ALUMINA CERAMIC 3.6 IN FLOTATION SPHERES FOR 11 KM ROV/AUV SYSTEMS

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***ABSTRACT* - Spherical flotation units of 99.9% Al_2O_3 ceramic have been successfully produced by Deepsea Power & Light for application to 11 km ROV/AUV systems. The 3.6-inch (91.45 mm) OD seamless hollow spheres with 0.34 weight/displacement ratio have routinely withstood proof testing to 30,000 psi (207 MPa), 1000 hour sustained pressurization to 25,000 psi, and 10,000 pressure cycles to 20,000 psi (138 MPa). Each of the spheres provides 0.6 lb (272 gr) of lift. When encased in a 0.2-inch thick buoyant elastomeric boot, they withstood impact on concrete from a 6 ft elevation. Together with syntactic foam, they will provide most of the required lift for the WHOI HROV system with 36,000 ft (11 km) depth capability. An extensive QA procedure has been developed for each sphere, which requires not only adherence to tight dimensional and thickness specifications but also acoustic emission criteria during pressure testing.**

Deepsea Power & Light is also in the process of developing a roto-molding process for casting of alumina ceramic spheres with larger diameter for the whole range of ocean depths from 10,000 ft (3000 m) to 36,000 ft (11,000 m). Spheres with 5-inch (127 mm) and 8-inch (203.2 mm) outside diameter have already been successfully cast. The casting of even larger spheres will proceed upon acquisition of a larger furnace.

I. BACKGROUND

To support a payload while submerged, all underwater vehicles require buoyancy that is provided either by the pressure hull, flotation units attached to the hull, or both. Flotation units for deep submergence vehicles have traditionally been made from syntactic foam and glass or ceramic spheres. The syntactic foam, a composite of plastic and glass microspheres, receives its buoyancy from the glass microspheres embedded in a plastic matrix.

The buoyancy of the foam is a function of the wall thickness of the glass spheres and of their packing density in the plastic matrix. By screening of the glass spheres for size and wall thickness, one can tailor the pressure resistance of the syntactic foam. Utilizing this process, industry has developed syntactic foams for the whole range of ocean depths. The factor limiting their buoyancy is ultimately the packing density of microspheres in the plastic matrix that does not provide any buoyancy.

By minimizing the volume of plastic matrix, the buoyancy of the syntactic foam can be increased. One of the approaches is embedding in the foam large glass or ceramic spheres with higher buoyancy than the foam itself. The reason that large spheres can provide more buoyancy than equivalent volume of foam is that they are not burdened with plastic matrix.

In some cases the glass or ceramic spheres are not embedded in syntactic foam but are held in place in a framework made of lighter than water plastic. The sizes of spheres and their pressure resistance can be tailored to the requirement of the vehicle. The crucial items in maximizing their pressure resistance are material with high compressive strength, absence of joints, and minimum deviation from perfect sphericity and uniform thickness.

A major stumbling block to achieving maximum buoyancy at utmost reliability was the lack of fabrication processes that would deliver seamless spheres with uniform sphericity and shell thickness. The requirement for absence of joints derived from the fact that presence of joints introduces local tensile stresses causing the spheres to fail under long-term, and/pr cyclic pressurizations at a lower pressure than it would in the absence of joints (Reference 1).

This problem was resolved in 1964 by COORS PORCELAIN by developing a casting procedure that allowed production of seamless hollow spheres of 10 inch OD with a nominal depth rating of 20,000 ft (Reference 2). Although the spheres were less than perfect they performed satisfactorily. Because of the large variation in shell thickness the critical pressure of these spheres varied $\geq$5000 psi, and the peak stresses at failure by >200,000 psi. Still, because of their conservative design, the lowest critical pressure exceeded the 9000 psi design pressure by $\geq$100 percent. However because of the large variation in structural performance between individual spheres, they were considered too risky for application on manned submersibles. As a result, their share of the market decreased to the point where the fabrication costs became unprofitable and by the late 1960’s COORS PORCELAIN closed their production for good.

