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INTRODUCTION

Since the days of Prof. A. Piccard design of an acrylic window for Bathyscaphe TRIESTE in 1956, a sufficient number of window studies have been performed and their results documented in technical reports and papers to provide sufficient information for the creation of new window design for any size, or pressure rating. The engineers employing this information can produce designs and fabrication specifications that will result in safe and economical pressure resistant acrylic components of pressure hulls for operation in the –14.5 to +20,000 psi (0.1 to 138 MPa) pressure range.

Alas, there are some engineers that due to lack of knowledge, or experience will generate designs and specifications resulting in acrylic pressure resistant components of the pressure vessel that will fail either during hydro or pneumatic pressure testing prior to placing the pressure vessel in service, or subsequently in service.

It is to prevent such unfortunate occurrences that the American Society of Mechanical Engineers Pressure Vessels for Human Occupancy (ASME PVHO-1) Safety Standard was conceived (Reference 1). Its **primary purpose** was to assist engineers in design and fabrication of acrylic windows for pressure vessels. Its **secondary function** was to serve as a tool for enforcement by statutory authorities of safety codes for pressure vessels for human occupancy. Unfortunately, with the development of a litigious climate in the engineering environment, it is its secondary function as a mandatory safety code that today defines its character and development.

HISTORICAL BACKGROUND

Since the catastrophic failure of a viewport in the pressure vessel containing people always results in casualties to occupants of the pressure vessel, a resolution was submitted in 1971 by Dr. Stachiw, Chairman of Ocean Technology Division, American Society of Mechanical Engineers to the ASME Board on Nuclear Codes and Standards to have a Safety Standard established for viewports in pressure vessels for human occupancy.

Recognizing the need for such a Safety Standard, the ASME Policy Board. Codes and Standards established in 1971 a Committee on Pressure Vessels for Human Occupancy reporting to ASME Pressure Technology Codes and Standards. Captain R. Dzikowski, USN, was appointed to serve as Chairman, with Dr. Stachiw serving as the Chairman of Subcommittee on Acrylic Viewports. As a result of efforts by the Committee on Pressure Vessels for Human Occupancy, an ASME PVHO-1 Safety Standard was drafted and subsequently published in 1977 (Reference 1) In the drafting of the Safety Standard, the Committee incorporated many of the findings and recommendations on the design of windows published previously as papers and articles in technical literature. It was immediately accepted by U.S. Coast Guard and U.S Navy for all pressure vessels under their jurisdiction. To date, the ASME PVHO-1 Safety Standard, Section 2 on Viewports has been accepted by the American Bureau of Shipping, Det Norske Veritas, Lloyd's Register, Germanischer Lloyd, and other foreign classification societies.

Any engineer undertaking the design, or purchase of acrylic windows for pressure vessels must, prior to initiation of design work, obtain and study the contents of the most recent issue of the ASME PVHO-1 Safety Standard (Reference 1) to insure that his design will not only meet or surpass the minimum operational requirements for the selected service environment, but will also qualify as a design meeting the criteria of statutory safety requirements. In addition to the Standard, he should avail himself also of an authoritative handbook on acrylics that will provide him with the technical background need for better understanding of the Standard.

A design not meeting the **minimum** ASME PVHO-1 requirements will have to be validated at great expense by extensive Finite Element Analysis (FEA) calculations and/or prototype testing.

Since the ASME PVHO-1 Safety Standard presents in great detail the design criteria for windows and mounting seat dimensions, seals, fabrication procedures, and material QC, they will not be enumerated in this paper. Instead, major concepts serving as foundation of the Safety Standard will be summarized and explained to the designer preparing to utilize the ASME PVHO-1 Safety Standard.

ASME PVHO-1 SAFETY STANDARD

The best way to conceptualize the Safety

Standard is to compare it to a four legged table. In order for the table to perform its function, all legs must be in place and of equal strength. It takes only one leg to be missing, shorter, or weaker and the table will fall. The same holds true for the Standard.

