# Design and testing of a large sub-hemispherical glass port for a deep-sea camera

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M B A R I

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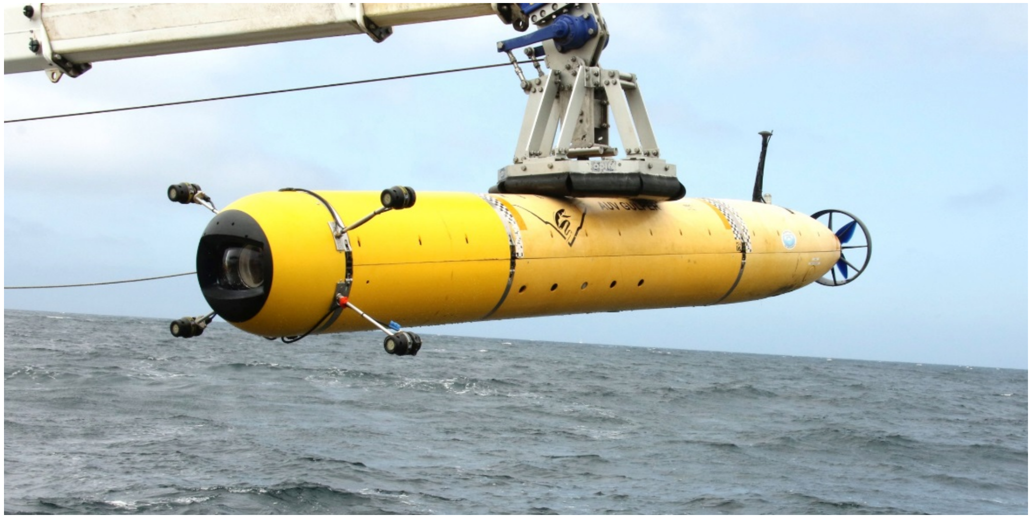
# Introduction

MBARI operates an autonomous underwater vehicle to carry out video surveys in Monterey Bay from 50m to 1000m depth.

A new camera system was designed with the goal of achieving the highest image quality and a depth rating of 1500m.

A glass dome port was designed, built and tested.

[ Note 1500m depth = 15.2 MPa = 2208 psi]



# *Glass composition and physical properties*

***Type: H-K9L (similar to Schott BK7)***

- ***Nominal composition (wt%):***

***69.1 $SiO_2$; 10.8 $B_2O_3$; 3.1 CaO; 10.4 $Na_2O$; 6.3 $K_2O$; 0.3 $As_2O_3$***

- ***Density = 2.55 g/cm3***
- ***Tg = 550°C***
- ***CTE = $70 \times 10^{-7}$/°C***
- ***E = 71.GPa***
- ***$\nu = 0.22$***
- ***$n_d = 1.523$***

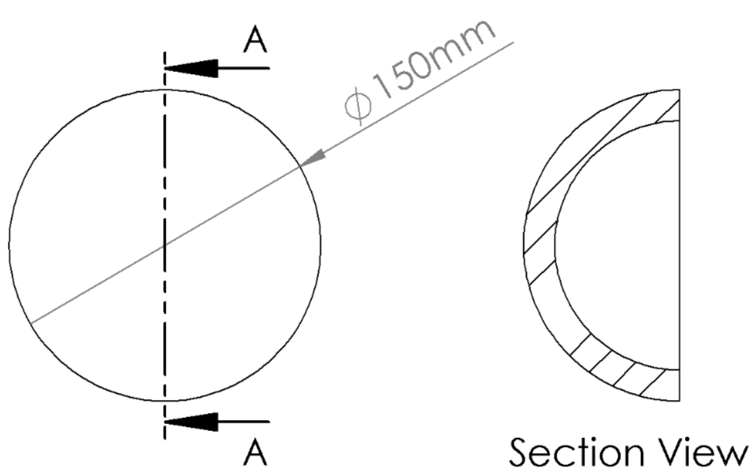
# Optical design

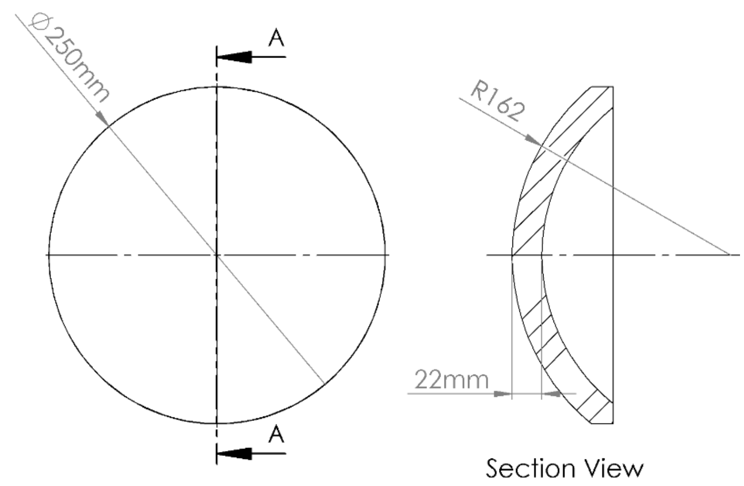
**Typical camera dome port**

- Shape is optimized to resist hydrostatic pressure
- Small diameter (<200mm)
- Hemispherical shape
- Even and easy to predict stress and strain.
- High distortion
- BK-7 glass

