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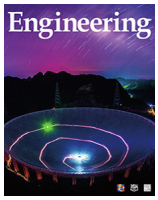

News & Highlights

Like the Titanic, Flawed Engineering—and Hubris—Doomed the Titan

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Early on the morning of 18 June 2023, far off the shore of Newfoundland, Canada, the Titan deep-sea submersible began its descent into the depths of the north Atlantic. Aboard was Titan's inventor and pilot, Stockton Rush, along with four "mission specialists," several of whom may have paid as much as 250 000 USD to accompany Rush on a voyage to the site of the infamous Titanic shipwreck on the ocean floor. About two hours later, Titan's launch vessel, the Canadian boat Polar Prince, lost communications with the submersible. Over the next four days, a frantic search ensued, culminating in the tragic realization that all aboard had died, the catastrophic result of the vessel imploding at a depth of roughly 3000 m [1]. Searchers found the vessel's wreckage just 500 m from the bow of the Titanic [2].

People around the world had watched the almost constant news of the unfolding saga with shock and hope that the crew remained alive and might be rescued. But while the tightknit submersible community also held out hope, they were not shocked—they had seen this disaster coming for years, having pleaded with Rush to reconsider Titan's novel design, or to at least have the craft's safety verified by a third party. Instead, the worst happened, calling into question the need for additional regulatory oversight of civilian submersibles. The Titan will likely also provide a notable entry to future engineering ethics textbooks, alongside such recent disasters as the Boeing 737 max crashes in 2018 and 2019 [3] and the Surfside condominium collapse in 2021 [4], as well as older entries like the Titan's namesake Titanic itself, which sunk after hitting an iceberg in 1912.

Before the Titan's final voyage, no fatal accident had occurred in a human-occupied submersible for nearly 50 years—despite a 2000% increase in the annual number of dives in that period [5]. Furthermore, no submersible had ever imploded in the 93-year history of crewed deep-sea exploration. "One word that sums up what happened is hubris," said Sal Mercogliano, an associate professor of history and nautical expert at Campbell University in Buies Creek, NC, USA. "Hubris in using a design that had never been tried before—every other submersible is a bubble."

Headed by Rush as its chief executive officer, OceanGate Expeditions (Everett, WA, USA), Titan's corporate owner and operator, first began offering paying customers voyages to the Titanic in 2021 [6]. Most submersibles that currently host tourists explore coral reefs and other natural phenomenon at depths of 500 m or less [7]. In contrast to Titan, the ten or so other submersibles in the world built to reach 4000 m—the depth OceanGate claimed Titan could safely dive to—are all dedicated to scientific inquiry [5]. They all also have a spherical design, titanium, steel, or aluminum construction, and design certifications by a third party verifying their safety. Titan had none of those.

A sphere is the ideal shape for deep-sea vessels because the water pressure exerts equal force across its entire surface. However, to increase its capacity to carry passengers, the Titan's designers opted for a novel cylindrical shape (Fig. 1). Rush, an aerospace engineer and former flight-test pilot and venture capitalist, was also determined to use a carbon fiber composite for Titan's main cylinder, sealed on the ends by titanium caps. The aerospace industry prizes carbon fiber for its strength-to-weight ratio, using it in aircraft wherever possible to save weight. The lighter weight made the Titan neutrally buoyant, preserving its limited battery power by allowing it to maintain depth with minimal use of its electric thrusters [8].

Cost was another notable factor in the choice of carbon fiber for the hull. "When you climb into a spherical submersible, the word that comes to mind is 'claustrophobic,'" said Mercogliano. "It is a tiny little ball. To make it bigger to fit more people, you must make the ball bigger. That is really, really expensive and using carbon definitely helps with that."

However, elongating the submersible cabin space to a cylinder redistributed the water pressure at depth, increasing it on the vessel's midsection and causing that area to experience higher fatigue and delamination loading. How well a carbon fiber structure like the Titan's cylindrical hull would handle that stress in repeated dives was essentially unknown. Because it is a novel use, engineers had not comprehensively studied the ability of carbon fiber structures to withstand repeated cycles of compressive stress under deep-sea pressures [9].

