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TECHNICAL REPORT 3673

**A LARGE CONTAINMENT CAPSULE FOR  
NUCLEAR REACTOR IRRADIATION OF  
EXPLOSIVE MATERIALS**

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APRIL 1968



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by

Louis Avrami  
Everett Dalrymple  
Frank Schwartz

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## ABSTRACT

The design and development of a large explosive containment capsule for the irradiation of up to 80 grams of explosive materials is described. The capsule will fully protect its surroundings, e.g., the core of a nuclear reactor, if its explosive content detonates. The minimum safety factor of two was used. The capsule contains provisions for the containment of gases produced by detonation or burning of the explosive material and the minimizing of any shock wave propagated outside the capsule. Also, provisions are made to monitor pressure or gas evolution and the temperature of the test material during irradiation. Dynamic pressure pulse and stress-strain measurement tests were conducted and are described. Analytical calculations were made for comparison with experimental data, first to determine the validity of the calculations and then to obtain information on configurations not actually tested.



## FOREWORD

This report was prepared under NASA Defense Purchase SNC-3. The program was sponsored for the past three years by the NASA Space Nuclear Propulsion Office, Cleveland and administered by Mr. Harry Smith and subsequently Mr. Paul Ordin.

This work was included as part of Phase II of the Countermeasures Radiation Effects Program of the overall NERVA Program which is being conducted by Aerojet-General Corporation as prime contractor for the NASA-SNPO-C.

The Explosives Laboratory of Picatinny Arsenal acknowledges the technical assistance rendered by Messrs. W. E. Voreck, M. E. Down, E. I. Lindberg, and Joel R. Norman, Aerojet-General Corporation, during the final development phase and qualification testing of the explosive containment capsule for acceptance by the General Electric Company for use in the General Electric Test Reactor at Vallecitos Nuclear Center, Pleasanton, California. The discussions with personnel from the Irradiation Processing Operation and Nuclear Safety Group of the General Electric Vallecitos Nuclear Center were informative and the problems regarding safety and operations were understandable and considered in every aspect. The efforts of Mr. P. J. Hollifield and Mr. J. F. Jaklevick, Jr. were appreciated.

The assistance and encouragement of the following are gratefully acknowledged. Dr. J. V. R. Kaufman, Chief Scientist, U. S. Army Munitions Command for initiating the program, Dr. H. J. Matsuguma, Picatinny Arsenal, for his suggestions, Dr. Paul W. Levy, Brookhaven National Laboratory for his criticisms, and Mr. E. E. Walbrecht, for his work on the instrumentation and testing. Also the efforts of Messrs. B. Aber and P. Flagler in the final design drawings and procedures are greatly appreciated.

Part of this report was presented at the Conference on Prevention of and Protection Against Accidental Explosion of Munitions, Fuels, and other Hazardous Mixtures, 10-13 October 1958, at the New York Academy of Sciences, New York, N. Y.

The authors wish to express their gratitude to Mrs. Barbara C. Nelson for the typing of this report.

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## INTRODUCTION

The study of effects of reactor irradiations on explosives was initiated in the nineteen fifties. At that time it became apparent that the safest way to irradiate explosives was in a container that would completely protect the surroundings if a detonation occurred. The specific requirement for the design and development of an explosive container that would contain relatively large amounts of explosives for irradiation in a nuclear reactor became mandatory, in 1962, to implement the NERVA Program conducted by the NASA Space Nuclear Propulsion Office in Cleveland. At that time Aerojet-General Corporation and Picatinny Arsenal initiated a program to study the effect of radiation on explosives, utilizing the General Electric Test Reactor at Vallecitos Atomic Laboratory, Pleasanton, California. Picatinny Arsenal was given the responsibility to design and develop a large explosive capsule for reactor irradiations. This was a continuation of an earlier program in which a broad range of materials and geometries for explosive containers were investigated.

## OBJECTIVE AND SCOPE

The objective of the work described in this report was to design a capsule that would enable 80 grams of explosives to be irradiated safely in a nuclear reactor. The container design was intended to incorporate such safety features that any internal dynamic impulse resulting from an explosion would not unduly affect the immediate surroundings, i.e., the nuclear reactor.

The study was divided into two phases. The first phase was an empirical determination of the ability of various metal cylinders to contain the detonation of explosive charges. The cylinders were fabricated from steel, lead, and different aluminum alloys. Numerous combinations of length to diameter for a range of wall thicknesses were employed. The tests were conducted by mounting the cylinders vertically on a steel plate and topping them with another steel plate weighed down by a 500-pound lead block. Uncased, spherical explosive charges were mounted at the geometric center and detonated along the cylindrical axis. An empirical expression was obtained relating the cylinder length, diameter,

wall thickness, and material to the maximum explosive charge satisfying the containment criterion. Incidentally, the criterion used was the ability of the cylinder to withstand the detonation of the explosive charge without any rupture occurring. This phase of the work was described by Mackenzie et al. (Ref 1, 2, and 3).

The second phase was the design and testing of a series of capsules. The final design successfully met the reactor safety and engineering requirements.

To grasp the scope of the problem more fully it should be noted that from all published reports on irradiation of explosives the amounts irradiated were very small (1 to 5 grams). As an example, Aerojet-General Corporation conducted a parallel program for a small capsule 2 1/8 inches in diameter by 9 inches in overall length to safely contain 1.8 grams of explosives during reactor irradiation (Ref 4) as compared to 10.5 inches in diameter by 36.5 inches in length for an 80-gram sample. For a weight ratio of over 40:1 a volume ratio of 100:1 had to be realized finally for the safe operation.

The detonation of an explosive in an explosive capsule occurs in the following way: First the explosive is in the form of a sphere in a thin aluminum casing. After initiation the detonation front propagates through the charge with a velocity characteristic of the explosive used. In this case the velocity obtained is about 8000 meters per second, with the pressure behind the front approximately 200 kilobars. Almost instantaneously the solid explosive is transformed into a gaseous fireball. Its volume is increased slightly, its temperature is 3000°C, and its internal pressure is near 50,000 atmospheres (Ref 5). The fireball is confined by the spherical casing for 2-3 microseconds, until the casing is vaporized. The shock wave and the blast pressure generated by the gases released from the explosive charge produce the destructive forces.

In other words, the detonating explosive propagates a pressure wave of finite amplitude into the surrounding medium. The shape of the pressure wave changes and, particularly in air, the pressure front becomes steeper and steeper until limited only by

viscosity and heat conduction. When the propagation velocity disturbance is greater than the velocity of sound in the undisturbed medium, as it usually is, the disturbance is called a shock wave.

After the shock wave propagates through the air and strikes the internal wall of the capsule the wall is instantaneously accelerated. The impulse in the shock point initially consisted of about half of the energy released. Since the response time of the wall is large relative to the duration of the shock wave the effect is practically instantaneous. Sections of the wall nearest the charge acquire the largest velocity and undergo the greatest deformation. The inertia and tensile strength of the capsule resist the impulse during the acceleration of the wall, and, unless rupture occurs, will be brought to rest by the tensile constraints.

The hot explosion gases behind the shock wave are confined by the capsule. The resultant internal blast pressure, in contrast to the short duration of the shock wave pressure, is a function of the total volume of the capsule and the ability of the entire system to act as a heat sink for the gases. Distortion of the capsule wall by the shock wave precedes the arrival of the blast pressure, and the total volume available to the explosion gases is the initial volume plus the enlargement caused by the shock. This is the same situation described by Wise and Proctor (Ref 6). However, their model contained water instead of air in order to simulate an excursion within a nuclear reactor.

The above describes an expanding detonation and how it interacts with the wall of the confining cylinder. To be considered also for the shock effects on an overall basis are the capsule length, reflections from the walls and ends when capped, repeated reflections with decreasing amplitudes, and the elastic-plastic properties of the container when subjected to dynamic loads.



## DESIGN AND DEVELOPMENT

Based on the considerations discussed in the previous section the following parameters were considered in the design of the irradiation capsule:

1. The type of material, size, geometry, and constraints required to attain confinement.
2. The amplitude and time duration of the shock wave incident upon the container wall. This will depend upon the medium surrounding the explosive charge.
3. The dynamic tensile strength and inertia of the wall, including a determination of the deformation or nonspallation limits in the elastic-plastic range.
4. The capability of the capsule to act as a heat sink.

The plastic response of a blast-loaded wall depends on the following: The inertia of the wall, which is a function of its mass. The mass stays fixed but the acceleration depends on the intensity of the shock wave and the dynamic properties of the wall. These dynamic properties in turn depend on the static strength of the wall. The gross strain, which is the final deformation, is influenced by the strain rate, which is high, and the shock wave intensity (Ref 6).

The design criteria include these conditions:

1. The capsule must be completely compatible with the nuclear reactor environment.
2. A capsule used to irradiate 80 grams must completely contain a detonation produced by 160 grams, i.e., twice the material to be irradiated. This might be called a safety factor of two. In actual fact it is greater than two.
3. A maximum capsule diameter of 10 1/2 inches for insertion in the water-filled reactor irradiation facility.

These conditions affected the geometry of the capsule and the nature of the material to be used. The mechanical requirements, plus the condition that the capsule must not acquire excessive amounts of long-lived radioactivity during irradiation, led to the selection of 6061-T6 aluminum as the material for the explosive containment irradiation capsule. In addition to the radioactivity requirements it was necessary that the capsule transmit the neutron flux without attenuation and retain its strength after irradiations.

A right-cylindrical geometry was based upon the data obtained in the initial phase of the program by Mackenzie (Ref 3). The relationships between the cylindrical parameters and the explosive charge weight led to an equation of the form

$$m = ct^k d^b \quad (1)$$

Using the 6061-T6 aluminum data from the family of curves for various wall thicknesses (Fig 2):

$$m = 15.5 t^{1.33} d^{1.78} \quad (2)$$

where

m = maximum amount of explosive, grams  
t = wall thickness, inches  
d = inside diameter, inches

The effects of irradiation upon the mechanical properties of 6061-T6 aluminum alloy, with exposures to  $10^{21}$  nvt, increased the ultimate tensile strength 10%, yield strength 7%, and the elongation 5% (Ref 7). In a cryogenic atmosphere—irradiated at liquid hydrogen ( $LH_2$ ) and tested at  $LH_2$  temperatures—to a total dose of  $6 \times 10^{16}$  nvt, small changes in the mechanical properties of 6061-T6 aluminum were noted (Ref 8).

All of the testing in this program employed the explosive Composition C4 (91% RDX, 9% binder). Its high explosive power (130% TNT) insured that the tested capsule could be used for most explosives.

In addition to the above the following had to be considered in arriving at the final design:

1. Simplicity.
2. Insertion into and removal from the reactor radiation facility in a minimum time without unduly affecting the reactor.
3. The ability to use any combination of sample sizes consistent with the maximum mass requirement.
4. The ability to remove the specimen after irradiation without destroying the container.
5. Sufficient container integrity after an explosion to permit the controlled release of gaseous products.
6. Provisions for monitoring the temperature and pressure.
7. The pressure pulse emitted must be below a level that would produce adverse effects on the surroundings.
8. The ability of the container wall to contain any fragments formed by the detonation of the explosive holder.

The overall length of the container was determined by the reflected shock waves and the volume of expanding gases. Earlier tests showed that the cylinders bulged in the middle and flared out at the ends when subjected to a detonation from a mass of explosive just below the amounts required to cause fragmentation. If the length-to-inside-diameter ratio (L/D) exceeds 6 the flaring does not occur. Below 6 the flaring could be eliminated by shrinking a support or reinforcement ring on each end and adding a closure plug or cap. The L/D ratio of the final design is 4.25. Specific testing on various threads led to the selection of the buttress-type threads for the final design.



The flaring of the ends was probably due to the compression stress, which was approximately doubled by reflection at the ends of the cylinder.

The gas pressure buildup inside the cylinder by the detonation of the explosive can be estimated. Assume that the volume of gas produced will be approximately the same for most explosives of the same weight. Thus 160 grams of Composition C-4 will produce 7.87 moles of gas, computed from the known chemical composition of C-4. If the cylinder is 6 inches in diameter and 36 inches long and the maximum effective temperature is assumed to be 3000°K, the maximum pressure is approximately 2000 psi (Ref 9).

The physical geometry or volume of the capsule also was used to evaluate the void effect which would be present in the nuclear reactor operations by the insertion and removal of the capsule. The applicable safety rules for the General Electric Test Reactor at the Vallecitos Nuclear Center (Ref 10) indicate that movable experiments, such as the capsule, should not, upon insertion, produce a change in reactivity greater than  $2 \times 10^{-5} \Delta k/k/\text{sec}$  or a maximum reactivity effect of 0.002  $\Delta k/k$  from full in to the fully retracted position. From the calculations furnished the resultant off-gas from leakage of a detonated capsule should result in an overall reactivity effect of less than 0.002  $\Delta k/k$ .

In order to sufficiently attenuate the shock wave or pressure pulse produced by a maximum explosion, an annular space was provided between the main chamber and the external container, i.e., the capsule had a double wall. The spacing between the walls was larger than the maximum bulge in the preliminary tests. Expansions ranging from 8-10% occurred in the 6061-T6 aluminum tubes. If the explosive weight was halved the deformation was less than 2%. Connections through the outer tube into the annular chamber were made with flexible stainless steel tubing so that pressure monitors or controllers could be used. For shock attenuation purposes a space was also provided at each end (Fig 3).

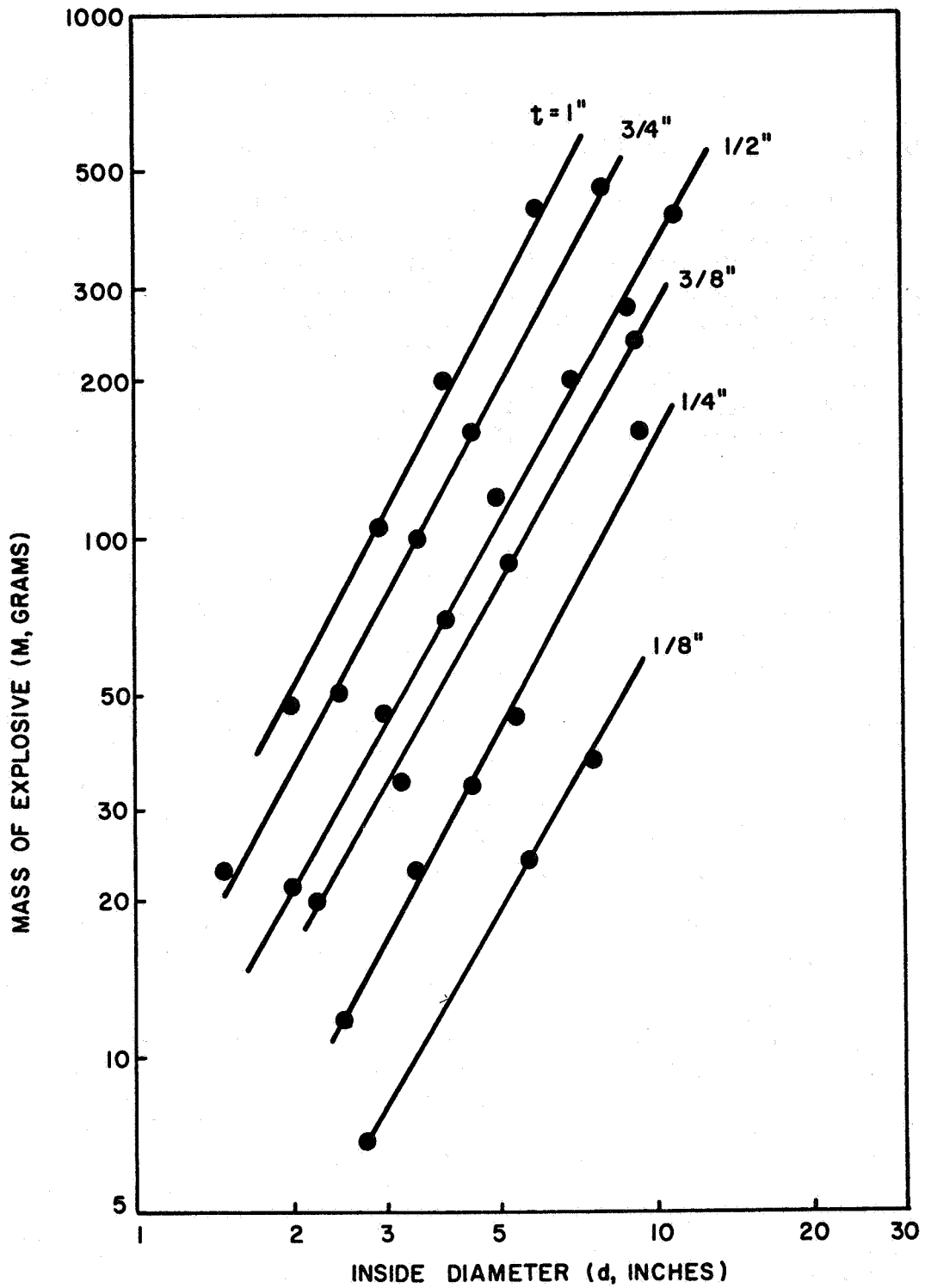


Fig 1 Maximum contained quantity of explosive as a function of inside diameter (d) and wall thickness (t): 6061-T1 aluminum

