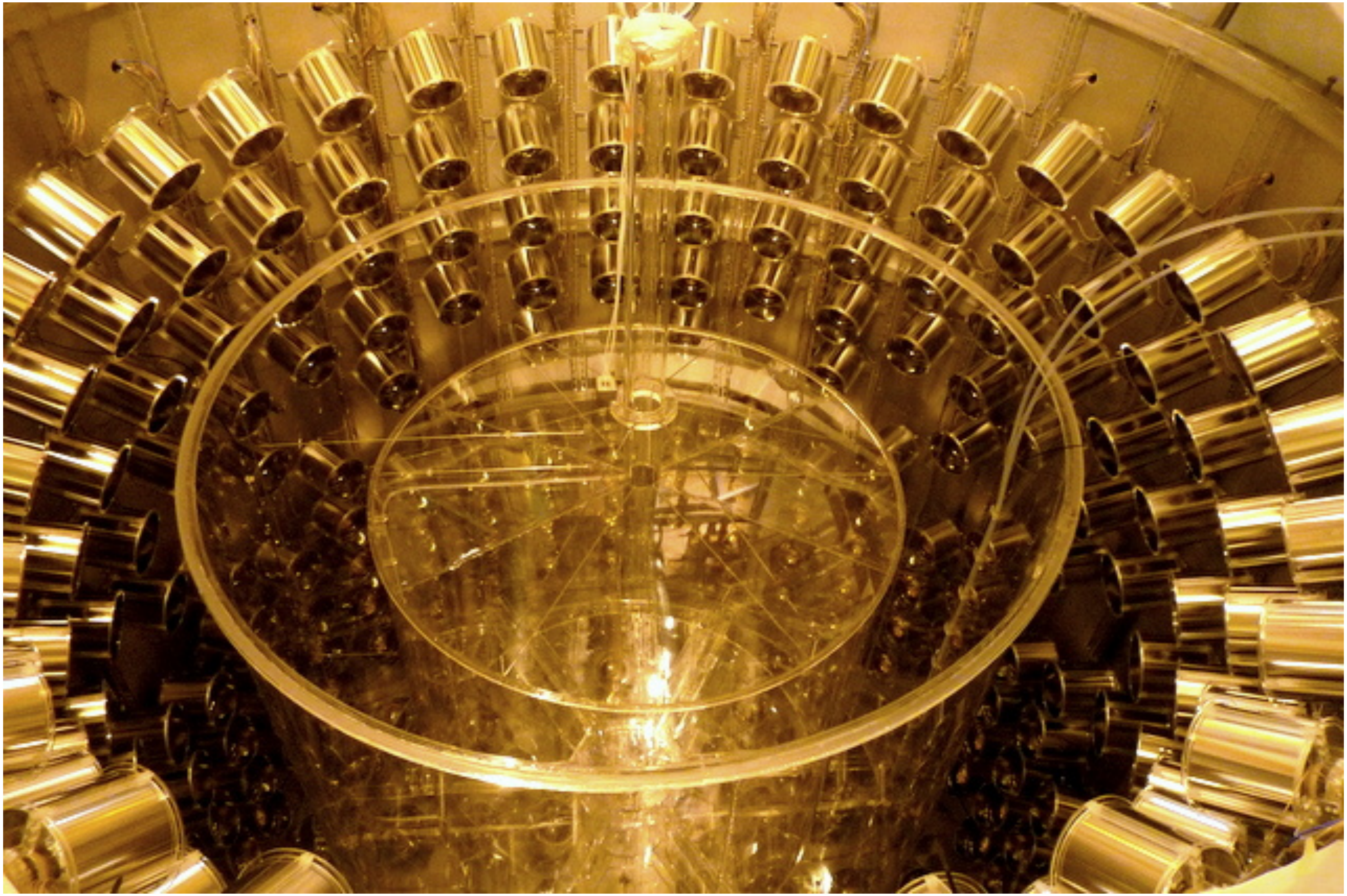
PMT WG Status

Robert Svoboda

20 May, 2018

UC Davis

Tilted Mount Concept



Request for Information (RFI)

- What is an RFI?
- We sent out RFI and got response from 3 companies
- Hamamatsu:
- HCZ Photonis:
- ETEL:

- We are working towards being ready to order PMTs by October 1, 2018

HAMAMATSU

PHOTON IS OUR BUSINESS

5/11/2018

ATTN: Ms. Aubry Eiras
Lawrence Livermore National Security, LLC
Re: WATCHMAN Project

Dear Aubry,

It is my great pleasure to inform you that Hamamatsu Corporation as the US subsidiary of Hamamatsu Photonics K.K., the leading global manufacturer of photomultiplier tubes (PMTs), is fully prepared to respond positively to your Request For Information (RFI) regarding the WATCHMAN project. After thorough and careful review of the project's photodetector performance targets, our team has concluded that specifications of Hamamatsu's **R7081-100-10 WA-S80** constitute a suitable technical solution for WATCHMAN.

Manufactured in Japan, **R7081-100-10 WA-S80** is a head-on PMT with a 253mm-dia. (10-inch) hemispherical bulb made of low-radioactivity glass whose photosensitive area is coated with Hamamatsu's proprietary super-bialkali (SBA) photocathode; the PMT has 10 box & line dynode stages and is assembled with a voltage divider in a water-proof casing attached to a single-lead cable of 80m length. Please find general characteristics and dimensional outline of **R7081-100-10 WA-S80** in the following table and mechanical drawing.

ADIT
Electron Tubes

ADIT Electron Tubes
Subject: **RFI for the WATCHMAN Water Cherenkov Photodetector**
May 17, 2018

The D784KFLB is an 11" (280mm) diameter photomultiplier tube with a blue-green sensitive bialkali photocathode on a hemispherical window, and 12 high gain, high stability SbCs dynodes of linear focused design for good linearity and timing.

At this time we do not have a proven encapsulation design, but we would be keen to work with the project to develop and validate an encapsulation design and carry out the production work to encapsulate tested pmts.

(Note: ANNIE will use 20 of these now being potted at UC Davis)

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The glass envelopes will be manufactured at our facility in Stourbridge, UK, and it is likely to take 9-12 months to get the required quantity of envelopes. This would indicate an estimated start date of Fall 2019.
Based on our estimated production yield, we would plan to deliver 1500 tubes per year.

The glass envelopes will be manufactured at our glass factory in the UK.
The dynode assemblies will be manufactured at our factory in Texas.
The Texas factory has ample facilities available to expand the photomultiplier and encapsulation production lines as needed for this project.

1. Photon Detection Efficiency

No.	Description	Minimum diameter of photo-cathode (mm)	Qty (pcs)	Total effective area (m^2)
Solution 1	XP1805 (230mm PMT Assembly) *	206	6,300	221
Solution 2	XP82B20 (88mm PMT Assembly) *	82	42,000	211
Solution 3	XP72B22 (80mm PMT Assembly) *	72	52,000	210

* Detailed specifications attached below

The history of contributions to other large projects of these types.

