SNO-STR-90-90

PMT Implosions and the Acrylic Vessel Current Status of Understanding

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Abstract

The energy associated with an imploding PMT located underwater in the SNO detector is considerable and represents a pontential threat to both the acrylic vessel and adjacent PMT's. A study was commissioned, plus independent reviews of the subsequent report by a number of experts. Their findings support those of the report and that the effect of an imploding 8" PMT is probably acceptable for the vessel, but may represent a serious threat to adjacent PMT's.

1 Introduction

The potential energy associated with an evacuated glass envelope of a PMT is a function of the volume of the envelope and the pressure to which it is subjected to. For the PMT's and water pressures under consideration for SNO, this may be equivalent to several grams of high explosive. The pressure wave arising from an implosion represents a potential hazard, both to the acrylic vessel containing the D_2O and those PMT's adjacent to the implosion.
Although considerable experience exists [1] with detectors containing large

numbers of PMT's immersed for long periods of time under water, the number of PMT's and expected operational life of SNO is unprecedented. Since the strength of the glass envelope of a PMT decreases with time, an implosion of a PMT during the operational life of SNO appears to be a reasonable possibility.

Consequently a study was undertaken by the Swanson Corp. to determine the effect of an imploding PMT and a report [2] was produced in July 1990. Since the physics of imploding objects is non-trivial, and Swanson Corp. had no previous experience in modeling this type of phenomena, the report was reviewed by a number of experts in the field in order to determine if the major findings were correct. As a result of these reviews, additional insights (and concerns) have arisen and are summarized below.

2 Swanson Study

The Swanson Corp. has done considerable modeling of the response of the acrylic vessel to static forces [3]. The same finite element model was used to examine the response of the vessel to dynamic forces. The study was carried out for the 20" Hamamatsu and the Burle PMT's, the volumes being 2.0 and 0.77 cu ft respectively. The implosion was assumed to occur at the bottom of the PMT array since this gives the worst case of maximum hydrostatic pressure (energy). In addition, Swanson considered the case of a PMT breaking loose from the bottom of the array and floating up to strike and implode against the vessel wall.

The first step was to characterize the energy associated with an imploding PMT. It was assumed that the PMT's were spherical and contained no internal structures (i.e. dynodes) which would damp the implosion. The energy release is given by;

$$\int_0^{V_o} P_0 dv = P_o V_o$$

It was then assumed that this implosion energy and the resultant shock wave could be represented by a quantity of high explosive and the weight of explosive was calculated according to an empirical formula obtained for underwater explosions by Cole [4].

The same reference is used to define the time dependence of the pressure pulse as:

$$P = P_m \exp(-t/\theta)$$

where P_m, the maximum pressure is given as;

$$P_m(psi) = 2.25 \times 10^4 \left(\frac{W^{1/3}(lb)}{R(ft)}\right)^{1.13}$$

Where W is the equivalent weight in high explosive and R is the distance of the pressure pulse from the point of implosion. Note that the pressure decreases as $\sim 1/R$. Using the above relationships the pressure of the pulse was calculated at a grid of points on the surface of the vessel. The duration of the pulse is short ($\sim$ 0.1 millisec.) and the propogation speed high ($\sim$ 8.0 millisec to traverse the vessel diameter) compared to the natural frequency of the vessel (0.25 Hz), and the pulse can be considered as being "all over" by the time the vessel responds. It was therefore considered a valid approximation to apply the pulse overpressure as static loads to the outside of the vessel in order to simplify the culculation of the stress in the vessel.
For the case of a PMT which breaks loose and strikes the vessel, the PMT was assumed to reach terminal velocity ($\sim$ 6.8 m/sec for the 20 inch Hamamatsu) over the 2.5m it travels before hitting the vessel. The implosion was assumed to occur at a distance equal to the radius of the PMT.
The principal finding of the study are given below;

CASE	MAX PRESS (PSI)	DECAY TIME (MSEC)	MAX STRESS (PSI)
20" Hamamatsu	311.0	0.13	1,400
Burle PMT	217.0	0.08	650
20" Hamamatsu Impact plus Implosion	8,017	0.08	10,000

Since the tensile strength of virgin acrylic is ~9,000 psi, it is clear that the impact and implosion of a 20" Hamamatsu PMT marks the end of the vessel and the experiment. Whether the other stress values are acceptable

depends on what the strength of the acrylic is after long term explosure to water. These properties are presently being determined at LANL.
Some of the assumptions and approximations made in the report were of concern to experts in this field, for example, is an implosion the same as an explosion? is it valid to apply the overpressure as a static load? etc. To answere these question, the report was reviewed by the experts. Their finding are discussed below.

3 Reviews and Summary of Findings

Reviews were carried out at the following institutes;

- **Chalk River:** W.N. Selander (comment).
- **LANL:** C. Mader, P. Blewett, C. Ragan (calculation and comment).
- **Oxford University:** P. Lush (calculation, experiment and comment).
- **Stachiw Associates:** J. Stachiw (experiment and comment).

Any reports or results of calculations received from these people are appended to the rear of this report, their findings are summarized below.
Chalk River: Bill Selander is an engineer associated with the Waste Management Systems Division at CRNL. His primary concern was the the assumption that the rebound from an implosion generates the same shock wave as an explosion of the equivalent energy.
LANL: Considerable expertize exists on the modeling of implosions and explosions at LANL. Chuck Mader is a Fellow of the Laboratory who currently resides in Honolulu where he runs Mader Consulting Co, specializing in numerical modeling. He visits the Laboratory for two months a year as a consultant. He has written books [5] on modeling detonations and water waves. He was a pioneer in establishing the computer codes at LANL and currently markets a 1-D code that runs on PC's. Using these codes he calculated the shock resulting from the implosion of a 25cm diameter sphere under a pressure of 3 bars. At a distance of 2.5 meters (the distance to the acrylic wall) from the implosion, a peak overpressure of 9 bars was recorded.

The pulse width was approximaitly 20cm, which at a velocity of 0.14cm/μsec corresponds to a duration of ~150μsec. The pressure decreases as R^{-1}, while the experimentally observed decay from bubbles formed by explosions decay as a function of $R^{-1.1}$. All this supports the findings of the Swanson report. Mader also notes that the pressure pulse from multiple bubble collapse can interfere constructively to give pressure pulses a factor of 2-3 higher. Also, bubble collapse frequently occurs asymetricaly, giving rise to high velocity "jets" of water. It is these jets which are responsible for the errosion of propeller blades and may represent a serious threat to adjacent PMT's, although the jet is unlikely to propogate as far as the acrylic vessel. Code for modeling such jets exists at LANL.

Pat Blewett (X-3 Div.) specializes in modeling implosions/explosions and has access to the neccessary codes and computational power. Blewett found pulse magnitudes and durations that supported the findings of the Swanson report. An additional concern of Blewett and Ragan was the local effects in the acrylic as the pressure pulse traverses the wall. A ~20 bar plane wave pressure pulse was propagated through a 5cm sheet of acrylic with water on both sides and reflection and transmission from the interfaces correctly accounted for. A maximum compressive stress of 30 bar and a maximum tensile stress of ~5 bar was obtained in the acrylic. Whether this level of tensile stress occuring at the surface of the acrylic would cause "spalling" (as occures when a BB strikes a glass window) is unclear at the moment. Profiles of the pressure pulse as it traverses the acrylic are given in the appendix.

Oxford University: Dave Wark (Oxford) conducted a series of pressure tests on 8" EMI PMT's, (see appendix). The test vessel was a barrel, 45cm in diameter by 150cm deep. Two bulbs were pressurized in increments to 22 bar, at which pressure one of the tubes developed a leak where the electrical pins penetrate the glass envelope, but did not implode. The glass surfaces of other PMT's were abraided to simulate aging. These PMT's failed at pressures between 13 and 20 bar. Although relatively crude, these tests represent the only experimental data generated within the SNO collaboration.

Wark also made contact with Peter Lush of the City University, London, who is a specialist on underwater implosion physics. Lush modeled the implosion for the 20" Hamamatsu and the Burle PMT at varying water pressures (see appendix) and obtained results which were essentialy in agreement with Swanson, including a $R^{-1.059}$ dependancy for the pressure pulse. He had a number of other concerns, primarily the high speed jets mentioned by Mader at LANL. These jets may have velocities of up to 250m/sec, and while Lush did not think they would travel the 2.5 meters to the acrylic vessel, they clearly constitute a threat to the PMT's. Another concern was the possibility of tensile stress arising inside the acrylic due to the reflection of the pressure wave as a rarefaction at the acrylic - D_2O interface. His culculation for a 20" PMT inploding under 3.5 atmospheres absolute pressure results in a pressure of 434psi at the surface of the acrylic and a maximum tensile stress of 160psi inside the the 2.5 cm thick acrylic wall. Given the different starting conditions and thickness it is difficalt to compare this to the value obtained at LANL. Lush then related this result to the "Fracture Toughness" (FT), defined as;

$$\text{FT}=\text{Stress.}(\pi\times.\text{half length of critical crack})^{0.5}$$

The critical crack length is that length of crack, which for a certian level of stress, if exceeded will cause the vessel to fail catastrophically. For a pressure of 51 bar, the critical crack length is ~1cm and the conclusion is that the vessel will leak before it breaks.

