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# Test Report for Perforated Metal Air Transportable Package (PMATP) Prototype

Jeffrey G. Bobbe and Jim D. Pierce

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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# Test Report for Perforated Metal Air Transportable Package (PMATP) Prototype

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Prepared for Japan Nuclear Cycle Development Institute (JNC)

## Abstract

A prototype design for a plutonium air transport package capable of carrying 7.6 kg of plutonium oxide and surviving a "worst-case" plane crash has been developed by Sandia National Laboratories (SNL) for the Japan Nuclear Cycle Development Institute (JNC). A series of impact tests were conducted on half-scale models of this design for side, end, and corner orientations at speeds close to 282 m/s onto a target designed to simulate weathered sandstone. These tests were designed to evaluate the performance of the overpack concept and impact-limiting materials in critical impact orientations.

The impact tests of the Perforated Metal Air Transportable Package (PMATP) prototypes were performed at SNL's 10,000-ft rocket sled track. This report describes test facilities calibration and environmental testing methods of the PMATP under specific test conditions. The tests were conducted according to the test plan and procedures that were written by the authors and approved by SNL management and quality assurance personnel. The result of these tests was that the half-scale PMATP survived the "worst-case" airplane crash conditions, and indicated that a full-scale PMATP, utilizing this overpack concept and these impact-limiting materials, would also survive these crash conditions.

This work was supported by the Japan Nuclear Cycle Development Institute (JNC) under contract DE-FI04-88AL5272.

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# Preface

A conceptual design for a plutonium air transport (PAT) package capable of carrying 7.6 kg of plutonium oxide and surviving a "worst-case" plane crash has been developed and tested by Sandia National Laboratories (SNL) for the Japan Nuclear Cycle Development Institute (JNC). The package is based on technology developed by SNL for the Department of Energy (DOE) as described in U. S. Patent No. 5337917. The design consists of a robust primary containment vessel within an overpack of layered perforated aluminum sheet, aramid cloth, and thermal insulation. This report discusses a series of impact tests conducted on half-scale models for various orientations for impact onto simulated weathered sandstone.

These "worst case" conditions are stipulated by the Murkowski Amendment, Public Law 100-203, Section 5062, and are technically defined as a 282-m/s impact onto a defined weathered sandstone target to match the crash parameters of the Pacific Southwest Airlines (PSA) Flight 1771 crash that occurred on December 7, 1987.

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# Executive Summary

A conceptual design for a plutonium air transport (PAT) package [Reference 1] capable of carrying 7.6 kg of plutonium oxide and surviving a "worst-case" plane crash has been developed and tested by Sandia National Laboratories (SNL) for the Japan Nuclear Cycle Development Institute (JNC). The package is based on technology developed by SNL for the Department of Energy (DOE) as described in U. S. Patent No. 5337917 [Reference 2]. The design consists of a robust primary containment vessel within an overpack of layered perforated aluminum sheet, aramid cloth, and thermal insulation as illustrated in Figure ES.1.

The impact limiting materials have been well characterized and tested [References 3, 4] to provide constitutive material properties for the finite element analyses that were documented in Reference 1.

This report describes a series of impact tests conducted on half-scale prototype models of this design, the perforated metal air transportable package (PMATP). These impact tests were in the side, end-on, and center-of-gravity over corner orientations at velocities close to 282 meters per second (m/s) onto a target designed to simulate weathered sandstone. These tests were conducted to evaluate the performance of the overpack and impact-limiting materials in critical impact orientations.

The testing reported here has shown the success of the PMATP in a prototype stage for half-scale models. The next phase of work is to design, fabricate, and test a full-scale prototype. Following that, a working model should be designed and constructed. Discussions with the U. S. Nuclear Regulatory Commission (NRC) should be carried out for the purpose of coordinating the series of regulatory steps required for the certification process.

Four impact tests of the PMATP prototypes were performed at SNL's 10,000-ft rocket sled track. This report describes how the test facilities were calibrated. It also describes the performance of the PMATP under the specific test conditions. The tests were performed according to the test plan, and procedures were written by the authors and approved by SNL management and quality assurance (QA) personnel. The half-scale PMATP survived the "worst-case" airplane crash conditions, and these results indicated that a full-scale PMATP, utilizing this overpack concept and these impact-limiting materials, would also survive these crash conditions.

The U. S. government passed Public Law 100-203, Section 5062 [Reference 5], also known as the Murkowski Amendment, which stipulated that any aircraft carrying nuclear material through U. S. airspace would have to ensure that, in the event of a worst-case crash, no spillage or release of nuclear material would ensue. Worst-case crash conditions, in the case of this legislation, are based on the December 7, 1987, crash of Pacific Southwest Airlines (PSA) Flight 1771, and are technically defined as an impact at a velocity of 282 m/s onto a severely weathered sandstone hillside target. This legislation required a significant enhancement of the then existing regulations concerning air transport of plutonium.

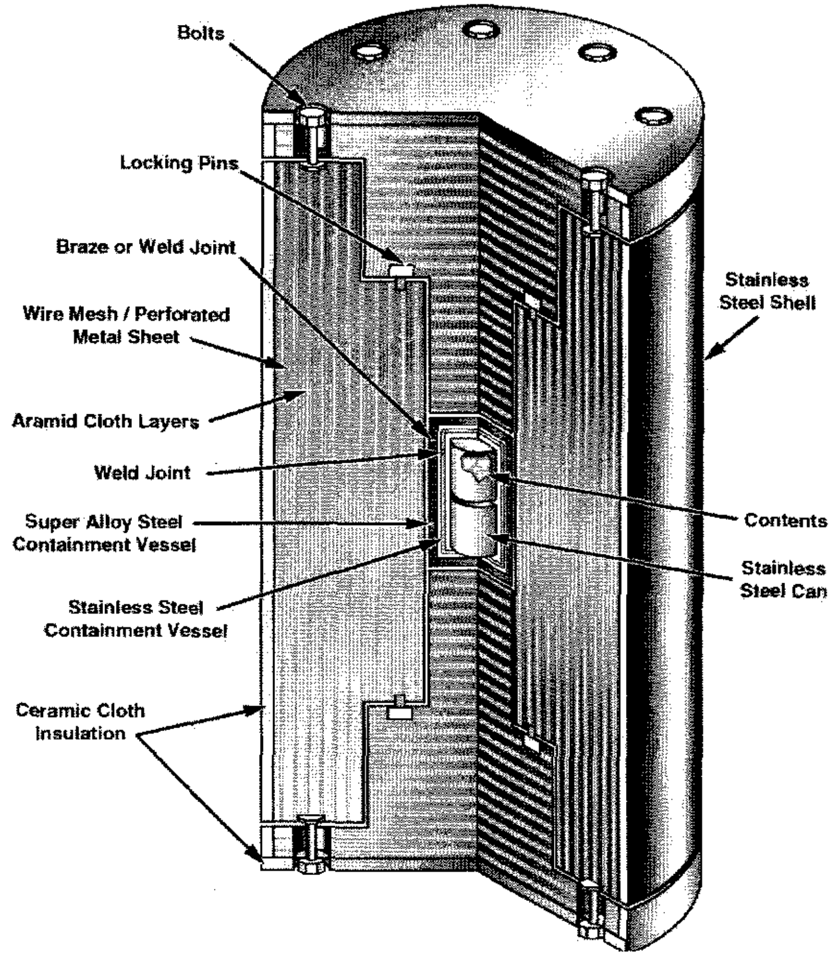


**Figure ES.1. Perforated Metal Air Transportable Package (PMATP) Prototype.**
This crash-resistant container utilizes perforated aluminum sheet and aramid cloth as a protective overpack. The prototypes tested were 30 to 32 inches long and 15 inches in diameter.

The existing regulations at the time, NUREG 0360 [Reference 6], stipulated an impact at a velocity of 129 m/s. Because of the more difficult conditions required by the Murkowski Amendment and the unavailability of a package that would meet these conditions, JNC resumed sea transport for plutonium oxide shipments from France and England to Japan, while continuing to research air transport methods for future consideration. The testing reported here for the PMATP prototypes are significant for JNC because they provide the technical justification for the air shipment of plutonium as an alternate mode. This methodology also provides JNC with the availability of an option for plutonium oxide transport at a reasonable cost.

# Nomenclature

| | |
|---|---|
| CGOC | center-of-gravity over corner |
| CTU | calibration test unit |
| DOE | U. S. Department of Energy |
| EO | end-on |
| ft/s | feet per second |
| fps | frames per second |
| IM | image motion |
| JNC | Japan Nuclear Cycle Development Institute |
| m/s | meters per second |
| NQA | nuclear quality assurance |
| NRC | U. S. Nuclear Regulatory Commission |
| PAT | plutonium air transport |
| PMATP | perforated metal air transportable package |
| PSA | Pacific Southwest Airlines |
| pps | pictures per second |
| psi | pounds per square inch |
| QA | quality assurance |
| QAP | quality assurance procedure |
| QAPP | Quality Assurance Program Plan |
| SNL | Sandia National Laboratories |
| SO | side-on |
| SVHS | super VHS |
| TSDD | Transportation System Development Department |
| TTD | Transportation Technology Department |
| w/c | water-to-cement |

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# 1. Test Administration

The Perforated Metal Air-Transportable Package (PMATP) Development Test Program is a nuclear quality assurance (NQA) Minor Level 3 project. A test plan and procedures were prepared before the tests were conducted to each task to be performed for the testing of these packages. The Transportation Technology Department (TTD, formerly known as the Transportation Systems Development Department) manager, the program manager, and the task leader/QA coordinator approved all test plans and procedures.

## 1.1 Data and Records

The program manager kept all program records, data sheets, and correspondence, and the QA coordinator kept copies of these records. All day-to-day activities were recorded in the PMATP record sheets and maintained by the task leader, or were recorded in the task leader's daily record book. A checklist for each test was used to ensure that all critical activities occurred.

## 1.2 Quality Assurance

Activities for the design evaluation tests followed QA policies outlined in the Quality Assurance Program Plan for the Transportation System Development Department (TSDD QAPP). This document describes the QA program as it applies to all TTD-sponsored work. Contract personnel working with TTD personnel are subject to the TSDD QAPP.

The TSDD QAPP specifies, in general terms, TSDD QA policy and requirements. QA procedures (QAPs) are documents that elaborate on those quality requirements specified in the QAPP. The quality plan contains the policies that govern the activities that affect the quality of products and services performed by Sandia National Laboratories (SNL).

## 1.3 Individual Responsibilities

This section defines the organizational structure, responsibilities, levels of authority, and lines of communication within the TTD at SNL for the PMATP program at the time of the evaluation and test program.

**TTD Department Manager: G. F. Hohnstreiter**

> The department manager is responsible for and authorized to perform functions to attain quality objectives, including implementing this QAPP. These responsibilities and authorities may be delegated to other SNL organizations and individuals but the primary responsibility for attaining quality objectives rests with the department manager and, ultimately, with the program manager.

**TTD Program Manager: J. D. Pierce**

The program manager is responsible for implementing all activities performed to attain quality objectives, as well as all QA functions, including work executed by other SNL organizations and by contract personnel. The program manager has the authority to resolve disputes involving quality that arise from differences between the TTD QA coordinator and program staff members.

**TTD Task Leader: J. G. Bobbe**

The task leader has overall responsibility for all aspects of the program and for overseeing the work of all individuals involved. He is responsible for approving and implementing the support procedures and must approve any changes to the program, including changes to the procedures or related documents. The task leader has the authority to delegate specific tasks or responsibilities to other members of the project team.

**TTD QA Coordinator: J. G. Bobbe**

The QA coordinator is responsible for implementing all program QA activities. The QA coordinator has the authority and sufficient organizational freedom to identify quality problems, initiate and recommend solutions to those problems, verify solutions, stop unsatisfactory work, and delegate authority to others to perform QA functions. The QA coordinator is programmatically independent, reporting directly to the department manager.

Because J. G. Bobbe served as the task leader for the PMATP program, D. L. Bolton was assigned the acting role of the TTD QA coordinator for this program.

**Albuquerque Full-Scale Experimental Complex Engineer: S. R. Heffelfinger, TA III Experimental Facilities**

The Albuquerque Full-Scale Experimental Complex engineer is responsible for implementing the test plan at the facility, providing the specified environment, and ensuring test safety.

# 2. Design of Target to Simulate the Pacific Southwest Airlines Crash Site

The worst-case crash for an airliner has been defined as similar to the crash of Pacific Southwest Airlines (PSA) Flight 1771, as described in References 7 and 8. The package requirement to survive such an aircraft crash originated in the Murkowski Amendment [Reference 5].

The location of the PSA crash was a severely weathered sandstone hillside. Typical concrete targets have much higher strength than this material, so a different type of target had to be designed. The important target parameters used to model a high-speed impact onto a crushable target are density, shear strength (defined by the deviatoric yield surface), hydrostatic crush behavior, and degree of confinement. During an impact onto a true rock target, surrounding rock provides nearly perfect confinement of the impacted material. For this reason, it is desirable to have a target significantly larger than the package being tested and to have the edges of the target confined. The target was cast into a 12-ft-diameter by 8-ft-deep steel vessel. The steel around and in the back of the target provided excellent confinement, and simulated the boundary conditions provided by the semi-infinite real target.