Project name	Description	Qty	Delivery time
JUNO (Jiangmen Underground Neutrino Observatory) – CAS IHEP	80mm PMT XP72B22 with waterproof packaging	26000	Jan. 2018 – Dec. 2019
LHAASO (The Large High-Altitude Air Shower Observatory) – CAS IHEP & SDU	39mm PMT XP3960 with electronic base	6400	Jan. 2018 – Dec. 2019
CHIPS – NIKHEF & UMN	88mm PMT XP82B22 with electronic base	5500	Mar. 2018 – Aug. 2018

Solution 1 6300 pcs XP1805 (230mm PMT Assembly)			
Batch No.	**Description of progress**	**Lead Time**	**Percentage of progress**
1	Delivery of 360 PMTs	4 months	6%
2	Delivery of 540 PMTs	7 months	14%
3	Delivery of 540 PMTs	10 months	23%
4	Delivery of 540 PMTs	13 months	31%
5	Delivery of 540 PMTs	16 months	40%
6	Delivery of 540 PMTs	19 months	49%
7	Delivery of 540 PMTs	22 months	57%
8	Delivery of 540 PMTs	25 months	66%
9	Delivery of 540 PMTs	28 months	74%
10	Delivery of 540 PMTs	31 months	83%
11	Delivery of 540 PMTs	34 months	91%
12	Delivery of 540 PMTs	36 months	100%

First 125 PMTs have arrived

- Julie and Tomi put SHV connectors on six and did an acceptance test - all passed
- These six will be distributed as needed in the test plan ASAP
- 100 PMT shipment to UK in July, 2018 for exercise of the test stand and testing to see if **production testing** can be done above ground

Mechanical Testing

1. Strength and Radioactivity testing
    a. Low radioactivity 10-inch PMTs have no history of strength testing or long-term testing in Gd-water.
    b. Long term soaking of **1 PMT** in Gd-Water (1% gadolinium sulfate) at UC Davis with testing of the water and visual inspection of PMT. Test to crush failure after testing.
    c. Crush batch **2 PMTs** for radiological counting to ensure they meet expectations
    d. Pressure test **5 Non-Op PMTs** to failure in order to compare with non-LRI tests. To be done at LLNL or Hawaii (who has facilities?)
    e. Measure strength parameters of the LRI glass for use in the DYNA Software. Need **batch 1 PMT (crushed?)**. Need a System Engineering Analysis.
    f. Mechanical testing to be done in PSL mounting shell

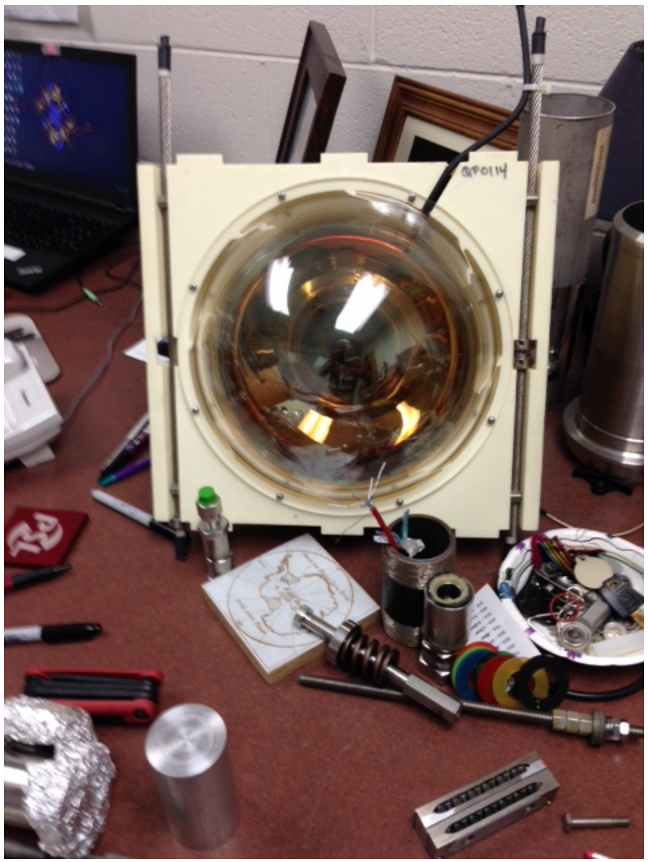
Performance Testing

2. Verification of Electronic performance
    a. Measure magnetic performance of **1 PMT** at UC Davis – not high priority
    b. Measure precision timing and detailed QE testing of **10 PMTs** at Penn
    c. Large-scale measurement of **100 PMTs** at Boulby, to include operating voltage at a standard (TBD) gain, dark noise (after settling), and full-face illumination – P/V, relative QE. This should be the system we ultimately use for production testing.
    d. **1 PMT** to Penn State for electronics testing
    e. **1 PMT** to Hawaii for electronics testing

Transport Development

3. Design and construction of PMT transport vehicle
   a. Design and build one transport cart capable of safely and cleanly taking PMTs from the surface to the site. How many per cart is possible/desirable? Will PMTs change characteristics after transport? Need an institution to design and build.

Engagement with Physical Sciences Laboratory at Wisconsin



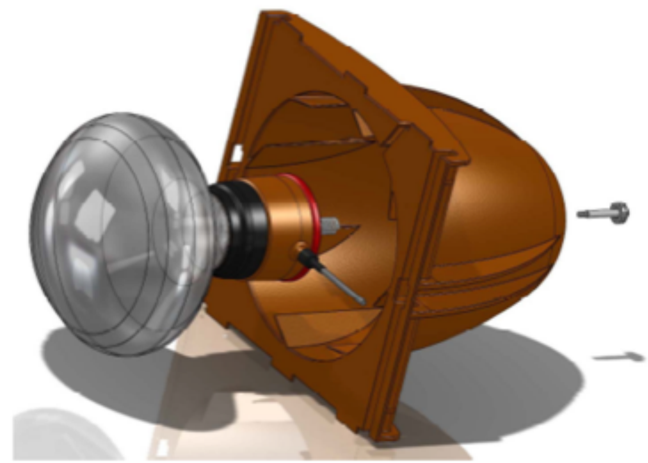


Figure 1: Reference Design showing PMT, Shell, Encapsulation Cup & Coax Cable

LBNE PMT Implosion Studies

The Issues

- In 2001 a chain reaction of implosions triggered by a single PMT failure destroyed 7,877 PMTs (6,777 20-inch and 1,100 8-inch) in the Super-Kamiokande detector in Japan.
- Super-K did a series of studies for their 20-inch PMTs on muffling the explosions with FRP covers with UVT acrylic faceplates
- LBNE also did a series of studies (summarized here)
- Low radioactivity glass has not been studies for implosion chain reaction resistance - how serious is this potential problem?

