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Design and Fabrication of a Cast Titanium Sphere for 4000m Ocean Depth

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***Abstract*—A spherical pressure housing slightly greater than 1 meter inside diameter has been designed, fabricated from near-net-shape Ti-6Al-4V castings, and tested for remote operations in 4000m seawater. This paper discusses the design considerations, methodology, fabrication processes, and hyperbaric testing of the sphere. An additional note on mounting equipment inside the sphere is included.**

***Index Terms*—near-net-shape cast titanium, spherical pressure housing, hyperbaric testing.**

I. Introduction

A PRIMARY goal of the Monterey Bay Aquarium Research Institute (MBARI) is to extend the operating depth and duration of ocean scientific instrumentation. The Environmental Sampling Processor (ESP) program utilizes complex, robotic laboratory instruments for *in situ* identification and quantification of larvae, bacteria and other microscopic organisms in near real time [1], [2]. This avoids the time lag and changes of state that occur when samples are sequestered and transported to the laboratory for analysis. As a robotic system it can be deployed for months, enabling new research in tracking microbial activity over time without human presence. Although typically deployed in less than 50m sweater, MBARI undertook the task of bringing the ESP scientific capabilities into the deep sea.

The ESP instrument is several times larger than typical deep water pressure housings, such as 400mm glass spheres. However, the casting of near-net-shape titanium structures can drastically reduce fabrication costs [3], and a feasibility study determined that developing a large spherical pressure housing to fit the current ESP architecture, would be more cost and time effective than developing a smaller scientific instrument to fit within conventional 4000m rated pressure housings.

With past success designing and utilizing cast titanium housings, MBARI engineers developed a spherical Ti-6Al-4V housing, greater than one meter in diameter, for use up to 4000m depth. This paper focuses on the design, fabrication, assembly and testing of this sphere.

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II. Pressure Housing Size Selection

The two directions for developing a 4000m deep ESP system were to either create a large pressure housing to fit the current technology, or create a miniature version of the technology to fit within existing pressure housings.

For size comparison, the 50m rated surface pressure housing is a welded aluminum cylinder, providing 210 L internal volume. Originally designed for additional buoyancy, the extra volume allows for system expansion as the technology evolves. An early 1000m deep ESP project used a 103 L cylinder of spun cast NiBrAl, half the volume of the surface housing. This provided the minimum volume for the bare ESP instrument, but no analytical modules or support equipment could be added, significantly limiting the functionality of the instrument (fig 1).

The small pressure housing option, such as a 400mm glass sphere of 34.5 L volume, would have required an order of magnitude size reduction without changing functionality, a complicated development with high risk. For the large pressure housing option, it was proposed to be a sphere for efficient mass use, and modeling determined that a 860mm sphere, 333L internal volume, is the smallest the core ESP instrument could fit within. However, a 1015mm sphere would allow whatever equipment that could deploy in the surface housing to be deployed unmodified. This sphere would have 540 L of internal volume.

Nearly 50-person-years of engineering development were necessary to develop the current ESP instrument, and refine its functionality. Much of these those development activities were expected to be repeated for a miniaturized instrument. However, the large pressure housing would require less than 1-person year to develop, and was chosen as the most time and cost effective, but also would allow for future resources to be focused on expanding the scientific capabilities of the instrument, rather than miniaturizing the current capability.

III. Design

The pressure housing design was refined to a horizontally split, spherical housing of 1015mm inside diameter (fig. 2). Most of the design work involved iterative FEA to manage the stress concentrations from bolting flanges, mounting points, and penetrator holes.

For bolting, sealing, and penetrations, there are areas of the sphere that do not follow the perfect spherical geometry. A thickened cylindrical hub at the equator provides area for penetrators and fittings, and gradually transitions to the spherical shell. At the crown of the hemisphere, the outside of the sphere transitions to a truncated cone top to reinforce a lifting point, but the inside maintains spherical geometry.

