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

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M B A R I

Outline

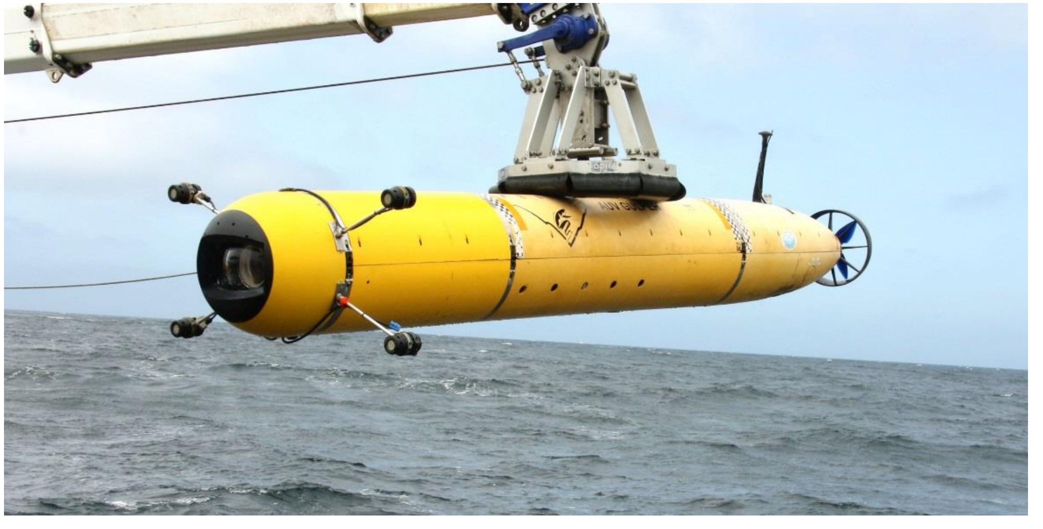
- Optical design
- First structural design and failure
- Fractography
- Modified design
- Material testing
- Reliability analysis
- Chemical strengthening
- Proof testing

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.