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

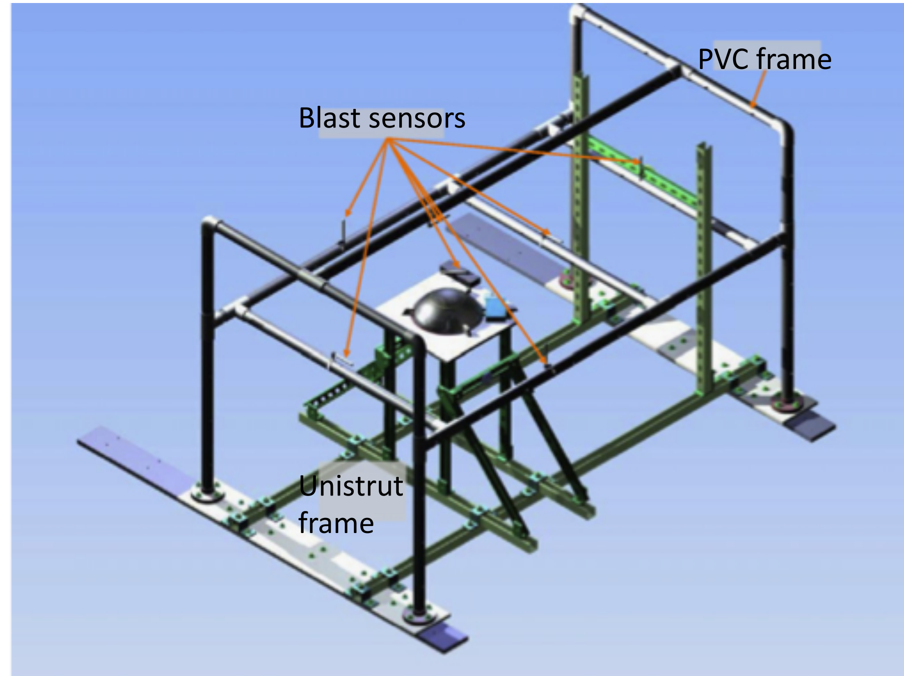
journal homepage: www.elsevier.com/locate/nima

Underwater implosions of large format photo-multiplier tubes

Milind Diwan[a], Jeffrey Dolph[a], Jiajie Ling[a,*], Thomas Russo[a], Rahul Sharma[a], Kenneth Sexton[a], Nikolaos Simos[a], James Stewart[a], Hidekazu Tanaka[a], Douglas Arnold[b], Philip Tabor[b], Stephen Turner[b]

[a] *Brookhaven National Laboratory, P.O. Box 5000, Bldg 510E, Upton, NY 11973, USA*
[b] *Naval Underwater Warfare Center, Newport, RI 02841, USA*

Detailed study of hydrostatic implosion mechanism for Hamamatsu 10-inch PMTs made with standard glass



Propulsion Noise Test System (PNTS) at NUWC in Newport, R.I.

15 meters in diameter, nearly two kilotons of water. Can be pressurized up to 0.69 MPa (about 6.9 bars). WATCHMAN will be about 2 bars.

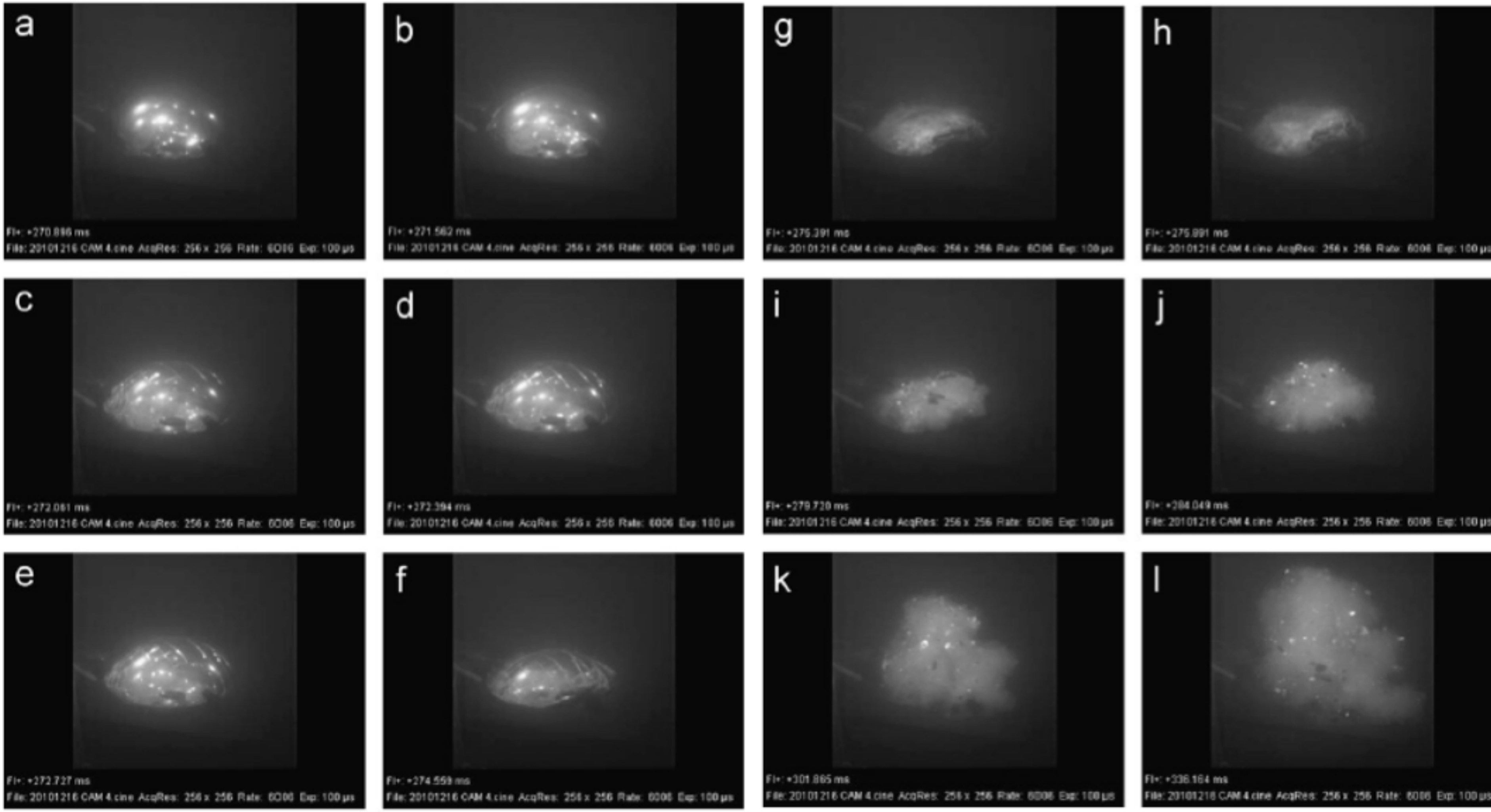
Fast cameras and blast sensors used to characterize implosion