Once the size and shape of the target were determined, the material to be cast had to be designed. The properties of the severely weathered sandstone at the crash site are described below [References 9, 10]:

Density – 143 lb/ft$^3$
Unconfined crush strength – 1000 pounds per square inch (psi)
Yield strength – see Figure 2.1
Volumetric response – see Figure 2.2

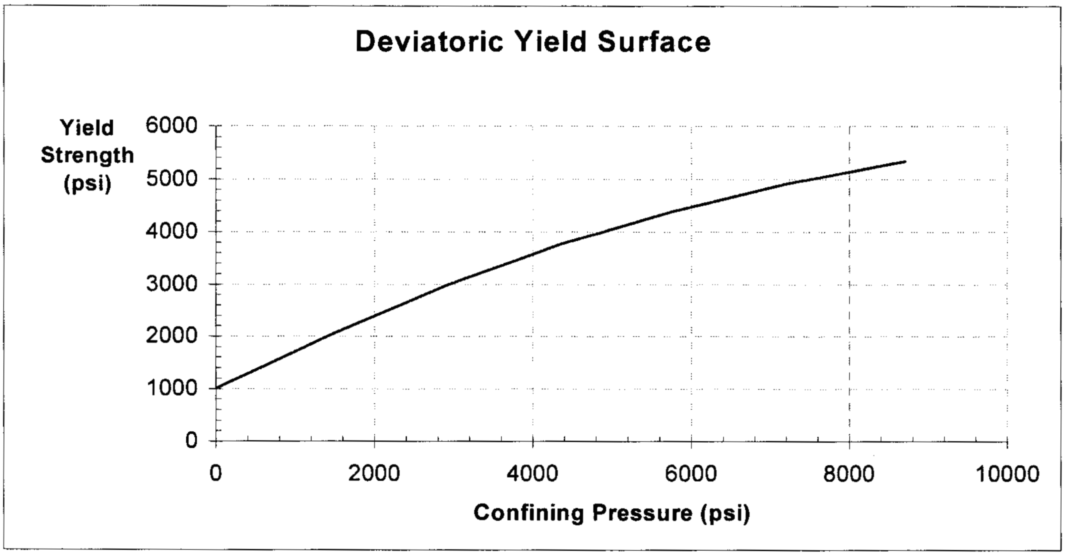


**Figure 2.1. Shear Behavior of Sandstone at the Site of the PSA Crash.**

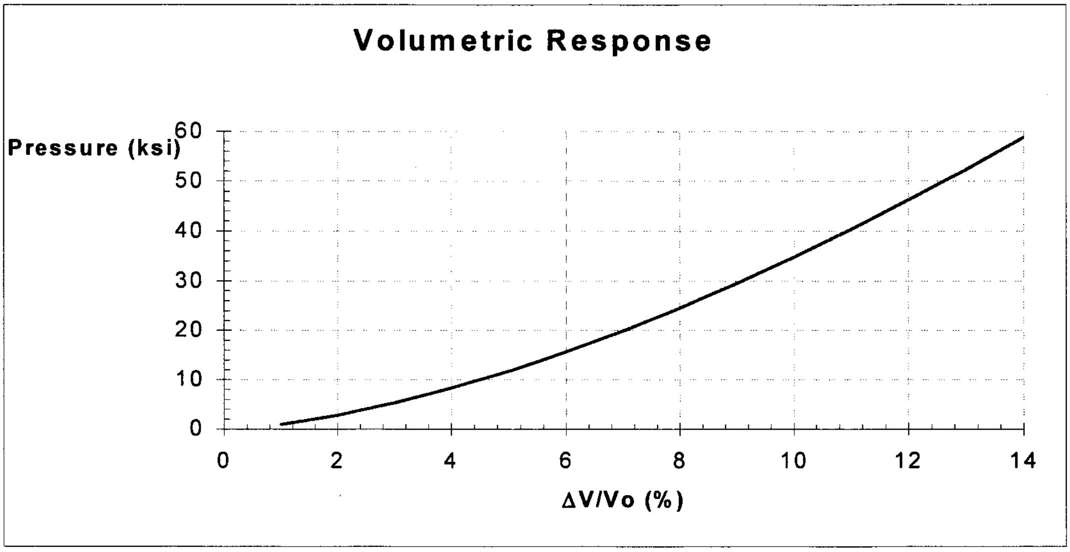


**Figure 2.2. Volumetric Response of Sandstone at the Site of the PSA Crash.**

In order to obtain these behaviors, a concrete mix with the following proportions was designed:

Sand – 2366 lb
Cement – 470 lb
Air entrainment – 17 oz
Water – 375 lb

The lack of coarse aggregate achieved the desired low unconfined crush strength and shear behavior that simulates sandstone. The air entrainment admixture was included to achieve the correct hydrostatic behavior because sandstone has a relatively large void volume.

# 3. PMATP-CTU1

## 3.1 PMATP-CTU1 Package Description

A calibration test was performed to ensure proper acceleration, velocity, and associated sled hardware performance. To take advantage of the calibration test data, a low-fidelity test unit was prepared in lieu of accelerating a simple mass with the proper weight and geometry.

The PMATP calibration test unit (CTU) was a right circular cylinder. PMATP-CTU1 was 15 inches in diameter by 30 inches long and weighed approximately 256 lb. This package, as shown in Figure 3.1, had an inner containment vessel 3.5 inches in diameter by 11.8 inches long with a 0.5-inch wall thickness and was constructed of S13-8 H1100 stainless steel. The containment vessel was filled with No. 6 steel shot to simulate mass as shown in Figure 3.2.

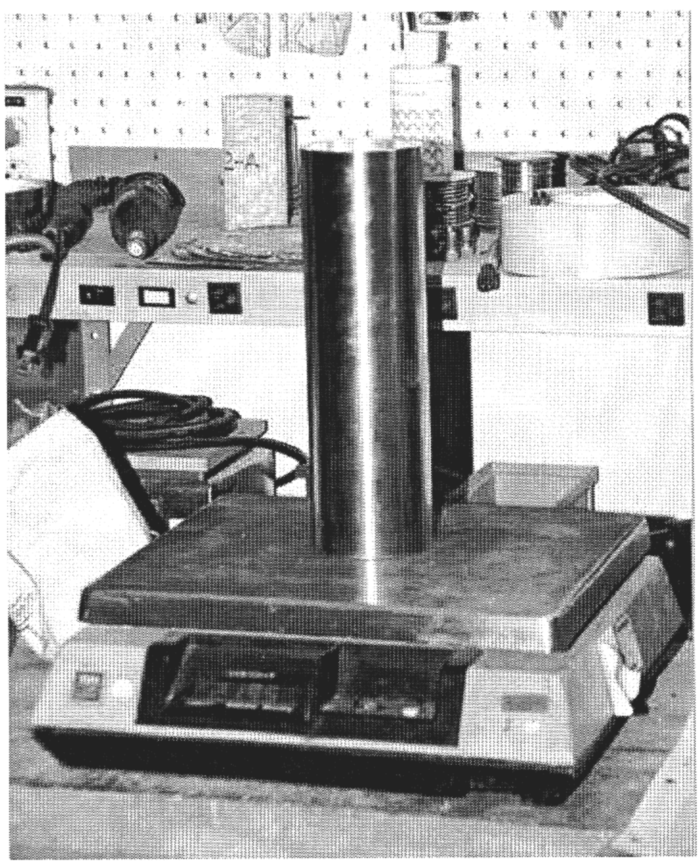

**Figure 3.1. PMATP-CTU1 Inner Containment Vessel.**

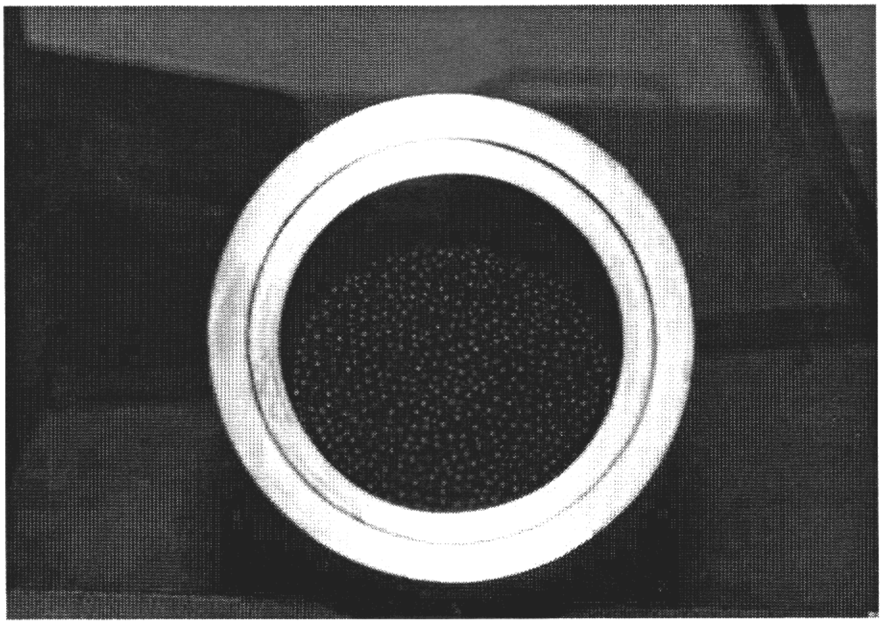

**Figure 3.2. PMATP-CTU1 Inner Containment Vessel Loaded with Steel Shot.**

The PMATP CTU was prepared in much the same way as the actual prototypes. The major differences were the inner tube, the outer shell, and the end plugs. The inner tube was a single-diameter tube that extended the full length of the package. The end plugs were 0.032-inch thickness of perforated aluminum rolled to 3.5-inch diameter. The outer shell and end plates were made from 0.125-inch mild steel.

The 16-gauge 304 stainless-steel inner tube was wrapped with perforated aluminum sheet and Kevlar™ cloth as shown in Figure 3.3. The wrap cycles included three wraps of perforated aluminum sheet and two wraps of perforated aluminum with Kevlar™ cloth. The perforated aluminum was 0.032-inch-thick 3003-H14 with a 51% open space made with 0.115-inch-diameter staggered holes 0.117 inch apart. The Kevlar™ cloth was approximately 0.018 inch thick. The containment vessel was placed in the inner tube as shown in Figure 3.4. The end plugs were loaded on each end of the inner containment vessel inside the inner tube as shown in Figure 3.5. The PMATP-CTU1 mild steel outer shell was welded to the outer plates as shown in Figure 3.6.

The PMATP-CTU1 prototype was painted white with red stripes to ensure high-quality photometrics (Figure 3.7). The paint scheme included one-inch red stripes every 90° the length of the package and a one-inch red-stripe cross on each end.

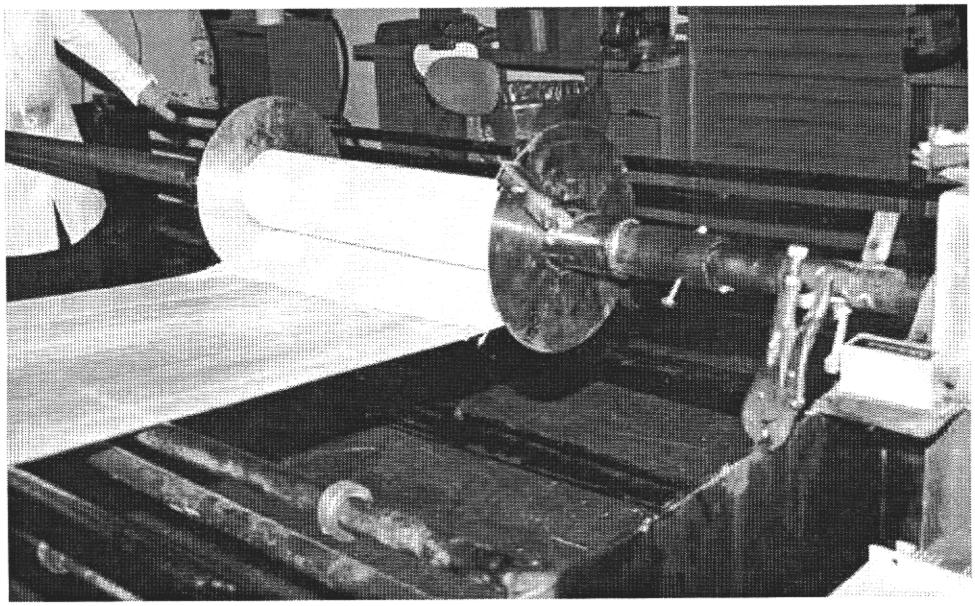

Figure 3.3. Wrapping of PMATP-CTU1 Overpack.