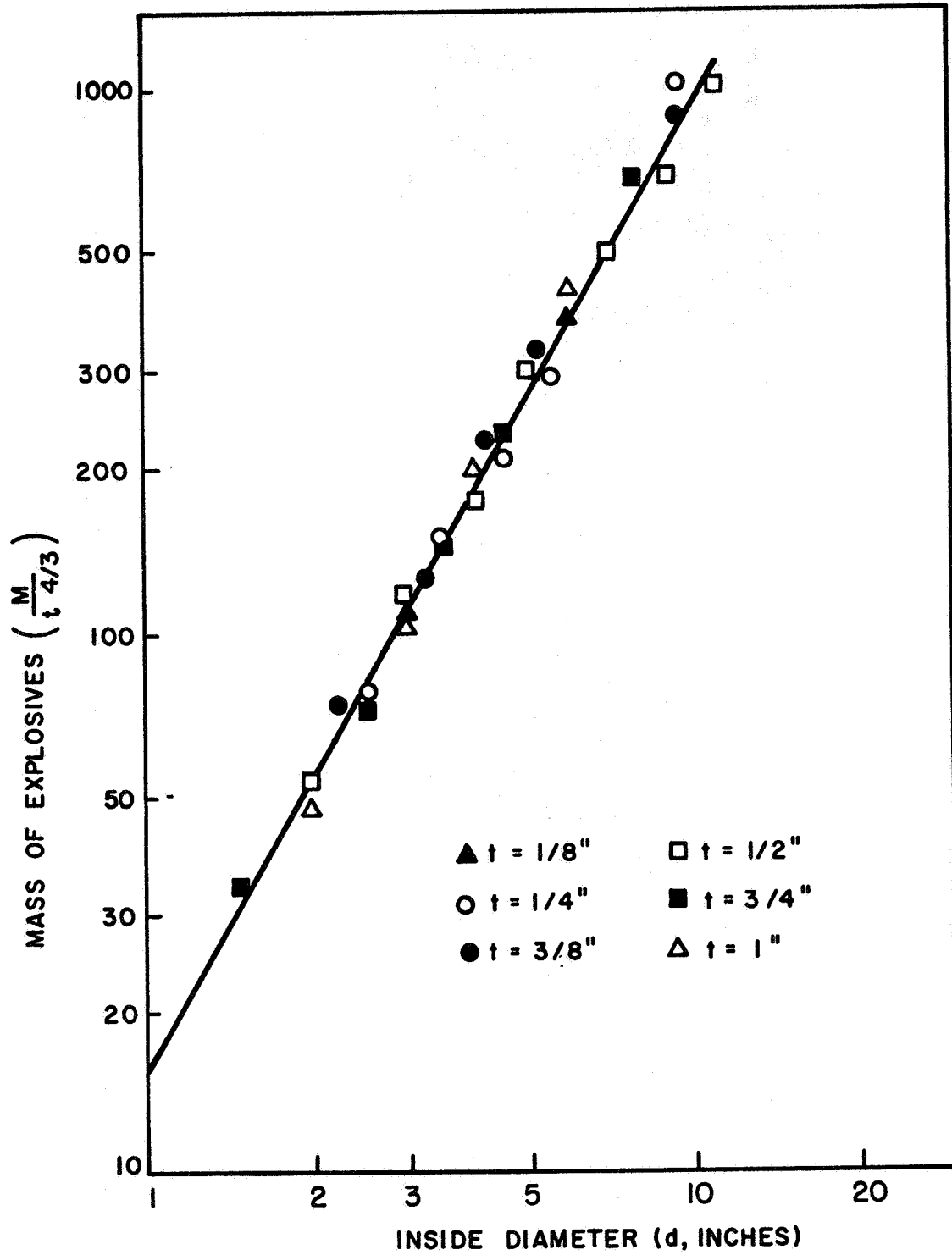


Fig 2 Agreement of data with equation  $m = 15.5 t^{4/3} d^{1.78}$

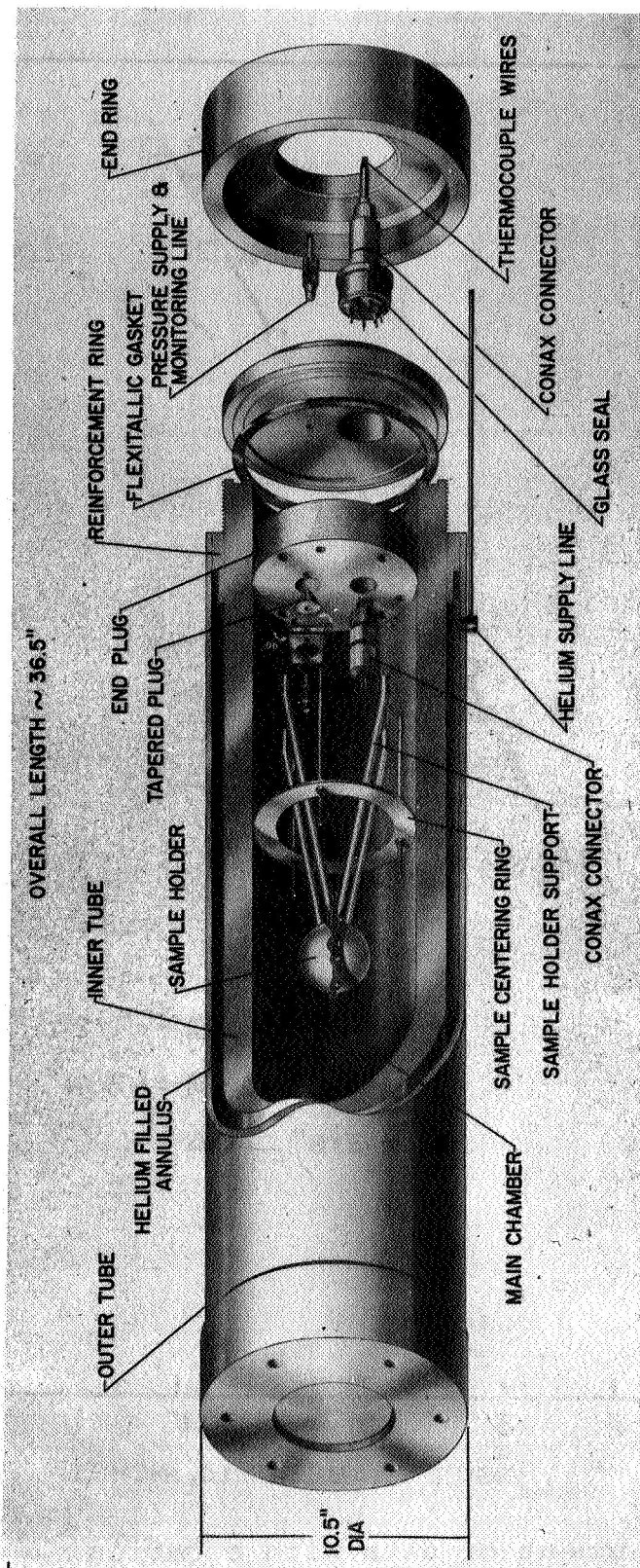


Fig 3 Exploded view of explosive container for reactor irradiation

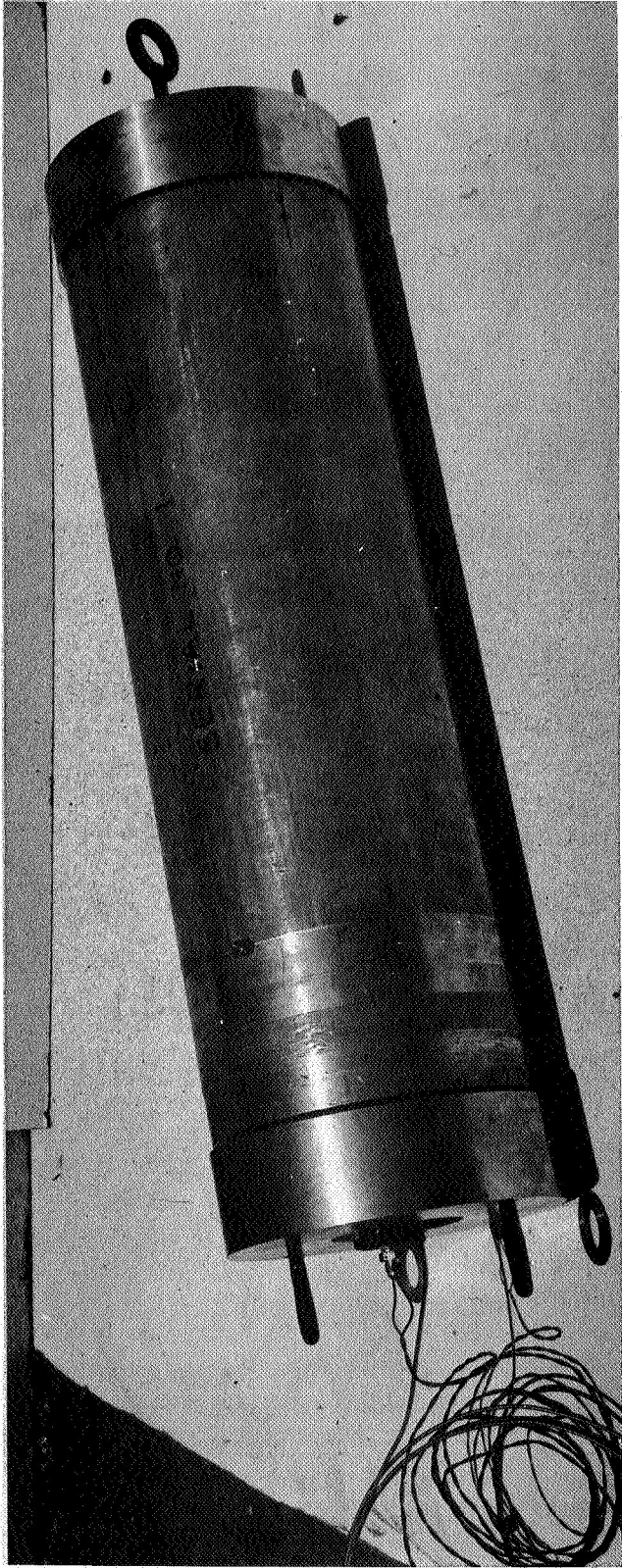


Fig 3a Explosive containment capsule assembly

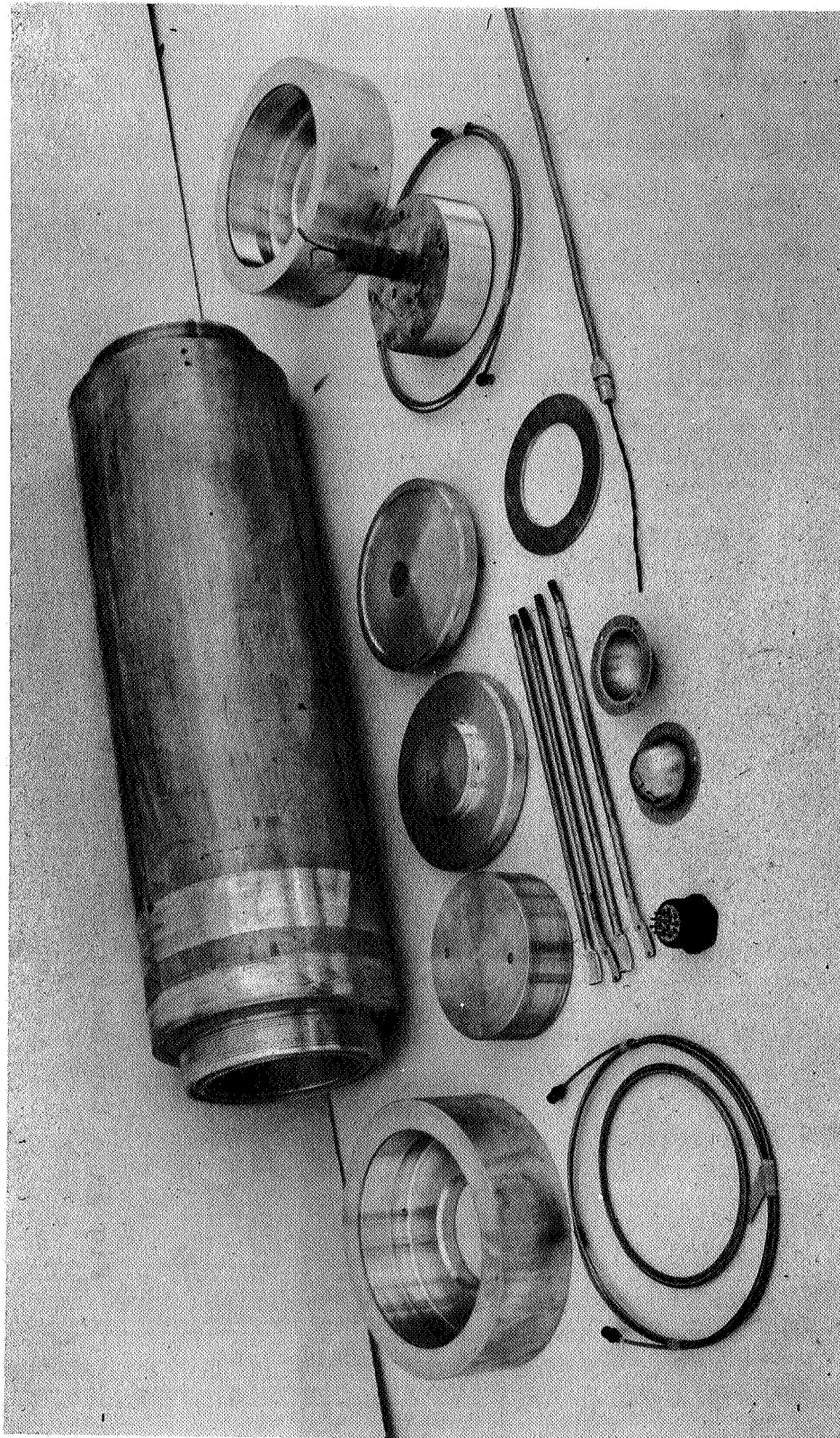


Fig 3b Explosive containment capsule



The explosive with the thermocouples and flux wires is held with a spherical holder composed of two aluminum hemispheres .025 inch thick positioned in place by four support rods mounted on one of the inner plugs. The thermocouples will measure the temperatures at different locations in the explosive sphere while the flux wires will provide means to determine the radiation level to which the material will be exposed. The explosive charge holder assembly was designed so that in case of a detonation only a minimum shock would be transmitted to the rest of the capsule. In case of an accidental drop a spacer was added to minimize the deflection so that the explosive sphere will not be too close to the wall if a detonation occurs. A complete set of detailed drawings of the explosive containment irradiation capsule is included as Appendix I.

Consistent with the philosophy of "maximum credible accident" which the nuclear reactor industry has followed, added specifications were placed upon the design of the explosive containment irradiation capsule:

1. The direction of detonation was changed from central initiation or along the axis (axisymmetric) to lateral initiation (asymmetric) so that the detonation was across the diameter of the explosive charge, and perpendicular to the cylindrical axis. In all testing the detonations were directed towards the wall nearest to the explosive charge.

2. Drop tests were conducted from a height of at least 10 feet.

3. Since the capsule was to be located 1/4 inch away from the reactor vessel wall in order to obtain the maximum flux, all stress-strain and pressure pulses were measured on the capsule and the reactor components at that location.

The purpose of these added requirements was to eliminate all possible safety and operational hazards that may occur during transportation and irradiation. With these built-in features the design of the capsule could withstand any internal experimental failures—the worst being a detonation—without affecting, or leading to the direct failure of, any nearby experiment or reactor fuel element that may hinder or interfere with any reactor operations.

## EXPERIMENTAL INVESTIGATIONS

These additional engineered safeguard specifications had a definite effect on the design of the system. The relationships derived by Mackenzie (Ref 3) were no longer applicable for the specific charge weights due to the confinement of the explosive and the change in the direction of detonation.

Knowing the maximum expansion or deformation before rupture of 6061-T6 aluminum tubes of different diameters and wall thicknesses enabled the investigators to select the maximum permissible diameter and wall thickness and still allow for the annular space. The measurements selected were 8-inch OD, 6-inch ID, and 1-inch wall thickness.

Mackenzie's relationship for 6061-T6 aluminum (Eq 2) predicted that the 6-inch-ID tube with a 1-inch wall thickness would withstand 378 grams of uncased Composition C-4 explosive detonated along the axis. Experimentally, up to 425 grams have been contained in cylinders of the same size. With the .025-inch-thick spherical aluminum casing and the direction of detonation changed 90°, the maximum explosive charge of C-4 that can be contained in an 8-inch-OD, 1-inch-thick 6061-T6 aluminum cylinder is 170 grams, or 45% of the predicted value.

The possibility of missiles being formed upon the detonation of the explosive in the thin spherical holder and penetration being effected through the wall was investigated. High-speed photography indicates that the thin shell-like casing either vaporizes or breaks up into minute pieces. Although a momentary confinement was noted no penetrations occurred through the capsule wall for the dimensions selected (Fig 6) in any of the tests.

The purpose of changing the direction of detonation from central initiation to a point on the surface in the direction across the diameter of the explosive sphere perpendicular to the axis of the capsule was to simulate the point of detonation that would have the worst possible effect. The most literal assumption was made that a fast reaction occurs on the surface at



a point on the diameter perpendicular to the axis, develops into a high-order detonation, and propagates across the diameter. This stringent test requirement adds an additional safety factor which is very conservative. It can be visualized as an explosive sphere whose radius is equal to the diameter of the actual explosive being centrally initiated without bringing into account the orientation.

