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# DESIGN PARAMETERS FOR GERMANIUM WINDOWS UNDER UNIFORM PRESSURE LOADING

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## Abstract

Thermal electro-optical imaging systems require windows fabricated from materials that are not only transparent to infrared radiation but also possess adequate structural strength to successfully withstand loads imposed on them by operational scenarios Optical grade mono- and polycrystalline germanium has found wide acceptance for applications in the 8 to 12 micron wavelength region where the windows are exposed to high pressure in the presence of moisture, or water The paper addresses itself to physical properties of germanium and structural parameters of windows and their mountings that must be considered in the successful design of germanium windows for external pressure service

## Introduction

Germanium is an elemental semiconductor, metallic in appearance It is both hard and brittle and is stable in the face of widely varying environmental conditions It can be readily shaped with diamond tools and loose abrasive grinding and takes a high polish by conventional polishing techniques

Germanium has found widespread application in optics for infrared energy spectrum for the following reasons:

1 It has high transparency over a wide spectral interval, i e , 2 0 to 11 5 micrometers, which cover the two atmospheric windows of most interest to IR system designers, i e , 3 to 5 and 8 to 12 micrometers

2 It is readily available in virtually any size and shape at more competitive prices than some other IR optical materials

3 Its physical properties are all "good," not being hygroscopic, soft, soluble in water, or toxic

4 Its optical properties are also "good," exhibiting low intrinsic absorption, excellent homogeneity, and high index of refraction Thick sections of polycrystalline germanium have shown excellent MTF values in the 8 to 12 micrometer wavelength region

Germanium's greatest drawback is its low thermal threshold, which precludes its use for high speed missile/aircraft applications where window temperatures will exceed 85°C (Fig 1) At temperatures below 30°C, however, the free carrier absorption of germanium is very low Increasing the thickness, for example, from 1 mm to 38 mm increases the absorption in the 2 to 11 μM wavelength region insignificantly (Fig 2) The transmissivity of three samples, (Fig 2), which were all cut from the same boule depict the effect of free carrier absorption vs thickness in high quality, uncoated, optical germanium The absorption band at 11 8 micrometers is the first harmonic of the fundamental lattice vibration, is intrinsic, and has a value of 0 22 $cm^{-1}$ Many more bands appear at wavelengths longer than 11 8 micrometers and limit germanium's usefulness at these wavelengths When coated with a Broadband Multi-layer Anti-Reflection Film (BMLARF) the transmissivity of optical germanium is raised to values in excess of 90 percent (Fig 2)

## Factors Limiting Shapes and Sizes

Virtually any optical component can be manufactured from germanium (Fig 3) Windows as large as 26 inches diagonal have been made and by no means represent the maximum possible

(Fig. 4) Size limits would be set by furnace constraints but existing art can easily be scaled to 72 inches (6 feet) in diameter at thicknesses of about 12 inches, or thicker for smaller diameters Fabricating techniques and equipment can be scaled up as necessary

It is desirable to maintain a diameter-to-thickness ratio of 20-to-1 or smaller for plane parallel FLIR windows if control over surface figure, and therefore transmitted wavefront is to be maintained Domes can be thinner if the only consideration is wavefront deformation In the case of hyperhemispheres the opening should be no smaller than twice the distance from the equator to the edge of the opening measured on the inside surface For example, the opening in a hyperhemispherical lens that also serves as a pressure-resistant imaging system is 6 4 inches in diameter, while the distance from the equator to the window the opening is 3 2 inches This lens is produced with a wall thickness variation of less than 0007 inch (Fig 5)

Exotic has produced germanium FLIR windows of plano-parallel configuration, as circles, rectangles or irregular shapes in sizes from 1/4 inch to 26 inches, with flatness specifications as tight as one wave over 15 inches, or parallelism of 2 seconds of arc Dome shaped windows as big as 14 inches segment diameter and hyperhemispheres of 10 inches outside diameter have also been produced Windows or lenses as large as 30 inches diameter and hemispheres as large as 24 inches diameter can be processed with existing facilities In general, the art of fabricating very large optics is well documented in the literature and can be applied to the manufacture of very large germanium optics as well

Between the tasks of producing a very large optical quality germanium boule and fabricating it into a finished component, the former is the more difficult This is because control of the freezing interface becomes increasingly difficult with size and control of the freezing interface is essential to produce good optical quality germanium

## Pressure-Resistant Windows

### Shapes

Pressure-resistant windows which also often serve as the objective lenses of thermal imaging systems are required for many applications in hydro-or aerospace Of these two media hydrospace imposes greater stresses inside the windows and for this reason special considerations must be taken in the design of windows for this environment Although the requirements for pressure-resistant germanium windows is only recent, this is not the case for glass or plastic windows serving the visible energy spectrum successfully for many years[1,2]

Through analytical studies and experimentation several window shapes have been developed over the last twenty years for applications where the loading on the window is primarily of hydrostatic or hydrodynamic nature These windows served their intended purposes reliably in the 10 to 20,000 psi pressure ranges Since germanium in many aspects behaves structurally like glass the designs developed for glass windows can, without any changes, also be used with germanium

Currently there are six proven window designs for withstanding pressure in the 10 to 20,000 psi range (Fig 6) Of these shapes the ones with spherical faces are more suited to high pressures than the ones with plane faces The reason for it lies in the peculiar physical properties of brittle materials, like glass or germanium, that have compressive strengths which exceed by factors of 10 to 50 the tensile strengths of the same material

Since windows with plane faces flex under applied hydrostatic loading high tensile stresses can be generated on the low pressure faces, initiating tensile cracks in that surface Beveled edges tend to decrease the magnitude of tensile stress on low pressure face, but unfortunately their presence, as a rule, introduces high shear stresses in the conical bearing surface that tend to initiate shear cracks at that location For this reason windows with plane surfaces fabricated from brittle materials are generally limited to pressure less than 1000 psi, and preferably to less than 500 psi

### Magnitude of Membrane Stresses

Only the windows with spherical faces can readily withstand hydrostatic pressures in excess of 1000 psi The spherical surfaces are admirably suited for resisting external pressure since only compressive membrane stresses are generated in windows with such surfaces The magnitude of the maximum compressive membrane stress, which is found on the concave, and the maximum radial stress, which is found on the convex surfaces, can be easily calculated with Lame's equation for thick spheres[3]:

$$S_1 = S_2 = -p\frac{R_o^3 (R_i^3 + 2r^3)}{2r^3 (R_o^3 - R_i^3)}$$

$$S_3 = -p\frac{R_o^3 (r^3 - R_i^3)}{r^3 (R_o^3 - R_i^3)} \qquad (1)$$

where

$S_1$ = meridional membrane stress, psi

$S_2$ = hoop membrane stress, psi

$S_3$ = radial wall stress, psi

$p$ = external hydrostatic pressure, psi

$R_o$ = external radius of curvature, inches

$R_i$ = internal radius of curvature, inches

$r$ = radius to point where stress is being calculated, inches

Prediction of Critical Pressure

Since spherical windows may also fail by elastic buckling the critical pressure of spherical windows must be calculated also[4] If the critical pressure due to elastic buckling is found to be lower than twice the operational pressure of the window the thickness of the window has to be increased until the critical pressure is at least 100 percent higher than the operational pressure

$$p_{cr} = \frac{0\ 8E\ (t/R_o^2)}{\sqrt{1 - \mu^2}} \qquad (2)$$

where

$p_{cr}$ = critical pressure at which elastic instability takes place, psi

$E$ = modulus of elasticity, psi

$t$ = shell thickness, inches

$\mu$ = Poisson's ratio

$R_o$ = external radius, inches

Edge Effects

Meridional and Hoop Stresses. So far the discussion centered on classical spherical shells not influenced by the restraints imposed by the mounting The effect of mounting must be, however, taken into consideration as its effect on the distribution of stresses in the window near its edges is significant. Experimental measurements of stresses near the edges of spherical windows simply supported by seats with plane conical bearing surfaces have shown that in windows with included angles less than 180° the compressive membrane stresses near the edge are, as a rule, less than the values calculated with Lame's equation[3] For windows with included angle equal to 180° (hemispheres) the calculated and measured stresses at the edge are about the same In windows with included angle larger than 180° (hyperhemispheres) they are significantly larger[5] For hyperhemispheres approaching the shape of a complete sphere (included angle ≥ 270°) the meridional stress on the concave surface near the edge has been noted to exceed the calculated membrane stress value by 100 to 300 percent depending on the elastic compliance of the mounting in which the seat is located

Thus, a simplistic rule of thumb for predicting the magnitude of meridional and hoop stresses at the edge can be formulated which in effect states that in spherical windows

with included angle ≤ 180° the increase in meridional and hoop stresses on concave surface due to the mounting can be ignored, while in windows with included spherical angle > 180° the increase in meridional stress may be assumed to be at least 100 percent above calculated membrane stresses