Constructing Titan's 12.7 cm thick hull from carbon fiber involved a challenging manufacturing process. To build the hull, 480 layers of interwoven carbon fibers were wound around the full length of a metal core cylinder (approximately 2.5 m long, with a 1.4 m diameter), bonded with epoxy, bagged in plastic, and cured in an oven at 137 °C for seven days [10]. Any mistakes would be permanently baked in, so perfect consistency was a critical objective. Ensuring the hull's integrity would have meant scanning it with thermal imaging, X-rays, or ultrasound to reveal any potential flaws, Mercogliano said. Such scans would point out any weak

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(a) (b)

Fig. 1. (a) In an unprecedented departure from the spherical design and metallic construction of virtually every other deep-sea submersible, the hull of OceanGate's Titan, shown here in an artist's illustration, was constructed as a carbon-fiber cylinder with 12.7 cm thick walls, capped on either end by 8.3 cm thick titanium shells. The design made the interior large enough to hold five occupants, meeting OceanGate's objective to offer voyages to "mission specialists" who could pay to visit the wreck of the Titanic. In contrast, (b) the pilot pod of the Deepsea Challenger shows the standard spherical design of other deep-sea submersibles. The pod has 6.4 cm thick steel walls and sat at the base of the 7.3 m long, 11.8 tonne vehicle that was piloted by Canadian film director James Cameron to a depth of almost 11 km. With a diameter of just 109 cm, the pod's interior is large enough for only one occupant. Credits: (a) Madelgarius/Wikimedia (CC BY-SA 4.0); (b) Z22/Wikimedia (CC BY-SA 4.0).

spots, which the company could monitor with additional scans following every dive. "Water eventually finds the crack," he said. "Unfortunately, there is no margin for error at depth because a fault is instantaneous and catastrophic."

In 2015, according to a 2018 press release [11], OceanGate subjected a one-third scale model of the Titan to four rigorous tests in a pressure chamber "which validated carbon fiber as a viable material for hull design." The company further announced [11], as part of Titan's "extensive testing program," a successful test of the newly built but unmanned Titan "to validate the hull to a depth of 4000 m," with additional testing of the vessel piloted by Rush as its sole occupant to follow.

Before its fateful last descent, about two dozen previous expeditions had subjected Titan's hull to repeated stress. Still, OceanGate never scanned the hull, which would have been required for certification by a third party such as Det Norske Veritas (DNV), a Norway-based international marine classification society widely accepted for setting the gold standard for maritime safety [5]. Although OceanGate never had the Titan certified, it claimed in marketing material that the vessel "would meet or exceeded DNV-GL safety standards" [12].

"Scanning is not really expensive, and it is not rocket science either," said Jasper Graham-Jones, an associate professor of mechanical and marine engineering at Plymouth University in the United Kingdom. "It is standard stuff and they refused to do it." Instead, OceanGate, in another first for a submersible, relied on "real-time hull structural health monitoring" in which acoustic sensors and strain gauges were placed throughout the hull [11], sounding an alarm if the carbon fiber filaments began to audibly break. Such real-time monitoring "is a nice idea," Graham-Jones said. "The problem is, when you start getting cracks, it is too late."

In January 2018, David Lochridge, an engineer and three-decade veteran of submersible construction and piloting, OceanGate's then-director of marine operations and head pilot, prepared—at Rush's request—an internal report stating that the carbon fiber of Titan's hull was visibly deteriorated, riddled with air gaps and delaminations [5,12]. His recommendation? The only way to fix it was to start over from scratch. He also noted more than two dozen items requiring immediate attention, including missing bolts, improperly secured batteries, components zip-tied to the outside of the sub, O-ring grooves incorrectly machined, and loose seals [5,12]. OceanGate fired Lochridge within weeks of receiving his report, an act Lochridge claimed was retaliation for pointing out Titan's safety flaws [13]. Lochridge filed his report as part of a whistle-blower complaint with the United States' Occupational Safety and Health Administration (OSHA); he ultimately withdrew the complaint after being sued by OceanGate, although OSHA reportedly had passed a copy to the US Coast Guard (USCG) [12].

Outside groups also warned OceanGate that failing to pursue third-party scrutiny of the vessel could result in catastrophic problems. One such group, the Marine Technology Society (Washington, DC, USA), an international community of 3800 ocean engineers, technologists, policymakers, and educators, sent a letter to Rush in 2018, voicing concern about the Titan's lack of certification [14,15]. "While this may demand additional time and expense," the signatories wrote, "it is our unanimous view that this validation process by a third party is a critical component in the safeguards that protect all submersible occupants."

