History of Submarine Composites

The use and contemplated use of composite materials for major submarine components has a rich history within the U.S Navy. Indeed composite materials were once considered the likely choice for building submarine hulls that are subjected to massive compressive loads at extreme depths. As early as the 1960s, cylindrical models were being built and tested in an effort to build a pressure hull with a strength-to-weight ratio superior to high-strength steel. In a 1966 article published in *Marine Technology*, J.A. Kies surmised "that no type of material has improved as rapidly as reinforced plastic and that, given the necessary funding and research effort, reinforced plastic material suitable for deep research submersibles will be available in five years." Owing to the end of the Cold War, a composite combatant submarine hull has ever been produced, although research submarines have been. However, critical components external to the pressure hull have been in service for decades.

Daniel Spurr in his fact-filled book *Heart of Glass*, which is a must read for anyone building fiberglass boats today, points to a small, two-man submarine called "the Toy" that had two 15-inch watertight spheres made of fiberglass as "among man's earliest creations in fiberglass" according to Art Javes who developed the sub for the Office of Strategic Services during World War II. Spurr goes on to show that before the late 1950s, only a handful of builders were producing small runabouts in fiberglass.

In 1954 the U.S. Navy developed a fiberglass replacement for the aluminum fairwaters that were fitted on submarines. The fairwater is the hydrodynamic cowling that surrounds the submarine's sail. The motivation behind this program was electrolytic corrosion and maintenance problems. The laminate used consisted of style 181 Volan glass cloth in a general purpose polyester resin that was mixed with a flexible resin for added toughness. Vacuum bag molding was used and curing took place at room temperature.

The fairwater installed on the ***U.S.S. Halfbeak*** was examined in 1965 after 11 years in service. After performing testing on portions of the laminate, the conclusion that the materials were not adversely affected by long term exposure to weather was reached. Flexural strength and stiffness values were near 90% of original values. A detailed analysis of the component indicated that a safety factor of four was maintained throughout the service life of the part. The navy stopped using the GRP fairwater design when icebreaking capability became a requirement. However, the practice of utilizing composite materials for submarine bow domes developed just two years after the fairwaters in 1956 is with us today, fifty years later.

Submarine Bow Domes

Composite construction is now the material of choice for sonar domes on surface ships and submarines. The domes provide a smooth flow around sonar transducers and protect the transducers from impact damage. Domes on submarines are truly massive structures that can measure almost 34 feet across and weigh over 43,000 pounds, as they are built to match the hulls cross section shape. The domes are water-filled, so they are not subjected to the tremendous compressive loads that the pressure hull sees. Even so, demanding performance requirements are imposed on submarine bow dome structures.

The domes must have a high degree of acoustic transparency. To avoid signal distortion, stiffeners are undesirable. Early sonar domes were made with polyester resin and alternate plies of woven roving and mat E-glass. Minimizing void content was also paramount, both to improve acoustic transparency and overall part strength.

In 1966, Captain Heller of the U.S. Navy provided a concise history of sonar dome early development. "Investigation of material properties indicated that good sonar transmission at various frequencies was achievable with glass-reinforced plastics. When this attribute is coupled with weight-saving, freedom from maintenance and corrosion, and ease of fabrication of complex shapes, there is little wonder why there was early interest in using GRP in place of rubber and steel for sonar domes."

The U.S. Navy was quick to realize the advantages of GRP and fielded 54 domes in 1954 on an experimental basis. Captain Heller reported that only one of these failed, which isn't bad considering the state-of-the-art of composite construction in 1955. A larger dome built without stiffeners was next outfitted on the ***U.S.S. Albacore*** (AGSS 569), with excellent service being reported.

Heller goes on to report "After several abortive attempts to produce a plastic dome with plastic ribs for the U.S.S. Nautilus (SSN571), the structural problems were solved by designing and installing a composite dome – steel trusses for ribs with a GRP skin. This composite dome proved to be eminently satisfactory, both structurally and acoustically, during Nautilus's history-making voyage under the North Pole. This success led to several similar installations."

