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Research Article

Effect of refraction and field of view of acrylic viewports of shallow water spherical pressure hull

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Abstract

A shallow water spherical hull for manned submersible has been designed and developed by National Institute of Ocean Technology, India. During the design phase, a detailed study was carried out concerning the conical acrylic viewports, to understand the limit of aperture, field of view through viewports, field of view of seafloor, and reflection. It is also important to understand the effect of refraction due to acrylic and sea water, which is significant for making engineering judgements while collecting samples from the seabed. This study recommends having larger diameter viewports and larger angles between the primary and secondary viewports. A limitation would be that increasing the diameter of the viewport would increase the size of the viewport flange.

1. Introduction

Manned submersibles are necessary for shallow and deep water explorations. A pressure hull is the primary component of manned submersibles. The pressure hull can be of any shape, but most manned submersibles are built with spherical pressure hulls as manned cabins. This is a complex structure, consisting of a shell, viewports, a hatch, and geometric discontinuities, such as flanges, lifting or mounting lugs, etc. (Busby, 1976; Allmendinger, 1990).

Proper design of acrylic viewports is required to ensure the safety of the pressure hull. The material non-linearity and temperature effects are considered in the full ocean depth analysis of acrylic viewports. Acrylic is a viscoelastic material. It is mainly affected by temperature, time strain, etc. (Stachiw, 2003, 2004; Wang 2019). Trowbridge presented the location discrepancies of the NEMO submersible produced while the object is viewed through the acrylic spherical pressure hull (Trowbridge, 1971).

Based on the design and experimental results, Mavor concluded that plexiglass/acrylic windows can be designed with high confidence (Mavor, 1965). There is a considerable optical distortion in thick plane surface windows, due to air-acrylic interface. On the basis of refractive indices, the use of glass would not provide an advantage in optical improvement over acrylic. With the use of a single eye or a camera, optical distortion would be less while using a spherically machined window. Practically, it is not possible to use a single eye for 4 to 5 hours; hence, it is necessary to use both eyes to reduce eye fatigue. Suitable optical components or instruments can be

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used at the low-pressure face of the acrylic window to achieve air-water correction and improvement in field of view (Mavor, 1965).

The layout of the observation windows, field of view, field of view of the sea floor, and refraction effects are studied and explained in this paper. One of the important tasks of a manned submersible is to take samples from the seabed with the help of manipulators. Very few papers related to underwater refraction and field of view are available in the public domain. Hence, it is necessary to study the field of view of the sea floor.

2. Geometric parameters and material properties

The shallow water research submersible is operated by three crew members sitting inside the spherical pressure hull. Hence, it is required to have a minimum of three viewports for ease of manned submersible operation. **Figure 1** shows the shape and components of the spherical pressure hull. The middle-front viewport is called the primary viewport and the front-left and front-right side viewports are called secondary viewports. Design and sizing of viewports should guarantee operability and maintainability by the owner of the submersible. Design limits shall be based on 95th percentile face dimensions. Face dimensions are considered as per MIL-STD-1472C based on the 95th percentile, shown in **Figure 2**. The distance between the free edges of each eyelid is called the biocular breadth. Biocular breadth for the 95th percentile is 109 mm. Hence, the minimum dimension of the viewport should be higher than the biocular breadth. The sizes (inner diameter of the flanges) of the primary and secondary viewports are 200 and 110 mm, respectively.