It required the appearance of ROV’s and AUV’s for deep ocean exploration to renew the demand for ceramic floats with buoyancy superior to syntactic foam available on the market. One of such ROV’s is Woods Hole Oceanographic Institution vehicle for exploration of abyssal depths. Not satisfied with the buoyancy provided by the commercially available syntactic foam for 36,000 ft (11 km) service, WHOI canvassed ceramic manufacturers to find supplier capable to manufacture ceramic seamless spheres for 36,000 ft (11 km) service. Only two, Technical Custom Ceramics (Reference 3) and Deepsea Power & Light, demonstrated their ability to cast seamless spheres. Both were commissioned to produce ceramic spherical seamless shells for the 11 km HROV, CTC 10-inch (Reference 4) and Deepsea Power & Light 3.6-inch spheres. This paper focuses on the design, fabrication, structural performance, and quality control of 3.6-inch OD spheres supplied to WHOI by Deepsea Power & Light.

II. INTRODUCTION

Before the spheres could be incorporated into the 11 km HROV under construction by WHOI, several issues had to be resolved satisfactorily to preclude implosion in service. Implosion even of a single sphere may initiate sympathetic implosions of other spheres on the vehicle and the resulting loss of buoyancy would sink the vehicle. To preclude implosion in service sufficient care had to be exercised over the design, fabrication procedure, quality inspection, and performance testing. With proper attention to details, the ceramic spheres should be as reliable in service as are the acrylic plastic spheres serving as the pressure hulls on manned submersibles.

Unfortunately this was not the case with the first generation of ceramic spherical buoys by COORS PORCELAIN in the 1960's resulting in some unexplained implosions in service that made their use questionable. The sole criterion was, and in some case continues to be today, that the fabricated spheres be proof tested to operational, or some minor overpressure, prior to placement in service. Experience has shown that an over pressure test demonstrates only that the tested sphere was able to withstand successfully one short-term pressurization without failure and nothing more. A proof test is the last step in QC only if it is preceded by all the other steps called for in the QA program.

III. DESIGN

The design criterion selected for the 3.6-inch OD spheres was a safety factor of two based on the 16,500 psi (113.8 MPa) pressure specified by WHOI for its 11 km HROV with 36,000 ft (11,000 m) service depth. The same safety margin had to apply both to the magnitude of stresses as well as elastic stability at critical pressure.

To achieve the 100 percent safety margin, the average shell thickness of the spheres was calculated to be 0.060-inch (1.5 mm) using Equations 1 for prediction of material failure (Reference 5) and 2 for prediction of buckling (Reference 5 and 6):

EQ 1

$$p_{cr} = \frac{\delta\,(R_o^3 - R_i^3)}{1.5 \times (R_o^3)}$$

EQ 2

$$p_{cr} = K \times E \times (t^2 / R_o^2)$$

Where E = 56,000,000 psi, modulus of elasticity, δ = 550,000 psi, compressive strength of 99.9% Al_2O_3, K = 0.56 has been derived by Dr. Stachiw from destructive testing of over thirty 10-inch OD ceramic seamless spheres fabricated by COORS PORCELAIN for the Naval Ship Research and Development Center in 1969 (Reference 2).

The calculated critical pressures of 34,844 psi by buckling and 35,209 psi by material failure were high enough to allow ±0.01-inch variation in local wall thickness without reduction of calculated critical pressures below 33,000 psi mandated by the SF = 2 requirement.

IV. VALIDATION OF DESIGN CRITERIA

The selected SF = 2 based on short-term destructive testing is more than adequate to provide a safety margin for a single service dive to design pressure. Whether it is adequate to provide a safety margin for long-term and/or cyclic pressurizations to design pressure, typical of ROV and AUV's had to be experimentally validated, as it has been experimentally proven that the implosion pressure under long-term and/or cyclic pressurizations is significantly less than under short-term pressurization. This is due to the fact that ceramic under tensile strain exhibits time dependent failure. Although the loading on the spheres under hydrostatic pressure is compressive, some tensile strains are always present at microscopic discontinuities in the material causing it to fracture under time depending static or cyclic load application.