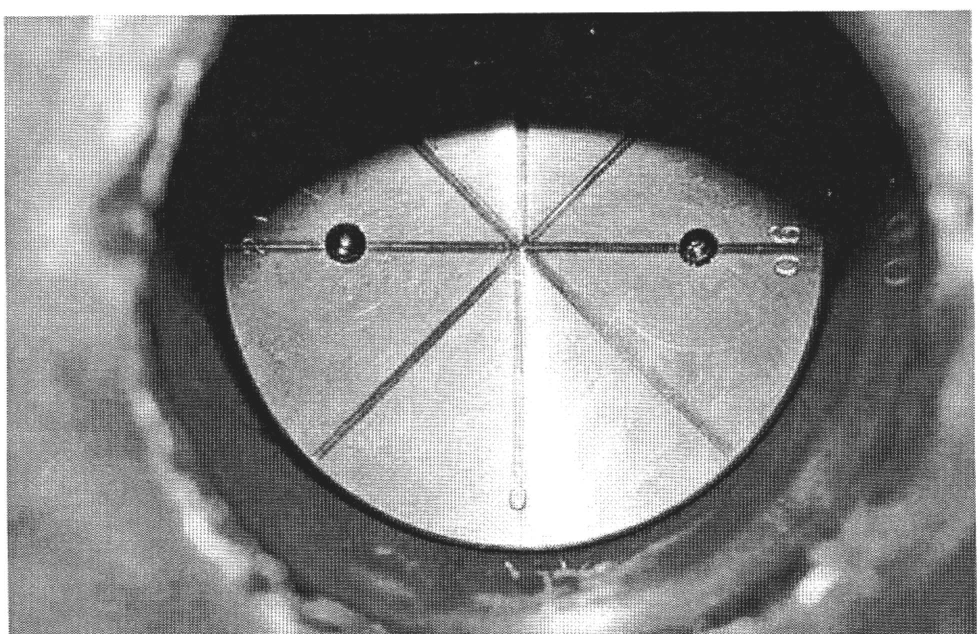

Figure 3.4. PMATP-CTU1 Inner Tube.

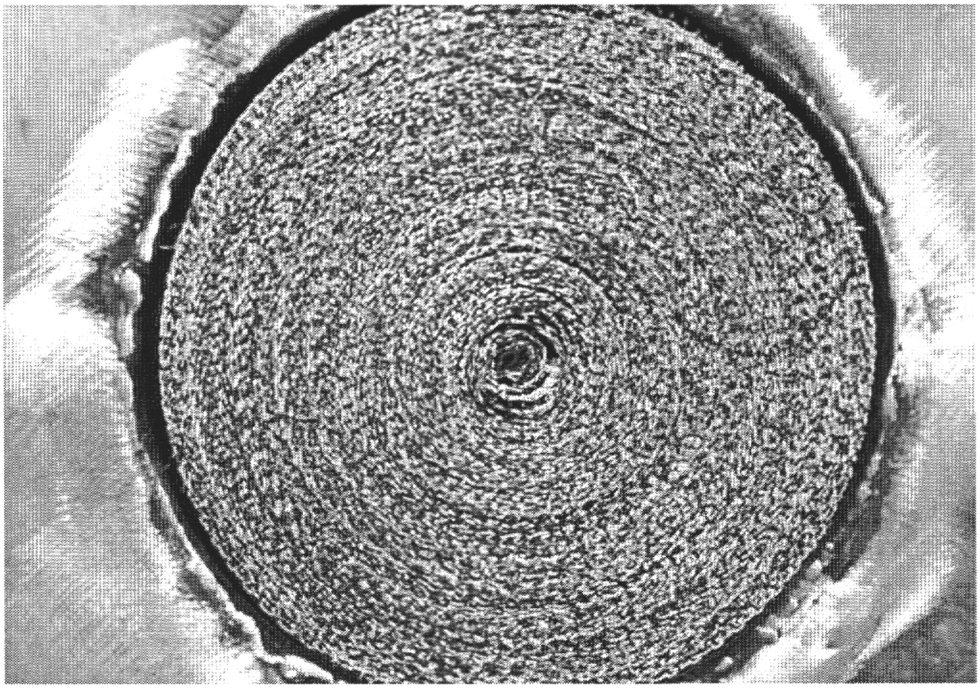

**Figure 3.5. PMATP-CTU1 End Plugs.**

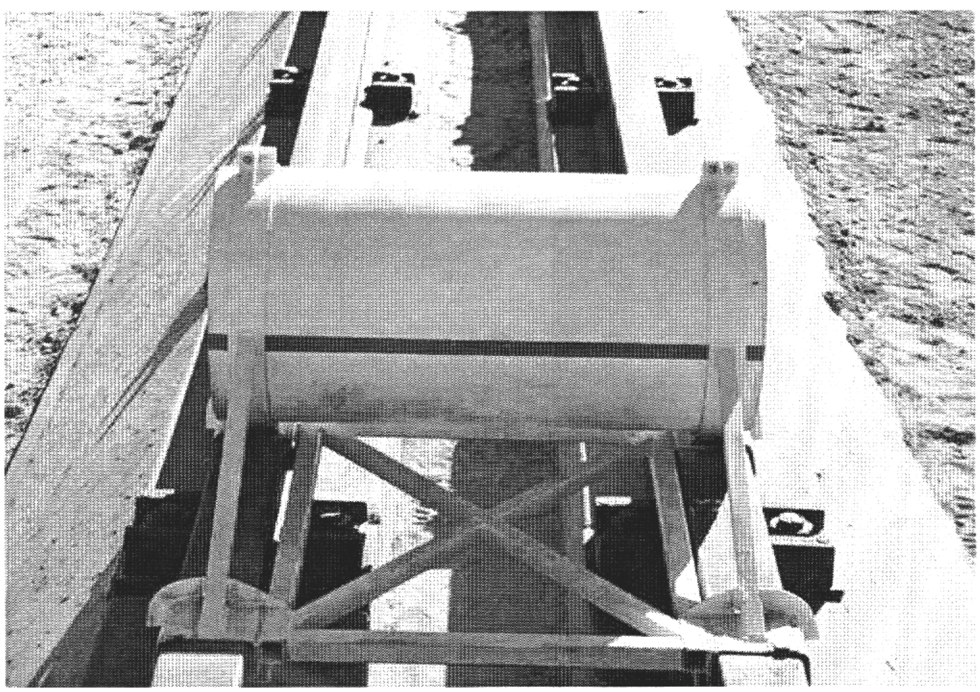

**Figure 3.6. PMATP-CTU1 Overpack Body.**

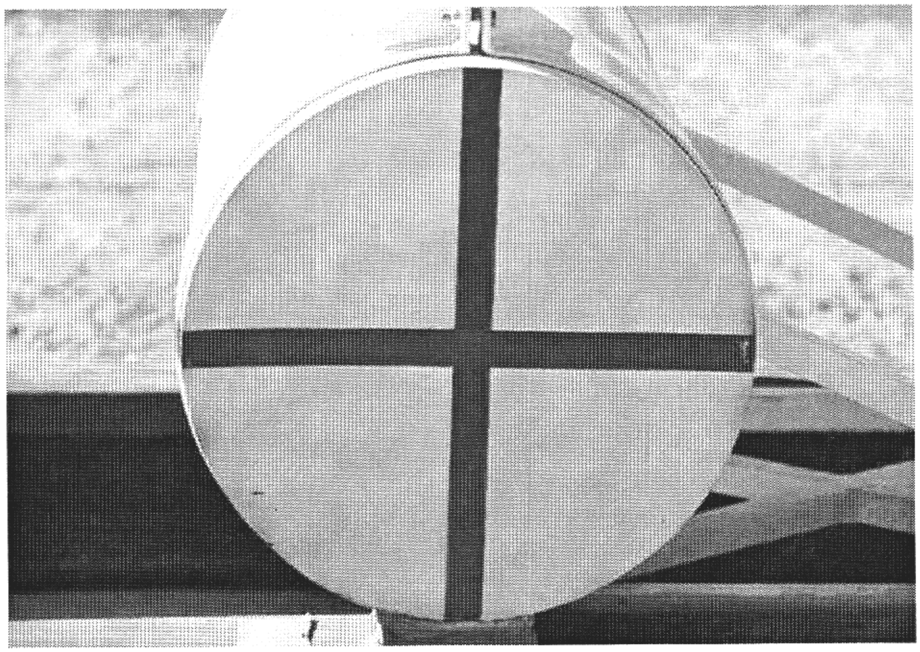

**Figure 3.7. End View of Assembled PMATP-CTU1.**

## 3.2 PMATP-CTU1 Target Description

The target for the PMATP-CTU1 consisted of three concrete blocks placed side by side on the track as shown in Figure 3.8. Each block was approximately a 60-inch cube. The total weight of the three blocks was approximately 50,000 lb.

## 3.3 PMATP-CTU1 Test Requirements

The PMATP-CTU test was a calibration side-on impact test. The desired velocity for this test was 925 ft per second (ft/s) (282 meters per second [m/s]) at impact. To achieve this velocity, the package was accelerated to provide a velocity greater than 1400 ft/s before sled braking and allowing the package to glide to the target for impact at the desired velocity.

The calibration side-on impact test required that the package be oriented horizontally across the sled track in order to impact the 0° side of the PMATP-CTU1 into the center of the target.

### 3.3.1 Test Facility

The 10,000-ft rocket sled test facility at SNL Tech Area III is a two-rail system as shown in Figure 3.9. The area between the rails is filled with water dams of increasing depth to gently stop the first-stage pusher sled. The first-stage pusher sled consists of the rocket mounting area, pusher saddles, and a water-brake chute as shown in Figure 3.10.