Stachiw Associates: Jerry Stachiw reviewed the problem of imploding PMT's in the light of existing experimental data he had obtained for acrylic spheres subject to underwater explosions [6]. He cautioned that the radius of curvature of the test spheres were approximately an order of magnitude smaller than the SNO vessel, and considerable extrapolation was involved in reaching a conclusion. He concludes (see appendix) that a 1" thick sphere will definitely fail if struck by a 20" Hamamatsu PMT which subsequently imploded although a 2" thick vesel would probably survive. A 2" wall would survive the impact and implosion of the Burle and 8" Hamamatsu PMT and would probably survive sympathetic implosion of several PMT's.

4 Conclusions and Recommendations

During the time these studies were underway, the large 20" PMT was dropped from the group of PMT's under consideration for SNO. This was due to the difficalty of fabrication the tube with sufficient wall thickness to tolerate the

hydrostatic pressure. It was probable that the tube would have been eliminated due to the threat posed by the possibility of implosion. We now only consider the Burle and the 8" spherical PMT's.
The primary conclusions to be drawn from the report and reviews are:

- The findings of the Swanson report are supported by the independent reviews of the report.
- The compressive and tensile stresses resulting from an implosion of a Burle or 8" PMT *in situ* will not cause the vessel to fail if the walls are 2" thick and there are no major imperfections which approach the critical crack length.
- A vessel with walls 2" thick would *probably* survive the impact and implosion of a Burle or 8" PMT striking the wall. More confidence in this statement will result from a better understanding of the longterm properties of acrylic immersed in water.
- The formation of high speed jets of water resulting from an imploding sphere are unlikely to threaten the vessel, but represent a real danger to adjacent PMT's.

It is recommended that the following work be carried out:

- The work on the longterm properties of acrylic should continue.
- A number of PMT's should be imploded at ~3.5 atmospheres to determine that the magnitude of the pressure pulse is in the regime predicted by the models.
- An attempt should be made to determine if jets are produced by imploding PMT's and what is an appropriate way of protecting the tube.
- A PMT should be imploded in contact with a sheet of bonded acrylic under stress and immersed in water, to determine if spalling is a problem.

References

[1] Personal correspondence, Hank Sobel, IMB Collaboration, University of California, Irvine, CA 92717.

[2] "Analysis of PMT Implosion for Sudbury Neutrino Observatory", Swanson Service Corp., July 1990.

[3] "Final Report on Spherical Vessel Design for Sudbury Neutrino Observatory", Swanson Service Corp., Report #306689, July 1989. "Buckling Analysis of Sudbury Neutrino Observatory Acrylic Containment Vessel", Swanson Service Corp., October 1989.

[4] R.H. Cole, "Underwater Explosions", Princeton University Press, Princeton, NJ (148).

[5] "Numerical Modeling of Detonations", C.L. Mader, University of California Press, (1979). "Numerical Modeling of Water Waves", C.L. Mader, University of California Press, (1988).

[6] "Spherical Acrylic Plastic Hulls Under External Explosive Loading", J.D. Stachiw, Journal of Engineering for Industry, Vol. 99, No 2, May 1977.

Appendix A:

Memo from W.N. Selander, AECL Chalk River.

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WASTE MANAGEMENT SYSTEMS
Storage & Disposal Technology

MEMORANDUM

1990 June 25

TO: E.D. Earle

FROM: W.N. Selander

Review of SSC Report No. 60190
"Analysis of PMT Implosion for SNO"

I have reviewed the report in as much detail as time would allow. My overall reaction is that while the authors may have come up with a rough estimate of the shock wave overpressure, the key assumption in the report, namely that the implosion generates the same shock wave as an underwater explosion of the same energy, is unrealistic.

I am familiar with the first two references, Rayleigh (1917) and Hunter (1960). These are key papers on the subject of implosions, but I can appreciate the difficulty in trying to get an expression for the shock strength and shock profile, especially from the highly mathematical treatment of Hunter. It is true that the rebound of an imploding bubble will generate an outward travelling shock wave, as does an underwater explosion. It is also true that the initial potential energy of the bubble, equal to the bubble volume multiplied by the initial ambient pressure, is a key parameter in describing system behaviour near the collapse point. I doubt, however, that the shock profile taken from Cole (1948) for an underwater explosion of the same energy would describe the rebounding wave. In bubble collapse, the potential energy is converted to kinetic energy during the implosion, following which much of the inward-moving water retains its kinetic energy until stopped by the outward-travelling shock wave. This is the spherical analog of water hammer in a pipe. In an underwater explosion, some of the energy must continue to reside in the hot gas at the centre, which also occupies a finite volume, in contrast to the collapsed bubble which remains closed. To an observer a long distance away, the results in the two cases might appear to be the same, but near the collapse point they differ so much in detail that any agreement would be coincidental.

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I also note that:

(i) the authors did not refer to any of the papers of M.S. Plesset and his co-authors, who have published many papers on bubble collapse. A reading of their work may lead to a more realistic formulation of the problem;

(ii) it is not clear what the finite element calculation does, i.e. what equations are being solved. If they are using compressible hydrodynamics to describe the response of the water, then an equation of state is needed, and there seems to be no reference to this;

(iii) the details of the PMT rise calculation in water are not clear. I recognise the correct value of 0.4 for the drag coefficient, but a more detailed description of the other parameters should be included, especially since a rather high terminal velocity of 15 m/s was obtained.

WNS/ln

Appendix B:

LANL Memo and results from C. Mader and P. Blewett

Los Alamos

Los Alamos National Laboratory
Los Alamos New Mexico 87545

memorandum

TO: John Moses, P-3, MS D449

DATE: July 13, 1990

FROM: Charles L. Mader
Retired Fellow and T-14 Associate

MAIL STOP/TELEPHONE: B214/7-7869

SYMBOL: T-14-90-97

SUBJECT: **BUBBLE COLLAPSE IN WATER**

This is to document the numerical studies I described to you and Peter Doe on July 10.

The SIN code was used to calculate the collapse of a 12.5 cm radius sphere in water and the magnitude of the shock wave formed. The code and equations of state for water used are described in the monograph **Numerical Modeling of Detonations** published by the University of California Press in 1979. The code has been used for 20 years to calculate the formation and collapse of bubbles formed in water by explosives as described in the monograph.

The following is a summary of the calculated shock wave as a function of radius. The mean pressure in the center cm of water upon collapse was 2-3 kilobars for an initial water pressure of 3 bars.

Radius cm	Peak Pressure bars	P - Initial P (3 bars)
10	250	247
25	100	97
50	50	47
100	25	22
150	18	15
250	12	9
300	10	7
500	8	5

The pressure is decaying as a function of 1/radius which is similar to the experimentally observed decay for bubbles formed from explosions which decay as a function of 1/radius to 1.1 power.

One should also consider that multiple bubble collapse can result in interacting shock waves that can result in regions of increased shock pressure (factors of 2 or 3).

Another effect to be considered is the formation of jets which occur when bubbles collapse from one side. Pictures of such collapse are attached and are taken from "Al Album of Fluid Motion" by M. Van Dyke. Because the jets cause damage to ship propellers. there is considerable literature on the topic. Jet formation from bubble collapse has been studied using PHERMEX and modeled at Los Alamos by several investigators (LA-3614). T-3 or T-14 (and others in and outside the Lab) could perform jet modeling. Some references of interest are:

- J. R. Blake and D. C. Gibson. "Growth and Collapse of a Vapour Cavity Near a Free Surface." J. Fluid Mech.. Vol. 111. pp 123-140 (1981).

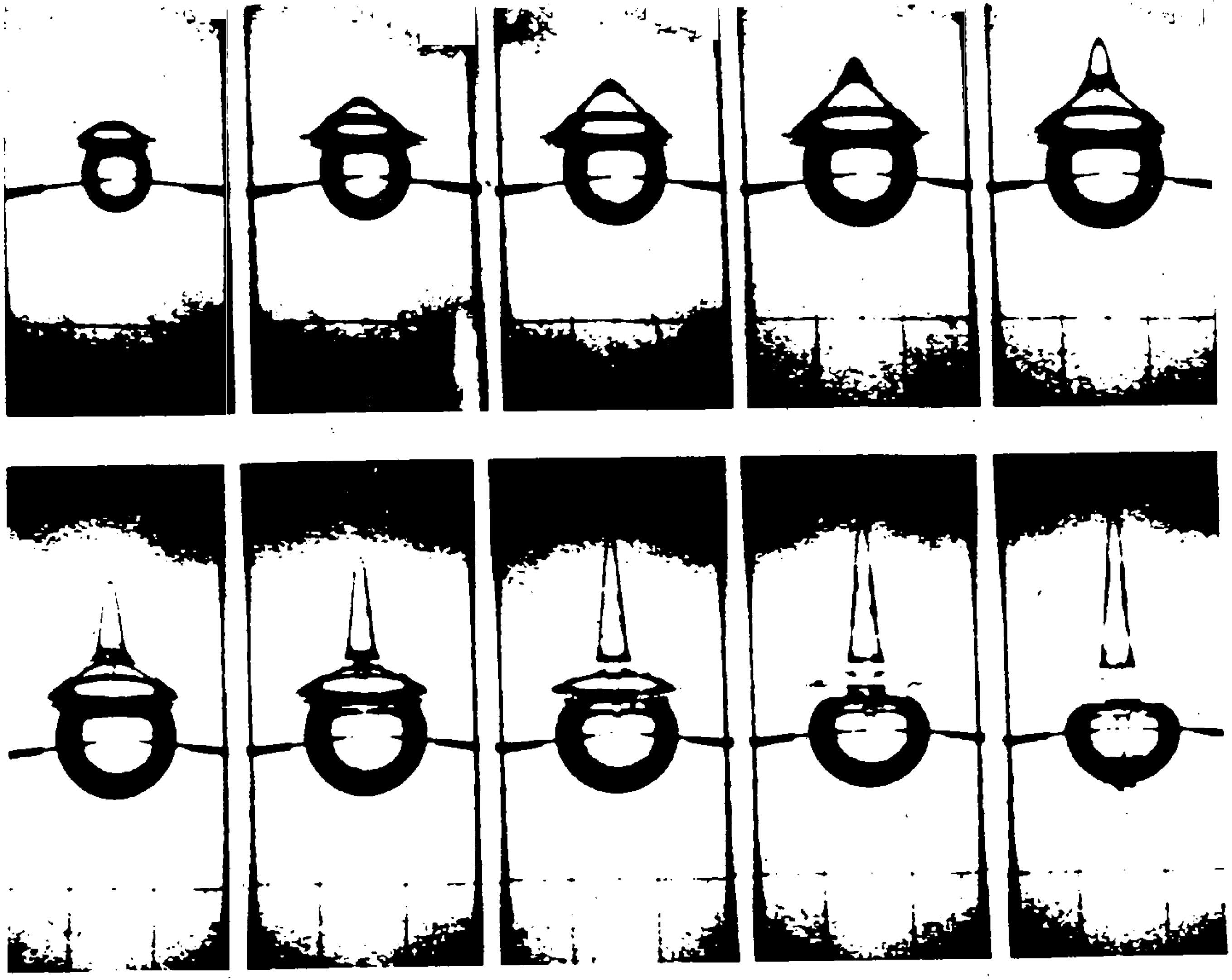
- M. S. Plesset and R. B. Chapman. "Collapse of an initially Spherical Vapour Cavity in the Neighbourhood of a Solid Boundary," J. Fluid Mech.. Vol. 47. pp 283-290 (1971).