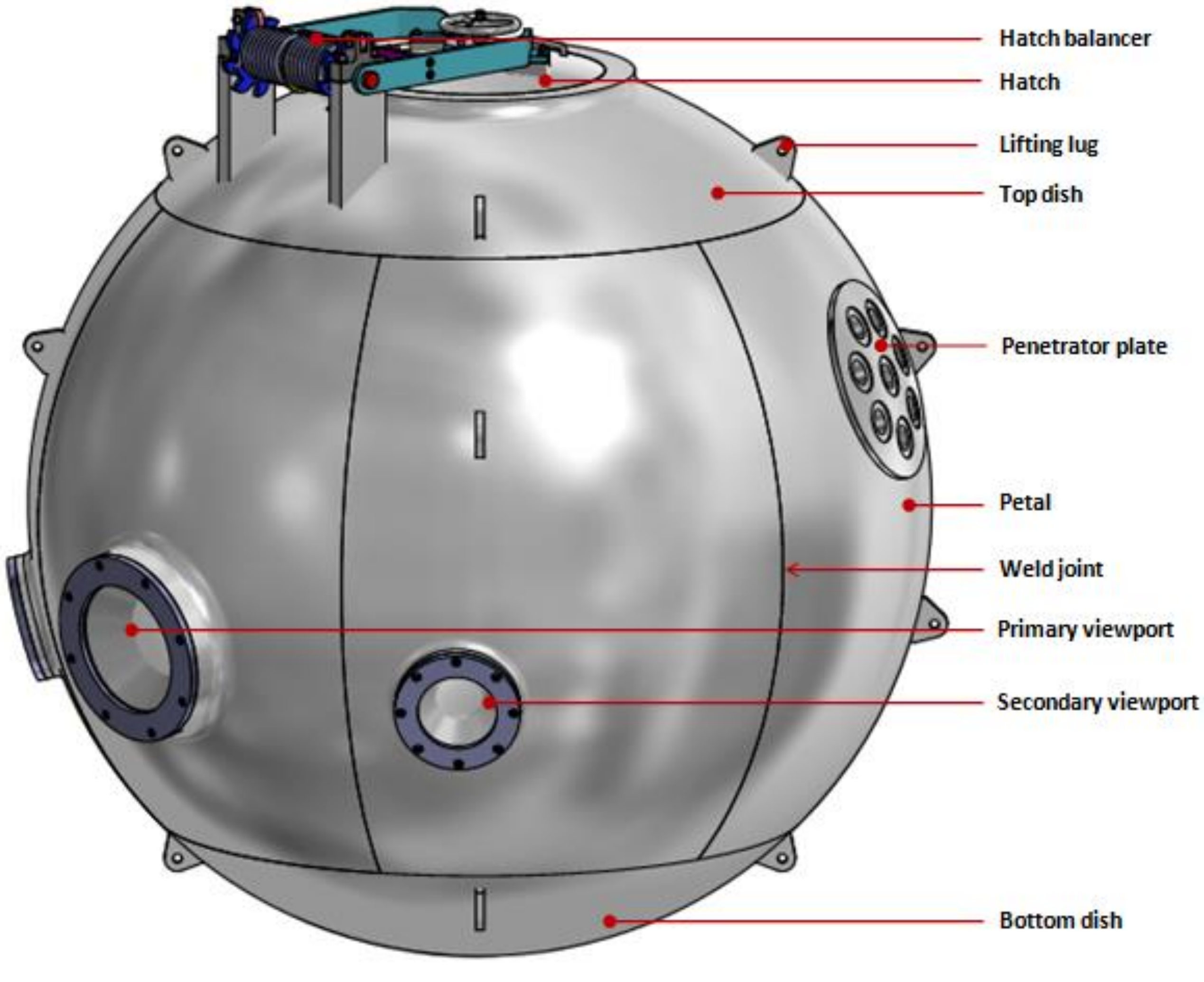

Figure 1 Components of spherical pressure hull (Pranesh et al., 2020).

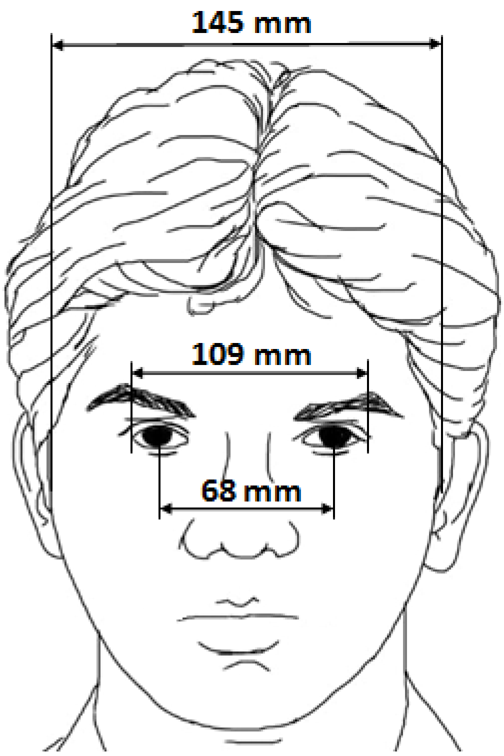

Figure 2 Face dimensions (95th percentile).

Various possible window configurations are flat, conical, and spherical, but the conical shape is the preferred one for manned submersible applications. The dimensions of the primary and secondary viewports are shown in **Figure 3**. The components of a viewport are the window, the supporting flange, the locking plate/bezel, and seals.

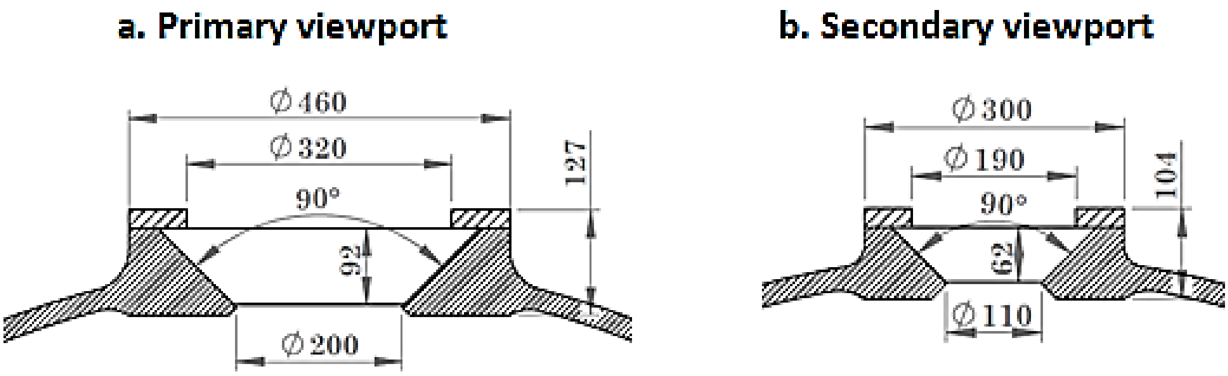

Figure 3 Basic dimensions of primary and secondary viewports.