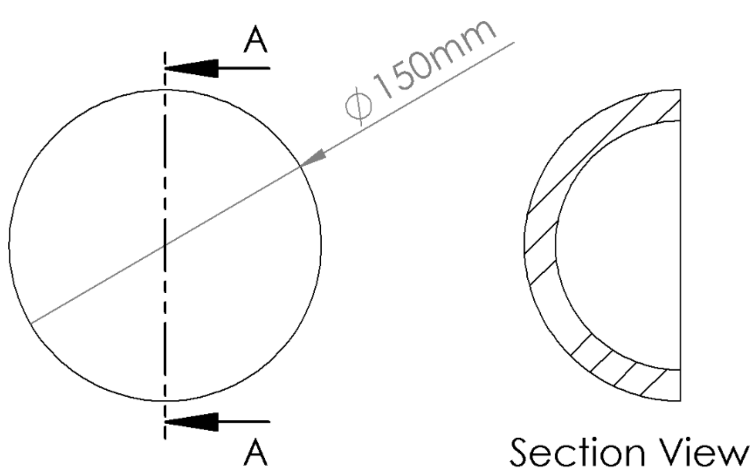
Optical design

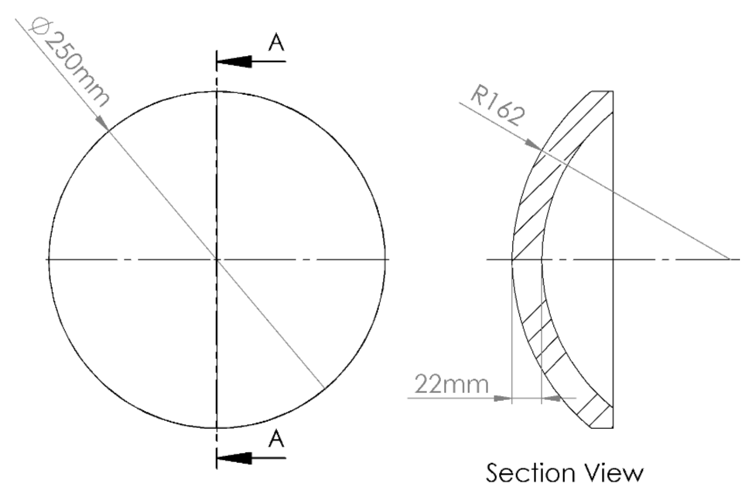
Typical COTS dome port

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

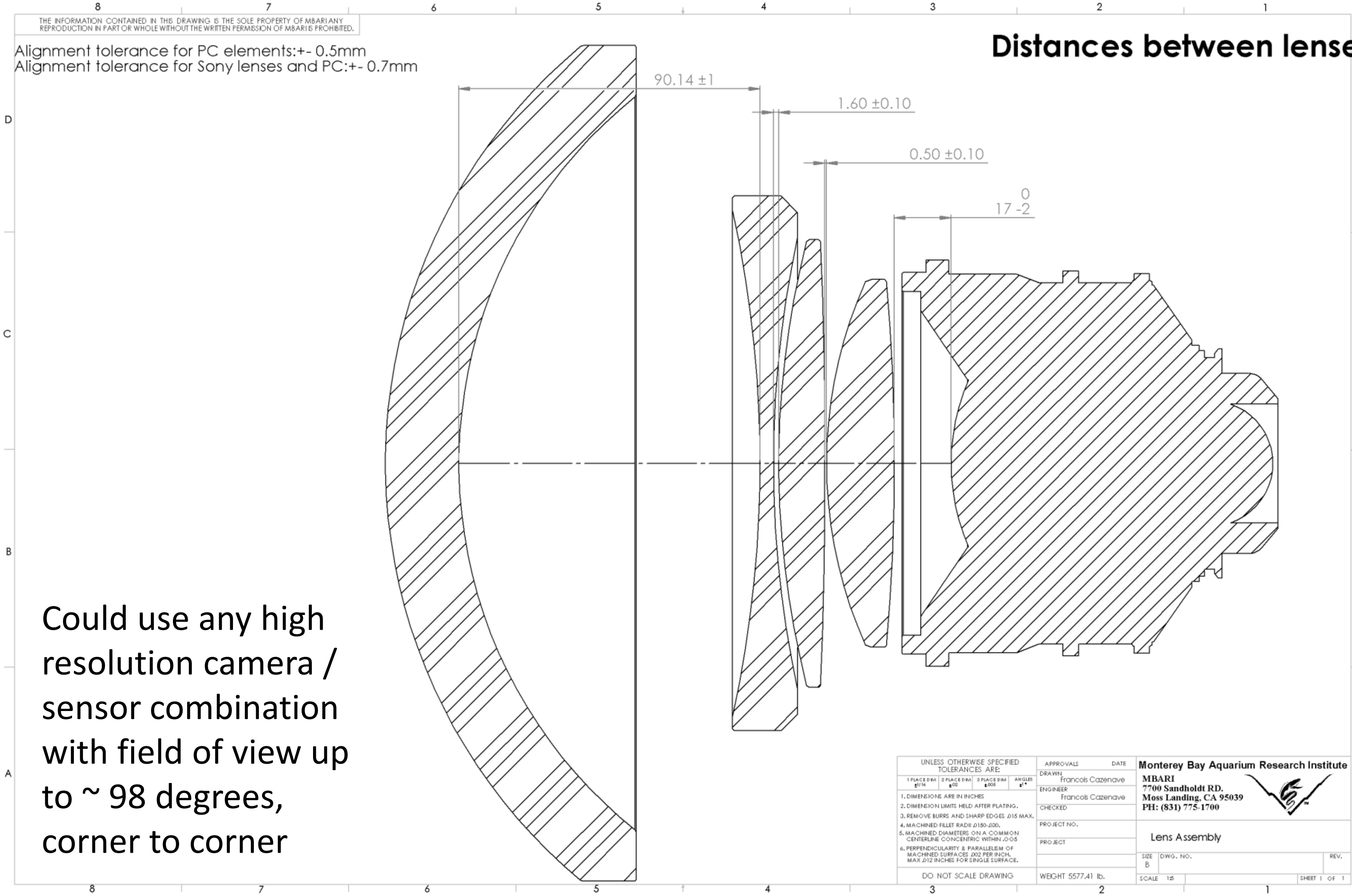
I2map dome port

- 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)



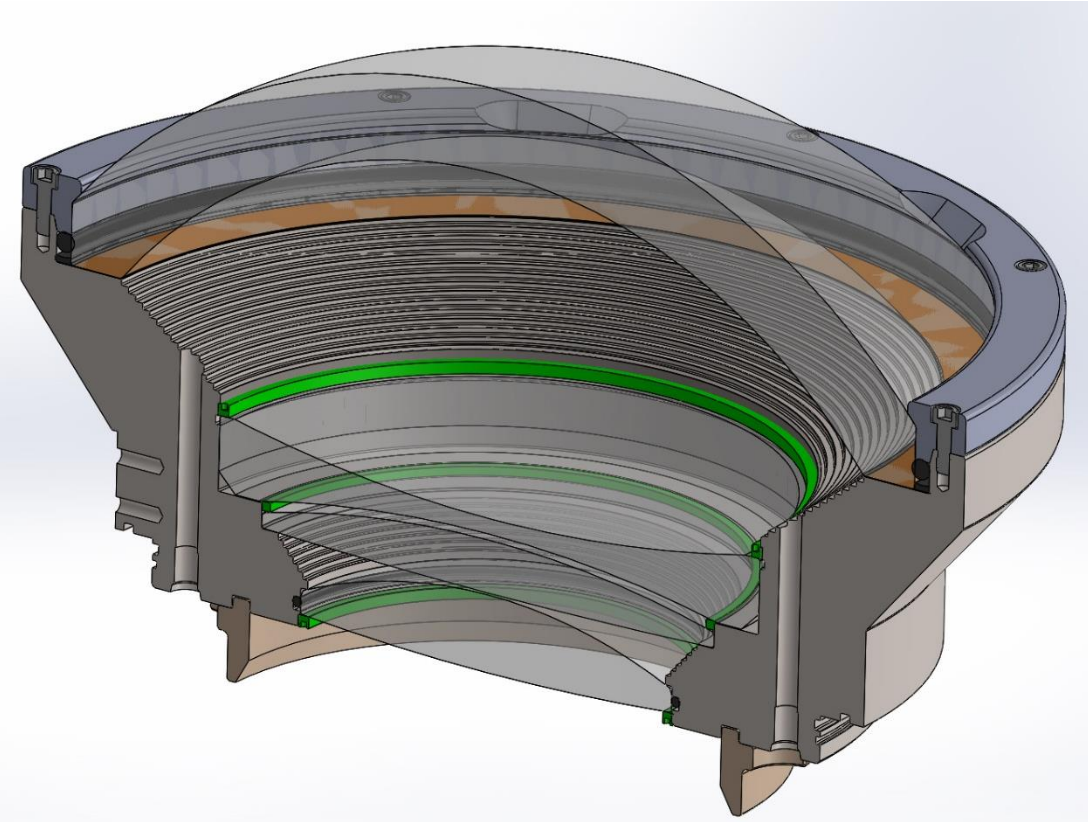


Distances between lenses

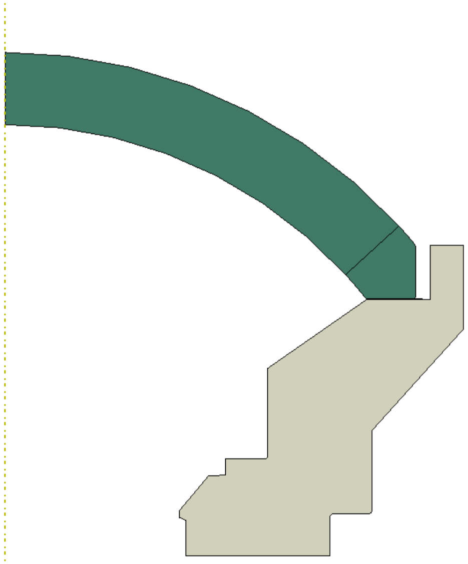


Could use any high resolution camera / sensor combination with field of view up to ~ 98 degrees, corner to corner