- C. Mader. "Theoretical and Experimental Two-Dimensional Interactions of Shocks with Density Discontinuities," LA-3614 (1966).

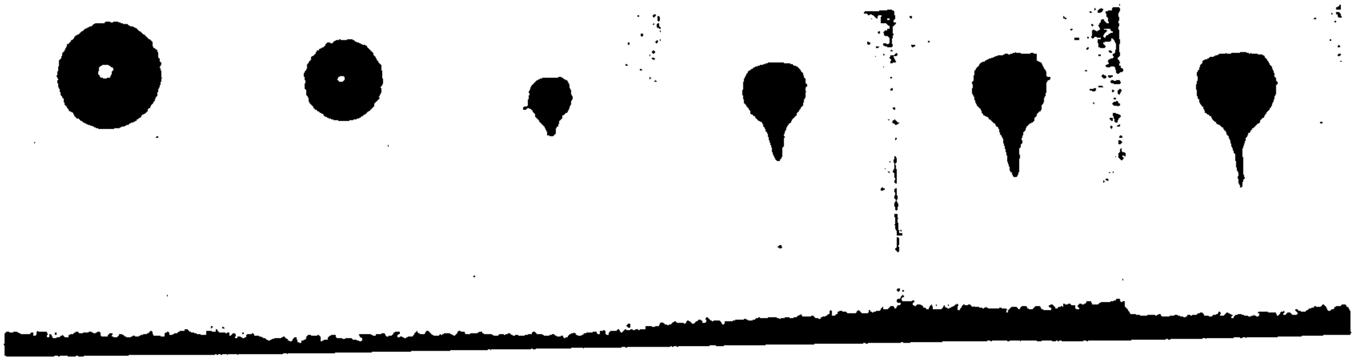
CLM:bg

Attachments

cy: P. J. Blewett, X-3, MS F663
F. H. Harlow, T-3, MS B216
P. J. Doe, P-3, MS D449
C. E. Ragan, P-3, MS D449
J. P. Ritchie, T-14, MS B214
R. C. Slansky, T-DO, MS B210
T-14 File

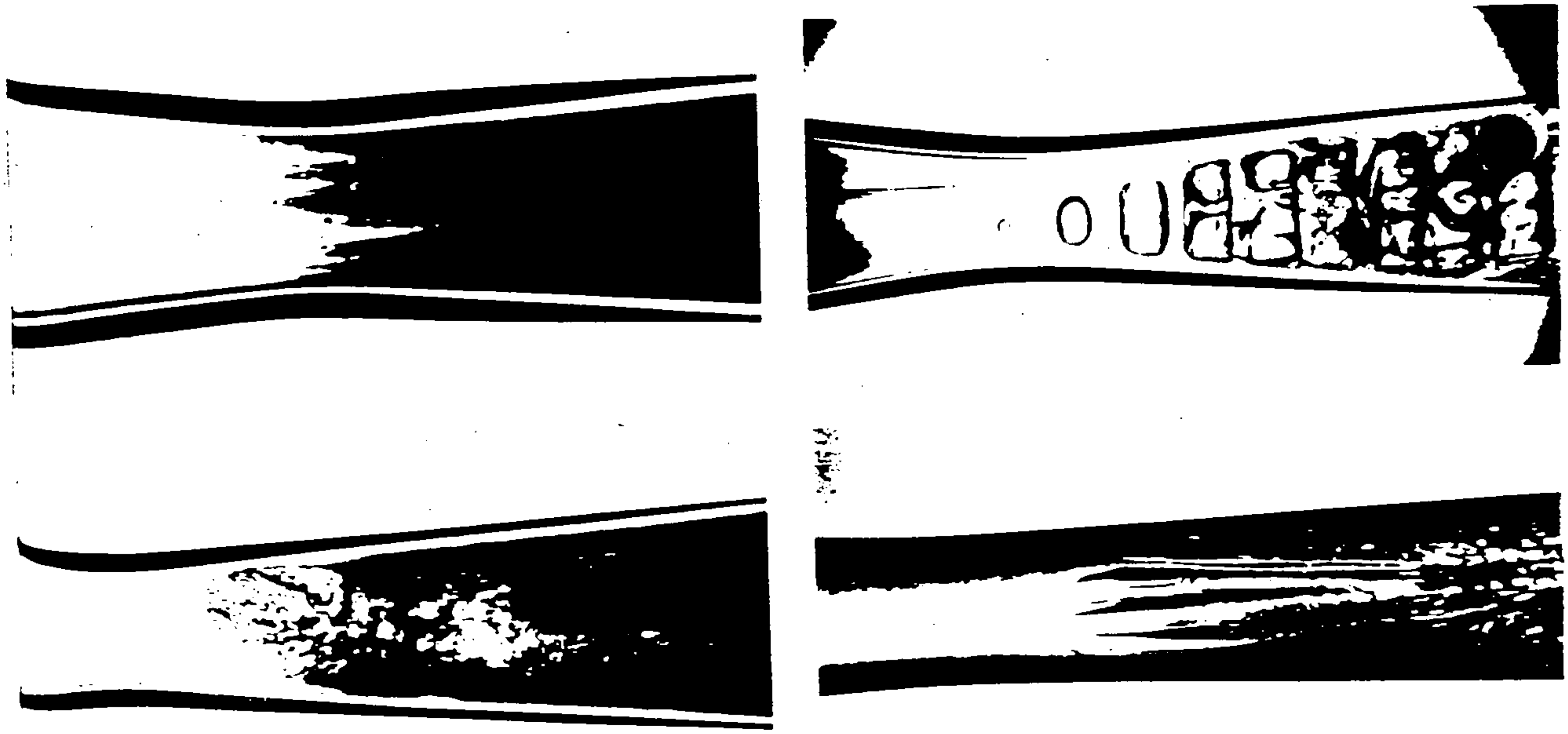


187. Collapse of a bubble near a free surface. This sequence shows the growth and collapse of a vapor bubble in water close to a free-air surface. The bubble is formed by a high-voltage spark discharge between the two probes. A spike of water penetrates the air during growth and collapse, and is balanced by a slender downward jet of water that threads the bubble from its top during the collapse. Buoyancy effects were eliminated by performing the experiment in free fall. The camera runs at about 11,000 frames per second, and the grid at the bottom is 25 mm square. *Blake & Gibson 1981*



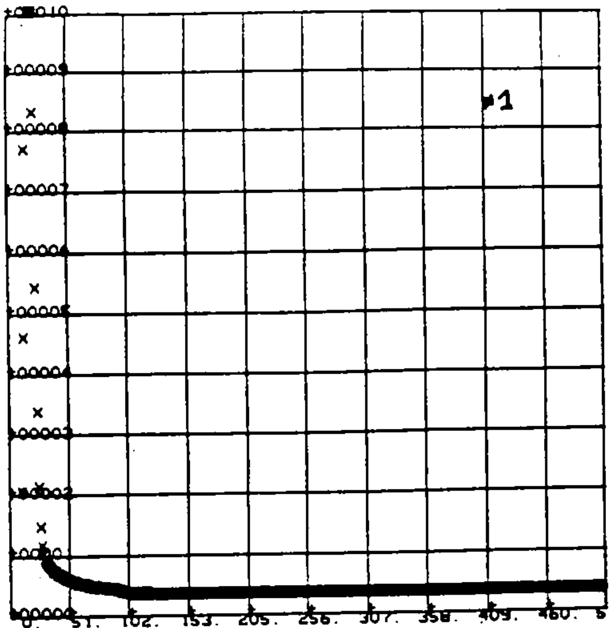
188. Collapse of a bubble near a wall. This sequence shows the collapse of a spherical bubble in still water near a plane solid surface (the dark diffuse boundary at the bottom of each frame). The bubble is produced 4.5 mm from the wall by focused ruby laser light, and has started its collapse after expanding to a maximum radius of 1.1 mm. It is photographed at the rate of 75,000 frames per second. Illumination is from behind through a ground-glass plate. The bright spot in the middle of the bubble results from light passing through undeflected. *Lauterborn 1980*

