0.173a\gamma\sqrt{F/S}$
	Single thickness tempered glass:	$t = 0.077a\gamma\sqrt{F/S}$
	Single thickness plastic:	$t = 0.100a\gamma\sqrt{F/S}$
	Laminated annealed glass	$t = 0.123a\gamma\sqrt{F/S}$
	Laminated tempered glass:	$t = 0.054a\gamma\sqrt{F/S}$

Window subjected to full vacuum (F/S = 10)

Circular,	Single thickness annealed glass:	$t = 0.121d$
	Single thickness tempered glass:	$t = 0.055d$
	Single thickness plastic:	$t = 0.073d$
	Laminated annealed glass:	$t = 0.086d$
	Laminated tempered glass:	$t = 0.039d$
Rectangular,	Single thickness annealed glass:	$t = 0.546a\gamma$
	Single thickness tempered glass:	$t = 0.242a\gamma$
	Single thickness plastic:	$t = 0.315a\gamma$
	Laminated annealed glass:	$t = 0.388a\gamma$
	Laminated tempered glass:	$t = 0.170a\gamma$

Window subjected to pressure differential = 6 in. water gage (any F/S)

Circular,	Single thickness annealed glass:	$t = 0.0047d\sqrt{F/S}$
	Single thickness tempered glass:	$t = 0.0021d\sqrt{F/S}$
	Single thickness plastic:	$t = 0.0028d\sqrt{F/S}$
	Laminated annealed glass:	$t = 0.0033d\sqrt{F/S}$
	Laminated tempered glass:	$t = 0.0015d\sqrt{F/S}$
Rectangular,	Single thickness annealed glass:	$t = 0.021a\gamma\sqrt{F/S}$
	Single thickness tempered glass:	$t = 0.0093a\gamma\sqrt{F/S}$
	Single thickness plastic:	$t = 0.012a\gamma\sqrt{F/S}$
	Laminated annealed glass:	$t = 0.015a\gamma\sqrt{F/S}$
	Laminated tempered glass:	$t = 0.0065a\gamma\sqrt{F/S}$

Allowable working pressure (any F/S)

Circular,	Single thickness annealed glass:	$q = 10000(t/d)^2/F/S$
	Single thickness tempered glass:	$q = 50000(t/d)^2/F/S$
	Single thickness plastic:	$q = 30000(t/d)^2/F/S$
	Laminated annealed glass:	$q = 20000(t/d)^2/F/S$
	Laminated tempered glass:	$q = 100000(t/d)^2/F/S$
Rectangular,	Single thickness annealed glass:	$q = 500(t/a\gamma)^2/F/S$
	Single thickness tempered glass:	$q = 2500(t/a\gamma)^2/F/S$
	Single thickness plastic:	$q = 1500(t/a\gamma)^2/F/S$
	Laminated annealed glass:	$q = 1000(t/a\gamma)^2/F/S$
	Laminated tempered glass:	$q = 5000(t/a\gamma)^2/F/S$

Factor of safety when thickness and pressure differential are known

Circular,	Single thickness annealed glass:	$F/S = 10000(t/d)^2/q$
	Single thickness tempered glass:	$F/S = 50000(t/d)^2/q$
	Single thickness plastic:	$F/S = 30000(t/d)^2/q$
	Laminated annealed glass:	$F/S = 20000(t/d)^2/q$
	Laminated tempered glass:	$F/S = 100000(t/d)^2/q$
Rectangular,	Single thickness annealed glass:	$F/S = 500(t/a\gamma)^2/q$
	Single thickness tempered glass:	$F/S = 2500(t/a\gamma)^2/q$
	Single thickness plastic:	$F/S = 1500(t/a\gamma)^2/q$
	Laminated annealed glass:	$F/S = 1000(t/a\gamma)^2/q$
	Laminated tempered glass:	$F/S = 5000(t/a\gamma)^2/q$

How is the diameter or length of sides of windows to be measured? Properly, these distances should be measured center to center of the gasket seats. Since it is not always possible to remove the frame to determine the actual size of the glass and the actual location of the gasket seat in an existing chamber, it seems reasonable to use the smaller of (1) the actual dimension of the glass, (2) the clear opening of the window plus one glass thickness, or (3) the center-to-center dimension of the gasket. This is acceptable for the usual window mountings, but it is necessary to recognize and consider mountings that are not usual.

Any mounting that permits glass-to-metal contact, that permits the clamping mechanism to twist or bend the glass, that can apply a nonuniform loading around the edge of the glass, or that requires holes or irregular edges in the glass should be considered unusual. If the geometry of the chamber is not symmetrical to the extent that the chamber structure, in deflecting under differential pressure, can impose a twist on the glass, this should be considered unusual. The following sketches indicate some usual and unusual configurations.

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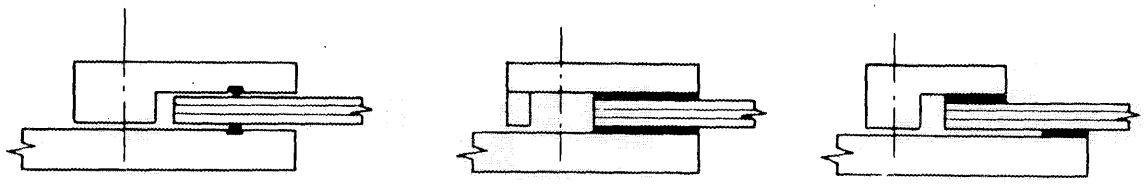

USUAL USUAL UNUSUAL

For windows that have holes, irregular edges, or other discontinuities, some correction must be made to conventional design to accommodate the weakening and/or stress concentration caused by the discontinuity. Since the calculation of precise stresses in such cases is not simple, and since the calculations described here are not necessarily precise, it is suggested that a stress concentration factor[6] of 2 be imposed to account for any such discontinuities. This requires that a window with holes must be $\sqrt{2} = 1.414$ times as thick as the same window without holes.

For windows of irregular shape, design using the smallest circle or rectangle that circumscribes the window should provide a reasonable design. Special shapes (perhaps a triangle) should be recognized and given special consideration.

6. Raymond J. Roark, op cit., p. 384.

V. RELIABILITY AND REDUNDANCY

It was said in Sect. III that the strength of glass should be considered in a statistical sense because of the large coefficient of variance associated with its breaking strength. For conventional services, the design of glass windows is performed using factors of safety (relative to the mean modulus of rupture in flexure) which range from 2-1/2 for building windows subject to wind loads to 10 for windows exposed to water (the presence of water or water vapor reduces the strength of glass). Factors of safety do not directly provide a meaningful basis for assessing the reliability and consequent safety of windows. It is therefore necessary to convert the factors of safety to probabilities of failure.

Probability of failure

The usual practice[7] in assigning probabilities of failure to windows of annealed plate glass is to assume that the breaking strength of glass follows a normal distribution and is characterized by a mean modulus of rupture of 6000 psi and a coefficient of variance (CV) of 0.25. This modulus of rupture value is appropriate for the short-term loadings characteristic of applications like building windows. The relationship between the factor of safety F/S (with respect to the mean modulus of rupture) of a design, the coefficient of variance, and the probability of survival (nonfailure) P of the design is

$$P = F(z) = F\left[\left(1 - \frac{1}{F/S}\right)\frac{1}{CV}\right] = F\left(\frac{F/S - 1}{F/S \times CV}\right) ,$$

and the numerical value of the survival probability for any particular case can be obtained from a table of the normal distribution function

7. PPG Industries, op. cit., p. 23.

F(z) for any combination of F/S and CV. The probability of failure occurring on application of the design (short-term) load to windows of annealed glass for different factors of safety is given in Table 1.