Leaning on his training as an aerospace engineer, Rush justified his decision to not have the Titan certified for safety by contending that the regulatory process was time-consuming and stifled innovation [12]. "One lesson here is that engineers should keep safety in the forefront of their minds, especially when they are caught up in the business world and trying to further their inventions," said Deborah Johnson, emeritus professor of applied ethics at the University of Virginia School of Engineering in Charlottesville, VA, USA.

Even as OceanGate and Rush disregarded the strong recommendations from outside experts to have the Titan's safety certified by a third party, there were no regulations or regulatory bodies—unlike for companies selling space tourism [16,17]—to stop OceanGate from boarding passengers willing to pay dearly. "Titan was a vessel loaded on another vessel, so what exactly was it, and who was responsible for it?" Mercogliano said. "It was built in the United States, its parent company was incorporated in the Bahamas, and it was on a barge towed out by a Canadian vessel, taken out of a Canadian port. There is a big gray area regarding who should oversee any submersible visiting the Titanic."

Though there was no authority policing the Titan, at least four countries—the United States, Canada, the United Kingdom, and France—quickly launched a massive search and rescue operation, deploying substantial assets including planes, ships, and underwater remotely operated vehicles (ROVs) [18]. In total, the operation was estimated to cost tens of millions of US dollars [18,19].

Even after the disaster, Mercogliano foresees more, not less, deep-sea tourism in the coming years. "If people are going to go to the Titanic, they are going to go to the Hood and the Bismarck, as well as wrecks in the Pacific," he said. Regardless, it may be some time before the Titanic receives another human visitor. Currently, no crewed scientific excursions to the Titanic are planned [20], and a commercial expedition initially set for 2024 to retrieve artifacts from the shipwreck must first overcome a court challenge filed by the US government [21].

Not surprisingly, OceanGate ceased all exploration and commercial operations in early July 2023 [22]. Pieces of the Titan and some "human remains" have now been recovered by ROV and are being examined in a joint USCG, US National Transportation Safety Board, and Transportation Safety Board of Canada investigation of the accident that could last as long as two years [23]. In any case, the fact that the remains of two famous shipwrecks lay close together—for at least a brief time—at a deep, lonely site at the bottom of the north Atlantic provides a tragic illustration of why the submersible community is "pretty conservative," as Graham-Jones put it. "There are limits to what you can do," he said. "Titan has shown us that having checks and balances is a good thing."

References

[1] Pratt M. How the unconventional design of the Titan sub may have destined it for disaster [Internet]. New York City: Associated Press; 2023 Jun 23 [cited 2023 Oct 1]. Available from: https://apnews.com/article/titan-titanic-submersible-design-49b8c2a713f316ce5987a394a27d23e8.

[2] Regan H, Renton A, Picheta R, Sangal A, Hammond E, Meyer M, et al. Missing Titanic sub crew killed after 'catastrophic implosion' [Internet]. Atlanta: CNN; 2021 Jul 13. [cited 2023 Oct 1]. Available from: https://edition.cnn.com/americas/live-news/titanic-missing-sub-oceangate-06-22-23/h_05c8ceaff3f9757f768cf25df5e60784.

[3] Palmer C. The boeing 737 max saga: automating failure. Engineering 2020;6(1):2–3.

[4] Ellis R, Silverman HA, Jones K. Death toll in Surfside condo building collapse reaches 94 [Internet]. Atlanta: CNN; 2021 Jul 13. [cited 2023 Oct 1]. Available from: https://www.cnn.com/2021/07/12/us/miami-dade-building-collapse-monday/.

[5] Casey S. The Titan submersible disaster was years in the making, new details reveal [Internet]. New York City: Vanity Fair; 2023 Aug 17 [cited 2023 Oct 1]. Available from: https://www.vanityfair.com/news/2023/08/titan-submersible-implosion-warnings.

[6] Betts A. OceanGate expeditions was created to explore deep waters [Internet]. New York City: New York Times; 2023 Jun 19 [cited 2023 Oct 1]. Available from: https://www.nytimes.com/2023/06/19/us/oceangate-lost-submarine-titanic.html.

[7] Brooks B, Trotta D. Titanic sub: how is submersible tourism regulated and what's next for industry? [Internet]. London: Reuters; 2023 Jun 23 [cited 2023 Oct 1]. Available from: https://www.reuters.com/world/after-titanic-sub-disaster-industry-faces-scrutiny-2023-06-23/.

[8] Charalambous P. PlayStation controller and acoustic messaging: how the missing Titanic tourist sub works [Internet]. New York City: ABC News; 2023 Jun 21 [cited 2023 Oct 1]. Available from: https://abcnews.go.com/US/playstation-controller-acoustic-messaging-how-missing-titanic-tourist-sub-works/story?id=100256552.