PMT installed in holder that is attached To PMT equator

Far from wall, but also offset from center

Pneumatic plunger used to break PMT

Pressure at PMT 6.1 bars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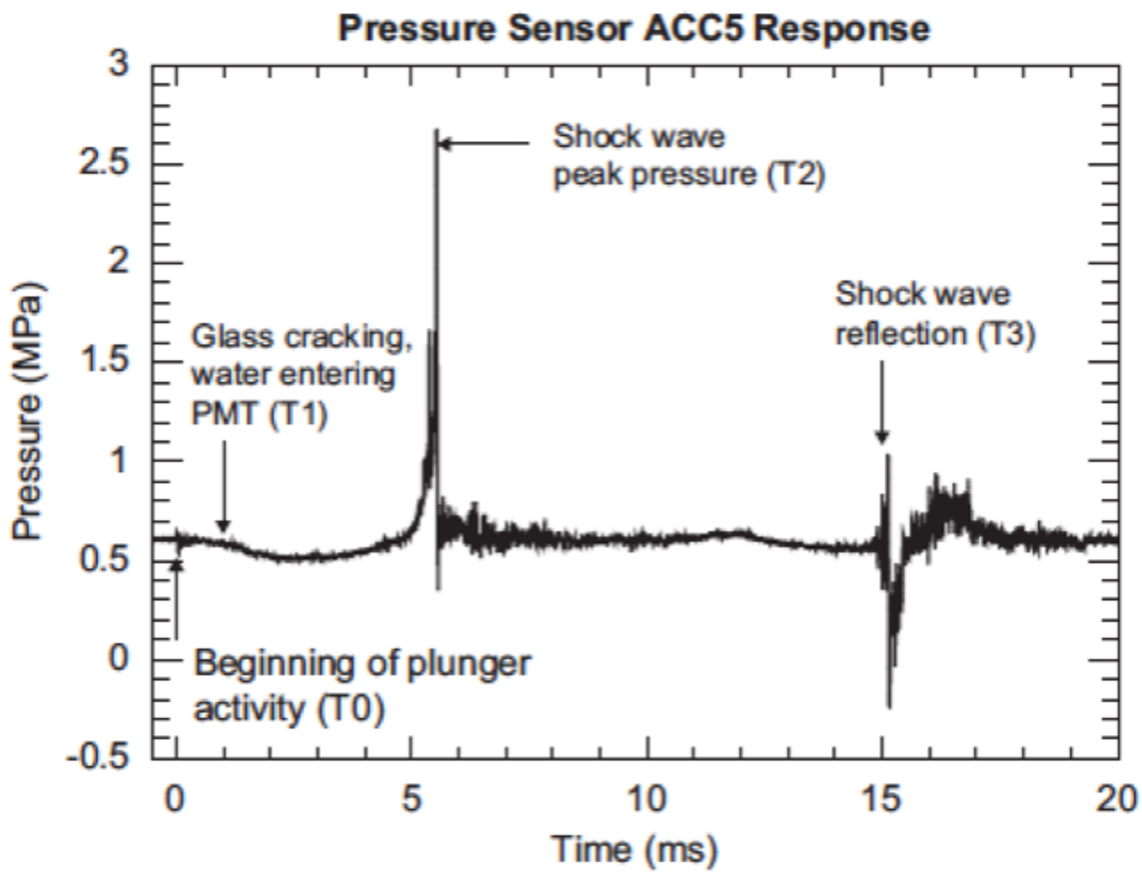


Fig. 6. The pressure waveform data of the PMT-1 implosion recorded by blast sensor ACC5.

Code developed to model implosion results

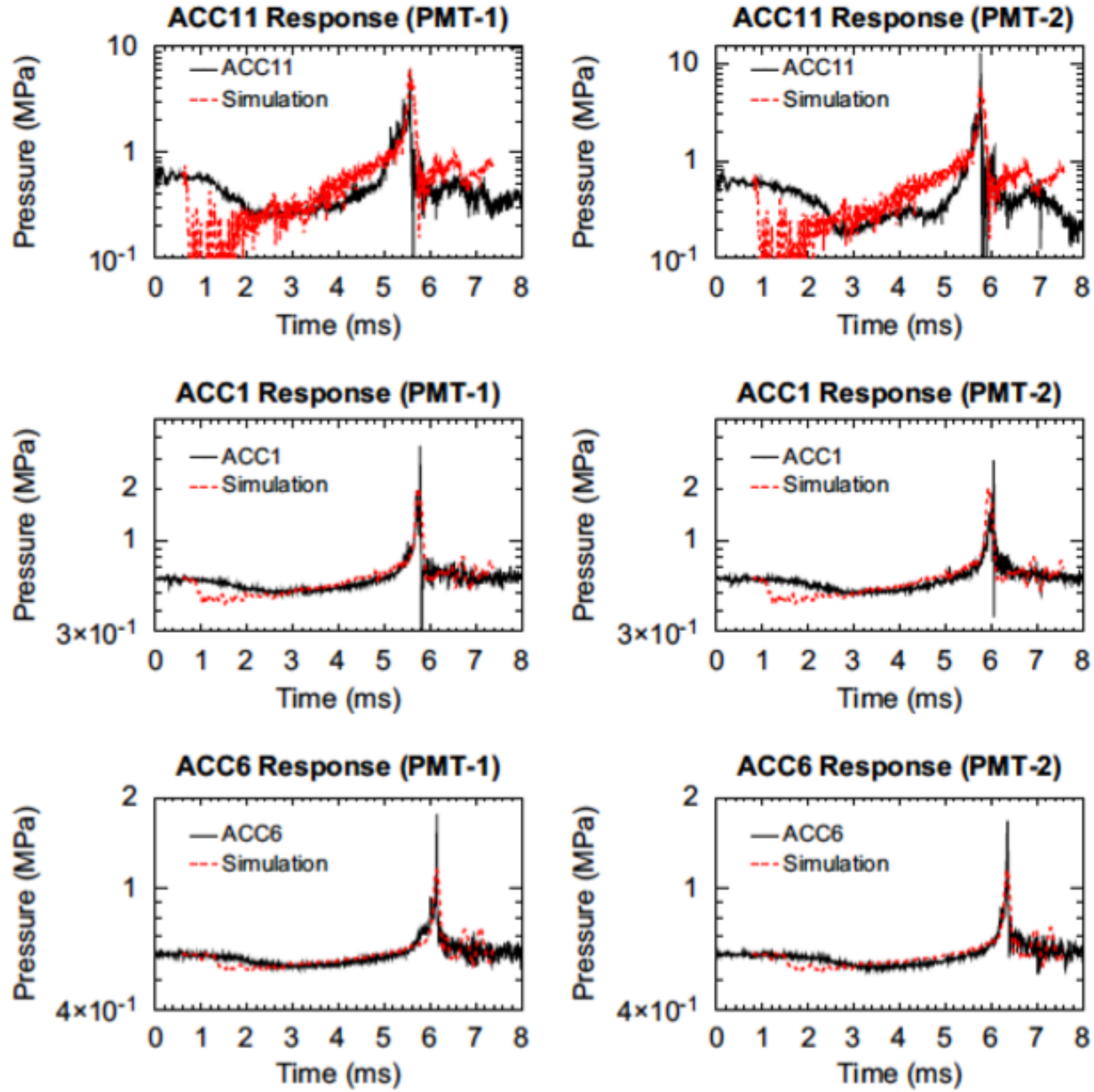
LS-DYNA from LSTC Software, Livermore, California

(Does LLNL have expertise and license?)