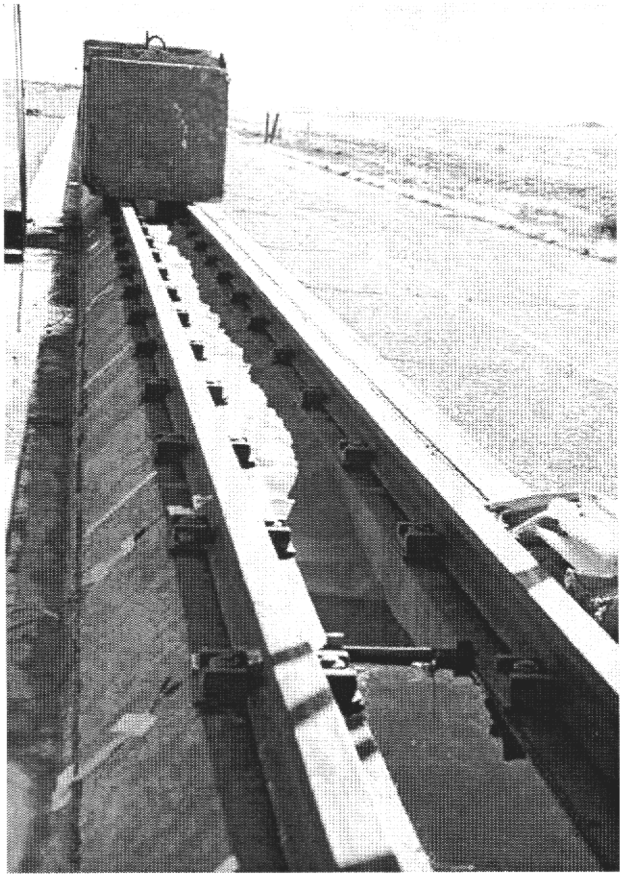

**Figure 3.8. Calibration Test Unit Target.**

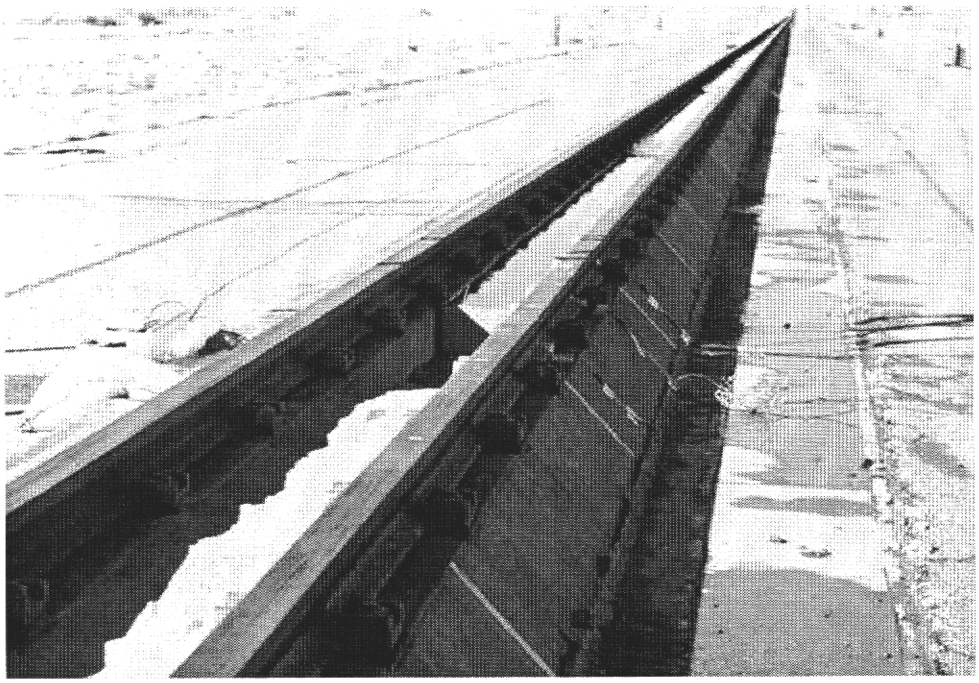

**Figure 3.9. Rocket Sled Test Facility.**

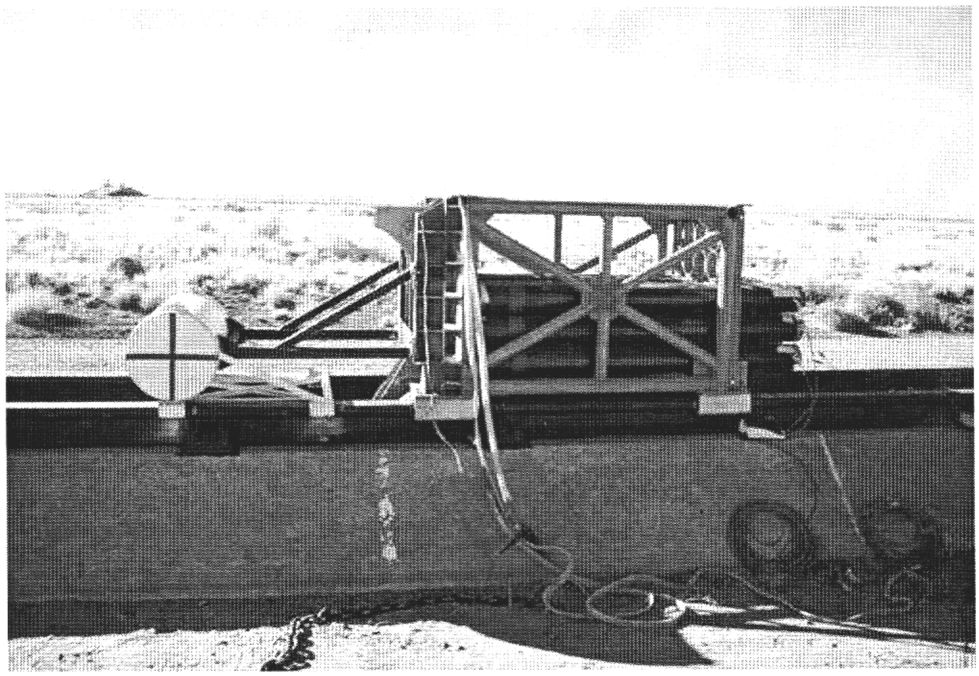

**Figure 3.10. PMATP-CTU1 First-Stage Pusher Sled.**

The test setup for the calibration test was very similar to that of the actual side-on impact test, the principal difference being the target. The test unit was supported above the track on a separate expendable sled. This second-stage sled was propelled along the track by a first-stage pusher sled containing 14 Zuni rockets. At burnout of the first-stage rocket motors, the first-stage pusher sled was slowed by water braking, at which time the second-stage sled separated and coasted along the track to the target.

### 3.3.2 Photometrics

Pre- and post-test documentary photographs were taken. These included 35-mm still photographs of the test site, the equipment, and the instrumentation to be used: fixtures, hardware, and rigging needed for the test. The top, bottom, and all four sides of the test package were photographed before the test and again after the test.

High-speed cameras were positioned for a side view of the container to determine the impact velocity. The test setup is shown in Figure 3.11.

A laser tracker was positioned to track the package during the test to accurately determine package location and velocity throughout the test. The laser tracker locked onto a reflective marker located on the package, and thus followed the package throughout the test. High-speed cameras were mounted onto the tracking platform to provide additional photometric documentation of the test.

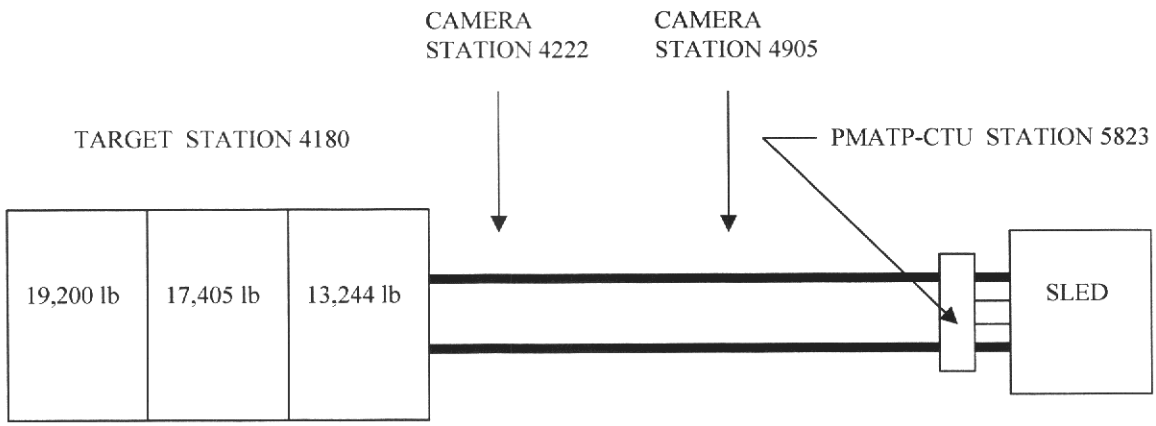


**Figure 3.11. PMATP-CTU1 Test Setup.**

### 3.3.3 Inspection Measurements

The inner containment vessel was inspected by SNL personnel before assembly for pretest measurements and again after disassembly for post-test measurements. Diameters were measured at 0° – 180°, 45° – 225°, 90° – 270°, and 135° – 315°.

The closure was measured at one location on the largest shoulder diameter. The container body was measured at five locations including the top, midway between top and center, center, midway between center and bottom, and bottom. Lengths were measured every 45° with and without the closure installed.

### 3.3.4 Test Unit Weight Measurements

The weights of various components were documented before the impact test. The inner containment vessel was weighed empty and after the steel shot mass was loaded. The overpack body, End Plug 1, and End Plug 2 were weighed before assembly. The total package was weighed after final assembly of the test unit.

## 3.4 PMATP-CTU1 Test Results

### 3.4.1 Calibration Test (Side-on Impact)

The test article was configured for a side-on impact test of 925 ft/s (282 m/s). The as-tested weight of the test article was 256 lb as listed in Table 3.1. The first-stage pusher sled weighed 1809 lb with rockets, and the total weight of the second-stage sled and test package was 293 lb. The test unit was launched from Station 5823, and the target was placed at Station 4180 for a travel distance of 1643 ft.

**Table 3.1. PMATP-CTU1 Weight Measurements (lb)**

| | |
|---|---|
| Containment vessel empty | 16.75 |
| Containment vessel full | 23.00 |
| Overpack body | 230.90 |
| End Plug 1 | 1.00 |
| End Plug 2 | 1.10 |
| Total assembled weight | 256.00 |
| Target weight | 50,000.00 |

Figures 3.12 through 3.16 show the PMATP-CTU1 being prepared for the side-on impact test.

The PMATP-CTU1 calibration test was performed on January 12, 1999, at 3:19 p.m., Mountain Standard Time. The rockets fired as desired, and the first-stage pusher sled accelerated the second-stage guide sled and package as expected. The package impacted in the desired orientation (at 0° from the target) at a velocity of 1028 ft/s. The impact velocity was determined by averaging the data from the following two methods:

| Method | Velocity (ft/s) |
|---|---|
| Laser tracker | 1030 |
| Timing switches | 1025 |

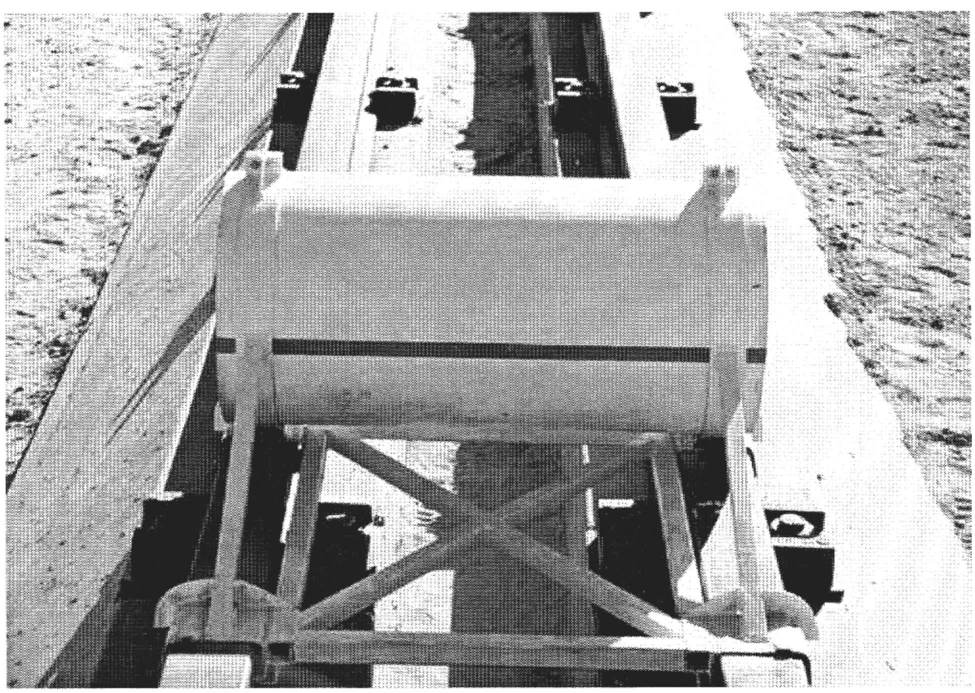

**Figure 3.12. PMATP-CTU1 Mounted in Stage 2 Guide Sled.**

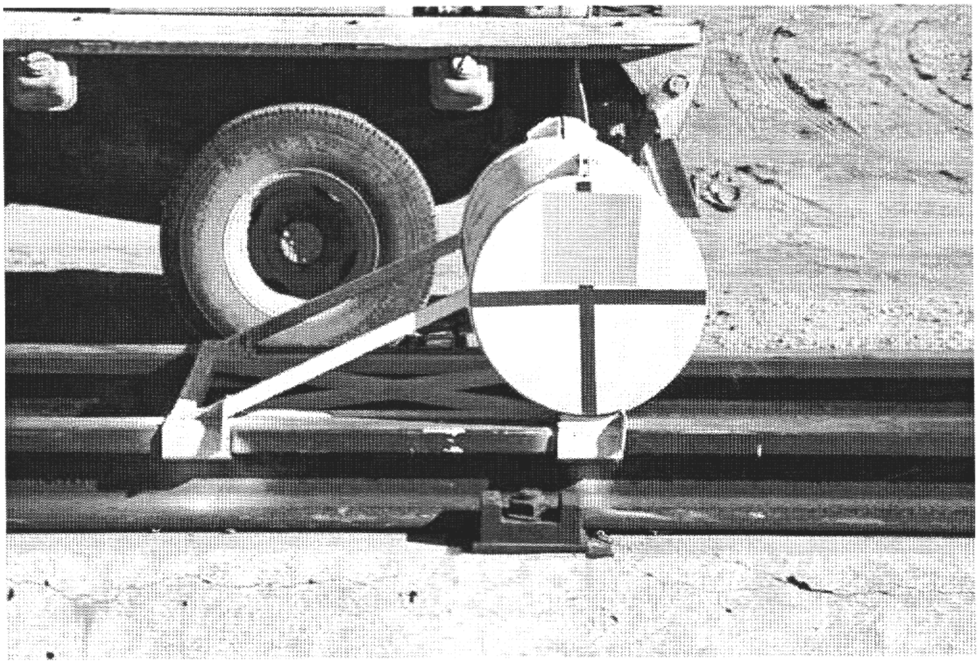

Figure 3.13. PMATP-CTU1 Reflective Marker for Laser Tracker.