The sphere is sealed with two concentric o-rings, creating a redundant face seal. The o-rings are compressed 25% during assembly, and a narrower than standard groove is used to provide more metal to metal contact between the hemispheres, reducing the bearing stress.

Large diameter o-rings must be custom fabricated, but are available from many manufacturers as spliced or serpentine molded. The serpentine molded o-rings, although more expensive, have better material consistency without the splice and provide a more reliable seal. The o-rings are ordered 1.25% smaller in diameter than the groove. The slight stretch during installation holds the o-ring against the inner wall of the groove and in the direction of the pressure gradient. Serpentine molded o-rings have been supplied by both Marco Rubber (North Andover, MA) and Atlantic Rubber (Littleton, MA).

A. *Design Factors*

The Deep ESP is a robotic system, serviced by remotely operated vehicles. As such the sphere was required to pass a hyperbaric test equal to the depth rating of the sphere, 4000m of seawater. Design factors were set to provide a high likelihood that the finished pressure housing would pass the 41.4 MPa hyperbaric test. After considering the novel design, casting and machining tolerances, material inconsistencies, and other complications that could affect the strength of the sphere, MBARI engineers used four design factors when evaluating the sphere. These factors varied depending upon the failure mode and consequences.

A design factor of 2.0 for critical pressure buckling was used on the spherical shell, and subsequently became the limiting condition for the spherical wall thickness.

The following stress design factors are applied with the limiting condition being minimum yield compressive strength.

A factor of 1.5 was applied for the pressure shell. Although most of the shell is design limited by buckling, stress concentrations were mitigated to this.

A 1.375 factor was applied for regions that require dimensional stability, but yielding will not likely affect stability of the pressure shell. These are mostly around holes and sealing faces for the fittings and penetrators; places where yielding might affect the fitting, but would be unlikely to result in a leak or buckling deformation to the pressure.

A 1.10 factor was applied for regions that are not dimensionally critical, nor likely to affect the pressure shell stability. The holes that pass wires and fluid piping from the fittings and penetrators into the sphere are designed to this factor. If yielding occurs, the result is a smaller, somewhat deformed hole and residual material strains.

Note that by design; all the stresses in the sphere are compressive, which yield to a stable state. During yielding, the material deforms and expands the area supporting the load. The result is lower stress as the same force is now supported by a larger area. Whereas tensile yielding results in thinner material, higher stresses, and may continue yielding until failure. If any section of the sphere were to be under tensile stresses, a 1.5 design factor to minimum tensile yield strength would have been used for those areas. The material properties used for design are: minimum compressive yield strength (Syc) of 930 Mpa, minimum tensile yield strength (Syt) of 827 Mpa, Modulus of Elasticity (E) of 113 Gpa. However, during testing the modulus of elasticity was found to be lower, and will be discussed later in this paper.

By the design factors and material properties, a 4000m depth-rated Ti-6Al-4V spherical shell, of 1015mm ID, is limited by buckling at 23mm thick. The combined weight of the assembled sphere is 405 kg, and displaces 660 kg of seawater, making it buoyant. The mass to displacement ratio in seawater is 0.61.

B. *Computer Modeling, FEA*

The sphere was designed with Solidworks, with the Simulation package for finite element analysis (FEA) to determine the maximum static stresses and mitigate concentrations. This also was used to predict the deformation of the sphere under pressure loading, such that predictive stains could be compared against during hyperbaric testing. The FEA modeling was done on one quarter of the hemisphere, fixed by symmetry on the cut faces, and a sliding, on-plane contact for the o-ring sealed face (fig. 3).

The hub required significant attention to manage the sealing face bearing pressure and minimize the stress risers due to the fitting holes. To balance the bearing pressure of the two hemispheres across the seal face, the cylinder of the hub is a smaller inside diameter than the sphere; 990mm opposed to 1015mm. If not balanced, the hub could “smoke ring”, deform in a toroidal roll, which could cause gapping, extrusion of an o-ring, and potential for seal failure.