Table 1

Factor of safety	Probability of failure
1	0.5
2	0.023
3	0.0038
4	0.0013
5	0.0007
6	0.00044
8	0.00023
10	0.00016
16	0.000088
∞	0.000032

It should be noted that this calculation implies a limiting P for any particular CV, the limit being P = F(1/CV). This limiting value represents the area under the tail of the distribution function that lies to the left of the ordinate representing zero stress. The calculated probabilities of failure and the limiting probability seem reasonable when viewed in the context of conventional windows.

When the same variance (there is no reason for the variance to change with time) is applied to the smaller long-term breaking strength of 3000 psi, however, the coefficient of variance becomes 0.50, and the limiting value P = 0.023 is approached rapidly. Probabilities of failure for this case are given in Table 2.

The probability represented by the area under the tail of the distribution function has, in this case, become significant and interferes with the interpretation of the data. It is necessary to replace the normal distribution function with another distribution function which goes to zero at the ordinate representing zero stress and so does not

Table 2

Factor of safety	Probability of failure
1	0.5
2	0.16
3	0.09
4	0.067
5	0.055
6	0.047
8	0.040
10	0.036
16	0.030
∞	0.023

have a limiting probability of failure. Such a distribution is the Weibull distribution, which has been used[8] to characterize the breaking strength of glass. For comparison, Fig. 2 presents a Weibull distribution having arbitrarily selected parameters $\beta = 2$ and $\alpha = 8.7 \times 10^{-8}$ and a corresponding normal distribution. Both of the distributions plotted have a mean of 3000 psi and a standard deviation of about 1500 psi. Probabilities of failure determined using this Weibull distribution are given in Table 3. Even after this improved assumption is made, an underlying fact is evident and should be recognized: a design can be no more reliable than the materials used in executing it.

It is recognized that the use of ordinary statistics to predict probabilities of failure for extreme conditions ($F/S > 10$, $P < 0.0001$) is not necessarily meaningful. It is not intended here that the numerical values presented be accepted as being precise, but rather that the underlying philosophy be described in meaningful terms.

In considering tempered plate glass, and presuming the tempering process does not introduce additional variation, a spectacular advantage

8. J. W. Heavens and P. N. Murgatroyd, "Analysis of Brittle Fracture Stress Analysis," *J. Am. Ceram. Soc.* 53(9): 503-5 (September 1970).

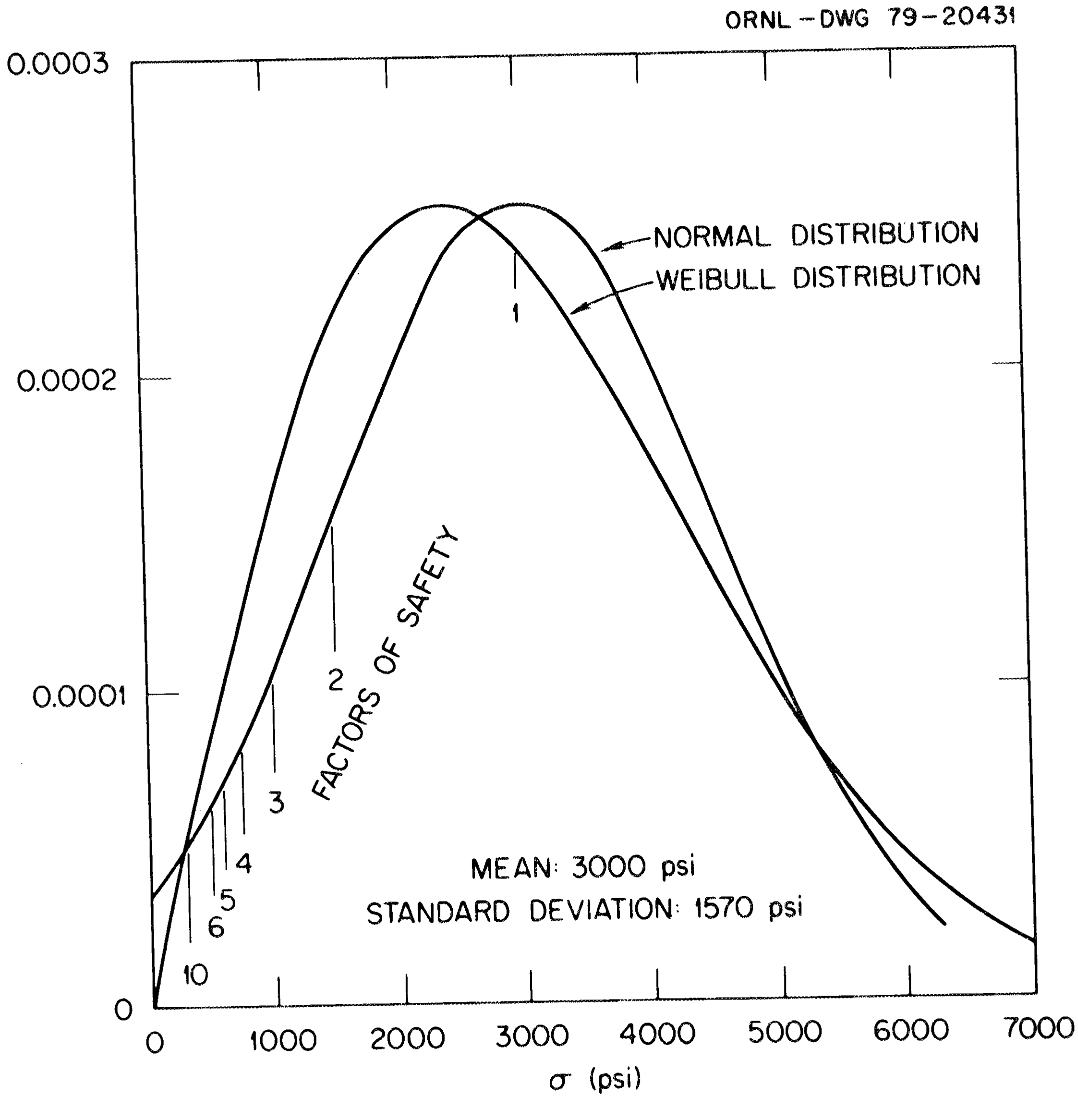

Fig. 2. A Weibull distribution compared with a similar normal distribution.

Table 3

Factor of safety	Probability of failure
1	0.72
2	0.22
3	0.105
4	0.046
5	0.031
6	0.022
8	0.012
10	0.0078
16	0.0029
∞	0.0

is evident. In this case the modulus of rupture is increased by a factor of 5, while the variance remains unchanged; so the coefficient of variance becomes 0.10 (considered with respect to the long-term breaking strength). The probabilities of failure associated with different factors of safety are given in Table 4.