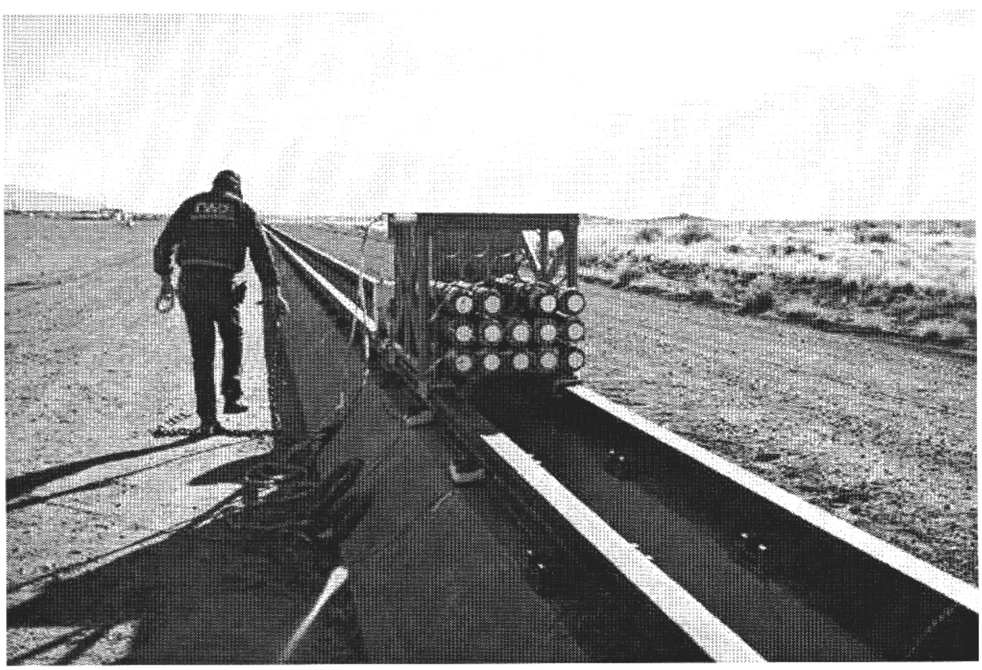

Figure 3.14. PMATP-CTU1 Stage 1 Rocket Sled with 14 Zuni Rockets.

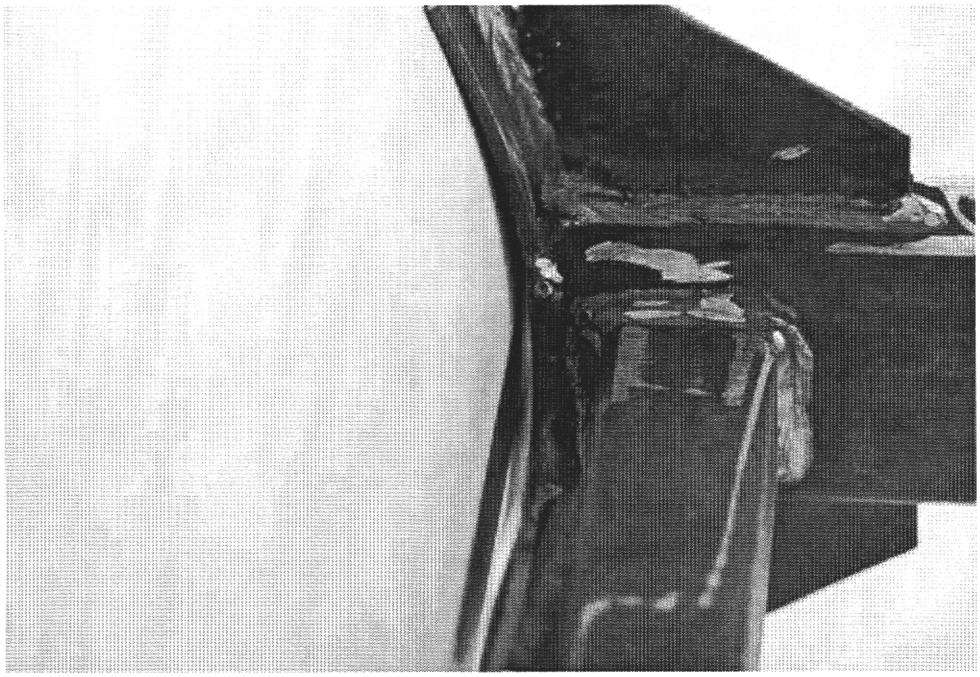

**Figure 3.15. PMATP-CTU1 Stage 1 Pusher Sled to Stage 2 Guide Sled Interface.**

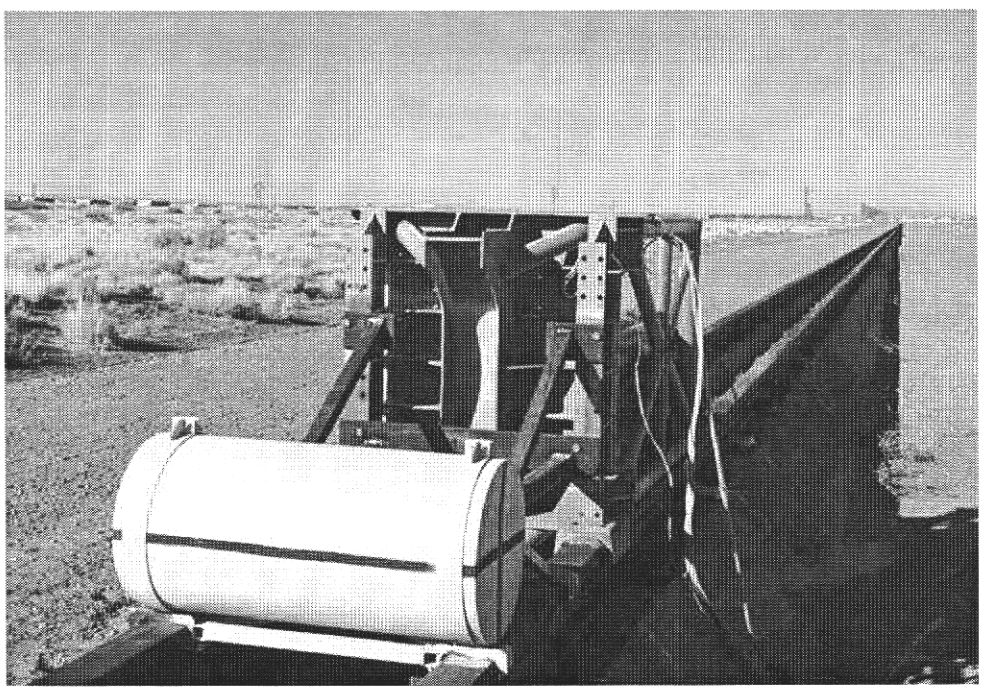

**Figure 3.16. PMATP-CTU1 Ready for Test.**

Figure 3.17 illustrates the test unit and target following the impact test. The package skin ruptured the full length opposite the impact side and at the welded seam as shown in Figure 3.18. The welded end caps were also sheared from the overpack body as shown in Figure 3.19. Damage of this type was anticipated for this low-fidelity unit because of the extra mass in the overpack steel. The actual velocity for this unit was 100 ft/s faster than planned. As a result, the package was subjected to approximately 24% more energy than planned for the later test units.

**Figure 3.17. PMATP-CTU1 Test Article and Target After Impact Test.**

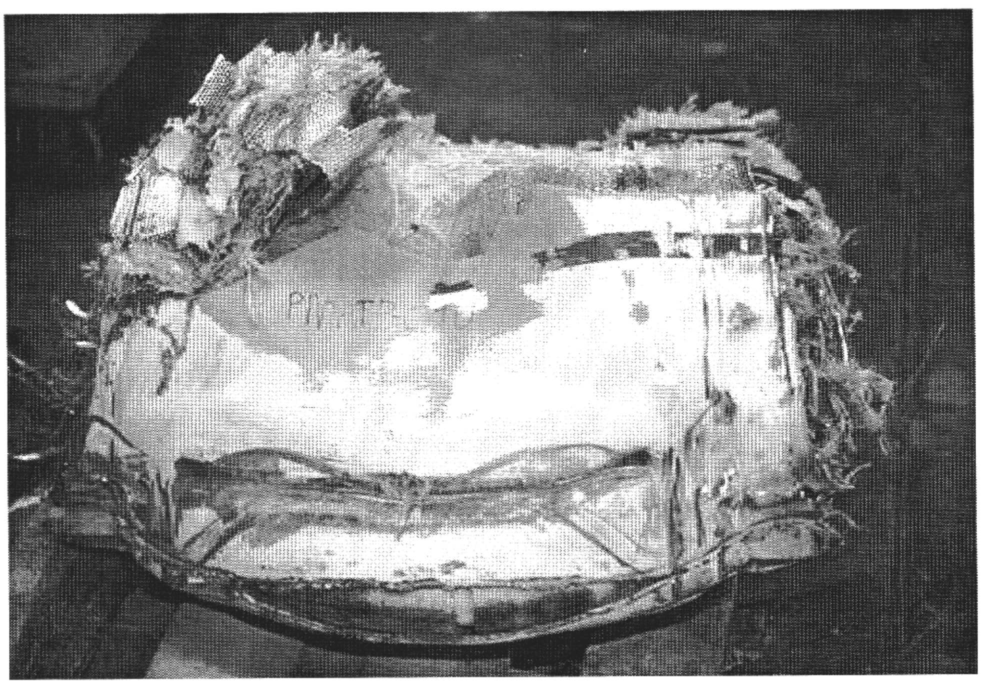

**Figure 3.18. PMATP-CTU1 Ruptured Skin.**

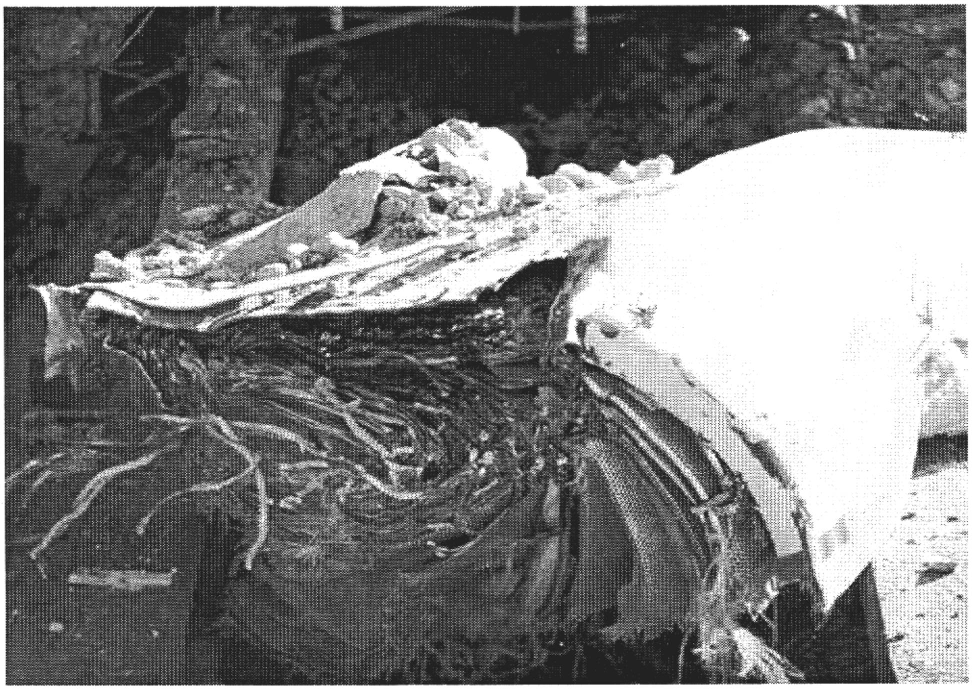

**Figure 3.19. PMATP-CTU1 Exposed Ends.**

The test conditions for the side-on calibration test are documented in Table 3.2.

**Table 3.2. Test Conditions for Side-on Calibration Test**

| | |
|---|---|
| Temperature | 57.3° F at 15:19 |
| Lighting | Full sun |
| Wind direction | Out of northwest |
| Wind velocity | 5.1 mph |
| Number of rockets | 14 Zuni rockets |

# 3.5 PMATP-CTU1 Disassembly and Evaluation

After the side-on impact test, the PMATP-CTU1 was retrieved for disassembly and evaluation. The weight of the unit was measured to be 232 lb including some guide carriage hardware.

The inner containment vessel remained intact and within the overpack. The inner containment vessel was removed from the overpack for inspection. The inner containment vessel deformed as shown in Figure 3.20. Physical dimensions of the inner containment vessel are documented in Tables 3.3 and 3.4. The closure was not removed from the container body; therefore, there are no post-test length measurements without the closure.