All the stress and buckling analyses were duplicated using differing methods, providing high confidence in the design. MBARI performed FEA on a solid model, with validating results from a cross section shell analysis using Ansys. The critical pressure for buckling was calculated with a spreadsheet implementation of Roark’s formulas for stress and strain, with validating results using the Under Pressure software from Deep Sea Power and Light.

C. *Fittings*

All fittings and penetrators are mounted on the bottom half of the sphere so that the ESP instrument, wiring and plumbing remains intact and functional while the sphere is open. System requirements called for a minimum of 11 electrical fittings and four fluid penetrators. Three spare electrical fittings were added for future expansion, making the spacing work out well at 18 equidistant ports, between the 36 sphere closure fasteners. There are also six blind holes tapped into the outer hub of each hemisphere for use in lifting and mounting the sphere on a deployment platform.

The electrical fittings selected are SeaCon Mini-con MINK FCR in titanium. The FCR version was chosen as opposed to the BCR body as it eliminates the risk of accidentally unthreading the fitting from the housing when disconnecting a cable.

Of the four fluid penetrators into the sphere; two pass a decompressed seawater sample through the ESP instrument for microbial identification, and two are used for venting, helium leak detection, and nitrogen purge cycles when sealing the sphere for deployment.

D. Galvanic Isolation

Titanium is a very noble metal, even the Ti-6Al-4V alloy. As there is a lot of exposed surface area on a sphere this size, it can sustain aggressive galvanic reactions. Material matching and isolation is necessary for protecting against corrosion. The electrical fittings and all fasteners are titanium for this reason. The four fluid penetrators are made from 316 stainless steel to material match to the tubing and valves feeding seawater to the ESP. As these penetrators are of dissimilar metal to the sphere, an o-ring sealed PEEK dielectric isolator was designed and included during hyperbaric testing. If the external tubing and valves are replaced with titanium components for long deployments, these penetrators can be replaced with ones made from titanium.

E. Forward Design

As there is a long lead time for casting such hemispheres, the sphere design needed to be completed early in the project. The critical design review and print check of the sphere design was completed in December 2007, when the rest of the Deep ESP system was only at a conceptual stage. It would take 14 months before the sphere would be ready for use. The castings were available in August 2008; completed machining in November 2008, and completed hyperbaric testing in February 2009.

IV. Casting

Casting can provide a near-net-shape blank for final machining, thereby making affordable the manufacturing of larger, complex geometries from expensive materials such as titanium [4]. Each finished hemisphere is 200 kg and although they could be machined from billet, each would start out over 2500 kg, at substantial material cost. In comparison, the cast blanks averaged 250 kg each (fig. 4).

As pattern costs can be significant, the sphere was designed for both hemispheres to be machined from castings of the same pattern. Wah Chang (Albany, OR) produced the castings and coordinated the fabrication of hardwood patterns based upon MBARI machining drawings. The mold cope and drag are made from this pattern with rammed graphite. The castings were poured from Ti-6Al-4V, with coupons cast and processed at the same time for material property validation.

Post casting processes included weld repair of voids, annealing or other heat treatment. The casting process forms a thick oxidized surface layer, an alpha phase case on the casting. This highly brittle surface can initiate stress concentrating cracks into the base metal, reducing the load capacity. Sandblasting and chemical stripping are used to remove this surface material.

A concern with any casting is the potential for porosity and void pockets in the metal. Instead of just annealing, the cast hemispheres underwent hot isostatic press (HIP) treatment. In the HIP process, the casting is heated above the annealing temperature, in an inert, high pressure atmosphere. Any voids collapse and the material diffusion bonds, effectively eliminating porosity. With the one exception being that any voids open to the surface equalize pressure during the HIP and do not collapse. One such open void was found in the machining of the top hemisphere (fig. 5). However, as this void was in the thick hub section, it was determined to not be a stress risk and was not repaired.