In the case of the Safety Standard for acrylic windows, the four basic foundations are:

1. Material Specification
2. Window Design
3. Fabrication Procedure
4. Mounting Arrangement.

Material Specification

There are many types of acrylic plastic with widely differing physical properties. Any of them could be used for fabrication of windows provided their physical properties under short- and long-term loading are understood and properly applied in calculations. To simplify the problem, only acrylic plastics with mechanical and chemical properties meeting the minimum requirements of ASME PVHO-1 Table 2-3.1were selected for the design of windows. The short-term critical pressure graphs on which the design of windows is based in the Standard were generated by testing of hundreds of windows fabricated from cell cast monomer acrylic that not only met, but in most cases surpassed the magnitude of the minimum physical properties specified by the Standard.

Acrylic materials whose properties **do not** meet the minimum requirements of the Standard cannot be used by discounting the Short-Term Critical Pressure values of the Standard by the difference between the values of the mechanical (tensile strength, compressive yield, flexural strength and creep) properties in the material and the minimum magnitude of properties specified by the Standard. Similarly, credit is not extended in the design of windows fabricated from materials whose mechanical properties exceed the specified values of Table 2-3.1 in the Standard.

All acrylic materials cell cast from acrylic monomer, or slush mixture made up of acrylic polymer powder dissolved in acrylic monomer resin meet the criteria of the Standard. Cell cast acrylic sheets meeting the requirements of military specifications MIL-P-5425 satisfy the physical requirements of the Standard. Prior to their use, however, they must be tested and certified according to Standard specifications.

Continuous cast, or extruded acrylic sheet do not meet the Standard's criteria for mechanical properties and, therefore, are not accepted by the Standard for fabrication of windows. In this category are also thick sheets built up by lamination of several thin sheets which, by themselves, meet the material specifications.

The key point worth remembering about the mechanical, optical and chemical properties listed on Table 2-3.1 is that they represent the proven **minimum, and not the typical values** of acrylic castings.

Window Design

The Standard makes a distinction between **Standard** and **Non-Standard Window Geometries.** The Standard Window Geometries (Figure 1)are those for which exhaustive test and operational data exists, allowing the Standard to include empirical Short-Term Critical Pressure (STCP) graphs for these geometries. Those of Standard Geometry are included in the Standard and the selection of their t/D_i ratio for a given design pressure and temperature is based on experimentally derived STCP graphs and Conversion Factors (CF) developed by the Standard. No further tests or calculations are required in selection of window dimensions for windows of Standard Geometry. Windows of Standard Geometry outside angular or dimensional limits listed in the Standard require additional testing to verify their structural performance. Bevels on the edges of Standard Geometry windows are acceptable provided that their magnitude does not exceed the dimensions of bevels allowed by the Standard.

The experimentally generated STCP graphs and empirically derived CF factors for the Standard Window Geometries are presented in the Standard for the different window geometries, and will not be presented here.

The Standard has assigned windows whose maximum positive stress exceeds the maximum negative stress in their body a **design life** of 10 years, cyclic fatigue design life of 10,000 cycles, and static fatigue design life of 80,000 hours. Windows whose maximum negative stress exceeds the maximum positive stress in their body are assigned a design life of 20 years, cyclic fatigue design life of 10,000 cycles, and static fatigue design life of 80,000 hours.

The Standard requires that the windows of non-standard geometry (i.e. flat square, rectangular, oval , ogive shaped windows or canopies) prior to acceptance by the Standard must meet a series of test criteria specified for this purpose (Reference 1).

A minimum of 8 model or full scale window test specimens and 10,000 hours of hydrostatic testing in pressure vessels are required to complete the test procedure for a single window design at an estimated cost of more than $150,000.

The acceptance test procedure for non-standard window geometries is long and expensive. However, if the new window geometry meets the test criteria of ASME PVHO-1, it assures acceptance by all American and foreign Standards for viewports in pressure vessels for human occupancy. Substitution of Finite Element Analysis and analytical calculations for the test procedure specified by ASME PVHO-1 Safety Standard for non-standard geometry windows is **not acceptable** until such time that the Standard decides to accept it, which is not likely to happen in the near future.