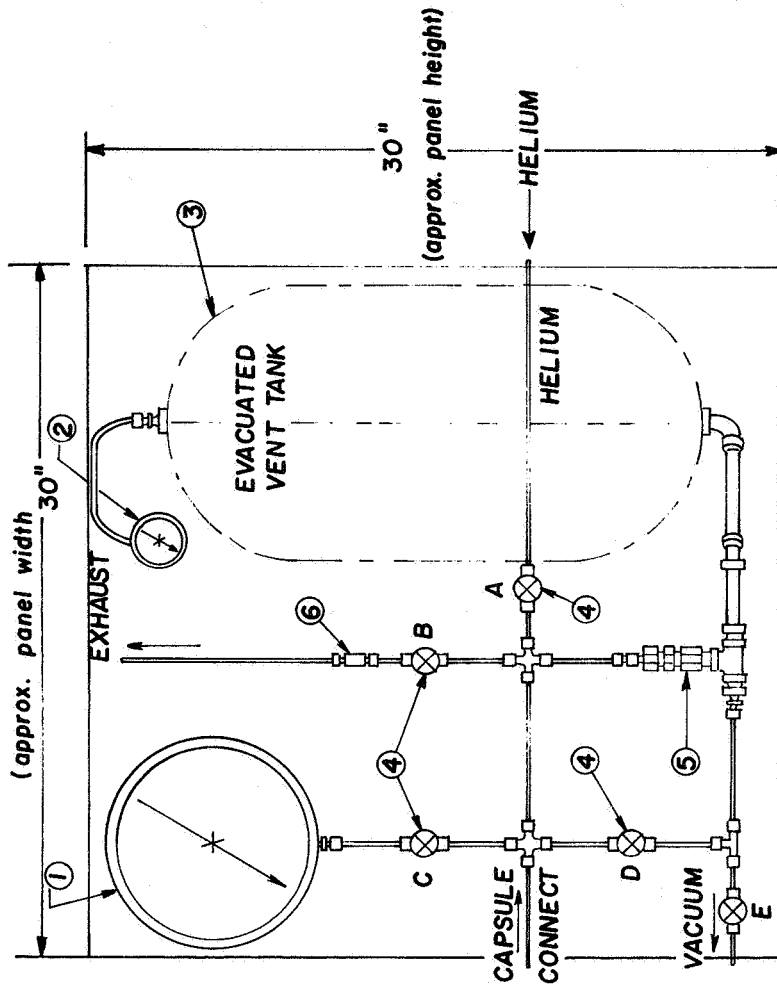
For instrumentation purposes special multiple-lead Conax connectors<sup>1</sup> designed to withstand static pressures up to 10,000 psi were incorporated in the container design to provide a leak-proof leadthrough for the thermocouple leads. Tests conducted on these Conax connectors in similar capsules indicate that they can easily withstand the detonation of 160 grams of explosive. A Conax connector is also installed on the inside of the inner plug, where the explosive charge holder with the spacer assembly is mounted. The thermocouple leads from the explosive holder go through the Conax connector in the inner plug, then on through a glass-to-metal seal in the outer end cap. From the seal the leads go through another Conax connector which serves as a back-up of the glass-to-metal seal in case of leakage due to hot, corrosive gases caused by a detonation. A flexible 5/16-inch aluminum tubing of required length encasing the leads is connected from the Conax connector to a recorder. For pressure or gas release measurements the method developed by Aerojet-General Corporation for its small capsule was used (Ref 1). Penetrations of 1/32 inch were made in both the inner and outer end plugs. A 1/8-inch stainless steel tubing from a pressure supply and monitoring panel is fitted on the outer end plug with an adapter. On the inside of the inner plug the penetration widens into a conical recess for a tapered plug suspended in an offset position backed by a steel spacer. By maintaining a constant pressure the differential can be measured when gases are evolved during irradiation. If a detonation occurs the shock wave would drive the plug into the recess, sealing off the pinhole.

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<sup>1</sup> Conax Corporation, Buffalo, New York

Experimentally it has been shown that after detonation the gases will eventually leak through the pressure-measuring line. To compensate for this a large gas collection tank was installed as part of the system, which was designed to include a rupture disc in the pressure measuring line. Upon rupturing the disc the gases would vent into a large gas collection tank (Fig 4). A filter installed in the pressure-monitoring line will prevent radioactive particles from contaminating the measuring apparatus. This controlled method of gas release is in a closed system but, as stated previously, the "top hat" exhaust system in the General Electric Test Reactor can handle any leakage into the water environment that would be caused by the escape of any gases in the containment capsule upon detonation.

A series of drop tests were conducted from an arbitrarily selected ten-foot height in order to demonstrate the safety of the explosive containment irradiation capsule during normal handling operations. The purpose was to determine the deflection of the explosive charge holder and the effect of such a deflection on the integrity of the capsule in case of a detonation due to an accidental drop. A single-wall capsule was dropped from the height selected onto a steel plate from three different angles or positions: (a)  $0^\circ$  or perpendicular to the cylindrical axis, (b)  $45^\circ$  to the axis, and (c)  $90^\circ$  parallel to the axis, or flat on its side. Preliminary drop tests were conducted with an explosive charge of 160 grams in a holder of spherical diameter of  $2 \frac{7}{16}$  inches, with a flange giving an overall diameter of  $3 \frac{1}{2}$  inches. The condition considered most drastic if a drop occurred was the complete shearing of the explosive holder from the support rods and the detonation of the explosive upon contact with the inner wall. Tests indicated that the worst case occurred when the capsule was dropped flat on its side or parallel to the axis and the flange of the holder in line with the impact. Although the explosive holder did not shear off from the support rods in any of the tests, the force of the impact of the drop caused a deflection so great that the explosive charge holder hit the wall of the capsule but without causing a detonation. This gave rise to the question of how close to the wall a charge could be detonated with containment or integrity still being maintained.



QUANTITY	DESCRIPTION
1	PRESSURE GAUGE, HEISE 0-100 psi, 8-1/2" DIAL, .2psi per DIVISION, 1/5 SUBDIVIDED, WITH REMOTE 5K POTENTIOMETER, 316 s.s.TUBE.
2	VACUUM GAUGE, MARSHALLTOWN NO. 22B, 2' DIAL SIZE
3	VACUUM TANK, 2000 CU. IN., 12 X 24", s.s.
4	NEEDLE VALVE, WHITEY NO. OKS 2-316, 1/8" SIZE, s.s. W/SWAGelok FITTINGS.
5	SAFETY HEAD, SCREW TYPE, BLACK, SMALLS & BRYSON ASSY NO. SA-9; s.s.-100 PSIA BURSTING PRESSURE.
6	FILTER, NUPRO "F" SERIES INLET FILLER, CAT.NO. SS-2F-7, 5-10 MICRONS s.s.

Fig 4 Pressure measurement panel diagram

Detonation experiments using the designed explosive holder for an 80-gram charge revealed a forbidden zone. Capsule integrity could not be preserved if an 80-gram charge was detonated close to the wall. In a 6-inch-ID, 1-inch-thick 6061-T6 aluminum cylinder, this zone was found to be an annular space  $\frac{3}{4}$  inch wide from the inner wall in the plane of the explosive charge. This permitted a maximum deflection of  $1\frac{3}{8}$  inches from the axis. To prevent a deflection greater than  $1\frac{3}{8}$  inches, a spacer or support ring with tie-rods was added to the assembly, thereby eliminating the extended cantilever effect. The location of the spacer placed the fulcrum at about the midpoint of the length of the support rods, thus substantially reducing the amount of deflection. Also the spacer is used as a centering device for the explosive holder for axis alignment (Fig 5). For the 160-gram charge, experiments disclosed that the annular forbidden zone was widened to such a degree that a deflection of more than  $\frac{3}{16}$  inch from the axis by the explosive sphere was required to produce ruptures. With the spacer assembly installed, tests indicated that this configuration in the capsule could withstand the designated drop of ten feet with a 160-gram weight without excessive deflection or permanent distortion. Also the testing of the detonation of a 160-gram charge with the spacer assembly did not produce any missiles that were able to penetrate the wall of the capsule (Fig 6).

In order to maintain proper alignment within the acceptable limits a quality control feature was incorporated to determine the location of the holder with explosive after assembly and shipment to the specified receiving station at the reactor. X-ray radiographs of the explosive holder area of the capsule would be taken  $90^\circ$  apart soon after arrival at the reactor in order to certify the proper alignment. It was also stipulated that if any accidental drop occurred the capsule would be returned as soon as possible to the loading area for disassembly.

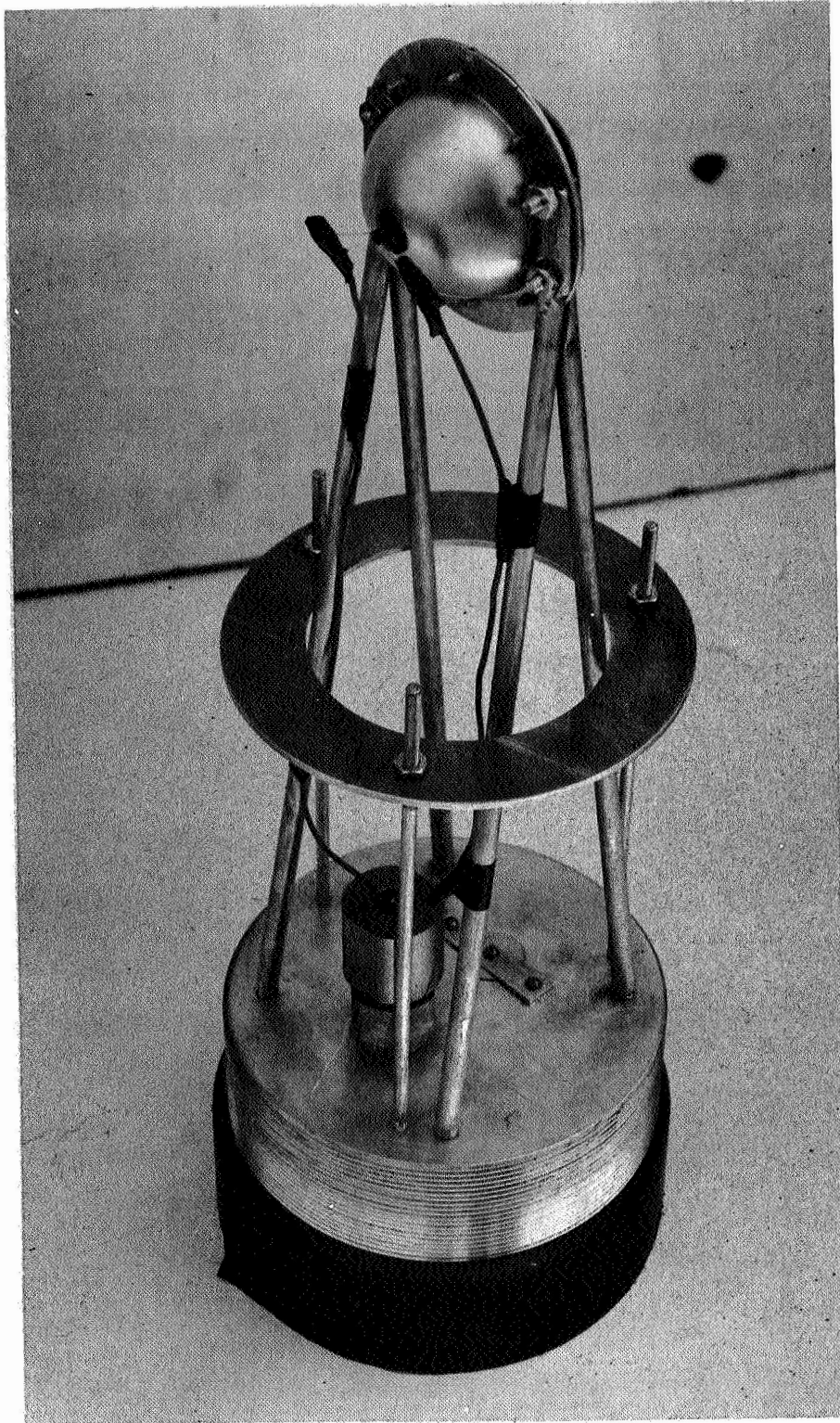


Fig 5 Explosive charge holder with spacer assembly



Fig 6 Remains of explosive charge holder with spacer assembly after detonation of 160 grams of explosive while in capsule



Another modification was incorporated in the containment capsule as an additional engineered safeguard. The original intent had been to have a vacuum in the annular space, which is the principal feature for the attenuation of any shock wave, but the possibility of a leak presented a problem. The filling of the annular space and the rate involved would be noticeable on the pressure-monitoring system but the removal of the capsule was controlled. To eliminate this situation, helium gas at a pressure of 25 psi was used instead of a vacuum. This pressure value was chosen since the pressure at the depth in the water where the containment capsule would be located by the reactor pressure vessel is 20 psi. The positive pressure in the annulus will prevent any water from flowing into that space if a leak develops. This pressure will be monitored continuously with a pressure controller and flow alarm. Any decrease in the pressure will be cause for the immediate removal of the containment capsule. The shock attenuation features will be discussed later.

#### CONTAINMENT CAPSULE TESTS

A series of tests were conducted to qualify the designed features of the containment capsule. The first four qualification tests were conducted at Picatinny Arsenal and the final four were completed at the Aerojet-General Corporation facility at Downey, California. The main purpose of the investigations, besides verifying the containment and integrity of the capsules, was to measure the stress-strain levels encountered within the containment capsules and the pressure pulses transmitted from the external surfaces at designated locations. Both single-wall and double-wall capsules were tested. The purpose of the single-wall tests was to obtain the stress/strain levels on the inner wall and also the pressure pulse emanating through the inner wall to a point in the air where the outer wall would be located.

Since these types of measurements had been obtained in preliminary tests on an earlier design (Ref 12), Brewer Engineering Laboratories, Inc., Marion, Massachusetts was engaged to make pressure and strain measurements during the qualification tests (Refs 13, 14).

The Picatinny tests included three single-wall and one double-wall capsule. The single-wall capsule assembly consisted of the 8-inch-OD, 6-inch-ID 6061-T6 aluminum cylinder with support rings shrunk fit on the ends and threaded plugs to compare the confinement. These tests were conducted by suspending the single-wall capsule in air (Fig 7) so that stresses, strains, and pressure pulses were measured at specified locations (Fig 8). The pressure transducers were located 1/4 inch away from the capsule while the strain gages were bonded to the capsule at the specified locations.

In the double-wall capsule test at Picatinny, the explosive containment vessel was suspended in water 1/4 inch away from a 1/2-inch-thick aluminum plate simulating the reactor vessel wall. A pressure transducer was located just below the aluminum plate to determine the pressure pulse being transmitted into the space where the inside of the pressure vessel would be located (Fig 9). In the Aerojet series a glass plate was added under the aluminum plate to simulate a beryllium reflector (Fig 10). Instrumentation for these tests consisted of seven pressure transducers adjacent to the capsule surfaces and three strain gages attached to the bottom side of the glass plate (Fig 11).

These tests were to simulate as closely as possible the actual effects resulting from the high-order detonation of 160 grams of C-4 explosive propagating across the diameter of the explosive sphere perpendicular to the cylindrical axis in a double-wall capsule underwater 1/4 inch away from the reactor pressure vessel wall and beryllium reflector. The double-wall capsule was immersed in a glass aquarium with only a few inches clearance between the capsule and the glass sides.

For each of the tests, signals from the pressure transducers and the strain gages were recorded simultaneously on oscilloscope cameras and an FM instrumentation tape recorder (Fig 12). A high-speed framing camera was used to photograph the capsule during detonation. The scopes were activated from the camera and fed in parallel after a delay to a firing unit. This instrumentation is listed in Table 1.