Table 4

Factor of safety	Probability of failure
1	0.5
2	$10^{-6.5}$
∞	10^{-23}

The phenomenon called "fatigue" (loss of strength under long-term loading) in glass is well established,[9] as is the large variance associated with the breaking strength. Considering the probabilities

9. R. E. Mould and R. D. Southwick, "Strength and Static Fatigue of Abraded Glass under Controlled Ambient Conditions: II, Effect of Various Abrasions and the Universal Fatigue Curve," *J. Am. Ceram. Soc.* 42(12): 588 (December 1959).

indicated in Tables 3 and 4 for long-term service leads to a conclusion that, in circumstances where failure cannot be tolerated, single panes of annealed glass windows should not be used.

Redundancy

The probability of surface damage occurring to both the inner and the outer panes of the double containment design described in Sect. III during the relatively short time interval between routine inspections is small. If, then, the most probable cause of an in-service failure is surface damage to the glass, it can be argued that the two panes can provide adequate safety if they are designed with individual factors of safety of something less than the value prescribed for a single pane.

Considering the probabilities of failure of the two panes to be statistically independent, the probability of simultaneous failures of both becomes

$$P = P_a \times P_b \ .$$

If a single design is to be replaced by two identical designs in series and the survival probability is to be held constant, each of the two must have an individual failure probability of

$$P_a = \sqrt{P} \ .$$

From this it is evident that one design having an F/S of 10 (in annealed glass) can be replaced by two in series if each of the two has a P of $\sqrt{0.0078} = 0.088$ (for which the F/S = 3.3). Further, this indicates that the double containment design, carried out using the formulas in Sect. V for tempered glass, where each of the panes has a factor of safety of 5 with respect to the full load, provides an overall probability of failure of less than 10^{-30}, rendering failure (mathematically at least) truly inconceivable.

Applying this philosophy to the comparison of two annealed glass windows having equal total thickness, one of which is a single pane and the other consisting of two panes, it appears that the single pane is safer when its F/S is less than about 4, and the double pane is safer when the single pane F/S is greater than this value. Thus, when a window is limited in thickness and so must have a low factor of safety, it is best made of a single thickness of glass.

The attractions of these statistical manipulations are enticing, and it appears that the imputed advantages (for tempered glasses) and disadvantages (for annealed glass) are real. In the actual selection of criteria for window design and in the preparation of supporting design formulas, allowance has been made for the indicated disadvantages, but credit has not been taken for apparent advantages. Any additional margin of safety that is present in these advantages is accepted as a serendipitous gift.

VI. TESTING GLASS WINDOWS*

Because glass is an unreliable material, there is a great urge to subject glass windows to some form of a proof test to demonstrate their adequacy. The use of a hydrostatic test, for instance, is routine in the manufacture of pressure vessels fabricated of very reliable and consistent engineering materials such as steel, to detect major construction flaws. The compulsion to perform a comparable test on glass windows is irresistible, particularly since the design is probabilistic in nature.

Glass, however, always contains Griffith microcracks, and the overstress imposed during a proof test will cause these cracks to propagate, weakening the material and shortening its service life. The question, then, is whether the reassurance gained by successfully passing the test is worth enough to offset the damage done to the material by the test itself. This question is pursued here.

To establish a basis for evaluating the damage imposed on glass by testing, it is necessary to digress and to discuss the derivation of the Universal Fatigue Curve.[9] The major variable contributing to the variance in glass-testing data is the loading rate. At liquid-nitrogen temperature (77 K), however, glass is insensitive to the loading rate. By performing tests at this low temperature, it was possible to minimize the scatter in the data and to obtain a precise determination of the true fatigue curve. Several analytical solutions of the problem have been reported, and that of Charles,[10] presented graphically in Fig. 3, conforms to the experimental data in a rational manner.

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*The author appreciates the assistance of Mr. W.C.T. Stoddart, of ORNL Engineering, in clarifying the concepts discussed here.

10. R. J. Charles, "Static Fatigue of Glass. II," *J. Appl. Phys.* 29(11): 1558 (November 1958).

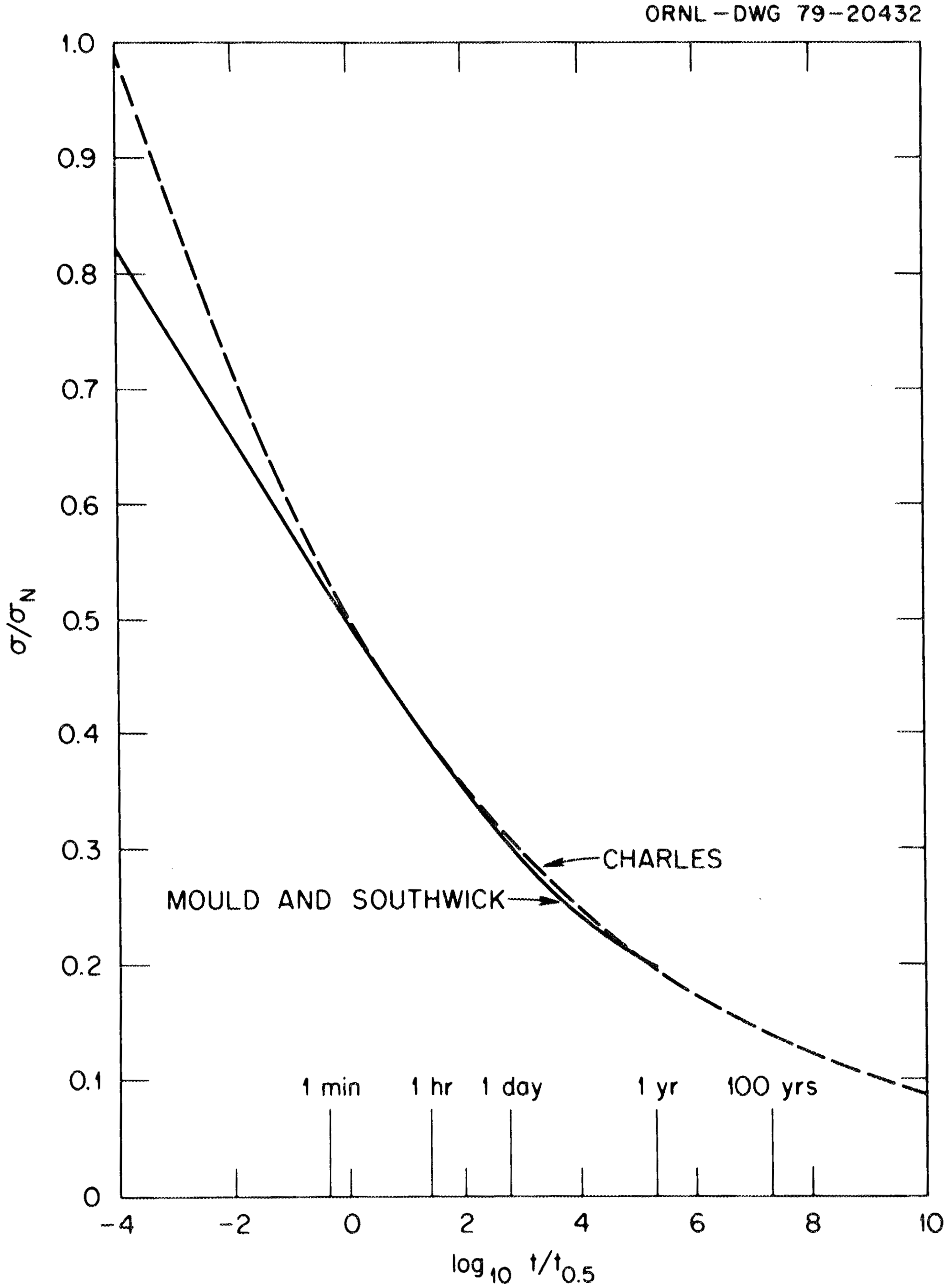

Fig. 3. Charles' approximation to the universal fatigue curve.

