Pressure Hull Requirements for Passenger Submersibles

[redacted]
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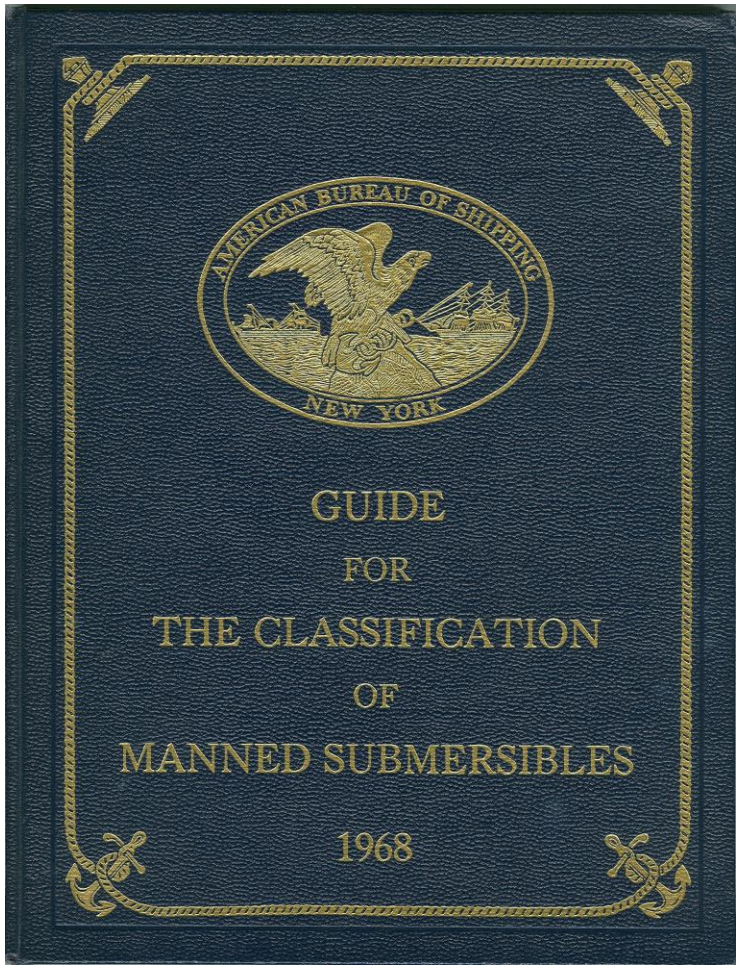
Presentation Outline

- Classification and Class Societies
- ABS Experience with Underwater Units
- Submersible Rules, Regulations and Standards
- Carbon Fiber Pressure Hulls

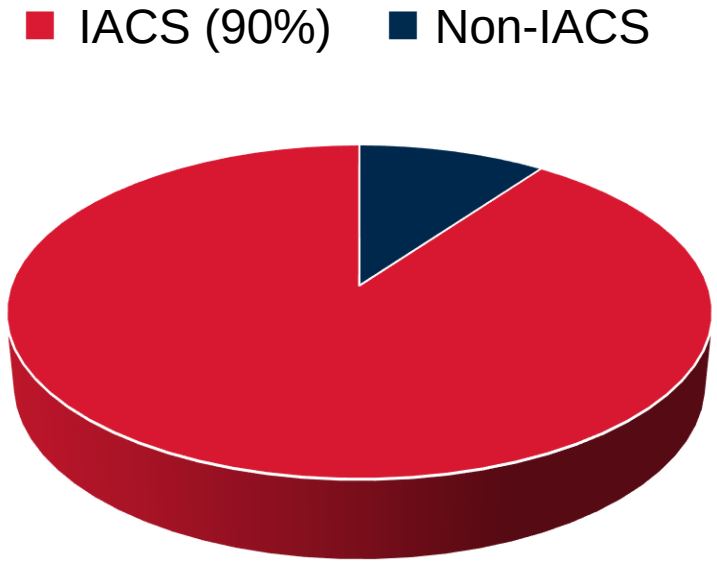


ABS Guide for the Classification of Manned Submersibles (*1968*)

Classification and Class Societies

Classification Societies

- More than 50 organizations around the world offer classification services.
- 12 Class Societies, including the American Bureau of Shipping (ABS), are members of the International Association of Class Societies (IACS).
- IACS' Mission is to establish, review, promote and develop minimum technical requirements in relation to the design, construction, maintenance and survey of ships and other marine related facilities, and,
- IACS also works to assist international regulatory bodies and standard organizations to develop, implement and interpret statutory regulations and industry standards in ship design, construction and maintenance with a view to improving safety at sea and marine environmental protection.