Early design of dome

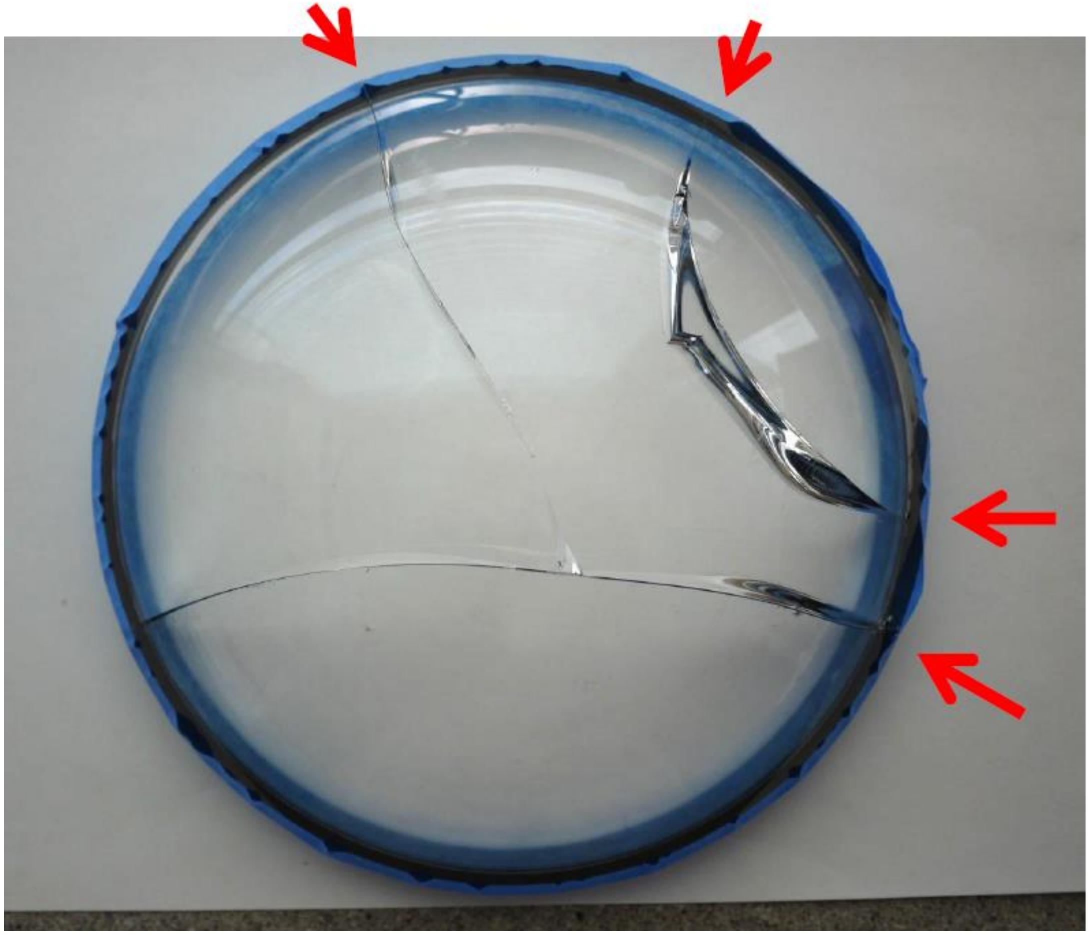


- Dome sits on kapton gasket
- Dome is held with plastic retainer.
- O-ring around dome

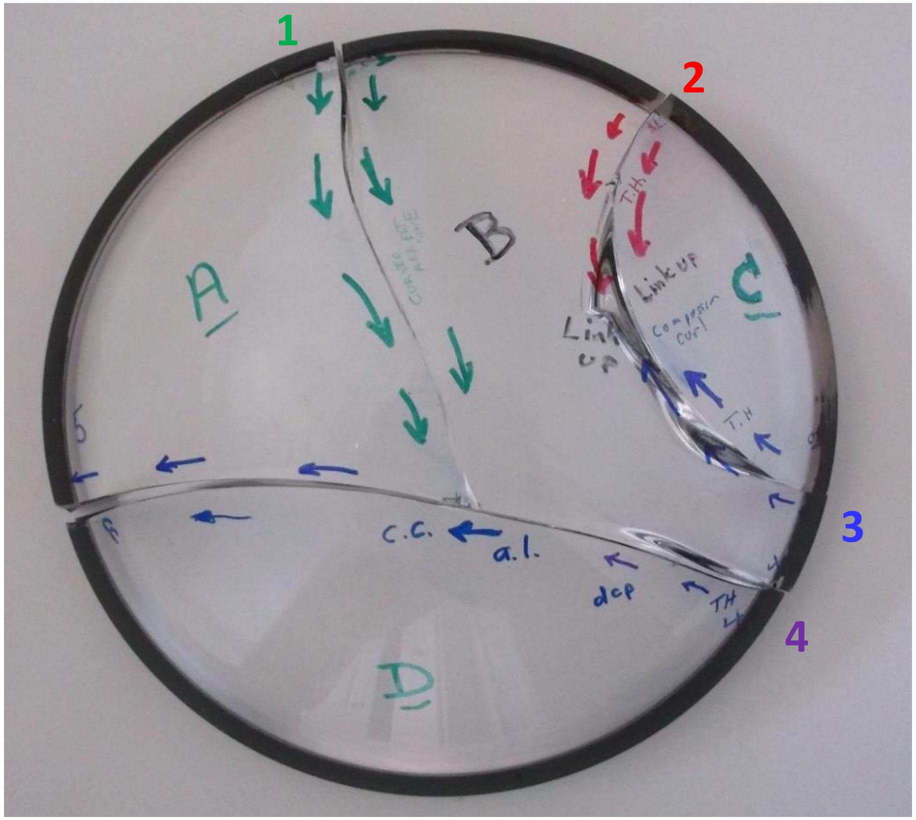


Failure of early design

Dome failed during external pressure test after numerous cycles to 2750 PSI (19MPa)



