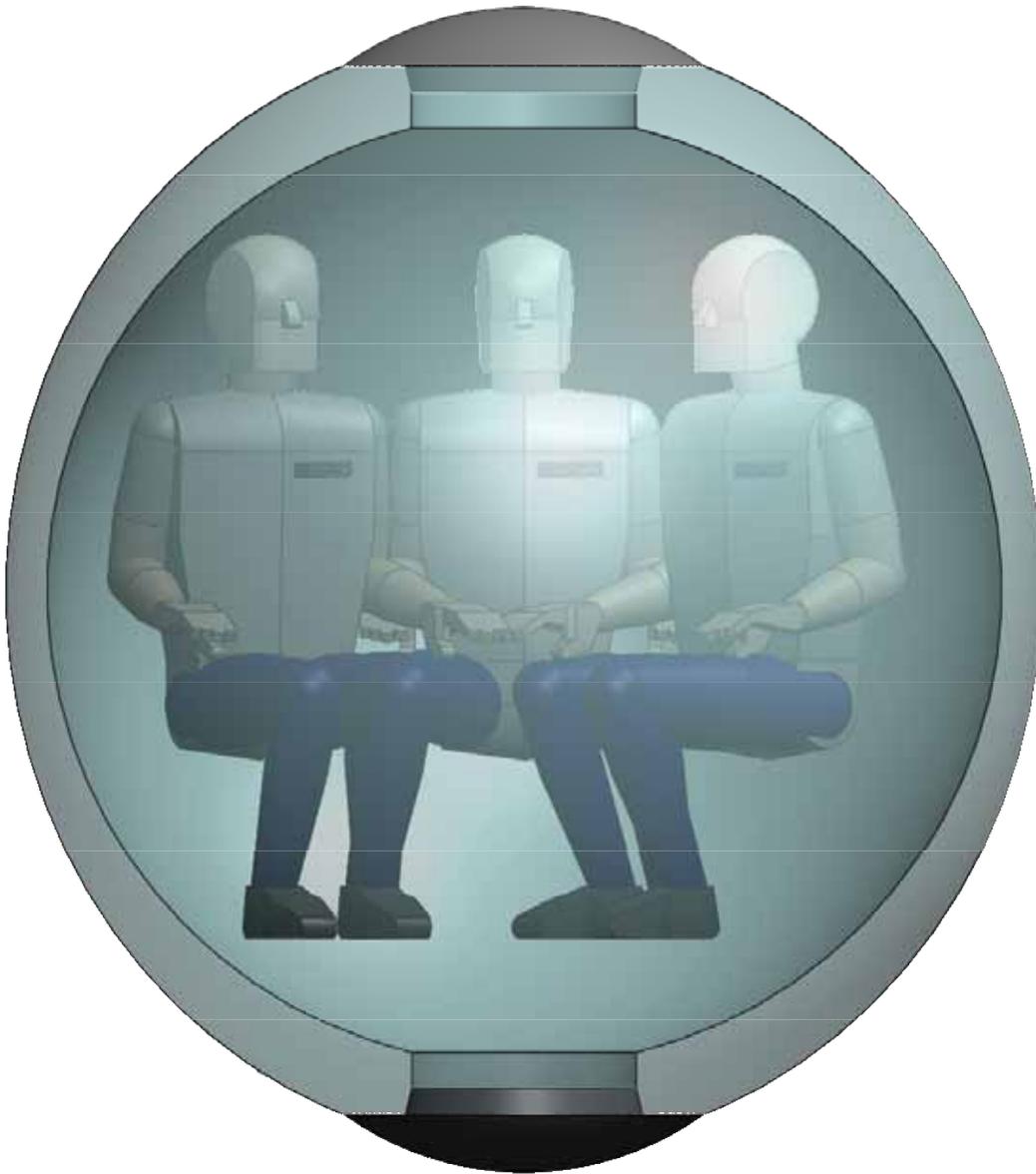


**1.2.7.20.1 Glass Research Activities Report (2-12 to 4-7-09)**

**Note: Portions of this document have been removed or truncated to facilitate web posting.**



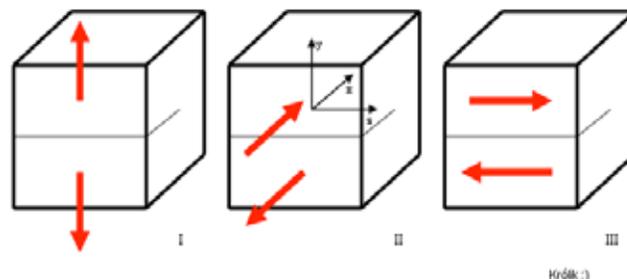
## Summary

No single component area will be as innovative as the proposed glass personnel sphere. Glass is a fantastic material for subsea use. It's incredibly strong in compression, transparent, and also relatively light. This combination of properties made glass very attractive to DOER for use in Deepsearch because it is the only pressure hull considered that could actually add buoyancy to the design. A glass pressure hull would also eliminate the need for separate view port integration, lending to a beautiful simplicity in the design. For these same reasons, the US Navy used or investigated glass extensively in the late '60s. Glass however presented a number of technical challenges, the most prominent being that the mechanical properties of glass were not well understood and analysis tools like FEA were only just coming into being. At that time glass was considered a material with unusual, almost mysterious properties; there was huge scatter in strength test data of glass for instance. Engineers had difficulty in quantifying its properties well enough to have confidence in structural designs as the science of fracture mechanics was in its infancy. Glass hydrospheres were essentially designed by trial and error, which inevitably lead to failures. These failures were not understood. Without confidence, the engineers fell back to forged metallic pressure hulls. Large structural glass manufacturing had its heyday in the '60's and '70's and most of the experts with experience in manufacturing large glass spheres are now in retirement or beyond. Fortunately for DOER a number of these experts (including Dr. Sheldon Wiederhorn and Dr. Suresh Gulati) were excited about the project. There have been many enthusiastic discussions on how DOER could best analyze and manufacture the glass sphere. In our meetings with these and other experts, we learned that since the '70's a tremendous amount of research has been done with glass chemistry, properties, and reliability analysis. In fact, glass can now be so accurately modeled that some of its behavior can be predicted all the way down to the molecular level. This glass group DOER has assembled tells us that glass engineering is no longer a mystery and has given us absolute confidence that our solution will work. In fact, there are now options. However, manufacturability is still a major hurdle. This is where a focused push will be needed to gain 100% confidence in an achievable solution.