Worldwide Maritime Tonnage

Role of Classification Societies

- In most countries, only Classification Societies can "*class*" submersibles, ships and offshore facilities.
- The role of classification has been recognized by the International Maritime Organization (IMO) in the *Safety of Life at Sea (SOLAS) Convention*, as well as other international conventions.
- Classification Societies also act as Recognized Organizations (*ROs*) performing statutory inspections on behalf of Flag Administrations.

Classification Process

- As described in Part 1A of the ABS Rules:

1 Process *(1 November 2004)*

The Classification process consists of

a) The development of Rules, Guides, standards and other criteria for the design and construction of marine vessels and structures, for materials, equipment and machinery,

b) The review of design and survey during and after construction to verify compliance with such Rules, Guides, standards or other criteria,

c) The assignment and registration of class when such compliance has been verified, and

d) The issuance of a renewable Classification certificate with annual endorsements valid for five years.

The Rules, Guides, and standards are, in general, developed by the International Association of Classification Societies and by ABS staff, and passed upon by committees made up of naval architects, marine engineers, shipbuilders, engine builders, steel makers and by other technical, operating, and scientific personnel associated with the worldwide maritime industry. Theoretical research and development, established engineering disciplines, as well as satisfactory service experience are utilized in their development and promulgation. ABS and its committees can act only upon such theoretical and practical considerations in developing Rules, Guides, and standards.

Representations as to Classification

- As described in Part 1A of the ABS Rules:

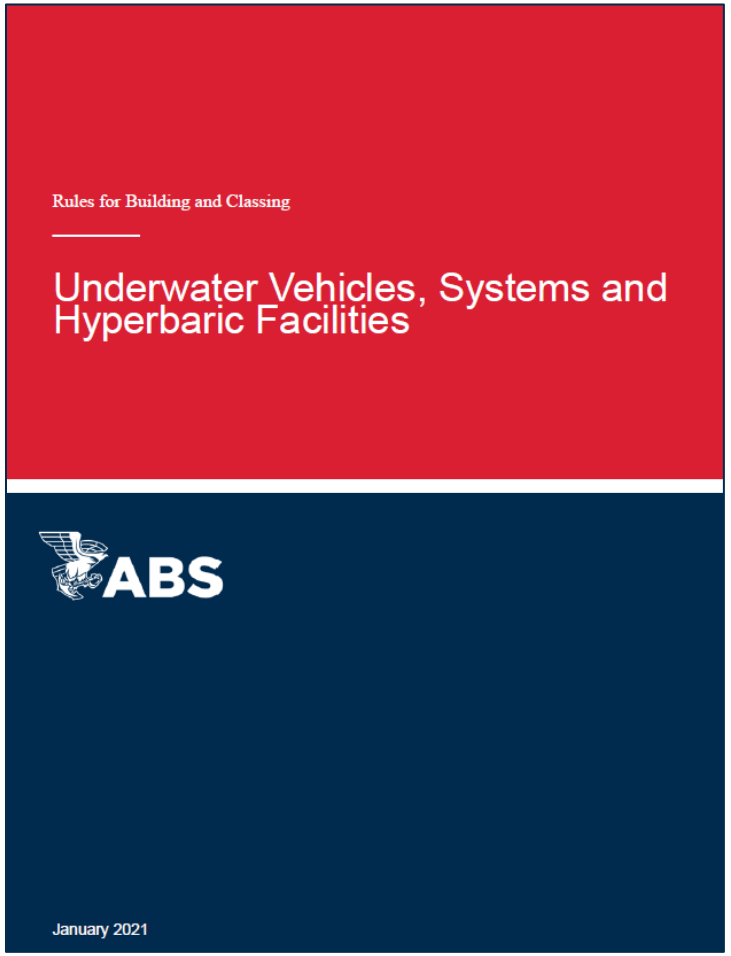
5 Representations as to Classification *(1 August 2011)*

Classification is a representation by ABS as to the compliance with applicable requirements of the Rules, Guides, and standards. The Rules, Guides, and standards of the American Bureau of Shipping are not meant as a substitute for the independent judgment of professional designers, naval architects, marine engineers, Owners, operators, masters, and crew, nor as a substitute for the quality control procedures of shipbuilders, engine builders, steel makers, suppliers, manufacturers, and sellers of marine vessels, materials, machinery, or equipment. ABS, being a technical society, can only act through Surveyors or others who are believed by it to be knowledgeable and competent.