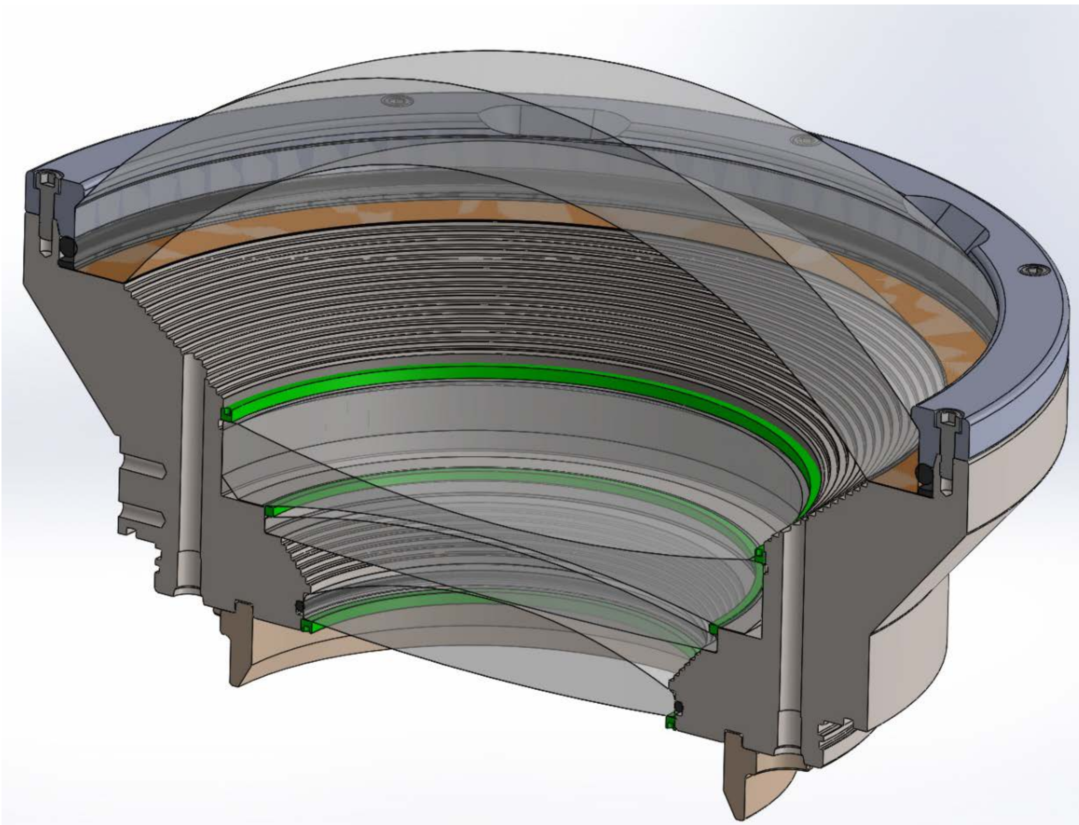
**New camera dome port**

- Shape is optimized for high optical quality
- Large diameter (250mm)
- Flattened hemispherical shape
- Uneven and hard to predict stress and strain.
- H-K9L glass (Chinese equivalent to BK-7)

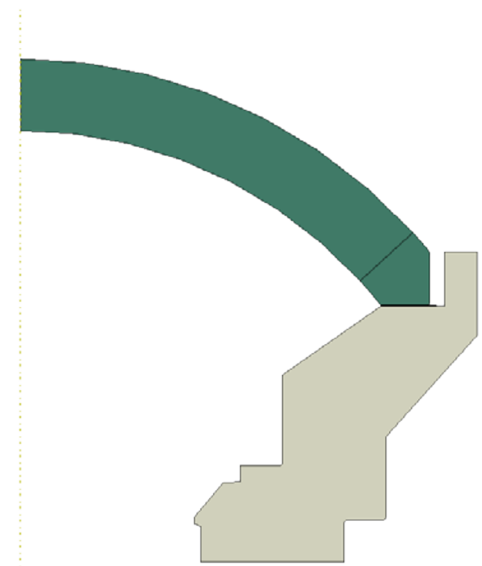


# Early design of dome

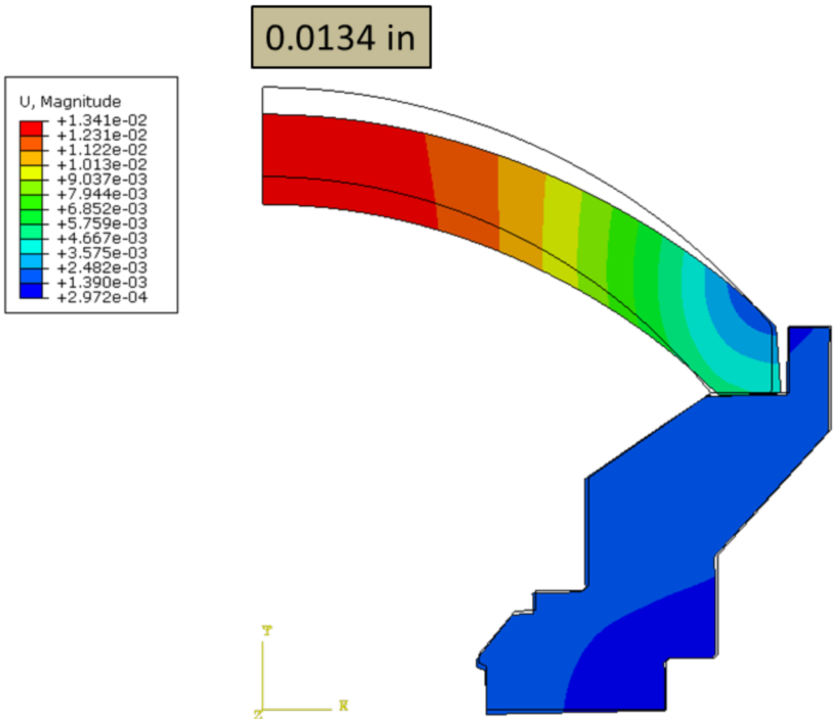


- Dome sits on kapton gasket
- Dome is held with plastic retainer.
- O-ring around dome