In the late 1960s, the ***Sturgeon*** class submarine (SSN-637) marked its appearance as the preeminent response to the Soviet submarine threat. The ***Sturgeon*** class submarines were built specifically for anti-submarine warfare. "Alongside the fact that it was quiet, a 637's large, spherical, bow sonar array gave its crew a wider angle view in both azimuth and elevation of its target than available on previous submarine. This effectively removed a set of blinders which constrained the field of regard to a narrow cone looking forward. The 637s made it feasible to develop tactics for routine, covert tracking operations that could be implemented on a force-wide basis. The ***USS Sturgeon*** (SSN-637), the lead ship of a 37-unit class, was commissioned in 1967. While almost all Cold War operations remain classified, recently declassified missions show that in 1978, USS Batfish (SSN-681) tracked a Soviet ballistic missile submarine (SSBN) sailing off the East Coast of the U.S." (www.GlobalSecurity.org)

Starting with the 637, bow domes needed to take a quantum leap in both structural and acoustic performance to meet engineering objectives. This is when HITCO jumped in and began their long run of being the exclusive builder of submarine bow domes in the U.S. According to their web site, HITCO's business in 1961 was 61% aerospace (Atlas, Minute Man, Titan, Polaris, Surveyor, Nike-Zeus, etc.). They also built the outer hull sections of the Navy's first Deep Submergence Rescue Vehicle (DSRV mini sub). Launched in 1970, this submarine hull consists of two HY-140 steel spheres surrounded by a fiberglass outer hull. Key to being able to build high quality parts for submarines was HITCO’s investment during the late 60's in the first Terminal Island autoclave and lay-up fixtures for the 637 and 688 domes. This enabled bow domes to be built using prepreg material, which greatly increased part strength and reduced void content.

In the mid 1980s a major research and qualification program to develop a high impact resistant (toughened) glass epoxy material system was conducted. In June of 1986, the following prepreg systems were qualified for submarine use under this program: U.S Polymeric 1583/E719LT; American Cyanamid Cycom 5920/1583; 3M SP 365/1583 and Fiberite MXB 7780/1583. Extensive mechanical testing and workability evaluation was done to qualify these products.

The Goodrich Corporation also has over 35 years of experience building sonar domes for the navy and recently inherited the submarine work from HITCO. They were selected by Northrop Grumman Newport News to supply six Virginia class submarine sonar bow domes at a rate of one per year beginning in 2005. This is the second order for bow domes received from Northrop Grumman Newport News in the past three years. The first order was awarded in August 2001 for three bow domes. The bow domes are manufactured at Goodrich's Engineered Polymer Products division in Jacksonville, Florida. Goodrich has also experimented with a Vacuum Assisted Resin Transfer Molding (VARTM) process for submarine bow domes, infusing a demonstration piece that weighed over 50,000 pounds.

Periscope Fairings

While bow domes may represent the largest manufacturing challenge for submarine composites, periscope fairings presented the navy with ongoing logistics concerns. Submarine periscope and antenna masts have foil-shaped fairings that have traditionally been made of GRP. The masts are all composite but the periscopes have a K-Monel “I-beam” structural core. The fairings are two-piece with a line of countersunk fasteners running up both sides of the fairings. Periscope fairings have been built of FRP since the early 1960s by Lunn Industries. These autoclave-cured parts are precision machined to meet the tight tolerances required of the periscope bearing system. The fairings are all glass, with a recent switch from polyester to epoxy resins. The post machining of the fairings and exposed edges around the fasteners makes the fairings susceptible to water uptake.

An RTM manufacturer, ARDCO of Chester, PA investigated the feasibility of building the entire structure as a monolithic RTM part, thereby eliminating the metal “I-beam” and bolted sections. Carbon fiber unidirectionals were proposed to match the longitudinal stiffness of the incumbent structure. Although never funded beyond a Small Business Innovative Research (SBIR) Phase Two effort, in the United Kingdom, Thompson Marconi Sonar offers a one piece molded GRP non hull penetrating mast. They claim low life cycle cost and half the weight of steel masts.