189. Jet from a bubble near a wall. The previous sequence shows the effect of a high-speed jet, directed downward, that forms at the top of the bubble during collapse. In this magnified view the jet is visible only as a thin dark vertical line through the bright spot in the middle of the bubble. Passing through the almost empty cavity, the jet impinges on its bottom and carries it along to form the spike that extends toward the wall. The jet is believed to extend far ahead of the spike, and to be the cause of cavitation erosion from a solid wall. The horizontal diameter of the bubble is about 2 mm. *Lauterborn 1980*

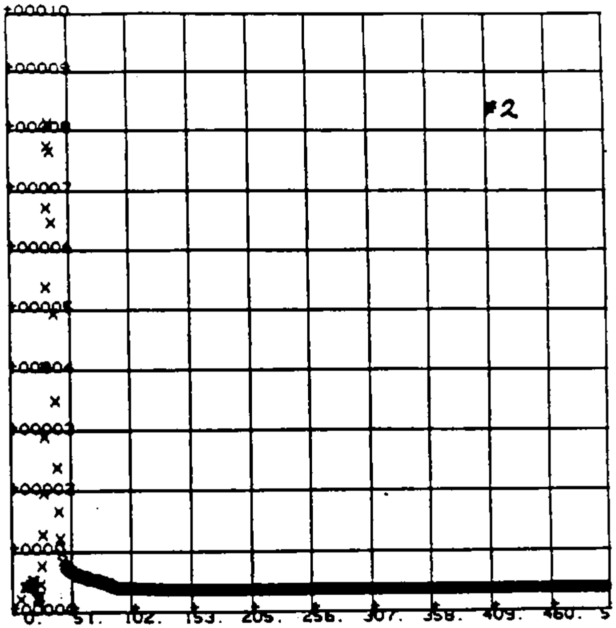


190. Cavitation in high-speed flow of water through a nozzle. Transition from simple liquid to a strongly accelerated two-phase system occurs in a nozzle throat during expansion, particularly in heated liquid. At the upper left, tap water at 204°C shows regular incipient cavitation with nuclei at the wall. The upper right shows missing nuclei, and cavitation initiated by single bubbles in the core, giving periodic pressure oscillations. At the lower right a higher fluctuation frequency is caused by retardation in boiling in water at 133°C. The lower right shows cavitation in water at room temperature containing air. *From DFG-Forschungsberichte* by E. Klein, courtesy of H. Fiedler

C. Mader. Graphical presentation of the propagation of the pulse from an imploding 25cm diameter sphere. Distance is in cm. pressure in Mbar. The time of each frame is shown.



***12 5 CM VOID WATER 500 CM WATER AT PRESSURE
PRESSURE (MEGABARS) VS RADIUS (CM) AT 6.200E+03 MICROSECONDS
CYCLE NUMBER 12401



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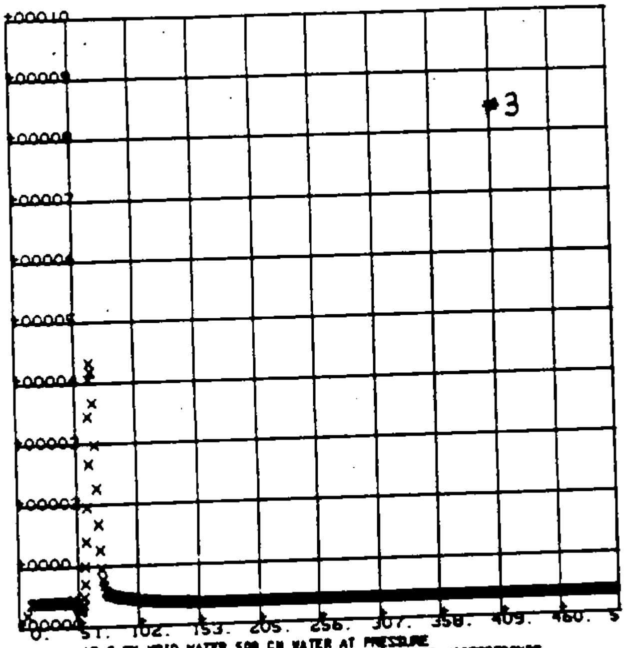
PRESSURE (MEGABARS) VS RADIUS (CM) AT 6.301E+03 MICROSECONDS
CYCLE NUMBER 12601



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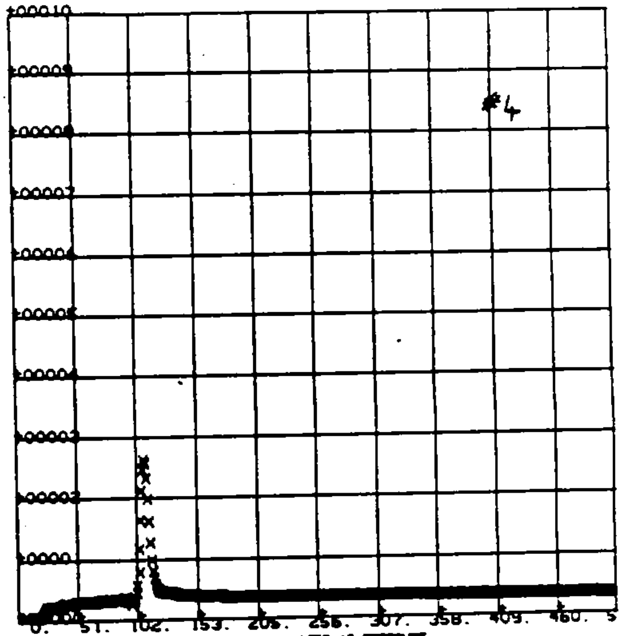
PRESSURE (MEGABARS) VS RADIUS (CM) AT 6 601E+03 MICROSECONDS
CYCLE NUMBER 13001



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PRESSURE (MEGABARS) VS RADIUS (CM) AT 6.801E+03 MICROSECONDS
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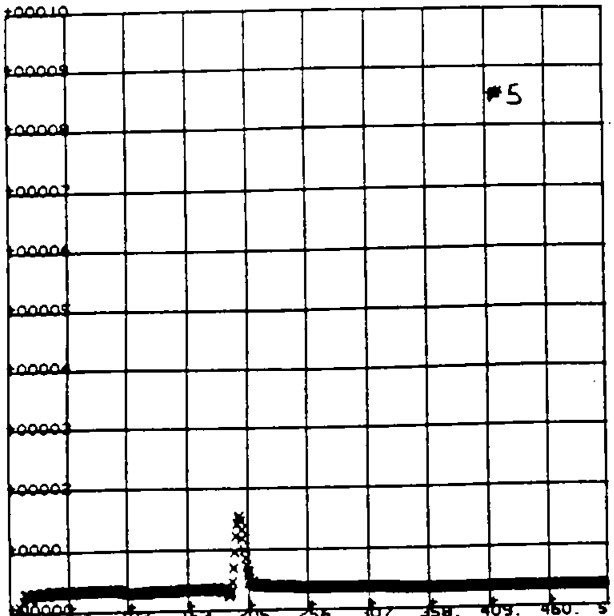

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PRESSURE (MEGABARS) VS RADIUS (CM) AT 7.400E+03 MICROSECONDS
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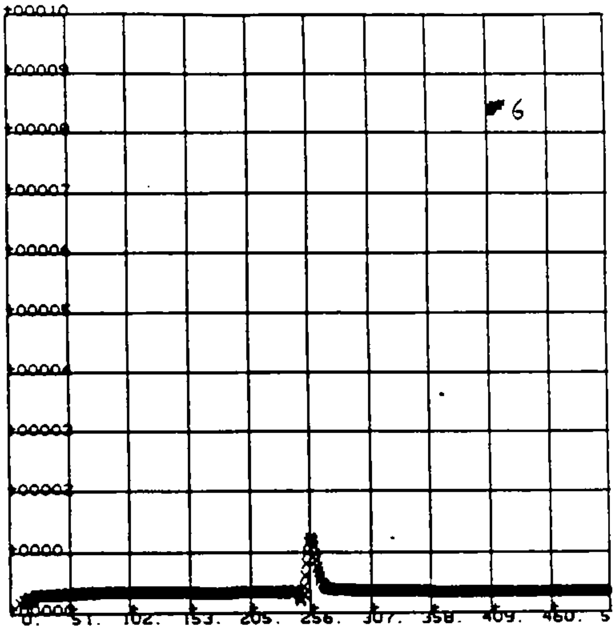