The validation of selected 100 percent short-term safety margin was focused on generating experimental data on the static and cyclic fatigue of 99.9% Al_2O_3 spheres with 3.6-inch OD cast by Deepsea Power & Light by the proprietary roto-molding technique. On the basis of this data a finding could be formulated whether the static and cyclic fatigue life of the 3.6 in OD spheres with 0.06-inch wall thickness cast by Deepsea Power & Light for 36,000 ft (11 km) depth service meet the minimum operational requirements of a typical ROV/AUV which, as a rule, cumulatively exceeds 10,000 hours of static and 1,000 cyclic pressurizations to service depth.

The classic approach to generation of data on which static and cyclic fatigue life could be formulated consists of subjecting several spheres to sustained design pressure loading until they implode. The average length of time to implosion would be considered their static fatigue life. By the same token, their cyclic fatigue life can be formulated by pressure cycling several spheres to design pressure loading until they fail. The number of cycles prior to implosion would be considered their cyclic fatigue life. Because the classical approach requires the utilization of pressure vessels for thousands of hours, it is not utilized frequently. Instead the spheres are tested at pressures above design pressure, substituting the pressure differential above design pressure for time.

When the durations of sustained loading prior to implosion of pressure above the 16,500 psi (113.8 MPa) design pressure are plotted on a single graph, one can extrapolate from it the static fatigue life at 16,500 psi (36,000 ft/11 km in service depth). This was the approach taken for prediction of static and cyclic fatigue life limit for the Deepsea Power & Light 3.6-inch OD spheres with 0.06-inch wall thickness (Figure 1).

V. DISCUSSION OF DESIGN VALIDATION RESULTS

The test results generated during the experimental design validation phase fall into three categories: *critical pressures under short-term pressurization, sustained pressurization, and cyclic pressurization*. Each one of these test categories plays a different role in the validation of chosen sphere design, i.e. thickness of shell selected for the 16,500 psi (113.8 MPa) design pressure.

It is an accepted practice in the industry to rely solely on short-term non-destructive proof tests to qualify a flotation unit for a given pressure rating. In the opinion of the authors, this is not sufficient, unless a pressure test program utilizing destructive short-term, sustained pressure and cyclic pressurizations has already validated the design of the sphere. Only after such a design validation program has been successfully completed can non-destructive short-term pressurization serve as QC acceptance tests.

Short-term destructive tests-their objective in the design validation program was twofold; it served as a check on the calculated magnitude of critical pressure based on EQ 1 and EQ2 for prediction of implosion either by material failure, or elastic instability, and as a quality control tool on the uniformity of structural performance of mass produced spheres.

For the spheres designed on the basis of 100 percent safety margin, the short-term critical pressure was expected to be 35,200 psi if the implosion was caused by material failure at 550,000 psi compressive stress level, and 38,400 psi if the implosion was triggered by elastic instability. Unfortunately, pressure vessels were available only with 30,000 psi capability and thus all the short-term pressurizations were conducted only to 30,000 psi level. However, by extrapolating static critical pressures of spheres with weight <139 gr, the critical pressure of 139 gr spheres has been predicted to be ≥35,000 psi (Figure 1).

Since testing to 30,000 psi stresses the material only to 85 percent of calculated material short-term strength and 78 percent of buckling pressure, any failure of a sphere at 30,000 psi would be an indication that the structural performance is inadequate and is caused either by shortcomings in material quality or shell construction. In either case it would not be a representative example for long-term or cyclic pressure testing.

Since over 100 percent of spheres meeting the technical specification requirements of weight, minimum shell thickness, and sphericity did not fail under short-term (<2 seconds) pressurization to 30,000 psi, it can be concluded that their structural performance exceeds 85 percent of design strength (Table 1).