Shear and Bearing Stresses The mounting which holds a spherical window also generates bearing and shear stresses in the very edge of the window during its pressurization[6] Of these two the average bearing stress is easy to calculate as it is equal in magnitude to the average membrane stress, providing that there is perfect match between the plane conical bearing surface of the window and the plane conical seat on the mounting Since a perfect fit is physically difficult to achieve during assembly and subsequently difficult to maintain during pressure application gaskets are utilized to take care of small (less than 1 minute) initial angle mismatches between the mating plane conical bearing surfaces

Depending on the magnitude of bearing stress generated by operational pressure loading different gasket materials may be utilized For average bearing stresses ≤ 10,000 psi thin neoprene rubber reinforced with nylon cloth has been found to be ideal Commercially available DuPont's Fairprene 5722 with ≤ 0 03 inches thickness bonded to the bearing surface on the window with Pliobond contact cement has been found to perform reliably for up to 1000 pressure loading cycles Gaskets of ≤ 0 03 inch thickness laminated from two layers of Kevlar 49 cloth and epoxy resin have been found to perform reliably under bearing stresses ≤ 40,000 psi up to 1000 pressure cycles When epoxy laminated gaskets are utilized the edge of the window must be lapped to the metallic seat of the mounting prior to installation of the gasket Epoxy laminated gasket should not be bonded to the window since epoxy adhesive has the tendency to pull away fragments of germanium In addition, the gasket's slick surface allows the window to slide upon it freely

Grease should not be used with neoprene or fiber reinforced epoxy gaskets as under the high bearing pressures grease has been observed to enter fine crevices in the brittle window material and act like fine wedges during depressurization, resulting in initiation of shear cracks on the bearing surface of the window The only requirement for the bearing surface on the window is that it be finished with at least 20 micron grinding powder, followed by acid etching The edges of the bearing surface should be chamfered (0 020" x 45°) to eliminate any chips and incipient fractures

The seat on the metallic mounting should have a 32 rms surface finish and match the angle of the window within 1 minute of arc Use of a lap is definitely recommended as it tends to provide a good angular match between the mating surfaces of the window and the seat Care must be taken to insure that both mating surfaces are plane and represent the spherical angle whose apex coincides with the center of the spherical sector Deviations between the center of window's curvature and apex of the spherical angle should not exceed 0 001 $R_o$ A suitable test for flatness of bearing and seat surfaces is lack of visible light under a commercial razor blade held at right angle against any one of these surfaces

The magnitude of shearing stresses generated in the edge of the window is primarily a function of the angle between the vertical and of the bearing surface Acute angles generate high shearing stresses while obtuse angles generate low shearing stresses Angles < 45° should be avoided in design of spherical bearing surfaces on the windows as the window will fail at relatively low compressive membrane stress levels (i e , <10,000 psi) The presence of appropriate bearing gasket ameliorates the effect of shear stresses to some degree, but not sufficiently to overcome the effect of geometry

## Structural Properties of Germanium

The structural properties of germanium differ very little from those of optical glass except for the modulus of elasticity which for germanium is substantially higher Tests conducted by the Naval Ocean Systems Center and others show that the compressive strength of mono- and polycrystalline germanium specimens tested between steel anvils is in the 30,000 to 80,000 psi range, while the flexural modulus of rupture (flexural strength) is in the 8000 to 16,000 psi range The flexural modulus of elasticity is in the 12 x $10^6$ to 17 x $10^6$ psi range, while Poisson's ratio is about ≃0 25 The shear strength has not been measured or described in literature, but its magnitude probably does not exceed 9000 psi

No difference has been found between the structural properties of monocrystalline and polycrystalline materials The tensile and flexural strengths vary with the surface finish; the highest values have been obtained with specimens that prior to polishing have been acid etched Compressive uniaxial strength has been found to be independent of specimen surface finish, but highly influenced by flatness, hardness and compliance of anvils Soft metallic or non-metallic gaskets substantially lower the compressive

strength of uniaxial test specimen Although sufficient number of tests have not been run to establish positively the absence of static fatigue in compression it appears that it does not have to be considered in design This is not the case with germanium subjected to tension or flexure in seawater

For design purposes the peak working stresses in a germanium window under external hydrostatic pressure should not exceed 40,000 psi in biaxial compression, 4000 psi in tension, and 4500 psi in shear Since, in most cases, it is very time consuming and expensive to predict analytically the magnitude of peak stresses at the edges, or other stress raisers, the windows are instead designed on the basis of nominal stresses whose magnitude is set sufficiently low to take care of unforeseen stress concentrations in the vicinity of bearing surfaces When the design is based on magnitude of nominal stresses the compressive stress is limited to 10,000 psi, tensile stress to 1000 psi, and shear stress to 1000 psi

For special applications, where either the magnitude of stresses will exceed above mentioned limits, or where performance of the window must be guaranteed to the customer beforehand full size structural models of glass and acrylic must be built and evaluated first Since acrylic plastic is inexpensive, readily available in many shapes, and can be rapidly machined by common machine shop tools, it is generally used first in construction of the structural models

The purpose for the acrylic plastic model is to serve as a specimen in the experimental evaluation of the magnitude and distribution of stresses in the proposed window design Since acrylic plastic is photoelastically active the strains may be measured not only with electric resistance straingages but also photoelastically After extensive instrumentation with straingages it is subjected to the same type of loading that the germanium window will see in service The magnitude of loading is, however, smaller to insure that the recorded stresses fall in the elastic strain region of the plastic If the magnitude of extrapolated stresses is found to be within acceptable limits for germanium another model is made of easily molded borosilicate glass (Pyrex) The glass model is generally subjected to a test schedule in which the pressure loadings are either equal to, or in excess of, those predicted for operational service Glass ceramic (i e , Cervit or Pyroceram) is often used instead of glass as it has the same modulus of elasticity as germanium, and thus its displacement and deformations will be the same as of a germanium lens

The glass model is also instrumented with straingages, but without sanding of the surfaces to insure adequate adhesion, as scratches could serve as potential crack initiators The purpose for the glass model is to serve primarily as a specimen in the experimental evaluation of the window's shape sensitivity to shear crack initiation Because the structural properties of glass are very similar to that of germanium the glass model can be, and, as a rule, is subjected to pressure loadings which not only equal, but often exceed, those predicted to occur in service The higher the magnitude of over-pressurization that the glass window can successfully withstand, the higher the degree of confidence in the successful performance of germanium window with dimensions identical to that of glass window model In practice the magnitude of proof pressure to which the glass window is subjected does not exceed the design pressure by more than 100 percent If time and money permits the glass model is subjected to at least $10^4$ operational pressure cycles so that the fatigue life of the window can be established Only if the glass model has withstood all of the simulated operational loadings successfully, is it fiscally prudent to fabricate and prooftest the germanium window

## Mountings

Mountings for germanium windows under external pressure must meet the same design criteria as mountings developed successfully in the past for glass or ceramic structural components under external pressure loading[7,8,9] These criteria are rather simple, but failure to heed them invariably leads to premature fracture of any brittle window The criteria can be summarized in two statements:

a The radial dilation, or contraction of the seat on the mounting under the combined actions of the pressurized window, hydrostatic pressure, and of the pressurized housing should be uniform all around its circumference

b The radial dilation, or contraction of the window circumference and the rotation of the window's bearing surface should be matched by the radial dilation or decrease, and angular rotation of the seat on the mounting

In practice it is impossible to meet both criteria totally Thus, every mounting is only an imperfect attempt to meet these ideal criteria Still, if compromises have to be

made it is best that they are made in the realm of matching the radial contraction, or dilation of the window to that of the mounting, and not in the realms of uniform radial displacement or excessive angular rotation of the mounting Unless the design stresses are set excessively high the compliant gasket between the mating surfaces will take care of minor angular or diametrical displacements of the seat relative to the window's bearing surface under hydrostatic loading

## Specific Designs for Hydrostatic Loading

To date only two germanium window designs have been specifically developed for high external hydrostatic loadings typically encountered in hydrospace or in the atmospheres of some planets Both designs utilize the spherical shape, but in one case the included angle is 150°, while in the other case it is in the 260° to 270° range

### 150° Sector Design

The 150° spherical sector window has been specifically designed for pressures up to 20,000 psi (Figures 7, 8 and 9) Because of the high nominal membrane stresses generated in the germanium window at 20,000 psi loading no efforts were spared to match the radial contraction and angular rotation of the seating surface on the mounting to that of the bearing surface on the germanium window A novel approach was used in the design of the mounting The mounting was conceived to be a separate structural component, independent of the structural characteristics of the housing on which it is to be mounted In this manner the displacements and deformations of the housing would have no effect on the performance of the window