[9] Strauss D. Missing Titanic sub once faced massive lawsuit over depths it could safely travel to [Internet]. New York City: The New Republic; 2023 Jun 20 [cited 2023 Oct 6]. Available from: https://newrepublic.com/post/173802/missing-titanic-sub-faced-lawsuit-depths-safely-travel-oceangate.

[10] Sloan J. Composite submersibles: under pressure in deep, deep waters [Internet]. Cincinnati: Composites World; 2017 May 10 [cited 2023 Oct 6]. Available from: https://www.compositesworld.com/articles/composite-submersibles-under-pressure-in-deep-deep-waters.

[11] Worlds largest carbon fiber manned submersible hull proven to 4000 meters [Internet]. Everett: OceanGate; 2018 Jun 27 [cited 2023 Oct 10]. Available from: https://mail.oceangate.com/news-and-media/press-releases/2018-0627-worlds-largest-carbon-fiber-manned-submersible-proven-to-4000-meters.html.

[12] Taub B. The Titan submersible was "an accident waiting to happen" [Internet]. New York City: The New Yorker; 2023 Jul 1 [cited 2023 Oct 6]. Available from: https://www.newyorker.com/news/a-reporter-at-large/the-titan-submersible-was-an-accident-waiting-to-happen.

[13] Yerushalmy J, Kassam A. Titanic submersible: documents reveal multiple concerns raised over safety of vessel [Internet]. London: The Guardian; 2023 Jun 20 [cited 2023 Oct 6]. Available from: https://www.theguardian.com/world/2023/jun/21/titanic-submersible-documents-reveal-multiple-concerns-raised-over-safety-of-vessel.

[14] Chang C. The murky regulations governing submersibles [Internet]. New York City: Curbed; 2023 Jun 21 [cited 2023 Oct 1]. Available from: https://www.curbed.com/2023/06/oceangate-titan-submarine-unregulated-tourism.html.

[15] MTS letter to OceanGate [Internet]. Washington: Marine Technology Society; 2018 Mar 27 [cited 2023 Oct 10]. Available from: https://int.nyt.com/data/documenttools/marine-technology-society-committee-2018-letter- to-ocean-gate/eddb63615a7b3764/full.pdf.

[16] Wilson EK. Space tourism moves closer to lift off. Engineering 2019;5(5):819–21.

[17] Leslie M. Space tourism begins to take off. Engineering 2022;10(1):4–6.

[18] Sharp D. How much did Titan search cost? US COAST GUArd's bill alone will be in the millions, experts say [Internet]. New York City: ABC News; 2023 Jun 23 [cited 2023 Oct 1]. Available from: https://abcnews.go.com/US/wireStory/titan-submersible-search-cost-100342315.

[19] Chung C. Money can buy a visit to space or the deep sea, but it can't guarantee safety [Internet]. New York City: New York Times; 2023 Jun 23 [cited 2023 Oct 1]. Available from: https://www.nytimes.com/2023/06/23/travel/titan-sub-oceangate-adventure-travel.html.

[20] Pagones S. Titanic trips nixed after deadly sub disaster—and it will likely be years before excursions resume: experts [Internet]. New York City: New York Post; 2023 Jun 27 [cited 2023 Oct 1]. Available from: https://nypost.com/2023/06/27/all-planned-trips-to-titanic-nixed-after-deadly-sub-disaster/.

[21] Reilly P. US opposes 2024 expedition to recover Titanic artifacts, says shipwreck is a grave site [Internet]. New York City: New York Post; 2023 Aug 29 [cited 2023 Oct 1]. Available from: https://nypost.com/2023/08/29/us-opposes-planned-expedition-to-titanic-says-wreck-is-a-grave-site/.

[22] Hauser C. OceanGate, operator of the Titan submersible suspends operations. New York City: New York Times; 2023 Jul 6 [cited 2023 Oct 12]. Available from: https://www.nytimes.com/2023/07/06/world/oceangate-titan-submersible-operations.html.

[23] Hauser C. Likely human remains recovered from the Titan submersible. New York City: New York Times; 2023 Oct 12 [cited 2023 Oct 12]. Available from: https://www.nytimes.com/2023/10/11/world/europe/titan-submersible-debris-human-remains.html?nl=todaysheadlines&emc=edit_th_20231012.