Pressure Hulls
In the early 1960s, a large R & D program was initiated by the US Navy's Bureau of Ships (now NAVSEA) to develop GRP for pressure hulls of research submersibles operating to depths of 20,000 feet. In a 1975 article in the *Naval Engineers Journal*, William Garner writes "The total program spanned ten years at a cost of about six million dollars, including the broad development of materials and structures technology. Cylindrical and spherical vessels, filament-wound of S-glass in an epoxy resin, were fabricated and tested. The program was terminated in 1972 as national priorities in oceanographic research and interest in deep-diving vehicles changed. However, during this program many significant state-of-the-art developments were effected in materials, processing, nondestructive testing, and structural analysis. Also, from this program the knowledge of the behavior of composite materials was greatly expanded."

Not surprisingly, HITCO was at the center of this early research, building filament-wound models that were pressure tested to failure. Myers and Fink, report in the April, 1965 issue of the *Naval Engineers Journal* that: "HITCO [has been exploring] the feasibility of using filament-wound, glass-reinforced plastics as a structural material for pressure hulls of deep-diving submersibles. Much of this work was conducted in conjunction and close coordination with programs of a similar nature performed at the David Taylor Model Basin (DTMB). Static and fatigue properties were investigated, unstiffened, ring-stiffened, and sandwich cylinder designs were studied, and closures, penetrations and joint design concepts were developed."

In the early 1990s, the Advanced Research Projects Agency funded research on thick sectioned composites for submersibles, both with thermosets and thermoplastic (PEEK) materials. The goal was to develop "a reliable, cost effective, proven construction capability for a full-scale, thick section, proof-of-concept, Man Rated Demonstration Article (MRDA) which is seen as a required step before prototype submarine construction. The completion of the MRDA program deliver[ed] preliminary design criteria, inspection and repair standards, material specification and large thick composite structure manufacturing methods that have been validated through proof-of-concept design/manufacture." As reported by George Leon, et. al. at the 1993 *Marine Composites Symposium* in Savannah, GA.

Other Applications of Composites on Submarines
With the ambitious title "Composite Hull for Full Ocean Depth," R.E. Garvey tells us in 1989 of an advanced Autonomous Underwater Vehicle (AUV) designed to operate at a depth of 20,000 feet. At about the same time, the U.S. Navy established the Advanced Submarine Research and Development Office (SEA 92R). Congress had moved money to the Defense Advanced Research Projects Agency (DARPA) in 1987 to further submarine advanced technology. The navy was determined to take the lead on developing new technologies for the upcoming SSN21/***Seawolf*** attack submarine. At a 1990 National Academy of Sciences conference on the "Use of Composite Materials in

Load-Bearing Marine Structures," Rear Admiral Thomas Evans, Director of SEA 92R outlined the following applications that were being pursued:

Propulsion Shaft
A thick-sectioned, filament wound tube was developed that resulted in a cost-effective, fatigue-resistant propulsion shaft. The section of the shaft between the first inboard coupling and the propeller will be tested in demonstrations aboard the Memphis.

Control Surfaces
This demonstration focuses on hydrodynamically loaded structures, initially fairwater planes, to be tested on the Memphis. Construction employs a simple box spar for stiffness and syntactic foam cells to provide the correct hydrodynamic form.

Air Flasks
This is a straightforward application aimed at weight reduction. Most of the sub-scale testing was completed under ONT technology block programs. The primary remaining issue is service life.

Engine Room Composites Applications
The project goal was to develop generic design technology for machinery foundations and supports. The technology demonstrator is a 1/4-scale main propulsion engine subbase. This will be followed by a yet-to-be-selected full-scale application to demonstrate the technology.

Fairwater
This demonstration involves a large, non-pressure-hull, hydrodynamic structure which, if built, would enhance ship stability through reduction of topside weight. Use of composites might also facilitate novel fairwater designs as might be required to accommodate new functions within the sail and to reduce wake.

Stern Structure
This demonstration, involving a large, non-pressure-hull, hydrodynamic structure would carry the fairwater demonstration a step further. It is expected to lead to the development of a structural "system" which will provide the basis for an all-composites outer hull for future designs.

Current Research
Goodrich remains committed to continued process improvement for the submarine bow dome. Meanwhile, the General Dynamics Electric Boat Division in Groton, CT has been busy reducing the cost of manufacturing submarine composites via the Navy's ManTech program. The Office of Naval Research Science and Technology ManTech web site summarizes a recent effort to manufacture low cost Main Seawater Pump (MSWP) impellers. These impellers are very costly as they are currently manufactured, and alternate manufacturing techniques to reduce the cost of metallic impellers have been proven impractical. The part has stringent geometric and acoustic performance requirements.