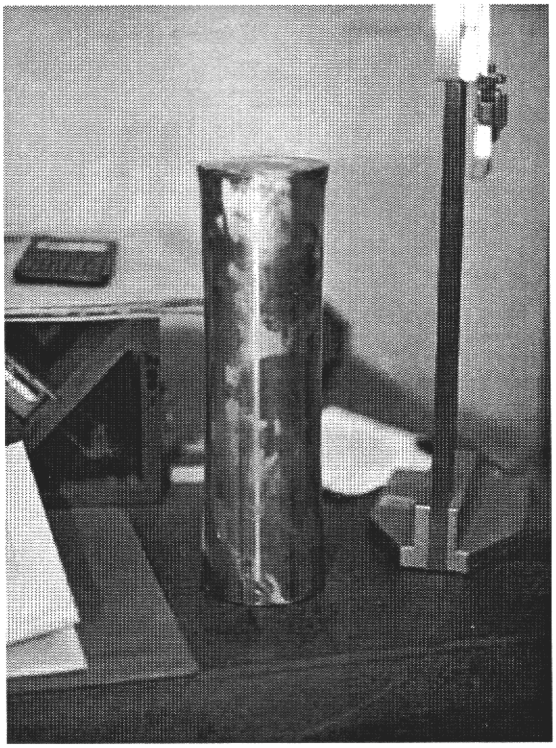

**Figure 3.20. Inner Containment Vessel Deformation.**

**Table 3.3. PMATP-CTU1 Inspection Measurement Lengths (inches)**

| | L0° | L45° | L90° | L135° | L180° | L225° | L270° | L315° |
|---|---|---|---|---|---|---|---|---|
| Pre no lid | 11.672 | 11.671 | 11.670 | 11.671 | 11.671 | 11.671 | 11.671 | 11.671 |
| Post no lid | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Difference (no lid) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Pre w/lid | 11.797 | 11.797 | 11.795 | 11.797 | 11.798 | 11.797 | 11.797 | 11.796 |
| Post w/lid | 11.844 | 11.844 | 11.835 | 11.825 | 11.800 | 11.800 | 11.825 | 11.836 |
| Difference (w/lid) | +.047 | +.047 | +.040 | +.028 | +.002 | +.003 | +.028 | +.040 |

**Table 3.4. PMATP-CTU1 Inspection Measurement Diameters (inches)**

| | D0° – 180° | D45° – 225° | D90° – 270° | D135° – 315° |
|---|---|---|---|---|
| Pre closure | 3.500 | 3.500 | 3.500 | 3.500 |
| Post closure | 3.498 | 3.500 | 3.502 | 3.502 |
| Difference (closure) | –.002 | 0 | +.002 | +.002 |
| Pre body top | 3.500 | 3.500 | 3.501 | 3.501 |
| Post body top | 3.475 | 3.472 | 3.602 | 3.550 |

**Table 3.4. PMATP-CTU1 Inspection Measurement Diameters (inches) (continued)**

| | D0° – 180° | D45° – 225° | D90° – 270° | D135° – 315° |
|---|---|---|---|---|
| Difference (body top) | –.025 | –.028 | +.101 | +.049 |
| Pre body TC (top, center) | 3.500 | 3.500 | 3.500 | 3.502 |
| Post body TC | 3.270 | 3.363 | 3.688 | 3.594 |
| Difference (body TC) | –.230 | –.137 | +.188 | +.092 |
| Pre body center | 3.500 | 3.499 | 3.500 | 3.500 |
| Post body center | 3.200 | 3.325 | 3.738 | 3.612 |
| Difference (body center) | –.300 | –.174 | +.238 | +.112 |
| Pre body CB (center, bottom) | 3.501 | 3.500 | 3.500 | 3.501 |
| Post body CB | 3.305 | 3.387 | 3.658 | 3.581 |
| Difference (body CB) | –.196 | –.113 | +.158 | +.080 |
| Pre body bottom | 3.500 | 3.501 | 3.501 | 3.501 |
| Post body bottom | 3.495 | 3.499 | 3.502 | 3.501 |
| Difference (body bottom) | –.005 | –.002 | +.001 | 0 |

## 3.6 PMATP-CTU1 Conclusions

A half-scale, low-fidelity plutonium air-transportable package calibration test unit identified as PMATP-CTU1 was successfully tested at the Full-Scale Experimental Complex 10,000-ft sled track in SNL's Tech Area III Test Facility. The PMATP-CTU1 was subjected to a side-on orientation impact test as specified in the Murkowski Amendment.

Lessons learned from this calibration test include modifying trajectory calculations and optimizing the overpack design. This test clearly demonstrated the viability of perforated aluminum sheet and Kevlar™ cloth as an excellent energy-absorbing overpack material.

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# 4. PMATP-SO1

## 4.1 PMATP-SO1 Package Description

The PMATP Side-on (SO) prototype is a right circular cylinder. The PMATP-SO1 was 15 inches in diameter by 30 inches long and weighed 256 lb. This package had an inner containment vessel 3.5 inches in diameter by 11.8 inches long with a 0.5-inch wall thickness and was made of S13-8 H1100 stainless steel as shown in Figure 4.1. The containment vessel was filled with No. 6 steel shot to simulate mass and is shown in Figure 4.2.

**Figure 4.1. PMATP-SO1 Inner Containment Vessel.**

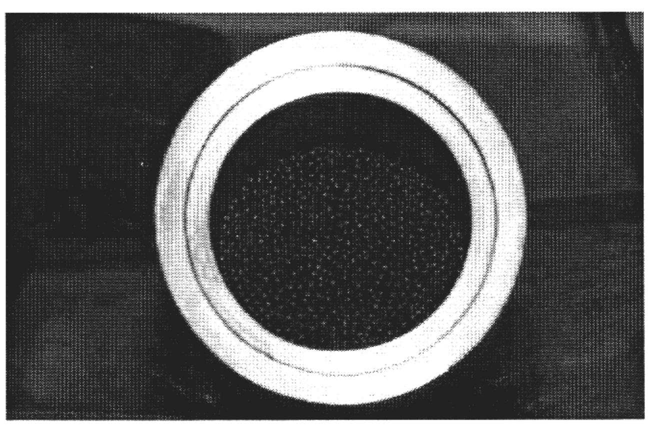

**Figure 4.2. PMATP-SO1 Inner Containment Vessel Loaded with Steel Shot.**

The containment vessel was placed in a two-step 16-gauge 304 stainless-steel inner tube as shown in Figure 4.3. The inner tube was wrapped with perforated aluminum sheet and Kevlar™ cloth as shown in Figure 4.4. The wrap cycles include three wraps of perforated aluminum sheet and two wraps of perforated aluminum with Kevlar™ cloth. The perforated aluminum was 0.032-inch-thick 3003-H14 with a 51% open space made with 0.115-inch-diameter staggered holes 0.117 inch apart. The Kevlar™ cloth was approximately 0.018 inch thick. The PMATP-SO1 had a 16-gauge 304 stainless-steel outer shell welded to the outer plates of the inner tube as shown in Figure 4.5.

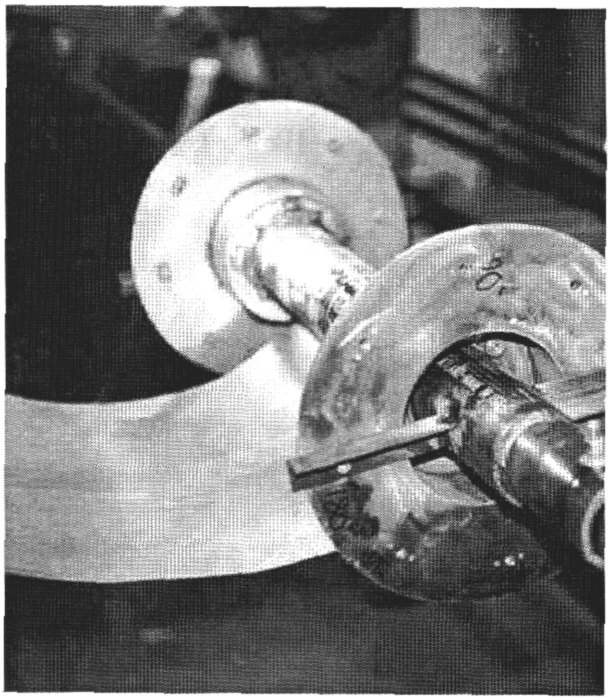

**Figure 4.3. PMATP-SO1 Inner Tube.**

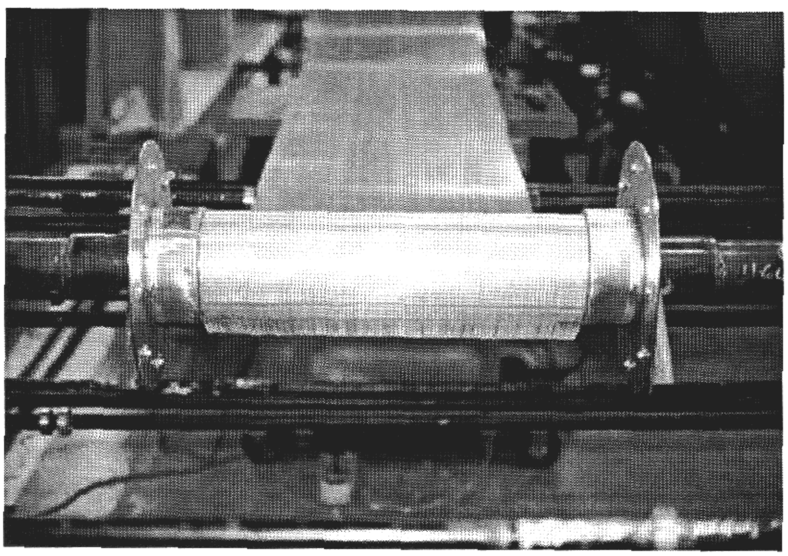

**Figure 4.4. Wrapping of PMATP-SO1 Overpack.**

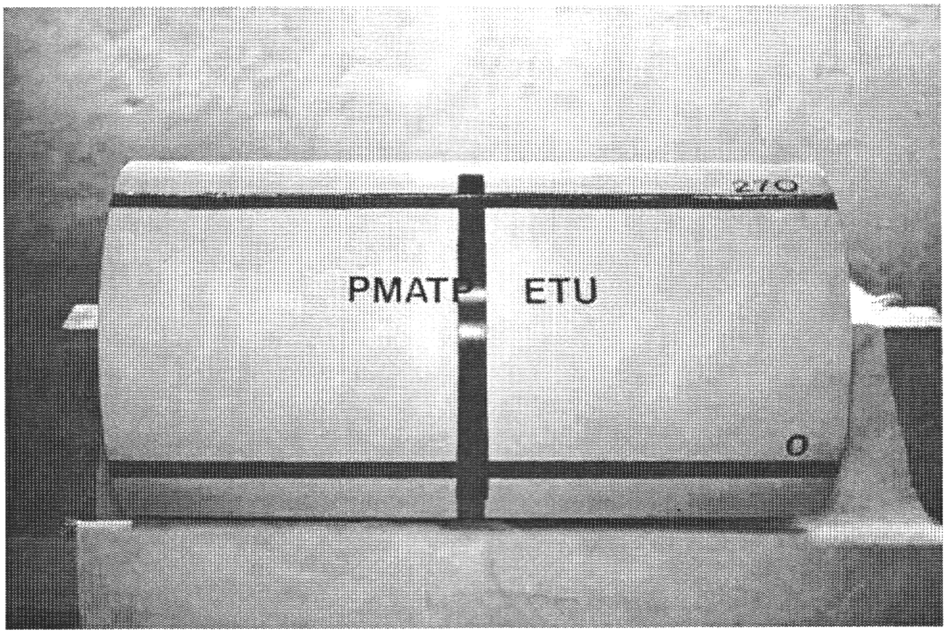


**Figure 4.5. PMATP-SO1 Overpack Body.**

The PMATP-SO1 had two end plugs made of 16-gauge 304 stainless-steel as shown in Figure 4.6. The end plugs were filled with three 3003-H14 0.063-inch perforated aluminum discs stacked as shown in Figures 4.7 through 4.9. The end plugs had a 16-gauge 304 stainless-steel outer plate welded to completely enclose the packing materials as shown in Figure 4.10.