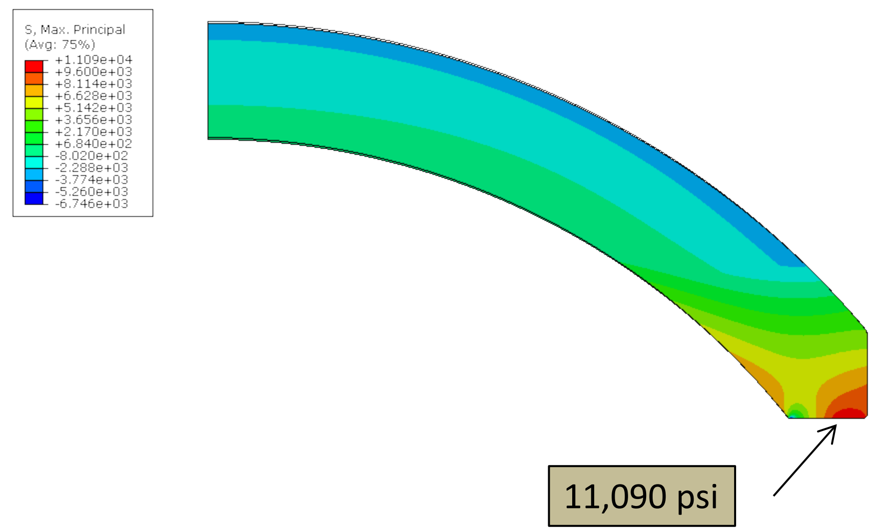
# FEA results at 2750 PSI (19MPa)

## Displacements




Maximum axial displacement
0.0134” (0.34mm)

## First principal (max tensile) Stress

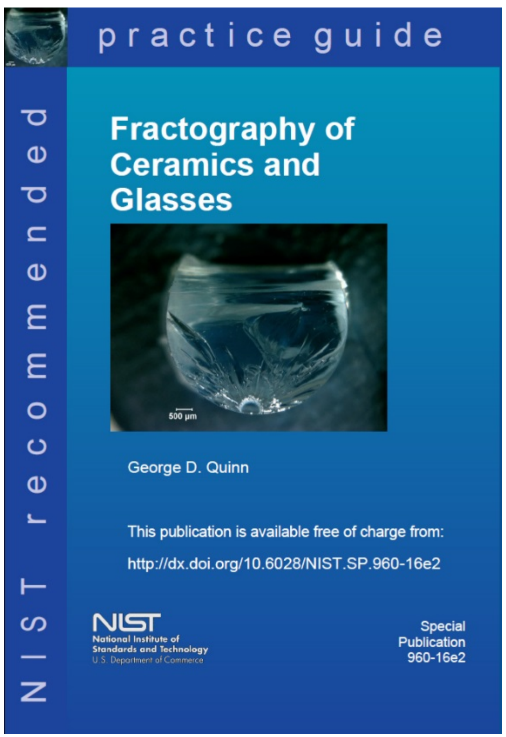



Maximum first principal stress
11090 PSI (76.5MPa)

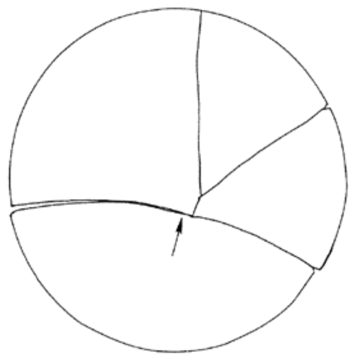
# Failure of early design

Dome failed during external pressure test after only 800 psi pressure
(5.6 MPa = 550 m depth)

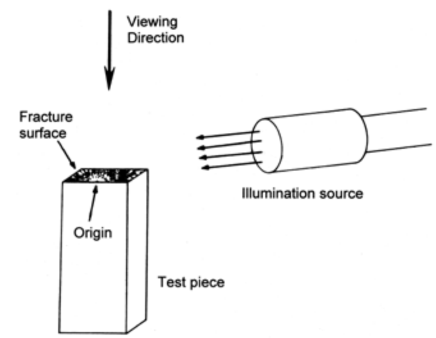
The broken dome was fractographically analyzed by G. Quinn using a WILD stereo optical microscope with a digital camera. The fractographic analysis included study of the crack patterns and the fracture surfaces.