In many engineering quarters the test procedure specified by the Standard for qualifying the design of a non-standard window is considered too cumbersome and too costly. It is true that the test procedure is long and expensive, and in most cases longer and more extensive than a FEA. However, where the results of FEA maybe questioned by the Classification Society or Statutory Authority and the FEA may have to be re-run one or more times to satisfy the reviewers, the results of the test procedure specified by the Standard are accepted at face value without further retesting.

Fabrication Procedure

The fabrication of acrylic windows requires the availability of appropriately sized castings, machining equipment, and annealing ovens. One, or more annealing procedures are usually applied to the windows during the fabrication process to minimize residual stresses resulting from casting and machining procedures.

Only the **final** annealing procedure applied to the finished window after all the machining, sanding and polishing operations have been completed is mandated by the Standard. The durations of heat application in the oven mandated by the Standard for the final annealing procedure are bare minimums. The additional heating time **does not degrade** the physical properties of the acrylic window, as at those low temperatures (<230^{0}F)/110^{0}C) the physical properties do not degrade, but in most cases improve.

Inspection

The Standard requires a thorough visual and dimensional inspection of the finished window. The objective of the visual inspection is to discover any blemishes on the exterior surfaces and inclusions in the interior of the window. If their magnitude or extent exceed the limits specified by the Standard, the window is to be rejected.

The objective of the dimensional inspection performed at 75^{0}F (24^{0}C) is to determine the conformance of the fabricated windows to dimensions called out on the fabrication drawings. To meet the requirements of the Standard, the window dimensions must also satisfy the dimensional tolerances called out by the Standard. These tolerances vary from one window geometry to another. Their magnitude is a function of both the sealing arrangement selected for the seat in the flange and their effect on structural performance of the window in service. The dimensions of corresponding seats in the flanges are also toleranced accordingly to meet the dimensional and angular tolerances on the windows.

There is no restriction on the variation in window thickness, provided that the thickness at all locations on the window is **equal to, or exceeds the minimum thickness** required by the Standard for the chosen window diameter and geometry at design pressure and temperature. In thermoformed windows of spherical configuration, the variation in thickness frequently exceeds 50 percent, but as long as one of its curved surfaces (convex or concave) is still within 0.5 percent of the specified nominal external spherical radius, and the minimum thickness equals or exceeds the minimum calculated value for the design pressure, the window is acceptable to the Standard. Many of the spherical sector windows in service today have been thermoformed and their service record is outstanding.

After inspection, initials and serial number is marked on the window's edge with the PVHO logo, window fabricator's name, design depth and temperature, and the date of fabrication.

Structural Proof Testing

The finished, inspected window meeting all the visual and dimensional inspection criteria of the Standard has to be proof tested prior to acceptance for service in pressure vessels for human occupancy. The objective of the pneumatically, or hydraulically applied pressure test is to demonstrate that the finished window performs structurally as specified by the Standard. The criteria for acceptance is absence of cracking or permanent deformation in excess of allowable magnitude.

Pressure testing is acceptable either to design pressure, or to over-pressure (<1.5 design pressure magnitude). The significant difference between the two allowable testing procedures is that at design pressure the test must be performed at design temperature of that window design, while for over-pressure testing, the temperature must be lowered from 25 to 35^{0}F (14 to 19^{0}C) below the design temperature.

The proof testing may be performed with the window mounted in the pressure vessel, or a test fixture with identical seat dimensions as the seat in the pressure vessel.

The proof tested window, accompanied by its certificates is now ready for mounting in the vessel. The ASME PVHO-1 certifications accompanying the finished window are:

1. Enclosure 1 Acrylic Window Design Certification
2. Enclosure 2 Material Manufacturers Certification for Acrylic
3. Enclosure 3 Material Testing Certification for Acrylic
4. Form PVHO-2 Fabrication Certification for Acrylic Windows
5. Enclosure 5 Pressure Testing Certification
6. Annealing Strip Chart

Absence of any of these certifications or identification markings on the window disqualifies the window as having met all of the Standard's requirements.