After a detailed and exhaustive finite element stress analysis of the window/mounting assembly acrylic and glass structural models were tested in the mounting Only after the acrylic window successfully withstood 100 pressure cycles from 0 to 4500 psi, and the glass window withstood 100 cycles from 0 to 20,000 psi were germanium windows fabricated and subjected to similar tests The analytical studies and the experimental development program were worth the time and effort as the 150° spherical sector germanium windows with 4-inch outside & 3 inside radii successfully withstood all the scheduled tests in the prooftest series; 100 cycles from 0 to 4500 psi, followed by 100 cycles from 0 to 9000 psi, followed by 100 cycles from 0 to 13,500 psi, and concluded by 100 cycles from 0 to 20,000 psi Detailed observation of the window surfaces failed to detect any incipient cracks There is no doubt that this window assembly design is more than satisfactory for service in the 0 to 20,000 psi range

### 264° Sector Design

Window The hyperhemispherical window design was specifically developed for applications in the 0 to 1000 psi pressure range where panoramic visibility by the thermal imaging system is required The 4 97 inch outside and 4 32 inside radii of the 264° hyperhemisphere provide the window not only with sufficient strength to withstand projected operational loadings but also with a 4 inch optical aperture for long range thermal imaging Prior to fabrication of the germanium window and titanium mounting assembly full size structural models of acrylic plastic and glass were fabricated and subjected to loadings which simulated the loadings to be expected in ocean environment during a whole range of projected operational scenarios

Several acrylic plastic structural models with different dimensions were built as it was not known until late in the window development program what dimensions the hyperhemispherical window should have in order to contain the optical, electrical and mechanical components of a typical gyro stabilized system for traversing the optical train elements in azimuth and elevation The differences in size between the two plastic structural models were minor enough where the experimental findings from one model ($R_o$ = 6 inches, $R_i$ = 5 inches, $\alpha$ = 270°) could be applied with confidence to the other one ($R_o$ = 4 965 inches, $R_i$ = 4 32 inches, $\alpha$ = 264°) Although the mounting for the 12 inch diameter model was made from 6061-T6 aluminum alloy and for the 10 inch diameter one from Ti-6Al-4V alloy this did not significantly influence the experimentally measured distribution of stresses in the acrylic window models as the ratio of the moduli of elasticity between plastic window material and metallic mounting materials was in the same order of magnitude in both cases

The stresses measured on the acrylic plastic models (Figures 10 and 11) showed that regardless of whether the applied loadings were external hydrostatic pressure or simulated hydrodynamic drag the peak compressive stresses were found at the edge Under hydrostatic loading the peak stress was on the interior oriented meridionally, while for simulated hydrodynamic loading it was on the exterior oriented in the circumferential direction (Figure 13) Of these two loadings the peak stresses generated by hydrostatic pressure were significantly higher, providing that the hydrostatic pressure was in excess of

100 psi, and the simulated window's velocity through the water was less than 20 kts At hydrostatic pressures < 100 psi, or velocities > 20 kts, the compressive peak stresses caused by hydrodynamic drag in the models tested may exceed the peak stresses caused by hydrostatic pressure It is interesting to note that the peak meridional stress in this hyperhemispherical window under external hydrostatic pressure was measured to be 100 percent* higher than the calculated nominal membrane stress on the window's interior, and that tensile stresses were totally absent (Figure 12 )

Under internal pressure loading the peak stresses were again located on the interior surface at the edge of the window (Figure 14) The peak stress however, was now of tensile character and was oriented in the meridional direction The peak tensile stress at the edge of the window was measured to be about 300 percent higher than the calculated nominal membrane stress on the window's interior Since the stress intensity (peak stress/pressure loading) for the hyperhemispherical window under internal pressure is approximately 14, while for external pressure it is only about 7, the hyperhemispherical window can be internally pressurized safely only to a small fraction of its external pressure capability

## Mounting Design

The mountings for the hyperhemispherical windows were for operational reasons designed to be integral with the pressure vessel covers protecting the thermal imaging system against sea environment Because several different applications were considered for the hyperhemispherical windows three different mountings were evaluated with acrylic windows, and two with glass and germanium windows Two of the mountings were integral with circular covers for cylindrical housings (Figures 10, 11, 15, 16) while the third one was integral with an oval cover for an elliptical housing (Figures 17 and 18)

Because the mountings were integral with the housing covers it was not possible to match the radial contraction of the mounting with that of the windows In the case of the circular covers it was at least feasible to keep the radial contraction of the mounting uniform around its circumference This was not the case with the mounting integral with an oval housing cover Because the wall of the oval housing deforms at different rates around its circumference under hydrostatic loading the circular mounting assumes a slightly elliptical shape (Figure 19) This makes it impossible to maintain a perfect match between the mating surfaces on the window and mounting Only the presence of the neoprene coated nylon cloth gasket (Fairprene 5722) and the low magnitude of the strain in the mounting at pressures < 1000 psi prevented the generation of serious stress concentrations leading to fracture of the brittle glass or germanium windows at the bearing surface in that pressure range

The mountings employed elastomeric 0-rings to seal and to hold the window in place Because highly compressed elastomeric 0-rings exert considerable, but uniform, bearing pressure against the exterior and interior edges of the window it is held securely against the seat of the mounting without generating local stress concentrations In addition, the compliance of the 0-rings allows for differential expansion or contraction between the window and the mounting due to pressure loading, or temperature variations without generation of stresses in the window Also, the presence of compliant barriers between the window and the mounting serves as a shock absorber against high frequency vibration of the housing generated by vortex shedding, wave slap or ship's engines

In the design of the grooves for 0-rings careful balance must be struct between providing adequate restraint for the window without generation of unacceptable tensile stresses in the window The peak stresses generated on the interior surface in meridional direction by tightening of the split retaining ring against internal 0-ring seal should be kept below 500 psi so that no opportunity is presented for microcracks to grow larger The dimensions chosen for 0-ring grooves achieved this delicate blance as the germanium window is safely retained under 100 psi internal pressure (Figure 20), or 17G lateral acceleration, while the peak tensile stresses generated by tightening of retaining screws are shown to be less than 500 psi (Figure 21)

## Window/Mounting Performance

Acrylic plastic, glass and subsequently germanium windows were mounted in the circular and oval pressure housing covers and subjected to hydrostatic pressure (Figure 22), simulated hydrodynamic drag (Figure 23), vibration (Figure 24) and simulated wave slap (Figure 25) All of the windows withstood successfully the whole gamut of tests imposed upon them

*The actual peak stress at the very edge of the concave surface is extrapolated to be about 200 percent higher than the calculated nominal membrane stress, but is was not measured with a straingage since the center of the 0 25" gage was approximately 0 25" from the edge

The results from the extensive test program have proven that acrylic plastic, glass, and germanium hyperhemispherical windows retained by appropriate mountings can successfully withstand hydrodynamic drag in the 0 to 30 ft/sec, 10,000 hydrostatic pressurization cycles in the 0 to 1000 psi, wave slap in the 0 to 30 ft/sec, and dynamic loading imposed by vibration in the 0 to 17G ranges Thus, as a result of this program there are, at the disposition of the optical engineers, several mounting designs with a choice of acrylic plastic, glass, or germanium hyperhemispherical windows With that many available choices of mountings and windows there should be no problem for an optical engineer to match the optical performance and operational parameter requirements of an electro-optical system to one of the existing window material/mounting combinations If the existing sizes of windows do not match exactly the requirements of the electro-optical system under consideration they can be scaled linearly either up or down without loss of structural performance

## Conclusion

It has been shown that germanium windows for thermal imaging systems (Figures 26 and 27) can be successfully designed and fabricated for external pressure service in the 0 to 20,000 psi range providing that careful consideration is given during their design to optimize their shape, mounting, and location of peak stresses, and attention is paid during their fabrication to generation of fine surface finishes and adherence to specified tight dimensional tolerances

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NOTE: The term "axial" used in Figure 9 a is the same as "meridional" in other figures and text of this paper

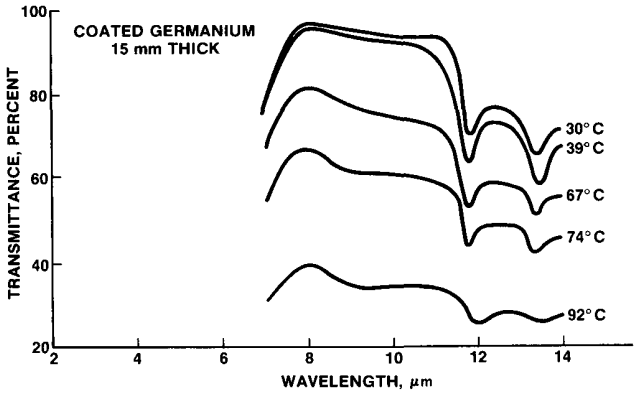



Figure 1 Effect of temperature on the transmittance of germanium

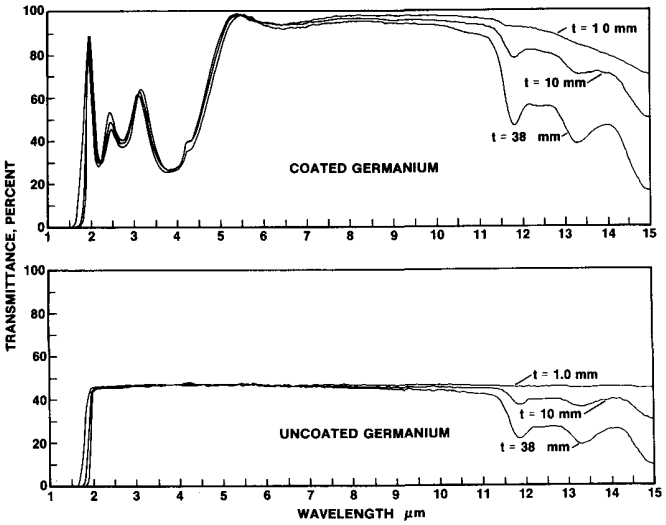



Figure 2 Effect of thickness on the transmittance of coated and uncoated germanium