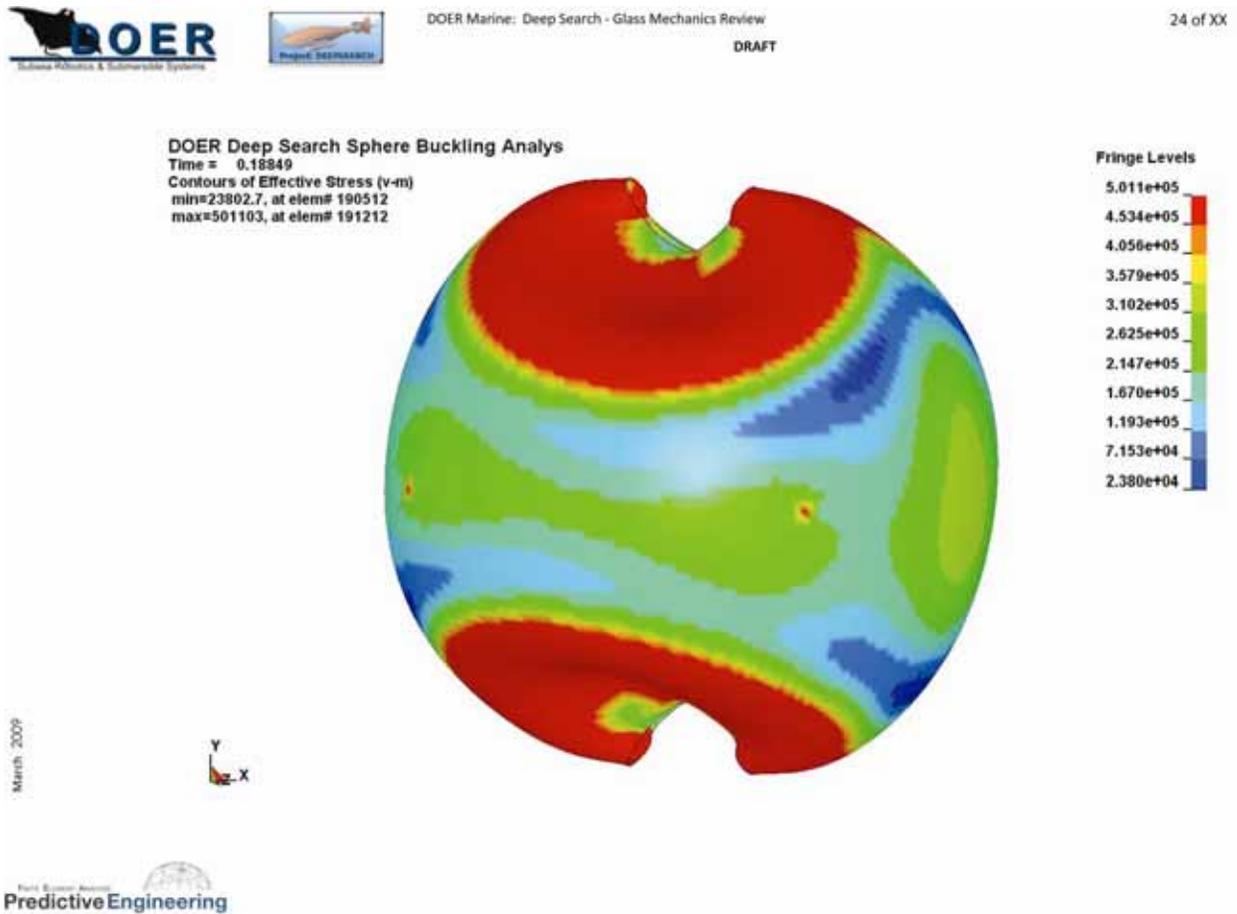
## Glass Expert Activity

Since the last review meeting, DOER engineers sought out and have consulted with world renowned experts in glass material science and glass manufacturing including:

- Dr. Sheldon Wiederhorn, Expert in subcritical crack growth. He verified that micro cracks will only propagate while glass is under tension. He advised us on efficiency of different treatments, coatings, claddings and inspection methods (or lack thereof). He has advised our FEA consultant regarding fracture mechanisms, and found research papers applicable to our project.
- Ron Argent – Glass manufacturing expert – He advised us on possible manufacturing methods and suitable manufacturing facilities. While he was confident that it could be made, he felt that no current capability existed to make the Hyper Hemisphere without some investment in infrastructure. He has advised DOER on a number of manufacturing techniques including slumping two halves, casting, and blowing the sphere into a roto-mold. He continues to work with existing manufacturing facilities to find a possible match.
- Dr. Suresh Gulati, Corning Research Fellow. He worked with Eroll Shand on borosilicate domes for submarine use, designed the Space Shuttle windows, including the reliability analysis therein. Dr. Gulati provided very useful insight toward initial mechanical feasibility analysis. He is available for further consulting. He feels that glass can be successfully utilized for a hydrosphere. He leans toward a dual hemisphere approach, but has not had time to evaluate the hyper-hemi design.
- Dr. George Laird, Predictive Engineering - DOER contracted with Dr. Laird to model and study glass mechanics and brittle material failure modes and mitigation using Finite Element Analysis (FEA) and other tools. In the initial meeting he theorized the likely failure mode of the Hyper-Hemi design may be from Mode II fracture growth (see center case below) around stones or other impurities in the glass. He will help us further investigate the Stress intensity factor for Mode II ( $K_{IIc}$ ) in glass, calculate acceptable values for flaw density, and develop scale model tests to quantify safe working stresses and cycle life. Studying