The viewport is made from acrylic plastic. Compared to any other materials, a unique property possessed by acrylic is transparency, which aids the visual experience. No machine can replace the human experience obtained when inside manned submersibles underwater (Allmendinger, 1990). The viewport windows, manufactured and tested by Indian firms according to ASME PVHO-1 standards, are shown in **Figure 4**. A comparison of different viewport materials is given in **Table 1**.

Figure 4 Photos of primary and secondary viewports manufactured and readability inspection by Dr. G. A. Ramadass.

Table 1 Comparison of different viewport materials and their properties.

Properties	Acrylic	Polycarbonate	Glass
Design and testing data	Available	Less	Very less
Machinability	Easy	Easy	Difficult
Reproducibility	Easy	Easy	Difficult
Catastrophic failure	Predictable	Predictable	Hard to predict
Visual clarity	Readable	Readable	Readable
Light transmission	92 %	88 %	90 %
Refractive index	1.49	1.6	1.58
Usage in manned submersibles	Extensively used	Less used	Very few
Design and manufacturing guidelines	ASME PVHO-1	Not available for underwater applications	Not available for underwater applications
Service guidelines	ASME PVHO-2	Not available for underwater applications	Not available for underwater applications

The researcher concluded that the viewport windows are acceptable for optical applications if they have no distortion of viewed objects underwater for the observer whose eyes are within 250 mm from the low pressure face (Stachiw, 1990).

3. Layout of observation windows

The present pressure hull can accommodate three crew members. The pilot is seated at the center, the co-pilot is at the right of the pilot, and the observer is on the left. The pilot operates the submersible at all times by looking through the primary viewport while observing the instruments and a video monitor inside the pressure hull. It is easy to operate the submersible if the pilot can see outside through the viewports (Shuichiro et al., 1990). The secondary viewports are arranged at 45° towards the left and right in order to get the perfect views while the vehicle is moving. The location of the viewports is shown in **Figure 5**. The location of the viewport primarily depends on the sitting position, line of sight, and different viewing angles of human beings. A slump sitting position is considered with 95th percentile occurrences. The seated anatomical dimensions considered for the present study are given in **Table 2** (Cohen, 1995; Design: Hyperbaric facilities, 2004).

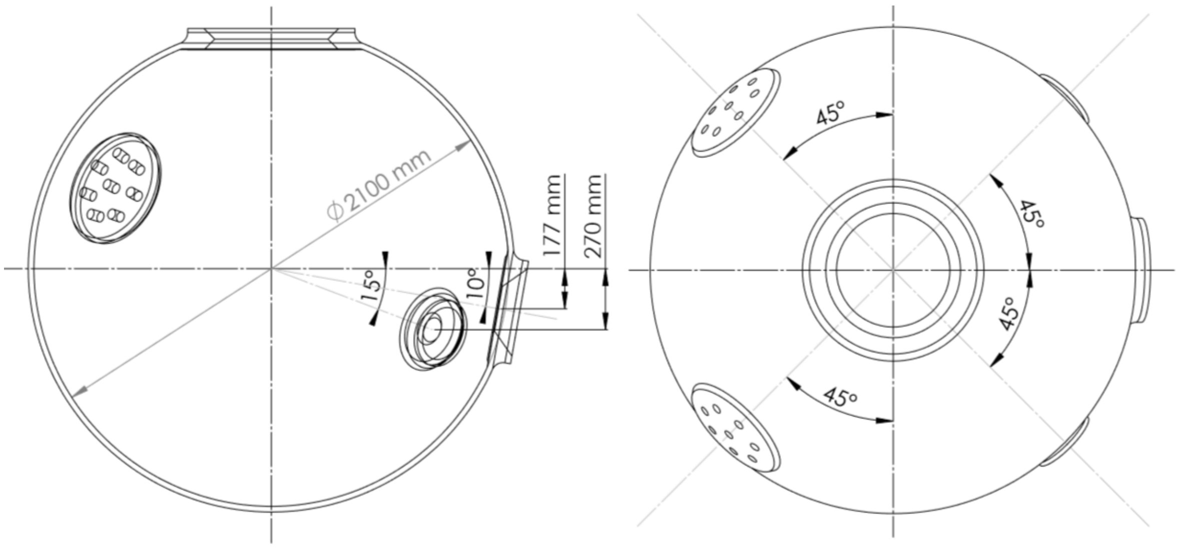

Figure 5 Primary and secondary viewport locations.

Table 2 Seated anatomical dimensions at slump sitting position (Cohen, 1995).

S. No	Description (95 percentile)	Dimension in mm
1	Sitting height (H1)	914.40
2	Eye height (H2)	800.10
3	Shoulder height (H3)	594.36
4	Elbow height (H4)	248.92
5	Knee height (H5)	619.76

At slump sitting position (**Figure 6**), eye height is 800.10 mm. The sitting position and viewing angles are shown in **Figure 7**. The lowest possible clear vision angle is 40° with respect to horizontal sight line and with downward head rotation; this lowest vision angle shall be increased to 70°. With the movement of head and eyes, the viewport position angles can be covered for better maneuvering. The viewing angles through the acrylic window can be different for different persons. Hence, it is recommended to have height adjustable seats as per standard.

