Operations to 11,000m: Nereus Ceramic Housing Design and Analysis

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***Abstract*—HROV Nereus, a full-ocean-depth hybrid remotely operated vehicle (HROV) built at the Woods Hole Oceanographic Institution (WHOI), dove nearly 7 miles to the bottom of the Marianas Trench in June 2009. Nereus was the third submersible to reach the bottom of the trench, but the first autonomous vehicle. Its hybrid design allows transformation from remotely operated vehicle (ROV) to autonomous underwater vehicle (AUV) simply by removing a work platform and releasing its tether.**

To achieve the enormous undertaking of operations at 11,000m as either ROV or AUV, the Nereus moves away from the standard ROV mode by taking several new technological approaches. For example, the vehicle utilizes a single fiber-optic strand as its tether, when tethered. It carries its own power in the form of lithium-ion batteries, removing the power supply link to the surface. And, as detailed in this paper, Nereus uses technical ceramics for its pressure housings.

This paper will present and discuss the design and analysis of the Nereus ceramic housings, which protect many of the systems critical to the function of the vehicle from the extreme external pressures (16,500 psi at maximum depth). Particular attention will be paid to details such as the end- and joint-rings, glass-dome mounting and the ceramic penetrations, as the actual ceramic housing analysis has been well documented.

Keywords—HROV Nereus, hybrid, AUV, ROV, Marianas Trench, ceramic housing, design, ocean technology

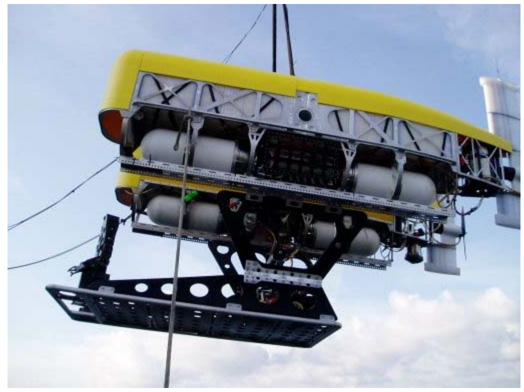

Fig.1 HROV Nereus in ROV mode with bottom skins removed, showing its white ceramic housings (Photo by Christopher Griner)

I. INTRODUCTION

Underwater vehicles require pressure-resistant housings for components such as computers, cameras, batteries, and electronics for communications and navigation. Because housings must be strong and corrosion resistant, titanium has become the material of choice for most deep ocean work. As titanium pressure vessels (PVs) are sized for depth, wall thickness increases and weight-to-displacement (W/D) ratios increase. Thick-walled titanium housings provide no floatation at full ocean depth.

As housings get heavier, greater floatation and power requirements become necessary; everything gets bigger—more foam, larger frame, bigger vehicle, and larger ship for deployment. For most science autonomous underwater vehicles (AUVs), weight is critical, and keeping it low is an aim throughout the design. Most science AUVs rely on low-weight, high-range geometries that have a good top speed and payload capability. These factors are directly affected by the housing used, and thus the housing material selection [1].

Traditionally, ceramics have been a marginalized material for underwater pressure housings due to their susceptibility to catastrophic failure. Housing materials that yield before they fail—metals such as steel, aluminum, and titanium—have been preferred because they are much more forgiving. Metals have the ability to plastically flow to relieve the effects of stress concentrations created by features such as transitions, penetrations, and O-ring grooves. This simple ability to plastically flow can relieve point loading though local yielding. Ceramics do not share that characteristic. They are brittle in nature and will crack or chip when forces are applied to an improperly designed feature.

In spite of the potential difficulties, the Nereus housings' trench-depth capabilities and floatation requirements drove material selection to 96% alumina ceramic [2]. Alumina ceramic provides excellent corrosion resistance and high compressive strength in a light material that can be used to build thin-walled, buoyant housings. 6Al-4V Grade 5 titanium (Gr5 Ti) was the material choice for housing end caps and connectors, as well as joint rings and housing couplings (Fig. 2 and Fig. 3). The Gr5 Ti provides a high strength-to-weight ratio, excellent machining capability, and very good corrosion resistance.