The project used the segmented manufacturing technique developed by General Dynamics Electric Boat (GDEB) and the material-tailoring techniques developed by the Applied Research Laboratory at Pennsylvania State University (ARL-PSU) to manufacture a high quality MSWP composite impeller. The manufacturing technology process has been transitioned to GDEB shipyard personnel for implementation. Based on the successful Manufacturing Verification Testing of the Composite Marine Impeller and the meeting with NAVSEA in June 2005, GDEB has developed a plan to recommend the use of composite impellers without the need for any additional qualification testing. The composite MSWP impeller passed a 2,000 hour endurance test with satisfactory marks.

Although I've undoubtedly left out some seminal uses of composites on submersibles, I hope you come away feeling that we are in debt to the early pioneers that saw submersible structures as an ideal application for composites. The world's largest autoclave was built to manufacture bow domes and thick-sectioned prepreg construction was pioneered. Analysis, nondestructive testing, materials development, and the study of cylinders under compression were developed especially for submarine composite materials. The cost per pound of composites for submarine use is easily an order of magnitude greater than composites that find their way on to surface ships. This is because submarine composites are marine composites done to aerospace standards.

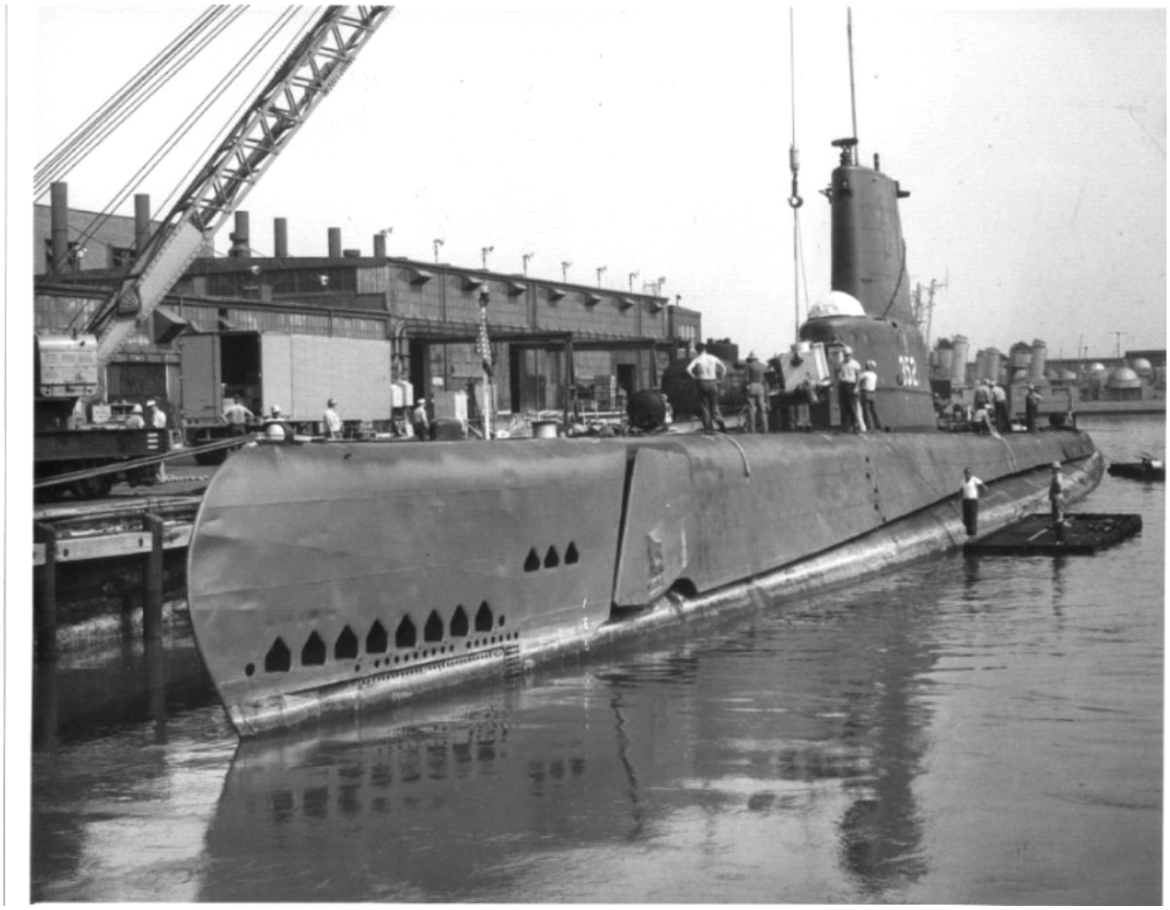


Figure 1. ***Halfbeak*** **(SS-352), at the Phila. Navy Yard, July 6, 1964 Courtesy of John Hummel [http://www.navsource.org/archives/08/08352.htm]**

Photo # NH 97661 USS Albacore off the Isle of Shoals, 5 April 1954

Figure 2. *Albacore* (AGSS-569), underway off the Isle of Shoals, 5 April 1954. Official U.S. Navy Photograph, USNHC # NH 97661, from the collections of the Naval Historical Center. [http://www.navsource.org/archives/08/08569.htm]

Figure 3. The *Nautilus* (SSN-571) entering New York harbor, August 25, 1958. Nautilus recently made a trans-polar voyage under the Arctic ice. US Navy photo courtesy of the US Navy Arctic Submarine Laboratory.

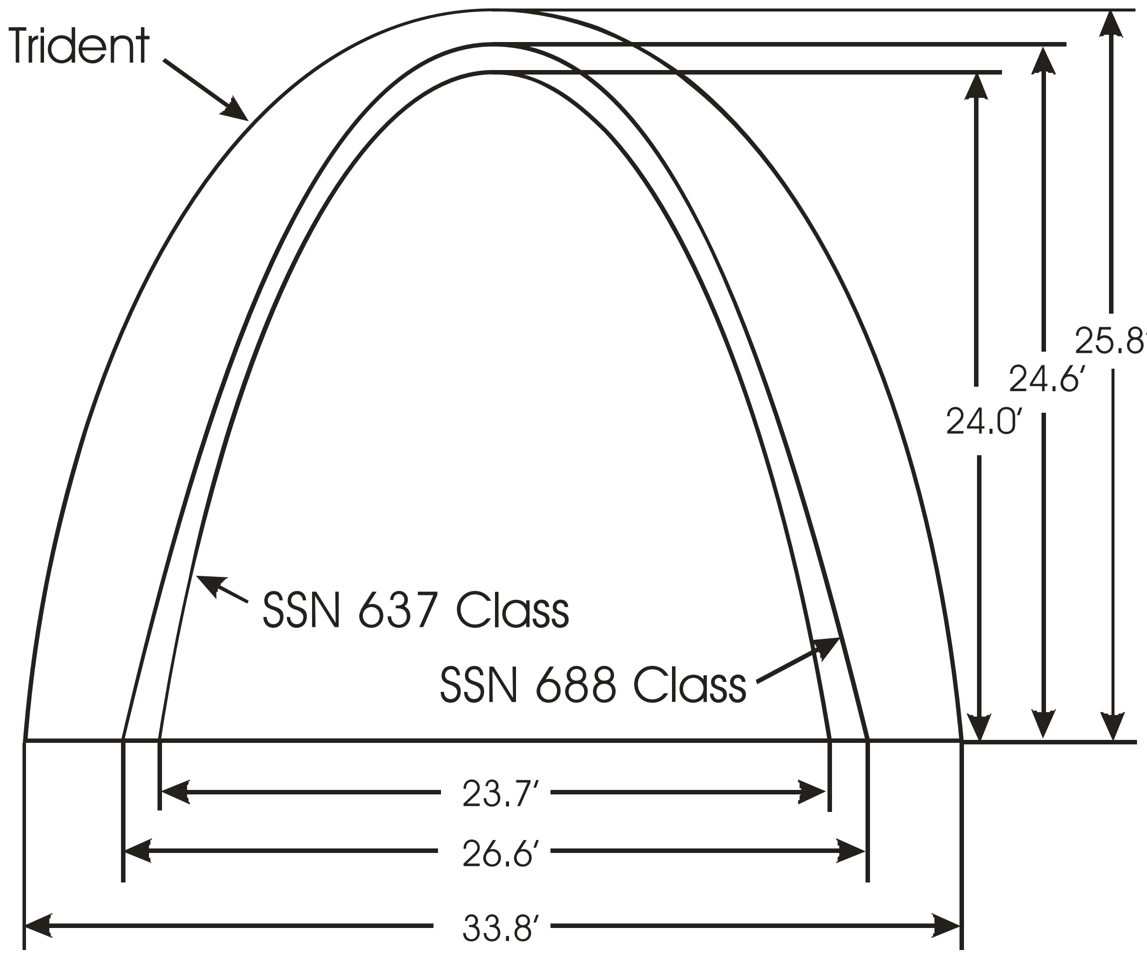
On Jan. 17, 1955, ***Nautilus*** put to sea for the first time and signaled her historic message "Underway on nuclear power." She steamed submerged 1,300 miles from New London to San Juan, Puerto Rico, in just 84 hours. The success of ***Nautilus*** ensured the future of nuclear power in the Navy. Now a museum, the historic ship attracts some 250,000 visitors annually.