Beginning with Charles' expression

$$\log t \approx n \log 1/\sigma_a - \log k''' ,$$

where

t = time

σ_a = applied stress

n = a constant, $\frac{d \log t}{d \log 1/\sigma_a}$

$-\log k'''$ = a constant, the value of $\log t$ when $\log 1/\sigma_a = 0$

a relationship describing the loss of "utility" (ability to resist stress over time without failure) will be developed. Letting

$a = k'''$

$b = n$

$\sigma = \sigma_a$

and rearranging, the expression is

$$\log \sigma = -1/b \ (\log t + \log a)$$

or

$$\sigma = a^{-1/b} \ t^{-1/b}$$

or

$$t^{1/b} = a^{-1/b} \ \sigma^{-1}$$

The values of the constants log a and b can be determined if two experimental values are known.

The desired relationship, f(t), when integrated over the mean service life T, should yield the mean utility U_T of the glass, so

$$\int_0^T f(t) = U_T = 1.0$$

and the integral of the product of the function and the applied stress is assumed to be described by a single constant k, so

$$\int_0^T \sigma\, f(t) = k$$

Transposition and substitution lead to

$$\int_0^t f(t) = k\sigma^{-1} = ka^{1/b}t^{1/b}$$

and the function is obtained by differentiating

$$f(t) = \frac{d}{dt}\left(ka^{1/b}t^{1/b}\right) = ka^{1/b}\,\frac{1}{b}\,t^{(1/b-1)}$$

and then integrating back

$$\int_{t_1}^{t_2} f(t) = U_{1-2} = ka^{1/b}t^{1/b}\Big|_{t_1}^{t_2} = ka^{1/b}\left(t_2^{1/b} - t_1^{1/b}\right)$$

The unique value of a new constant, $K = ka^{1/b}$, can be determined for each stress level by letting $t_0 = 0$ and letting t_1 assume the value at which U = 1.0:

$$K = \frac{U_T}{t_1^{1/b} - t_0^{1/b}} = \frac{1.0}{a^{-1/b}\sigma^{-1} - 0} = a^{1/b}\sigma$$

It is concluded that the fraction of the glass' utility that is consumed by subjecting it to a stress σ for the time interval from t_1 to t_2 is

$$U_{1-2} = \int_{t_1}^{t_2} f(t) = K\left(t_2^{1/b} - t_1^{1/b}\right)$$

Values of K_σ and approximate mean breaking times for a glass that has a mean breaking time of 2.5 minutes at a mean breaking stress of 10,000 psi (for which log a = -55.20 and b = +13.7) are given in Table 5.

Table 5

σ	K_σ	$t_{0.5}$
10,000	0.935	2.5 min
8,000	0.748	1 hr
6,000	0.561	1 day
4,000	0.374	1 year
2,000	0.187	10,000 years
1,000	0.093	

For instance, if a new piece of glass is subjected to a stress of 6000 psi for 20 min, the loss of utility is

$$L = 0.561\left(20^{1/13.7}\right) = 0.698 ,$$

and a glass designed with a factor of safety of ten (so σ = 1000), subjected to a 3× pressure test for 10 min when new, would lose

$$L = 0.281\left(10^{1/13.7}\right) = 0.332 .$$

This calculation is sensitive to the stress imposed on the glass, the length of time the stress is imposed, and the time in the stress history of the glass that the stress is imposed; and the utility of the glass at any time is the residual after all of the losses have been deducted from the pristine unity.

It follows from this logic that a window should be carefully conditioned — subjected to low stress levels during the early portion of its service life.

It also follows that a window that will have a limited service life can be safely subjected to greater stress than can one which must be expected to last forever.

An annealed glass window is designed to have a factor of safety of 10 over a service life of ten years. From Table 3 it is seen that this represents a probability of failure of 0.0078. From Table 1 we see that this same probability is represented by a factor of safety of 2.5 if the glass is tested now. Applying the F/S of 2.5 to the mean breaking strength appropriate to short-term service (twice long-term strength), we find that a test pressure $\frac{2/2.5}{1/10} = 8$ times the design pressure is necessary to represent a comparable probability of failure.

Subjecting the window to eight times the design stress for, say, 10 min would result in a loss of

$$L = 0.748\left(10^{1/13.7}\right) = 0.88 \ ,$$

almost all of its utility. It is unlikely that we would dare load the chamber itself to eight times its design pressure, and we would be hesitant to expend this fraction of the window's utility in a test; so a meaningful test does not seem to be possible.

What do we gain from testing a window to two or three times its design stress? We said earlier that a 3× test would cost 0.332 of the original utility. For the window under consideration, this represents a probability of failure of 0.0003 and an F/S of about 20. This indicates that failure of the window will not occur at 10/20 = 1/2 of the design load. This certainly does not provide confidence, in the mathematical sense, but would, in a practical vein, satisfy us that we did not have an extremely bad piece of glass.

These calculations dealing with loss of utility have been based on the variance-free Universal Fatigue Curve. For real windows it is necessary to consider these adjustments as corrections to the mean breaking strength and then, for probability of failure calculations, to impose the variance which is still present in the glass. This can best be illustrated by an example.

A rectangular window 37 × 28 × 1/4 in., made of laminated annealed glass, and containing glove ports, will contain a pressure of

$$q = \frac{1000}{2}\left(\frac{t}{a\gamma}\right)^2 \frac{1}{F/S} = \frac{1000}{2}\left(\frac{0.125}{28 \times .261}\right)^2 \times \frac{1}{10} = 0.014 \text{ psi} = 0.4 \text{ in. w.g.}$$

with a factor of safety of ten (q is the mean breaking pressure).

If this window is operated at a 0.4 in. w.g. pressure differential, it has a mean life t which can be calculated from

$$L = Kt^{1/b}$$

so

$$t = \left(\frac{1}{K}\right)^b = \left(\frac{1}{0.093}\right)^{13.7} = 1.35 \times 10^{14} \text{ min} = 0.26 \times 10^9 \text{ yr}$$

if subjected to a 1 in. w.g. differential, the life is 910 years and, for a 2 in. w.g. differential, it is 4.1 hours.

If the service is mixed, 0.0001 (9 sec/day) at 2 in., 0.005 (7 min/day) at 1 in., and 0.9949 (balance) at 0.4 in., K is weighted by these fractions to yield a composite K = 0.094 and the resulting life is 230×10^6 years.