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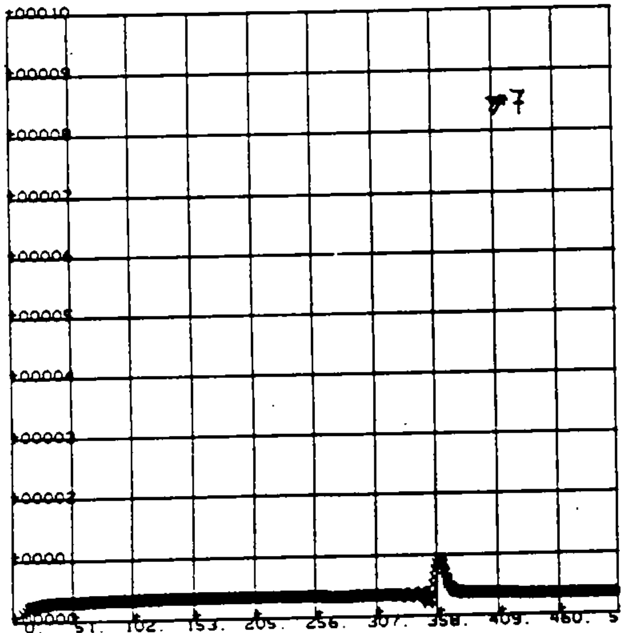
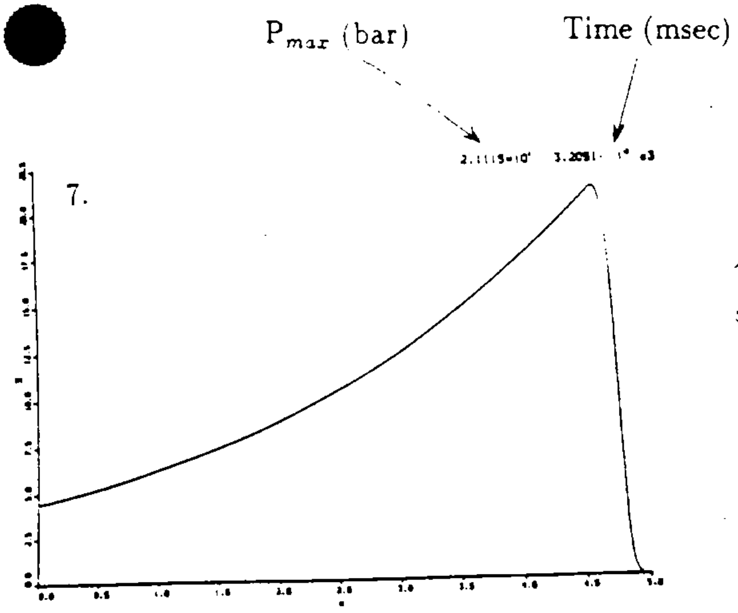
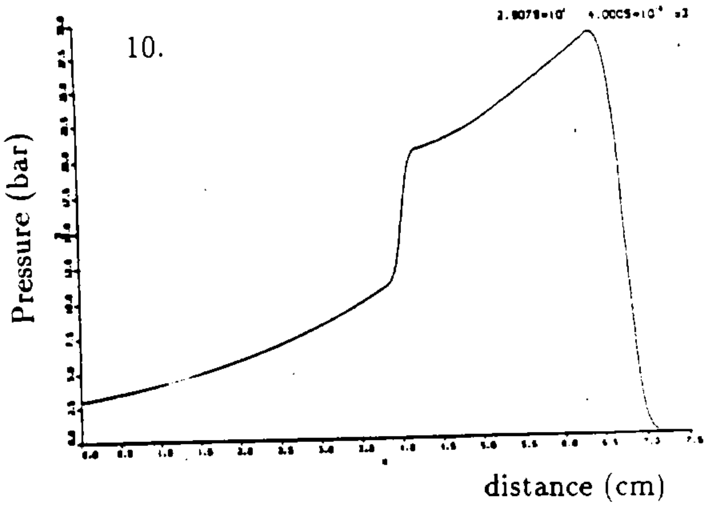
CYCLE NUMBER 15601

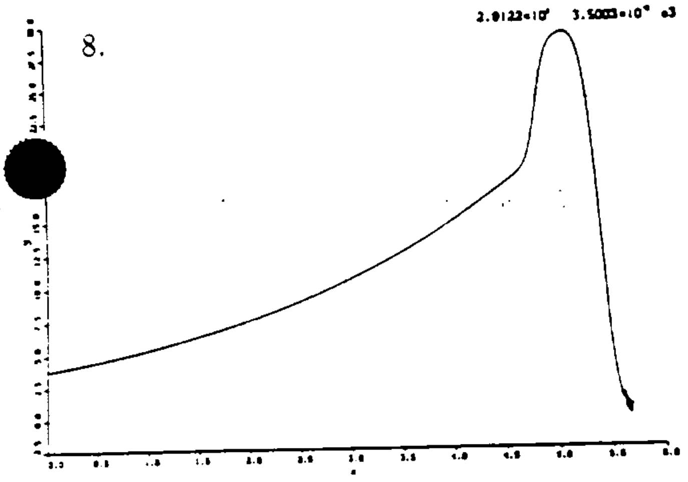


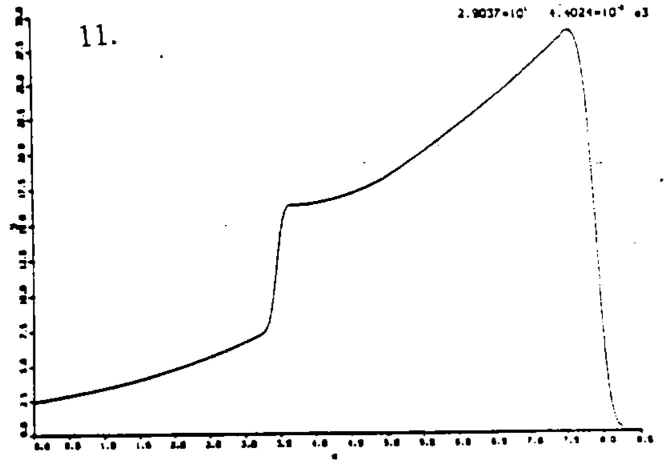
***12 5 CM VOID WATER 500 CM WATER AT PRESSURE
PRESSURE (MEGABARS) VS <

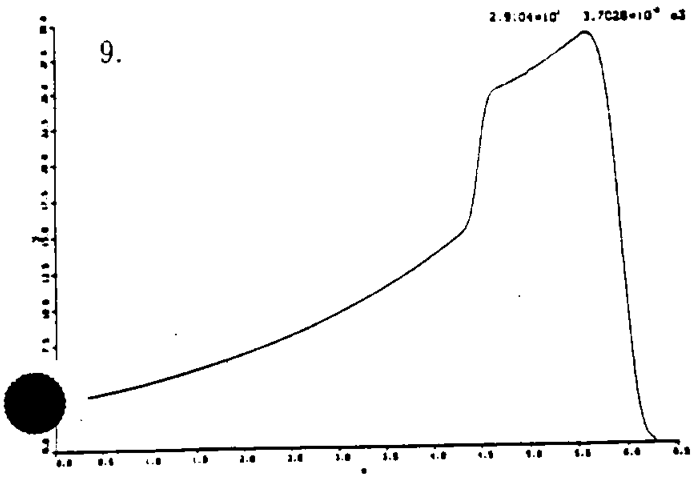
P. Blewett. Propogation of pulse through acrylic. The acrylic interfaces are at 5cm and 10cm.

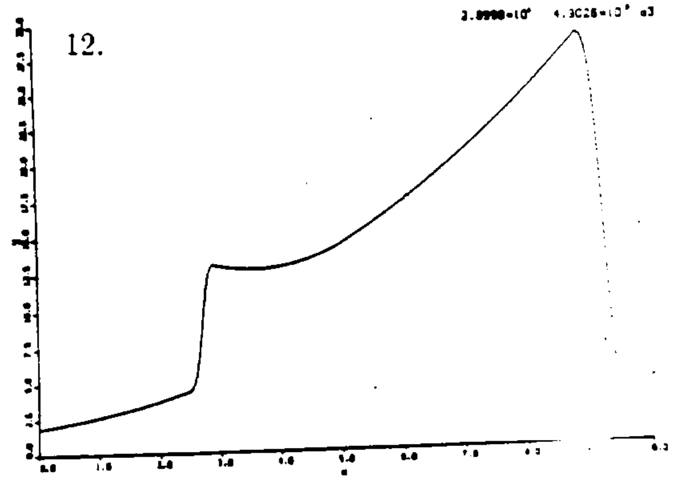












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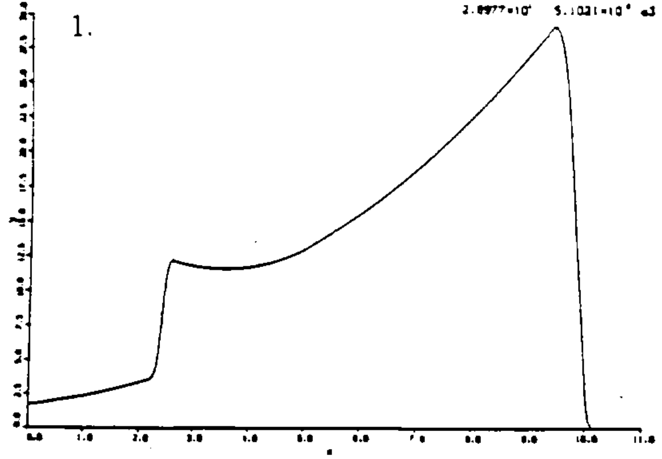
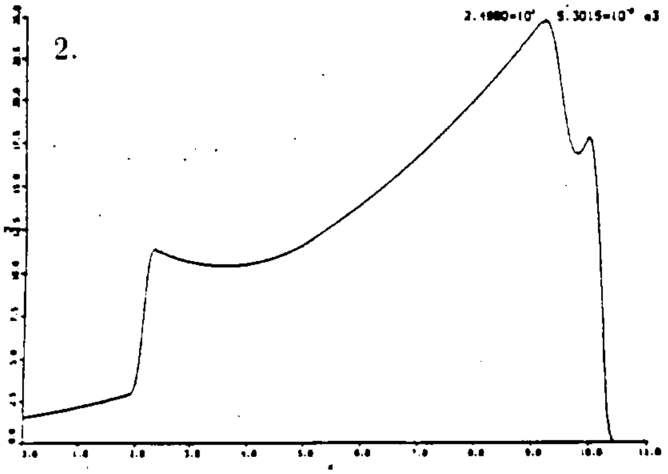


P_{max} (bar)

Time (msec)

2.