Mounting Arrangement

The Standard specifies in great detail the acceptable mounting arrangements for the different window geometries to insure good sealing under design pressure and adequate support to the window's bearing surfaces.

The Standard provides great latitude in the sealing arrangements that the designer may choose. There are four mandatory requirements, however, that must be satisfied by the sealing arrangement chosen by the designer.

1. Two seals, a **primary** and **secondary**, located in tandem are required. They may take the shape of 0-rings or gaskets. The interface between conical bearing surfaces of the window and the seat may be considered as a secondary seal.
2. The two seals together must provide pressure integrity over the whole range of ambient temperatures to which the pressure vessel may be subjected in service. This means that for diving systems, the seals must keep the interior dry regardless of whether the system will be employed in the Arctic (-40^{0}F/-40^{0}C) or the tropics (120^{0}F/48^{0}C). A few sealing arrangement and seal materials are competent to cover such wide temperature ranges.
3. At least one of the seals **must keep the joint water-tight after a long-term sustained pressure loading** causing the window to creep significantly. For the gasket seal under the window retaining ring acting as the primary seal for windows there must be sufficient precompression during assembly to insure that there is still enough compression of the gasket even at the end of the long-term pressurization that causes the window to displace significantly.
4. 0-ring grooves are not allowed on the surfaces of windows or on bearing surfaces in window seats as they act as crack initiators.

To deliver the full structural potential of the window, it must be supported properly by its seat in the flange. The Standard provides great latitude in the selection of flange configurations. There are four mandatory requirements, however, that must be met by the flange.

1. The flange configuration must provide **adequate reinforcement to the hull** around the penetration in the hull containing the flange. The penetration reinforcement must meet the requirements of Code Section VIII Division 1 or 2 and its radial and angular deformation at design pressure must not exceed 0.002D_i and 0.5 degree, respectively.
2. The flange configuration must provide **rigid support** to the acrylic window under design pressure to keep it from excessive deformation and/or displacement that, in effect, reduces the window STCP, LTCP and CCP.
3. The seat in the flange must provide **continuous support** to the whole bearing surface of the window through the whole range of pressures from zero to vessel test pressure which, in some cases, equals 1.5 x MWP and range of ambient temperatures encountered in service. For some standard window configurations (conical frustum, double beveled disc, spherical sectors, cylinders and hemispheres), the window's minor diameter D_i must be larger than the minor diameter of the seat D_f in order to provide support to the extruding window under pressure application.
4. The seat in the flange must provide **adequate clearances** for the window during assembly at 75^{0}F (24^{0}C) to allow for expansion of the window at highest expected temperature during shipment, or outdoor storage of the vessel.

PROJECTED PERFORMANCE OF THE WINDOW IN SERVICE

The Standard specifies **design life** for Standard Geometry windows configured on the basis of the Standard. Unfortunately, the statutory authorities confuse the concept of **design life** with **service life** insisting on removal of windows from service upon expiration of the design life, regardless of the actual condition of the window.

Experience has shown that frequently some of the window removed from pressure vessels at the expiration of their design life set by the Standard still meet the acceptance criteria for brand new window and, therefore, should have remained in service. **In other words, the expiration of design life assigned by the Standard on the basis of expected typical service conditions does not necessarily signify the termination of service life.**

One needs to distinguish here between the design and service life of acrylic windows. The **design life** is the <u>projected</u> service life in years of a window under typical service conditions and severe ambient environment.

The **service life, o**n the other hand, is the <u>actual life</u> of a window under **actual** service parameters and ambient environments that affect the windows after installation in a given pressure vessel. The service life terminates when the safety margin between the maximum working pressure (i.e. design pressure) and the short-term critical pressure at peak ambient temperature decreases to 2 (i.e. 100 percent margin of safety).

