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Technical note: Comparison of the Titan deep submersible to older designs

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Three types of underwater vessels

A modern submarine is a ship that has a powerful propulsion plant so that it can travel long distances without support vessels. With nuclear power, it is essentially an underwater airplane of almost unlimited range. They have a cylindrical pressure vessel with elliptical or spherical bulkheads on the ends. They are typically about 10 meters in diameter and use periodic stiffening rings to avoid a bucking failure, making them tricky to design, unlike an airliner which blows up in a stable and predictable fashion like a balloon instead of compressing in a more unpredictable fashion. They can use compressed air cylinders to blow water out of ballast tanks for rapid rising and during emergencies. At some point the thickness of the cylinders to maintain air at pressure higher than the surrounding sea water makes them too heavy, limiting the depth of submarines regardless of hull strength. A different design principle is needed.

A deep submersible like the Titan is designed with emphasis on the up and down motion. The increased depth argues for different ballasting methods and for a simpler and stronger spherical passenger compartment although the smaller diameter and hence reduced compressive stress makes a cylindrical design more possible. Submersibles need and have only modest translational ability. Hence, they must be lifted in and out of the water with a crane or floated onto a raft. In either case, the vessel must be delivered to and from the dive site on a mother ship.

Closely related to current deep submersibles are the earlier bathyscaphes where the passenger compartment is supported by a huge volume tank, like an underwater blimp. The “balloon” is full of virtually incompressible gasoline that remains equal in pressure to the outside. So, the tank can be thin and thus light. They routinely drop some weight when ascent to the surface is desired. It must drop all of its iron weight to rise quickly in an emergency. This can be a fail-safe design. If power fails, an electromagnet fails, and the iron is dropped.

The most famous bathyscaphe is probably Trieste. It had a claustrophobic spherical compartment and was crewed by only two people, a US Navy officer and an oceanographer. It went to the bottom of the Marianna Trench, known as the Challenger Deep, about 36 000 feet in 1960. It has long since been retired and is on display (Figure 1, left). Since then, only one other vessel has gone to the bottom of the trench in 2012. It was in fact a private effort with help from National Geographic in return for video rights. It is a vertically oriented design which is basically shaped like a submarine sail without being connected to a horizontal hull (see the figure in [1]). There is only a small spherical passenger compartment at the bottom. This design keeps it upright by horizontal pressure from two sides, built for descending primarily vertically, carrying and risking only James Cameron. He is, of course, the director of the movie Titanic. All of these connections to the Titanic...

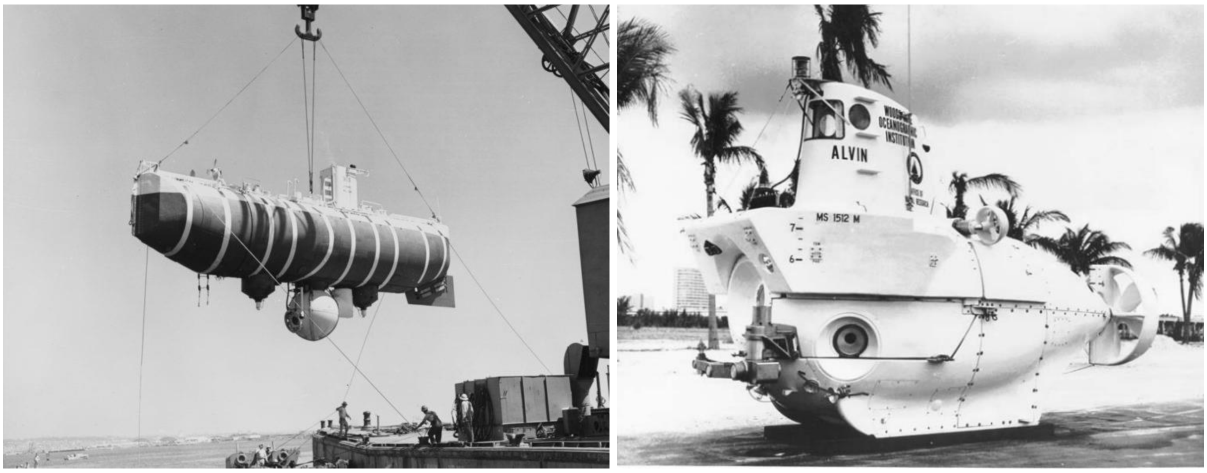

Figure 1. *Left:* Trieste, 1959 (https://navalunderseamuseum.org/trieste-ii/, U.S. Naval Undersea Museum). *Right:* Alvin DSV-2 (https://commons.wikimedia.org/, U.S. Navy)