This appears unquestionably safe until the associated variance is considered. The standard deviation for the stress life is 10^5 years. Although the average life is 230×10^6 years, there is a 0.023 probability that it is 8 days and a 0.0013 probability that it is just 7 seconds.

When the chamber contains sensitive materials the question is whether odds of 1000 to 1 are good enough. Increasing the thickness of the window by a factor of 1.7 will improve the mean stress life and make more remote the probability of failure in 8 days, each by a factor of 10^6.

Confusion results because we are not trying to predict the likely outcome — a long service life — but are trying to protect against an unlikely outcome — a very short service life. It is for this reason that we appear, to operators, to be unreasonably conservative.

VII. OPERATING PRECAUTIONS

After windows have been mounted in frames, precautions should be taken to minimize the likelihood of failure and to minimize the consequences if such should occur. Each glass should be carefully surveyed, using a bright light to detect scratches or other blemishes, by a member of the operating crew before each routine pump-down and at least once each week while the chamber is in service. During a pump-down, and while the chamber is evacuated, operating personnel should stay away from and to one side of the windows. Particular attention should be given to avoid thoughtless changes in the operating conditions of the chamber; for instance, replacing fluorescent lights with incandescents may impose an unanticipated thermal stress on the lighting windows.

In many cases it will not be possible to provide windows of the double containment type for a particular application. In these cases consideration should be given to the desirability of providing auxiliary safety features so that the overall safety is equivalent to that of the double containment window. Such a case exists in the instance of a window provided in a vacuum furnace to permit pyrometer readings to be taken. The double containment design is unacceptable on two counts: the temperature is too high for the plastic laminating material, and the distortion in the tempered glass interferes with taking the readings. It may be necessary to utilize a proprietary design quartz window that provides an F/S of four (an F/S of less than three should be unacceptable in any case). An additional margin of safety can be provided by securing a wire-mesh guard over the window, with a slit that can be opened when necessary to permit readings to be taken.

The relationship between size of window opening and the volume and shape of the chamber has some influence on the effective hazard that must be anticipated.

For chambers that are normally filled with inert gases, it may be necessary merely to provide metal covers for the windows, so they can be contained during pump-down and backfilling operations.

VIII. CONTROLLED-ATMOSPHERE CHAMBER CRITERIA

To achieve the objective of greater safety in the operation of ORNL, criteria for the design of chambers subjected to vacuum were formulated. These criteria were promulgated as Sect. 2.1, "Vacuum Equipment," of the ORNL Safety Manual. This section is reproduced in its entirety as Appendix I of this report.

Additional criteria were developed for glove boxes and were promulgated as Appendix A-3, "Glove Box Systems Safety Guide," of the ORNL Safety Manual. This appendix is reproduced in its entirety as Appendix II of this report.

For the purpose of stipulating safety criteria, two levels of hazard were defined: one where safety of personnel is the only consideration, and one where the potential release of radiotoxic material[11] compounds the hazard. This second, more sensitive, condition is recognized by according it a greater minimum factor of safety. The use of plastics in the construction of chambers for containment of radiotoxic materials was prohibited by Appendix A-7 of the ORNL Health Physics Procedures Manual; but this restriction has been relaxed, and plastics are now permitted in some applications.

A review of each chamber, existing or new, is required to determine that conformance to the criteria is achieved. For any window that can not strictly conform to the criteria, a further review is carried out to determine whether supplementary safety features (such as those discussed in Sect. VII) can be incorporated in the installation to provide a level of safety equivalent to that implied by the criteria.

The criteria do not require utilization of the double-containment philosophy, although this is strongly endorsed.

The criteria for vacuum chambers and those for glove boxes have now been consolidated into a single "Criteria for Controlled-Atmosphere Chambers," which is being published concurrently with this report.

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11. Criteria apply to combined quantities of radioactivity which exceed the hazard equivalent of 0.1 mg of ^{239}Pu.

IX. EXPERIENCE AT ORNL

In 1970, a program was initiated at ORNL to determine the degree of safety that existed in the windows of controlled-atmosphere chambers in use in the Laboratory, and to determine and implement any indicated remedial action. The program initially consisted of a survey of the vacuum chambers in use, the appraisal of the adequacy of the windows, and the replacement of any windows that did not conform to minimal criteria.

The survey covered 345 vacuum chambers (only chambers that might be subjected to a pressure differential of greater than 5 in. of water gage were included — glove boxes connected to exhaust manifolds were not) containing 910 windows. For each of these windows the factor of safety was calculated, and those that did not conform to the criteria were replaced.

Recognizing that low-pressure-differential windows can be just as hazardous as those subjected to full vacuum, the initial survey was extended to cover all controlled-atmosphere chambers. This extension covered an additional 424 chambers and an additional 1031 windows.

In the course of the survey, some information was acquired about previous unreported window failures. It appears that only a fraction of failures (those where reporting is necessary for some other reason) are actually reported through safety channels. Windows that have actually failed in service are ones that had factors of safety (probability of failure) of 1.37 (0.14), 1.53 (0.082), and 4.0 (0.0013).

As expected, the establishment and implementation of criteria did not eliminate window failures. Since 1970, three failures have taken place and their cause identified:

1. A press was being used to compress an assembly, and a stack of washers was used as a spacer. Off-center loading caused the stack to slip, and a resulting missile penetrated the window.
2. An operator connected a glove-box exhaust to a too-high vacuum exhaust line, and the window was broken.
3. An unexpected reaction took place with explosive force, blowing the window out of a vacuum chamber.

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APPENDIX I

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VACUUM EQUIPMENT

A. Policy

It is the policy of the Oak Ridge National Laboratory that vacuum equipment be considered as potentially hazardous and that special precautionary procedures be followed relative to its use.

B. Definitions

1. For purposes of this procedure, vacuum equipment is any equipment operated in such a manner that the pressure inside the container is more than 5" H_2O below atmospheric pressure outside the container.

2. Controlled Atmosphere Chambers are isolation chambers, usually glove boxes which are capable, by design or by manner of installation, of being operated as vacuum equipment. A chamber is considered to fall within this defintion if it is connected to an exhaust system capable of producing a vacuum unless a vacuum relief device is provided to limit the differential pressure between the chamber and surrounding atmosphere to $< 5"$ H_2O.

C. Responsibilities

1. Supervision is responsible for seeing that all employees working with or near vacuum equipment are properly instructed and trained in the use of safety practices appropriate to this class of equipment.

2. The Employee is responsible for the use of appropriate safety equipment and for utilizing safe operating practices.

3. The Division Safety Officer coordinates vacuum equipment safety within his division. If any deviations from this procedure become necessary in an operation, they shall be documented with a written justification which shall be approved by the Office of Safety and Radiation Control before the operation is begun.

4. The Inspection Engineering Department - The Inspection Engineering Department shall provide trained personnel and any necessary equipment to perform inspections and tests of vacuum equipment. They shall assemble and maintain a file of data on Controlled Atmosphere Chambers, shall ensure that each such chamber is properly marked with its safe operating limits and shall periodically re-inspect installed chambers.

D. General Precautions

1. Glass containers that are to be operated as vacuum equipment shall be visually inspected before use and periodically during use. The presence of defects or damage from handling which might materially prevent safe operation shall be cause for replacement of the container.