Typically such voids are readily visible on the surface and are weld filled. To verify that there were no other voids, Wah Chang recommended dye penetrant testing as a cost effective alternative to 100% radiography. After machining was completed, both sphere halves were shipped back to Wah Chang who performed dye penetrant testing, no other open voids were found.

The two hemispheres were cast separately, with several weeks between for the first hemisphere to complete processing and measured against the desired shape. If needed, the pattern could be modified so future castings will better fit the required geometry.

The first casting did deform somewhat, possibly during casting or during heat treatment. It ended up slightly shorter and a little wider at the hub diameter, as if the casting had sagged minutely. Although the pattern did get adjusted for the second casting, the first casting was close to desired geometry, and MBARI was given the option of accepting the first hemisphere as is or Wah Chang could weld repair it. The repair action would have been to weld build up material over the upper portion of the casting, adding thickness so that a full shell could more likely be machined from the casting.

Wah Chang provided a measured drawing of the post processed hemisphere, and MABRI compared that to the final machine model. It was likely that with some modification to the design, the full pressure rating could be met with the original casting. MBARI considered these options very carefully as the face seal of the hemisphere would require a very flat finish. Considerable stresses and material inconsistencies would be imposed in by the amount of welding required. Although annealing could mostly normalize these stresses, machining through the weld material could cause the sphere to deform. MBARI chose to accept the casting as is, rather than impose the uncertainties of the weld build up. This first casting article was chosen for the sphere top, as it would require less machining. If needed, it can be replaced at less cost.

V. Machining

The castings were fully machined on all surfaces for two reasons; primarily to remove excess mass, but also to bring the spheres to a specified shape and geometry. Prior to machining, the combined castings weighed about 500 kg, and 400 kg afterwards. Although casting provided a near-net-shape to the design, the actual wall thickness and curvatures can vary drastically. Indentations, thinned areas or even flats can be expected on the cast finish.

The design factors considered tolerances for a machined surface, not a cast surface. If much of the hemisphere surface were to be left as the uneven cast finish, the shape and wall thicknesses would be less uniform and strains could be unbalanced, invalidating the buckling calculation. If the surface were to be left cast, wall thicknesses and spherical geometry could be mapped in detailed and modeled for extensive FEA to estimate the critical buckling pressure, but accuracy would be suspect. Also, there is no expectation that one casting would have the same tolerances as another, even if the mold is rammed from the same pattern. Each casting would need to undergo mapping and FEA for critical buckling.

The finished castings were machined at Tapemation Inc (Scotts Valley, CA). Along with having the skill and equipment to machine the hemispheres, a major benefit of Tapemation was their location, a short drive from MBARI. Inspections were done regularly and at machining milestones, and design adjustments made when needed to obtain the best pressure rating from the emerging geometry.

Prior to machining, each hemisphere was mapped in a coordinate measuring machine, to generate point cloud models for comparison to the design final geometry. A change was made to the design to best fit the top hemisphere within the casting. This change was to shorten the height of hemisphere by 2.5mm. This would place the center of the sphere slightly below the face and additional FEA was done to ensure that it would not affect the bearing contact or the seals. The bottom hemisphere required no design changes.

After machining, a few cast surface spots were still present on the outside of the top hemisphere, making for a thinner wall at these locations (fig. 6). However, the inside did get full clean up and met geometry. These outside spots were measured and the worst case modeled as a flat spot 1.5mm deep and 80mm in diameter, to determine it is still within our design factor for stress (fig. 7). Buckling was modeled as well, but the analysis was not definitive. The critical pressure for buckling was estimated to be less than the design factor of 2.0, but still well above our planned pressure testing. MBARI engineers decided to continue with this top hemisphere and test for 4000m depth, with real-time strain monitoring of these points.