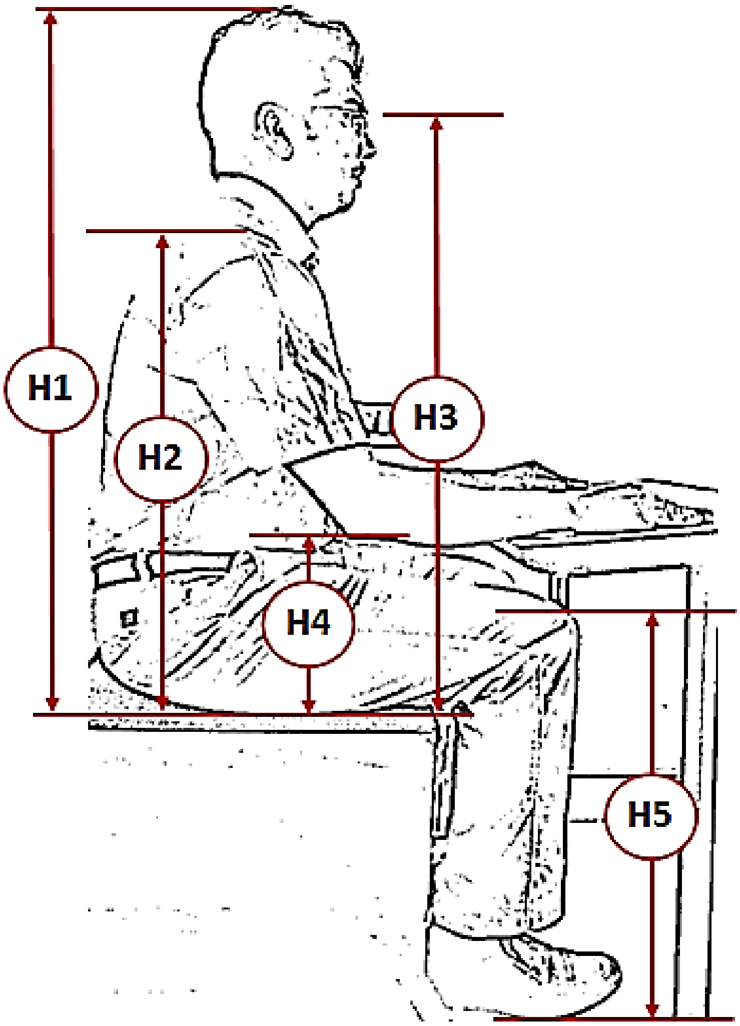

Figure 6 Slump sitting position.

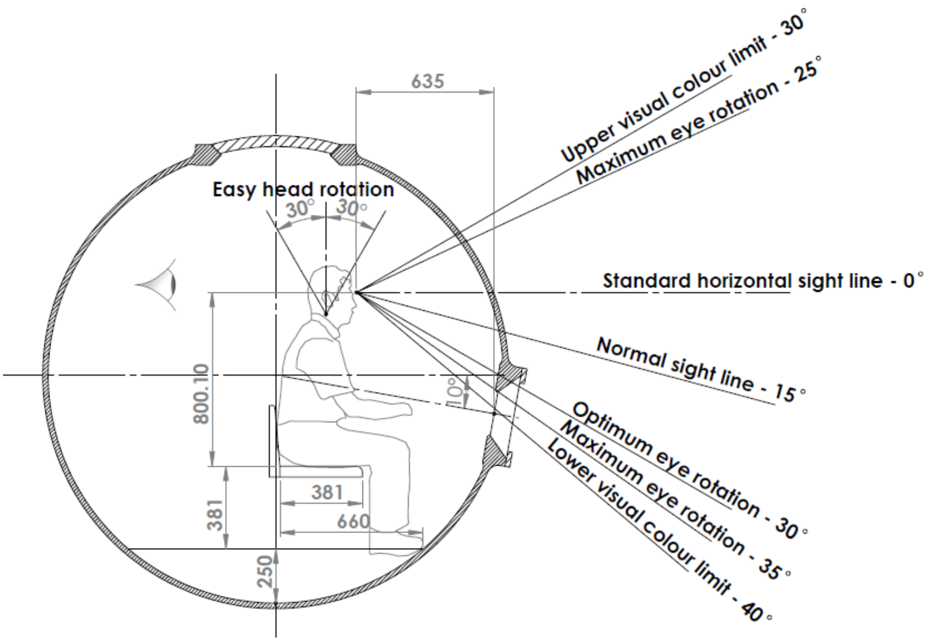

Figure 5 Line of sight and different view angles (Design: Hyperbaric facilities, 2004).

4. Limiting aperture

All viewport design will have minimum/limiting dimensions that will place restrictions on the field of view. The limiting dimension/aperture of the primary and secondary viewports are shown in **Figure 8**. For the primary viewport, if the viewing distance is greater than 198 mm, then the limiting aperture is the inner diameter of the viewport flange, and if the viewing distance is less than 198 mm, then the limiting aperture is the inner diameter (outer edge) of the viewport locking plate. For the secondary viewport, if the viewing distance is greater than 120 mm, then the limiting aperture is the inner diameter of the viewport flange, and if the viewing distance is less than 120 mm, then the limiting aperture is the inner diameter (inner edge) of the viewport locking plate. The limiting aperture of the viewport depends on the viewing distance.