Figure 3 Typical large germanium windows and lenses fabricated by Exotic Materials Inc

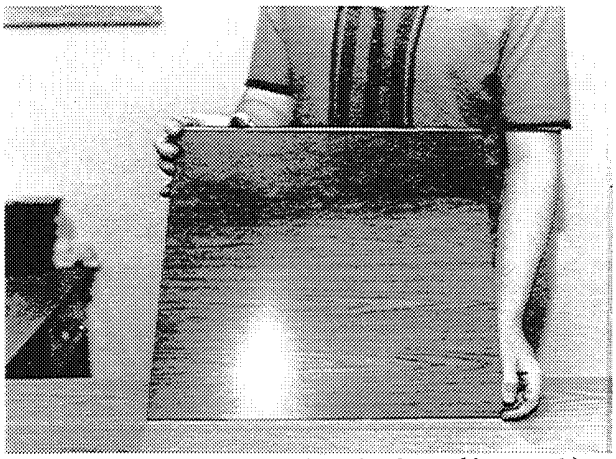


Figure 4 The largest (26 inches diagonal) FLIR window fabricated to date from germanium by Exotic Materials

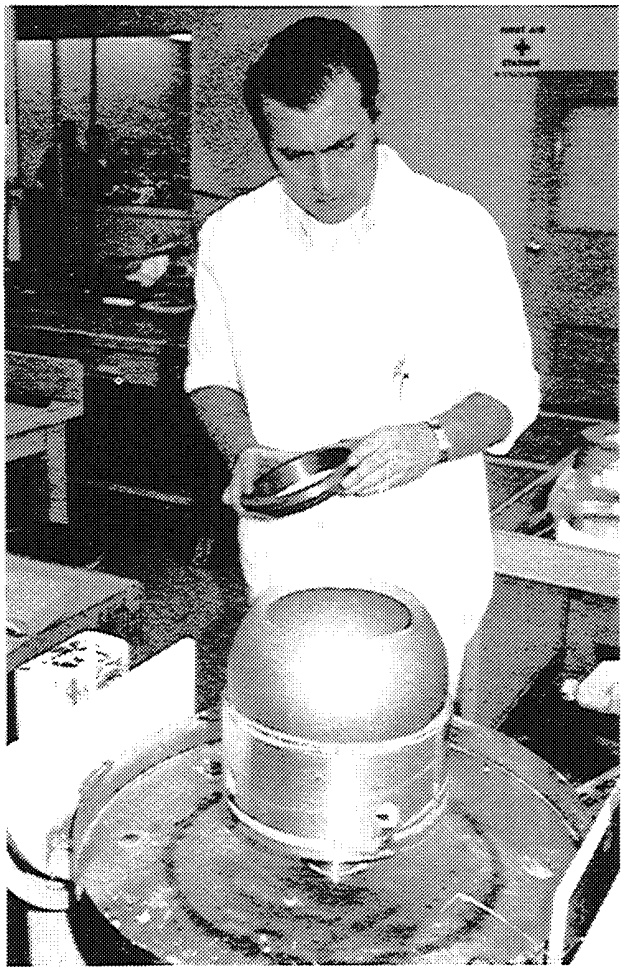


Figure 5 Lapping of the edge on a hyper-hemispherical germanium window at Exotic Materials Inc

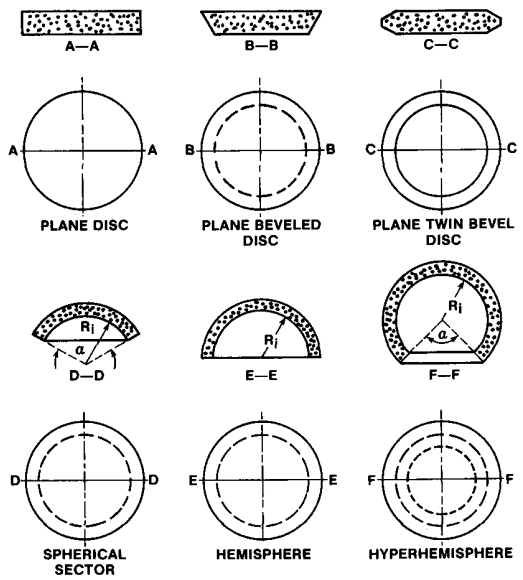



Figure 6 Typical shapes of windows for pressure service

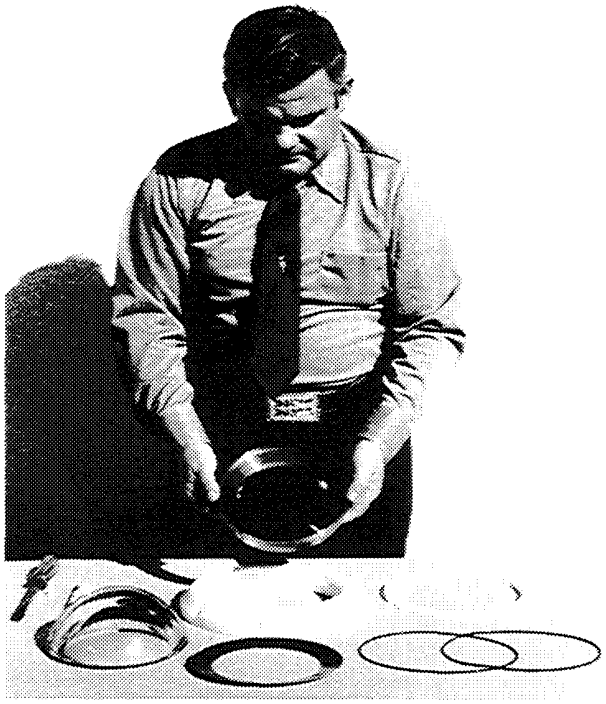


Figure 8 Components of the window/mounting assembly shown in Figure 7 The window shown is made of BK-7 optical glass

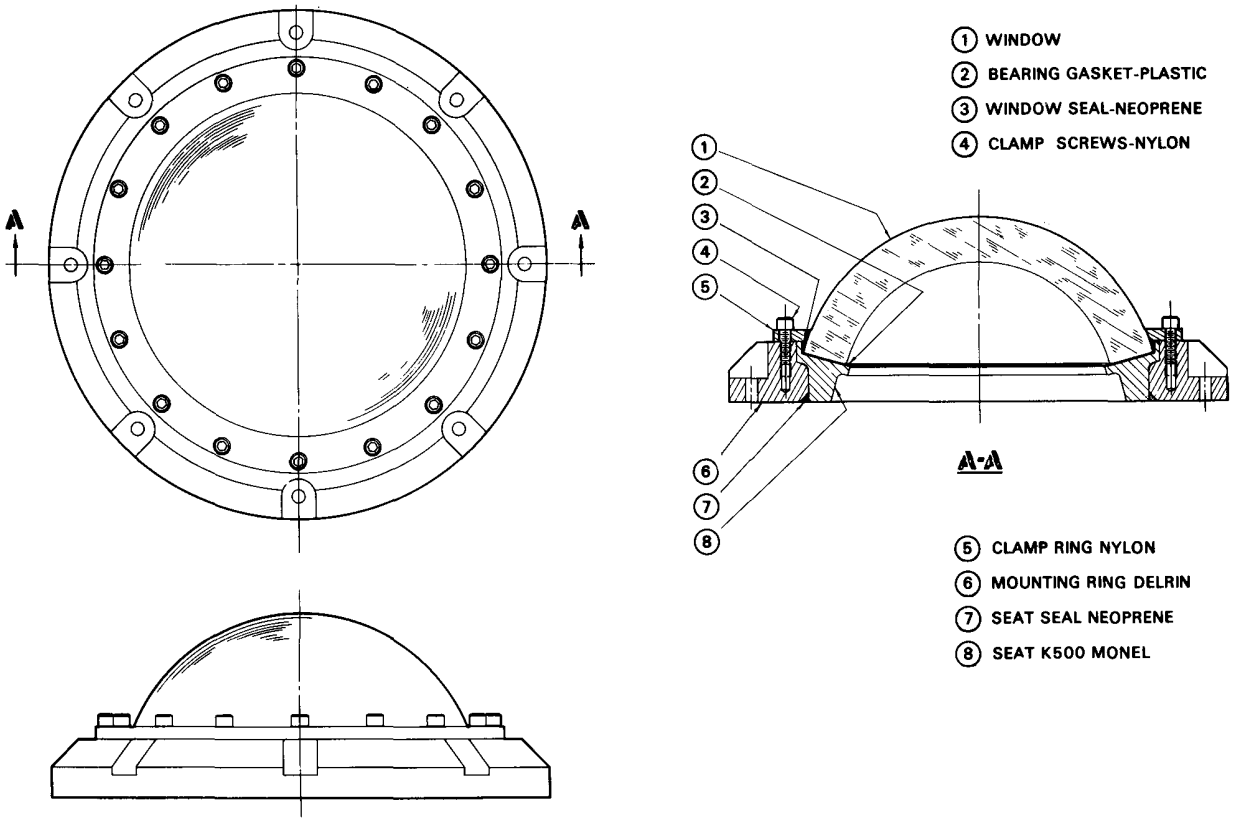



Figure 7 150° spherical sector window mounting assembly for pressure service in the 0 to 20,000 psi range