ABS represents solely to the vessel Owner or other client of ABS that when assigning class, it will use due diligence in the development of Rules, Guides, and standards, and in using normally applied testing standards, procedures, and techniques as called for by the Rules, Guides, standards, or other criteria of ABS for the purpose of assigning and maintaining class. ABS further represents to the vessel Owner or other client of ABS that its certificates and reports evidence compliance only with one or more of the Rules, Guides, standards, or other criteria of ABS in accordance with the terms of such certificate or report. Under no circumstances whatsoever are these representations to be deemed to relate to any third party.

The Classification Process for Submersibles

1. **Rule Development**: Establish and maintain recognized technical standards known as the “Rules”.
2. **Design Review**: Check that the design of the submersible is in compliance with the Rules.
3. **Material and Equipment:** Certify material and equipment that will be incorporated into the vessel complies with Rule requirements.
4. **New Construction Surveys**: Check that the submersible is built and tested per the Rules.
5. **Surveys After Construction**: Check that the submersible is maintained in compliance with the Rules throughout its life-cycle.



ABS Underwater Rules
(Source: ABS website www.eagle.org)

ABS Experience with Underwater Units

ABS Experience with Underwater Units

- Since the 1960s, ABS has classed around 100 submersibles worldwide.
- Currently, ABS has 30 submersibles in class.
- Other underwater units currently classed worldwide with ABS include:
  - 43 Saturation, Mixed Gas and Air Diving Systems
  - 1 Submarine Rescue System - Handling System
  - 1 Undersea Habitat
  - 3 Hyperbaric Facilities

ABS Experience with Underwater Units

- **OceanGate TITAN Submersible**
  - No ABS involvement with the Titan submersible.
  - No Request for Classification (*RFC*) submitted to ABS.
  - No design review or surveys conducted by ABS.