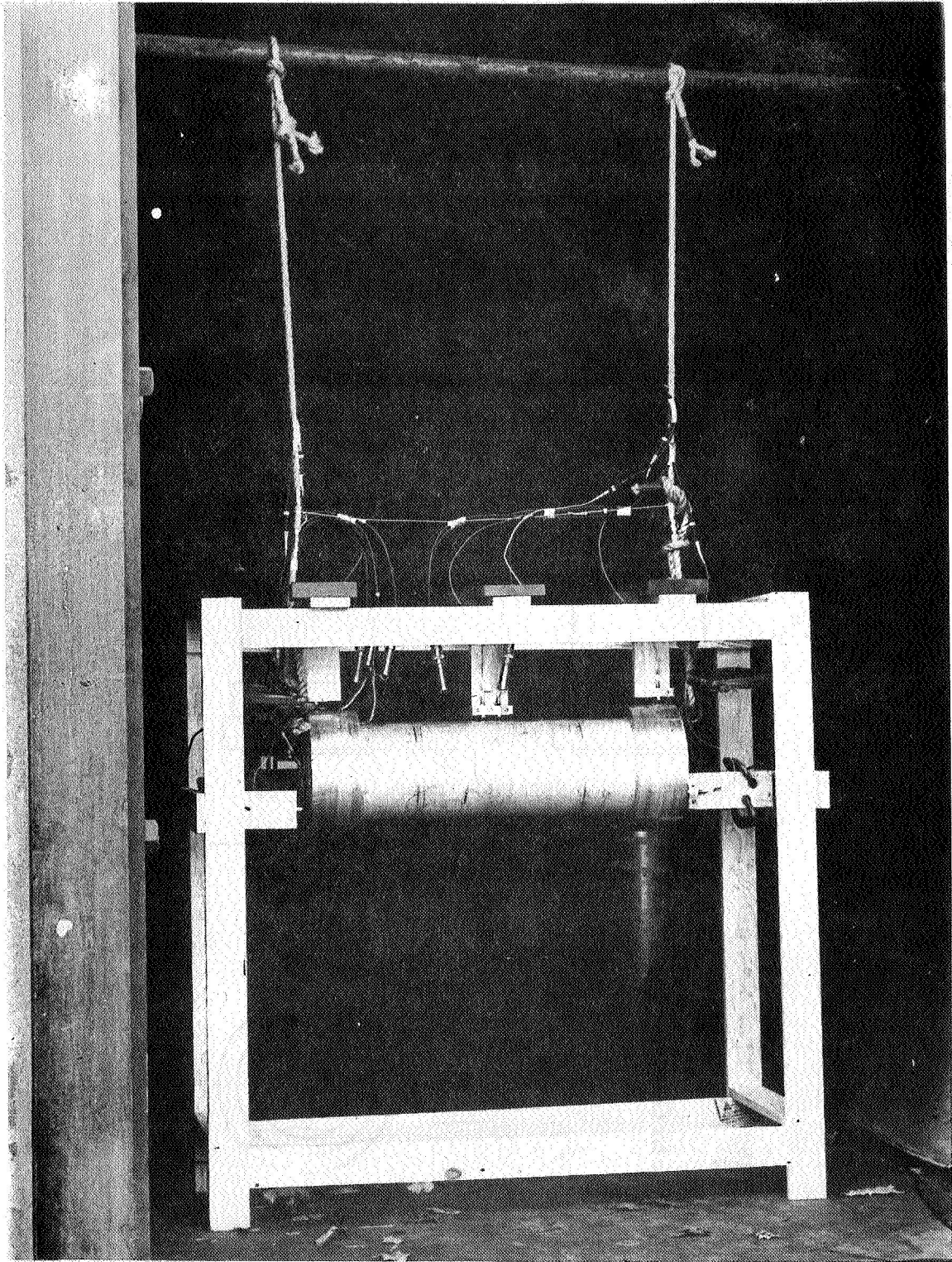


Fig 7 Single-wall capsule experimental test setup





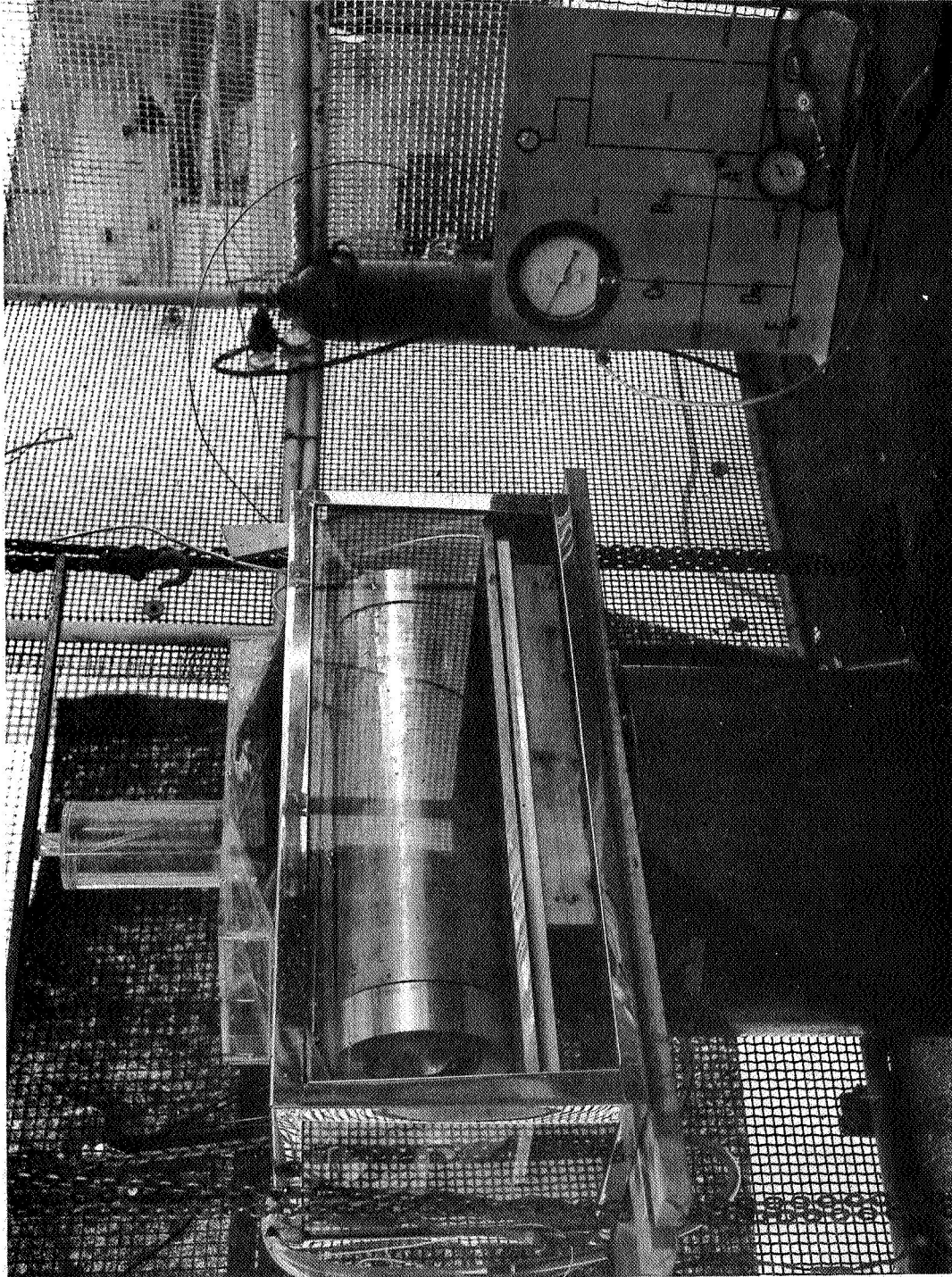


Fig 10 Experimental setup for explosive containment capsules  
for strain and pressure measurements

● Pressure Transducers  
( $\frac{1}{4}$ " from surface)

■ Strain Gages

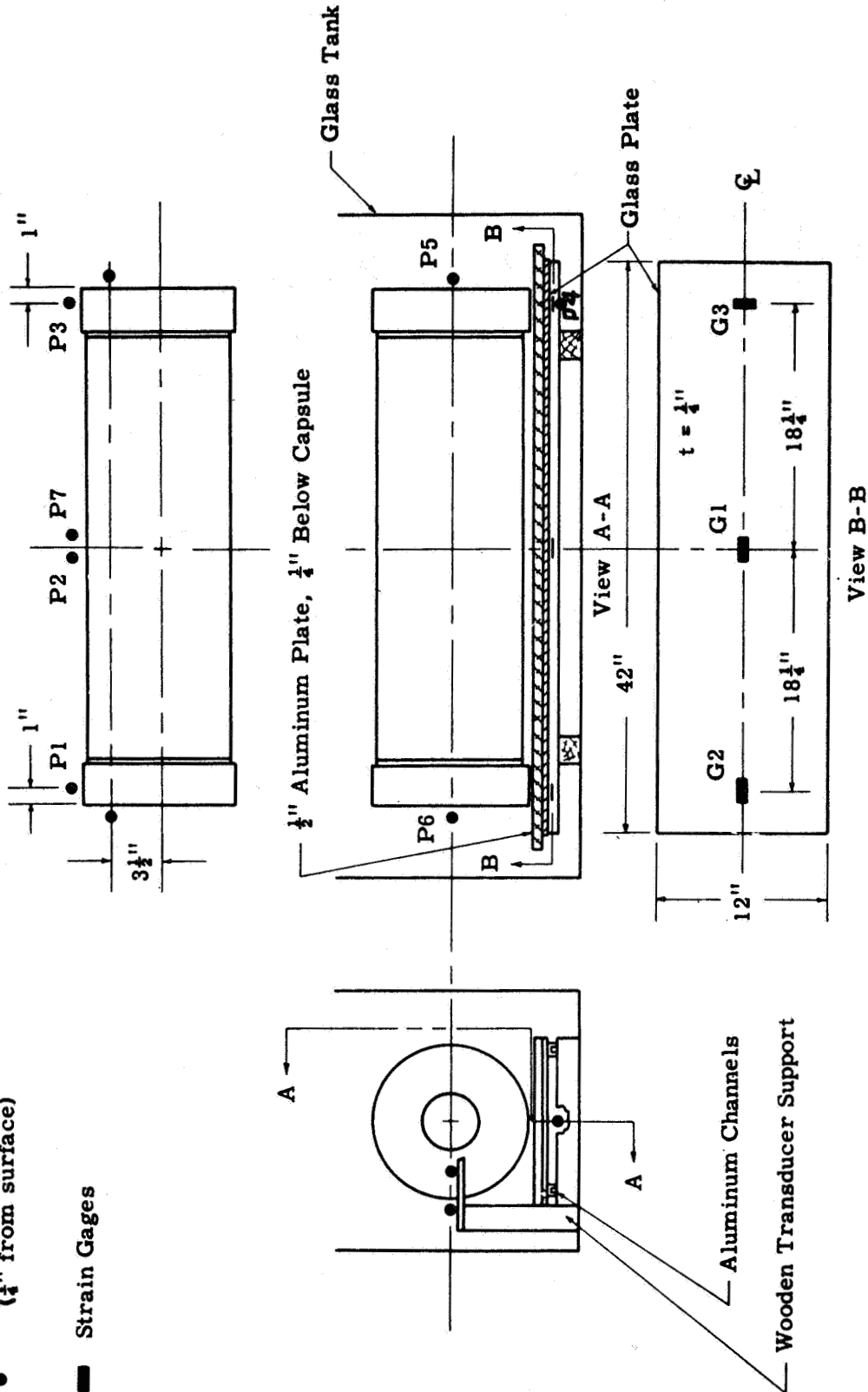


Fig 11 Typical test schematic showing pressure transducers and strain gage locations (Aerojet Series)

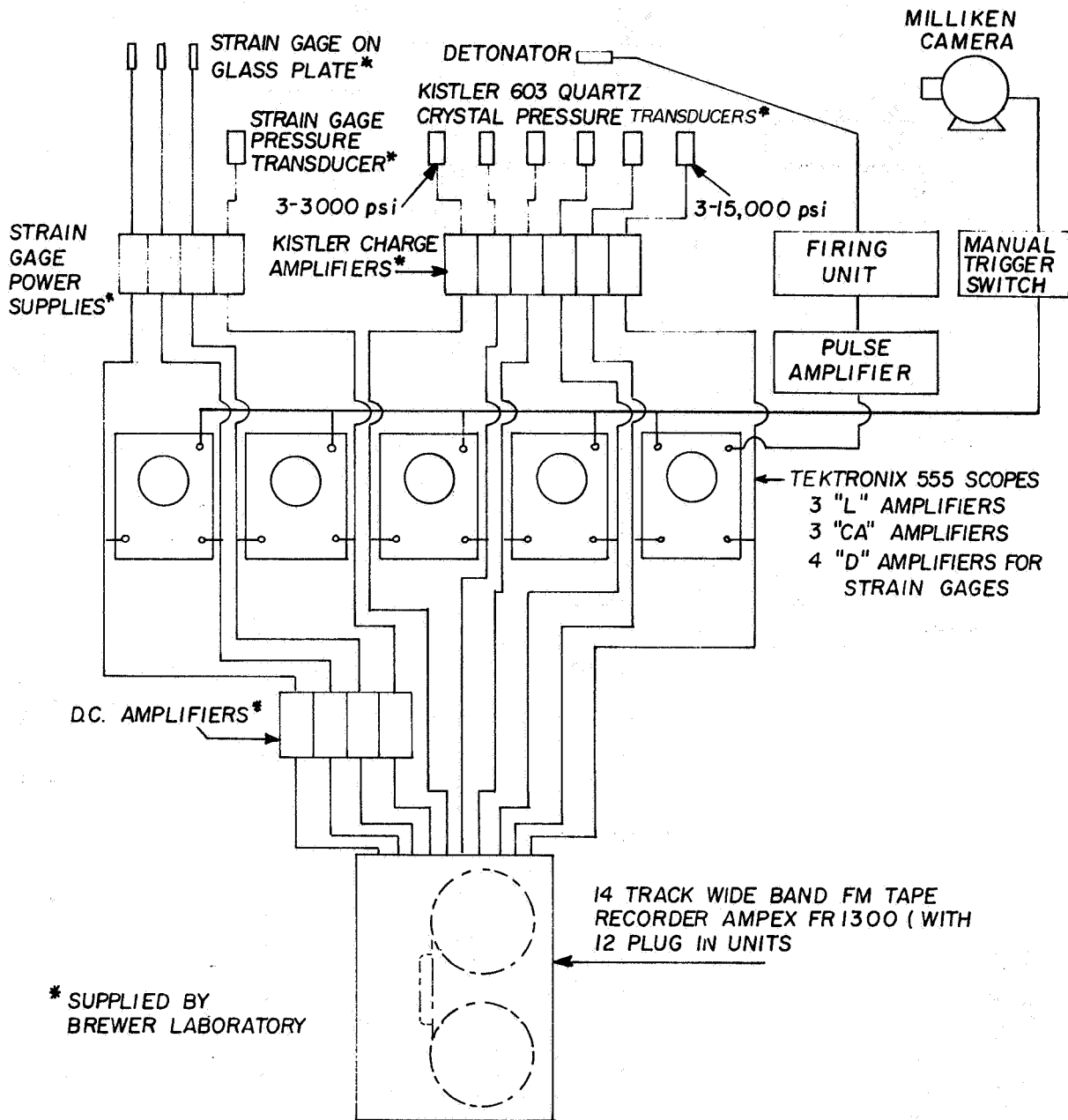


Fig 12 Phase II capsule instrumentation

TABLE 1

Phase II Explosive Capsule Instrumentation List

- A. Pressure transducers
  - 6 each Kistler quartz crystal pressure transducers
    - 3 Model 603A, 3000 psi range
    - 1 Model 603H, 1500 psi range
    - 2 Model 607A, 60,000 psi range
  - 1 each Baldwin-Lima-Hamilton bonded strain gage Model D-AFM(S), 4000 psi range.
- B. Strain gages
  - 3 each Baldwin-Lima-Hamilton FAB-25-12S6
    - Cement: BLH EPY-150 with C-3 overlay
    - Waterproofing: RTV-106 (2 coats)
- C. Charge amplifiers
  - 6 each Kistler Model 556
- D. D.C. amplifiers
  - 8 each Dana Lab Models 2000 and 3400
- E. Strain gage power supplies, total 4
  - System Research Corp., Model 3511-C
  - Video Instruments, Model SRB-200
- F. 5 each Oscilloscopes - Tektronix, Model 555
  - 4 Type "D" Pre-amplifier
  - 3 Type "L" Pre-amplifier
  - 3 Type "CA" Pre-amplifier
- G. 5 each Oscilloscope cameras, Tektronix C-12
- H. Tape recorder, Ampex FR-1300
- I. Firing unit

Description, specifications, and operations of this instrumentation, with the data obtained and data reduction, are noted in References 13, 14, and 15. The above was used in the AGC series with the firing unit supplied by Aerojet.



A complete set of the data obtained in both the Picatinny and Aerojet series is summarized in Table 2. This is also included in a summary report issued by Aerojet-General Corporation (Ref 16).

The tests indicated the following:

1. The stress levels on the outer surfaces of both single- and double-wall capsules (excluding the inner vessel for  $\pm 5$  inches from the center line) do not exceed published yield values when the capsules are subject to the internal detonation of 160 grams of C-4. The maximum stress level obtained was 25,600 psi, which is well below the published minimum tensile yield stress of 35,000 psi.

2. Pressures transmitted in air at the center of a single-wall capsule 0.25 inch away from the surface will not exceed 25 psi due to the internal detonation of 160 grams of C-4. This is the pressure pulse that would be going through the annular space onto the inner surface of the outer wall of the containment capsule.

3. In the double-wall capsule with 25 psig helium in the annular space the initial pressure pulse transmitted by the detonation of a concentrically placed 160-gram charge of C-4 will not exceed 5 psi in the direction of firing 0.25 inch from the surface of the capsule in a water medium. Subsequent pressure pulses are produced by the propagation of elastic stress-waves from the ends of the capsule. About 150  $\mu$ sec duration was noted at the center location (Table 3).

4. The radially transmitted initial pressure wave at the ends of the double-wall capsule will not exceed 50 psi. The axially transmitted initial pressure wave from the ends will not exceed 500 psi.

5. The pressure transient experienced in water 0.25 inch beneath the beryllium reflector mock-up was less than 3 psi and the maximum strain levels at the gage locations or the reflector mock-up did not exceed  $\pm 70$   $\mu$ in./in.