Near wall

1.0 m

0.5 m



Conclusion: Good implosion model but not breaking model
From this paper

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

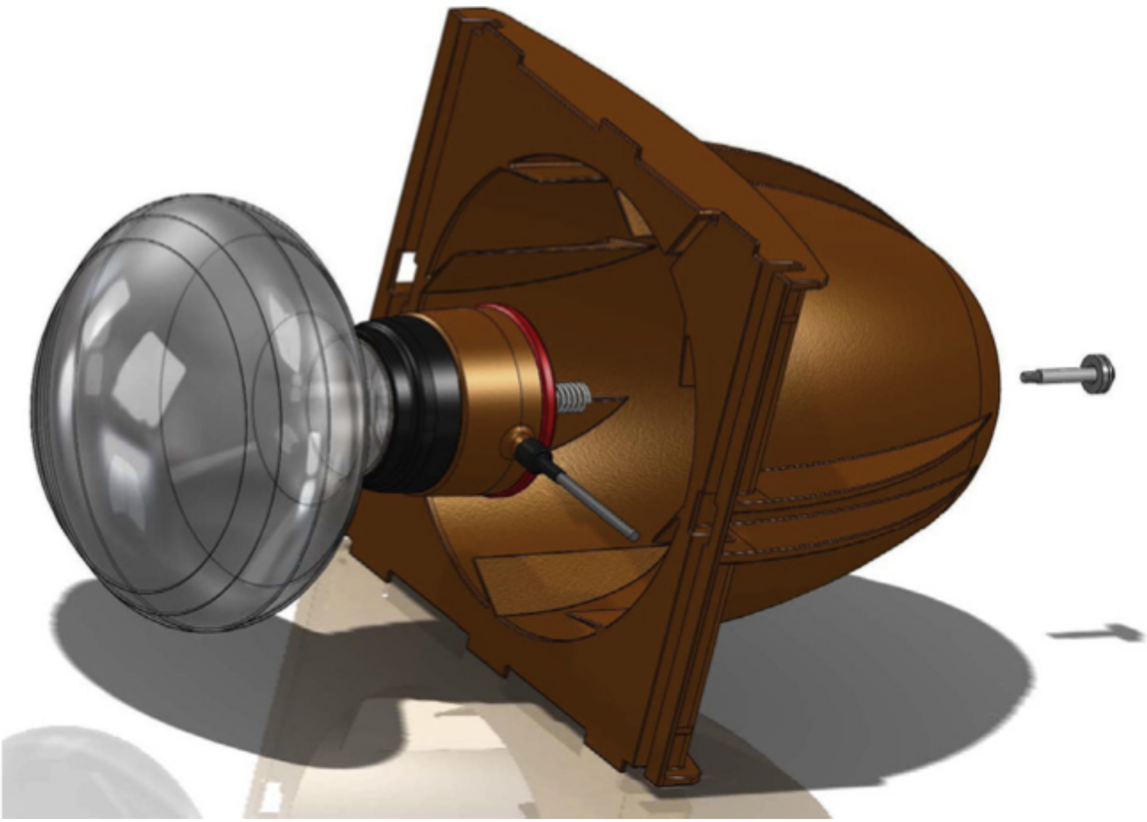
Implosion chain reaction mitigation in underwater assemblies of photomultiplier tubes

Jiajie Ling [a,*], Mary Bishai [a], Milind Diwan [a], Jeffrey Dolph [a], Steve Kettell [a], Kenneth Sexton [a], Rahul Sharma [a], Nikolaos Simos [a], James Stewart [a], Hidekazu Tanaka [a,f], Brett Viren [a], Douglas Arnold [b], Philip Tabor [b], Stephen Turner [b], Terry Benson [c], Daniel Wahl [c], Christopher Wendt [c], Alan Hahn [d], Marc Kaducak [d], Paul Mantsch [d], S.K. Sundaram [e]

[a] Brookhaven National Laboratory, Upton, NY 11973, USA
[b] Naval Undersea Warfare Center, Newport, RI 02841, USA
[c] University of Wisconsin-Madison, WI 53706, USA
[d] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[e] Alfred University, Alfred, NY 14802, USA
[f] Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo, 456 Higashi-Mozumi, Kamioka, Hida, Gifu 506-1205, Japan

Study of Implosion Chain Reactions. Used 10-cm standard glass PMTs mounted in plastic cones with a spacing of 50 cm

LBNE PMT Holder Design from PSL



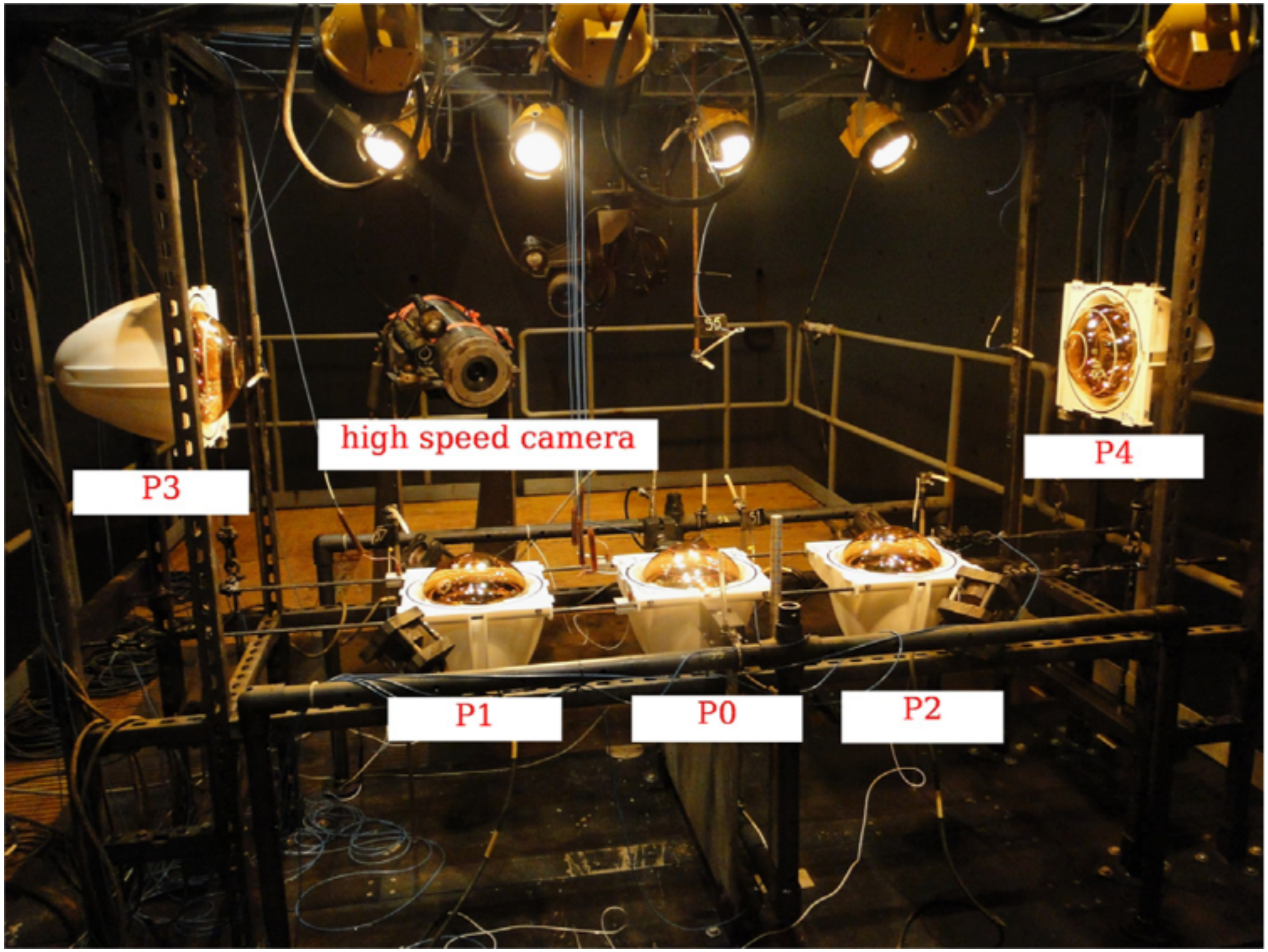
Injection molded ABS (may not be long-term compatible) 4 mm thickness