If a window designed on the basis of ASME PVHO-1 Safety Standard criteria is cycled less than 10,000 times to a working pressure of lesser magnitude than the design pressure, the sum of pressurization durations is less than 40,000 hours, the peak ambient temperature is less than the design temperature, and the window is not exposed to weathering, the service life of such a window will exceed its design life by 10, or more years, and its cyclic fatigue life by 10^4 or more cycles.

On the other hand, a window subjected over 10,000 cycles to design pressure at peak design temperature under continuous weathering may have to be replaced prior to expiration of design life if its STCP has decreased below the safety margin of 2 required by ASME PVHO-2 Safety Standard.

What this signifies is that **relying totally on the length of design life assigned by the Safety Standard as the sole reliable indicator of service life is neither safe, nor economical.** In one case, unsafe windows (i.e. with safety margins less than 2) are kept in service until design life expires, while in the other case a serviceable window (i.e. with safety margins in excess of 2) are removed from service. The only approach to prevent this is to rely on regularly scheduled inspections commencing immediately after installation in the vessel.

The in service inspection procedures for PVHO vessels are covered by ASME PVHO-2 non mandatory In-Service Guidelines. With the help of these procedures, it is feasible to detect early deterioration of the window or good condition at the end of the design life.

The underlying philosophy of the in service inspection procedures is that the **absence of visible deterioration** of acrylic (i.e. discoloration, crazing, or cracking) <u>by itself</u> does not guarantee absence of material deterioration that might make the window unsafe for continuing service. Only if that observation is additionally supported by test findings on windows of the same configuration in similar service environments can the absence of visible deterioration be considered to be a valid indication that significant deterioration of acrylic has not taken place and that the window may remain in service.

SUMMARY

The ASME PVHO-1 Safety Standard represents the **minimum design** requirements for a safe viewport with acrylic window for a given design pressure and temperature. The designer is encouraged to **exceed** those requirements within existing design constraints in order for the windows' service life to extend significantly beyond the minimum design life assigned to it by the Standard.

The minimum requirements mandated by the Standard that should be exceeded **routinely** during the selection of design criteria are:

1. **Select** the <u>upper limit</u> of the temperature range on the tables listing the CF factors (i.e. do no interpolate the CF factor on the basis of the selected design temperature)
2. **Increase** the calculated value of minimum window thickness by $\geq$ 0.250 in (6 mm) to provide extra material for future removal of gouges and spalls on window surfaces without reduction of the window's depth rating based on minimum thickness.
3. **Increase** the soaking time specified by the Standard for annealing of window after completion of all fabrication procedures.

The design details discussed and mandated by the Standard may seem for an experienced engineer to be very restrictive, however, for those not familiar with the acrylic window fabrication, sealing, and mounting, they serve as a very helpful guide in arriving at a safe, functioning viewport with an acrylic window.

It is worth remembering, that to date since its inception in 1977 the Standard has maintained a perfect safety record over –14.5 to 20,000 psi (-0.1 to 138 MPa) pressure range in hundreds of different manned and unmanned applications. It would, therefore, be foolhardy to ignore the guidelines for acrylic window installations in pressure vessels for human occupancy presented by the Standard..

The advice for the first time designer of a pressure vessel for human occupancy is to utilize in his design windows of Standard Geometry within the dimensional and angular limits stated in the Standard for these geometries. This relieves him of the need for a long and expensive (Reference 1) qualification program for the Non-Standard Window.

Although the Standard is self explanatory, it is very helpful to have access to the reports and papers on which the rules of the Standard are based. The papers and reports may be obtained by accessing website www.hydroports.com and ordering the desired publications on line. Furthermore, to reduce the expenses associated with procurement of pertinent publications and efforts required for their review, the findings of these reports and papers have been summarized and made available in a recently published HANDBOOK OF ACRYLICS FOR SUBMERSIBLES, HYPERBARIC CHAMBERS AND AQUARIA available online from the same website (Reference 3). With the aid of both the Standard and the HANDBOOK, one can look forward to a steady increase in the use of acrylic viewports in pressure resistant chambers.