The most famous submersible is probably Alvin, US Navy property (Figure 1, right; the figures in [2]). There were a few sister craft, but only Alvin was loaned out to Woods Hole Oceanographic Institute. It is a far more expensive system than Titan, including a dedicated mother ship with a crane that can lift Alvin directly aboard rather than floated off of a raft like the Titan. Like a submarine, it has a sail above an outer body that helps it to maintain its upright orientation and allow it to turn smoothly at a steady angle similar to a keel on a sailboat. (This is what my dynamics textbook called a non-holonomic constraint when degrees of freedom are interconnected.) The pressurized section was essentially a 5 cm thick titanium sphere with a hatch on top accessed through the sail, kept sealed by downward pressure. Other basic life support and control systems are in a non-pressurized body. Because the equipment is compact, it can be placed in small boxes designed to withstand high pressure as needed. The original Alvin carried two researchers plus an operator and had three viewing portals. It was updated several times with additional equipment since first certified in 1966 for a depth of 4500 meters. Alvin got a slightly bigger titanium sphere with five viewing ports instead of three which was then recertified for a depth of 6500 meters in 2014. This covers about 99 percent of the ocean, making accidental depth exceedances almost impossible. It remains in service. Remotely Operated Vehicles (ROVs) have both supplemented and supplanted the need for such vessels.

The expedition to find the Titanic was led by Dr. Robert Ballard using Alvin in 1985. Top secret at the time was that it was loaned out for this exploration only in return for first exploring the wrecks of the nuclear submarines USS Thresher and USS Scorpion which happened to be on either side of Titanic! Ballard had only 12 days left to find the Titanic. The first lighter pieces were found which were then followed until the full hull came into view. Very moving footage taken by a film crew that happened to be in the control room on the mother ship at the time of discovery can be seen on the internet [3].

Privately owned submersibles enter the scene

There are now some privately owned submersibles of varying depth maxima available for use for film making, scientific expeditions, and for tourism. These should not be confused with these aforementioned early bathyscaphes designed, financed and operated by governments for the purpose of deep-sea scientific research and perhaps low-profile military missions. These had dedicated support ships with rescue capability and the advantage of the redundant communication links used by military vessels.

There was so little deep sea research funding available from governments that wreck explorers could get permission to buy time on Alvin. Ballard also looked at other world-famous wrecks like the battleship Bismarck and aircraft carrier USS Yorktown sunk at the battle of Midway. The story of Robert Ballard is exemplary as a world-class geophysical researcher who combined this with creative funding from entertainment companies [4]. Perhaps the high cost of building and operating deep submersibles like Alvin was the driving force for the creation of for-profit companies to start designing lower-cost deep submersibles.

Hence, the Titan involves a simpler and lower-cost structural design and operating support protocol than Alvin. It sits on a pontoon raft barely above the ocean surface that can sink to release the Titan. There was not even a dedicated mothership, instead ships were leased. One of them was a retired Canada Coast Guard cutter. This is not just low budget, but the lack of a dedicated support ship and crew seems amateur for such hazardous missions.

The passenger area of Titan is only 2.5 by 1.4 meters. All passengers sit on the floor unrestrained. This apparently includes the operator. This too seems amateur as operators should be in a 3-point harness or at least a seat belt. Otherwise, strong un-commanded rolling or pitching motions can disorient the operator and perhaps even cause a dropping of the controller.

Structural design differences between military funded and private designs

The hull of Titan was a carbon fiber cylinder. The cylinder was attached to titanium rings at each end. One side of the ring has a lip of approximately 2 centimeters and a smooth contact surface. The mating surface on the cylinder also appeared to be smooth based on public videos during construction. There is apparently no press fit into this lip ring. The mating is entirely by adhesive paste. There do not seem to be any adhesives of the commercial off the shelf (COTS) variety and hence proven. One can see aerospace adhesives specifically designed for carbon fibers in a flying duty cycle environment. A look at the long lists of products finds none designed to bond titanium with carbon fiber in a marine environment, let alone a high-pressure marine environment [5, 6]. Thus, the designers seemed to have to improvise with a proprietary mix.