Designed for 10-inch Hamamatsu

These tests done with urethane instead of ABS

Note: this paper has a good description of the holder mechanism

NUWC Test Tank Setup



PMT P0 is intentionally broken to see if a chain reaction occurs

Three separate tests performed, with all PMTs changed out between tests

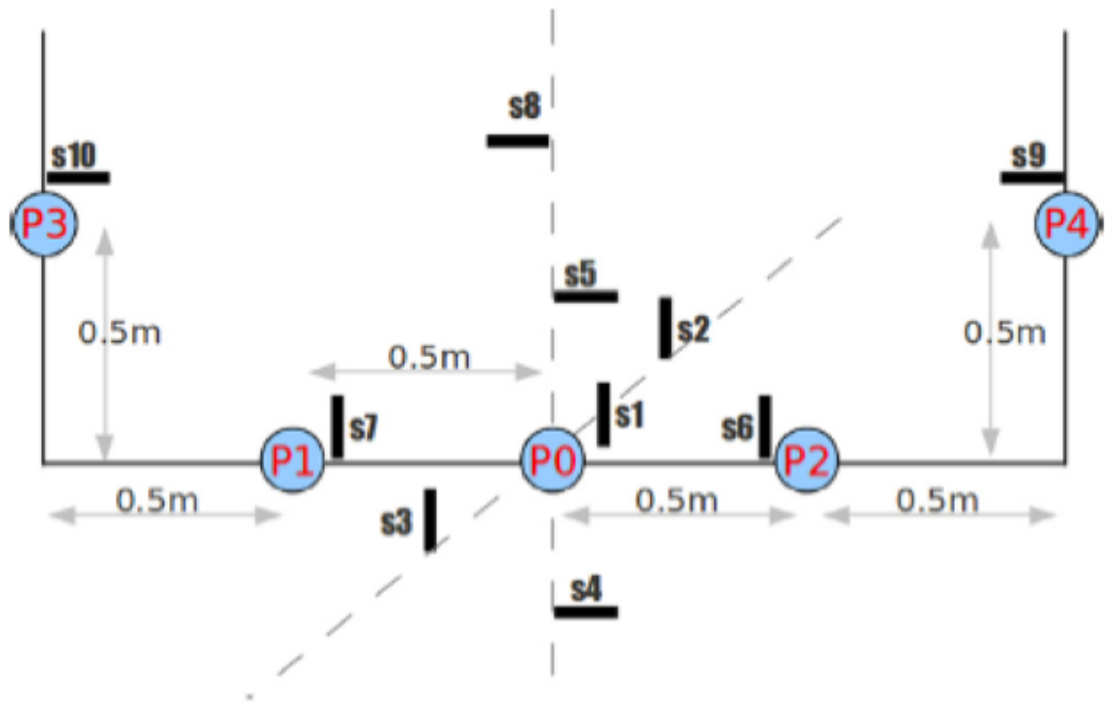
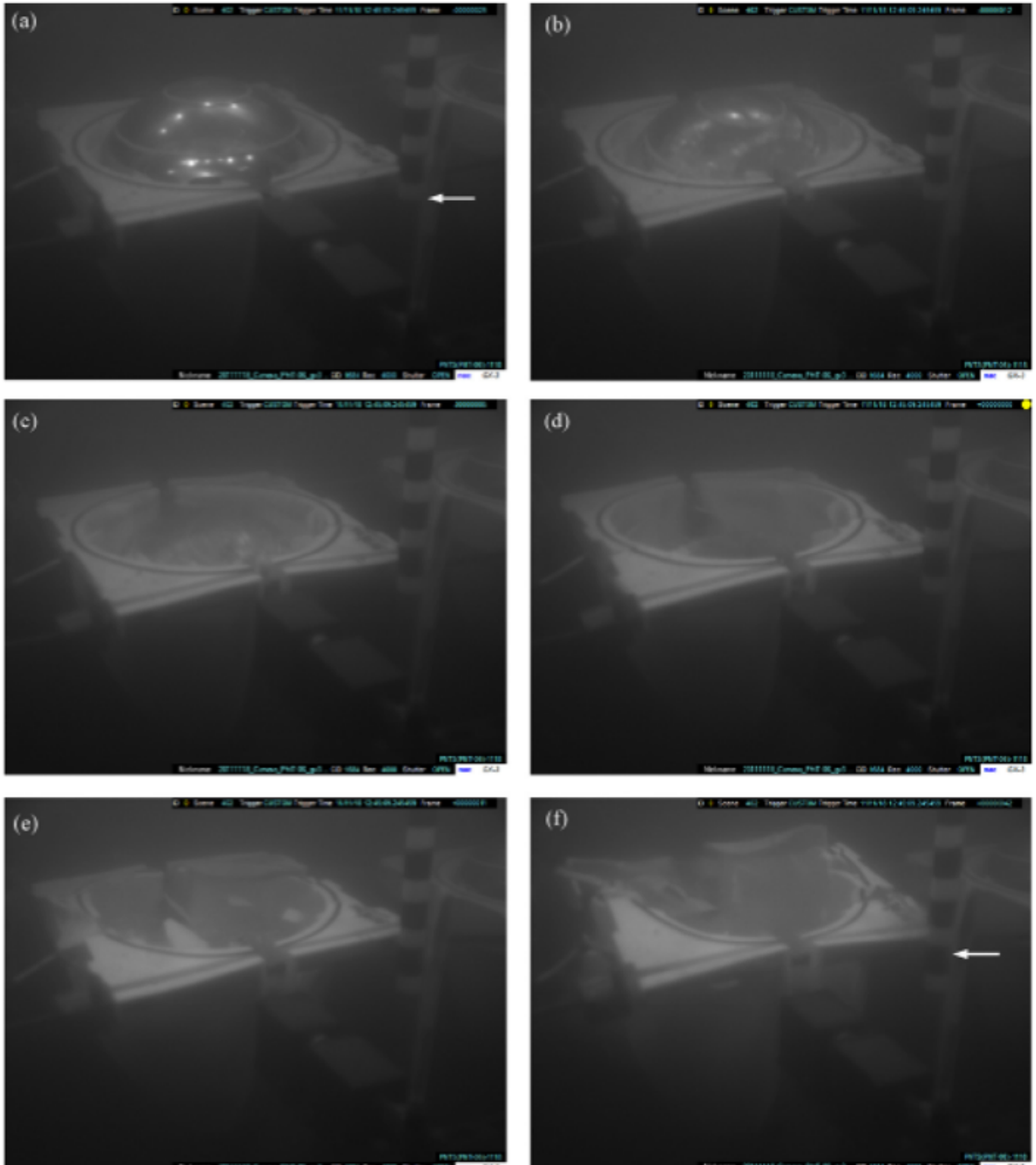


Fig. 3. The schematic drawing of the locations of the PMTs and PCB ICP blast sensors (not to scale). The imploding PMT is mounted at P0.