REFERENCES

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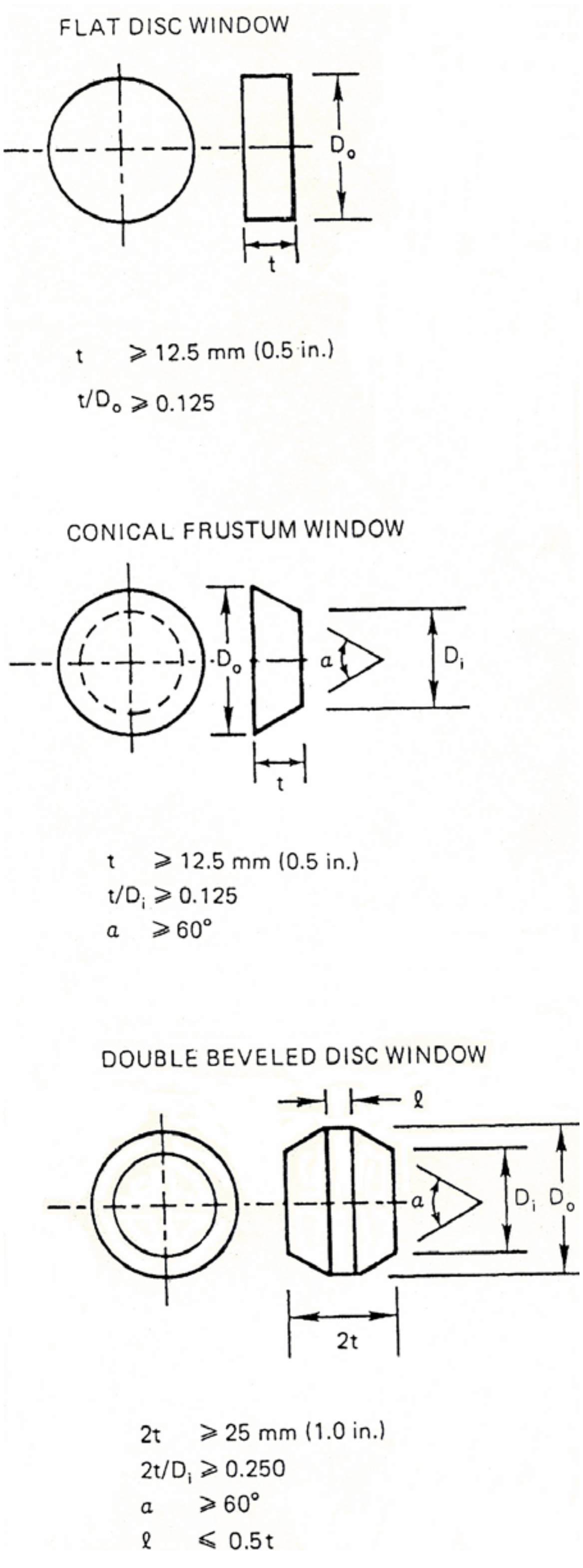
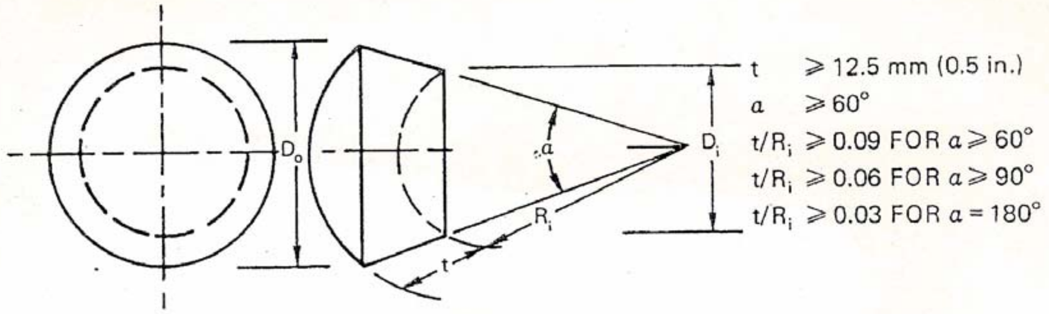
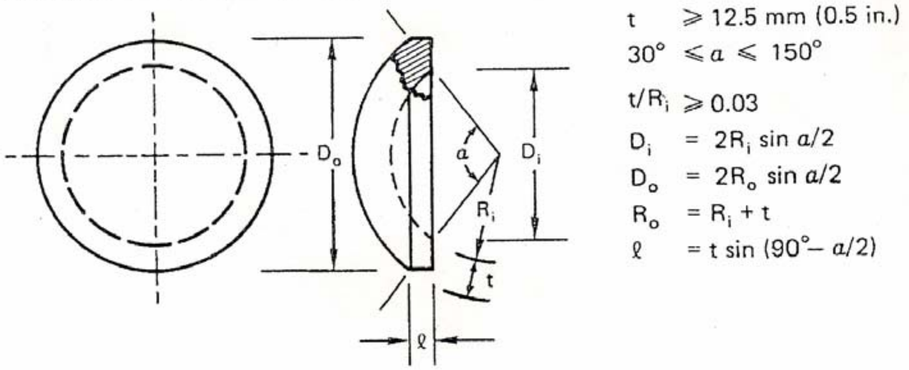