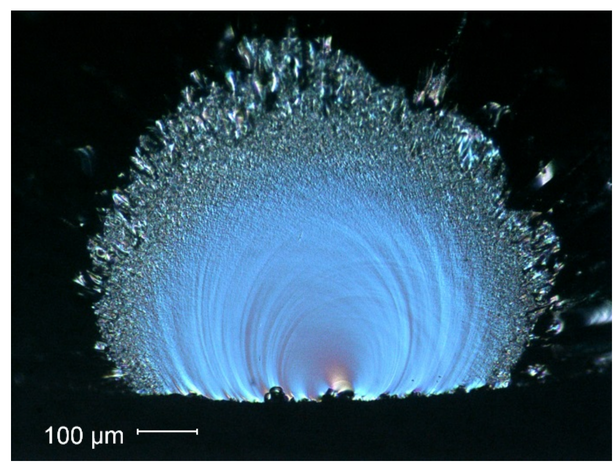

Patterns of breakage



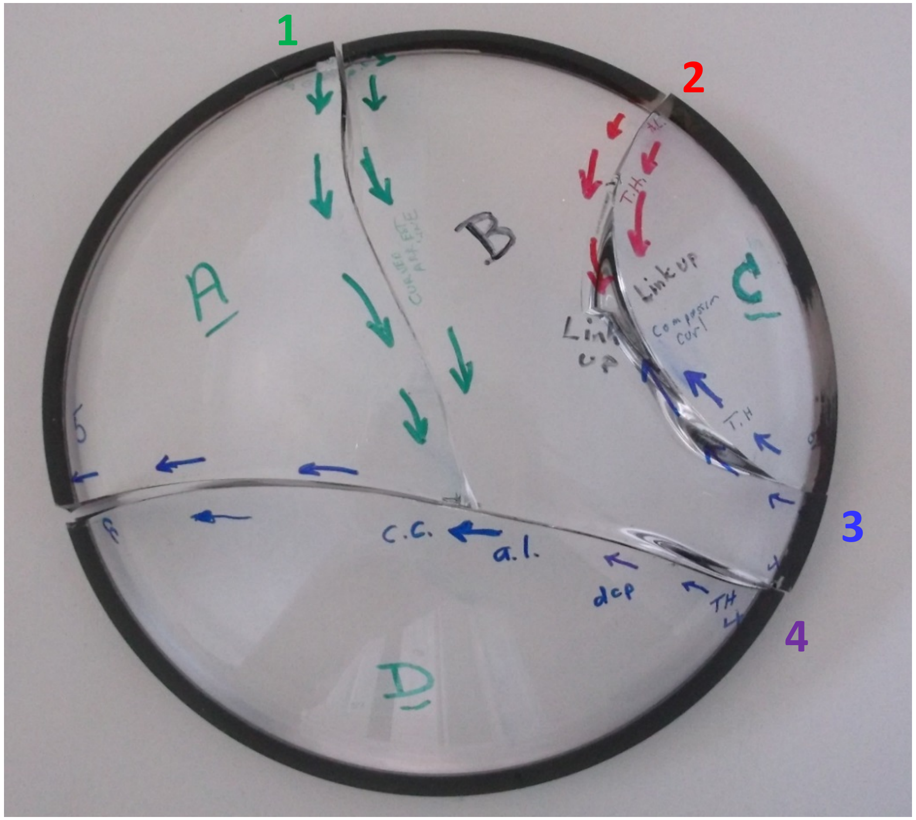
How to look




What to look for and how to interpret it.



# Fractographic analysis

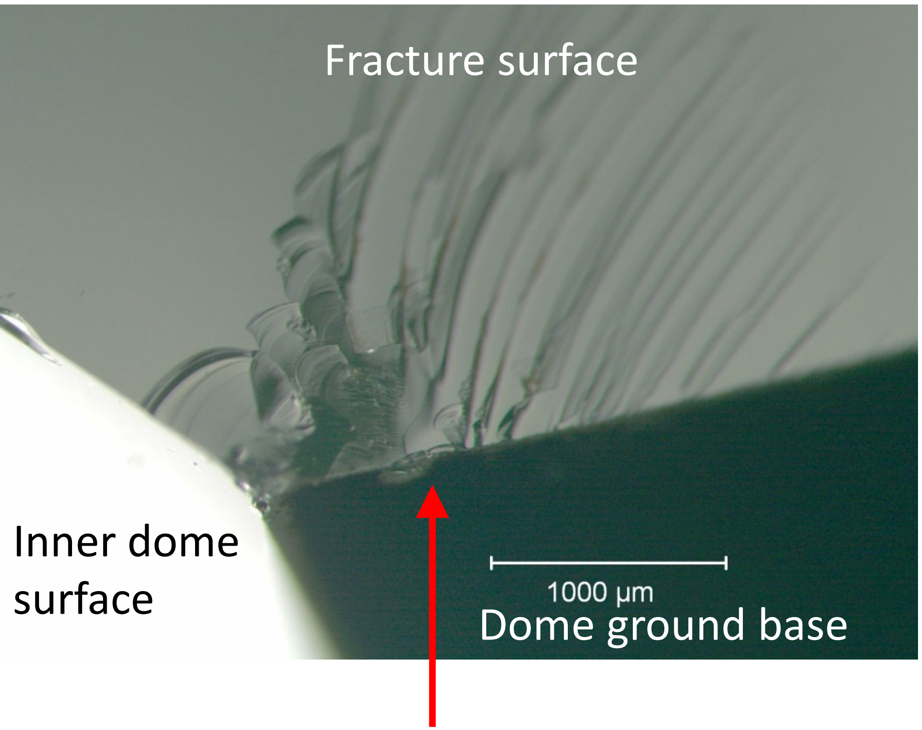


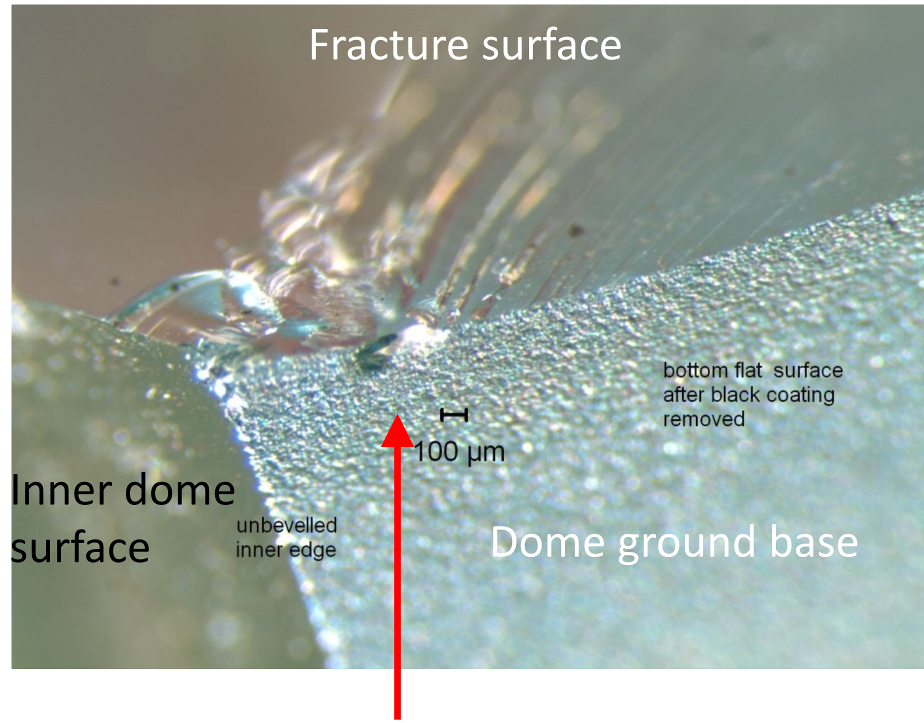

- All four origins were contact crack damage at the outer rim area.
- Origin 4 was the first to start the overall fracture.
- All flaws and initial crack propagation were driven by circumferential hoop tensile stresses.
- By the time the cracks propagated towards the middle, the stress changed to bending with tension on the inner dome surface.  This suggest that the  external pressure caused "splaying" of the dome.
- There were no fracture mirror boundary features, nor did any of the cracks branch.