theories presented to use by Corning for use in glass port seating. He has already started FEA modeling work. An amendment to this entry is that Mode II fracture has been deemed less likely than initially theorized. The current understanding is that a buckling failure is the most likely result; there is a 4X FOS in the current concept.



*Graphic illustration of Mode I, II, III stress intensity mechanisms for brittle fracture*



*Early FEA study that indicates FoS of ~4X for bucking failure of the concept sphere.*

- Dr. Reinhold Dauskardt, Stanford Prof. in Materials Research - He will make himself available to review our FEA results.
- Engineers and material scientists and the Univ. of Arizona Mirror lab – to learn from other groups who have successfully made and polished large glass structures. Tony and Seton traveled to Arizona and met with a group of eight who run the technical side of the mirror lab. The hyper hemi concept was discussed and consensus was that the lab staff felt that the concept was feasible and it could be made. They had particular confidence in post cast finishing of any shapes we presented.
- Dr. Murli Manghnani, high pressure physicist- Offered collaborative analysis using advanced testing and inspection equipment based at the University of Hawaii.
- Dr. John Brown, Retired Corning materials scientist, Technical Director GMIC- He has been a tireless advocate and organizer of contacts within the glass community, both for manufacture, design and testing.

- Dr. David Morse, Director of Research at Corning’s Sullivan Park
- Larry Sutton, Corning Canton Plant Product Line Manager
- Dr. Tim Roe, Corning Design and Construction leader, Mechanical Testing
- Dr. Eric Urruti, Director, Research and Development at Schott Glass US division. Initial contact has begun with Schott Glass. Corning and Schott have a sometimes competitive, sometimes collaborative relationship. Pushing both would hope to produce at least one with a manufacturing solution.
- Bill Raggio, Rayotek Scientific, Inc. Is currently engaged in final report on glass manufacture feasibility from a smaller company approach. Exploring other materials including sapphire.
- Discussed the project feasibility with numerous other experts.