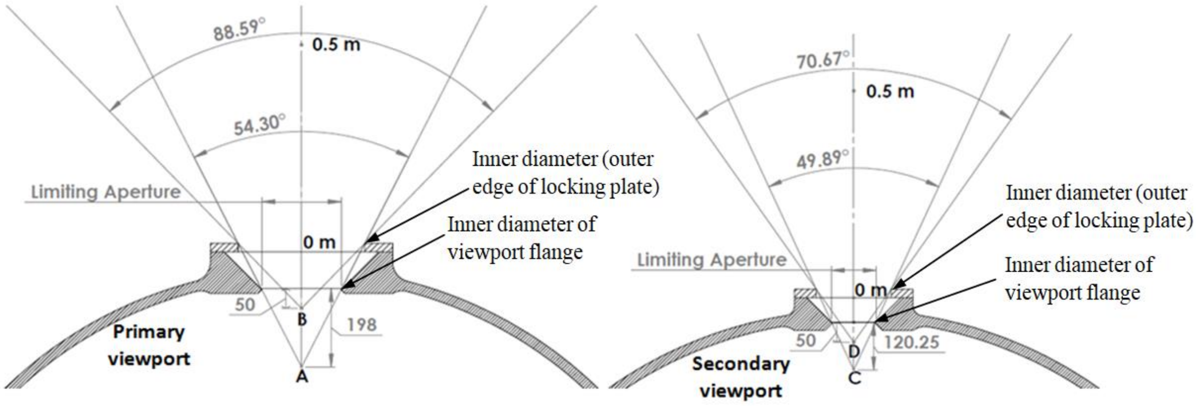

Figure 6 Limiting aperture location on primary and secondary viewports.

5. Field of view

Observations are limited by the size of the viewport. This limitation can be overcome by manufacturing the pressure hull with full or partially transparent material (Stachiw, 1990). The viewports are arranged in such a way that they cover the maximum field of view of the bow of the manned submersible. Observation through the viewport is carried out by the personnel at closer range, using both eyes. This gives a binocular field of view in the horizontal plane (Design: Hyperbaric facilities, 2004). The field of view is obtained through a simple graphical method. The monocular and binocular fields of view are shown in **Figure 9**.

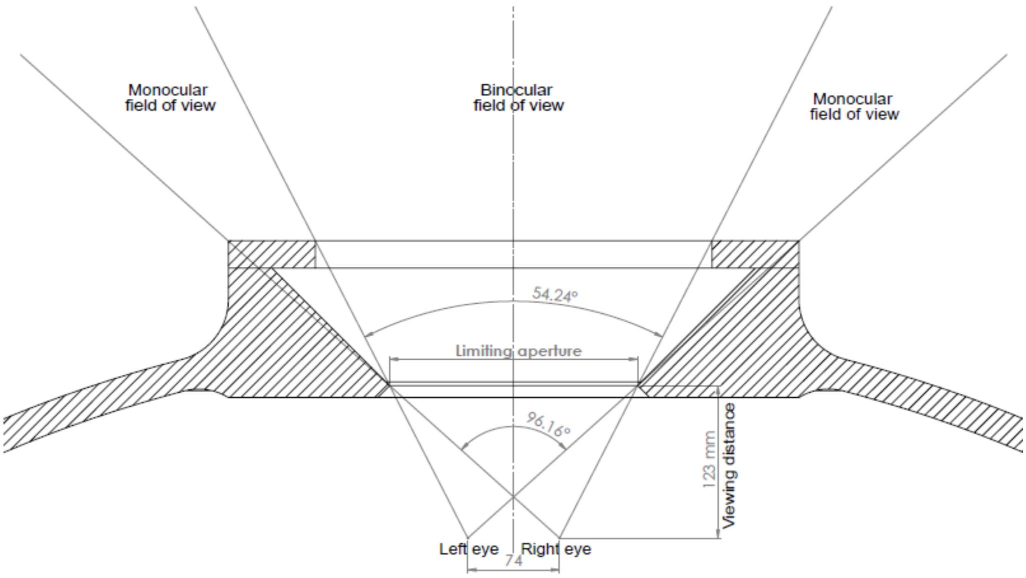

Figure 7 Monocular and binocular field of view in horizontal plane (primary viewport).

The range of pupillary distance for adults is between 54 to 74 mm, whereas for children it is between 43 to 58 mm (Cohen, 1995). For adults, the 95th percentile for pupillary distance is 68 mm. For the primary viewport, it is observed from **Figure 9** that, when the viewing distance is 123 mm or less, it gives a binocular field of view, whereas when the viewing distance is greater than 123 mm, it gives both a monocular and binocular field of view. A monocular or binocular field of view depends on the viewing distance, limiting aperture, viewport window thickness, and diameter of the viewport locking plate. In order to obtain depth perception, both eyes must be used. depth perception depends on the observer's previous knowledge of the object and surroundings (Trowbridge, 1971).