# Fractographic analysis

Example: One of the rim contact damage cracks

2 views with different lighting at same magnification

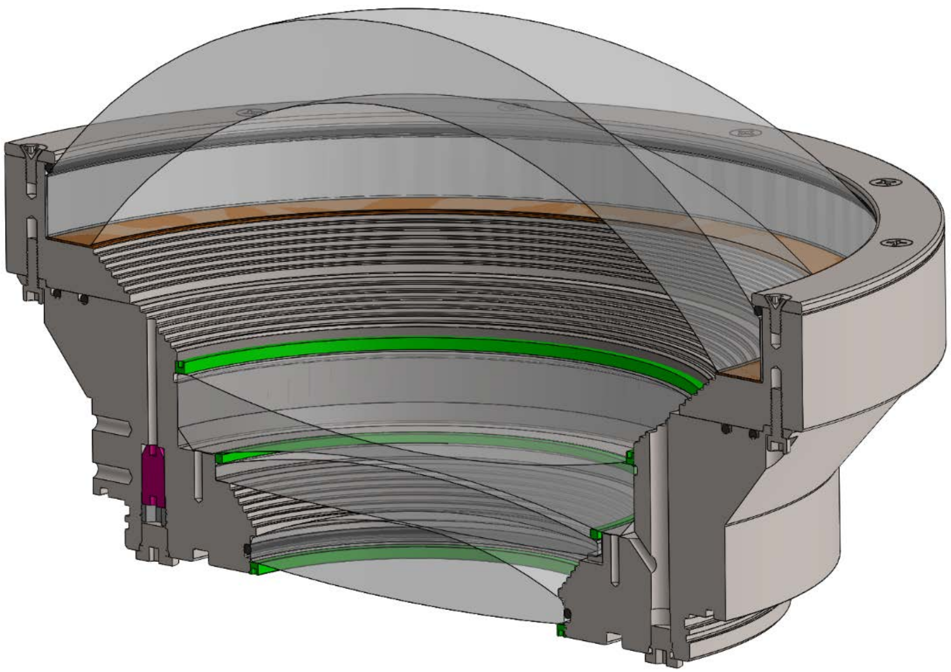


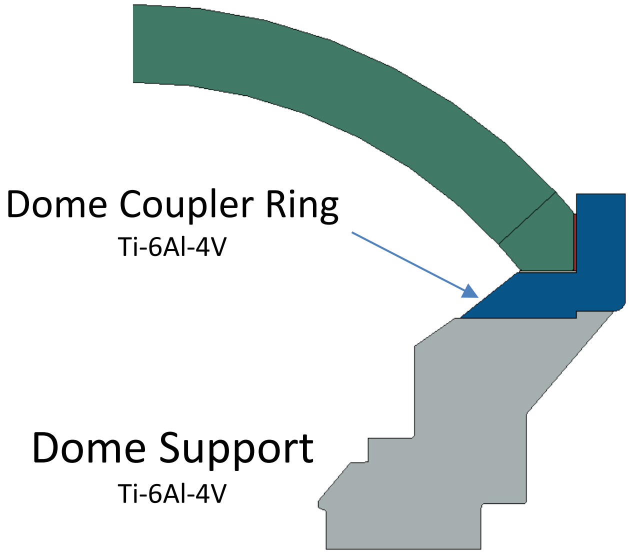

The origin is a contact damage crack on the bottom ground surface.

It is about 1 mm in from the unbeveled edge.

# Modified design

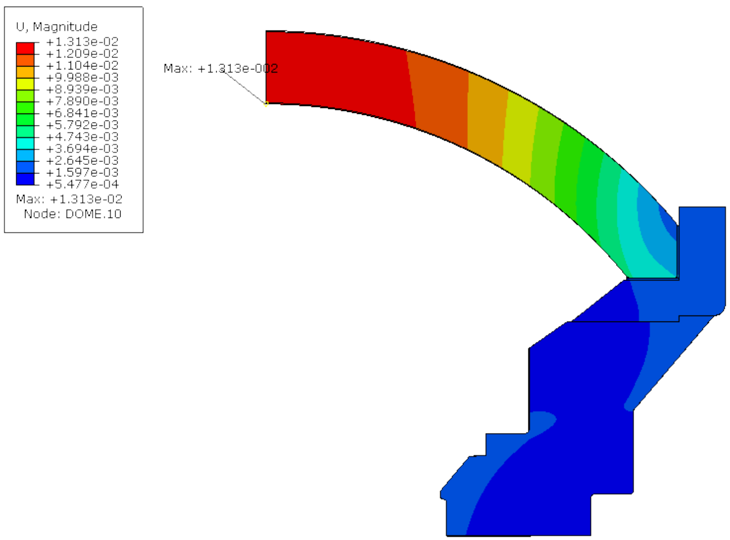


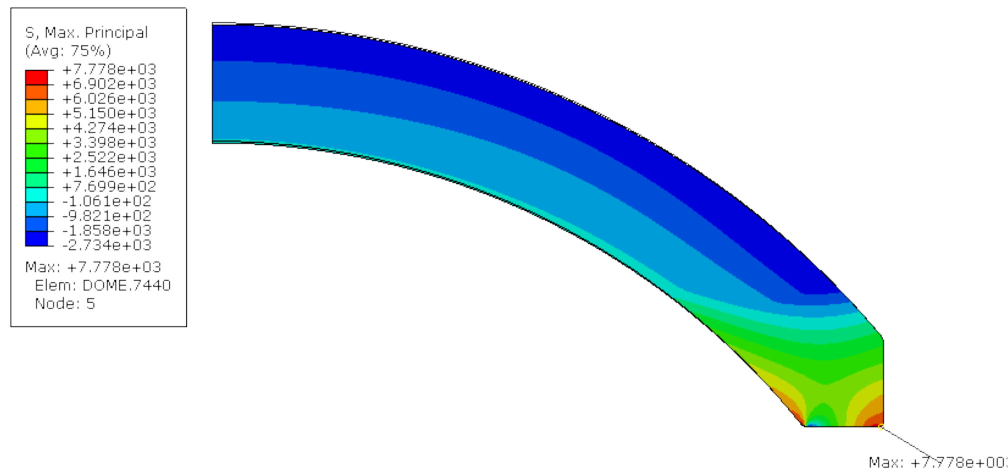
- Dome was bonded to titanium ring with epoxy to prevent lateral motion of dome seat
- Edges were beveled and polished
- Seat was polished and flatness tolerance was  decreased
- Thicker Kapton ring