## Engineering Concerns and Research

DOER Engineers sought to answer many questions. Historically, and even today, the majority of research and testing is applied to glass systems in tension. A spherical shell in hydrospace presents a unique, and somewhat ideal, loading case – pure biaxial compression. As such, many answers were not immediately forthcoming and require re-directing even to most scientific of minds. The most pressing questions are listed here:

- 1) What are the mechanical properties of glass in pure compression?
  - a) *Fused silica “flows” at ~600,000 PSI compression.*
- 2) How will bubbles (seeds), inclusions (stones), surface damage or flaws affect the strength and how can they be modeled in CAD?
  - a) *Fused silica can be made with virtually no stones or seeds. Corning produces large boules – 120” in diameter and 8”+ thick.*
  - b) *Initial reviews indicate that damage in the surface of the shell would not cause a catastrophic failure.*
  - c) *Regarding seeds, there are a couple of studies that have been done that are being provided by Dr. Wiederhorn.*
  - d) *FEA can model macro flaws. A gross imperfection (large flat spot) in the sphere was modeled, indicating a reduction in Factor of Safety to ~3.7, from 4.0 in a buckling analysis.*
- 3) Will a scale model simulate a full size model in testing?
  - a) *Scale model tests will yield important information, but a full scale test will be the final answer. Lab tests utilizing basic glass plates will yield valuable results even before scale model tests are initiated.*
  - 4) How can it be made? Rotomolding, Slumped halves fused, Blow molding, or cast? And who can make it for us?

- a) *This is still under investigation, but Corning and Schott are the main candidates as they have great research, analysis, and manufacturing resources.*

What glass chemistry is the right choice, and which treatments and coatings will be beneficial?

- a) *Fused silica and borosilicate are the main candidates. Research into surface coatings needs further effort but may prove more.*
- 6) How should it be finished / polished and who can do it?
- a) *University of Arizona Mirror Lab is the main candidate, but Corning and Schott are also viable. All are confident.*
- 7) What are the failure modes and which regions of the design will have the highest stresses?
- a) *Buckling failure is the main candidate for failure. The joint has been the main source of cracks historically, tension being the product of the connection. Dr. Gulati has engineering solutions to this problem.*
- 8) What will be the service life of a glass pressure hull?
- a) *This question remains to be answered, but research indicates that service life will be long as static fatigue (sub critical crack growth) is the main mechanism in service life failure. Fatigue only happens in tension above about 1000 PSI, our spherical design seeks to eliminate all tension or proof test to eliminate any crack growth.*
- 9) How can the glass be inspected?
- a) *Polariscope, Edge lighting, atomic force microscopy. Other methods still require investigation.*
- 10) How and where can the hyper-hemi design be tested and what pressure limits should it be tested to? What proof pressure?
- a) *Still under investigation.*
  - b) *This is still a major outstanding question. The basis is this: a critical minimum flaw size, under tensile stress, will fail catastrophically. If you can eliminate all flaws above a certain size with a proof test, then operate at a lower stress level that will not grow cracks in this known maximum flaw size. Failure is ruled out. Defining this differential needs to be worked out. Tensile systems use 3 times, which could prove onerous for the size of structure we are investigating.*
- 11) What will the approximate cost be to manufacture the glass spheres?
- a) *Still requires investigation. Intuitive responses from the glass community point to a cost of less than what was spent for the new Alvin hull.*

## Conclusion

Research on the use of glass for submersible applications mostly ended in the 1970's as world interest in the deep parts of the ocean shifted elsewhere. While glass had some early successes, research halted with the rise in acceptance of acrylics for shallow submersible ports and the realization by Naval research that glass is not a good material to resist nearby explosive detonations. Since that time considerable advances in fracture mechanics, reliability analysis, coatings, and manufacturing techniques have occurred. Software modeling tools like FEA have also improved to the point where we can model concepts and simulate both static and dynamic stresses. Luckily some of the older glass manufacturing experts and artisans that intuitively understand glass wanted to discuss our project. We also benefit from modern modeling tools which will shorten the design cycle, add confidence to our design, and reduce costly iterative models and tests.

DOER has sought out some of the world's leading glass scientists and manufacturing experts and worked with them to accurately model and evaluate the hyper-hemi glass personnel sphere concept. As we progress down this design path, virtually all research continues to increase our confidence that a massive glass hydrosphere can be built in some form, and reliability will be more than acceptable for a life support application. Additionally, these experts are unarguably the best minds to have present in a peer review atmosphere. As the FEA analysis has shown the model to be sufficiently within the known stress limits our focus has shifted from material properties and failure modes to investigating different manufacturing methods and facilities. The next phase will need to advance into testing glass samples, scale models, and scale hatch design testing.

The research to date has already yielded publishable findings that can be used for advanced hydrospace ports today. This information would yield glass ports that are larger and stronger than traditional acrylics utilizing advances in glass materials, fabrication, and materials science. We do notice substantial subsea industry resistance to glass from the previous era of failures. We are confident we can prove to open minds that the required advances have been made.