6. Field of view of seafloor

Most of the time, the range of view is closer to the window. The pilot or observer moves closer to the window to obtain the maximum field of view. The minimum distance between the eye and the viewport window is 50 mm. Hence, the field of view is drawn at a viewing distance of 50 mm for all viewports. The horizontal fields of view of the primary and secondary viewports are 88.79° and 70.67°, respectively (**Figure 8**). **Figure 10** shows the fields of view of all three viewports at the horizontal mid-plane of the primary viewport. The primary viewport has a larger field of view as compared to the secondary viewport. One of the important tasks of the manned submersible is to collect samples from the seabed with the help of sampling tools. Hence, it is necessary to study the field of view of the seafloor. Areas that are not covered through the viewport window need to be covered with the help of underwater cameras for effective sampling. There is a need for adequate lighting for underwater viewing through the viewport windows and cameras. A sufficient number of lights are mounted on the frame in front of the manned submersible to illuminate the front and seafloor.

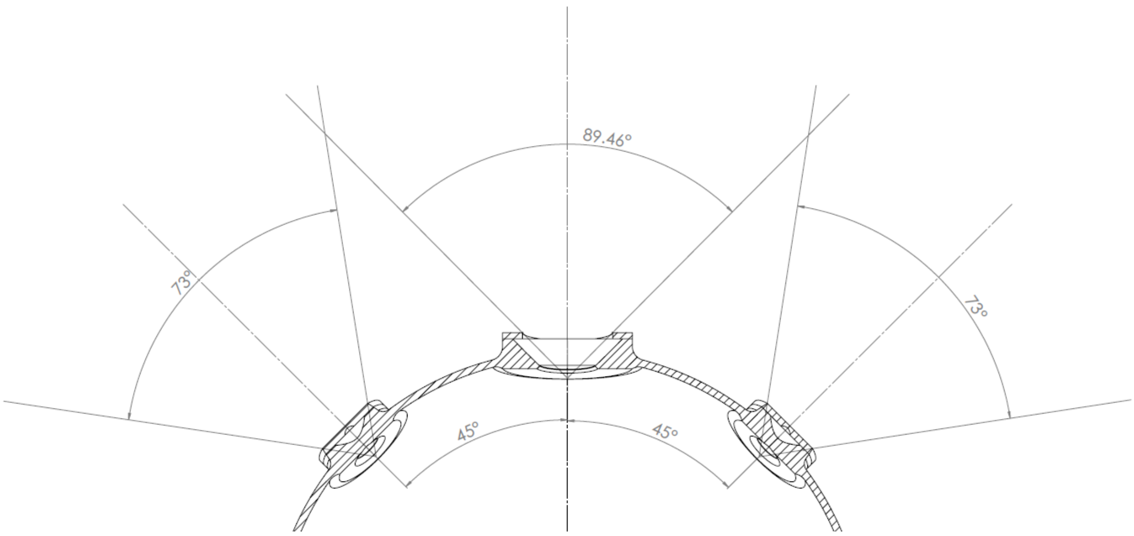

Figure 8 Fields of view of all three viewports at horizontal mid-plane of primary viewport.

The field of view on the seafloor for the present spherical pressure hull is shown in **Figure 11**. The present pressure hull does not cover the side views of the manned submersible. This shortfall in the location of the viewport with respect to the field of view can be compensated by installing a rotatable camera with a tilting up/down mechanism outside the pressure hull and a display unit inside the pressure hull. The field of view for future manned submersibles can be improved by increasing the diameter of the viewport windows and by increasing the angle between the viewports. If the diameters of viewports increase, either flange thickness increases, or depth rating of the vehicle decreases. There are manned submersibles where half of the sphere is acrylic, but they are all rated for less than 1,000 m water depth.

This field of view study is undertaken by increasing the size of the secondary viewports in such a way that the sizes are the same as that of the primary viewport and the angle between the viewports are kept the same. The overlapping fields of view seen through viewports on the seafloor is improved by two times. The horizontal distance between the seafloor view and the viewport is reduced from 1.46 to 0.78 m. The seafloor view of the modified geometry is shown in **Figure 12**. The improved geometry covers a 180° angle field of view. This satisfies the side view of the manned submersible. The area of the initial overlapping field of view is 6 m^2, whereas the area of the improved field of view is 12 m^2. It is recommended to have an overlap of at least 50% of the primary field of view area. In the initial overlapping, it is 34%, and in the improved geometry, as is the present case, it is 68%.