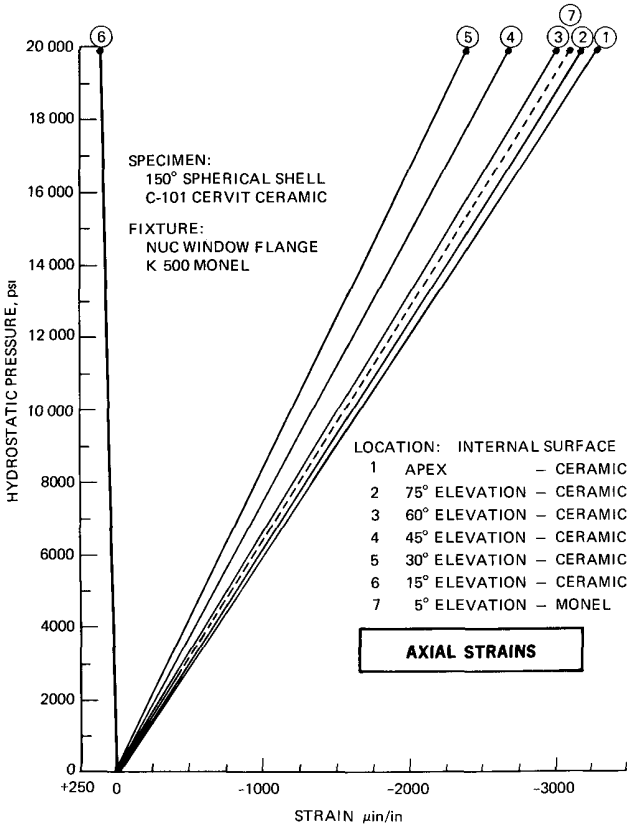



Figure 9a Axial strains recorded on the interior surface of the window/mounting assembly shown in Figure 7 The locations of straingages are referenced to the bottom surface on the mounting

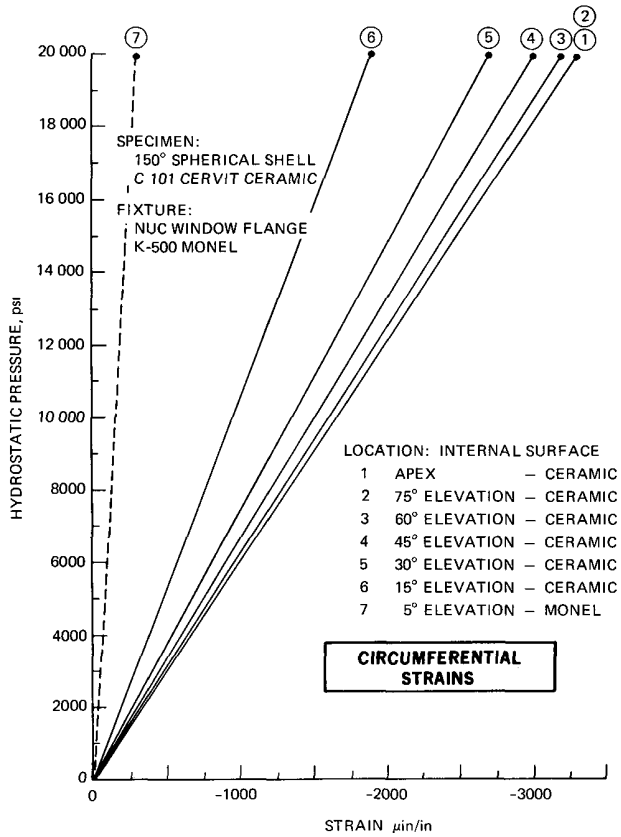



Figure 9b Circumferential strains recorded on the interior surface of the window/ mounting assembly shown in Figure 7

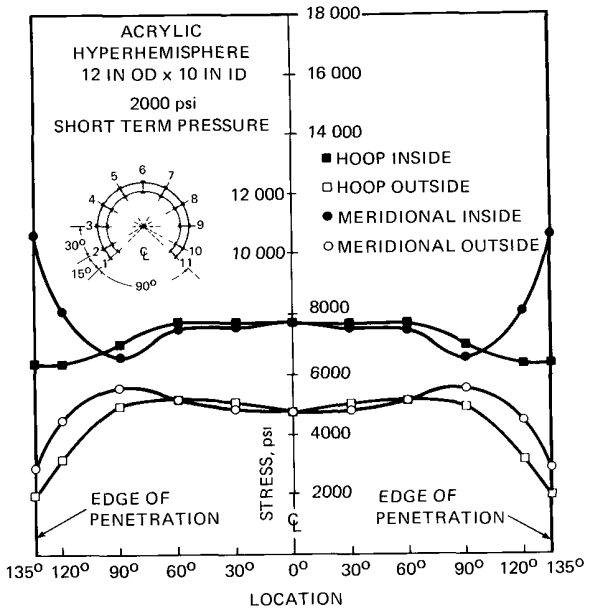



Figure 12 Distribution of stresses on the acrylic plastic hyperhemispherical window under short term external hydrostatic pressure

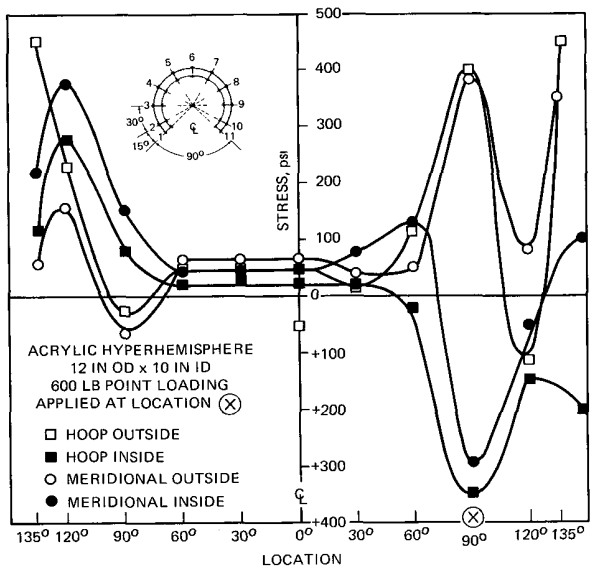
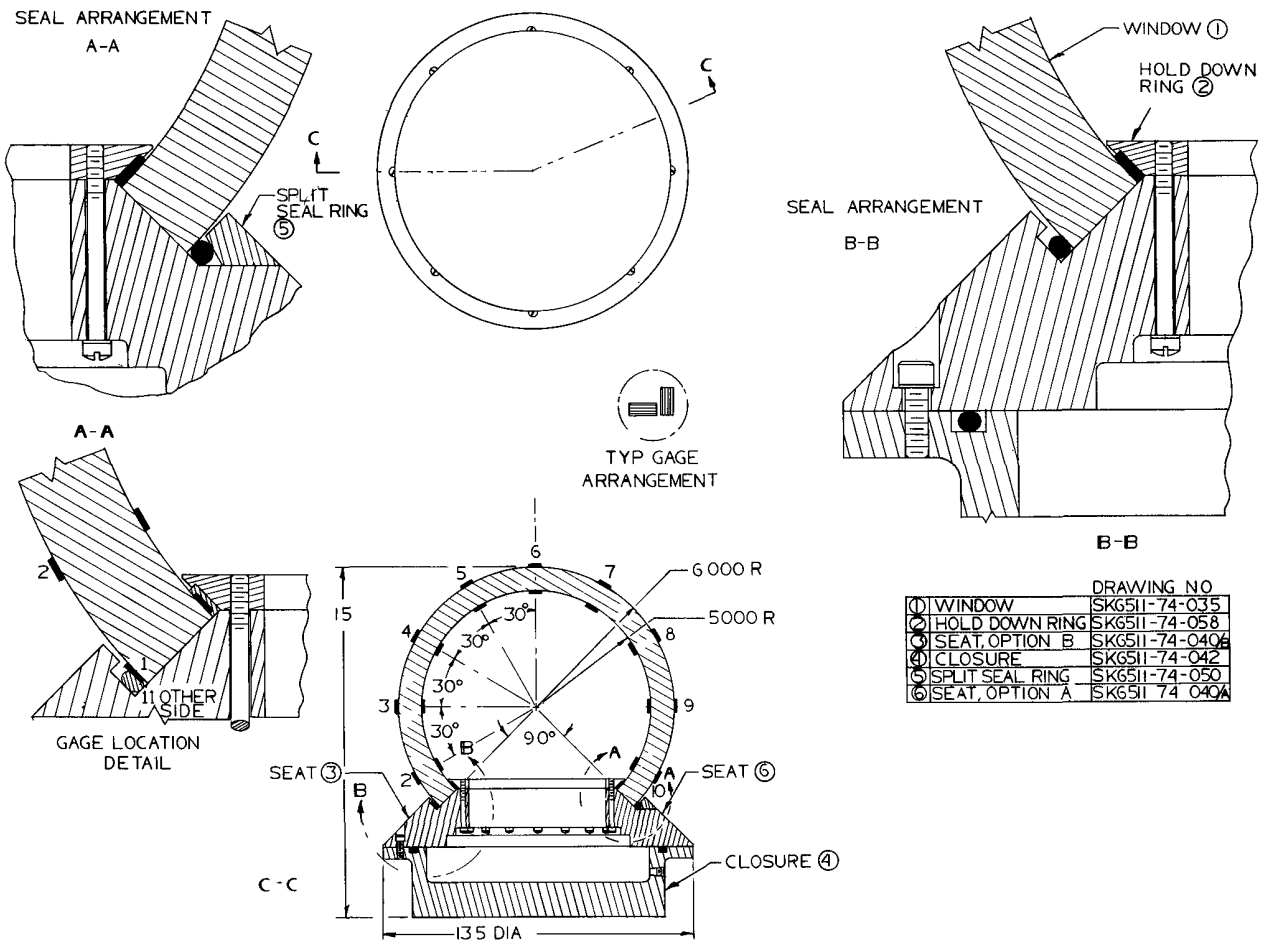