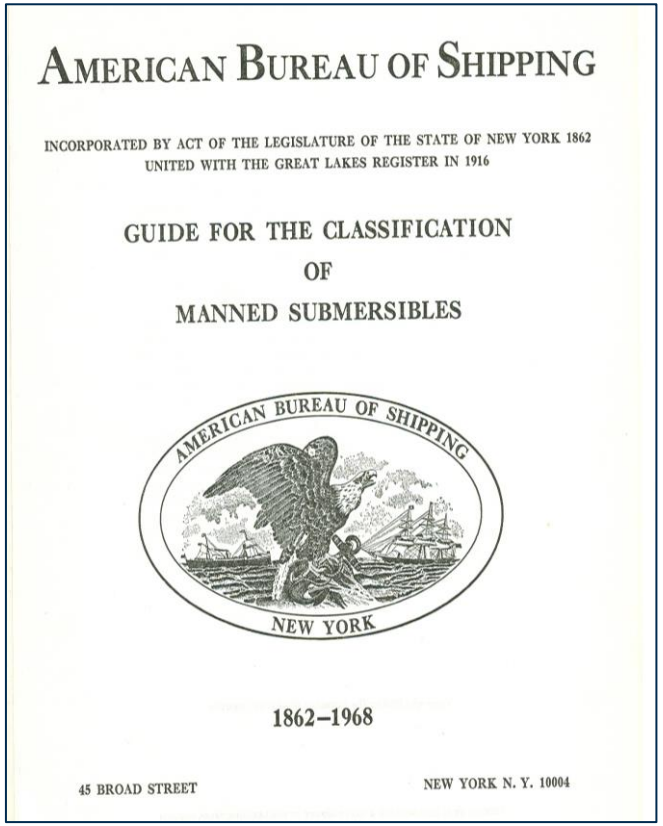
ABS Experience with Underwater Units

- **ANTIPODES Submersible**
  - Built in 1973 as the diver-lock out submersible **PC-1501** by Perry Submarine Builders. New construction submersible was classed with ABS.
  - Submersible has a steel pressure hull (*ASTM A537 Class 1*) and is designed for a depth of 305 MSW (*1,000 FSW*). Operated for several years in the North Sea oil fields of Europe transporting commercial divers.
  - Sold in 1988. Major modifications conducted during 1995 to 1997 under ABS survey. Converted to a 5-person submersible. Included removal of the diver-lockout compartment. Submersible rechristened as the **XPC-15**.
  - Sold in 1999 and renamed as the **ANTIPODES**.
  - Modifications conducted in 1999 under ABS survey to increase the electrical and life support capacity. Subsequently, this submersible conducted tourist dives in Milford Sound, New Zealand. Maintained ABS class during this period.
  - Purchased by OceanGate in 2009 as an ABS classed submersible.
  - Sold in January 2024.

Submersible Rules, Regulations and Standards

ABS Underwater Rules / Guides

- ***ABS Guide for the Classification of Manned Submersibles*** *(1968)*
  - Pioneering document - first set of published requirements for manned submersibles offered by any Class Society.
  - Development of this document was requested by the U.S. Navy, U.S. Coast Guard and the commercial industry.
- Updated and published as the ***ABS Rules for Underwater Systems and Vehicles*** in 1979.
- Updated and published as the ***ABS Rules for Building and Classing Underwater Vehicles, Systems and Hyperbaric Facilities*** in 1990.
  - *Incorporated additional requirements for passenger submersibles*.
- Latest edition of these rules is the ***ABS Rules for Building and Classing Underwater Vehicles, Systems and Hyperbaric Facilities, 2024***.


AMERICAN BUREAU OF SHIPPING

INCORPORATED BY ACT OF THE LEGISLATURE OF THE STATE OF NEW YORK 1862
UNITED WITH THE GREAT LAKES REGISTER IN 1916

GUIDE FOR THE CLASSIFICATION
OF
MANNED SUBMERSIBLES

AMERICAN BUREAU OF SHIPPING
NEW YORK

1862–1968

45 BROAD STREET
NEW YORK N. Y. 10004

ABS Guide for the Classification of Manned Submersibles (1968)

Pressure Hull Materials

ABS Rule Requirements

- Pressure hulls of submersibles are to be fabricated from materials produced to an approved material specification.
- **Approved Materials**:
  - Steel: ABS Hull Grades E, EH32, EH36; U.S. Navy Grades HY-80 and HY-100 per MIL-S-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
  - Acrylic Plastics: Cast Polymethyl Methacrylate (ASME PVHO-1)
- Note: *Carbon fiber composites are not included in the list of ABS Rule approved materials for pressure hulls of submersibles.*

Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?*

- **Material Considerations**
  - Carbon fiber composites are anisotropic materials (*i.e., materials whose mechanical properties vary with direction*).
  - Carbon fiber is weak in compression and strong in tension. Epoxy is strong in compression and weak in tension. The strength of the carbon fiber composite (*i.e., carbon fiber strands set in an epoxy matrix*) is a combination of these two.
  - Does not exhibit ductility or plasticity similar to steels. When loaded beyond its limits, the composite can fail catastrophically without much warning.
  - Prolonged exposure to UV radiation (*e.g., sunlight*) can cause the epoxy in carbon fiber to break down, leading to cracking or crumbling.
  - Susceptible to fatigue failure under repeated external pressurization / depressurization. (*Accumulated damage due to repeated pressurization can remain hidden and may not be readily visible*)
  - Sensitive to local damage (*e.g., cut on the surface from a mechanical impact can form a stress raiser*)
  - Saltwater ingress in the epoxy matrix under extreme external pressures can lead to delamination.

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Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?*

- **Fabrication**
  - Thick sections of carbon fiber composites with consistent mechanical properties are notoriously difficult to manufacture due to the filament winding of multiple layers over a long period of time and the curing of these layers at different rates.
  - Mechanical properties of the finished product (*i.e., composite*) depend on numerous factors including:
    - *Number of layers and thickness*
    - *Winding orientation (X-cross, hoop, etc.)*
    - *Winding tension*
    - *Type of epoxy*
    - *Epoxy wetting rate*
    - *Epoxy cure rate, direction and profile*
    - *Humidity*
    - *Temperature*
    - *Pressure*
  - Manufacturing defects such as Voids, Blisters, Porosity can weaken the composite sections and can accelerate collapse of the pressure hull under external pressure. The acceptance criteria for these defects need to be defined. (*Note: Immense water pressure at depth can exacerbate these defects*).
  - Bonding of carbon fiber composites and metallic elements poses challenges. Co-lamination using fins or other projections from the metallic material into the carbon fiber may be needed. Additionally, in the presence of saltwater, the metal may corrode if it is galvanically coupled to the carbon fiber.