VI. Assembly

The pressure envelope of the sphere, including all fittings and penetrators, was first assembled in January 2009, 14 months after ordering the patterns to be made for the castings. After a few assemblies, a process for assembling and sealing the sphere has been developed to ensure clean, reliable sealing with even o-ring compression. Although ocean pressure will quickly provide more than sufficient force to fully close the sphere, mechanically seating the seal guarantees even compression of the o-rings, avoiding any misalignment and pinching. This also allows for leak testing to be done on the identical seal geometry as when deployed. The 36 assembly fasteners are tightened in cross pattern, to a minimum of 4.5 Nm. A go/no-go gauge is used in the recessed groove around the equator to determine when the sphere is fully closed, seated metal to metal, indicating that the o-rings are fully within the grooves.

VII. Testing

A. *Helium leak testing*

Helium leak testing is a critical step in preparing the sphere for deployment, and the sphere was designed for this to be performed prior to every deployment. The ESP instrument contains many fluid reagents which cannot be exposed to the vacuum of internal leak testing, so a slight overpressure test is performed. The vent and purge penetrators are located on the hemisphere hub, but are tube connected to the spaces at the top and bottom of the sphere. The sphere is slowly filled with helium from the top down, displacing the air out the bottom vent. This provides a high concentration of helium along the equator seals and also displaces the oxygen out of the sphere. Because of the large pressure area of the sphere and relatively low tensile capacity of the fasteners, the helium is pressurized to 13.8 kPa only. The leak test is performed with a mass spectrometer detector in sniff mode around the seal perimeter and all fittings and penetrators.

After this leak testing is complete, the helium, which could otherwise be absorbed into the ESP reagents, is purged out with nitrogen from the bottom up. As many of the reagents used by the ESP are ethanol based and there are open electronics and brushed motors in the ESP, this nitrogen atmosphere is a simple safety precaution.

The first assembly of the sphere, prior to installation of any internal equipment, was vacuum helium leak tested to verify seal integrity of all the components. This testing method, although at much lower pressure than the deployment, is more sensitive than sniff testing. Also, encasing the sphere in a bag filled with helium not only provides a global leak rate, but tests the metal for porosity. With the sphere incased in a helium bag and full vacuum on the sphere, there were no detectable helium leaks.

B. *Hydrotesing*

After the initial assembly and vacuum leak testing verified that the sphere could be sealed, it was opened and packaged for shipment to Southwest Research Institute (San Antonio, TX) for hyperbaric testing.

Several strain gauges were placed at points inside and outside of the sphere, at the thin spots on the sphere top and nominal locations that did make geometry. These provided real-time monitoring of the nominal, maximum, and minimum strains at the inside and outside of the shell. All of the fittings and penetrators were installed for the testing, and one was used to pass the conductors to the internal strain gauges.

During hyperbaric pressure testing, these were compared to the FEA predictions (fig. 8). The initial pressurizing was done in stages, and if strains indicated a maximum shell stress had reached a design factor or that any strain had become non-linear, the pressure test could be stopped and the sphere de-rated. The test was completed to full design pressure for 4000m seawater, 41.4 Mpa (fig. 8). During pressure testing, the maximum stress seen in the shell, at one of the cast surface patches, was 520 MPa, compared to a nominal outside shell stress of 450 MPa. This matched very well with the FEA predicting max stress of 540 MPa. Stress wise, it is within the design factor, however this should not be construed as operational reserve as the limit to operation depth will be due to buckling.

The sphere stresses are calculated from the monitored strains, but required a new evaluation of the modulus of elasticity for the metal. During hyperbaric testing, all the strains were uniformly larger than predicted, by almost 10%. Either the shell was uniformly 10% thinner, which inspection had shown to not be the case, or the modulus of elasticity for the material was less than the design originally considered. Further investigation has found that the modulus of elasticity for Ti-6Al-4V can vary from 100 to 130 GPa [5]. Aligning FEA and calculated strains with the nominal shell strains monitored during testing determined that both castings have a modulus of elasticity around 104 Gpa (fig. 9). This modulus was used to determine the sphere stress during testing, and to recalculate the design factor to buckling as 1.8 instead of the original 2.0.