# FEA of Modified design

- Axial displacement unchanged
- Tensile stress reduced 30%

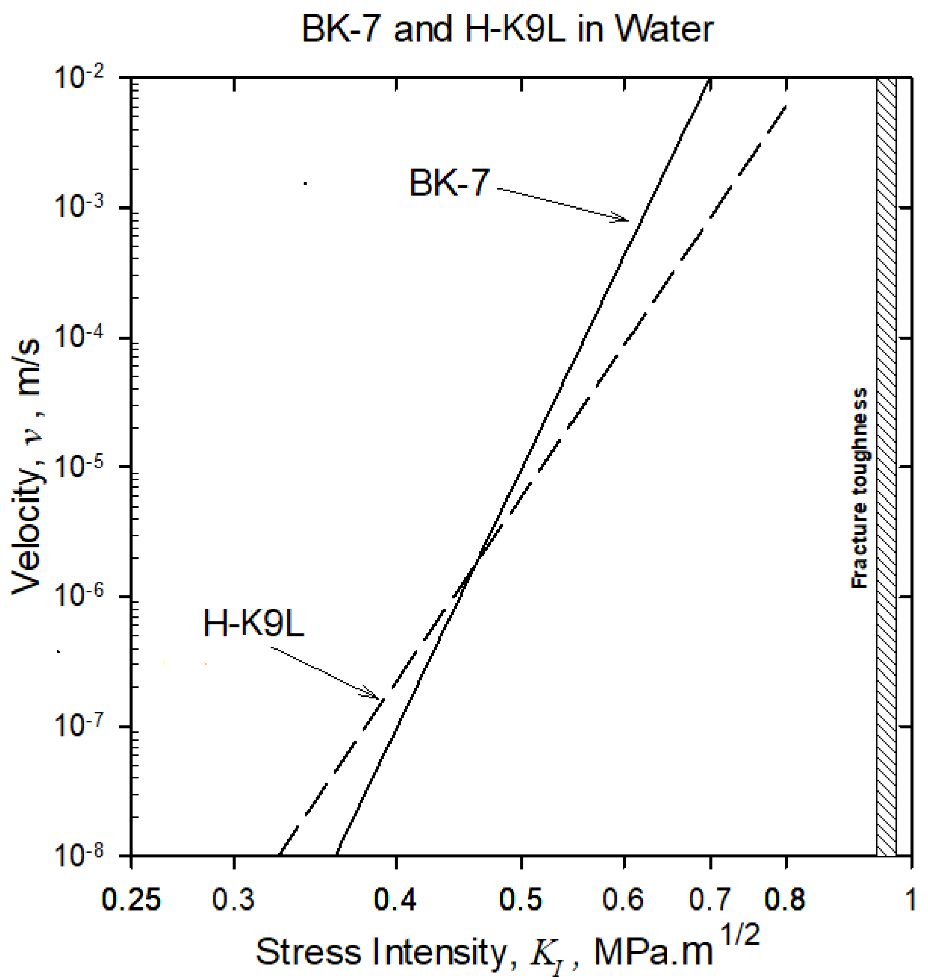


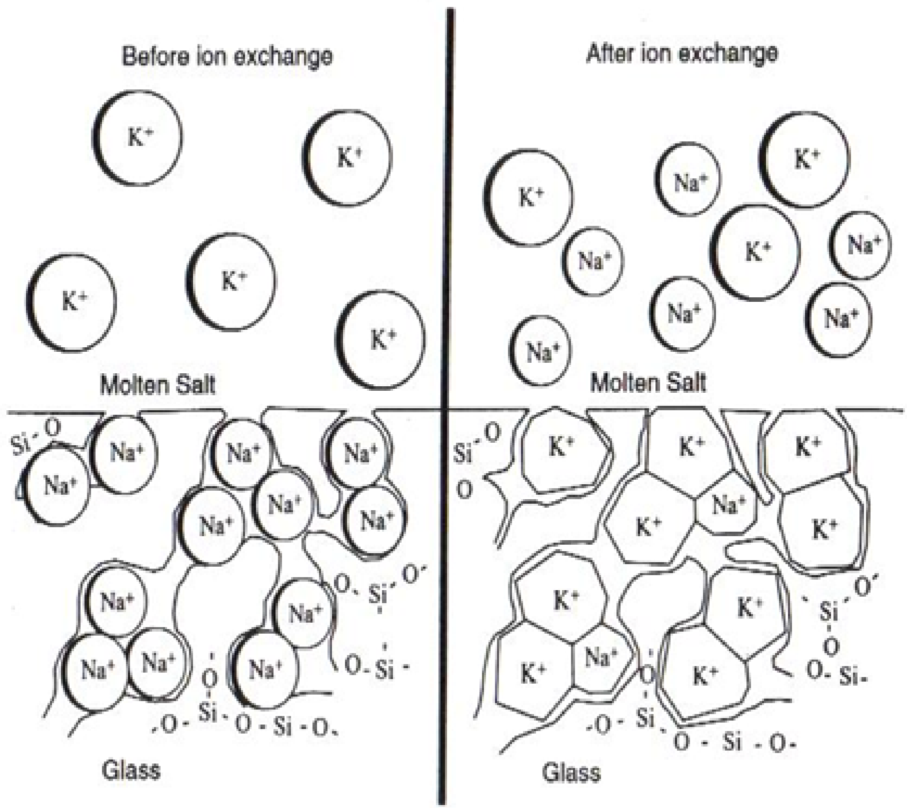

Axial displacement at 2750 PSI
Max = 0.013” (0.33mm)

First principal stress at 2750 PSI
Max = 7779 PSI (5.37MPa) (30% decrease)

# Results: crack growth behavior



# Chemical Strengthening of glass




- **Glass is immersed in a molten $KNO_3$ bath.**
- Sodium ions from glass surface diffuse out into the bath.
- **Potassium ions occupy those sites.**
- Stuffing leads to glass surface compression.
- **Compression leads to glass strengthening.**