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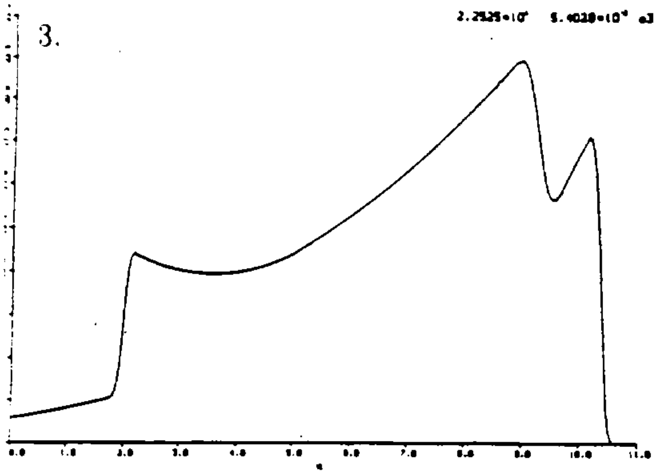
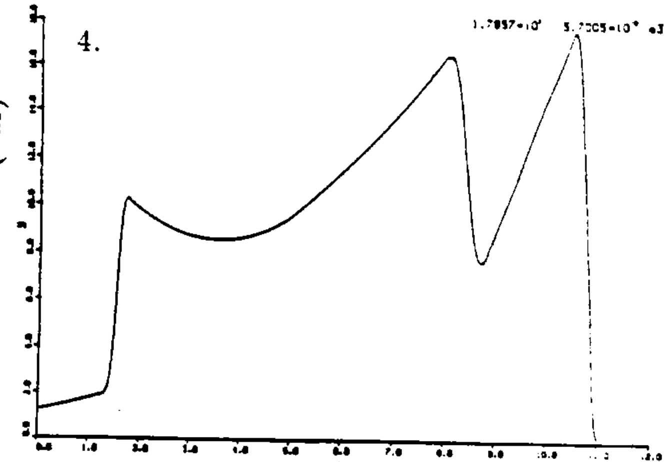


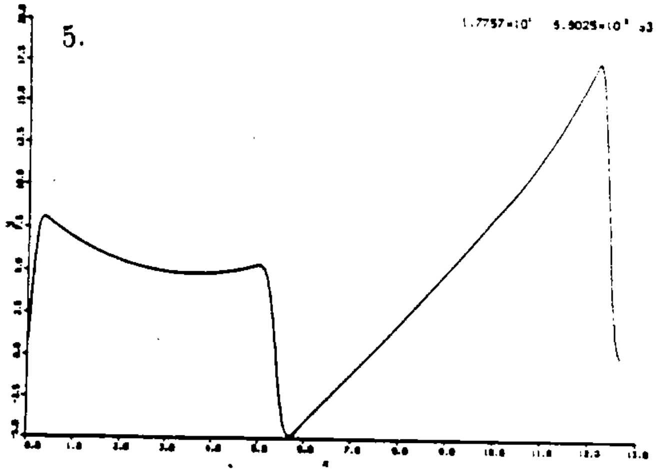
4.



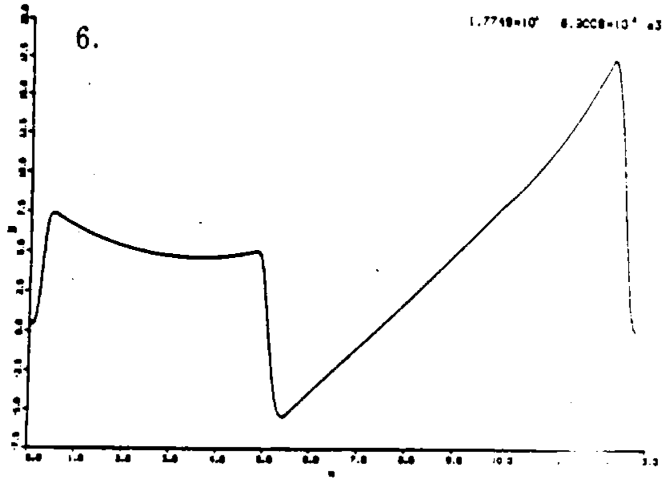
Pressure (bar)

distance (cm)

5.



6.



Appendix C:

Oxford Communications of experimental results and culculations of P. Lush.

From: OXPHV6::WARK "D. Wark" 2-JUL-1990 18:37:00.22
To: @PMTIMPLOSION
CC: WARK
Subj: Results of PMT pressure tests.

PMT IMPLOSION TESTS, JUNE 29, 1990

This note is to describe the results of some PMT implosion tests carried out recently at Oxford. All the tests were carried out on EMI bulbs manufactured by Schott and then sealed by EMI. The bulbs were sealed with pins in place but without any other internal parts using the same temperature cycle as will be used for the actual PMT's. The main purpose of these tests was to confirm that the general bulb design would meet the pressure test for PMT bulbs as specified by SNO, however some information (of questionable value) on the tube-to-tube implosion problem was obtained.

The first test was carried out with two bulbs of 8246 glass which had not been intentionally weakened. The bulbs were enclosed but not sealed in plastic bags. These were then placed in a cylindrical water-filled pressure vessel (radius 45 cm, height about 1.5 m), they tended to float at the top, in contact with the lid of the vessel. The vessel was then pressurized to 7 atm. (all pressures quoted are absolute) and left for 1 hour. The vessel was then pressurized to 10 atm., no problems yet. The pressure was then raised to the limiting pressure of the vessel (22 atm.). The bulbs were tested separately, at this point for one of the bulbs the pressure began to slowly fall. The pressure was then released and the vessel opened, the one of the tube had developed a small leak near one of the pins, the other was intact.

It was then decided to test bulbs that had been artificially weakened. First three bulbs made of 8246 glass were sanded with emery paper, 2 with 600 mesh and 1 with 400 mesh. The area sanded included the front and back of the hemispherical portion of the bulb, but not the neck. These bulbs were all placed in the vessel at the same time (they all floated at the top, touching the lid of the vessel and each other), they were enclosed in thin plastic bags through which numerous holes had been punched. They were then tested as above (1 hour at 7 atm. absolute, then the pressure was raised to 10 atm. in about 40 sec. and left there for several minutes, then raised at a rate of about few atm./minute until a failure). A loud bang was heard at 13 atm. and the pressure dropped to zero. The vessel was opened and it was found that the tube which had been sanded with 400 mesh was destroyed (no piece larger than about 0.5"). One of the other tubes was also broken, the hemispherical portion of the bulb was intact but the neck was sheared off. This damage must have been incured simultaneously with the failure of the other tube, otherwise a pressure drop would have been noted. The third tube appeared undamaged.

The same pressure cycle was then followed with 5 bulbs made of 8245 glass and sanded over a larger area including the neck. After a few seconds at 10 atm. a bang was heard and the pressure dropped to zero. The vessel was opened, one of the tubes which had been abraded with 600 mesh had failed (shattered into small pieces). The other tubes were intact. The 8246 bulb which had survived the test with 3 bulbs was then loaded into the vessel with the 4 survivors of this test. The pressure was then slowly raised without pausing, a bang was heard at 15 atm. and the pressure went to zero. The pressure was raised again (without opening the vessel). At 11 atm. another bang was heard, louder this time, and the pressure once again fell to zero. The vessel was then opened, and all of the 8245 bulbs were found to be broken. One was completely destroyed, one was in fairly large pieces, one had its bulb largely intact but the neck broken, and one had obviously had the pin assembly sucked down the neck and into the bulb (breaking the bulb). It is not certain how the breakage of these bulbs should be apportioned between the two bangs, but from their loudness it seems quite likely that one bulb was lost in the first case, and three in the second. As a final test the surviving 8246 bulb, which had already survived two tests, was returned to the vessel and the pressure slowly raised. It imploded at 20 atm. absolute.

In summary, these tests were designed to test the EMI PMT bulbs for their ability to withstand the pressure tests as specified by SNO. They passed these tests. The tests were also a very worst case test of the tube-to-tube problem, if no bulb had been broken by the implosion of another bulb then one could argue that there was no problem, as it seems certain that the bulbs were subjected to more severe shocks in this test than they ever would be in the SNO detector. However, as some tubes were broken by the implosion of other tubes, this test probably gives no useful information.

From: OXPHV6::WARK "D. Wark" 5-JUL-1990 11:38:45.43
To: DAVIS
CC: WARK
Subj: Plastic bags.

Dear Davis,

The purpose of the plastic bags was to catch the bits when the PMT went pop. We wanted to keep our pressure vessel from becoming full of broken glass, as it is difficult to get to the bottom of it to clean it out. It is also of some interest to collect the pieces from the individual tubes as they break in order to gain a little more information about where the break occured. The bags were not totally successful in this, as the force of the explosion tore them rather badly and some (in some cases most) of the pieces were lost. If we do further testing we will want to think about this some more. I hasten to point out that the bags were not sealed, and in the case of the roughened tubes even had large numbers of hole punched in them to guarantee that the bulbs were in contact with water as they were being 'aged'.