Woods Hole Oceanographic Institution (WHOI) brought in Dr. Jerry Stachiw, noted in the field of underwater housing design, to lead the Nereus ceramic housing development. Stachiw's years of work resulted in significant advances in many areas of ceramic housing design—strength and cycle limits, methods for joining ceramic sections, end cap shape, ceramic boss requirements. The Naval Command, Control and Ocean Surveillance Center (NCCOSC) technical reports developed through this work clearly document materials, geometries, testing, and lifespan. These reports provided a valuable path for design, construction, and testing. For further reading, please see [2]

II. Ceramic Housing Design

Leading design on the ceramics, Stachiw determined the ceramic material 96% alumina and chose a 1.5 factor of safety, which was a design departure from his previous NCCOSC work. This was deemed allowable due to the fewer cycles the Nereus was expected to see. Another departure from his previous work was the inclusion of the ceramic hemisphere to the main cylindrical body. This geometry can be seen on both the 355mm (14in) outside diameter (OD) Nereus main and the 191mm (7.5in) OD utility housing (Fig. 2 and Fig. 7). Benefits of the capped cylinder include a decrease in overall weight, cost, and complexity.

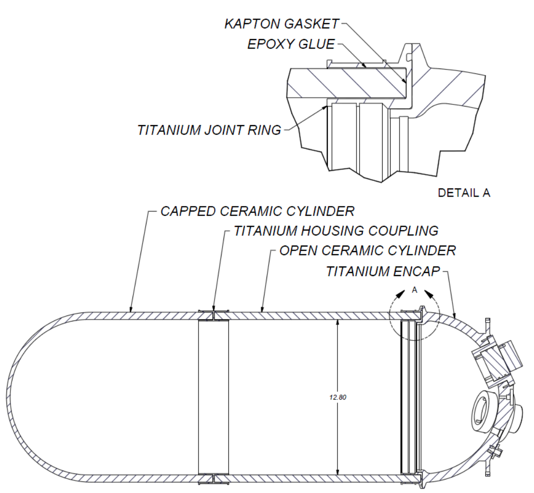

Fig.2 The Nereus main electronics housing shows typical ceramic housing construction.

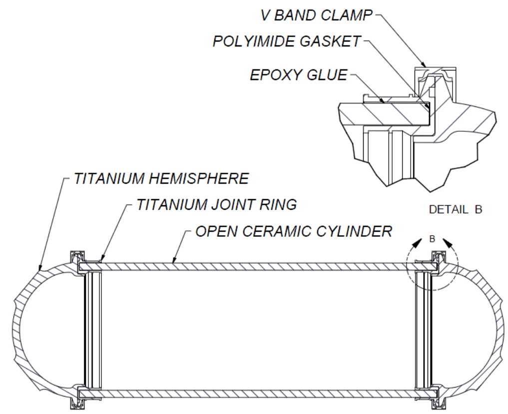

Fig.3 Open cylinder utility housing with two titanium end caps

Ceramics have high compressive strength and elastic moduli. They exhibit a linear stress/strain behavior very close to their point of failure. Therefore, staying safely within the elastic range is necessary. The alumina ceramic was specified to 300,000 psi compressive strength. With a 1.5 factor of safety, the maximum nominal hoop stress could not exceed –200,000 psi, and half of that for the nominal axial membrane stress [2].

Each housing component was designed within allowable stress limits. Ceramic and glass components fell under the Maximum Normal Stress Theory of failure, whereby minimum component stress was compared to their compressive strength [3]. Titanium was subject to the Distortion Energy Theory, whereby the von Mises stress defined the allowable stress limit. Solid modeling was done in Autodesk Inventor, and FEA was done in Structural Research COSMOS/DesignSTAR. The analysis utilized 5° axisymmetric model geometries to reduce mesh size and computation time. Deep Sea Power & Light's Under Pressure, a Roark's formula–based software program that provides stress, strain, and buckling information about housing shapes, was used to compare stress and strain results found in FEA. Each of the ceramic housings were proof tested to 124MPa (18,000 psi) and cycled to the working depth of 114MPa (16,500 psi) for verification of design and build.