TABLE 1

## Summary of Phase II Capsule Q

Test No.	Date Test Fired	Basic Type of Capsule	Media Tested in	Media & Pressure in Capsule Annulus	Media & Pressure in Capsule Interior	Type of Sealing (Vee) Plug	Gasket & Plug Installation	Type of Sample Support	Types of Outer Thermocouple Wire Lead thru Seal	Average Gasket Compression	Number of Gauges	
											Strain	Pressure
PA #1	3/14/66	Single Wall #1-1791	Air	N/A	Air @ Atmospheric		Dry	4-rod Cantilever	N/A	N/A	3	1
PA #2	3/16/66	Single Wall #1-1792	Air	N/A	Air @ Atmospheric		Dry	4-rod Cantilever	N/A	N/A	8	6
PA #3	3/17/66	Single Wall #1-1793	Air	N/A	Air @ Atmospheric		Dry	4-rod Cantilever	N/A	N/A	8	6
PA #4	3/18/66	Double Wall P-155371	Water	Helium @ 25 psig	Helium @ 25 psig	Frustum of Cone	Dry	4-rod Cantilever	Glass-to-Metal	Not Measured	8	6
AGC #1	6/7/66	Double Wall S/N 1	Water	Helium @ 25 psig	Helium @ 25 psig	Frustum of Cone	Dry	4-rod Cantilever, Support Ring & tie rods	Glass-to-Metal	0.012-0.015 inch	3	7
AGC #2	6/9/66	Double Wall S/N 3	Water	Helium @ 25 psig	Helium @ 25 psig	Full point Cone	"Blue goop" on threads of inner plugs & gaskets	4-rod Cantilever, Support Ring & tie rods	Conax connector	0.017-0.018 inch	3	7
AGC #3	6/10/66	Double Wall S/N 2	Water	Helium @ 25 psig	Helium @ 25 psig	Full point cone with back-up plate	"Blue goop" on threads of inner plugs & gaskets	4-rod Cantilever, Support Ring & tie rods	Conax connector	0.016-0.018 inch	3	7
AGC #4	8/3/66	Double Wall (Modified)(1)	Water	Helium @ 25 psig	Helium @ 25 psig	Full point cone with back-up plate	"Blue goop" on threads of inner plugs & gaskets	4-rod Cantilever, Support Ring & tie rods	Conax connector	0.020-0.024 inch	0	0

## NOTES:

- (1) Outer tube of steel in lieu of aluminum
- (2) Followed by a pulse of 90 psi of 20  $\mu$ sec duration
- (3) Measured with Calipers
- (4) Measured from X-ray

# Calification Test Results

Peak Pressures & Time After Detonation	Stress/Strain Levels	Maximum Inner Tube Expansion	Remarks	Gas Leakage	
#1 center radially 12.5 psi @ 55 μsec	Strain gauges suffered bond failures	~.20" (~2.5% elong)	Capsule used for drop tests. No adverse effects.	N/A	
#1 & 2 center radially ~17.8 psi	#2 16,900 psi } #3 11,500 psi } @ 190 μsec	~.20"	Capsule ruptured; probably due to off-centered charge.	N/A	
#4 end radially + 5 psi	#4 16,200 psi } #5 25,600 psi } ~800 in/in/sec	~.20"	No cracking of tube.	N/A	
#1 center radially 11 psi (Initial pulse 15.5 psi @ 2-3 μsec)	#1, 3 & 8 failed #2 23,300 psi } #3 -15,600 psi } @ 195 μsec	~.20"			
#1 center radially + 5 psi @ 530 μsec >30 psi @ 530 μsec	#8 13,700 psi 910 μin/in	Not Measured	Vee-plug sealed; gas leaked out around live-end gasket. Jacket pressure increased from 25 to 28 psig. Maximum pressure in live end compartment = 11 psig. No tube failure.	Not obtained due to gross external jacket leakage.	
#2 38 psi @ 350 μsec	#2 360 μin/in - Strain rate				
#3 data lost	48 in/in/sec				
#4 430 psi @ 300 μsec					
#5 & 6 + 48 psi @ 110 μsec					
P <sub>2</sub> P <sub>7</sub> radially center 4.5 psi P <sub>3</sub> radially live-end 32 psi P <sub>5</sub> axially live-end 200 psi P <sub>4</sub> below glass ~ 0 psi	Not obtained due to electrical interference.	Measured parallel to direction of detonation .24"(3) .29"(4)	Measured perpendicular to direction of detonation .16"(3) .22"(4)	Vee-plug failed to seal; gas jet melted solder in glass-to-metal lead wire seal resulting in blowout of aluminum conduit, etc. No tube failure.	Repressurized post tests gave: 2900 cc/min @ 49 psi 8000 cc/min @ 101 psi 5600 cc/min @ 25 psi 6720 cc/min @ 69 psi
P <sub>2</sub> P <sub>7</sub> radially center 5.0 psi P <sub>3</sub> radially live-end 8 psi P <sub>5</sub> axially live-end 170 psi P <sub>4</sub> below glass < 3 psi	Not obtained due to electrical interference	.19"(4)	.35"(4)	Vee-plug sealed good; inner plug @ dead end dislodged. Jacket pressure increased to 37 psig. Small leak at dead end. No tube failure.	1880 cc/min initially, 29 cc/min after 3000 cc released.
P <sub>2</sub> P <sub>7</sub> radially center 3.5 psi (2) P <sub>3</sub> radially live-end 45 psi P <sub>5</sub> axially live-end 475 psi P <sub>4</sub> below glass ~ 0 psi	Dead end 53 } Live end 49 } Strain in Glass Center 24 } Plate μin/in	.42"(4)	.74"(4)	No gas leakage into water; slow gas leakage through pressure line "triggered" rupture disc and gases vented into tank as predicted. No tube failure.	0 cc/min
No measurements made	No measurements made	.27"(3)	.15"(3)	Gas leakage through pressure line triggered rupture disc at 95 psi after 60 sec but small capacity filter prevented rapid flow of gas into vent tank so that capsule remained at above and vent tank at below atmospheric pressure after 30-min. No tube failure.	3000 cc/min initially, 1900 cc/min after 6-minutes 1600 cc/min after 15-min

TABLE 3

Pressure Pulse and Strain Measurements  
for Explosive Containment Capsule<sup>a</sup>

Location	Transducer or Gage	Item No.	Test 1 psi or $\mu$ in./in.	Test 2	Test 3
Radial pressure center	A	P2, P7	4.5	5.0 <sup>b</sup>	3.5 <sup>c</sup>
Radial pressure live end	B	P3	32	8	45
Radial pressure dead end		P1	~45	8	25
Axial pressure live end	C	P5	200	170	~475 <sup>d</sup>
Axial pressure dead end		P6	142	116	~400 <sup>d</sup>
Pressure beneath glass		P4	~0	<3	~0
Glass plate strain dead end		G2	-	-	53

Table 3 (continued)

Location	Transducer or Gage	Item No.	Test 1 psi or $\mu$ in./in.	Test 2	Test 3
live end		G3	-	-	49
center		G1	-	-	24

a Data presented are first pulse only. Positions related to Figure 11. Due to the symmetry of the capsules the readings are grouped under three headings: Position A is at the center, Position B is radially at the ends, and Position C is axially at the ends.

b Followed by + 25 psi at 125 kc.

c Followed by 90 psi pulse of 20  $\mu$ sec duration.

d pulse duration of 12-15  $\mu$ sec.

The following observations were made as a result of these investigations:

1. The average permanent diametrical expansion experienced with the 8-inch-OD, 6-inch-ID tube in both type tests ranged from .20 to .58 inch or an elongation from 2.5% to 7.0%. Readings were taken in the line of firing or perpendicular to it, as noted in Table 2. It is interesting to note that the maximum bulging of .74 inch was perpendicular to the line of detonation.

2. Because of the expansion and permanent deformation of the inner tube and the hot gases generated by the detonation of 160 grams of C-4 the pressure in the annular space was noted to increase on each test from the original 25 psi. The maximum value recorded was 37 psi.

3. The strain gages on the center in the single-wall tests did not survive the high strain rates. The maximum rate obtained was about 800 in./in./sec at  $\pm 5 \frac{1}{2}$  inches from the center. The maximum in the double-wall tests was 910 in./in./sec, which was recorded on the end of the capsule.

4. It is significant to note that the capsules were not excited into any high-amplitude vibrations at any of their own resonant frequencies. Such a phenomenon would result in a series of repetitive pressure waves into the surrounding water (Ref 14).

5. The shock arrival times (Table 4) at the strain gage and pressure transducer locations in the Picatinny series of tests give an insight into the strain rates experienced by the capsules.

The experience and knowledge obtained from the tests were put to use for the modifications required for appropriate holders to irradiate propellants and detonators. The propellant sample would be enclosed in a cylindrical assembly whose overall volume was based on the amount of explosives (80 grams) in the propellant, excluding binders and inert materials. This would replace the explosive sphere charge holder in the support assembly.

TABLE 4

Shock Arrival Times

Strain Gage No.	Pressure Transducer No.	Time, $\mu$ sec			Location on Capsule
		1-1791	1-1792	1-1793	
1	-	28	-	-	Radial in center
2	-	40	-	-	Radial in center
3	-	40	-	-	Diagonal
4	-	65	-	-	Diagonal on end
5	-	61	61	-	Diagonal on end
6	-	72	-	-	Axial on end
7	-	70	-	-	Axial on end
8	-	92	-	-	Axial on end
1	44	43	-	-	Under alum plate
2	-	-	-	-	Radial in center
3	-	-	-	-	Axial on end
4	-	~85	-	-	Axial on end
5	-	-	46	-	Diagonal on end
6	-	-	~125	-	Diagonal on end

<sup>a</sup>All referenced to detonator firing pulse.

<sup>b</sup>All times from oscilloscope photographs except transducer #6, double-wall capsule.

Table 4 (continued)

c\*Time measured from first significant strain on pressure amplitude.  
For example, strain amplitude at gages 1 and 2 double-wall capsule,  
due to pressure wave is too low to detect.  
Time is to elastic stress waves from ends of cylinder.  
dLocations of strain gages and pressure transducers referenced to  
Figure 9 (Picatinny Series).

For detonators or igniters the design is a flat rectangular can which will hold about 150 detonators with a total amount of explosive of about 40 grams. The insertion of the capsule into its irradiation position would orient the holder in order to minimize self-shielding and have a uniform radiation flux for the detonators.

A gas-cooling line using helium as a coolant has been designed which enters the capsule end caps, passes through the end plugs and into the sample holder. The return of the helium gas would be through the pressure measurement line used in the noncooled capsules. Assembly and detail drawings showing all these features are in Appendix II.

#### BEHAVIOR OF THE CAPSULE DURING DETONATION

The problem of trying to understand and explain the events that occur with the detonation of an explosive charge in an explosive containment irradiation capsule with respect to the effects on its surroundings when in a nuclear reactor is divided into three phases: (a) the detonation within the capsule, (b) the effects on the capsule, including dynamic loading, deformation, transmission, and attenuation, and (c) the effect transmitted to the surrounding media due to the pressure pulses emanating from the capsule.

All three aspects have been discussed as far as the experimental results are concerned. Dynamic stress-strain measurement is a difficult problem. The dynamic stress-strain relation is achieved when a solid is subjected to a compressive shock loading. The knowledge of the response of the medium to the loading behavior as well as the unloading behavior would help to solve the problem but few experiments have been reported. The literature on the dynamic characteristics of 6061-T6 aluminum (Refs 17-23) due to shock loading by explosives does not contain much information on the maximum deformation and rate of deformation in cylinders with thickness-to-radius ratios of 4 to 1.



The technique of Johnson, Stein, and Davis (Ref 21) regarding the dynamic symmetrical expansion of a thin ring closely represents this problem. With that method, dynamic uni-axial stress-strain data can be obtained at high strain rates. This technique was also used by Hoggart et al. (Ref 22) on 6061-T6 aluminum rings expanding symmetrically under the influence of their own inertia. Impulsively loaded to produce high initial radial velocities, the expanding circular rings are decelerated by the radial components of the hoop stresses. The technique excludes the wave propagation which normally occurs when contact between the ring and the core is broken as the tensile wave reflected from the outside surface arrives at the ring-core interface. Strain rate measurements in the range of  $10^3$  to  $10^4$  in./in./sec are considered feasible by this method.

The method devised by Fyfe (Ref 23) in which plastic stress waves propagating radially outward were created by exploding a copper wire along the axis was considered applicable for a small sample (4 inches long, 1 1/2 inches outside diameter, 1/4 inch thickness). Whether the experimental setup could be scaled upwards without prohibitive costs could not be determined but if it can then both experimental and theoretical approaches put forth should be investigated further.

The problem on hand is a bit more complicated. Due to the method of testing, it is not known whether the wave propagation and strain hardening effects can be ignored. The thin-walled aluminum spherical casing on the explosive plus the air gap to the wall of the tube may have the same effect as a plate impact shock. Add to this the temperature of the expanding gases and the problem becomes more complex.

The strain-rate sensitivity for 6061-T6 aluminum has been found to be quite small (Refs 17, 23-25), with the dependence becoming more pronounced in the region above  $10^4$  in./in./sec.

Perrone (Ref 26) has developed a simplified method for solving impulsively loaded structures of rate-sensitive materials. An adequate mathematical description of material behavior for important structural metals is given in the following power law:

$$\frac{\sigma}{\sigma_0} = 1 + \left( \frac{\dot{\epsilon}}{D} \right)^{\frac{1}{n}} \quad (1)$$

where

- $\dot{\epsilon}$  = strain rate
- $\sigma_0$  = static yield stress (when  $\epsilon = 0$ )
- $\sigma$  = dynamic yield stress
- $D, n$  = material constants

For cylinders the radial strain  $\epsilon$  is defined as

$$\epsilon = \frac{r - r_0}{r_0} \quad (2)$$

as shown in Figure 13 for symmetrical expansion. For the strain rate

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{1}{r_0} \frac{dr}{dt} = \frac{v}{r_0} = \frac{\dot{r}}{r_0} \quad (3)$$

with  $v = \frac{dr}{dt}$

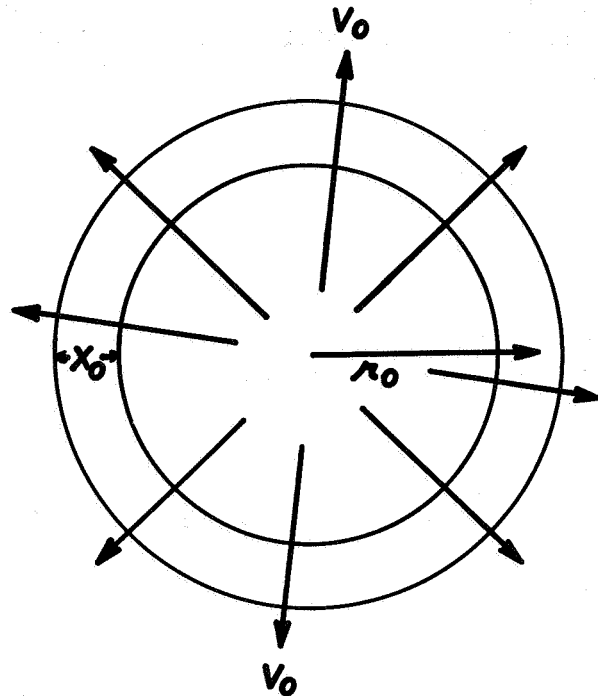
Normally the hoop stress  $\sigma$  can be solved from the equation of motion for a wall element with  $\rho$  = mass density, and differentiating (3), substitute in

$$\sigma = - \rho r \ddot{r} \quad (4)$$

or

$$\sigma = - \rho r r_0 \ddot{\epsilon} \quad (5)$$

to show the hoop stress as a function of the ring deceleration (Ref 21).



**INITIAL CONDITIONS**

$r_0$  = INITIAL MEDIAN RADIUS  
 $V_0$  = INITIAL RADIAL VELOCITY  
 $X_0$  = INITIAL RING THICKNESS

**INSTANTANEOUS CONDITIONS**

$r$  = FINAL MEDIAN RADIUS  $r > r_0$   
 $V$  = RADIAL VELOCITY,  $\dot{r}$   
 $X$  = RING THICKNESS  $X < X_0$

$\sigma$  = CIRCUMFERENTIAL STRESS

$\frac{V}{r}$  = STRAIN RATE,  $\dot{\epsilon}$

$$\sigma = -\rho r \ddot{r}$$

$$\text{or } \sigma = -\rho r r_0 \ddot{\epsilon}$$

**SYMMETRICAL EXPANSION**

Fig 13 The Expanding Ring

The strain rates obtained in these tests were obtained by using the permanent deformation values in Table 2 and the times obtained for shock arrivals at the different gages as well as photographs taken with a Beckman and Whitley 189 Framing Camera. More reliable data are required but the indications are that where expansions of 2.5% and over were experienced the time intervals show the possibility of strain rates approaching 10,000 in./in./sec. In no case was the ultimate strain of .15 in./in. for 6061-T6 aluminum reached.

Using that strain rate in Equation 1 with the values of  $n = 4$  and  $D = 6400/\text{sec}$  for 6061 aluminum (Ref 23) the dynamic yield stress is determined to be 72,000 psi based on a minimum static stress value of 35,000 psi.

The problem eventually centered on the effects transmitted outside the irradiation capsule to the surrounding media. Although engineered safeguards have been developed, the condition with the worst consequences was the shock wave emanating from the capsule when the annulus was filled with water. Additional data were also required to determine the pulses generated with the detonation of an 80-gram explosive charge under regular operating conditions, i.e., helium at 25 psig in the annular space. Also calculations were to be made to obtain a comparison with the experimental data to determine the accuracy of the method of computation. Time and the need for economy dictated the use of calculations.

In an effort to develop a mathematical model to predict the pressures at specified locations, several approaches were tried. A one-dimensional Lagrangian hydrodynamic code was the first attempt. This was a one-dimensional spherical calculation of the free expansion of a centrally initiated sphere of explosive into a spherical cavity and the subsequent interaction of the gases with a rigid spherical boundary. The equation of state for the detonation products of Composition B was used instead of that for C-4. Air in the cavity and the motion of the wall were neglected. Because of the cylindrical geometry only the initial pressure at the wall was obtained. The result for the peak pressure at the surface of the inner wall was

30 kilobars for a 160-gram charge. The experimental data indicate that the value obtained was at least an order of magnitude too high.

Due to the complexity of the problem, independent approaches were made by Picatinny Arsenal, Aerojet-General, and Lawrence Radiation Laboratory.

Three cases were considered to determine the peak shock pressure transmitted from the capsule under the conditions noted:

Case I, 80-gram charge of Composition B detonating when the annulus is filled with helium at 25 psig.

Case II, Same as Case I except annulus is filled with water.

Case III, 160-gram charge of Composition B detonating when the annulus is filled with helium at 25 psig.

Case I simulates the irradiation test conditions while Case II simulates the condition with the worst consequences. Case III simulates the actual testing conditions used in the qualification tests.

Manual calculations were made by this Laboratory assuming one-dimensional symmetry, a TNT spherical charge pressure-versus-distance scaling law, and impedance mis-match techniques. This is described in detail in Appendix III. Figure 14 shows a two-dimensional model of the capsule, the reactor pressure vessel, and a beryllium reflector, with the dimensions shown in inches. A, B, and C are the points at which the pressure pulses were calculated. Figure 15 shows a graphic presentation of the scaling law taken from the work by Granström (Refs 27, 28). This work was performed with TNT; the peak normal reflected overpressure values were used at the distance related to the explosive charge where the inner wall was located. At low pressures the pressure was assumed to be a linear function of the particle velocity (Ref 29). This method also assumed no attenuation of the shock; higher pressures than those measured would be predicted but the relative

magnitude of the pressure pulses should be correct. Figure 16 is a graphic presentation of Case II showing the pressures and velocities relative to time and distance using the peak pressure value obtained from Granström's curve (Fig 15) and the inside of the inner chamber as the reference point for the position. The calculations are compiled in Table 5 along with the results from Aerojet and LRL.

Aerojet-General used the WUNDY computer code (Ref 30), which assumes cylindrical geometry (Fig 14) and no material strength (i.e., that metals behave like fluids). These assumptions are acceptable with high pressures but not with the relatively low pressures generated under the stated conditions. This resulted in high calculated pressures that were conservative. The calculations were carried out (Ref 15) in the water-filled case and, in accordance with the program, the first peak shock pressures were considered to be the most accurate since metal motion did not affect the result. Subsequent pressures and motion are not as accurate so these should be ignored. Since the Picatinny calculations agreed better with the observed pressures the remaining cases were not calculated using the WUNDY code.