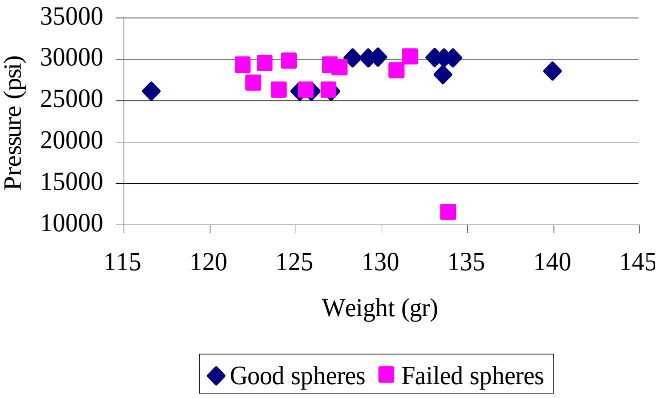
TABLE 1 SHORT-TERM PRESSURE TESTS

S/N	Weight(gr)	Shell Thickness(in)	Pressure(psi)
242	100.466	0.039	17,800*
245	100.247	0.039	16,100*
258	129.851	0.051	30,100
260	128.380	0.050	30,020
261	129.290	0.051	30,000
262	133.159	0.052	30,060
263	133.707	0.052	30,020
267	124.755	0.049	29,500*
271	127.680	0.050	28,700*
273	123.346	0.048	29,200*
274	122.672	0.048	26,800*
275	122.068	0.048	29,000*
277	125.746	0.049	26,000*
282	125.314	0.049	26,000
286	124.155	0.049	26,000*
287	127.07	0.050	26,000*
289	125.986	0.049	26,000
306	127.136	0.050	29,000*
314	131.786	0.051	30,000*
320	127.115	0.050	26,000
339	131.0	0.051	28,300
341	134.018	0.053	11,200*
415	134.211	0.053	30,000
500	140.000	0.055	28,410
561	116.661	0.045	26,000
573	133.636	0.052	28,000

Note: All spheres have a nominal 3.6 in OD.

*sphere imploded

FIGURE 1



Long-term destructive tests-their objective in the design validation program was to establish by experimental means the static fatigue life of the spheres at 16,500 psi design pressure. It was to be established by extrapolation of sustained pressure test results at 30,000 and 25,000 psi. Higher pressures than the design pressure were chosen to accelerate the implosion of spheres under sustained loading. Some tests were also conducted at other pressures in pressure vessels of opportunity.

The number of tests was not sufficiently large to provide an adequate number of data for statistical analysis. It was, however, large enough to establish confidence in the safe performance of spheres at design depth during mission of the WHOI 11 km HROV under extended duration. When the long-term data (Table 2) is plotted on a single graph (Figure 2) it becomes rather apparent that at 16,500 psi (11 km depth) design pressure the static fatigue life is in excess of 10,000 hours, providing adequate time for at least 100 missions each of 100 hours or 200 missions of 50 hours duration.