A. End- and Joint-Rings

As shown in the previous figures, the cylinder ends were glued into Gr5 Ti joint rings and housing couplings. These U- and H-shaped rings were made three times as deep as the wall thickness of the ceramic. The titanium face adjacent to the ceramic bearing surface was made as thin as possible, and the O-ring groove was placed outside the vertical landing zone of the bearing surface. This was necessary for several reasons, one being that the Poisson effect can occur as the metal compresses against the ceramic at depth (Fig. 4). As the Ti undergoes compression, it can expand in the direction parallel to the ceramic bearing surface, initiating circumferential cracking. The polyimide gasket was included to help deter this phenomenon by buffering the bearing surface from the Gr5 Ti [2].

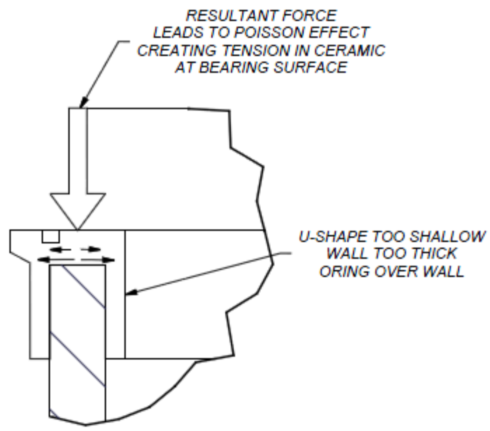

Fig.4 Poor joint ring design

Ceramic housing failure is most often initiated by circumferential cracking on a tube end [4]. Housings should be removed from service when cracks extend beyond the joint ring, as shown in Fig. 5 detail B. Therefore, lengthening joint rings can extend valuable service life to the ceramic housing. Unlike ceramic, the metal joint ring can easily be shaped to provide seals, closures, and in the case of the housing coupling, connectors for cylinder sections. The joint rings can also tolerate minor plastic deformation. In the case of accidental damage, a joint ring can be removed and replaced.

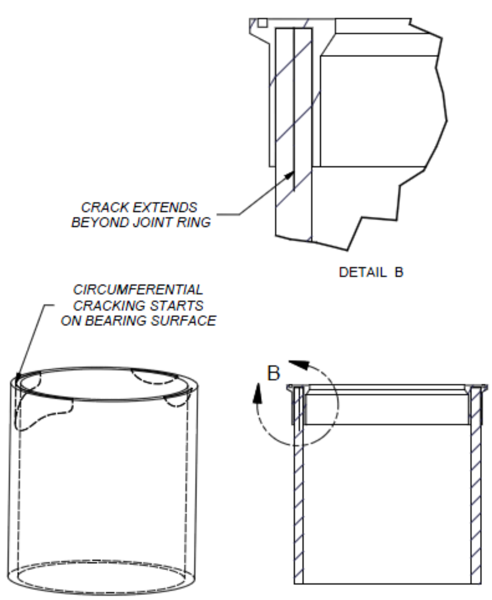

Fig.5 Circumferential cracking initiated by cyclic fatigue [4]

i. More Than Matching Deflections

Analysis showed that it is an effective approach not to impede or interfere with the movement of the ceramic parts. When external pressure is applied, the parts compress and move inward. When external pressure is removed, and keeping within the elastic limit, the parts will return to their original shape. FEA results showed the least amount of tensile stress in the ceramic parts when they were allowed to deflect naturally, suggesting the design should allow fluid motion.

Fig. 6 illustrates FEA results of the utility housing axial deflection with the resulting end cap force acting normally (and on center), through the joint ring and into the end of the ceramic housing wall (dark blue).

This was challenging geometry to create because the deflection mismatch between the end cap/joint ring assembly and the ceramic tube just below the joint ring sometimes results in motion that is referred to as "rotation." Parts must move together, and the joint ring surface must stay flat. Removing this rotation is necessary to deter cyclic fatigue and circumferential cracking.