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Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?*

- **Fabrication**
  - As carbon fiber composites have low resistance to impact loads and the hull is susceptible to deformation under applied external loading, hence lifting lugs and other attachments are generally not directly installed on the pressure hull.
  - Installation of penetrations on carbon fiber pressure hulls may weaken the hull if not adequately reinforced or supported.
  - The design and fabrication of carbon fiber composites should take into consideration in-service failure modes under sustained external pressure conditions, as well as repeated pressure cycling. These include:
    - *Delamination*
    - *Debonding*
    - *Fiber Breakage*
    - *Matrix Cracking*

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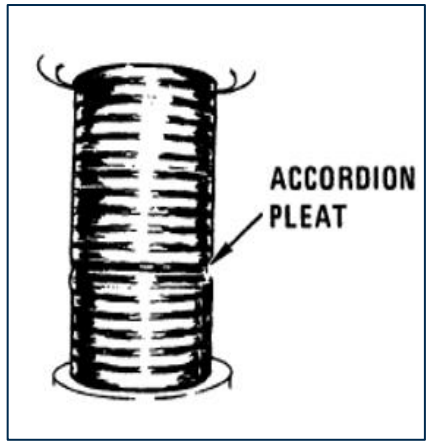
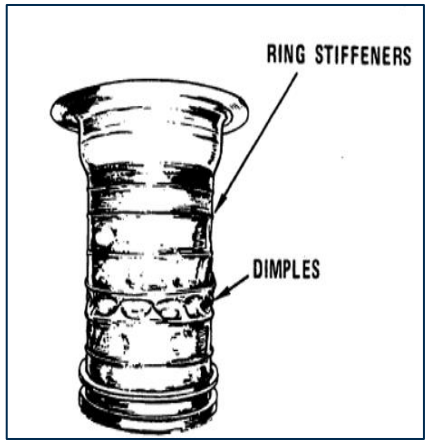
Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?* (*Continued*)

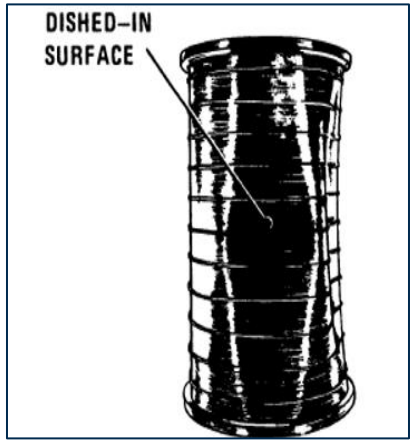
- **Design**
  - For metallic pressure hulls, there are well established failure modes and factors of safety that have been proven over many years of service experience.



Local Yielding



Local Buckling



General Instability

  - Additionally, the acceptance criteria for hull out-of-roundness and local departure from design geometry are well established for metallic pressure hulls.

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Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?* (*Continued*)

- **Design**
  - Currently, there are no recognized national / international standards for carbon fiber pressure hulls for submersibles that define aspects such as the failure modes to be addressed, the minimum factors of safety and the criteria for hull out-of-roundness and local departure from design geometry.
    - *Examples of these failure modes include collapse of the carbon fiber pressure hull due to snap-through bucking that is triggered by shape imperfections*.
  - As carbon fiber composites are anisotropic, have mechanical properties that are manufacturing process dependent, and are susceptible to manufacturing defects (*e.g., voids, porosity and blisters*), hence the mechanical properties for the design analysis (*e.g., Finite Element Analysis*) of the pressure hull would need to be determined through extensive testing using coupons from the as-built composite sections.
    - *Otherwise, the mechanical properties of the component being designed may not match that of the as-built product, leading to an incorrect pressure rating for the pressure hull.*

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Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?* (*Continued*)