Fractographic analysis

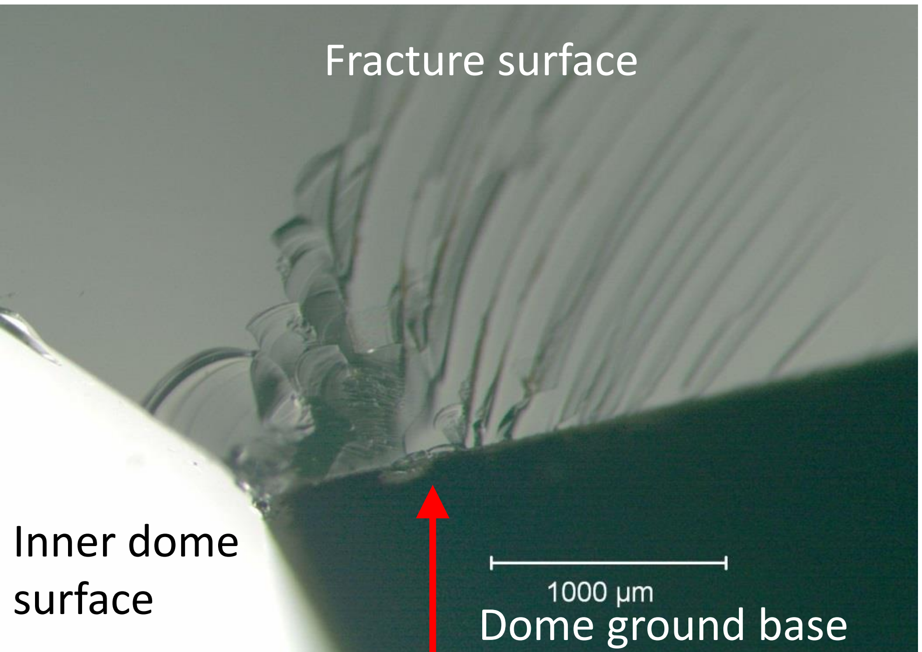


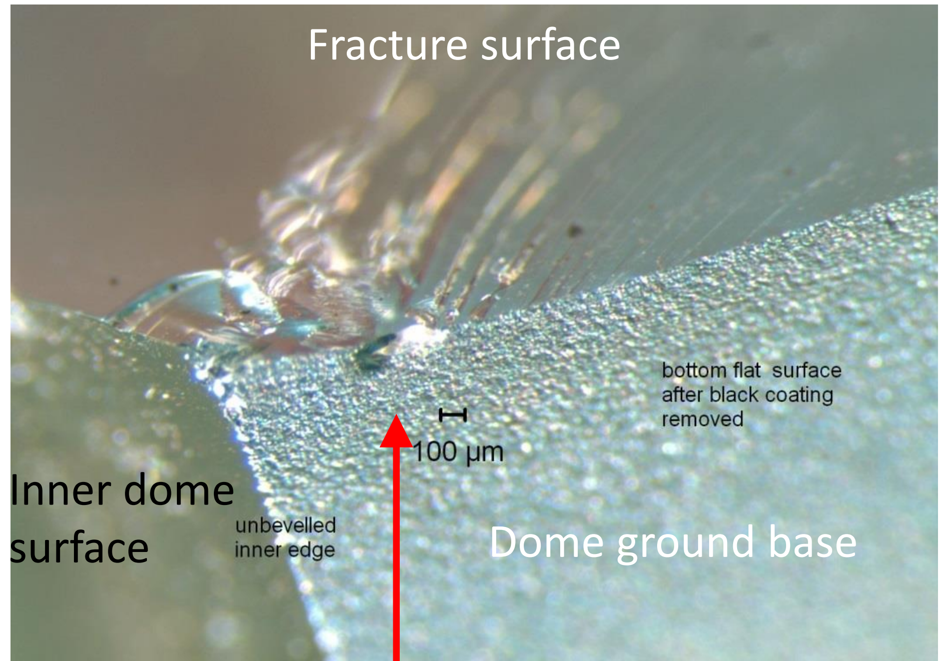
- All four origins were contact crack damage at the outer rim area.
- Origin 4 was the first to start the overall fracture.
- All flaws and initial crack propagation were driven by circumferential hoop tensile stresses.
- By the time the cracks propagated towards the middle, the stress changed to bending 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

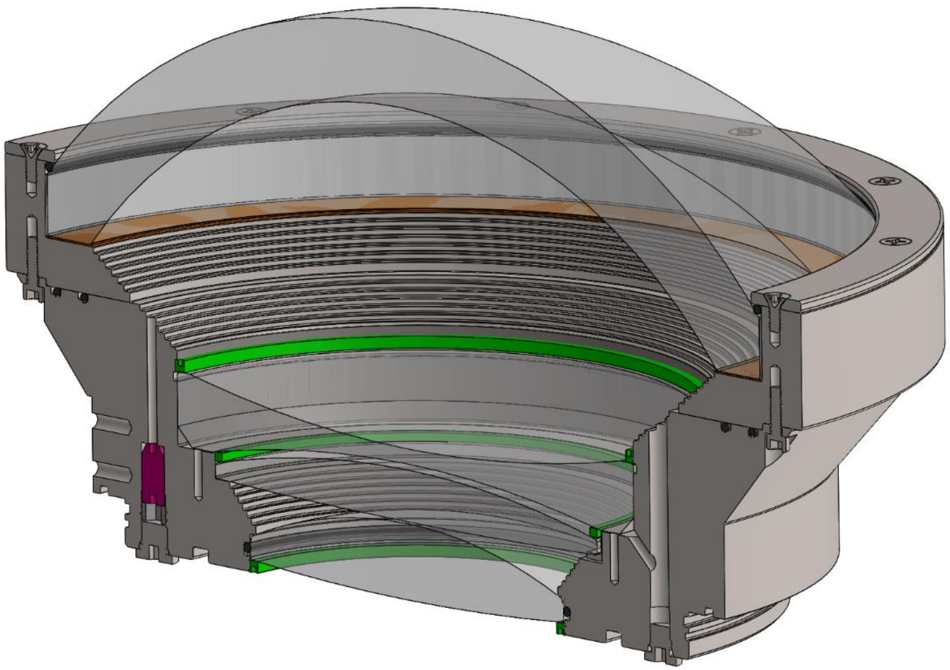




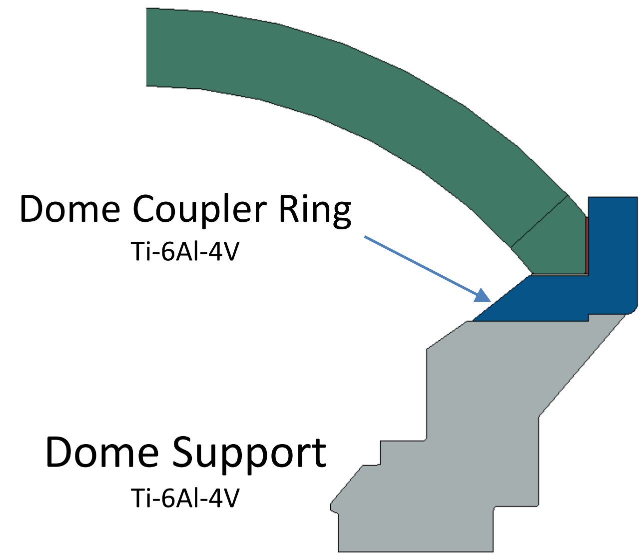
The origin is a contact damage crack on the bottom ground surface.