The actual buckling factor is probably even lower due to the cast surface spots, and the critical buckling pressure of the imperfect pressure shell has not been modeled effectively. It is important to remember, that the robotic operations called for a tested factor of 1.0, and that was accomplished. If required in the future, a new top hemisphere can be cast from the modified pattern and machined.

VIII. Deployment and Usage

The Deep ESP instrument and sphere has been deployed several times on a benthic freefall elevator to depths up to 1800m. Deployments up to 90 days have been accomplished with the system connected to the Monterey Accelerated Research System (MARS) cabled observatory (fig. 10).

IX. Valuable Notes

One action that reduced risk during machining was switching to finer threaded fasteners. The MINK FCR connectors are typically mounted with 6-32 screws. However, tapping 6-32 holes in Ti-6Al-4V is difficult and notorious for resulting in broken taps stuck in holes. A simple modification is to tap the holes for 6-40 screws, which requires much less tapping force due to the finer thread. The tap has a larger minor diameter and is less likely to break. The drawback is that 6-40 titanium screws are not common. These needed to be custom ordered at some additional cost, but well worth the expense compared to the risk. The 6-40 screws, as well as all other titanium fasteners for the sphere, were supplied in grade 2 titanium by United Titanium (Wooster, OH).

Mounting of equipment in the sphere posed a challenge, as any internal structure needs to isolate the sphere deformation from the internal components to allow the sphere to deform evenly under pressure, and prevent damage to the internal equipment. As with any pressure housing, sea pressure strains the shell of the sphere, slightly reducing its diameter. At 4000m seawater depth, the diameter of this sphere could decrease up to 5 mm. Many times, mounting posts are adhered to the sphere structure with flexible rubber mounts, providing the flexural isolation between the equipment and the pressure housing.

A different method was used for this sphere that allows the sphere to deform freely, but also securely supports the 60 kg of internal equipment. A segmented circumferential ring is supported at six locations by stems that have a loose sliding fit into the equatorial holes in the bottom hemisphere (fig. 11). These equidistant holes are there to pass the wires from the MINK FCR penetrators into the sphere. These stems are hollow and the wires feed through them, allowing use of those six electrical ports as well.

As the sphere deforms under pressure, its diameter reduces uniformly, but the sliding fit on the support stems keep the mounting ring from changing geometry and transfers no strain into the equipment. The ring itself is made in sections, so that parts of it can be removed and modified to mount new hardware. The ESP and all supporting equipment is mounted to this ring. The ESP itself hangs from a spider structure that sits on three points of the mounting ring.

X. Conclusion

A spherical pressure housing, slightly greater that 1m in diameter has been fabricated from near-net-shape Ti-6Al-4V castings and tested for robotic/remote operations to 4000m depth in seawater. The design factors chosen were sufficient to pass the 41.4 MPa hyperbaric test, however indications are that actual reserve factors are less than the design factors.

Residual cast surfaces can make stress concentrations in the pressure shell, although the action to repair such a material deficiency in the casting could be more detrimental to pressure rating, or sealing success. It would be beneficial to have comparative articles test the stability of significant weld repair to a casting.

Hyperbaric testing strains indicate that the actual material modulus of elasticity is significantly less than typically referenced. Although not commonly performed during material certification testing, actual modulus of elasticity and other material properties can be obtained from casting coupons if requested. Future efforts of similar scale should consider this.

Acknowledgment

The development of this sphere required the support of many individuals. Special thanks are given to Chris Scholin for leading the advancement of ESP technology, and the ESP team for considering novel engineering solutions. The author wishes to recognize Jon Erickson, designer of a 400mm cast titanium sphere, for the material input, debate about analysis methodology, and design reviews. Thanks to Mark Greise for the validating Ansys analysis. Special thanks to the crews of the R/Vs Point Lobos and Western Flyer for their expertise during field deployments.