2. Glass containers having volume greater than five litres which are operated as vacuum equipment shall be provided with perforated metal guards or with plastic missile shields.

3. When working with or near glassware, or equipment having viewing windows, operated as vacuum equipment personnel shall wear safety glasses with side guards or face shields.

4. The Division Safety Officer shall ensure that the materials of construction used in Controlled Atmosphere Chambers are compatible with the operations to be performed before operation commences.

5. Each controlled atmosphere chamber shall be reviewed for conformity with the criteria given in Table 1 on page 3. A report of the review of each chamber shall be submitted to the Office of Safety and Radiation Control.

6. Designs, drawings, and specifications for new chambers, and deviations from the designs and specifications as well as replacement glass requisitions, shall be reviewed by the Inspection Engineering Department for compliance with the requirements of Table 1.

Table 1

CRITERIA FOR CONTROLLED ATMOSPHERE CHAMBERS

Factor of Safety on Breaking Strength

	Minimum	Minimum for Interim Operation[1]
New Construction		
Metal Structure[2]	4	
Windows[3] - Personnel Safety	10	
Radioactivity[4]	10	
Existing Construction		
Metal Structure[2]	2.5	1.75
Windows[3] - Personnel Safety	6	3
Radioactivity[4]	8	6

[1] Equipment having factors of safety below the prescribed minimum but above this value may be operated pending replacement, provided a written justification for use, citing appropriate safety precautions, has been approved by the Division Safety Officer. In extreme circumstances, equipment having a safety factor below this value may be operated provided approval is obtained from the Safety and Radiation Control Office.

[2] Or a factor of safety 0.4 times this value on yield strength, if this results in a more conservative design.

[3] Laminated glass shall be designed using the prescribed factor of safety with half the pressure load applied to each layer of glass.

[4] Criteria apply to combined quantities of radioactivity which exceed the hazard equivalent at 0.1 mg of ^{239}Pu.

APPENDIX II

GLOVE BOX SYSTEMS SAFETY GUIDE

Scope

These criteria shall be applied to glove box systems where failure of one or more system components and subsequent loss of containment could create a radiation, fire, or explosion hazard to personnel or equipment. If application of these criteria imposes an unreasonable restriction, written justification for deviation from them should be submitted to the Office of Laboratory and Personnel Protection and the Environmental Control Engineering Department for consideration.

Definitions

Glove Box. A containment enclosure operating at a pressure differential and equipped with gloves for handling hazardous materials. The maximum enclosure pressure is limited to ±5" water gage.

Glove Box System. The system includes (1) glove box, (2) pressure and flow controls, (3) filters, (4) fire control, (5) associated gloves, bags, port closures, (6) pressure relief (if required), (7) exhaust fans (if required), (8) exhaust ducts, and (9) alarm indicators and monitors.

Normal Service. A service where inleakage of air creates no hazard.

Critical Service. A service where an inleakage of air could cause a fire or explosion, or an outleakage of air could cause a radiation hazard.

Safety Guide

1. **General** considerations for box design include (a) convenience, (b) good lighting, (c) ventilation inside box, (d) working height, (e) fire and corrosion resistance, (f) decontamination, (g) eventual disposal, (h) atmosphere, (i) material entry and exit, and (j) glove and bag port requirements.

2. Windows shall be laminated annealed safety plate glass. Use of plastics[1] and single thickness glass requires approval of Office of Laboratory and Personnel Protection. Single thickness glass is prohibited for critical service. Crazed or cracked windows shall be replaced unless approved otherwise by the Environmental Control Engineering Department.

---

[1] Health Physics Procedures Manual, Appendix A-7, Plastics Prohibited for Type A and B Laboratories.

3. Glove ports shall not exceed 8" nominal size, shall have a minimum separation of 15-inch center-to-center, and shall be located outside of the window area where possible or no closer than 2.5" to the edge of the glass where window mounting cannot be avoided.

4. Glove and bag port closures shall be provided for critical service .

5. The exhaust system shall normally maintain a negative pressure (-0.3" to -1" H_2O) in the enclosure.[2] The box flow-through rate may range from no-flow for simple box operations to high flows for boxes requiring dilution of flammable vapors or heat loads. High efficiency filters (HEPA) are required on the box inlet and discharge for critical service. Two stages of testable HEPA filters shall be provided before releasing exhaust to atmosphere. In those cases where HEPA filters are not adequate (some radioactive gases), scrubbers and/or absorbers shall also be used.

6. Pressure and/or flow controls shall be provided for single or multiple glove box systems. All unattended glove boxes or glove box systems shall be installed with remote alarms which will signal the malfunction of the pressure control system. These remote alarms shall be located in areas where there is a continuous presence of operating personnel. No pressure relief device shall be required when the source of pressure or vacuum connected to the glove box is less than ±5" H_2O gage. When the source of pressure or vacuum exceeds ±5" H_2O, a relief device must be installed to prevent the glove box from exceeding the safe limits (±5" H_2O). When a filter is required in the relief valve system, this filter shall not be shared with any flowing system to or from the glove box. Glove box pressure indicators shall be provided.

7. Window design[3] shall provide the following factors of safety at the maximum (relief) pressure, based on short-term breaking pressure.

	F/S*
a. Laminated annealed safety plate	
Existing enclosures for noncritical service	1
New enclosures for noncritical service	2
New or existing enclosures for critical service	25

---

[2]If a glove or bag is accidentally lost or severely torn, the negative pressure requirement is waived but the face velocity at the opening must be > 100 ft/min.

[3]See Glove Box Window Design criteria page 4.

*F/S (Factor of safety is the ratio of the calculated pressure at which the glass will crack to the minimum pressure that can be applied.)

	F/S
b. Single thickness glass or plastic	
Existing enclosures for noncritical service	10
New enclosures for noncritical service	20
New or existing enclosures (plastics only) for critical service	25

8. Pressurized gas supplies to glove boxes shall be controlled by pressure reliefs and flow regulators to prevent pressurization of enclosures, and, in cases involving the handling of flammables, to maintain the box atmosphere concentration at less than 25% of the lower explosive limit. In cases where the lower explosive limit can be exceeded, combustible gas sensors shall be used.

9. An inert atmosphere shall be required in enclosures where pyrophoric materials are handled; however, in some instances, reduced oxygen atmospheres may be adequate. Gas or vapor analyzers (Ar, O_2, or H_2O) may be necessary for the control of some gloved box environments.

10. The need for heat detectors, fire control systems, and explosion-proof equipment shall be considered when flammables are handled in air ventilated enclosures.

11. Boxes provided with water service shall be equipped with controls to prevent flooding in the event of a pipe leak or rupture.

12. Electrical safeguards shall be provided for equipment and personnel. The use of ground fault interrupters, independent fusing, and overload protection should be considered. Metal boxes shall be grounded unless otherwise approved by the Office of Laboratory and Personnel Protection.

13. The Environmental Control Engineering Department and the Office of Laboratory and Personnel Protection shall jointly review the glove box system and all safety related controls prior to construction of the glove box and system.

14. The proper functioning of all safety related controls, ventilation systems, pressure reliefs, etc., shall be tested and verified as operable prior to normal operation.