It is about 1 mm in from the unbeveled edge.

Modified design

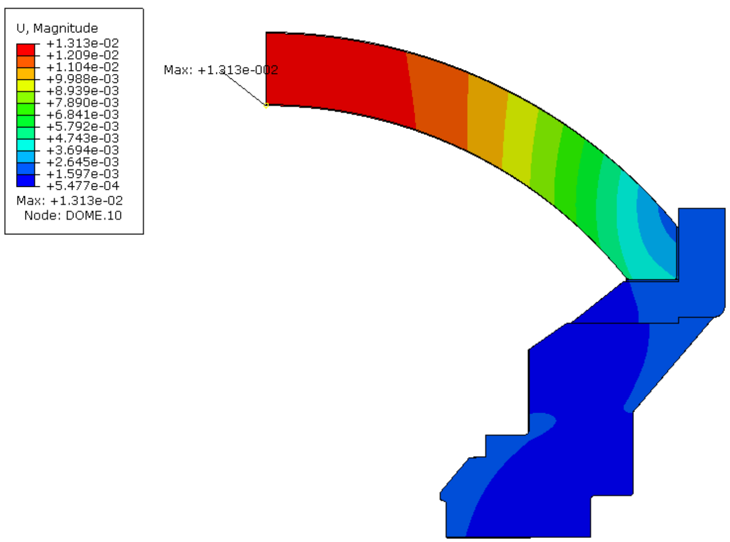


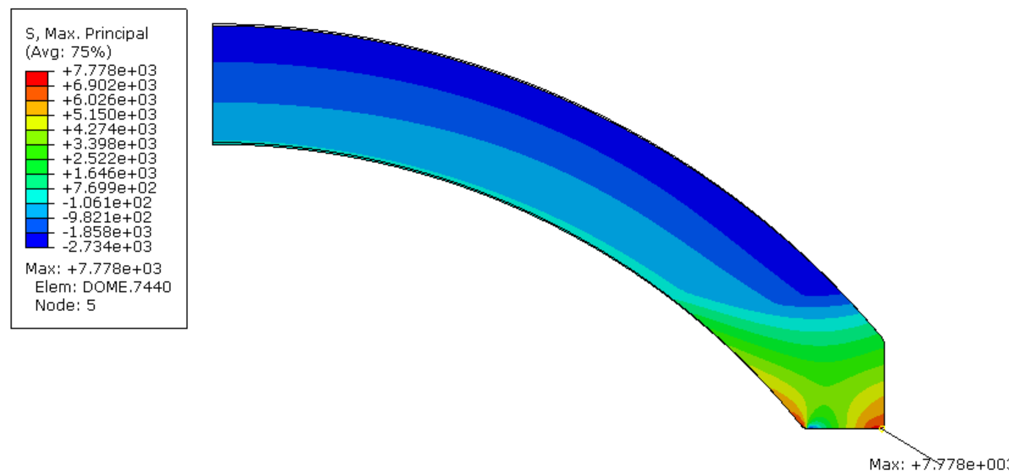
- Dome was bonded to titanium ring with epoxy to prevent lateral motion of dome seat
- Edges were beveled and polished
- Seat was polished and flatness tolerance was decreased
- Thicker kapton ring



FEA of Modified design

- Axial displacement unchanged
- Tensile stress reduced 30%





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

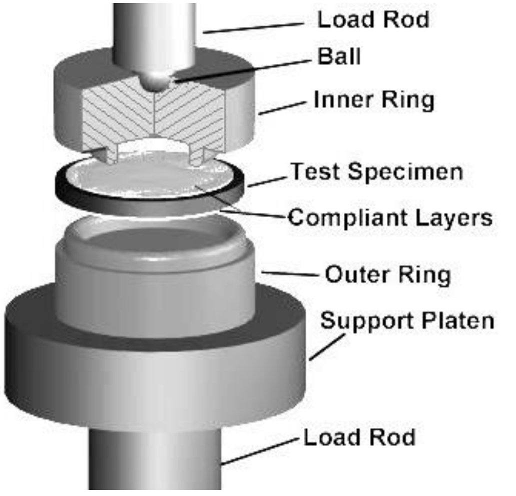
First principal stress at 2750 PSI
Max = 7779 PSI (5.37MPa) (30% decrease)

External consultants

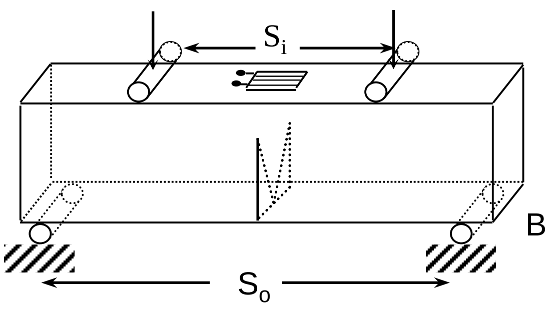
- MBARI hired Eric Baker, ceramics reliability expert (CRT), to perform an analysis of the glass dome
- MBARI hired Jon Salem, material scientist (NASA) to measure the mechanical properties of H-K9L glass and BK-7, and of chemically strengthened glass
- MBARI hired Arun Varshneya (Saxon Glass Technology) to perform the chemical strengthening of the glass

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 HK9-L (HK9-L is marketed as equal to BK-7 but is much cheaper) and BK-7.
- Chemically strengthened HK9-L was also tested.