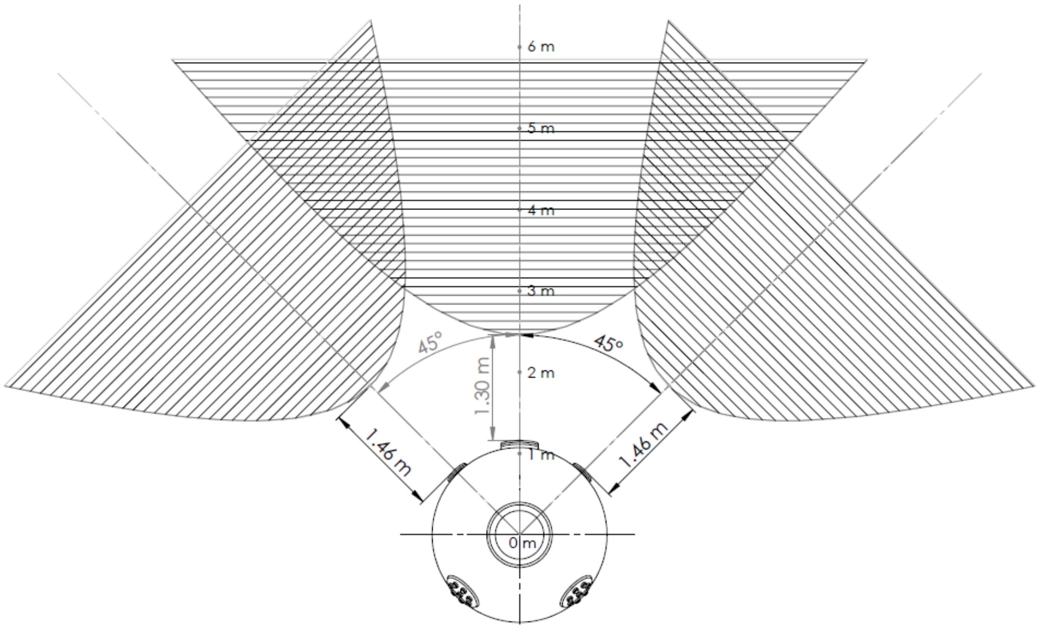

Figure 9 Fields of view of all three viewports on seafloor.

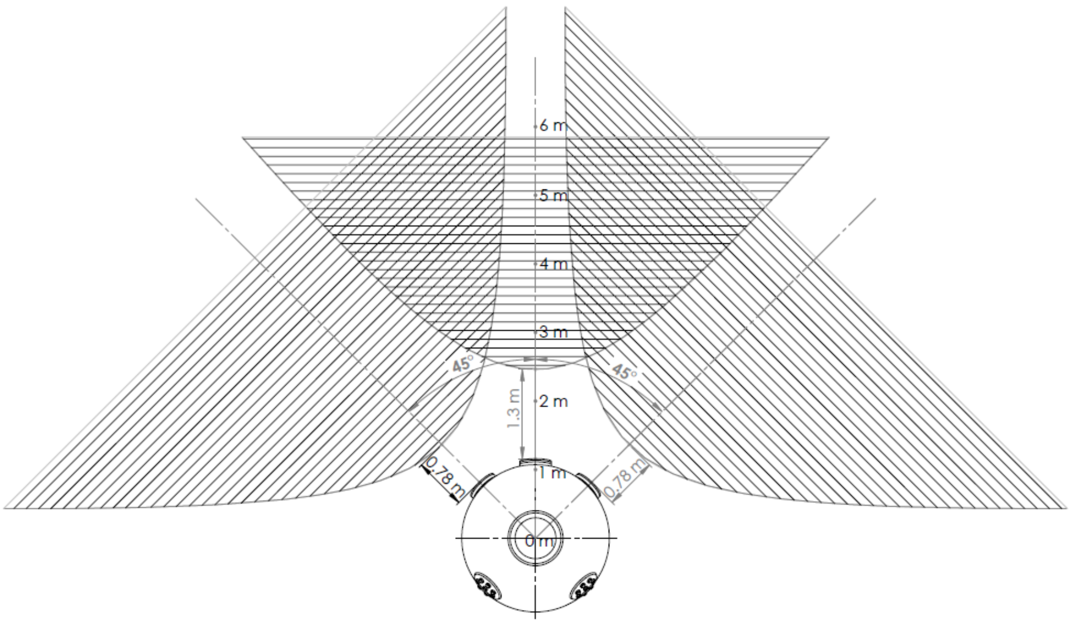

Figure 10 Improved fields of view of all three viewports on seafloor.

7. Reflection and effect of refraction

When the light is incident on the optical surface in air, the percentage of light transmitted depends on the angle of incidence. At 0° incident angle, the light reflected is given by;

$$r = \left(\frac{N' - N}{N' + N}\right)^2 \tag{1}$$

Where, N is the refractive index of the incident medium, and N' is the refractive index of the refractive medium. The acrylic viewport is in contact with air and sea water on inside and outside of the spherical pressure hull, respectively. When the ray is at 0° incident angle, the reflectance of air-acrylic interface is 3.9% and the reflectance of sea water acrylic interface is 0.3%. The percentage of reflections shows that the loss is less outside the hull interface. Anti-reflective coating applied on both high and low-pressure faces of an acrylic conical viewport would reduce the reflectance percentage, this coating also providing scratch resistance (Lones, 1980).

If the range of the view / viewing distance is closer to a thick window at an angle, then there is a considerable amount of distortion, due to refraction. The refractive effect is governed by Snell's law. Snell's law is given below.

$$n_1 \text{ Sin } Ø_1 = n_2 \text{ Sin } Ø_2 = n_3 \text{ Sin } Ø_3 \tag{2}$$

The suffix 1, 2, and 3 indicates air, acrylic, and sea water mediums, respectively. n_1, n_2 and n_3 are refractive indices of air, acrylic, and sea water, respectively. $Ø_1$, $Ø_2$, and $Ø_3$ are incident angle in air, refractive angle in acrylic, and refractive angle in sea water, respectively. It is generally stated that a ray always passes closer to the normal in a denser medium as compared to a ray in a low dense medium, and the refractive index of a yellow colour/line is used to describe the optical properties of most materials. The refractive index of sea water depends on wavelength, pressure, temperature, and salinity (Lones, 1980). An empirical relation for estimating the refractive index of water is given below (McNeil, 1977).

$$N_\lambda = 1.3247 + 3.3 \times 10^3\,\lambda^{-2} - 3.2 \times 10^7\,\lambda^{-4} - 2.5 \times 10^{-6}\,T^2 + (5 - 2 \times 10^{-2}\,T)(4 \times 10^{-5}\,S) + (1.45 \times 10^{-5}\,P)(1.021 - 6 \times 10^{-4}\,S)(1 - 4.5 \times 10^{-3}\,T) \tag{3}$$

Where, N_λ is the refractive index of water at wavelength, λ is the wavelength of light in nm (λ =589 nm), T is the temperature of water in °C, S is the salinity of water in ppt, and P is the pressure of water in bar.