Figure 13 Distribution of stresses on the acrylic plastic hyperhemisphere subjected to lateral point loading at point X on its equator simulating hydrodynamic drag of the window




| | | DRAWING NO |
|---|---|---|
| ① | WINDOW | SK6511-74-035 |
| ② | HOLD DOWN RING | SK6511-74-058 |
| ③ | SEAT, OPTION B | SK6511-74-040B |
| ④ | CLOSURE | SK6511-74-042 |
| ⑤ | SPLIT SEAL RING | SK6511-74-050 |
| ⑥ | SEAT, OPTION A | SK6511 74 040A |

Figure 10 Structural model of the hyperhemispherical window/mounting assembly

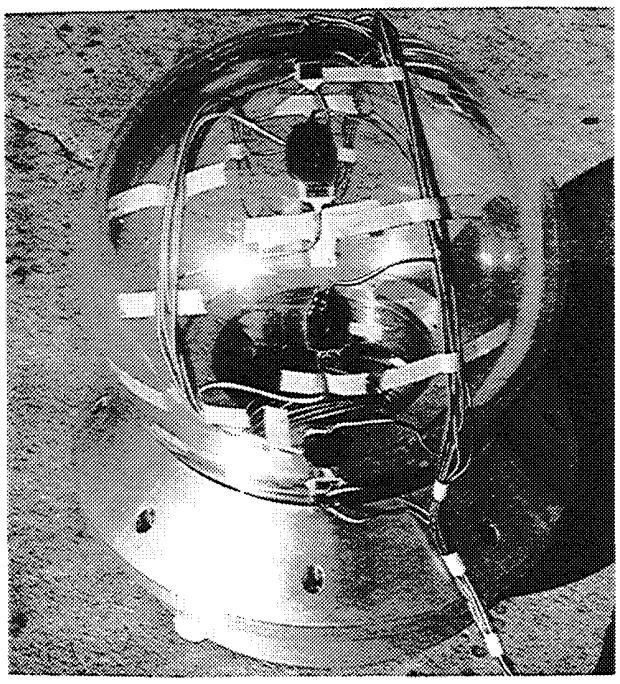


Figure 11 Structural model assembly with acrylic plastic window instrumented for hydrostatic testing

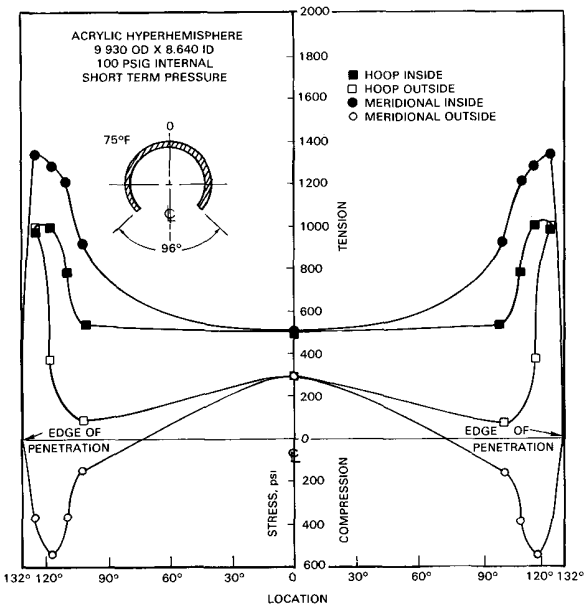



Figure 14 Distribution of stresses on the acrylic plastic hyperhemisphere under short term internal pressure loading

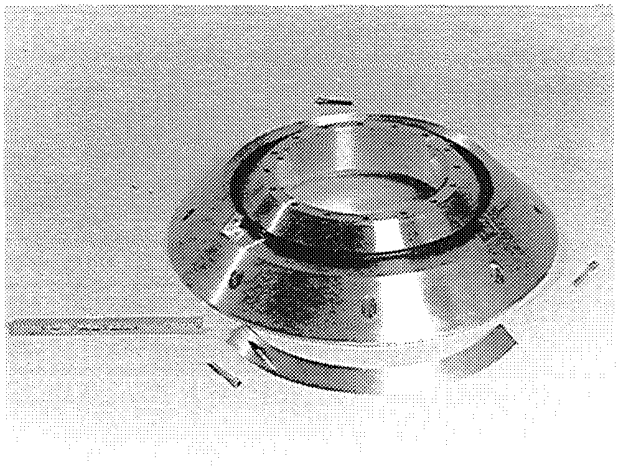


Figure 15 An experimental mounting for the 12-inch diameter acrylic plastic hyperhemisphere

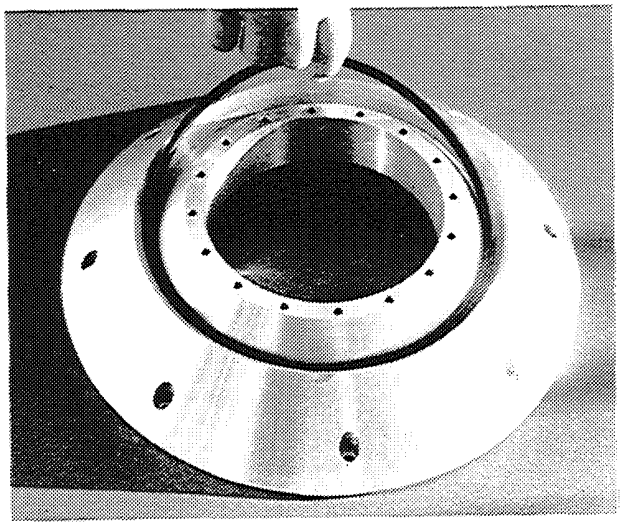


Figure 16 Final mounting design selected for the 12-inch diameter acrylic plastic hyperhemisphere Similar mounting was used for the glass and germanium 10-inch diameter hyperhemispheres

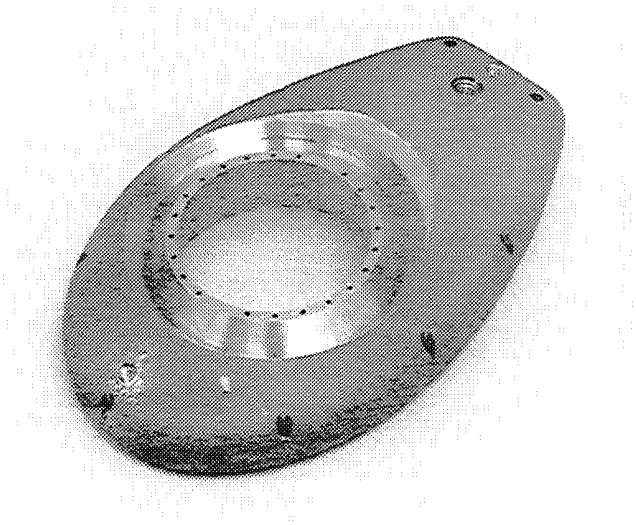


Figure 17 Mounting for the 10-inch diameter hyperhemispheres incorporated into an oval housing cover of cast titanium