We have finally made profitable contact with outside experts on the tube-to-tube and tube-to-acrylic questions. We are talking to a Roger Bettes at a place called Hydraulics Research, he has called in colleaques of his from the City University in London (a Prof. David Thorley and friends) who are experts on pressure waves in water, specifically the pressure waves generated by the collapse of large bubbles caused by cavitation. I have passed the Swanson report on PMT implosions along, Bettes has promised to take a critical look at it and let us know what he thinks. His first impression was that the method used (calculating the PV work and translating that to the equivalent amount of HE is not necessarily valid and may produce either an overestimate or an underestimate of the pressures being generated. He states that the critical parameter is the time which the PMT takes to collapse, the faster it goes the higher the pressure that will be generated when the incoming walls of water and glass collide. He stated that it will depend very much on the details of the collapse, will probably have substantial tube-to-tube variation, and will be very difficult to calculate. He thought experiments might be necessary, but that was a first guess. I will tell you more when I talk to him again.

Dave

From: OXPHV6::WARK "D. Wark" 6-JUL-1990 11:14:41.99
To: @PMTIMPLOSION
CC: WARK
Subj: Oxford contacts on PMT implosions.

This message is to briefly bring you up to date on contacts I have made with local experts who may be able to help us. I have contacted Dr. Roger Bettes at Hydraulics Research, who works on shock waves in water. He put me in contact with a group at City University in London lead by a Prof. David Thorley, I am currently working with Dr. Peter Lush who's area of expertise is the creation and propagation of sock waves in water from the collapse of 'bubbles' caused by cavitation. I have given copies of the Swanson report to Lush and Bettes who are currently looking them over and will contact me early next week with their thoughts. After talking on the phone to them they both thought that the method used by Swanson may or may not give a reliable estimate of the pressures involved. There was no quibble about the calculation of the energy available, but both stressed that the peak pressures in the shock depended critically on the speed of the collapse, and that this was not necessarily well represented by an explosion. Bettes commented that it would be very difficult to accurately model the collapse due to the complexity of the insides of a PMT. Lush agreed, but thought that he could calculate a 'worst-case' scenario where the PMT simply disappears and the resulting cavity collapses, this should give the most rapid collapse and the highest pressures. He thought peak pressures in the thousands of atmospheres were possible, but would get back to me when he had calculated something. Of course, whatever he calculates will be high, and neither had a good idea how we could get a theoretical estimate of how much the shock would be reduced by taking the PMT into account properly.

On the subject of a PMT floating up and hitting the acrylic sphere, Lush told me that when a cavity collapse occurs near a surface a 'microjet' tends to form directed at the surface. These microjets have sufficient force to carve pieces out of stainless steel, I would hate to think what they could do to acrylic. I think we must assume that any PMT, not just the large Hamamatsu, would destroy the acrylic sphere if they imploded next to it and design accordingly. I expect to get more quantitative information from these guys early next week and will pass along whatever I learn.

Dave

From: OXPHV6::WARK "D. Wark" 9-JUL-1990 15:30:31.31
To: @PMTIMPLOSION
CC: SUDBURY TANNER,WARK
Subj: Some numbers on PMT implosions.

I talked today with Peter Lush, who gave me the results of his first calculations for pressures generated by a PMT collapse. His calculations assume a spherical cavity appears in the water and then collapses, it uses a realistic equation of state for the water. The results of this type of calculation have been checked experimentally for 1 bar and agree at the few percent level. He calculated for 3.5 and 1.5 bar, I have added my own interpolations for 3.0 bar to compare to Swanson. An interesting result he gives is that the pressure when the shock wave rebounds to the original cavity radius is a constant depending only on the pressure, and outside this radius varies as ((radius of the pmt)/distance)**1.059 (note that Swanson uses 1.13 for the exponent, which he says is more appropriate for an explosion). Thus the results he calculates (for a r=25 cm sphere) can be used for any PMT by substituting the appropriate radius. I have calculated the pressures for a 20" Hamamatsu and a Burle assuming they are spheres with the volumes given in the Swanson report. The results are:

Pressure (bar)	Shock pressure at PMT radius (psi)	Shock pressure (psi) at distance of 2.5m	
		20" Hamamatsu	Burle
1.5	3881.	322.	156.
3.0	4954.	410.	198.
3.5	5233.	434.	210.

Note that the pressure for the 20" is 25% higher than in the Swanson report (I would call that reasonable agreement, all things considered). Also note that the Burle is down a factor 2 in this calculation as opposed to 1.4 for Swanson. However, this calculation is for an ideal case of unconstrained collapse which will not exactly apply in our case. Dr. Lush did not think the PMT glass would actually make that much difference, as the fracture speed of the glass is very high compared to the speed of the water during the beginning phase of the collapse. The other structure inside the PMT is more difficult to account for. He once again brought up the fact that asymmetric collapse tends to generate high-speed jets in the water (with speeds up to 250 m/sec), however he seemed to think it unlikely that the jets could travel through the 2.5 meters of water and reach the acrylic vessel. He did not seem as confident that we are in the "far-field" limit and did not have to worry about the shock waves traveling preferentially in one direction. He expressed interest in any experiments (which is easy for him, he doesn't have to do them), and didn't think there would be any problem in interpreting them (At least so far as he didn't think there would be much variation between tubes in the pressures generated when they were made to fail in the same way. Variation between tubes in the pressures they will withstand is another matter). He is currently considering the Swanson report and will get back to me with his opinion, which I will pass along.

Dave

From: OXPHV6::WARK "D. Wark" 10-JUL-1990 17:55:25.26
To: @PMTIMPLOSION
CC: SUDBURY TANNER,WARK
ubj: More about PMT implosions.

I have had another discussion with Peter Lush about PMT implosions. When pressed he thought it difficult to say whether we are in the 'far-field' limit, specifically he was unable to give a quantitative estimate of the asymmetry we could expect to see in the pressure wave from a PMT collapse. We discussed the idea of putting an acrylic shield around each PMT, he stated that a right-circular cylinder might be expected to focus some of the shock forward, but that a backward facing cone would not. Furthermore the shock passing through the forward aperature of a backward facing cone would tend to be diffracted, further reducing the peak pressure at the acrylic vessel. This led us into a discussion of the failure of acrylic under pressure waves. He stated that the compression wave hitting the front of the acrylic is partially transmitted and can produce a reflected tension wave when it interacts with the back surface. It is the interaction of this tension wave with the compression wave in the acrylic that will most likely produce failure. He felt that he could do a one-dimensional calculation of a shock passing through a light-water/acrylic/heavy-water sandwich that might help us estimate when the acrylic would fail. In order to do this calculation he needs to know the bulk modulus and the compression wave modulus (or Young's modulus and the Poisson ratio) for acrylic, and how these are likely to change with time. Can someone (P.Doe?) supply me with this information?

He also supplied references to the experiments refered to in my earlier note. They are:

Mellen, Spher. Press. Waves. in Underwater Blah blah blah, U.S. Navy Underwater Sound Laboratory Research Report 326, Sept. 1956

lellen, Journal of the Acoustical Society of Am., Vol. 28, page 447 (1956)

Dave

From: OXPHV1::WARK "D. Wark" 11-JUL-1990 17:30:22.94
To: @PMTIMPLOSION
CC: SUDBURY TANNER,WARK
Subj: Some info on acrylic failure.

Peter Lush has given me the preliminary first results of his calculation of shock failure in the acrylic. He points out that the worst case shock pressures are far too small to induce the acrylic to fail due to compression. However, a mechanism exists that can produce tension within the acrylic. If we model the shock as a square wave and consider what happens when it hits the acrylic vessel, we have a compressive shock traveling into the front face of the acrylic, through it, and reflecting off of the back face. In what turns out to be the worst case we assume that it is totally reflected at that point and becomes a rarefaction wave which then travels back through the acrylic, cancelling out the increased pressure from the shock. When it meets the the 'release wave' (the trailing edge of our square shock), it can then generate a tension wave in the acrylic whose pressure is equal (but opposite) to the initial shock. Peter points out that in our case:

1. The acrylic is too thin for this to happen. For the 1/e time he calculates for the shock (.03 millisec, in agreement with Swanson), the reflected wave is through the acrylic before the release wave gets there, thereby tension is not generated. Tension is only generated if the acrylic is >4 cm. thick.

2. Even if the acrylic were thicker, you can't generate a tension wave of higher pressure than the initial shock. Since this is only something like 430 psi, and the minimum tensile strength of the acrylic is 9,000 psi, (Swedlow recommend <3000 psi for a dynamic load) we should have an adequate safety margin.

Furthermore, changing the main approximations in the above calculation (complete reflection at the Acrylic/D2O interface, square wave shock) will further reduce the tensile shock. Peter then brought up the questions of bonds (what is their tensile strength?) and of flaws. The Swedlow report has bond strenghts ^.5 of the values for the bulk acrylic, so we should be ok there. He wanted to know the 'fracture toughness' of acrylic, does anyone have this number? From this he said he can work out the maximum size of a flaw we could tolerate based on the max. tensile shock we anticipate. However, he needs to know what the maximum static tensile pressure that will be in the acrylic vessel, as this will of course add to whatever the shock produces. From the Swedlow report I make this something like 600 psi. Is this correct/current?

Dave

From: OXPHV1::WARK "D. Wark" 16-JUL-1990 15:20:29.83
To: @PMTIMPLOSION
C: SUDBURY TANNER,WARK
Subj: More on acrylic failure.