Figure 1 Standard Window Geometries Defined by ASME PVHO-1 Safety Standard 2002

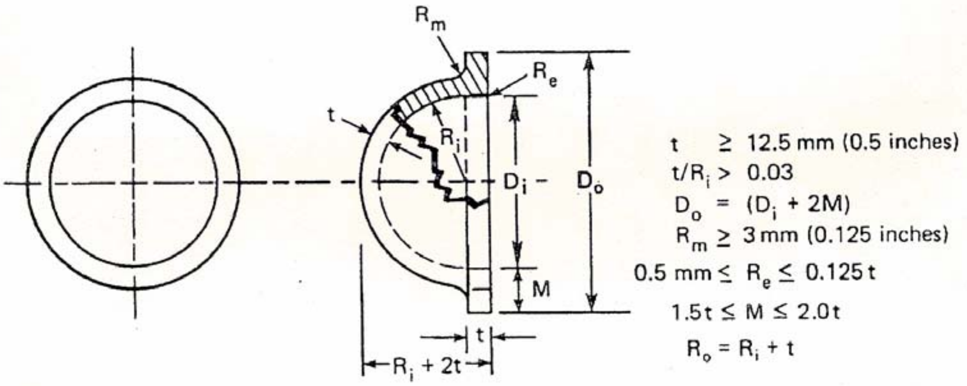
SPHERICAL SECTOR WINDOW WITH CONICAL EDGE