Table 1
The distance of blast sensors to the center of the imploding PMT.

Sensor	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Distance (mm)	279	546	508	508	508	711	711	1016	1143	1143


(a)
(b)
(c)
(d)
(e)
(f)

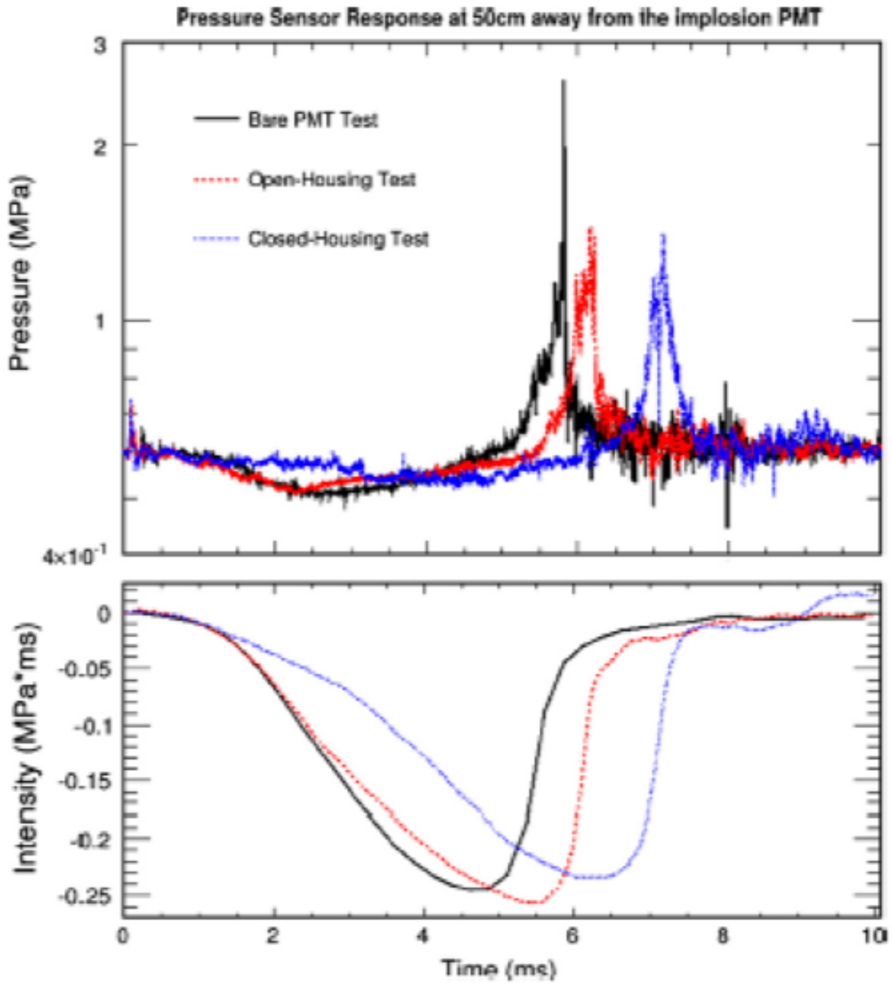


Fig. 8. The pressure waves and intensities of three different PMT implosion setup configurations recorded by the blast sensor 50 cm away from the PMT. No averaging of the data was performed for this plot, so that the sharp rise of the shock wave can be seen.

Bare PMT versus

Open-Housing versus

Closed-Housing (i.e. a UVT acrylic cover)

The pulse is spread out and reduced in peak intensity

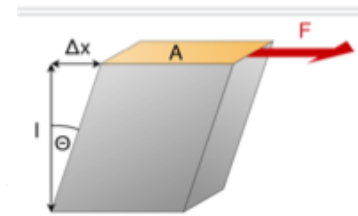
PMT Fracture Simulations using LS-DYNA code

Assumed Borosilicate glass properties:

Density 2530 kg/m^3

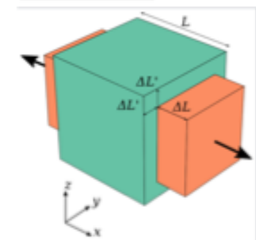
Shear Modulus 30.4 GPa

$$G \stackrel{\text{def}}{=} \frac{\tau_{xy}}{\gamma_{xy}} = \frac{F/A}{\Delta x/l} = \frac{Fl}{A\Delta x}$$



Poisson ratio 0.08

$$\nu = -\frac{d\varepsilon_{\mathrm{trans}}}{d\varepsilon_{\mathrm{axial}}} = -\frac{d\varepsilon_{\mathrm{y}}}{d\varepsilon_{\mathrm{x}}} = -\frac{d\varepsilon_{\mathrm{z}}}{d\varepsilon_{\mathrm{x}}}$$