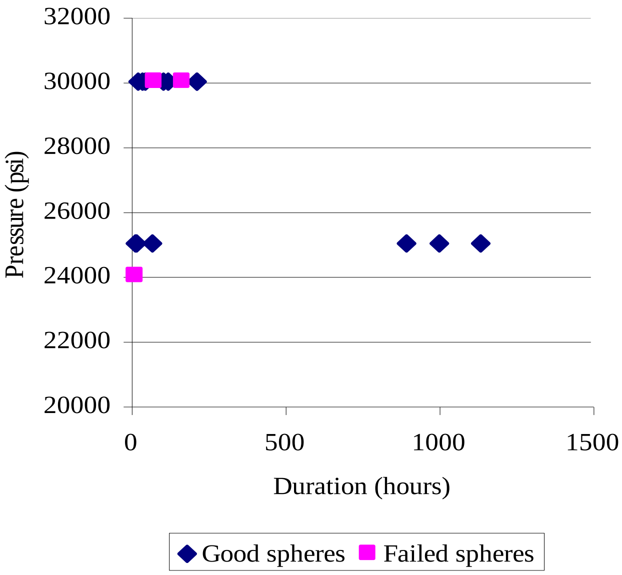
TABLE 2 LONG-TERM PRESSURE TESTS

S/N	Weight(gr)	Shell(in)	Pressure(psi)	Duration(hrs)
266	126.9	0.050	30,000	39
277	125.7	0.049	24,000	16*
282	125.3	0.049	30,000	122
309	131.2	0.051	30,000	215
314	131.8	0.051	30,000	169*
317	128.8	0.050	30,000	24
345	134.8	0.053	30,000	107
347	135.6	0.053	30,000	78*
351	138.4	0.054	30,000	78*
384	138.8	0.054	30,000	47
392	139.9	0.055	30,000	215
550	139.66	0.055	>25,000	1137
556	139.52	0.055	>25,000	1002
592	139.238	0.055	25,000	15
598	140.511	0.056	25,000	19
603	140.577	0.056	25,000	71
604	140.202	0.056	25,000	896

Note: All spheres have a nominal 3.6 in OD.

*sphere imploded

FIGURE 2



Cyclic pressurization destructive tests-their objective was to establish the cyclic fatigue life of the spheres under design pressure. Since the spheres are of seamless construction there was no opportunity to develop cracks at the equatorial joint, typical of spheres assembled from hemispheres. It is known from other studies conducted on ceramic and glass specimens that the intrinsic cyclic fatigue life of those materials under cyclic compressive loading is large enough to be beyond the engineering design scope of flotation units and housings for oceanographic service.

Only if mechanical joints are present in ceramic pressure vessels for an oceanographic applications does the cyclic fatigue life become the controlling factor of their service life. For example, at compressive bearing stress of 100,000 psi, the cyclic fatigue life is only about 500 cycles.

The cyclic pressure testing conducted on the seamless spheres has, on the other hand, demonstrated that their cyclic fatigue life at compressive membrane stress of 478,000 psi is >5000 cycles and under compressive stress of 337,000 psi is $\geq$15,000 cycles (Table3). Needless to say, at design stress of 256,000 psi generated by 36,000 ft design depth, the cyclic fatigue life of spheres with 0.06-inch thick wall will exceed the above values by a factor of at least 2.

Since the service fatigue life requirement for 11 km HROV is less than 1000 dives to 36,000 ft design depth, generating 256,000 psi membrane stress in the shell of the sphere the experimentally demonstrated cyclic fatigue life in excess of 5000 cycles under 478,000 psi membrane stress surpasses by a wide margin the specified 1000 pressure cycle fatigue life requirement at 256,000 psi. Although the typical duration of the pressure test cycle was less than 4 seconds, while that of a service dive is on the order of 10 to 20 hours, their effect on the cyclic fatigue life is the same. Published data indicates that it is the cumulative time under load rather number of cycles that define the cyclic fatigue life of brittle materials (Reference 7).

Since the demonstrated 6 x 10^4 seconds cumulative duration of 15,000 pressure cycles at 337,500 psi membrane stress is less than the demonstrated static fatigue life of 36 x 10^4 seconds at the same pressure on ceramic spheres, the effect of cycling can be disregarded so long as the static fatigue life at design depth exceeds the cumulative time under pressure during pressure cycling.

TABLE 3 CYCLIC PRESSURE TESTS

S/N	Weight(gr)	Shell(in)	Pressure(psi)	# of cycles
288	126.3	0.050	21,730	7,400*
285	128.94	0.051	20,000	5,108
475	141.059	0.056	20,000	11,753*
499	140.173	0.055	20,000	4,180
500	140.00	0.055	28,400	5,900*

Note: All spheres have a nominal 3.6 in OD.

*sphere imploded

VI. FABRICATION

The seamless spheres were fabricated by roto-molding in spherical molds assembled from well-fitted plaster hemispheres to meet the technical specification developed by Dr. Stachiw for 3.6-inch OD ceramic spheres with 16,500 psi pressure rating.