SPHERICAL SECTOR WINDOW WITH SQUARE EDGE



HEMISPHERICAL WINDOW WITH EQUATORIAL FLANGE



CYLINDRICAL WINDOW

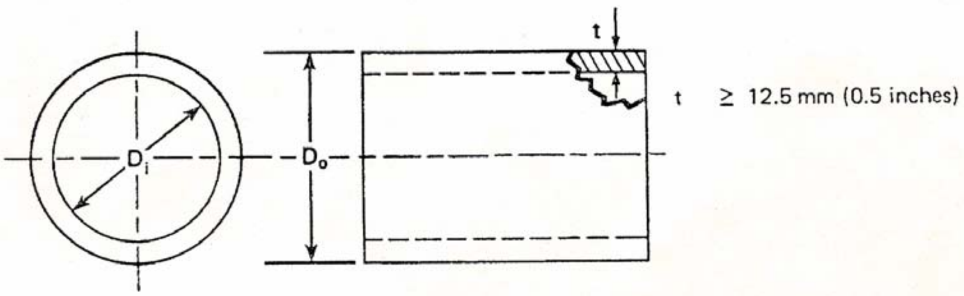


Figure 1 continued

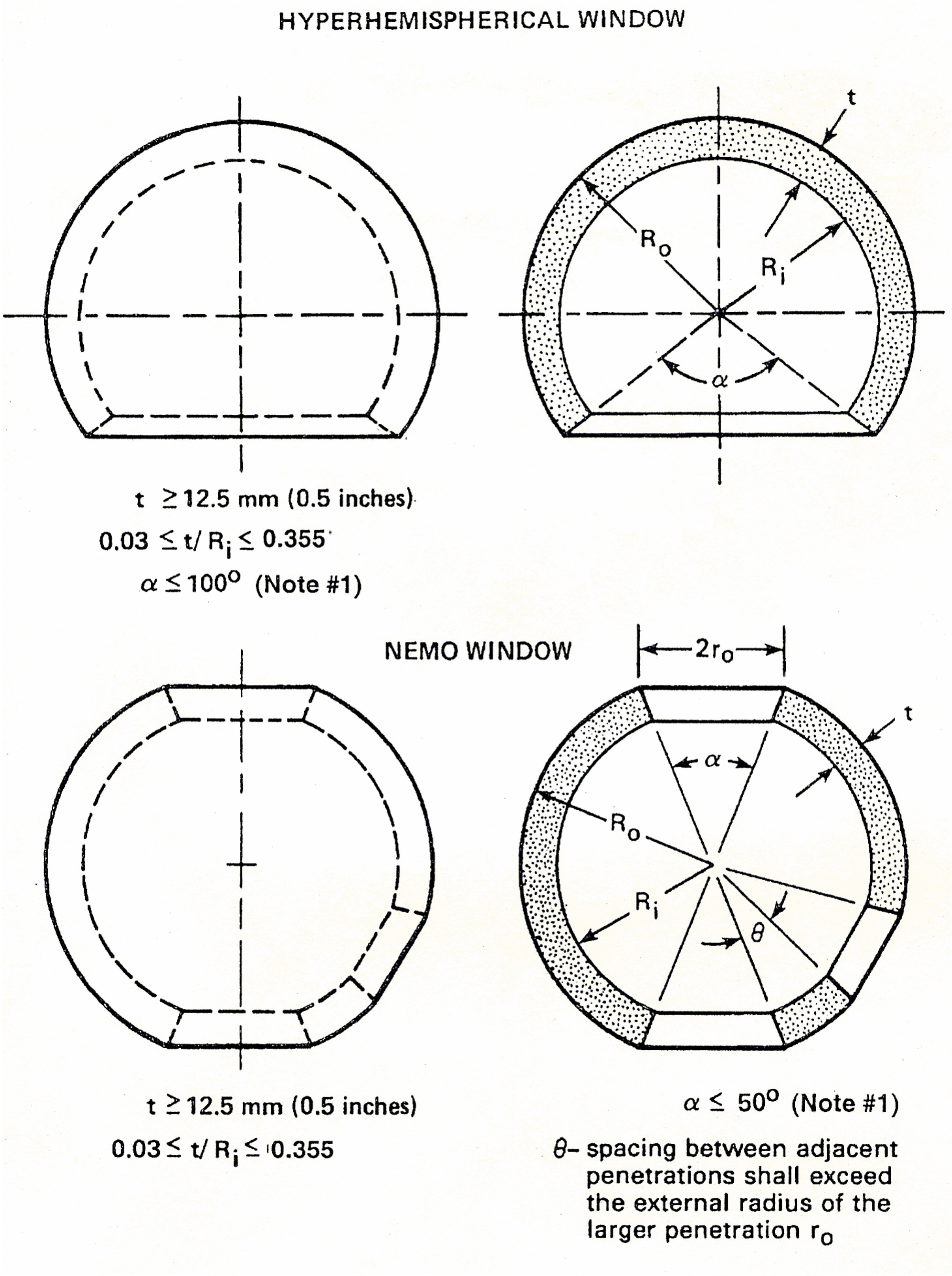


Figure 1 continued

Figure 2 Representative Acrylic Windows of Standard Geometries