Figure 4. The *Sturgeon* (SSN-637) lies in shallow broken ice at the North Pole, 17 April 1989. US Navy photo courtesy of US Navy Arctic Submarine Laboratory & csp.navy.mil. [http://www.navsource.org/archives/08/08637.htm]

Figure 5. [http://www.dt.navy.mil/pao/hi%20res%20images/Sept/seawolf21.jpg]

Figure 6. SSN-688 Los Angles Class Bow Dome
[http://www.globalsecurity.org/military/systems/ship/images/ssn-773-p01.jpg]

Figure 7. SSN-688 Los Angles Class Bow Dome, [http://www.globalsecurity.org/military/systems/ship/images/ssn-716_030516-n-2383b-044.jpg]



	Surface Area sq-ft	Weight lbs
SSN 637 Class	1388	26,260
SSN 588 Class	1519	28,177
Trident	2282	43,700

Figure 8. Comparison of Bow Dome Sizes

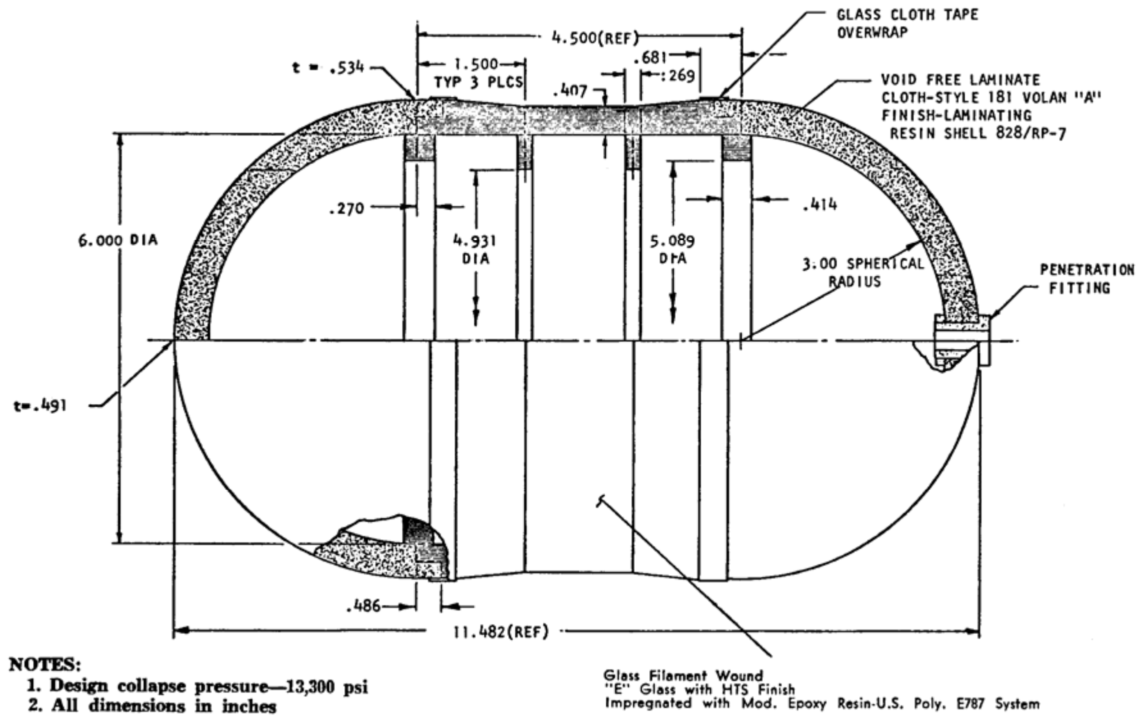


Figure 9. Six-Inch Diameter Test Specimen used for collapse testing. [N. Myers and B. Fink, "Filament Wound Structural Model Studies for Deep Submergence Vehicles," Naval Engineers Journal, April 1965]

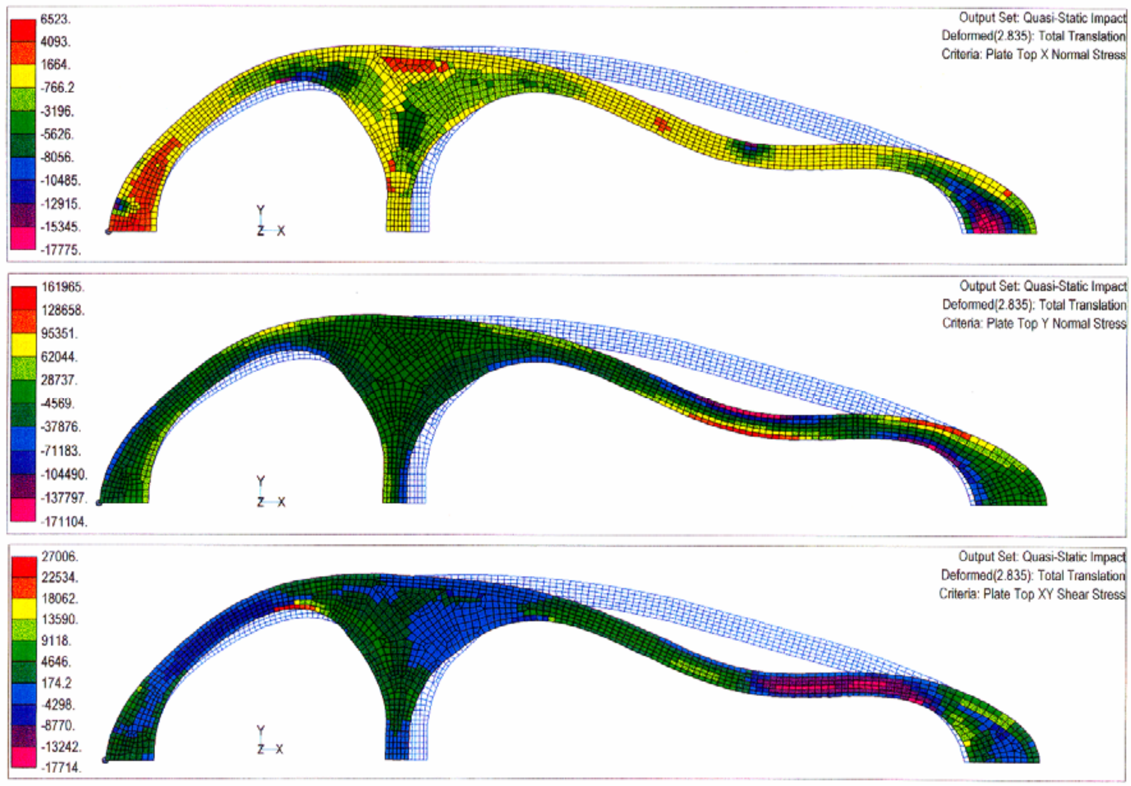


Figure 10. Monolithic Composite Mast by ARDCO FEA Analysis, NAVSEA [contract#N00024-94-C-4177, May 1996]