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Fig. 1. Size comparision of ESP pressure housings.

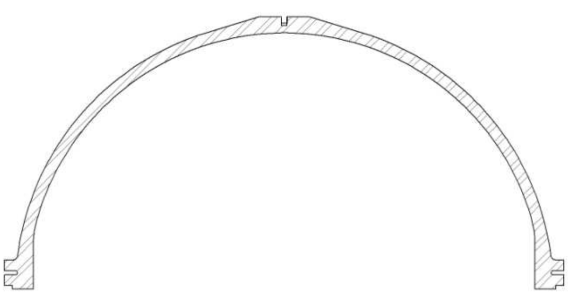

Fig. 2. Cross section of top hemisphere.

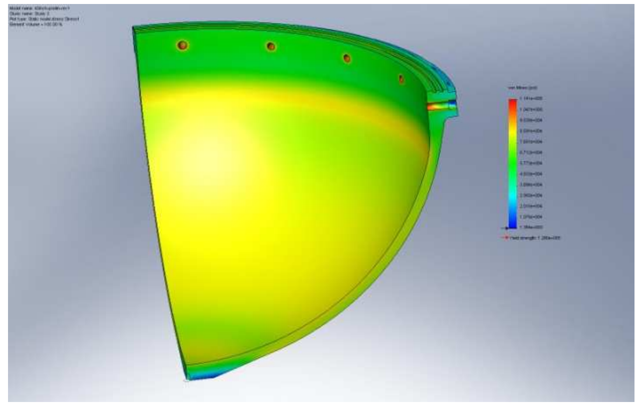

Fig. 3. FEA analysis of quarter hemisphere.

Fig. 4. Cast Ti-6Al-4V hemisphere, weighing 250 kg.

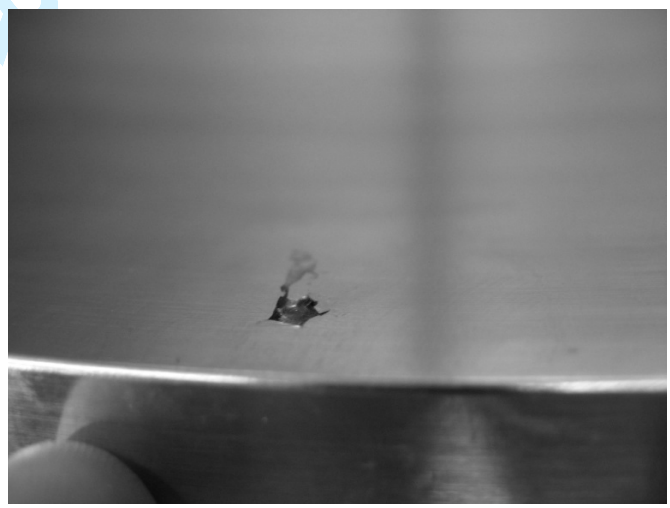

Fig. 5. 5mm wide void uncovered during machining.

Fig. 6. Residual cast surfaces on top hemisphere.

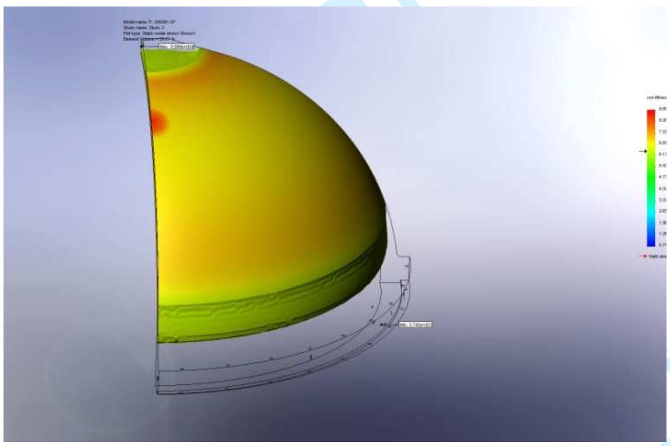

Fig. 7. FEA modeling of surface stress at residual casting spot.