GLOVE BOX WINDOW DESIGN CRITERIA

The formulas used for calculating breaking strength of windows are developed from the conventional elastic-stress formulas for uniformly loaded simply supported circular and rectangular plates. The following simplified formulas for short-term breaking pressure were developed from the basic formulas, using values of modulus of rupture and of Poisson's Ratio for different materials:

Circular:

Single Thickness Annealed Glass:	$p = 554 \times 10^3\ t^2/d^2$
Single Thickness Tempered Glass:	$p = 2770 \times 10^3\ t^2/d^2$
Single Thickness Plastic:	$p = 1960 \times 10^3\ t^2/d^2$
Laminated Annealed Glass:	$p = 1111 \times 10^3\ t^2/d^2$
Laminated Tempered Glass:	$p = 5540 \times 10^3\ t^2/d^2$

Rectangular:

Single Thickness Annealed Glass:	$p = 27.7 \times 10^3\ t^2/\gamma^2 s^2$
Single Thickness Tempered Glass:	$p = 139 \times 10^3\ t^2/\gamma^2 s^2$
Single Thickness Plastic:	$p = 83.1 \times 10^3\ t^2/\gamma^2 s^2$
Laminated Annealed Glass:	$p = 55.4 \times 10^3\ t^2/\gamma^2 s^2$
Laminated Tempered Glass:	$p = 277 \times 10^3\ t^2/\gamma^2 s^2$

p is breaking pressure in inches of water,
t is thickness of each layer,
d is the diameter of a circle, and
s is length of the short side of a rectangle;
all dimensions in inches.

Values of γ have been computed for Poisson's Ratio of 0.20 (glass) and of 0.40 (plastic), and are presented in Figure 1.

Windows that have glove ports are presumed to be weakened by a factor of two, so the calculated pressure must be halved for such a window.

Figures 2 and 3 indicate the upper limit of sizes for new and existing windows of 1/4" safety plate in consonance with the criteria. Existing circles less than 59" and new circles less than 42" in diameter of 1/4" safety plate (without ports) also meet the criteria.

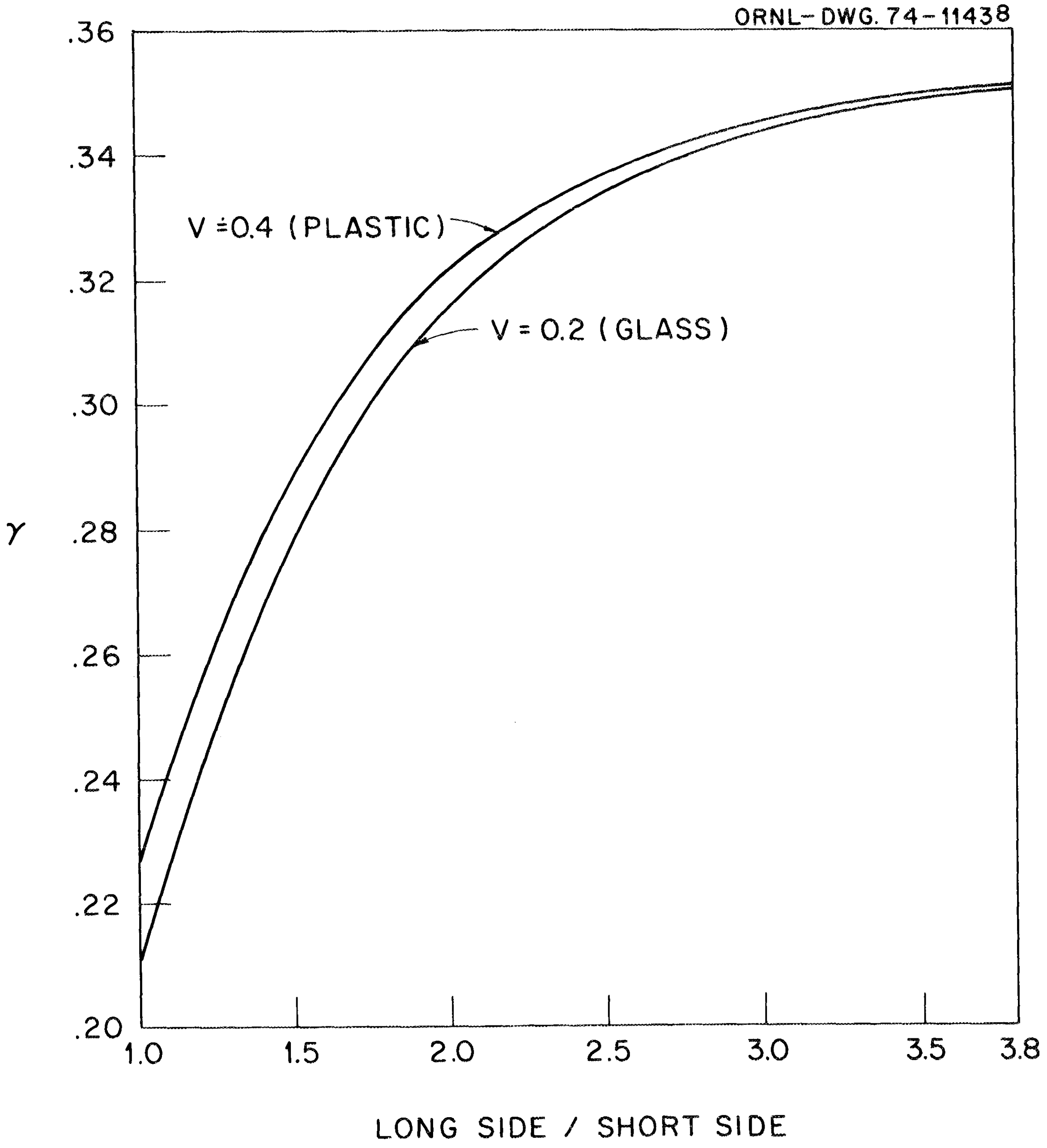
ORNL-DWG. 74-11438
γ
.36
.34
.32
.30
.28
.26
.24
.22
.20
1.0
1.5
2.0
2.5
3.0
3.5
3.8
V ≐0.4 (PLASTIC)
V = 0.2 (GLASS)
LONG SIDE / SHORT SIDE