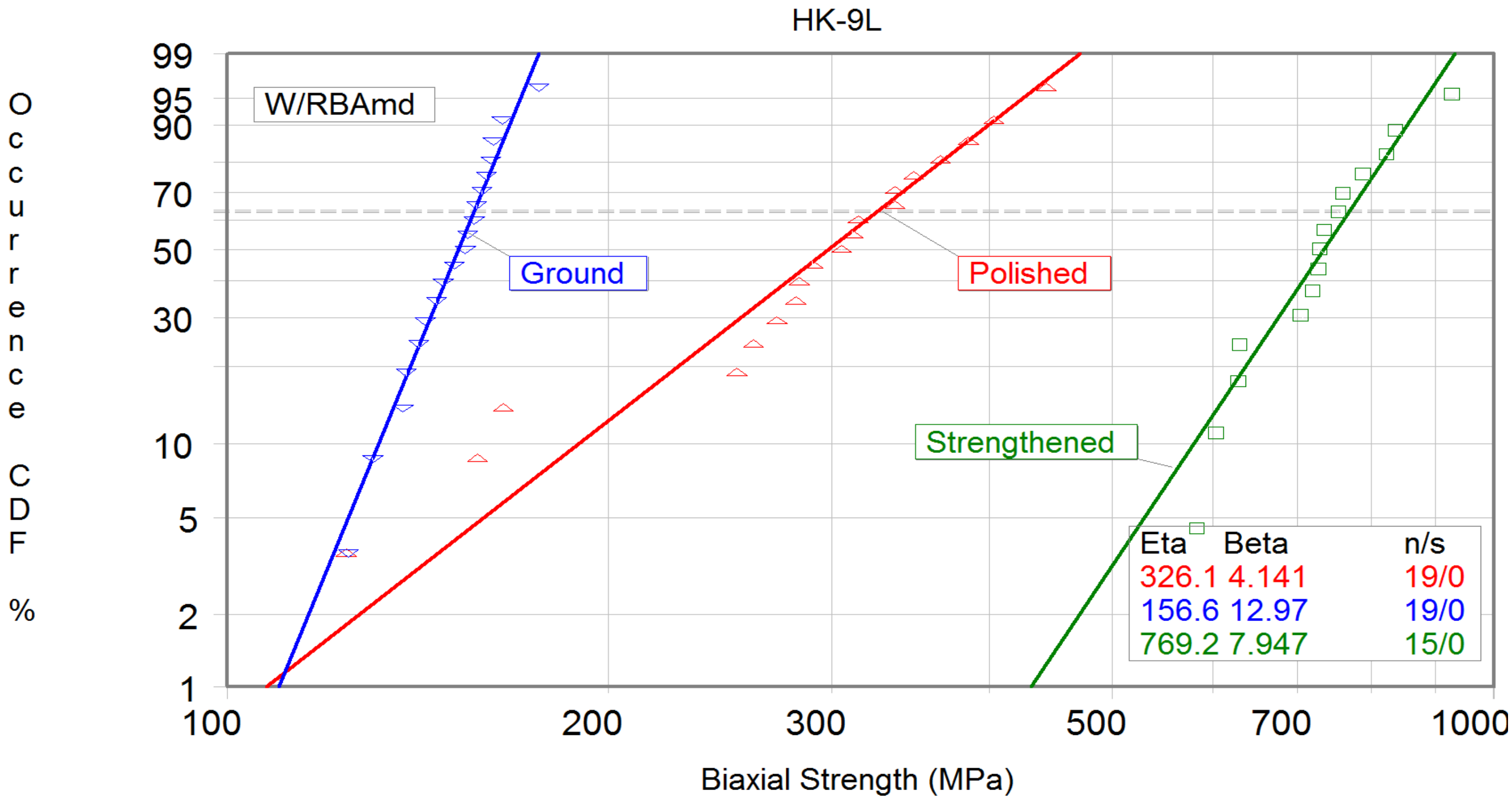


ASTM C1499



ASTM C1421

Results: Comparison of plain and strengthened glass

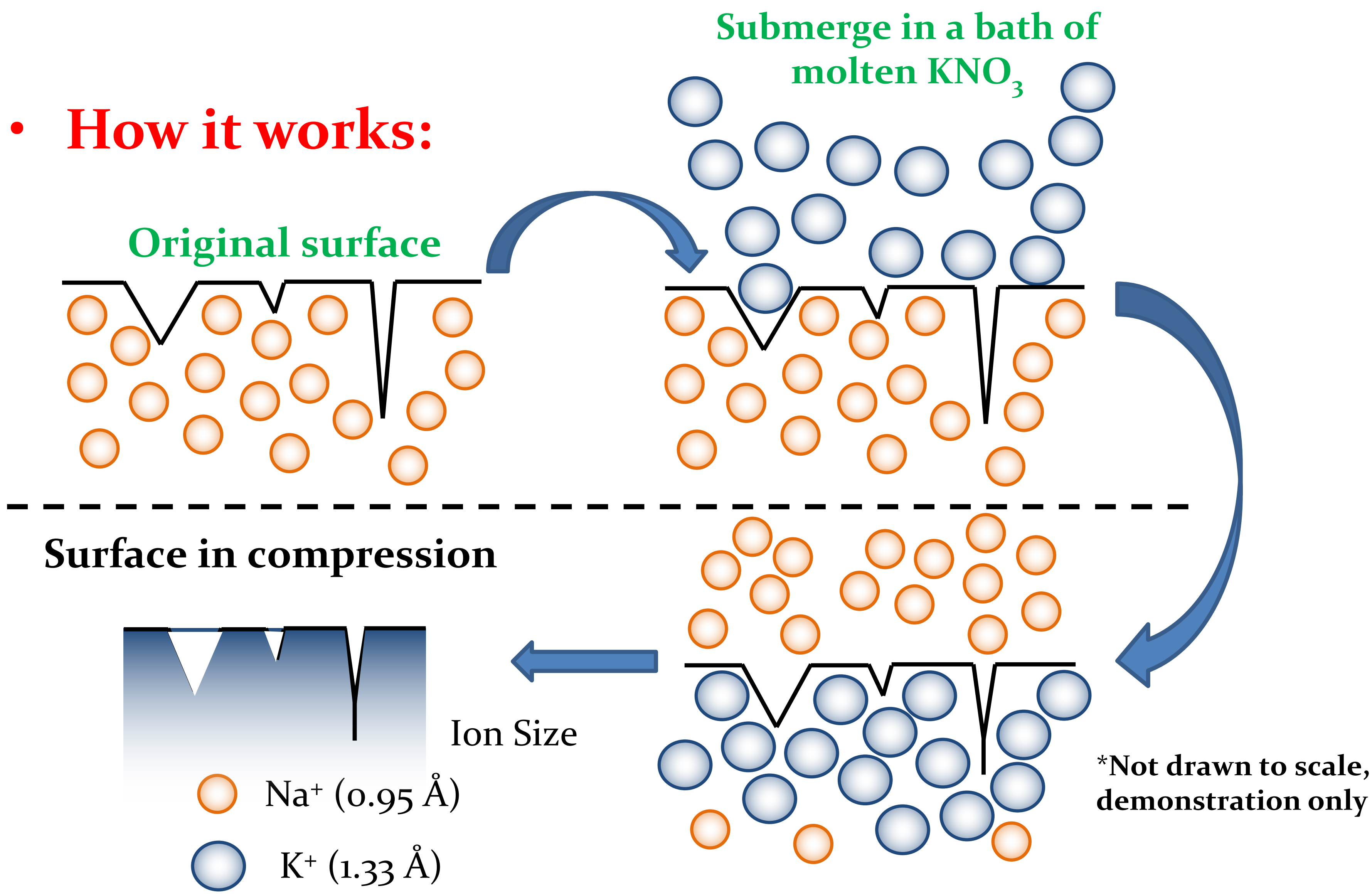


Condition	Characteristic	Weibull
HK9-L	Strength	Modulus
	(MPa)	
Ground	157	13.0
Polished	326	4.1
Strengthened	769	7.9

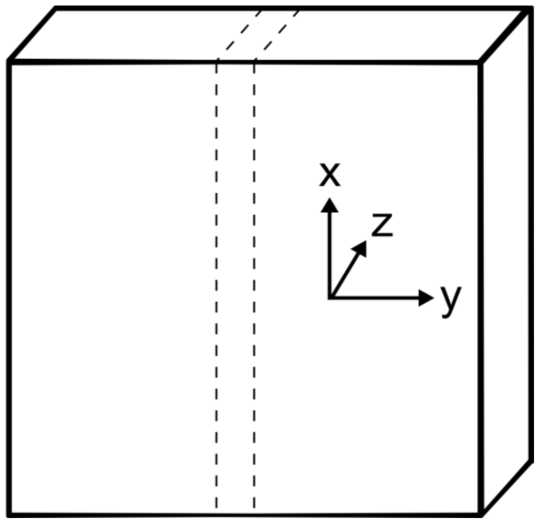
Eta = Weibull Modulus
Beta = Characteristic strength
n = number of specimens
s = number of censored specimens

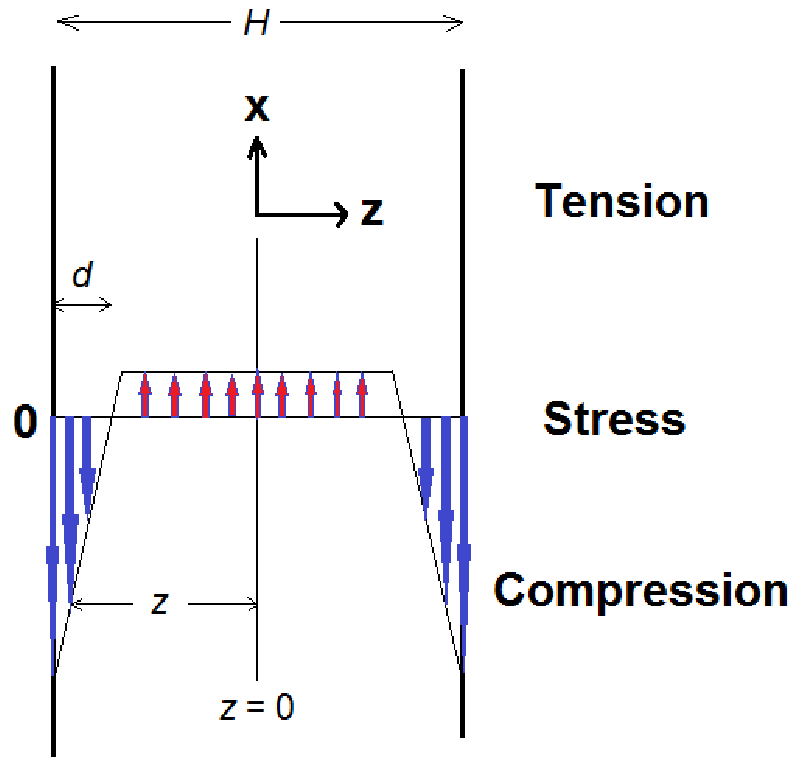
Chemical Strengthening of glass

- **How it works:**



The Math…





In-plane stresses

$$(\sigma_{xx})_z = (\sigma_{yy})_z = \left[\frac{(BC)_z\, E}{(1-v)}\right] - \left[\frac{E}{(1-v)\, H}\int_{\frac{-H}{2}}^{\frac{+H}{2}} (BC)_z\, dz\right]$$ **= CS**

perpendicular stress