TABLE 4 TECHNICAL SPECIFICATIONS

a. Slurry composition, 99.9%Al_2O_3
b. Weight, 140 ±1 gram
c. Minimum thickness, 0.06 in ±0.01in
d. Outside diameter 3.60 ±0.05in
e. Diameter variation on each sphere, ≤0.03 in

Typical Characteristics of Roto-molded 3.6 in Ceramic Spheres for 11 Km Service

	Maximum	Minimum	Average
Weight (gr)	140.761	139.128	139.901
Diameter (in)	3.629	3.565	3.597
Thickness (in)	0.065	0.052	0.058

VII. QUALITY ASSURANCE PROGRAM

To minimize departure in structural performance from the test data generated during validation of design, a strict QA program was applied to the production of 3.6-inch OD ceramic spheres for service on WHOI vehicle.

Main features of QA Program:

a. Checking of weight for conformance to technical specification
b. Checking for minimum thickness for conformance to specification.
c. Checking of diameter and diametrical run-out for conformance to technical specifications.
d. Visual inspection for surface flaws and other anomalies.
e. Weeding out unacceptable structural deviations by subjecting each sphere to two pressure cycles, first to 30,000 psi, followed by a second one to 20,000 psi while monitoring for acoustic emissions.

The acoustical testing was accomplished by the use of a custom-built pressure chamber. The chamber was fitted with wave-guides that penetrated the lid and carried the acoustic signal directly from the test specimen to transducers mounted outside of the chamber.

VIII. DISCUSSION OF QUALITY ASSURANCE PROGRAM RESULTS

A sample batch of 20 spheres was selected and subjected to our quality assurance program. The spheres were tested based on the Technical Specifications (Table 4). Of the 20 samples only 2 were failed because they had surface flaws, which translates to a 90% success rate.

IX. FINDINGS

The 3.6-inch alumina ceramic spherical buoys with 0.06-inch wall thickness in production by Deepsea Power & Light meet the design and service requirements of buoys for 36,000 ft (11 km) service; they do not implode under short-term proof pressure to 36,000 psi (207 MPa), and 10,000 dives of 10,000 hours cumulative duration to 35,000 ft (11 km) design depth.

The quality assurance program developed for the production of these spheres assures that the spheres delivered to the customer for mounting on the ROV/AUV vehicles will perform in the same manner as the spheres tested in the design validation program. This is accomplished by checking each sphere for conformance to the Technical Specification (i.e. weight, diameter, thickness of shell) and structural performance requirements (i.e. proof testing to 30,000 psi followed by cyclic testing to 20,000 psi without increase in acoustic emissions).

This is the first time in the history of deep submergence enclosures made up of glass or ceramics that prior to releasing a product to the customer its design under static and cyclic pressurizations has been experimentally validated by the fabricator and its performance assured by a Quality Assurance program.

This was not the case with the first generation of ceramic and glass spheres marketed in the 1960's. Even today some of the glass buoys on the market were not subjected to design validation testing and it is up to the user at his own expense to perform the necessary pressure testing so that their static and cyclic fatigue life may be defined.

X. CONCLUSION

Deepsea Power & Light has succeeded in developing an economical mass production process for roto-molding alumina ceramic spheres whose dimensions and structural performance are repeatable, making them interchangeable in application. At the present time the production process is being applied only to 3.6-inch OD spheres with 0.06-inch wall thickness and their performance experimentally defined for 36,000 ft (11 km) service. Spheres with 3.6-inch OD but lesser wall thickness are also being produced by the same manufacturing process and equipment for structural evaluation.

Future plans call for modifying the roto-molding production process for economical fabrication of spherical buoys with diameters up to 18 inches for the whole range of ocean depths. Availability of spherical buoys with different diameters would allow for tighter packing of spheres in fairing envelopes of ROV/AUV vehicles regardless of the size selected.

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