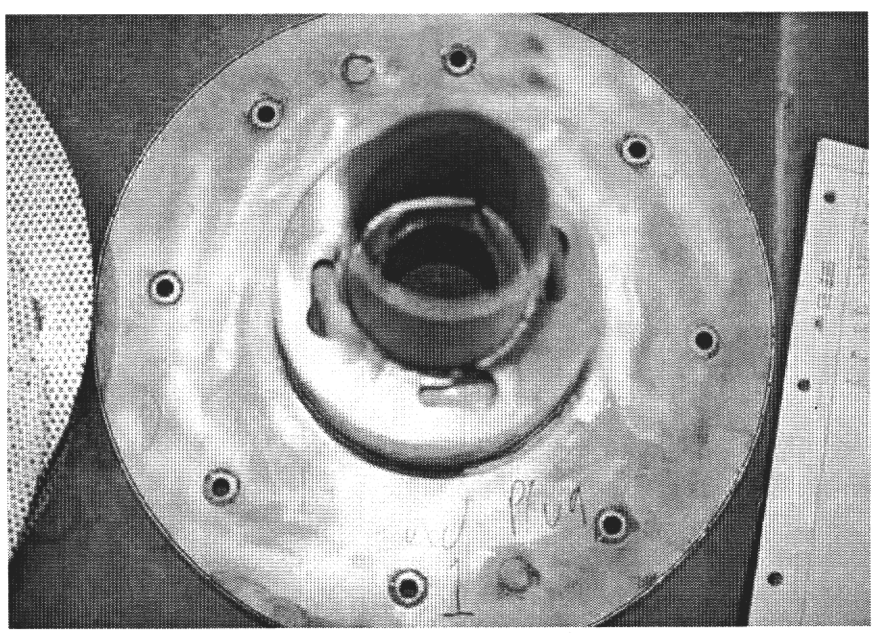

**Figure 4.6. PMATP-SO1 End Plugs.**

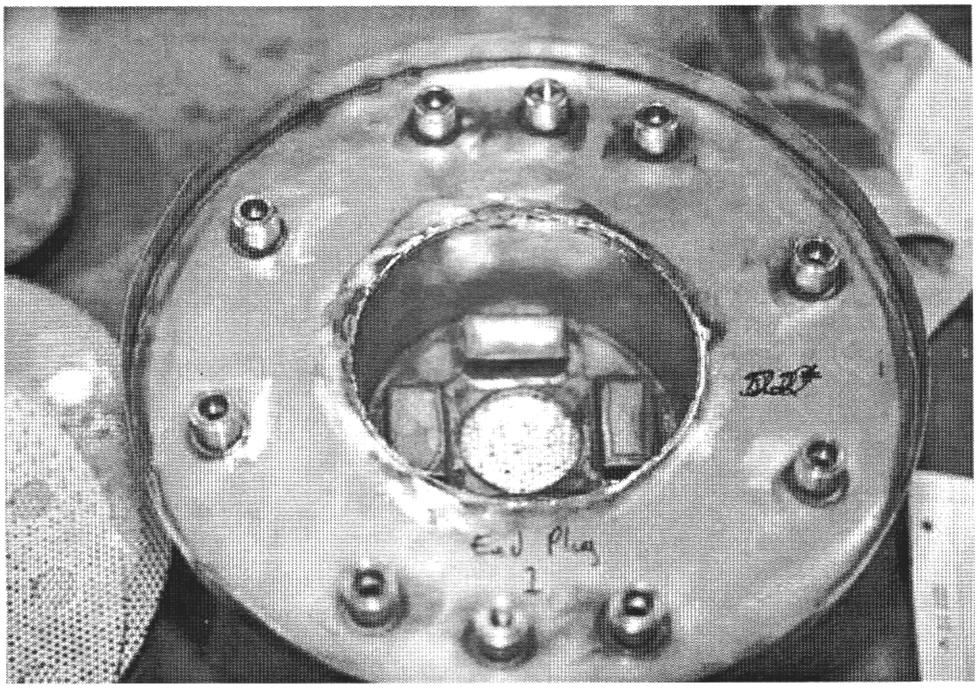


**Figure 4.7. PMATP-SO1 Packing of End Plugs (Small Diameter).**

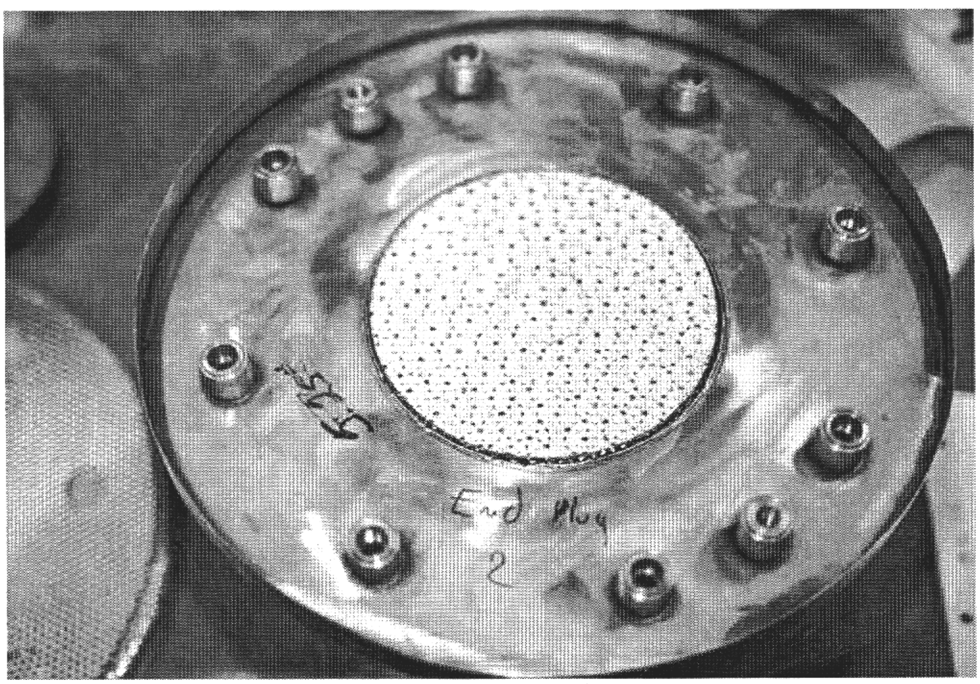


**Figure 4.8. PMATP-SO1 Packing of End Plugs (Medium Diameter).**

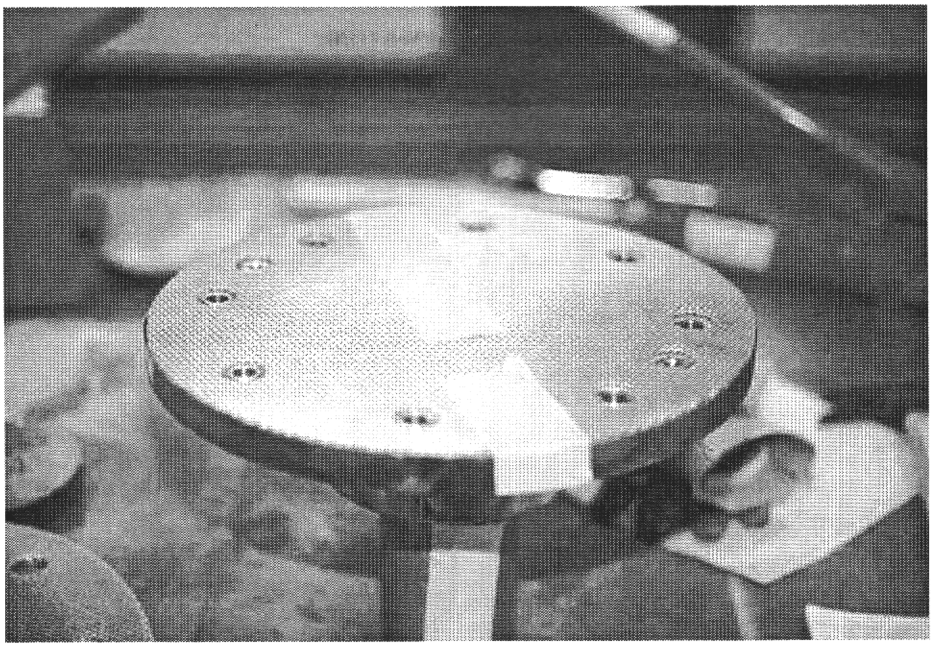

**Figure 4.9. PMATP-SO1 Packing of End Plugs (Large Diameter).**

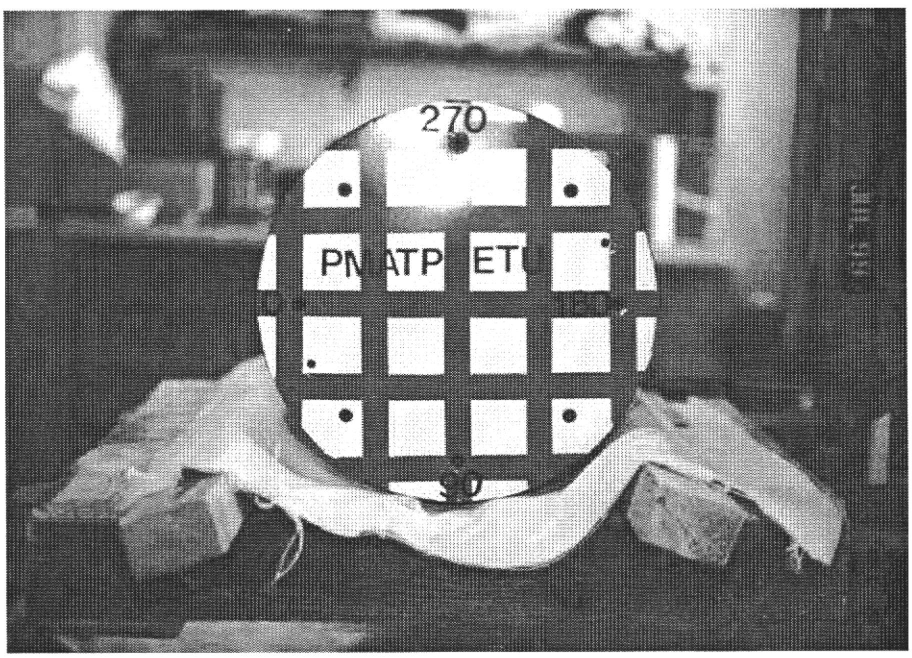


**Figure 4.10. PMATP-SO1 Welded End Plug.**

The inner containment vessel was loaded in the inner tube of the overpack body as shown in Figure 4.11. Each end plug was assembled to the overpack body with four tee slots and buttons as shown in Figure 4.12. The end plug was rotated 15° and locked with eight bolts as shown in Figure 4.13.