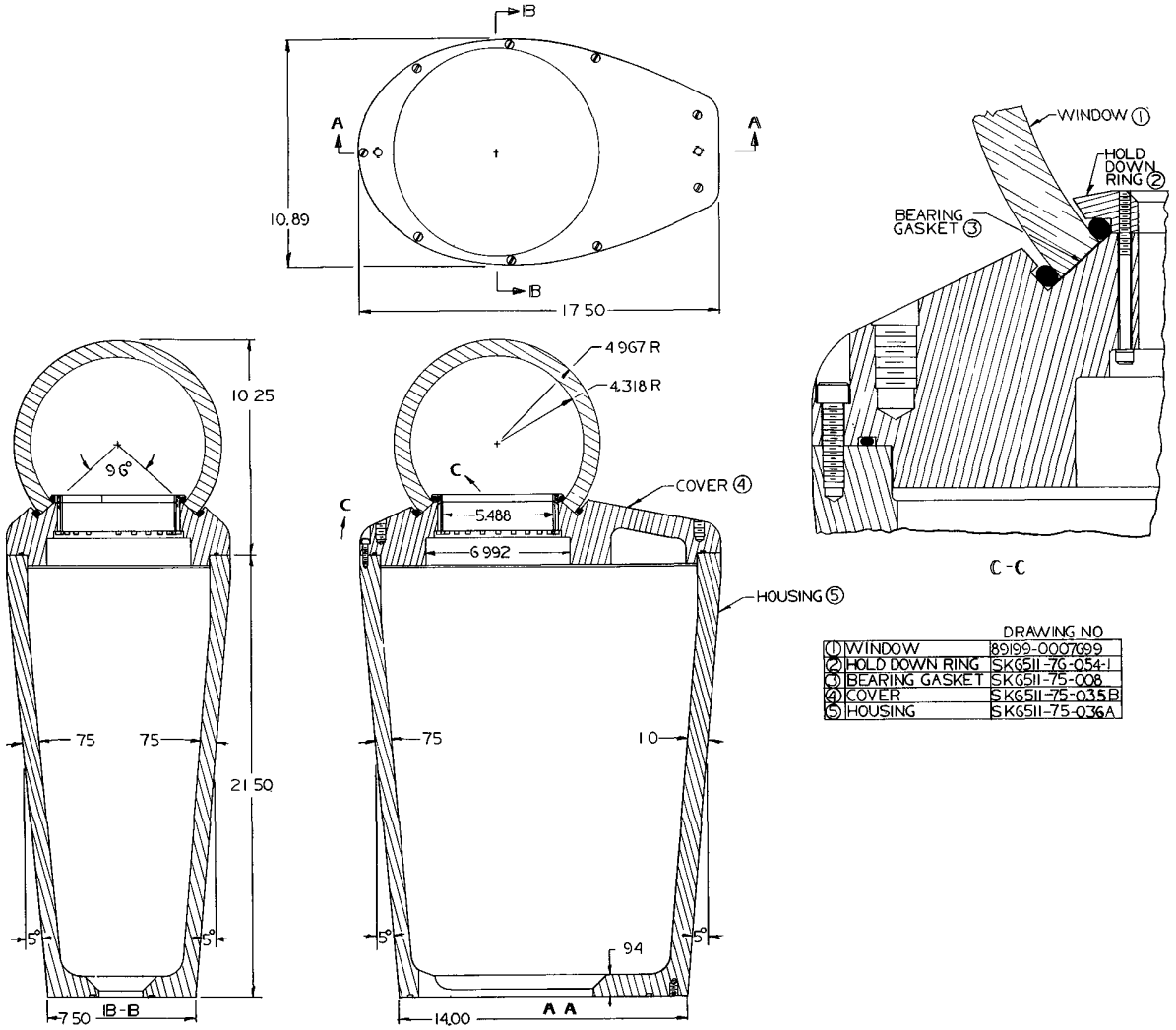



Figure 18 Hyperhemispherical window/pressure housing assembly for external pressure service

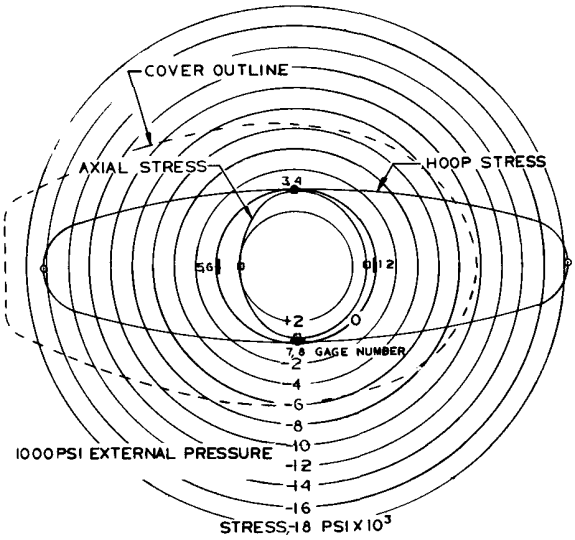



Figure 19 Distribution of stresses on the throat of the window mount in the oval cover of the pressure housing in Figures 17 and 18

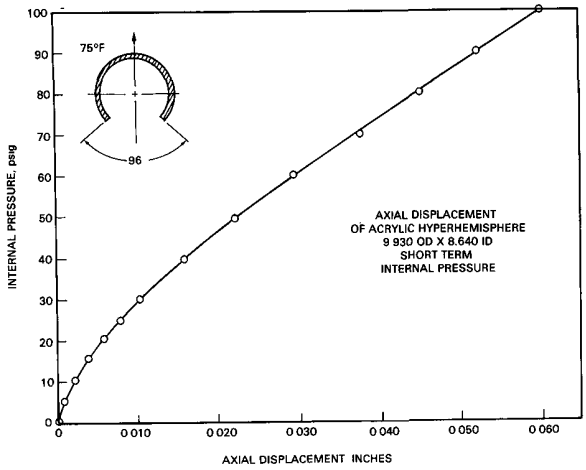



Figure 20 Axial displacement of the 10-inch diameter acrylic plastic hyperhemisphere mounted on the housing of Figure 18 under short term internal pressure loading

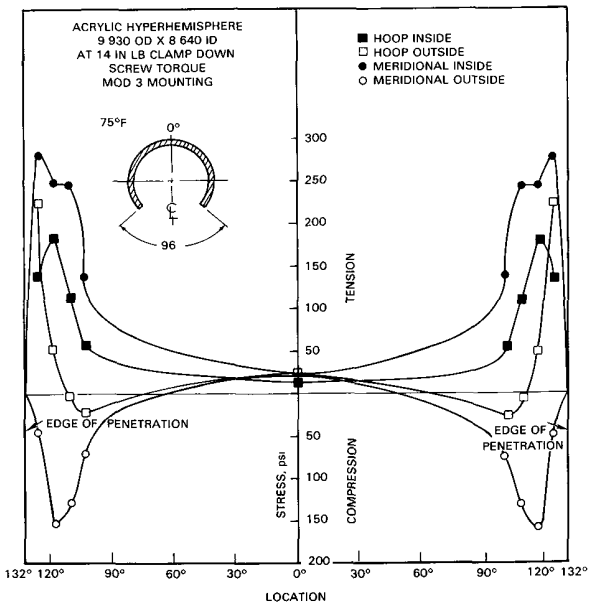



Figure 21 Distribution of stresses in the 10-inch diameter acrylic plastic hyperhemisphere generated by tightening of retaining ring against the mounting shown in Figure 18

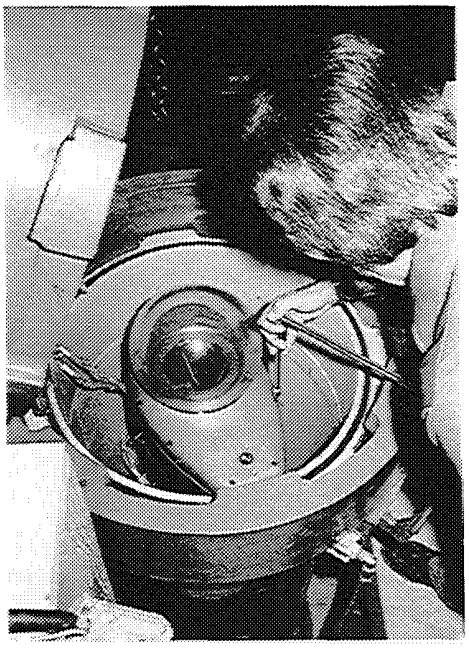


Figure 22 Preparation for external hydrostatic pressure testing of the oval housing assembly equipped with a glass hyperhemisphere fabricated by Precision Lapping and Optical Co