The Lawrence Radiation Laboratory (LRL) made one-dimensional calculations assuming spherical symmetry and the elastic-plastic version of the K.O. computer code. Figure 17 depicts the spherical configuration used as input for these calculations. Since this code is generally used for higher pressure calculations, pressures less than  $10^{-9}$  megabars are normally rounded off. The megabars dimension is due to the high pressure range that the K.O. code normally uses. To determine the errors that can be expected with this code, Case III (160 grams with helium in the annulus) was calculated a second time and rounding off was eliminated, as shown in Table 6. No permanent deformation of the inner tube was calculated although expansion did occur in the tests (Table 2). Also included were the maximum tensile stresses and the arrival times for the pressure pulses and tensile stresses.

TABLE 5

Comparison of Experimental and Calculated Peak Pressure Pulses (psi) in Water Outside Containment Capsule

Position Direction	CASE I 80-Gram Charge Helium in Annulus			CASE II 80-Gram Charge Water in Annulus			CASE III 160-Gram Charge Helium in Annulus			CASE IV 160-Gram Charge Water in Annulus		
	A Radial	B Axial	C Diagonal	A Radial	B Axial	C Diagonal	A Radial	B Axial	C Diagonal	A Radial	B Axial	C Diagonal
Experimental <sup>a</sup>	2.1 - 3.0	5 - 27	70 - 285	-	-	-	3.5 - 5.0	8 - 45	116 - 475	-	-	-
Picatinny calculations	≈ 0	<370	296	3000	<370	296	≈ 0	<600	500	-	-	-
Aerojet WUNDY calculations	-	-	-	100,000	-	-	140	-	-	-	-	-
LRL K.O. calculations	-	-	-	-	-	-	14.7	-	-	-	-	3.8

<sup>a</sup>Case I values extrapolated from CASE III' test data.

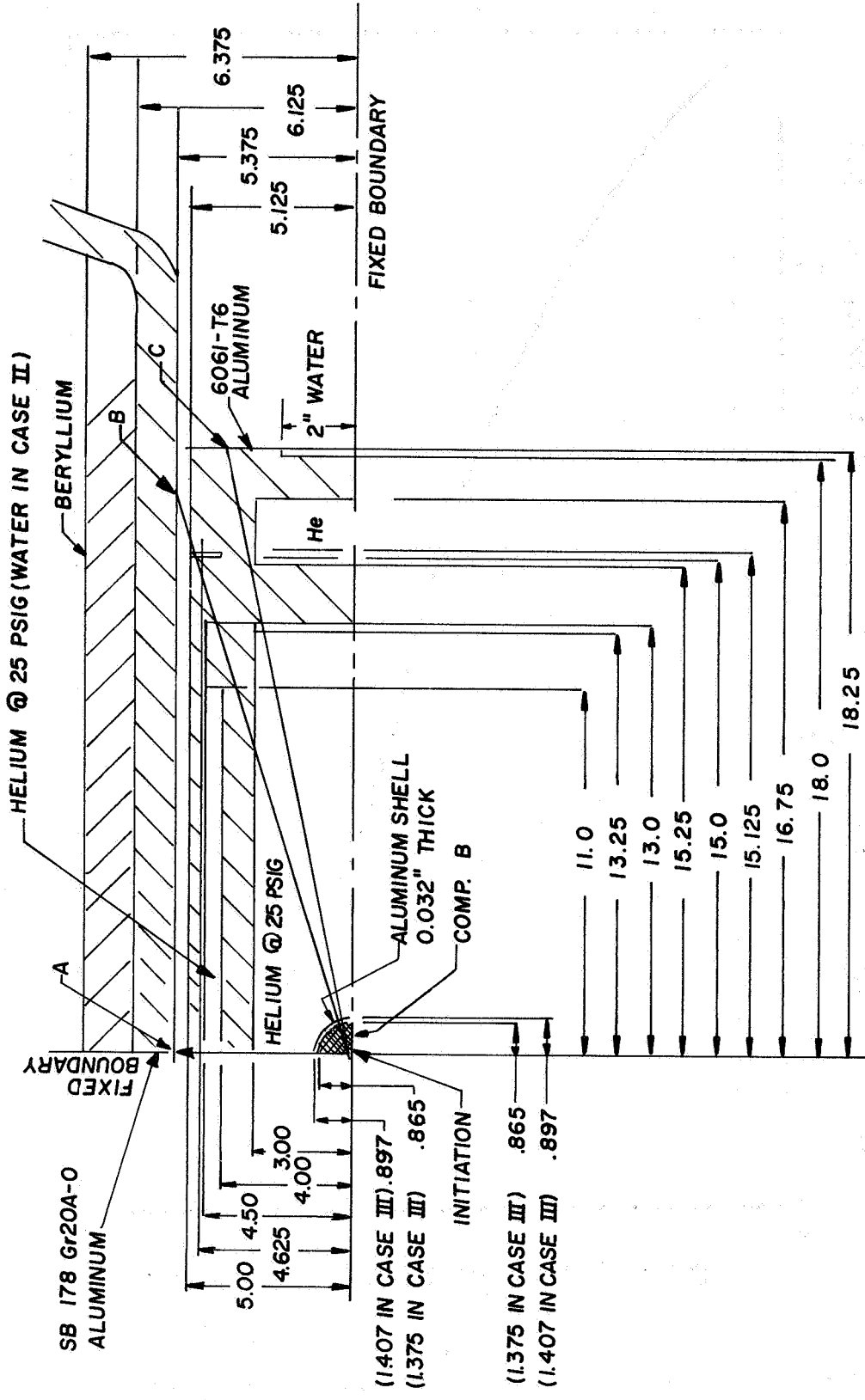


Fig 14 Two-dimensional model of capsule with dimensions and materials



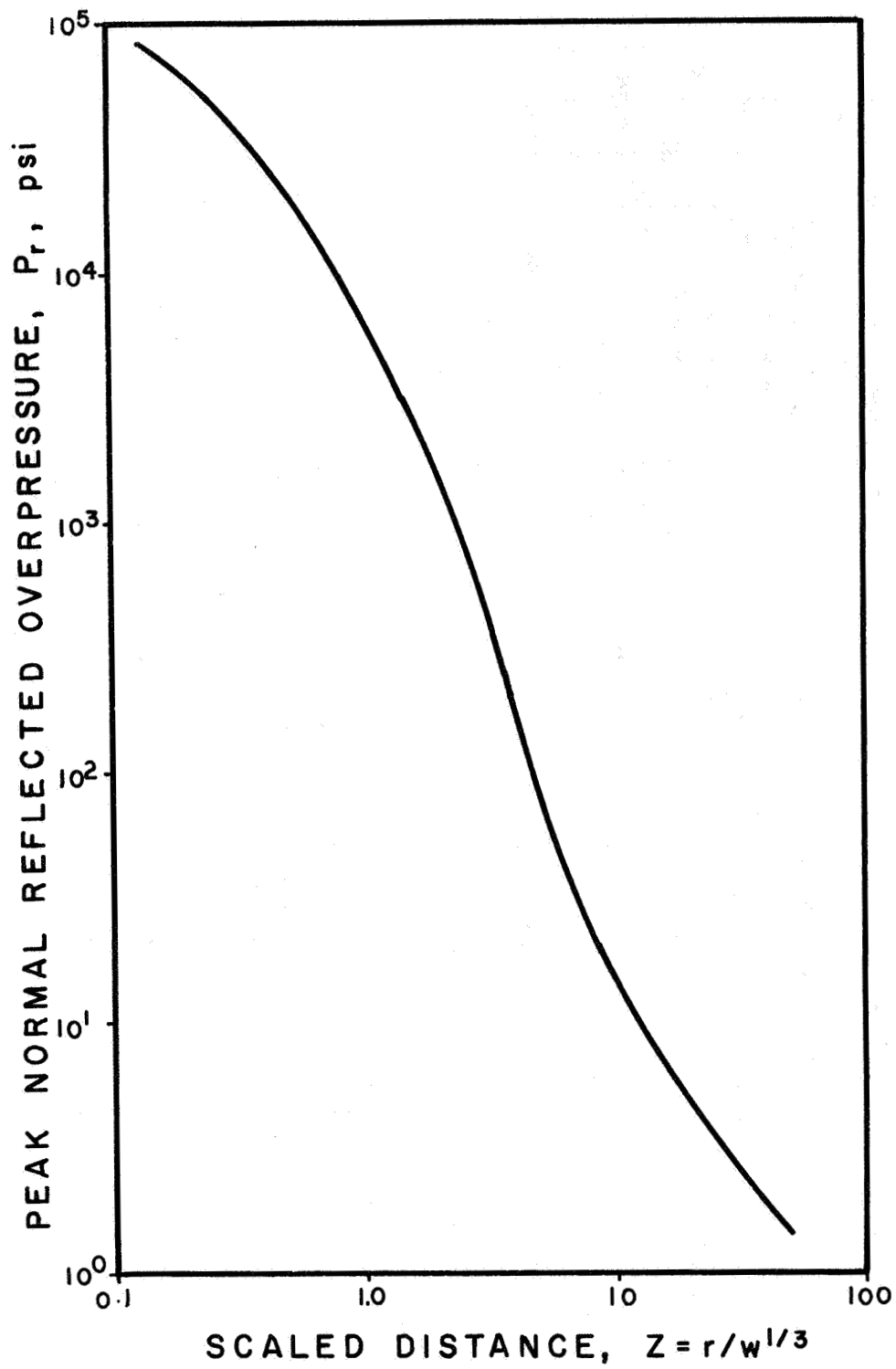


Fig 15 Curve for peak reflected overpressure versus scaled distance. TNT spherical charge pressure-versus-distance scaling law.

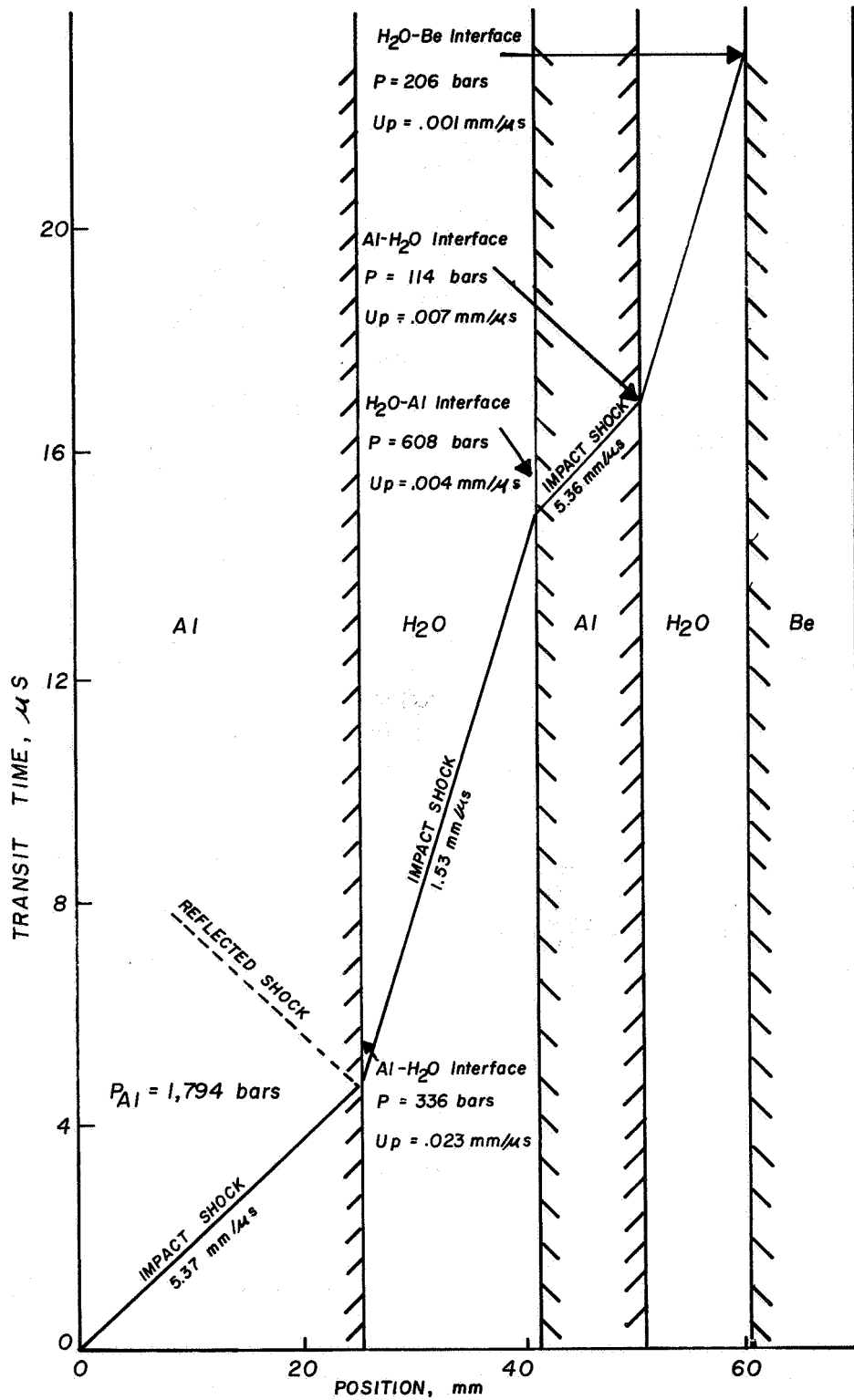
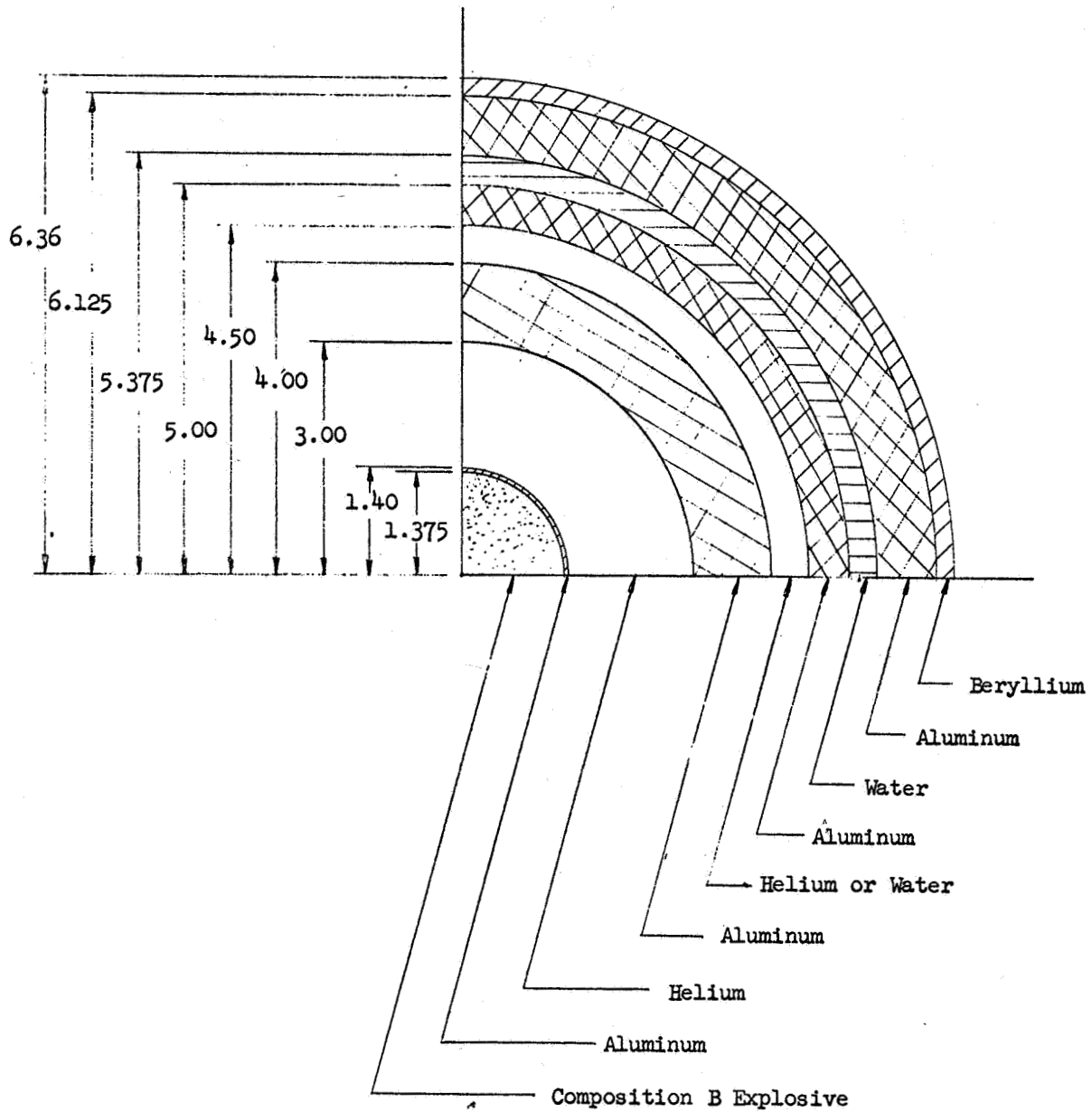


Fig 16 Pressures and velocities in capsule with 80-gram detonation and water in annular space.