$$(\sigma_{zz})_z = 0$$

C = concentration of the invading ion

H = plate width ; *d* = case-depth = **DOL**

E = Young's modulus; ν = Poisson's ratio

B = linear network dilation coefficient (= "Cooper Coefficient")

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)

Reliability analysis

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

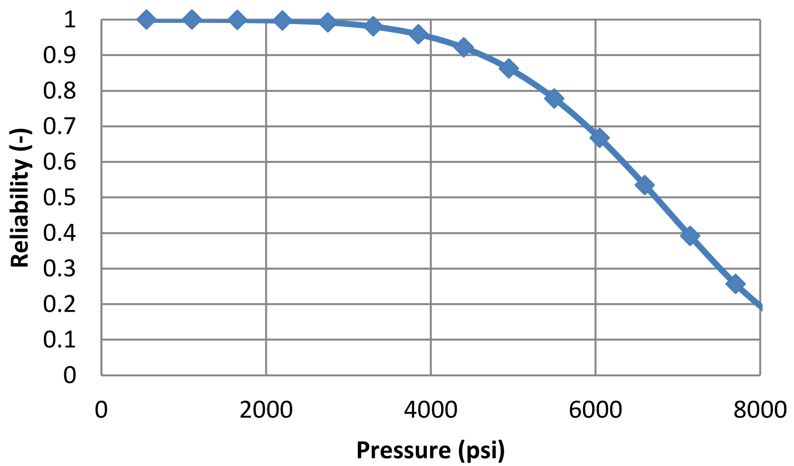
- Generated finite element analyses of dome configurations and calibrated models to MBARI FEA as well as pressure test measurements
- Estimated Weibull Material Properties from provided test data using WeibPar program
- Applied the Ceramics Analysis and Reliability Evaluation of Structures (CARES) program 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