Figure 1

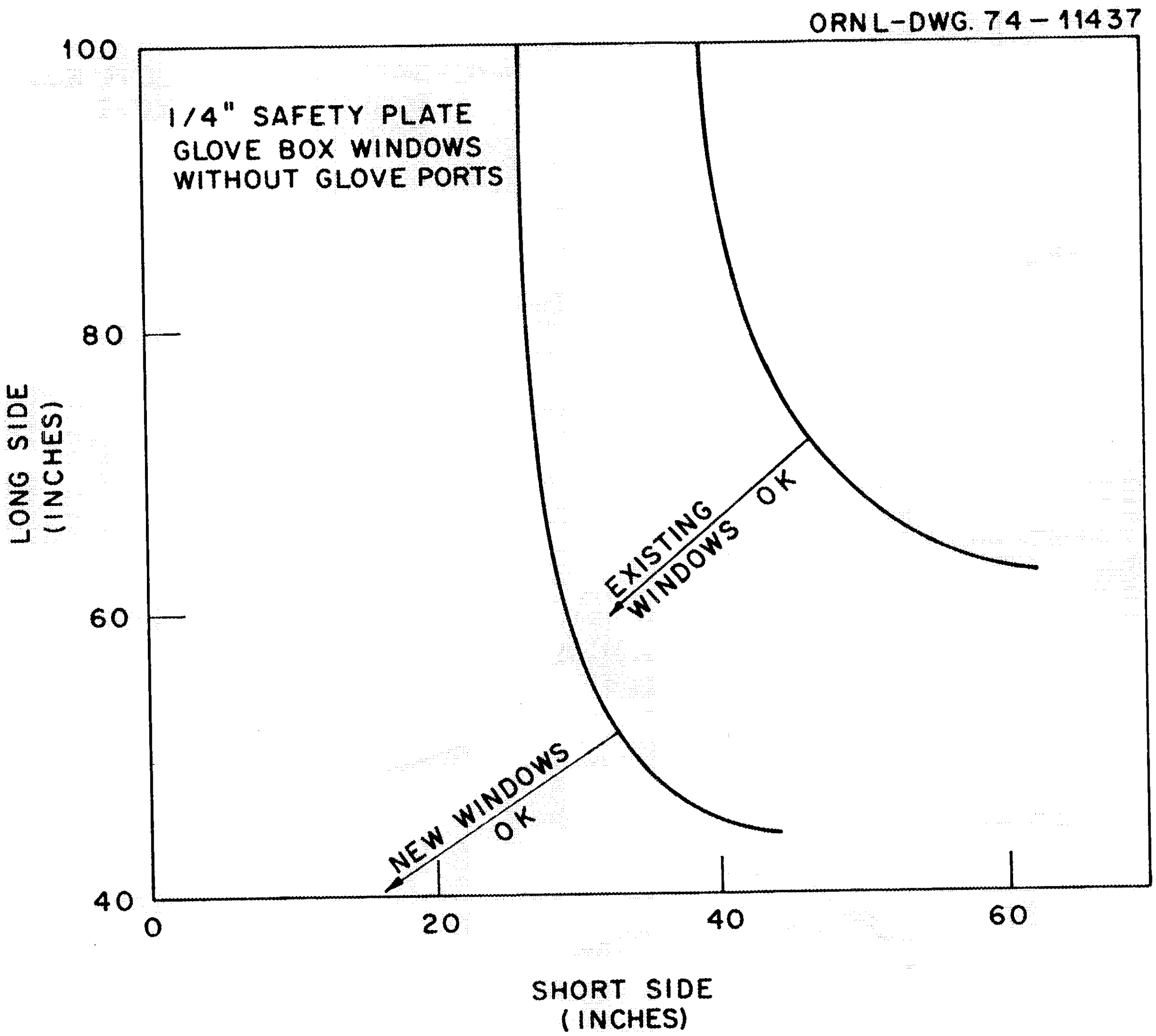
ORNL-DWG. 74-11437
1/4" SAFETY PLATE
GLOVE BOX WINDOWS
WITHOUT GLOVE PORTS
EXISTING WINDOWS OK
NEW WINDOWS OK
100
80
60
40
0
20
40
60
LONG SIDE (INCHES)
SHORT SIDE (INCHES)

Figure 2

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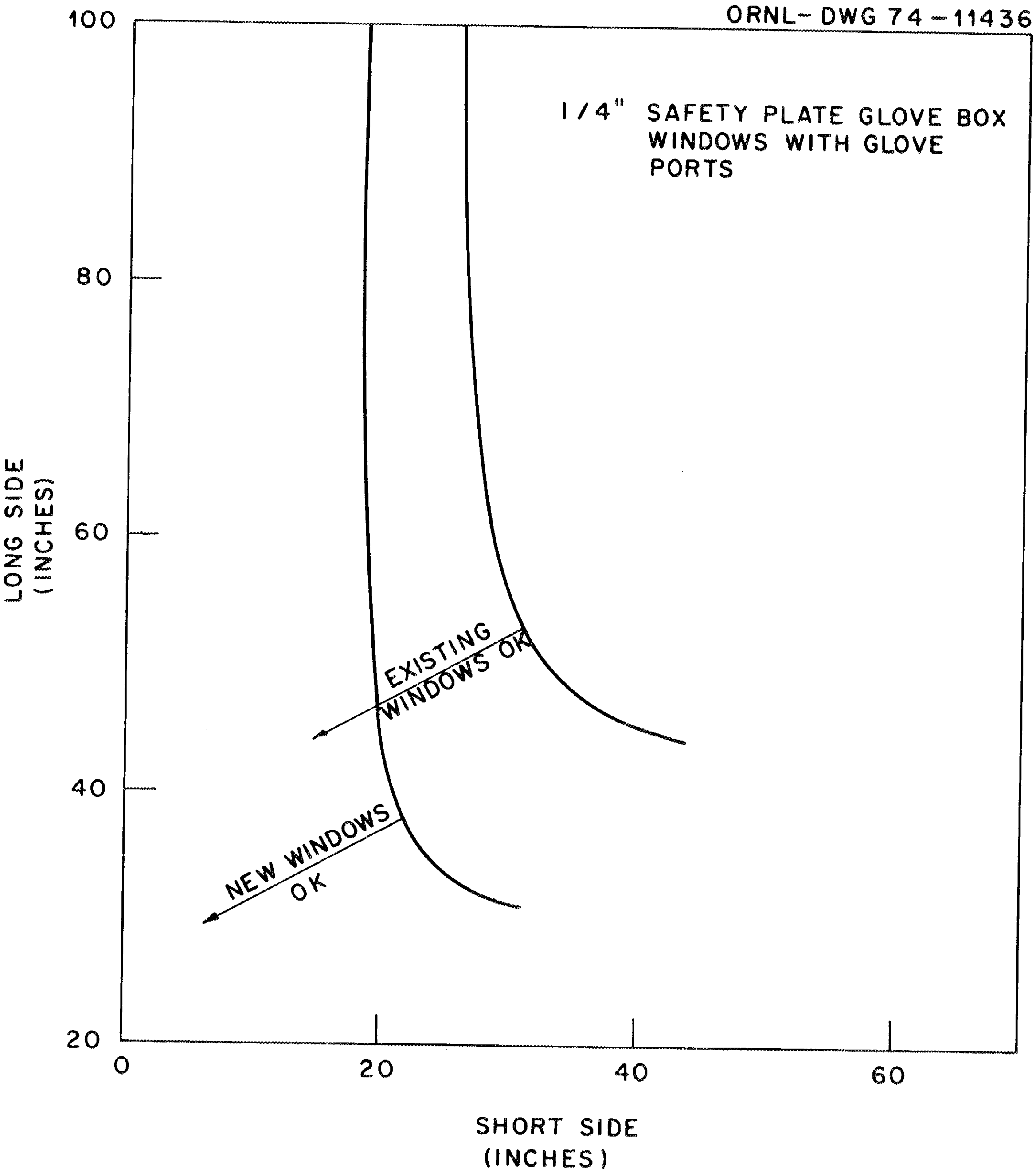

Figure 3

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