I have had yet another conversation with Peter Lush about imploding PMT's, and he has passed along some more information that may be of general interest. The basic situation is little changed from my last note. The actual values he gets from the calculation are smaller than the worst-case, as expected. Using the case of the 20" tube in 3.5 atm. his actual number is a maximum tensile stress in the acrylic vessel of 166 psi, which is not enough to cause it to fail. He did say some interesting things about a quantity called the fracture toughness of the acrylic which I thought I would pass along. The fracture toughness (Ft) is defined by:

Ft=(pi**0.5)*stress*(half length of critical crack)

so if a flaw exists in your material with a size larger than the critical crack at a given stress, it will fail catastrophically, otherwise it won't. Peter found a number in a textbook for PMMA of Ft=0.9-1.4 Meganewtons/meter**3/2. Putting in this number, Peter states that for a stress of 51 bar, the half-length of a critical crack is 1 cm. Since this is about the max stress anticipated for our vessel (and much larger than any number we have been getting from the PMT collapse), the conclusion is that our vessel will leak before it will break. Maybe this is well known to the folks in engineering land (he said it was very basic stuff), but it was news to me, so I thought I would pass it along. He gave me a basic reference on the topic of fracture toughness, it is Engineering Materials, an Intro. to Their Prop. and Appl.; Micheal Ashby and David Jones, Pergammon Press, page 127.

Dave

From: OXPHV1::WARK "D. Wark" 16-JUL-1990 16:59:42.99
To: @PMTIMPLOSION
CC: SUDBURY TANNER,WARK
Subj: Oops.

It has been pointed out to me that my notes must be garbled and that the correct equation must be:

Ft=stress*(pi*half length of critical crack)**0.5

in order to be dimensionally consistent with the number quoted. The "half-length" refered to means into the material (that being the direction that cracks tend to propogate). For a surface crack it is just the depth, for an internal flaw it is half the depth. For further details see an engineering book, because its over my head.

Dave

Appendix D:

Report and recommendations of J. Stachiw.

6/10/90

From: Dr. J.D. Stachiw
Stachiw Associates

To: Dr. P. Doe
Los Alamos National Laboratory

Copy to: Dr. A. McDonald
Queens University

Subject: Effect of PMT Implosions on Structural Integrity of Acrylic Sphere in Sudbury Neutrino Observatory

SUMMARY

A buoyancy propelled PMT which implodes upon impacting the acrylic sphere may initiate local fracture in the acrylic shell. To eliminate this possibility, it is recommended that large Hamamatsu PMTs be eliminated from the tube array and that the acrylic sphere be fabricated from 2 inch thick material.

INTRODUCTION

There appears to be some concern about structural failure of the acrylic sphere initiated by the dynamic pressure and/or impact of an imploding PMT. This concern in very appropriate as dynamic pressure waves and point impacts have been experimentally shown to originate fractures in submerged acrylic pressure housings (References 1,2,3). In all cases, the experiments were performed on spherical windows, or spheres with wall thickness in 0.5 to 4 in range and spherical radii in 4 to 33 in range while submerged in water, and subjected to underwater explosions, or impacts by moving objects.

TEST RESULTS

Underwater Explosions

Test data indicates that cracks can be initiated in the acrylic shells by dynamic pressures whose peak magnitude was significantly less than the magnitude of static pressure required to initiate general implosion of the shell. The cracks were located on the interior surface of the acrylic shell, facing the location of the explosive charge. The cracks are oriented radially with the ends of cracks flaring out into plane fracture surfaces. The number of experimental data points is insufficient to formulate a relationship between the magnitude of dynamic pressure, impulse, thickness of acrylic, curvature of shell, and initiation of fractures.

There is, however, a strong indication that there appears to be a linear relationship between shell thickness and peak dynamic pressure needed to initiate fractures in spherical shells with 7.5 in radius. It appears that it requires approximately 1400 psi peak dynamic pressure and 0.045 psi sec unit impulse to generate a crack in a 1 inch thick shell (i.e. 8.2 grams of 50% PETN and 50% TNT at 36 inches standoff). Same dynamic pressure and impulse, however, did not generate any cracks in a 1 inch thick shell with 4 in radius. A 0.5 inch thick shell fractured under 1035 psi peak dynamic pressure and 0.033 psi sec unit impulse (i.e. 8.2 grams of explosive at 48 in standoff). A 4 in thick shell with 33 in radius did not fracture when subjected to 4927 psi peak dynamic pressure and 0.611 psi sec unit impulse (i.e. 688 grams at 53 inches standoff). When external static pressure of 1000 psi magnitude was superimposed on the spherical shell during dynamic pressure application, the magnitude and severity of cracks was decreased, or totally eliminated, since the compressive membrane stresses in the shell generated by static pressure loading were higher than the local tensile stresses generated on the inside surface by dynamic pressure pulses.

Point Impacts

Data generated by impacting a spherical acrylic shell with a flat faced impactor indicate that the initiation of a crack on the interior surface of the shell directly under the point of impact is related to the kinetic energy of the impactor required to generate a tensile strain in excess of 10000 microinches/inch on the inside surface of the shell. Experiments have shown that it requires approximately 400 ft. lbs of kinetic energy to initiate cracks in a 2.25 in thick spherical shell and 1750 ft. lbs of kinetic energy to initiate cracks in 4.0 in thick spherical shells with 24 inch radius (i.e. the critical kinetic energy increases with the thickness squared). Based on this relationship, the kinetic energy required to initiate cracks in 1 and 1.5 in thick shells with 24 inch radius is estimated to be 110 and 250 ft lbs, respectively. Superposition of static pressure on the spherical acrylic shell increased its resistance to fracture initiation by impact loading due to introduction of compressive membrane stresses.

DISCUSSION

Dynamic Pressure Loading

Not many conclusions can be drawn from the sparse experimental data, except that (1) fractures initiate on the concave surfaces of shells when tensile strains exceed 10,000 microinches, (2) the resistance to crack initiation increases with shell thickness and external static pressure, and decreases with increase in the radius of shell curvature. Considering the fact that the radius of SNO shell is an order of magnitude larger than most of the above test specimens, I would estimate that it will require less than 500 psi of peak dynamic pressure to initiate fracture in a 1 in thick SNO shell and 1000 psi in a 2 in thick SNO shell.

Point Impact Loading

Not many conclusions can be drawn from the meager data, except that (1) fractures initiate on the concave surfaces of shells when the tensile strains exceed 10,000 microinches, (2) the resistance to crack initiation increases with shell thickness, and external static pressure, and decreases with an increase in shell radius of curvature. In view of the fact that the radius of SNO shell is an order of magnitude larger than the above test specimens, I would estimate that it requires less than 50 ft lbs of kinetic energy to initiate cracks in 1 in and 100 ft lbs in 2 in thick SNO shells, respectively.

CONCLUSIONS

Comparison of values calculated by Swanson Service Corporation (Ref. 4) for dynamic pressure of imploding PMTs and kinetic energy of impacting PMTs with experimental data in technical literature indicates that a 1 in thick SNO acrylic sphere will without a doubt fracture when impacted at the South Pole by a large Hamamatsu tube that implodes upon contact with the sphere. A 1.5 in thick sphere will probably fracture under the same conditions, and a 2 in thick sphere probably will not fracture under the same conditions.

In other words, large Hamamatsu PMTs pose a liability to the structural integrity of the SNO acrylic sphere containing heavy water, as even a 2 in thick shell may fracture when simultaneously subjected to point impact and dynamic pressure pulse of the imploding tube. Since there is no guarantee that one of these large tubes may not break free, there are only two options available to the designer: (1) either eliminate large Hamamatsu tubes from SNO, or (2) make the shell thick enough to withstand simultaneous impact and implosion of a Hamamatsu tube.

The thickness of the shell needed to withstand simultaneous impact and implosion of the Hamamatsu tube can be calculated by finite elment procedure. There is no doubt, however, in my mind that the thickness will have to exceed 2 inches, which is highly undesirable from radioactive contamination viewpoint.

RECOMMENDATION

1. Large Hamamatsu PMTs <u>should be eliminated</u> from further consideration for SNO as otherwise the wall thickness of acrylic sphere will have to exceed 2 inches in order to provide the sphere with adequate protection against fracture initiation by point impact and implosion of a large Hamamatsu tube.

2. If large Hamamatsu tubes are eliminated from SNO PMT array, the thickness of the sphere can be reduced to 2 inches, which should provide adequate protection against fracture initiation by point impact and implosion of the small Hamamatsu or Burle PMTs.

3. The 2 inch wall thickness is probably also adequate to prevent fracturing of the sphere during sympathetic implosion of several smaller PMTs.

References

1. J.D. Stachiw, "Spherical Acrylic Plastic Hulls Under External Explosive Loading," American Society of Mechanical Engineers, Paper No. 76-WA/OcE-4, ASME Journal of Engineering for Industry, Vol. 99, No. 2, 1977.

2. J.D. Stachiw, "Deep Submergency Spherical Shell Window Assembly with Glass or Transparent Ceramic Windows for Abyssal Depth Service," Americam Society of Mechanical Engineers, Paper No. 74-WA/OcT-3, ASME Journal of Engineering for Industry, Vol. 97, No. 3, 1975.

3. J.D. Stachiw and O.H. Burnside, "Acrylic Plastic Spherical Shell Window Under Point Impact Loading," American Society of Mechanical Engineers, Paper No. 75-WA/OcE-6, ASME Journal of Engineering for Industry, Vol. 98, No. 2, 1976.

4. Swanson Service Corporation, SSC Report No. 60190, "Analysis of PMT Implosion for Sudbury Neutrino Observatory," June, 1990.