While water pressure acts to keep the bearing stress on this joint very high, there are no backup bolts or tapered locking hooks that twist into place should the glue degrade for some reason or fatigue cycles cause weakening to the interfaces. The other side of the forward ring involves a heavy flange and a bolt circle that connects like materials. This front hemisphere covers the entrance to the pressure hull, that is, the passenger compartment. A power drill is used to quickly install and remove the bolts and a hinge supports the immense weight as it opens. At least one trip was interrupted for a "loose pipe" so that the submersible had to surface. The passengers had to wait inside as it heated to 50 degrees as it took so long to open it would probably have caused a cancellation of the mission. This is a money-making operation. Too many incomplete descents is bad for business. Thus, there is more financial pressure to deliver trips than a purely scientific vessel operating on a more casual schedule.

The front hemisphere had an acrylic window of conical design such that the outside pressure seals it. It was so thick that it was far too heavy to be lifted by one person. This was the only viewing portal. Having only one requires that all riders must take turns. A failure of this acrylic would not merely flood the vessel, it would probably burst the cylinder no matter what material is used for the cylinder or the opposing hemisphere. As Thunderf00t (the chemist professor Phil Mason) demonstrates in his video, unlike gasoline, water is not really incompressible. At the depth of the Titanic, water is 4 percent compressed. Exposure to a 1 atmosphere chamber would be like releasing a spring with high explosive force into it at the speed of sound as visualized by Thunderf00t [7].

The stern end titanium hemisphere has another difficult penetration to seal, the electronics cabling in the aft non-pressurized space delivering primary battery power to the control unit, magnets, and primary oxygen/CO2 scrubber systems designed to provide breathable air for 5 people. Should anything begin to fail the submersible must immediately climb to the surface, but there would be time to wait for help while the Titan bobs around. Should the electric power to drive the propulsors fail, or higher ascent speed be desired, the entire set of ballast weights can be dropped. These had apparently been dropped shortly before the accident.

Multiple trips were made in development but not perhaps enough before it carried passengers. Deflection had been noted in the acrylic. At least one other expert not involved with the company who rode in it noted sounds after 12000 ft (3600 meters) suspected to be hull defects and also heard loud sounds, while rising at about 300 feet (90 meters). This expert suspected it to be the structure releasing compression energy in large pulses instead of gradually, suggesting non-linear behavior. On the other hand, at least one other external person who rode a deep trip heard nothing.

Carbon fiber is nowadays used extensively on airliners, but the development has been rough. An F117 stealth fighter fuselage and wings had shattered at an air show, fortunately not over crowds, something that an aluminum airliner does not do. This demonstrates the increased importance of not having any defects since parts cannot be designed to predictably yield before total failure. The first airliner to use significant parts was the Boeing 767 back in 1982. My father happened to be a lead structural airframe engineer at Boeing (with his lowly bachelor's degree from Finland). He related that early planes operated by United Airlines were returned to the factory to have carbon fiber flaps replaced with the traditional aluminum. The issue was bubbles indicating delamination. Since the 767, such structural parts made of composites are much larger, including entire wing structures and fuselage sections. These are now routinely put in an autoclave, a pressurized oven, to be certain all bubbles are pushed out and strength is uniform.

The Titan used a "wet" approach instead. Keep in mind that carbon fiber is strongest in tension but weaker in compression unlike structural metals. A deep dive causes enormous compressive stresses around the cylinder for its full length. The fiber layers were spun only circularly and not crisscrossed at 45 degrees at some layers, which would have increased the strength by putting fibers in more tension if the cylinder were put into bending for some reason, bubbles appeared, or the vessel had contact damage. The proper resin bonding to fibers using an autoclave would be exceptionally important to guarantee uniform full strength.

This design and manufacturing combination makes buckling of the cylinder or delamination causing overstress two major suspects in the implosion. How fatigue affects such failure modes is really unknown unlike steel which is used on submarines and aluminum used on airliners. Airliner airframes are retired when their takeoffs and landings exceed a certain number N representing the number of loading cycles with a maximum stress S allowed, declining in the familiar log-linear relationship. The Titan had made a total of approximately 24 deep trips depending upon the source. But it was not known if this would be too many.

A third suspect is the glued connection of two dissimilar materials, carbon fiber composite and titanium. There are aerospace adhesives for this purpose, but, of course, this is for use in a gas medium decreasing between 1 and 0.25 atmosphere, not liquid of steadily increasing pressure from 1 to 100s of atmospheres. There apparently was no destructive testing done to a prototype where the joints of a test vessel are dissected afterwards to test for degradation of the glue, air pockets, bonding surface molecular interchange, and so on. To be certified, civilian airliners undergo both a fatigue test where the fuselage and wings are cycled 24/7 for a few years plus a test to destruction of one airframe where the wingtips and fuselage extremities are bent. Wing bending and cycling can be seen in a video by [8].