The refractive index of air, sea water, and acrylic plastic are 1, 1.34 (at 20 ºC and 33 % salinity), and 1.5, respectively (ASME PVHO-1, 2016; Carruthers, 1944; Taylor, 1971). The refractive index of acrylic changes with respect to temperature. The light transmittance is almost constant until the angle of incidence is 56°, after which it decreases (Lones, 1980). The effect of refraction on an underwater spherical pressure hull is shown in **Figure 13**.

Sampling is one of the important tasks of manned submersibles using manipulator arms. Assume that an object to be picked up from the seafloor is at 1 m distance from the viewport window. If the ray is at an angle of 25º from the inner sphere of the hull, then the ray is deflected by 16.42º in the acrylic window and, further, is deflected by 18.43º in the sea water. If the object to be picked up is at a distance of 1 m from the viewport window, then the deviation is 148.86 mm. The pilot or observer who is handling the manipulator should have very good engineering judgement while carrying out underwater works. It is observed that if the viewing angle across the window is less, then the distortion is less. The distortion depends on the viewing angle, thickness of the viewport window, and object distance inside the sea water. The refractive index of sea water depends on temperature and salinity. If the temperature reduces, the refractive index of sea water increases, and vice versa; and if the salinity increases, the refractive index increases, and vice versa (Carruthers, 1944).

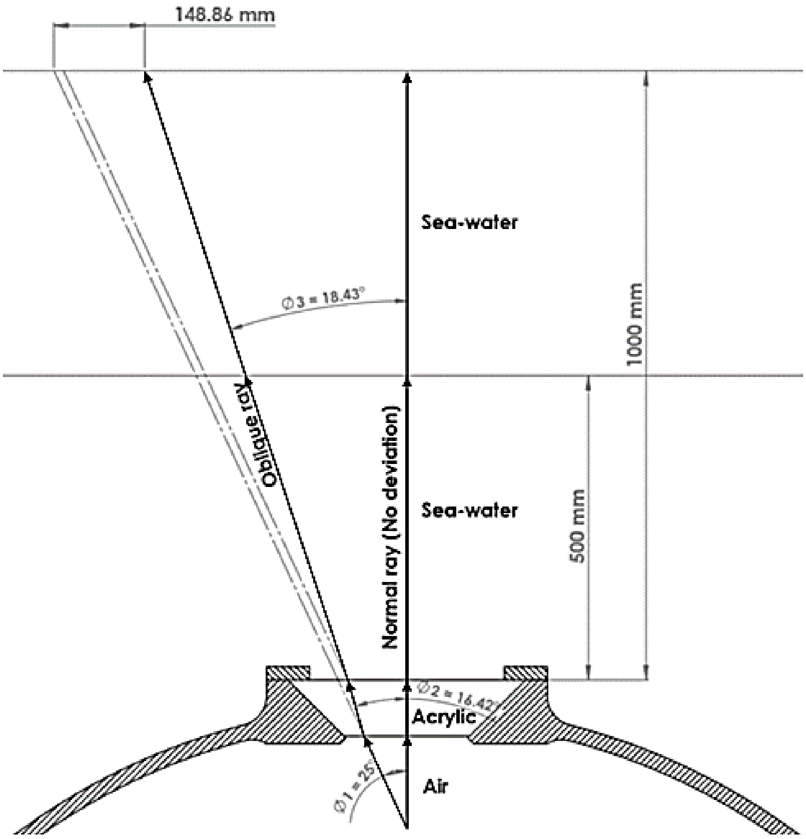

Figure 11 Refractive effect of acrylic viewport window and sea water.

8. Summary and conclusion

The following observations are made during the above investigation.

- The viewing position through acrylic window is different for different persons. Hence, it is recommended to have height adjustable seats as per human engineering standards (Design: Hyperbaric facilities, 2004).
- The distortion depends on the viewing angle, thickness of the viewport window, and object distance inside the sea water.
- The present pressure hull does not cover the side views of the manned submersible. In order to cover the side views, a high-end camera and lights with pan, zoom, and tilt options need to be installed on the manned submersible for better manoeuvring. This side view coverage needs to be addressed in future spherical pressure hull designs.
- The field of view can be improved by increasing the diameter of the viewport and by increasing the angle between the primary and secondary viewports. Minimum overlapping regions in the fields of view of viewports need to be maintained so that two crews can see the objects together which fall in the common field of view. This will aid in sample collection from the seafloor.

A minimum of 50 % of the primary field of view area should overlap, and a 180° field of view should be covered using both the primary and secondary viewports.

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