- **Nondestructive inspection (NDI) of Thick Carbon Fiber Sections**
  - Nondestructive inspection (NDI) of thick carbon fiber sections (*e.g., 5-inch thick*) with multiple layers poses challenges. Ultrasonic examination may not suffice due to lack of penetration of the ultrasonic waves.
  - For thick carbon fiber sections, NDI technologies such as X-Ray Computed Tomography are more effective. From a practical standpoint, conducting this level of NDI on a periodic basis for carbon fiber pressure hulls could be challenging due to the following items (*which are not exhaustive*):
    - Most likely, one would first need to strip the fully outfitted pressure hull to its bare hull configuration (*i.e., remove all equipment and systems, as well as lining, insulation, coverings, etc.*).
    - If the NDI equipment is not readily available on-site, the pressure hull may have to be shipped to a specialized facility for the NDI.
    - If the NDI identifies deterioration or damage, then the pressure hull may need to be repaired or scrapped.
    - Upon completion of the NDI and repairs (*if warranted*), the pressure hull would need to be re-outfitted.
    - Most NDI techniques for composites also often require an initial baseline examination that is used as a reference for comparison during subsequent examinations.

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Carbon Fiber Pressure Hulls

Q.) *What are the key concerns with carbon fiber pressure hulls for submersibles?* (*Continued*)

- **Post-Construction Inspection and Testing Criteria**
  - For composite pressure hulls in-service, it is important to verify that no out-of-specification deformation, degradation or flaw development is taking place that may weaken the pressure hull.
  - The post-construction inspection and testing criteria for carbon fiber pressure hulls over their entire service life is currently not addressed in recognized national / international standards. As a minimum, this should include:
    - *Nondestructive Inspection (NDI) criteria*
    - *Dimensional measurement criteria for out-of-roundness and local departure from design geometry*
    - *Periodic test dive requirements*

Carbon Fiber Pressure Hulls

Q.) ***Do existing Class Society rules, statutory regulations or industry standards address carbon fiber pressure hulls for submersibles?***

- Under the ABS Underwater Rules, carbon fiber composites are not approved materials for the pressure hull of submersibles.
- To the best of our knowledge, the existing statutory regulations, industry standards and Rules of other IACS member Class Societies do not include any specific requirements for carbon fiber composite pressure hulls.
- A number of ***ASME PVHO Cases**** have been developed for the use of non-metallic materials for pressure vessels for human occupancy (PVHOs):
  - Examples include ASME PVHO Case #11, 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*)

* *Note: An **ASME PVHO Case** is a document developed by the designer / builder and approved by the American Society of Mechanical Engineers (ASME) - Pressure Vessels for Human Occupancy (PVHO) Standards Committee that provides alternative requirements to those specifically indicated in the ASME PVHO Standard due to the use of new technology, materials, or other special circumstances.*

Carbon Fiber Pressure Hulls

Q.) ***Do class rules allow for the use of alternative requirements or equivalent standards for carbon fiber PVHOs?***

- While the ABS Rules do have provisions for consideration of alternative arrangements and novel concepts, these provisions have not been used for carbon fiber composite pressure hulls in the many decades ABS has been classing submersibles and other underwater units.
- When non-standard designs, materials or construction techniques are intended to be used, one of the options available in the industry is to develop an ***ASME PVHO Case**** following the guidelines outlined under *Non-Mandatory Appendix D of the ASME Safety Standard for Pressure Vessels for Human Occupancy (PVHO-1).*

* *Note: An **ASME PVHO Case** is a document developed by the designer / builder and approved by the American Society of Mechanical Engineers (ASME) - Pressure Vessels for Human Occupancy (PVHO) Standards Committee that provides alternative requirements to those specifically indicated in the ASME PVHO Standard due to the use of new technology, materials, or other special circumstances.*

ASME PVHO Standard

<u>Non-Mandatory Appendix D of ASME PVHO-1</u> (*for non-standard designs and materials*)

- Requires detailed information on the proposed materials, along with a detailed design analysis considering all applicable loads and environmental conditions.
- **Prototype Testing**:
  - **Proof Pressure Testing**: *3 full-scale pressure hulls to be pressure tested to 6 times Maximum Allowable Working Pressure (MAWP) without failure.*
  - **Creep Testing**: *Model or full-scale pressure hulls to be subject to 10,000 hours (1 year and 1-1/2 months) of sustained pressurization without failure. Options including testing 1 pressure hull to 3 times MAWP or 5 pressure hulls to 2 times MAWP.*
  - **Cyclical Pressure Testing**: *Full-scale pressure hull to be cyclically pressure tested over multiple pressure cycles to MAWP. The number of approved operational cycles would then be limited to half the number of cycles tested minus 1,000 cycles.*
- **Production Proof Testing**: The production unit (*i.e., actual pressure hull*) to be subjected to a hydrostatic pressure test of 1.5 times MAWP for 1 hour.
- **Third-Party Witnessing of the Testing**: All testing is to be witnessed and signed-off by an independent third-party agency *(e.g., a Class Society*).