To summarize, while the design had questionable design features from a strength and safety redundancy standpoint, the most likely failure modes appeared to be a fatigue failure in the composite hull or water penetration through one of the interfaces between unlike materials. The compressibility of titanium is a small fraction, about one fifth, of the compressibility of the composite material used. That alone risks overstress from the tendency of the glued materials to push and pull apart as the temperature changes during multiple trips.

Non-structural design features of Titan

Another aspect of the Titan design is that the lines are not clean. Cables should not be unshielded if they are absolutely necessary to be outside the pressure hull. Whales and sharks can bite them if trying to chase off this intruder and fishing nets can snag these. This is not a minor problem, as fishing nets are drowning whales, turtles, and sharks in huge numbers and in one dive, a swordfish got caught on the hull and forced a mission abort of Alvin. The propulsors are on external mounts, two for port and starboard, two for ascend and descend, perhaps unavoidable given the small hull size, but power cables should not be visible.

The operator uses a video game controller making it more reminiscent of an Xbox video game or other such system than a military submarine where two operators sit like in an airliner cockpit. The primary control was to change the speed and direction of the propulsors mounted on opposite sides on the outside of the hull. Numerous commentators have pointed out that game controllers are not so unusual, as even military drones and other modern devices use these since the functionality needed already exists. But, to repeat, what seems genuinely amateur is to have the operator merely sitting on the floor with the other passengers. Especially so if the propulsors are the means of recovering from an un-commanded pitch or roll large enough to possibly throw the passengers out of balance. The deft use of up and down propulsors would be required to recover from large angle rolls that occur in turbulence because of the lack of rolling motion resistance from a sail.

Apparently, one of the horizontal propulsors was mounted backwards in a trip such that the response was opposite to that intended by the operator. This would result in the vessel going in circles. They continued the dive. This should have been grounds for an immediate trip abort. Instead, the controls were used in a temporary fashion after some confusion. This demonstrates a ridiculous lack of discipline in both preparation and mission cancellation protocols. As does the lack of a transponder automatically activated when the vessel bobs on the surface, which would allow the raft team to get to the vessel immediately in case of an emergency. There were apparently no external lifting points either for lifting a stalled vessel, yet another sign of amateur design.

Preliminary official findings

At the time of this writing, the Coast Guard did not bring up any composite pieces large enough to be visible over the fence in Newfoundland to immediately implicate the composite hull fracturing from stress overload or from buckling. Later analysis will probably shed more light on the precise failure mode.

Video from over the fence where the titanium rings were visible appears to show no traces of either adhesive or shards of composite still attached. This suggests that the adhesive surfaces were not properly treated with chemical etching or sandblasting or otherwise prepared to strengthen the molecular bonding between two unlike materials to its maximum. This means there could be excessive tension on the adhesive due to differential compression of the two materials. Specifically, this could have allowed a small amount of water to penetrate which would then decompress into the passenger compartment. As the water expanded slightly even with only 4 percent compressibility at the failure depth, it might release enough energy into the passenger compartment to possibly blow off the hemispheres in a tension failure of the adhesive.

Over the fence shots of the bow titanium ring shows the acrylic was missing from the front hemisphere since the lifting cables ran through the portal opening. It was apparently not rated to this depth and might possibly have just failed in compression along one of its edges, again decompressing a small amount of water into the passenger compartment. Small amounts of water might quickly widen the hole. Witness high pressure cutting tools to see how easily they cut through metals.

Finally, note that military submarines do not use any viewing portals of any kind in the pressure hull, relying instead on a sphere with hydrophone arrays in the bow and cable trailing sensors behind the stern. Unlike metals are avoided at the penetrations unless absolutely necessary. All of these precautions for vessels that go a fraction of the depth of a submersible. And they pay the price for being blind once in a while. In 2001, the USS Greeneville surfaced under Japanese fishing training boat off Pearl Harbor. There was no upward visibility and apparently the routine hydrophone contact plotting was disrupted by visitors to the control center. In 2005, the USS San Francisco struck a sea mount at high speed (see the figure in [9]). Active sonar would have spotted it, but this gives away the sub's position and is not normally used. Scientific study is perhaps the only reason there should still be submersibles. Nowadays, an ROV with strong lights can both collect samples and transmit spectacular television images, but there is nothing like seeing it with the human eye. Only a bathyscaphe or submersible can provide that!

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