Adding material (joint rings) to the ends of the ceramic tubes increases the moment of inertia in that area, resulting in uneven cylinder deflection at pressure. As a result, analysis is then also an effort in end cap shaping that will couple the assembly, matching deflection to create even motion and remove rotation.

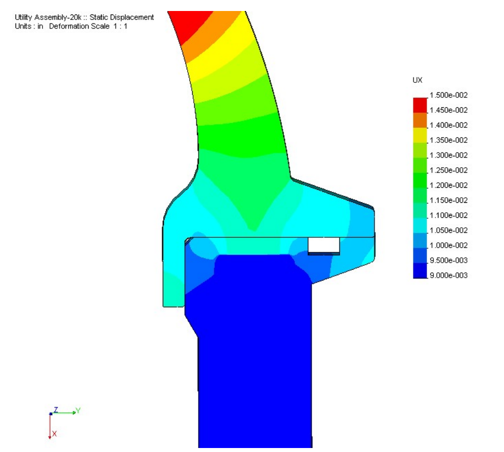

Fig.6 FEA shows wall-centered displacement results and joint rotation removed.

B. Glass Dome Mounting

A BK-7 optical glass dome is used on one of the high-definition camera housings. Glass, brittle like ceramic, has a very low tolerance for tensile stress. A Gr5 Ti seat was added to join the glass dome to the ceramic housing (Fig. 7). Special attention was needed to design the geometry of this section. The dome-to-seat interface and seat-to-joint-ring interface provided the design challenge to create an assembly that moves as one; when hydrostatic pressure was applied and removed, the unit would contract and expand completely together. There could be no slip of the glass on the Ti seat and no rotation at the interface of the seat base and joint ring. The glass and titanium did sandwich a thin neoprene gasket, but this was used only to buffer the metal microgroove finish.

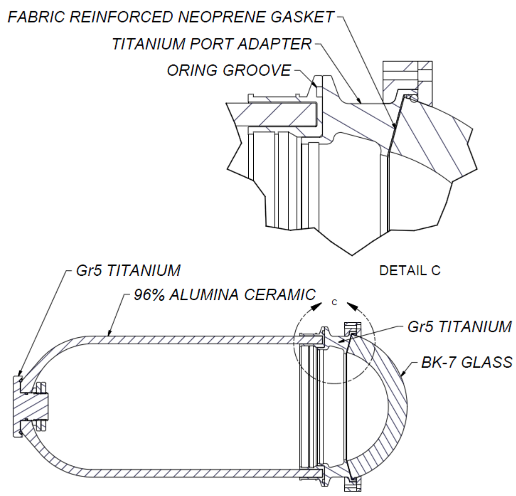

Fig.7 Camera housing with glass seat detailed

Fig. 8 shows FEA results of the camera housing. The results display axial deflection—shrinking lengthwise of the housing. Left to right, note a slight removal of rotation as axial deflection becomes more normal to the joint. The results range is halved to localize the results at the planar face. A slight decrease in the fillet radius (marked with * and ** in the figure) helped remove the rotation and align the resulting force through the joint ring and into the center of the ceramic housing wall. Note the difference between Fig. 6 and Fig. 8 as both display the axial deflection resultant of their forced geometry.

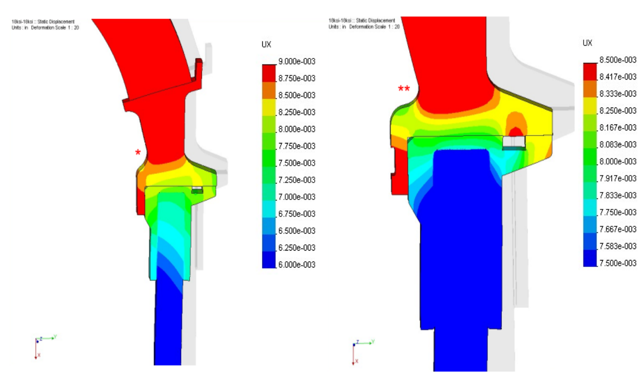

Fig.8 Glass dome seat/ joint ring FEA. Axial results improve left to right as radius marked with * is decreased.