<u>Metal</u>	<u>Shear Modulus</u>	<u>Yield Strength</u>	<u>Density, g/cc</u>
Be	$17.65 \times 10^6$ psi	14,700 psi	1.84
Al	$364.5 \times 10^6$ psi	44,100 psi	2.70

Fig 17 LRL K.O. input geometry

TABLE 6

LRL K.O. Computer Code Results

Case	Description	Max Pressure in Water Psi	Time After Detonation μsec	Max Tensile Strain in Beryllium μin./in.	Time After Detonation μsec
III-A	160-gram charge, helium in annulus, round-off pressure at 10 <sup>-9</sup> megabars	14.7	130	48.2	145
III-A	Same as above but no rounding off of pressures	23.2	125	53.3	150
IV-A	160-gram charge, water in annulus, round-off pressure at 10 <sup>-9</sup> megabars	3.78	150-165	20.1	175

An additional calculation was made by LRL in which 160 grams were detonated with the annulus filled with water so that a comparison could be made. Making this very simple change in the code was easier than repeating the calculations with the 80-gram charge. This is denoted as Case IV in Table 5. The shock pressures transmitted or propagated through the water in the annulus were expected to be higher than those through helium; however, the LRL calculated pressures were lower. The indications are, therefore, that this method of calculation is not accurate at low pressures. The Picatinny and Aerojet calculations did show that the pressure pulses would be higher with the water-filled annulus than with the helium-filled case.

Although peak shock pressures as high as 100,000 psi were calculated by Aerojet for the water-filled case, as compared to 3000 psi for Picatinny, these were not expected to cause any permanent deformation or damage to the reactor components because of the absence of permanent strain reported in the LRL calculations. This was confirmed in the Aerojet small-capsule tests where a peak pressure of 74,000 psi produced no permanent deformation of the mock-up of the trail cable tube less than one inch away. For irradiation the Z trail cable tube assembly of the General Electric Test Reactor was used for insertion of the small capsules into the reactor irradiation location. Also, qualitative tests showed that this pulse moving at velocities ranging from 120 to 340 meters per second would not break a 0.0008-inch-thick aluminum foil immersed in water 7 inches away or break a 150-watt light bulb 19 inches away (Ref 4). Indications are that the high-order detonation of an explosive sample in the small capsule during an actual irradiation in the reactor did not affect the surroundings.

Table 5 summarizes the calculations made by the three groups and also includes a grouping of the experimental data from Table 3. As the table indicates, the Picatinny calculations were in closer agreement with the measured test data than the values calculated by Aerojet or Lawrence Radiation Laboratory. The Picatinny calculations show a 40% decrease in peak shock pressure when the weight of the explosive charge was reduced from 160 to 80 grams. This ratio was used to

predict the extrapolated test values shown in Table 5 that would be observed if 80 grams were detonated with a helium-filled annulus.

Good agreement is shown with Positions A and C. The difference of an order of magnitude with respect to the values in Position B is probably due to the obliqueness of the shock without considering any reflections in what is almost a two-dimensional corner.

The measurements of the peak pressure at Position C should be analogous to those of the water-filled radial gap. Since the shock propagates through aluminum the pressure would be higher; conversely, the distance from the explosive charge to the capsule corner is greater than the radial distance, tending to lower the calculated pressure in accordance with the scaling law.

The experimental data also indicated that all the shock pressures measured were of low energy content since the pulse durations or pulse widths were 20 microseconds or less. The time intervals and the tensile stresses calculated by LRL seem to agree with the shock arrival times in Table 4 and the strain measurements in Table 3.

This brings up the point as to the type of waves, either shock or sound, that are actually emanating from the containment capsule. It should be noted that in the pressure profile of a sound wave the pressure difference between any two successive points is infinitesimal, implying that the pressure profile in a sound wave is continuous. A finite difference at any point is a discontinuity and denotes a shock wave. In a sound wave, the medium merely vibrates and passes its energy on to the next layer. In a shock wave the material moves physically in the direction of advance of the pulse. Another way of saying this is that in a sound wave the material transport averages zero whereas in a shock wave it is greater than zero. This explains why the walls of the aquarium did not collapse during the testing.

## CONCLUSIONS AND RECOMMENDATIONS

In summary it can be stated that the major problems in the design and development of a large explosive containment irradiation capsule have been solved and that an 80-gram sample can be irradiated safely. Through engineered safeguards and conservative approaches, with a minimum safety factor of two, the integrity of the capsule can be maintained if an explosion occurs, a controlled release of the gaseous products can be achieved, and any pressure pulse emanating from the container will have been reduced to such a degree as to preclude any adverse effect on the surrounding medium.

The safe operation of the nuclear reactor is still the responsibility of the nuclear safety group and the operating management. Qualified approval for the capsule has been given. Nevertheless, further clarification or study is needed to eliminate the persistent doubt as to whether the reactor will be affected by any low pressure pulses that would be transmitted by the capsule should a detonation occur. The engineered safeguards, precautions, and safety factors were incorporated in the design, development, and operation of the explosive containment irradiation capsule to prevent the "credible" accident with the worst consequences but the doubt still persists. The solution can be approached in either of two ways:

1. Conduct dynamic loadings on reactor components or equivalent to the maximum obtained in tests.
2. Incorporate an additional or wider annular gap in the capsule or an equivalent shield between the capsule and reactor to completely attenuate any pressure pulse.

Further study should be conducted on computer calculations, which would predict accurately the pressures, stresses, and strains, and the time references for each.

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APPENDIX I

Detail Drawings for Phase II Explosive  
Container for Reactor Irradiation,  
Including Concept for Rail Cable Fixture  
for Inserting and Locating the Explosive  
Container in the General Electric Test Reactor





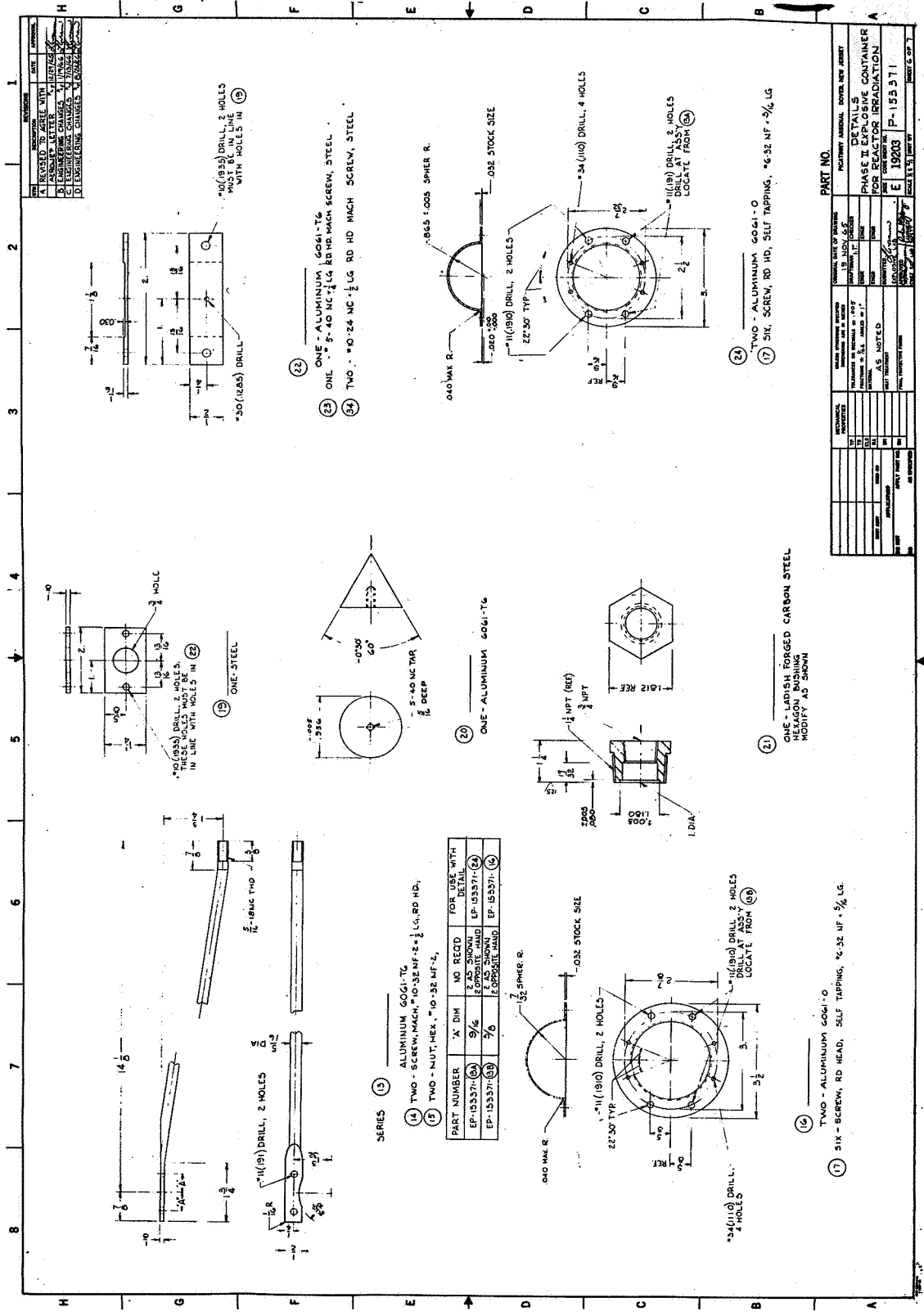










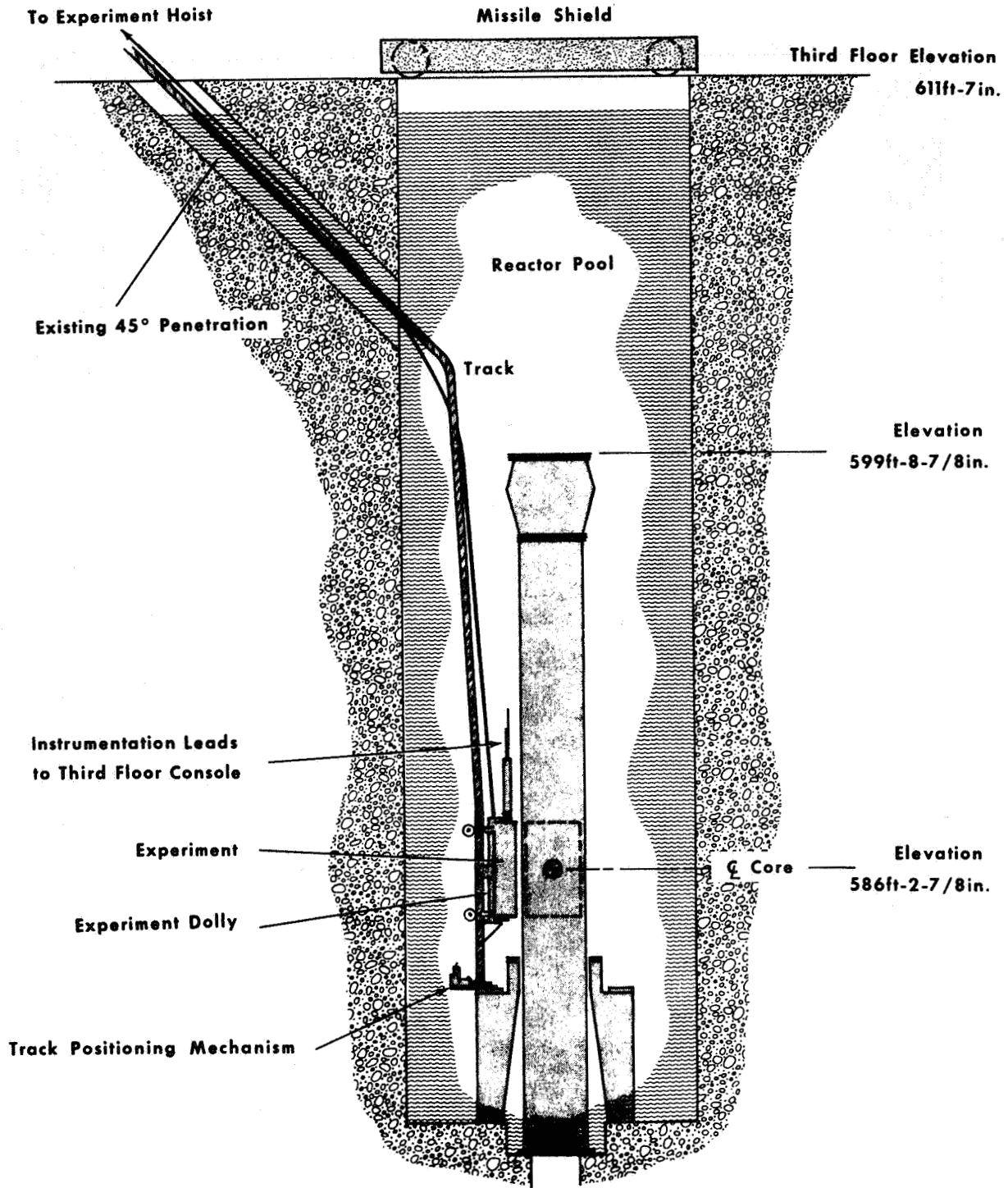


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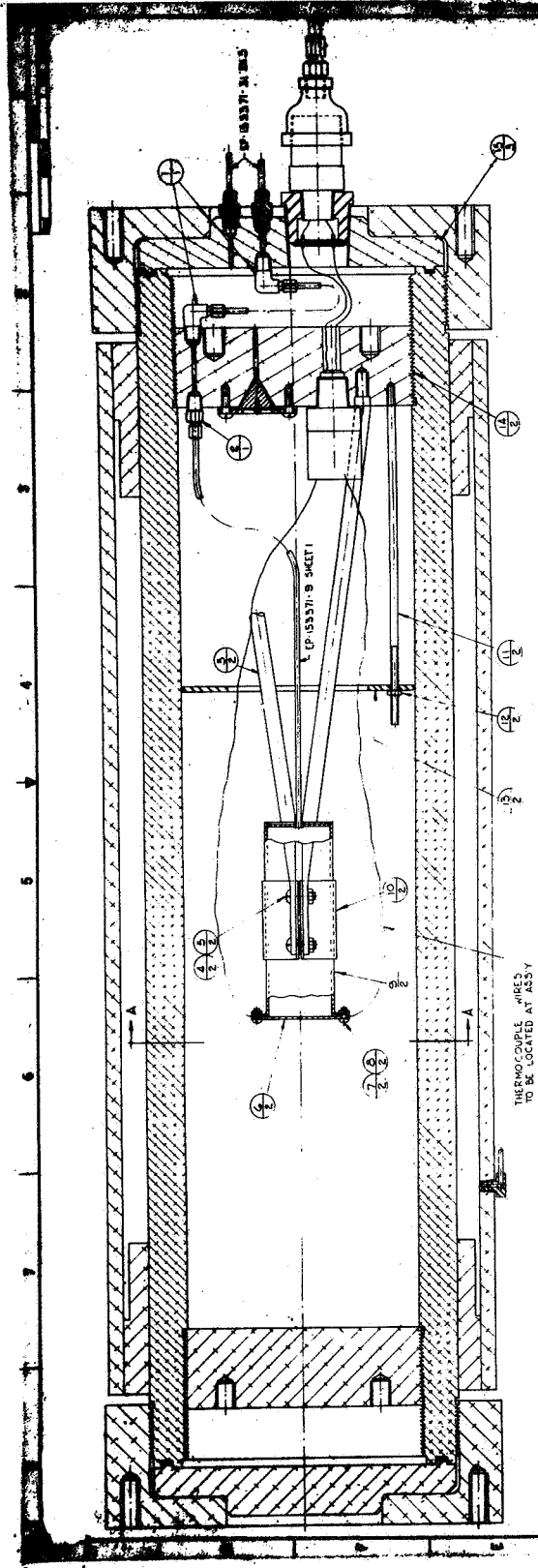




**RAIL CABLE FIXTURE**  
**GENERAL ELECTRIC TEST REACTOR**  
**AEROJET GENERAL PHASE II CAPSULE IRRADIATION CONCEPT**

APPENDIX II

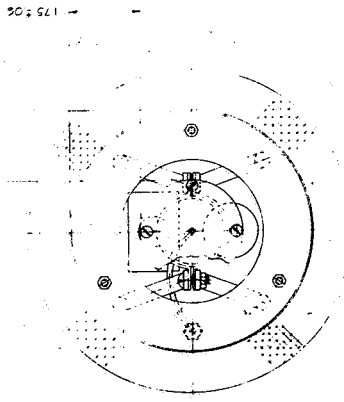
Detail Drawings for Phase II Explosive  
Container for Reactor Irradiation of  
Propellants and Detonators (Set of 4)



ASSEMBLY  
FOR PARTS NOT IDENTIFIED.  
SEE EP-153571 (ASSY & DETAIL)