# Chemical strengthening of the domes

Four domes
15 witness disk samples 2” dia x 2 mm thick,
(for subsequent biaxial testing and CS/DOL measurement)

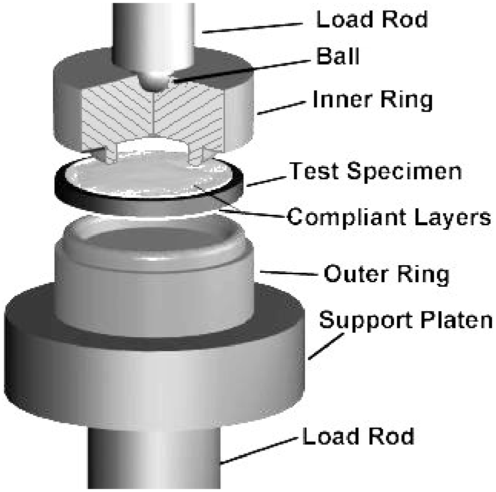
Hold domes in a stainless steel wire cage
Immerse in electrically heated steel tank containing molten $KNO_3$ salt.

Ion exchange at 450 °C for 24 hrs.

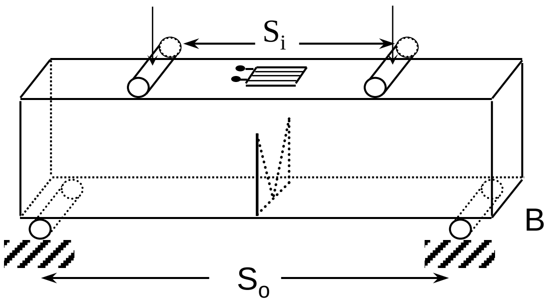
After extraction, carefully cool, wash and dry.
Compression layer (case depth “DOL”) = 45 μm.
Compression (“CS”) = - 430 MPa
(measured by FSM-6000LE)

# Material testing

- Fracture strength, slow crack growth parameters and fracture toughness are needed for the reliability analysis but are not published by the manufacturers.
- MBARI hired Jon Salem to measure these parameters for H-K9L (H-K9L is marketed as equal to BK-7 but is much cheaper)
- Chemically strengthened H-K9L was also tested.

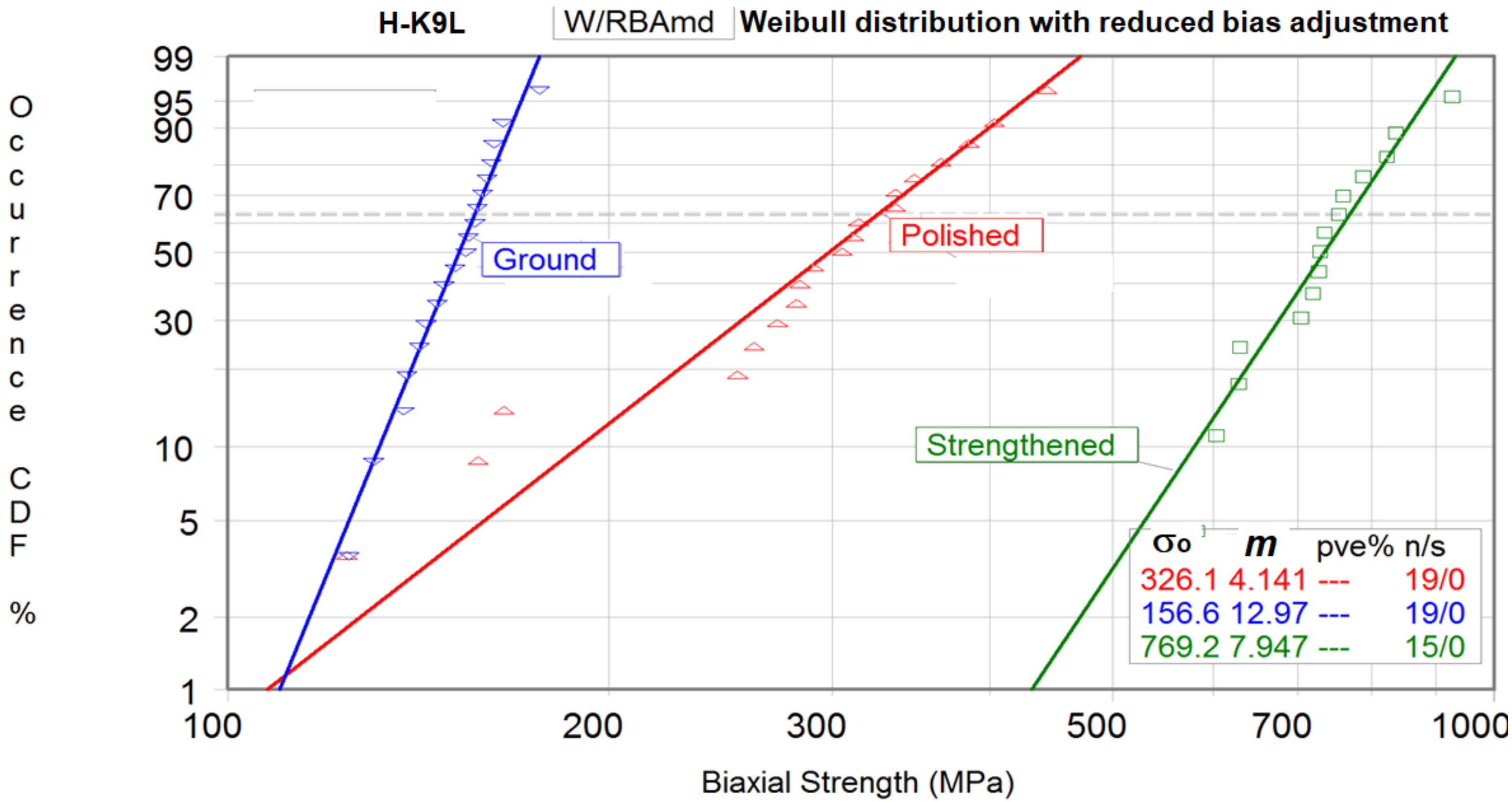



ASTM C1499




ASTM C1421

# Results: Comparison of plain and strengthened glass




| Condition | Normalizing | Weibull |
|---|---|---|
| H-K9L | Strength | Modulus |
| | (MPa) | |
| Ground | 157 | 13.0 |
| Polished | 326 | 4.1 |
| Strengthened | 769 | 7.9 |