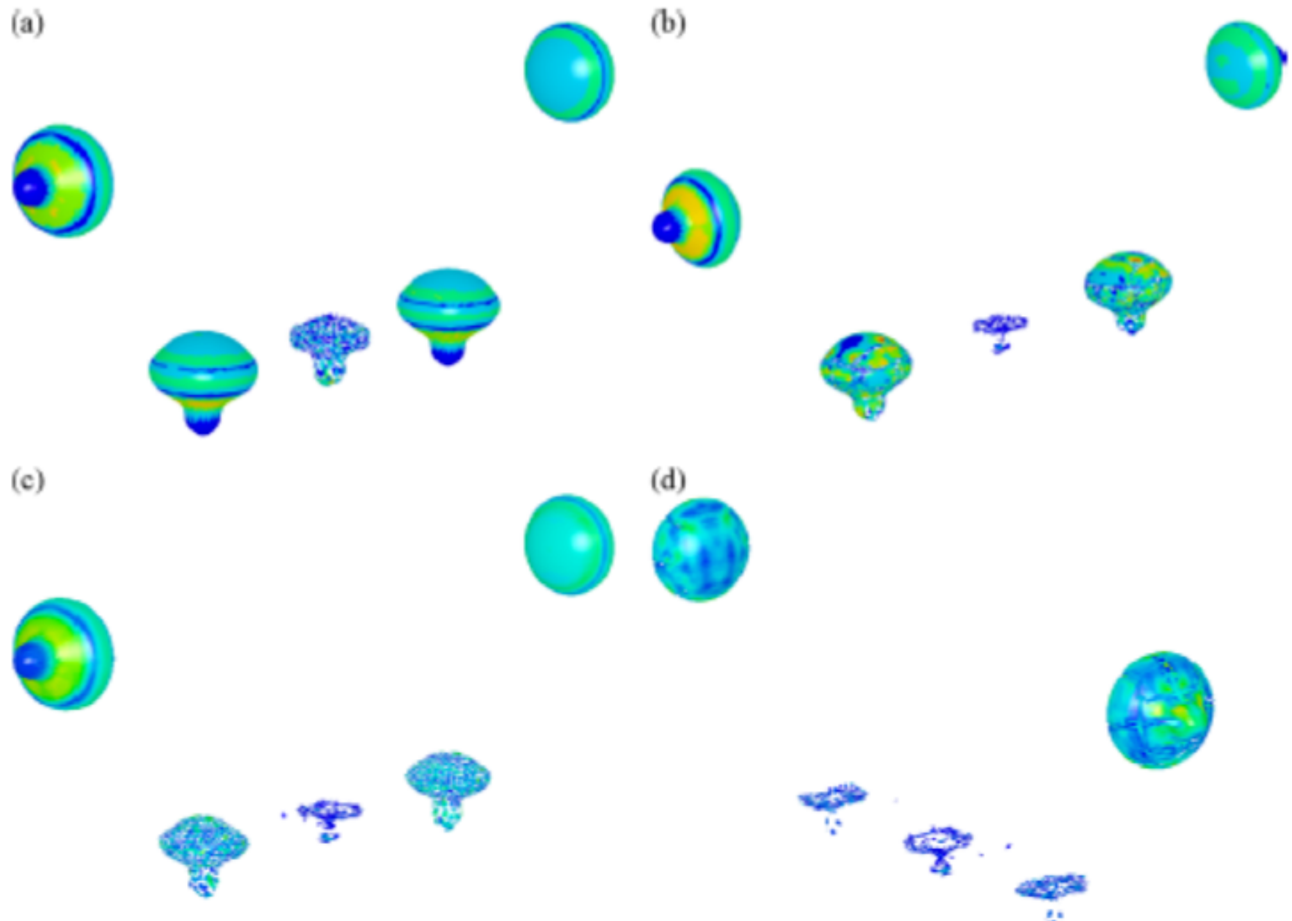
Tensile strength 0.15 GPa

(Strength numbers for housing also given)

Results for bare PMTs

- The fracture model showed that bare 10-inch PMTs with standard glass separated by 50 cm at a pressure of 7 bars *do* have the potential to have a chain reaction
- The (open) housings were predicted to prevent this chain reaction implosion under these conditions, with standard glass

Simulated chain reaction of 10-inch bare PMTs



Implied Scaling

Based on empirical fitting of the numerical calculation results of the differential equations provided by Keller and Kolodner [20] with different initial conditions, we can get an estimation of the relationship of the shock wave pressure with the PMT volume and water pressure, assuming that the implosion is spherical and the water static pressure is not affected by the implosion,

$$P_{peak} \propto \frac{P_{static}^{1/2} \times V_{tube}^{1/3}}{r} \qquad (1)$$

where P_{peak} is the peak shock wave pressure, P_{static} is the static water pressure, V_{tube} is the volume of the PMT, r is the distance from the center of the PMT, and r is large enough to be always in the water phase. Based on this empirical formula, we can easily estimate the scale of peak pressure of the shock wave for any PMT

This test was done at 7 bars, whereas in WATCHMAN our maximum depth is 2 bars. This reduces the peak shock by a factor of 1.8, but we don’t know the importance of the glass strength in determining If this is too high still

Proposed Plan (for Discussion)

- Measure LRI glass strength from an exiting PMT to measure strength
- Engage the LS-DYNA Livermore-based company to simulate our situation for WATCHMAN (including PMT bucket mounts). Also predict crush pressure.
- If we have a safety factor >3 (?) then we are OK
- Crush 5 PMTs to see if simulation is reasonable
- If we have a safety factor less than 3, or if the simulation cannot be validated, use Standard Glass

First Draft Installation Plan

This document describes the basic plan for obtaining Photomultiplier Tubes (PMTs) from a Vendor located outside of the U.K., testing them, cleaning them, and transporting them to the Advanced Instrumentation Testbed (AIT), cleaning them, and installing in WATCHMAN.

Work Flow:

1. When in full production, delivery rate will be 200 per month (this is conservative, as the actual delivery rate may be lower). If we need 3600 PMTs this will take 18 months. This drives many requirements. Faster installation means larger capacity facilities.
2. It will be necessary to place PMTs under power for 48 hours prior to testing in order to allow them time to stabilize gain and dark noise, and to have an initial "burn in" to tag defective units.
3. Initial testing will include setting individual operating HV to achieve a standard gain, then measuring the dark noise rate, after-pulsing rate, pre-pulsing rate, and relative full-face illumination efficiency at operating HV. Initial PMT testing will be done at the Boulby Surface Facility (BSF)
4. PMTs will be cleaned at the BSF before transport underground. Transport will be done using the original shipping boxes as shock protection.
5. PMT holders and associated fasteners will cleaned at the BSF and transported underground separately from the PMTs
6. PMTs will be integrated with their holder at an underground clean room at the AIT site. A final QA check consisting of a visual inspection, final cleaning, base resistance, and test of power-on visible pulses before installation.
7. PMTs will be installed in a clean environment established in the tank
8. PMTs will be checked after tank installation via power up to operating HV and observation of pulses. Plans will be made for replacement/repair of identified defective units *in situ* as needed.

Assumptions:

1. Surface clean room will need to hold at least 400 PMTs at a time (two months delivery, assuming installation could sometimes be delayed). Conservatively estimating we have 12-inch PMTs with boxes 50cm x 50cm x 75 cm, this would require a floor space of (0.5 x 0.5 x 400)/2 = 50 m^2 if they are stacked two high. CONSIDER RACKS WITH 3-4 HIGH
2. ADD IN CLEAN LAY DOWN AREA AT BUL
3. The BSF test stand would operate 5 days/week and thus need have a nominal test rate of 10 PMTs/day. Allowing for a factor of two for unplanned delays and equipment problems, the BSF should be capable of testing 20 PMTs at a time. Estimated floor space needed would be about 25 m^2
4. Electronic testing need not be done in a clean environment. PMTs can be tested and then moved through a cleaning area located next to the test stand.
5. The underground clean room should be capable of holding at least three days of PMT backlog, or about 30 PMTs. THINK ABOUT TWO DAYS/WEEK INSTALLATION

General Facility Requirements:

1. The BSF test stand + storage will require a nominal area of 50 m^2 plus 25 m^2 = 75 m^2. Assuming a 100% access space allowance, this corresponds to about 150 m^2 (1080 ft^2).
2. The BSF clean room estimate is 10 meters x 4 meters = 40 m^2. Assuming a 50% access space allowance, this corresponds to 60 m^2 (650 ft^2).
3. BSF needs to be climate controlled
4. The AIT site clean room should have a storage area of at least 30 x 0.5 x 0.5 = 8 m^2 and a clean room of about 6m x 4m = 24 m^2. Assuming an access allowance of 100% means 64 m^2 (690 ft^2).
5. The transport cart should only need to make 1-2 trips/day if possible. So, the cart should be able to transport 10 -20 PMTs at a time through the cage and drifts.