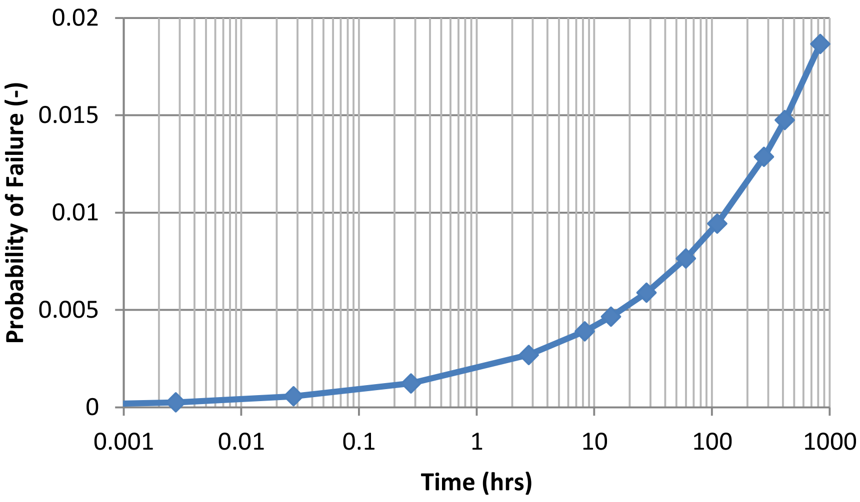
Reliability as a Function of Service Pressure

where Service Time is 60 hrs.



Reliability as a Function of Service Time

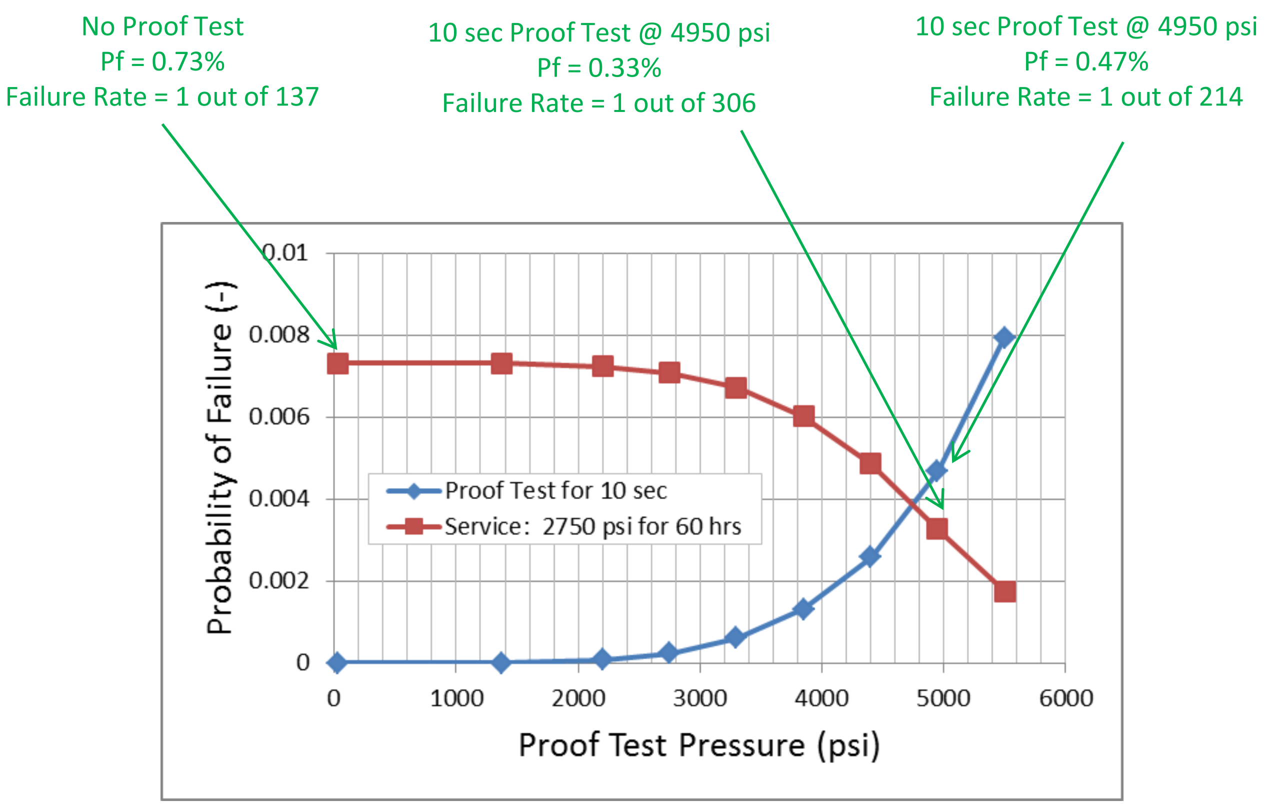
@ Applied Pressure 2750 psi



- FEA Stress Solution @ 2750 psi (19MPa)
- Assumes Stresses Scale Linearly with Pressure
- Assumes other parts of Assembly can handle the increased Applied Pressure

Example of proof test

The dome is subjected to a high pressure for a short time to decrease its probability of failure during service.



Blue line shows probably of failure during 10s proof test.
Red line shows probably of failure during 60-hour service life of proof-tested dome

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).
- 1 strengthened dome was tested to 5000 PSI (34.5MPa).

Cost of components

- Dome port: $1500-$2000
- Adapter lens set: $1200-$1500
- Chemical strengthening: $4000 per batch
- Mounting parts: $2500 materials, 3 weeks of machine shop time.

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. The residual stress field should be incorporated into the model for a better prediction.

Conclusion

MBARI owns what may be the highest quality deep sea optical system in existence.

The I2map dome can be operated at 2000m with very low probability of failure.

Deeper operation is possible, with some modifications.

It’s currently only used for one application (I2map). Let’s use it for other applications!