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1. Is there a classification standard for carbon fiber pressure vessels for human occupancy (PVHO)?

   a. If yes, what are the construction, testing, and inspection standards?
   b. If no, does class rules allow for equivalency standards to be implemented for carbon fiber PVHOs

   ABS Response: The ABS Underwater Rules do not permit the use of carbon fiber composites for PVHOs. To the best of our knowledge, the Rules of other IACS member Class Societies do not include any specific requirements for carbon fiber composite PVHOs.

   While the ABS Rules do have provisions for consideration of alternative arrangements and novel concepts, in the many decades ABS has been classing submersibles and other underwater units, these provisions have not been used for carbon fiber composite PVHOs.

2. Are there any ABS classed carbon fiber PVHOs? Or have there ever been any?

   ABS Response: No, ABS has never classed submersibles or other underwater units that employ carbon fiber composite PVHOs.

3. What materials are allowed to be used from ABS rules for PVHOs?

   ABS Response: The acceptable materials for PVHOs are specified under Section 4/3 of the ABS Rules for Building and Classing Underwater Vehicles, Systems and Hyperbaric Facilities (*ABS Underwater Rules*).

   - For metallic plates, the acceptable materials include:
     - Steel: *ABS Hull Grades E, EH32, EH36; U.S. Navy Grades HY-80 and HY-100 per MILS-16216; ASTM A516 Grades 55, 60, 65, 70; ASTM A537 Class 1 and 2; ASTM A517 Grades A, B, E, F, J*
     - Aluminum: *ASTM B 209 alloy 6061-T6; ASTM B 928 alloys 5083, 5086, 5383, 5456*
     - Titanium Alloys: *ASTM B265 Grade 5*
     - Stainless Steel: *ASTM A240 Type 304 or 316*

   - Metallic materials used for bolts, extrusions, forgings, and shapes are required to comply with a recognized standard and are to be at least of similar quality to the plate materials specified above.

   - Acrylic PVHOs (*e.g., spheres, hyper-hemispheres, cylinders, etc.*): Cast polymethyl methacrylate material per ASME PVHO-1.

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- Note that the ABS Underwater Rules do not list carbon fiber composites as an acceptable material for the pressure boundary of PVHOs.

a. What are the testing requirements for initial certification?

ABS Response: The new construction survey requirements for PVHOs are specified under Sections 4, 5, 6, 8 and 11 of the ABS Underwater Rules. These include the following:

- Material testing and inspection
- Qualification of the weld procedures and welders
- Impact testing of the weld metal
- Post-weld heat treatment
- NDE
- Hydrostatic pressure testing
- Off-gas testing
- Test dive

b. What are the periodic testing requirements for the life of the hull?

ABS Response: The post-construction periodic survey requirements for PVHOs are specified under Section 7-11 of the Rules for Survey After Construction. These include the following:

- Visual examination of the PVHO pressure boundary after removal of protective coatings and thermal insulations in selected locations
- Gauging of the pressure hull, if required
- NDE of highly stressed areas such as lifting lug welds
- Out-of-Roundness measurements, if required
- Test dive

4. Is it possible to conduct periodic NDT on a carbon fiber hull with multiple layers of carbon fiber and equivalent thickness to TITAN's 5-inch hull?

ABS Response: We understand that technologies such as X-Ray Computed Tomography are available for NDE of thick carbon fiber composite sections. In our understanding, UT may not suffice for thick carbon fiber composite PVHOs such as those on the TITAN.

From a practical standpoint, conducting this level of NDE on a periodic basis for composite PVHOs could be challenging due to the following items (*which are not exhaustive*):

- Most likely, one would first need to strip the fully outfitted PVHO to its bare hull configuration (*i.e., remove all equipment and systems, as well as lining, insulation, coverings, etc.*).

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- If the NDE equipment is not readily available on-site, the PVHO may have to be shipped to a specialized facility for the NDE.
- If the NDE identifies PVHO deterioration or damage, then the PVHO may need to be repaired or scrapped.
- Upon completion of the NDE and repairs (*if warranted*), the PVHO would need to be re-outfitted.

Most NDE techniques for composites also often require an initial baseline examination that is used as a reference for comparison during subsequent examinations.

5. If the answer to question 4 is no, what alternative options are available for monitoring the long-term integrity of a carbon fiber hull?

   ABS Response: ABS has no previous experience in classing submersibles or other underwater units with carbon fiber composite PVHOs. Therefore, ABS has no further comments on the alternative options for monitoring the long-term integrity of carbon fiber composite PVHOs.

6. The TITAN submersible had a hull monitoring system consisting of strain gauges and acoustic sensors. Is ABS familiar with these types of active monitoring systems for submersibles or other types of vessels?

   ABS Response: ABS is familiar with the use of strain gauges and acoustic sensors for real time structural health monitoring of surface vessels, and has developed the following publications:
   - ABS Guide for Hull Condition Monitoring Systems, 2020
   - ABS Guidance Notes on Structural Monitoring Using Acoustic Emissions, 2016
   - ABS Guide for Condition Based Program for Government Vessels, 2022
   - ABS Guide for Smart Functions for Marine Vessels and Offshore Units, 2022

   Additionally, ABS is also familiar with the use of industry standards such as ASTM E1932-12 for acoustic emission monitoring.

   Our understanding is that with the exception of the TITAN, the underwater industry has not been employing real time structural health monitoring systems on submersibles or other underwater units. In ABS' experience, such systems have not been used so far on ABS classed submersibles or other underwater units.

7. What is the proper method or class approved inspection procedure for inspecting/ testing carbon fiber?

   ABS Response: For carbon fiber composite PVHOs, there are currently no ABS class requirements for inspection and testing.

   For carbon fiber composite surface vessels, the ABS inspection and testing requirements are outlined under Chapter 6 of the ABS Rules for Materials and Welding (*see attached*).

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8. Does ABS know of any other classification or standards society that issues guidance or classification for carbon fiber, PVHO's?

   ABS Response: To the best of our knowledge, neither the ABS Underwater Rules, nor the Rules of other IACS member Class Societies address carbon fiber composite PVHOs.

   Further, ABS is not aware of industry standards that address carbon fiber composite PVHOs for external pressure applications.

   ABS is aware that a number of ASME Code Cases have been developed for the use of non-metallic materials for PVHOs. Examples include ASME PVHO-1 - Code Case 11, Code Case 12, etc. However, these are for surface based internal pressure applications (*e.g., medical hyperbaric chambers, transfer trunks for diving, etc.*) that operate at relatively mild pressures. (*in the range 4 to 80 psig*)

9. What are acceptable materials used for viewports of PVHO's

   ABS Response: The only acceptable material per Section 4/3 of the ABS Underwater Rules is cast polymethyl methacrylate that meets the requirements of ASME PVHO-1.

   a. To what degree shall they be tested.

   ABS Response: For new construction acrylic windows, the detailed testing and inspection requirements are specified under Section 2 of the ASME PVHO-1 Standard. This includes material testing, pressure testing, as well as inspection for manufacturing defects and flaws.

   For in-service acrylic windows, the detailed testing and inspection requirements are specified under Section 2 of the ASME PVHO-2 Standard. This includes inspection for in-service damage, as well as testing for window life extension.