**$\sigma_o$ = Normalizing strength**
***m* = Weibull modulus**
**n = number of specimens**
**s = number of censored specimens**

# Reliability analysis

MBARI hired Eric Baker of Connecticut Reserve Technology to perform brittle material reliability predictions on the camera port:

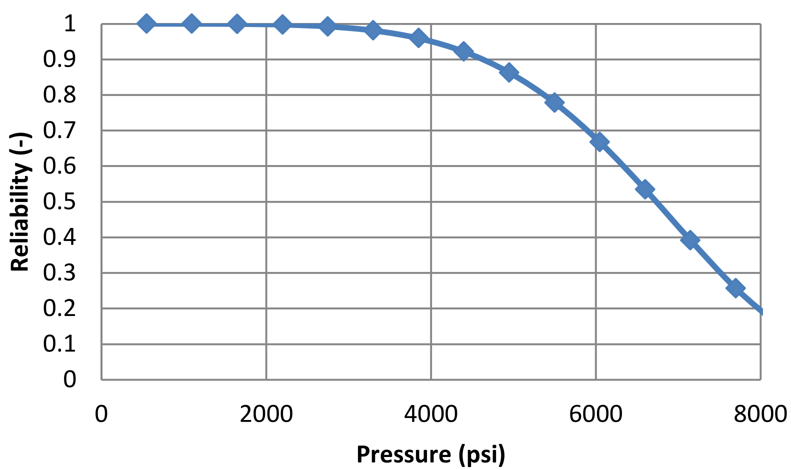
- Generated finite element analyses of dome configurations and calibrated models to MBARI FEA as well as pressure test measurements
- Estimated Weibull Material Properties from provided test data using WeibPar program
- Applied the **Ceramics Analysis and Reliability Evaluation of Structures (CARES)** program to predict the brittle material reliability of the dome configurations
- Established a proof test protocol to improve the reliability
- This analysis was performed for unstrengthened and strengthened glass.

# Example of CARES output

## Unstrengthened H-K9L glass

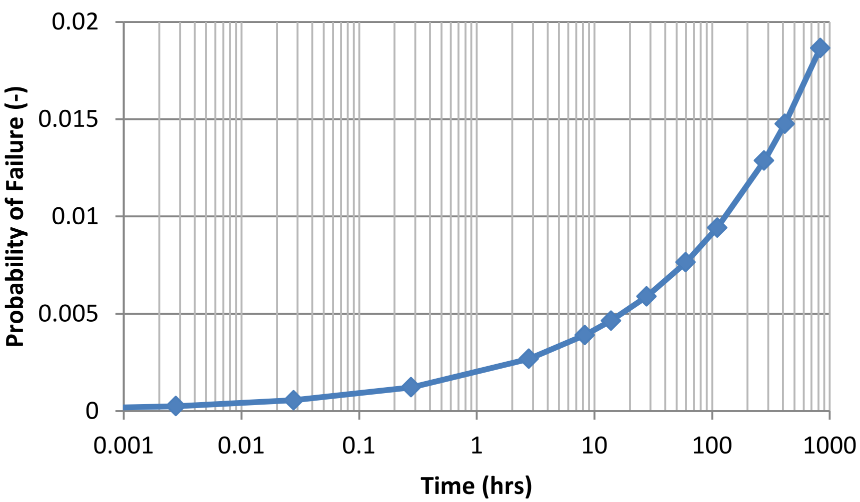
### Reliability as a Function of Service Pressure

where Service Time is 60 hrs.




### Reliability as a Function of Service Time

@ Applied Pressure 2750 psi




- FEA Stress Solution @ 2750 psi (= 19MPa = 1,875 m depth)
- **Probability of failure = about 0.75% at 2,750 psi for 60 hours.**
- Assumes Stresses Scale Linearly with Pressure
- Assumes other parts of Assembly can handle the increased Applied Pressure

# Reliability of chemically strengthened dome

**RELIABILITY OF INDIVIDUAL STEPS**

| Case | SERVICE Duration (hr) | SERVICE Pressure (psi) | Weibull Normal Individual Step Pf | Rel |
|---|---|---|---|---|
| 1 | 0 | 3000 | 9.55E-15 | 1.00000 |
| 2 | 10 | 3000 | 8.50E-10 | 1.00000 |
| 3 | 100 | 3000 | 3.92E-09 | 1.00000 |
| 4 | 200 | 3000 | 6.21E-09 | 1.00000 |
| 5 | 400 | 3000 | 9.85E-09 | 1.00000 |
| 6 | 1000 | 3000 | 1.81E-08 | 0.99999998 |

Pf = probability of failure

Predicted reliability of strengthened dome is very high even without proof test.

# Proof testing

- Domes were proof tested following the protocol determined by Eric Baker.
- Pressure and axial displacement of glass port were logged. Displacement matched FEA prediction.
- 2 strengthened domes were tested to 3000 PSI (= 20.7MPa i.e., ~2000m depth).
- 1 strengthened dome was tested to 5000 PSI (= 34.5MPa, i.e., 3400m depth).

**All domes survived**

# Conclusion

After the failure of an early design, several steps were taken to improve the reliability of the glass port:

- The edges and the base of the dome were polished, the flatness of the base was controlled.
- The dome was bonded to a titanium ring to prevent hoop tensile stress from appearing.
- Chemical strengthening greatly improved the strength of the glass.
- Reliability was predicted using CARES software.

**The camera housing can now be operated at 1500m with very low probability of failure**.

Using this method, deep sea cameras are no longer limited to small hemispherical domes. **Sub-hemispheres with large radii with better optical performance can be used and their reliability can be predicted**.

More research is needed on **life prediction for strengthened glass in sea water**. The residual stress field should be incorporated into the model for a better prediction.