Fig. 8. Sphere being removed from hyperbaric chamber at SwRI after pressure testing to 41.4 MPa.

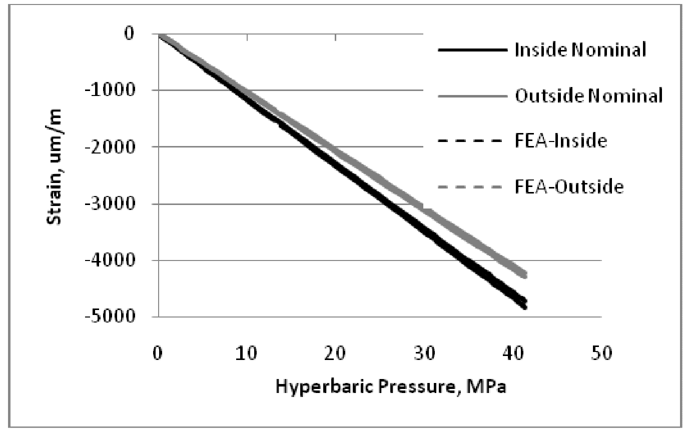

Fig. 9. Nominal strains during hyperbaric testing aligns with calculated strains for reduced modulus of elasticity.

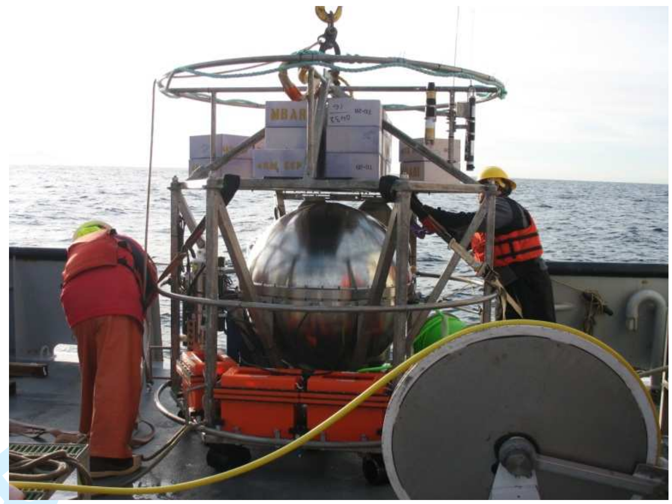

Fig. 10. The sphere, mounted in freefall elevator, is readied for deployment in the Monterey Cayon.

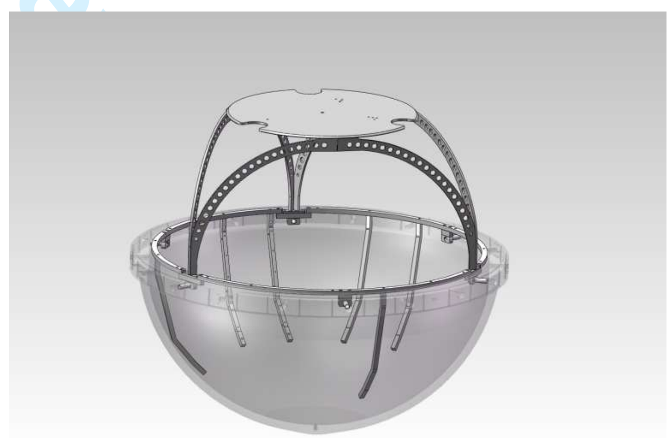

Fig. 11. Strain isolated internal mounting structure.