C. Penetrations

Ceramic penetrations cause stress concentrations and should be made as simple and smooth as possible, as shown in detail F of Fig. 9. Local or global shell thickness must also be considered. Stachiw et al. determined a thickness-to-diameter ratio of equal to or greater than 0.023 for 96% alumina ceramic [3].

Nereus utilized undersized bulkhead connectors, designed to float in the penetration so as not to impede ceramic deflection. At maximum depth, the ceramic never makes contact with the concentric connector. A sealing O-ring was used on the outside flange. A Kapton® polyimide gasket was placed between mating surfaces to prevent machined microgrooves in the titanium penetrator from damaging the ceramic boss. An O-ring was used to center the connector body; a nylon spacer, machined to match the hemisphere's inside diameter, and nuts hold the penetration assembly in place (Fig. 9).

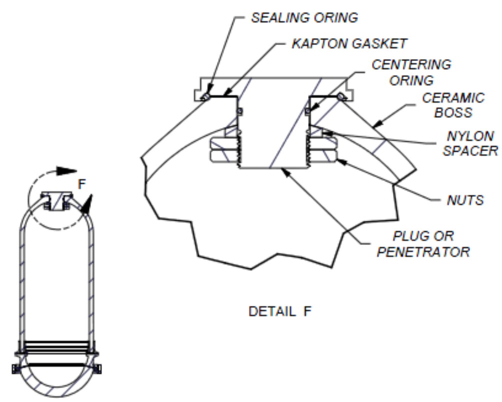

Fig.9 Ceramic boss with floating penetration

III. SUMMARY

Finite element analysis was successfully used to optimize the shape of the Nereus housing components. Metal parts were intricately shaped in areas requiring penetration, connection, mating, and sealing surfaces. Rotation was removed from ceramic/titanium interfaces. All unnecessary material was removed, creating as much buoyancy as possible. Each Nereus ceramic housing was proof tested to 124MPa (18,000 psi) and cycled to 114MPa (16,500 psi).

Fig.10 The Nereus main housing end cap with vacuum port sealing assembly

Times have changed from the old way of empirical testing to production, when a misjudgment could end in catastrophic results. With solid modeling, FEA, and software programs such as Under Pressure, multiple design iterations can be done on a personal computer (PC) before cutting metal or producing ceramic. Prototypes can be tested with results returned to FEA for verification or correction, enabling optimization on PCs. FEA shows trends that help the designer acquire an expert eye. Better analysis improves the product.

IV. Conclusion

Technical ceramics are changing the way we do deep oceanography. They are a viable material selection for PV components. Currently, alumina is a cost-effective alternative to titanium at abyssal and hadal depths. Circumferential crack development is the primary mode of failure, and great care must be taken in handling, shipping, and wrench wielding on the vehicle.

As ceramic material strength increases, so does the PV's resistance to cyclic fatigue and incidental damage. NCCOSC reports conclude [5], and current ceramic oceanographic products demonstrate, that silicon nitride housings offer great promise due to increased material strength [6, 7].

Stachiw et al. generated a guideline for the design, analysis, and testing of ceramic housings. This paper illustrates several examples of housing design that successfully followed that guideline—the Nereus main, utility, and camera housings. These housings are just one of the technical advancements that allow HROV Nereus to dive to the deepest parts of the earth's oceans repeatedly [8].

Acknowledgments

I am thankful to have had the opportunity to work with Jerry and Joan Stachiw. Regrettably, Jerry passed away in 2007 and did not see this work enable the exploration of the Marianas Trench in 2009.

Special thanks to WHOI colleagues Dana Yoerger, Andy Bowen, Casey Machado, Christopher Griner, Christopher Lumping, Daniel Duffany, Daniel Gomez-Ibanez, Donald Peters, Fredrik Thwaites, John Trowbridge, and Megan Carroll and SPAWAR's Richard Johnson.

Thank you to the National Science Foundation, the Office of Naval Research, the National Oceanic and Atmospheric Administration, and the Russell Family Foundation for funding support.

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