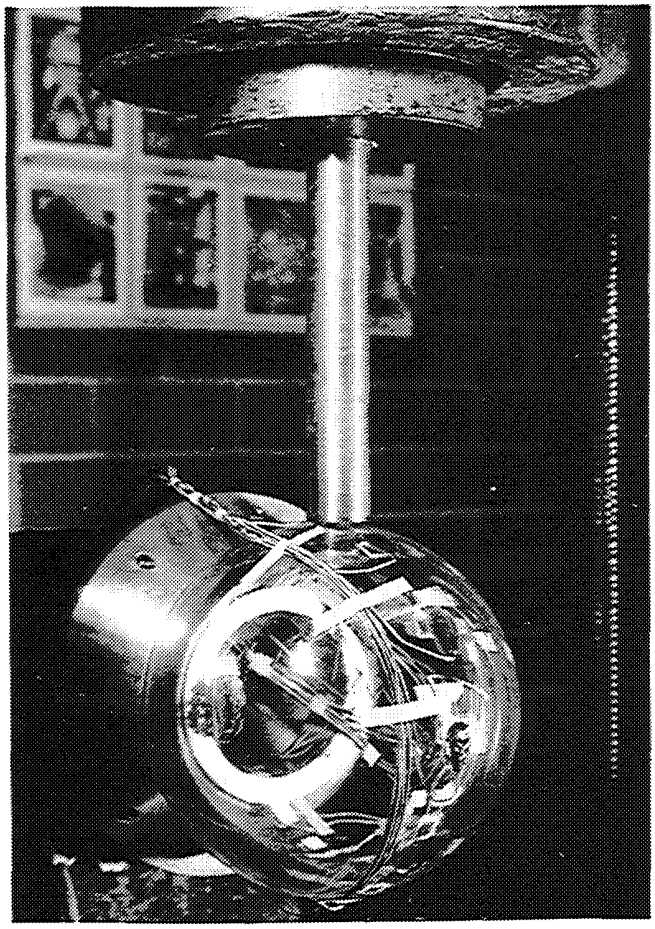


Figure 23 Test setup for simulating hydrodyanmic drag of the hyperhemisphere

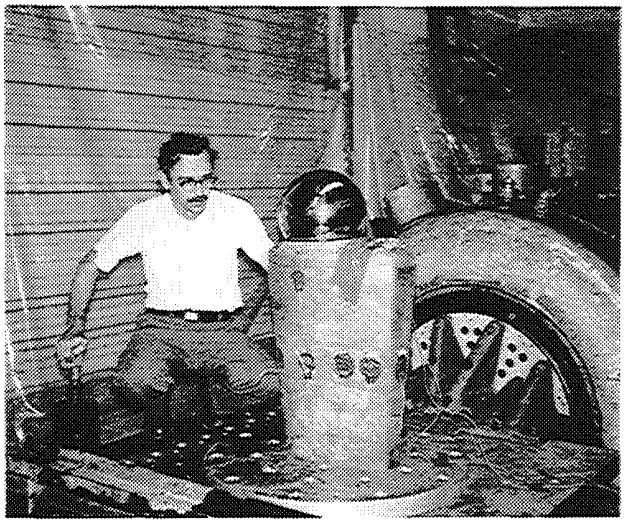


Figure 23 Germanium lens/pressure housing assembly mounted on a shaker table for vibration testing

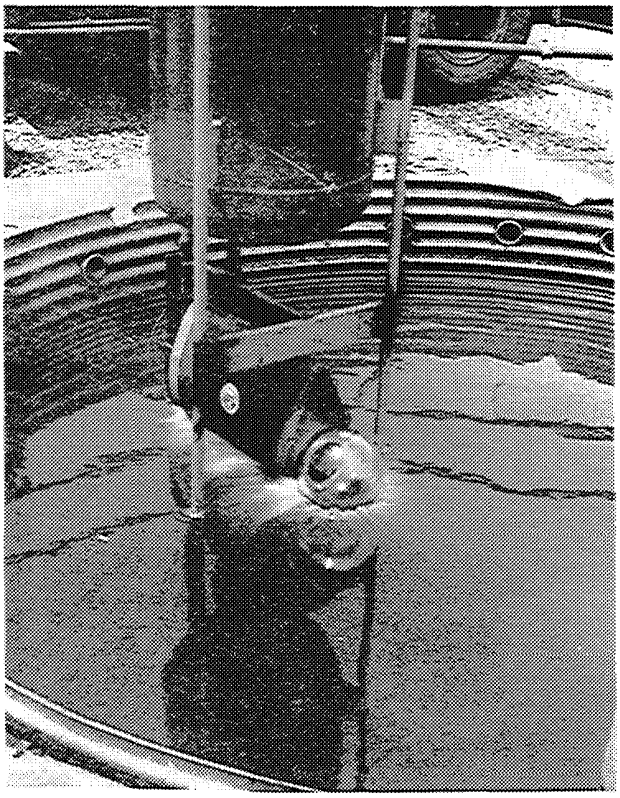


Figure 25 Simulated wave slap testing

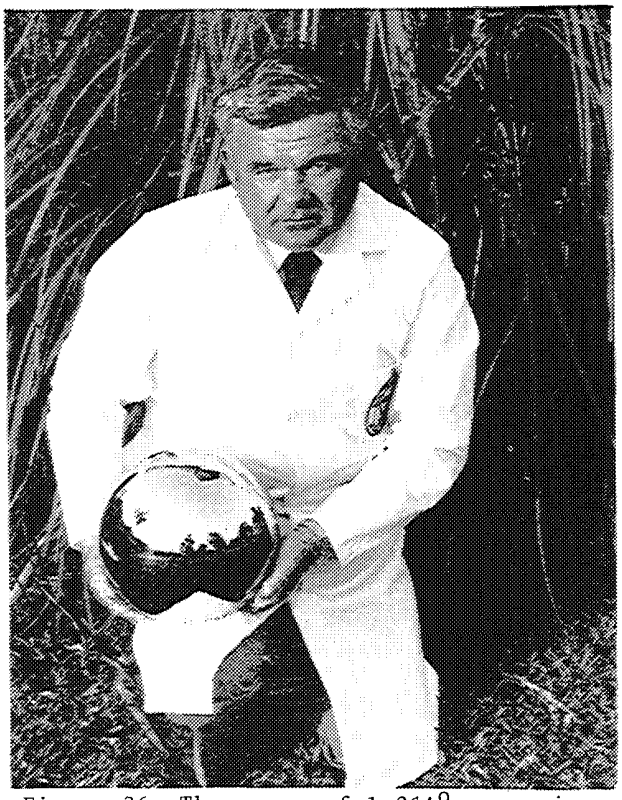


Figure 26 The successful 264° germanium hyperhemispherical window for 0 to 1000 psi pressure service

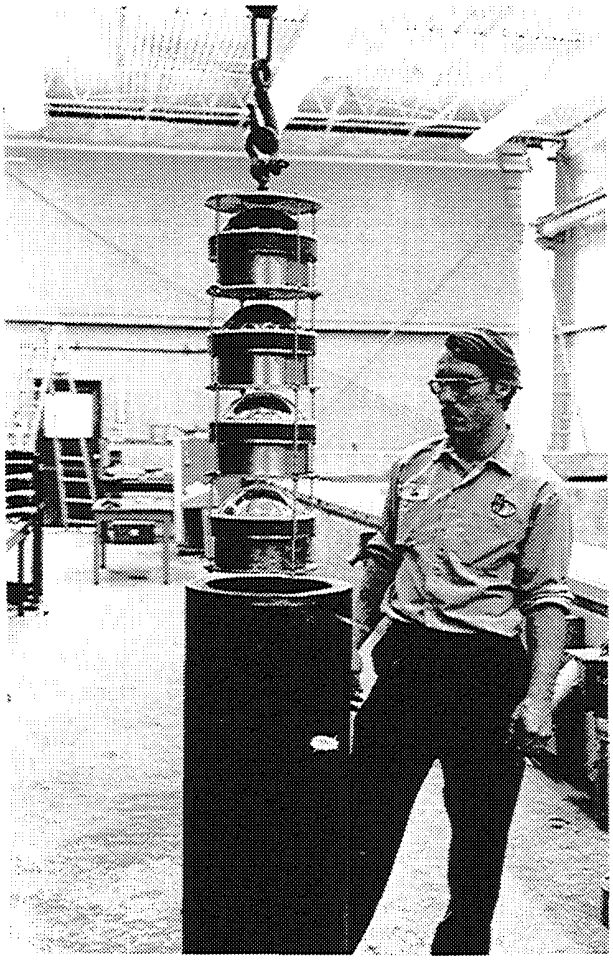


Figure 27 The successful 150° glass, and germanium spherical sector windows for 0 to 20,000 psi pressure service after completion of the 100th pressure cycle to 20,000 psi in the pressure vessel at Southwest Research Institute