TEMPERATURE SENSORS  
TO BE LOCATED AT ASSY

175136



SECTION A-A

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CHICAGO, ILL

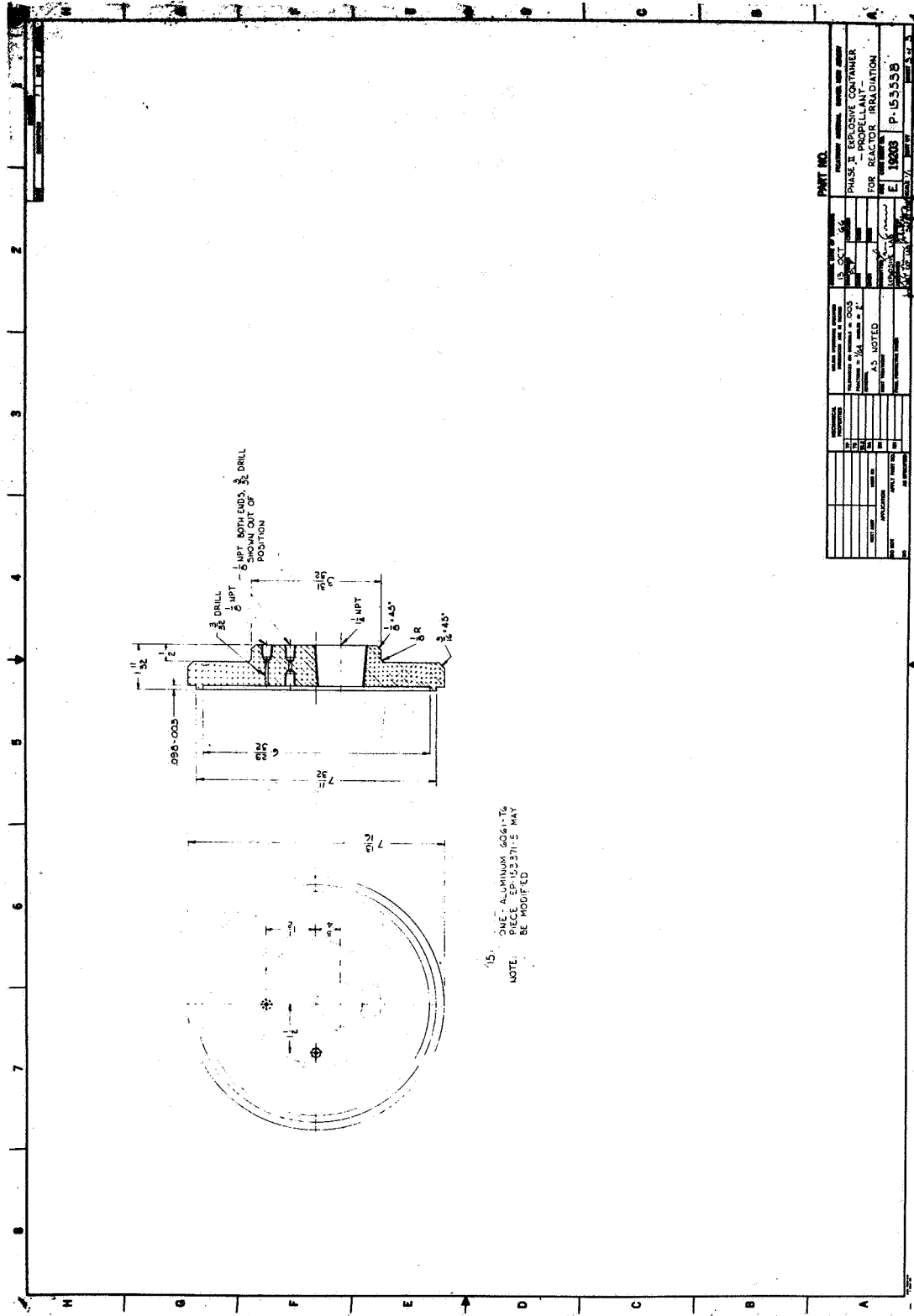
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NOT IDENTIFIED		
NOMENCLATURE, COMMERCIAL ITEMS		

BILL OF MATERIAL

DATE	13 OCT 66
DESIGNED BY	PHASE I, EXPLOSIVE CONTAINER, ASSY.
CHECKED BY	PHASE I, EXPLOSIVE CONTAINER, ASSY.
APPROVED BY	PHASE I, EXPLOSIVE CONTAINER, ASSY.
PROJECT	PHASE I, EXPLOSIVE CONTAINER, ASSY.
SCALE	AS SHOWN
QUANTITY	1
DESCRIPTION	PHASE I, EXPLOSIVE CONTAINER, ASSY.
REVISION	1
DATE	13 OCT 66
BY	16098
APP'D	P-153536







15.  
 ONE - ALUMINUM 6061-T6  
 NOTE: PIECE EP-152371-5 MAY  
 BE MODIFIED

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DATE: [Date]		DATE: [Date]	
APPROVED BY: [Signature]		APPROVED BY: [Signature]	
DATE: [Date]		DATE: [Date]	
REVISIONS:		REVISIONS:	
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1	AS NOTED		
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## APPENDIX III

### One-Dimensional Calculations of Pressure Pulses Emanating from Phase II Explosive Containment Irradiation Capsules Under Certain Conditions

One-dimensional analytical calculations were performed to determine the pressure pulses at various preselected interfaces noted as points A, B, and C on the explosive containment irradiation capsule. These points are shown on the two-dimensional model in Figure 14 in the main body of this report.

In any calculations, certain assumptions must be made to facilitate the mechanics of the calculations and to extrapolate the data from known geometries to those under study. For the work covered in this Appendix, the following assumptions were made:

1. That the scaling laws wherein the pressure  $P_r$  at any distance from a spherical charge can be related to the scaled distance  $Z$  from the center of the charge. Also

$$P_{r\text{TNT}} \cong P_{r\text{Comp B}}$$

2. That the pressure pulses are approximated by square waves whose durations are longer than the transit times (unattenuated shocks).

3. That low pressures can be approximated by a linear function of the particle velocity  $P = k u_p$ .

The purposes of these analytical calculations were to predict the peak shock-pressure pulse emanating from the explosive containment capsule due to the detonation of an 80-gram charge should the annulus fill with water, and to obtain a comparison with experimental data to determine the accuracy of the methods of calculation.

### Case I

The central sphere contains 80 grams of Comp B explosive (.865 inch radius at 1.8 g/cm<sup>3</sup>) with annular space filled with helium at 25 psig.

For Comp B, W = 80 g = .176 lb  
ID of containment vessel = 6 inches

The pressure incident on the chamber wall is based on the calculated reflected overpressures Pr with the provision as noted that TNT  $\cong$  Comp B (Ref 1).

#### Position A (Case I)

$$W^{1/3} = .56 \text{ lb}^{1/3}$$

$$Y^1 = .25 \text{ foot distance from center of charge to wall collinear with point A}$$

$$Z = \frac{Y^1}{W^{1/3}} = \frac{.25}{.56} = .446 \text{ ft/lb}^{1/3} \text{ scaled distance}$$

From the curve for spherical charge of TNT (Fig 2.14 in Reference 1; Fig 15 is a portion of that curve)

$$Pr = 26,000 \text{ psi} \approx 1794 \text{ bars}$$
$$\text{Assuming } P_{A1} = 1.54 u_{P_{A1}}$$

where  $P_{A1}$  is pressure in megabars and  $u_{P_{A1}}$  is particle velocity in cm/ $\mu$ sec

$$u_p = 1.242 \times 10^{-3} \text{ cm}/\mu\text{sec} = .0124 \text{ mm}/\mu\text{sec}$$

$$\text{From } U_{A1} = .533 + 1.34 u_{P_{A1}}$$

where  $U_{A1}$  is shock velocity

$$U_{A1} = 5.37 \text{ mm}/\mu\text{sec}$$

Transit time  $t$  for shock through 25.4 mm of aluminum, assuming no attenuation of a square wave pulse

$$t_{Al} = 4.73 \text{ } \mu\text{sec}$$

From scaled impulse curve (Ref 1)

$$\frac{I_r}{W^{1/3}} = 1250 \frac{\text{lb-ms}}{\text{in.}^2 \text{-lb}^{1/3}} \text{ from which } I_r = 700 \text{ lb-ms}$$

$$I_r = \int_{t_1}^{t_2} P \, dt = P(t_2 - t_1)$$

$$\text{or } \Delta t = \frac{I_r}{P} - .027 \text{ ms} = 27 \text{ } \mu\text{sec}$$

Assuming a square wave pulse of 27  $\mu\text{sec}$  duration, pressure pulse  $P_r$  should be transmitted through 25.4 mm of Al unattenuated. Moreover, from  $P$  versus  $u_p$  curve for aluminum, since the subsequent interface is between Al and He, and since He is a highly compressible gas, the pressure at that interface will approach 0 and the particle velocity  $u_p$  would double ( $u_p \cong .0248 \text{ mm}/\mu\text{sec}$ ). There  $P_A \cong 0$  for position A in case 1.

#### Position B (Case I)

A point on the inner chamber wall collinear with both the center of the charge and position B would lie 10 inches from the center of the charge.

$$y^1 = 10 \text{ inches or } .82 \text{ foot}$$

$$z = \frac{y^1}{W^{1/3}} = 1.46 \text{ ft}/\text{lb}^{1/3} \text{ scaled distance}$$

From the curve for TNT charge (Fig 2.14, Ref 1)

$$P_r = 3250 \text{ psi} \approx 224 \text{ bars}$$

$$U_{A1} \approx .535 \text{ cm}/\mu\text{sec} \text{ (roughly sonic)}$$

$$u_p = 1.55 \times 10^{-4} \text{ cm}/\mu\text{sec}$$

Moreover, since this is an oblique shock in relation to the vessel wall, calculations assuming normal incidence would be much higher than the actual value. Such calculations give a value of 26 bars or 370 psi, which can be considered as an upper limit. For position B (case I) the calculations indicate that the pressure pulse > 370 psi.

Position C (Case I)

$$W^{1/3} = .56 \text{ lb}^{1/3}$$

$Y^1 = 1.13$  feet distance from center of charge to wall collinear with position C.

$$Z = \frac{Y^1}{W^{1/3}} = 2.02 \text{ ft}/\text{lb}^{1/3} \text{ scaled distance}$$

From the curve for TNT (Fig 2.14, Ref 1)

$$P_r = 1600 \text{ psi} \approx 110 \text{ bars}$$

$$U_{A1} \approx 5.35 \text{ mm}/\mu\text{sec}$$

Transit time  $t$  for shock through 127.0-mm wall

$$t_{A1} = 23.7 \mu\text{sec}$$

From scaled impulse

$$\frac{I_r}{W^{1/3}} = \frac{120 \text{ lb-ms}}{\text{in.}^2 \text{-lb}^{1/3}} I_r = 67.2 \text{ lb-ms}$$

$$\Delta t = .042 \text{ ms} = 42 \mu\text{sec}$$

Assuming a linear relation between P and  $u_p$  at low pressures

$$P_{Al} \approx 1.445 u_{p_{Al}}, \text{ and } P_{H_2O} \approx .148 u_{p_{H_2O}}$$

Using the reflected curve technique for equating pressures and particle velocities at an interface.

$$\text{Reflected curve for } P_{Al} = -1.445 u_{p_{Al}} + 2.20 \times 10^{-4}$$

where at

$$P_{Al} = 0, u_{p_{Al}} = 2(.76 \times 10^{-4})$$

$$P_{Al} = 1.10 \times 10^{-4} \text{ megabars}$$

$$\text{at } u_{p_{Al}} = .76 \times 10^{-4} \text{ cm}/\mu\text{sec}$$

$$P_{Al} = -1.445 u_{p_{Al}} + 2.20 \times 10^{-4}$$

$$P_{H_2O} = .148 u_{p_{H_2O}}$$

$$1.593 u_p = 2.20 \times 10^{-4}$$

$$u_{p_{Al-H_2O}} = 1.38 \times 10^{-4}$$

$$P_{Al-H_2O} = .204 \times 10^{-4} \text{ megabars}$$

Therefore P at interface  $\approx 20.4$  bars or 296 psi for position C (case I).

## Case II

Same as case I except annular space filled with water.

### Position A (Case II)

$Z = .446$  and  $P_r = 26,000 \text{ psi} = 1794 \text{ bars}$  (of case I, position A).

Assuming that pressures are linear functions of particle velocities, then

$$P_{Al} \approx 1.445 u_{P_{Al}}$$

$$P_{H_2O} \approx .149 u_{P_{H_2O}}$$

$$P_{Be} \approx 1.435 u_{P_{Be}}$$

Using the reflected curve technique (graphical) for matching pressures and velocities at the various interfaces:

At 1st interface, Al-H<sub>2</sub>O

$$P_{Al} = -1.445 u_{P_{Al}} + 3.59 \times 10^{-3} \quad (\text{reflected curve for Al})$$

$$P_{H_2O} = .149 u_{P_{H_2O}}$$

$$1.594 u_{P_{Al-H_2O}} = 3.59 \times 10^{-3}$$

$$u_{P_{Al-H_2O}} = 2.251 \times 10^{-3} \text{ cm}/\mu\text{sec}$$

$$P = 335.7 \text{ bars}$$



At 2nd interface, H<sub>2</sub>O-Al

$$P_{H_2O} = -.149 u_{P_{H_2O}} + 6.7 \times 10^{-4} \text{ (reflected curve for H}_2\text{O)}$$

$$P_{Al} = 1.445 u_{P_{Al}}$$

$$1.594 u_p = 6.7 \times 10^{-4}$$

$$u_{P_{H_2O-Al}} = 4.21 \times 10^{-4} \text{ cm}/\mu\text{sec}$$

$$P = 608 \text{ bars}$$

At 3rd interface, Al-H<sub>2</sub>O

$$P_{Al} = 1.445 u_{P_{Al}} + 1.216 \times 10^{-3}$$

$$P_{H_2O} = .149 u_{P_{H_2O}}$$

$$1.594 u_{P_{Al-H_2O}} = 1.216 \times 10^{-3}$$

$$u_{P_{Al-H_2O}} = .736 \times 10^{-3} \text{ cm}/\mu\text{sec}$$

$$P = 113.7 \text{ bars}$$

At 4th interface, H<sub>2</sub>O-Be

$$P_{H_2O} = .149 u_{P_{H_2O}} + .227 \times 10^{-3}$$

$$P_{Be} = 1.435 u_{P_{Be}}$$

$$1.584 u_{P_{H_2O-Be}} = .227 \times 10^{-3}$$

$$u_{P_{H_2O}} = 1.43 \times 10^{-4} \text{ cm}/\mu\text{sec}$$

$$P = 206 \text{ bars}$$

Position A, case II is graphically depicted in Figure 16. It has been assumed that the incoming pressure pulse is 1794 bars and that the associated impact shock passes through the various media unattenuated (square pressure pulse). It is further assumed that because of the low shock velocities through the various media the reflected shocks would not appreciably reinforce the primary impact shocks because of the long transit times involved. For Position A (case II) the pressure pulse would be  $P = 206 \text{ bars} = 2987 \text{ psi}$ .

Positions B and C (Case I)

Positions B and C would be the same as those for case I, since the geometries are identical. Therefore for position B (case II),  $P = 370 \text{ psi}$ , and for position C (case II),  $P = 296 \text{ psi}$ .

Case III

Central sphere contains 160 grams of Comp B explosive (1.375 inches radius at  $0.9 \text{ g/cm}^3$ ), annular space filled with helium at 25 psig.

For Comp B,  $W = 160 \text{ g}$  at  $\rho = 0.9 \text{ g/cm}^3$

Position A (Case III)

The deduced pressure  $P_r$  is based on the scaled distance  $Z$  which considers only the total mass of the explosive; the density of the charge does not appear in any of the calculations

$$Z = \frac{r^1}{W^{1/3}} = \frac{.25}{.352^{1/3}} = .354 \text{ ft/lb}^{1/3}$$

From curve for spherical TNT charge (Ref 1)

$$P_r = 34,000 \text{ psi} \approx 2,346 \text{ bars}$$

$$u_p = 1.52 \times 10^{-2} \text{ mm}/\mu\text{sec}$$

$$U_{A1} = .537 \text{ cm}/\mu\text{sec}$$

Moreover the pressure at position A should be  $\approx 0$  for the same reason as in case I (see above).

#### Position B (Case III)

Considering a point on the inner chamber wall col-linear with the center of the explosive charge and position B, this point would experience an oblique shock with a peak pressure of 5200 psi at a distance approximately 10 inches from the center of the charge. This linear path up to position B encompasses aluminum, water, aluminum, water, and beryllium. An analysis using pressure and particle velocities at the inter-faces assuming normal rather than oblique pressure pulses gives a value of 41 bars of approximately 600 psi. This value will only be obtained under the most adverse of conditions. The true value should be less than this. Therefore for position B (case III)  $P > 600$  psi.

#### Position C (Case III)

Assuming a linear distance from the center of the charge to the wall in the vicinity of point C as 13.6 inches

$$r^1 = 13.6 \text{ inches} = 1.13 \text{ feet}$$

$$z = \frac{r^1}{W^{1/3}} = 1.60$$

From the curve for TNT,

$$Pr = 2650 \text{ psi or } 183 \text{ bars}$$

$$u_p = 1.27 \times 10^{-4} \text{ cm}/\mu\text{sec}$$

$u_p \approx .535 \text{ cm}/\mu\text{sec}$  or close to sonic velocity. Transit time  $t = 23.7 \mu\text{sec}$  for 127 mm wall, assuming a square pulse.

As in case I, position C, using the reflected wave technique

$$P_{Al} = - 1.445 U_{P_{Al}} + 3.67 \times 10^{-4}$$

$$P_{H_2O} = .149 u_{P_{H_2O}}$$

$$1.594 U_{P_{Al-H_2O}} = 3.67 \times 10^{-4}$$

$$U_{P_{Al-H_2O}} = 2.3 \times 10^{-4} \text{ cm}/\mu\text{sec}$$

$$P = 34 \text{ bars} \approx 500 \text{ psi}$$

Therefore, for position C (case III) the pressure pulse is approximately 500 psi.

The assumption of a linear relationship between pressure and particle velocity at low pressures is based on the following considerations

$$P = \rho U_s u_p \quad (1)$$

where

$P$  = pressure

$\rho$  = density

$U_s$  = shock velocity

$u_p$  = particle velocity

For most metals the shock velocity  $U_s$  is a linear function of the particle velocity,  $U_s = a + b u_p$  (Ref 5).

Substituting for  $U_s$  in Equation 1

$$P = \rho u_p (a + b u_p) \quad (2)$$

At low pressures or shock velocities the contribution of the second term is so small that it can be neglected

$$P \approx \rho a U_p \quad (3)$$

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<p>The design and development of a large explosive containment capsule for the irradiation of up to 80 grams of explosive materials is described. The capsule will fully protect its surroundings, e.g., the core of a nuclear reactor, if its explosive content detonates. The minimum safety factor of two was used. The capsule contains provisions for the containment of gases produced by detonation or burning of the explosive material and the minimizing of any shock wave propagated outside the capsule. Also, provisions are made to monitor pressure or gas evolution and the temperature of the test material during irradiation. Dynamic pressure pulse and stress-strain measurement tests were conducted and are described. Analytical calculations were made for comparison with experimental data, first to determine the validity of the calculations and then to obtain information on configurations not actually tested.</p>			

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