Hydrostatic Pressure Testing of Pressure Hulls

ABS Rule Requirements

- Externally pressurized hulls to be externally hydrostatically proof tested to a pressure equivalent to a depth of 1.25 times the design depth for 2 cycles.
- For external proof testing, triaxial strain gauges are to be fitted in-way of hard spots and discontinuities.
  - *Location of strain gauges and the maximum values of stress permitted by the design at each location to be submitted for approval prior to testing.*
  - *Strain gauge measurements to be recorded after shakedown effects have ceased.*
  - *Designer to submit a report comparing the calculated stresses versus the measured stresses, in order to validate the design of the pressure hull.*
- Following the hydrostatic pressure test:
  - The pressure hull welds are to be non-destructively examined.
  - Out-of-roundness measurements to be taken and reviewed to verify compliance with the acceptance criteria. These measurements are retained as reference values for the life of the submersible.

Test Dive for New Construction Submersibles

ABS Rule Requirements

- A manned test dive to the design depth is to be conducted on the fully outfitted submersible in the presence of the Surveyor.
- The submergence is to be increased in increments of approximately 20 percent of the design depth until the design depth is reached.
- At each 20 percent increment, constant depth is to be maintained, and the hatches, penetrations, and welded joints are to be inspected, and the operation of the pressure boundary valves is to be checked.
- The test dive is also to demonstrate satisfactory performance of life support systems, propulsion systems, electrical systems, and other essential systems at full depth.

Post-Construction Surveys

- **Examination of the Pressure Hull**
  - **Annual Surveys**: Requires visual examination of the hatches, sealing surfaces, penetrations, welded joints, viewports, foundations, attachments, frames, lifting lugs, and shut-off valves on the pressure hull.
  - **Special Periodical Surveys**:
    - Requires visual examination of the pressure hull after removal of protective coatings and thermal insulation in selected locations. Highly stressed parts such as lifting lugs and their welds to be non-destructively examined.
    - Measurements for out-of-roundness and local departure from design geometry may be required to verify that the pressure hull has maintained its original dimensions. Measurements to be compared with the reference measurements for the new construction pressure hull.
- **Test / Operational Dive**
  - **Annual Surveys**: Operational dive to be conducted annually, and all systems are to be operationally tested.
  - **Special Periodical Surveys**: Full depth test dive to be conducted in the presence of the Surveyor. Demonstrate proper functioning of systems / equipment at full depth.

IMO Submersible Guidelines

- Developed to provide an international standard for passenger submersibles, so as to facilitate their safe international movement and assure passenger safety.
- Compliance with these Guidelines is voluntary unless required by the Flag Administration or the Coastal State. (*Compliance with these Guidelines not mandated under the International Maritime Organization (IMO) - Safety of Life at Sea (SOLAS) Convention*)
- Requires the pressure hull materials, design, fabrication and testing to comply with the requirements of a Recognized Organization to the satisfaction of the Administration.
- Requires the issuance of a ***Design and Construction Document*** by the Administration. This document is to list the standards used in the design and construction of the pressure hull and other key components and systems.
- Requires the issuance of a ***Safety Compliance Certificate*** by the Administration after initial survey of the passenger submersible.
- Requires the management of passenger submersible operations to comply with the ***International Safety Management (ISM) Code***.

USCG NVIC 5-93

- Provides guidance for the certification of passenger submersibles that fall under the purview of 46 CFR Subchapter T - Small Passenger Vessels (under 100 gross tons).
- Applies to submersibles that carry one or more passengers for hire (*per H.R.1159 - Passenger Vessel Safety Act of 1993*)
- Requires the pressure hull to meet the ASME PVHO Standard or ABS Underwater Rules.
- Applies to U.S. flagged submersibles or submersibles operating under U.S. jurisdiction. (*Does not apply to non-U.S. flagged submersibles operating in international waters*)

Thank You

www.eagle.org