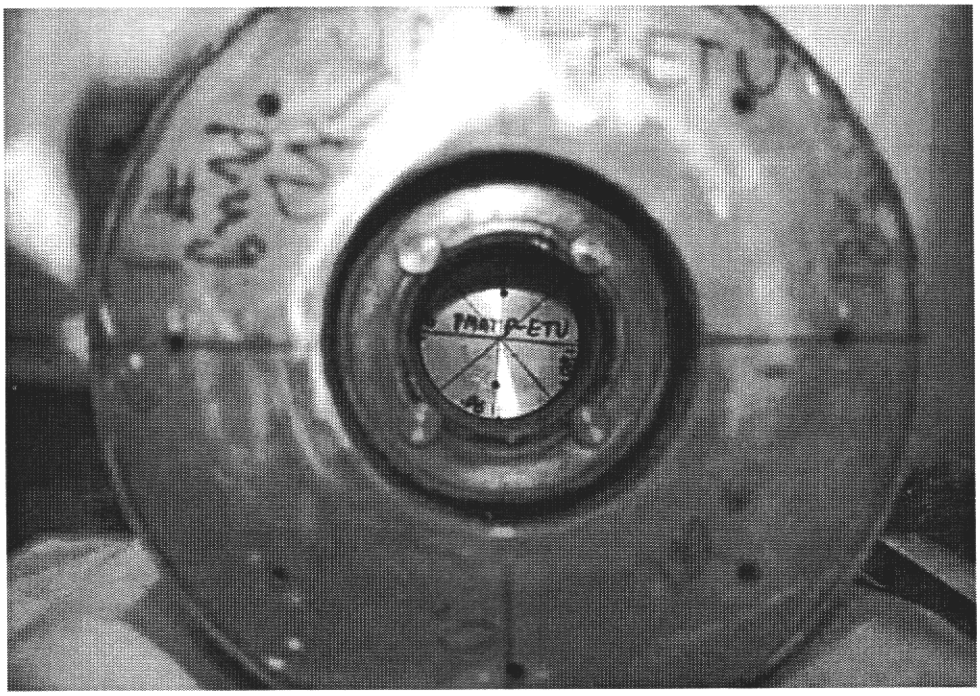


**Figure 4.11. Loading of Inner Containment Vessel.**

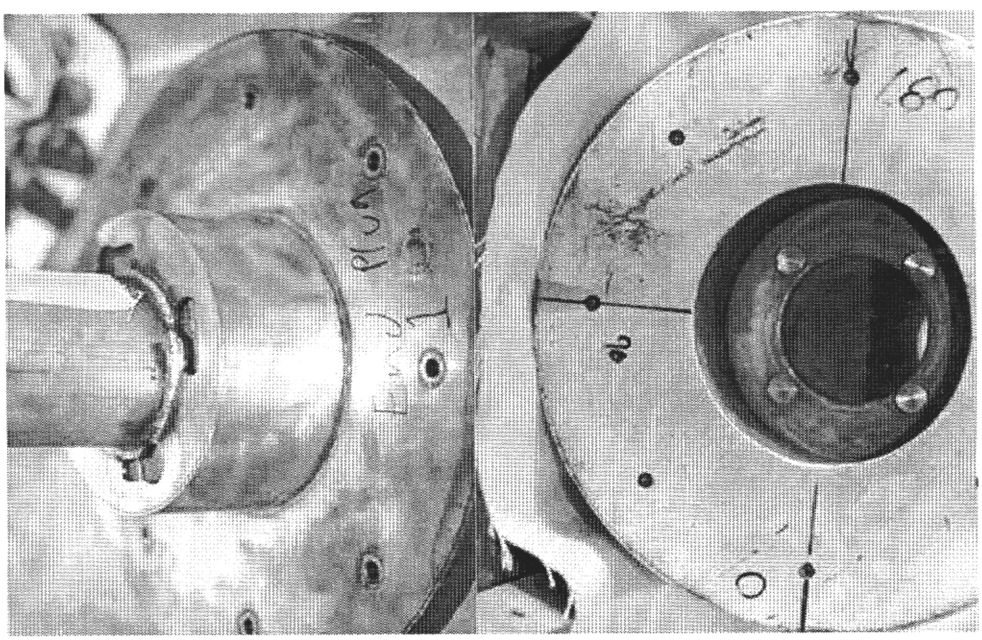

**Figure 4.12. PMATP-SO1 Tee Slots and Buttons.**

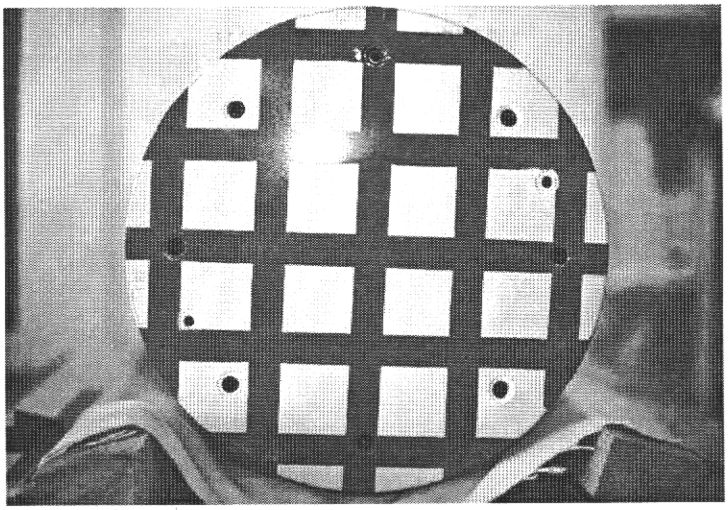

**Figure 4.13. End View of Assembled PMATP-SO1.**

The PMATP-SO1 prototype was painted white with red stripes to ensure high-quality photometrics. The paint scheme included one-inch red stripes every 90° the length of the package and a one-inch red stripe around the circumference at the midpoint of the overpack body. Each end of the PMATP-SO1 had one-inch red stripes painted on three-inch center-to-center in a horizontal and vertical grid pattern.

# 4.2 PMATP-SO1 Target Description

The target shell for PMATP-SO1 prototype consisted of a 0.5-inch-thick mild steel right circular cylinder with a flat bottom as shown in Figure 4.14. The target shell was filled in the vertical position with light-strength concrete (approximately 1200 lb psi).

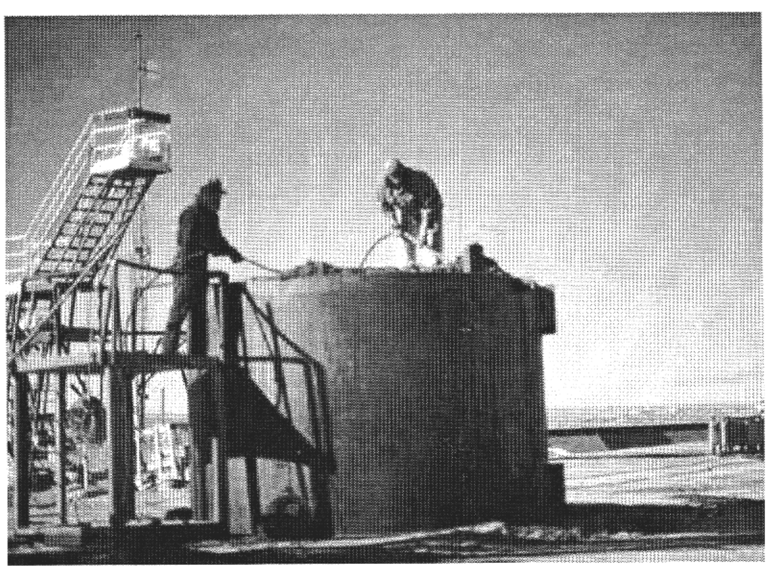

**Figure 4.14. Target Cylinder.**

Five separate batches of concrete were poured into the steel cylinder target as shown in Figure 4.15. Several sample cores, poured from each batch of concrete, were tested for compressive strengths after 7 days, 14 days, 21 days, and the day of the test. Compressive strength tests after a seven-day cure showed the average compressive strength to be in excess of 3000 psi. This was considered to be out of tolerance for the impact test. It was decided to remove a 6-ft-diameter by 18-inch-deep section of the concrete from the center of the impact area as shown in Figure 4.16. This area was repoured with a more precise batch of the light-strength concrete mix as shown in Figure 4.17.


**Figure 4.15. PMATP-SO1 Target Pour.**

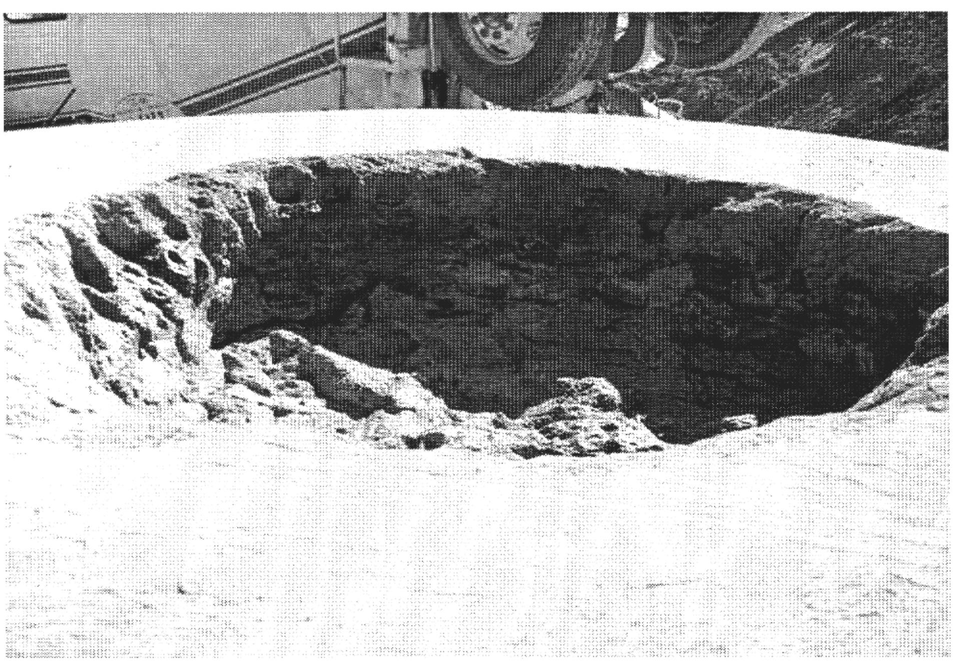

**Figure 4.16. PMATP-SO1 Concrete Removed.**

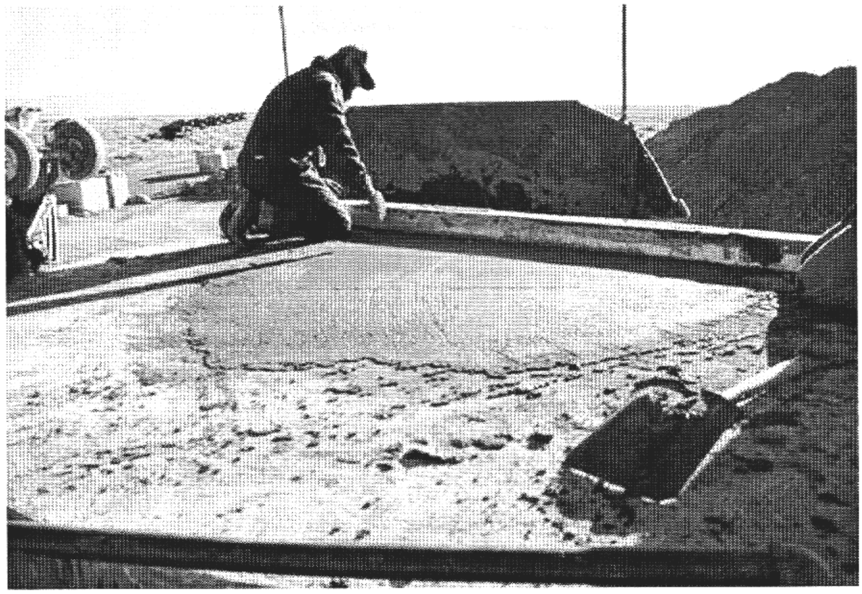

**Figure 4.17. PMATP-SO1 Target Repour.**

The target, shown in Figure 4.18, is 12 ft in diameter by 8 ft long and weighs approximately 140,000 lb after the concrete has cured.

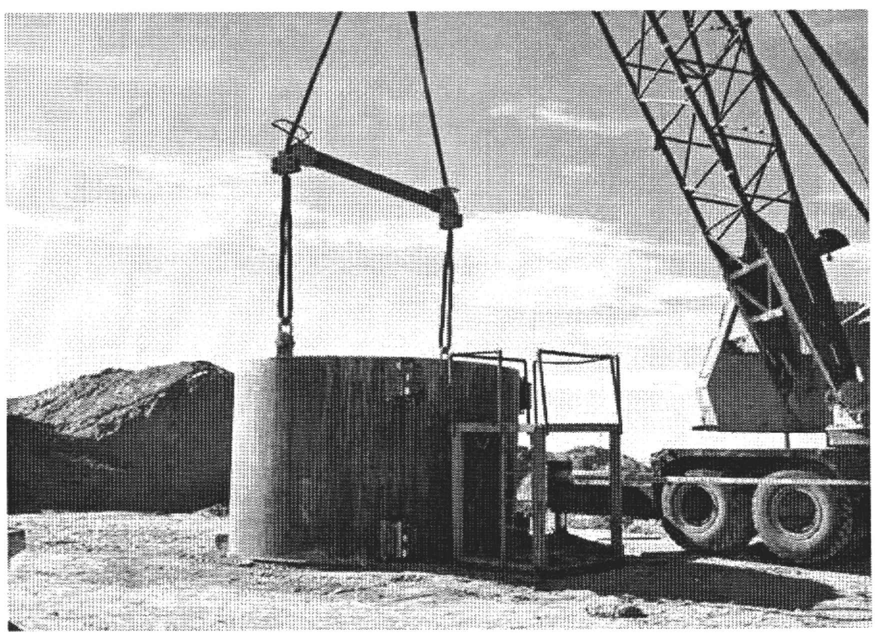

**Figure 4.18. PMATP-SO1 Prototype Target Ready for Rotation.**

The target has four roller bearings mounted to the target cylinder as shown in Figure 4.19. The target was rotated and placed on two I-beam rails as shown in Figures 4.20 through 4.23. The roller bearings allow the target to move along the impact axis.

Figure 4.19. PMATP-SO1 Target Roller Bearings.

Figure 4.20. PMATP-SO1 Target Plate.

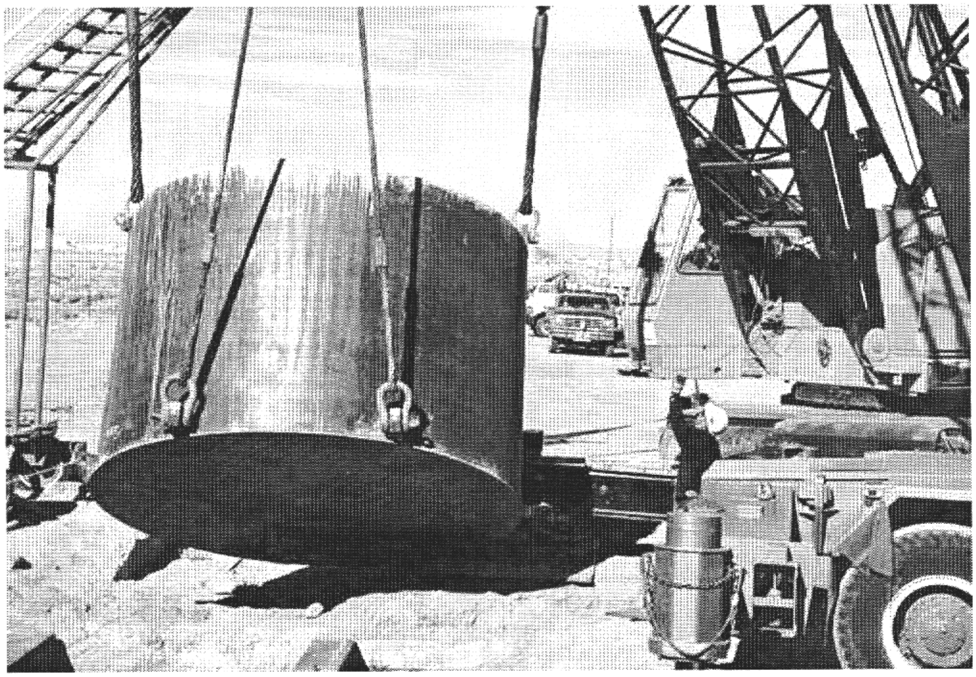

Figure 4.21. PMATP-SO1 Target Rotation.

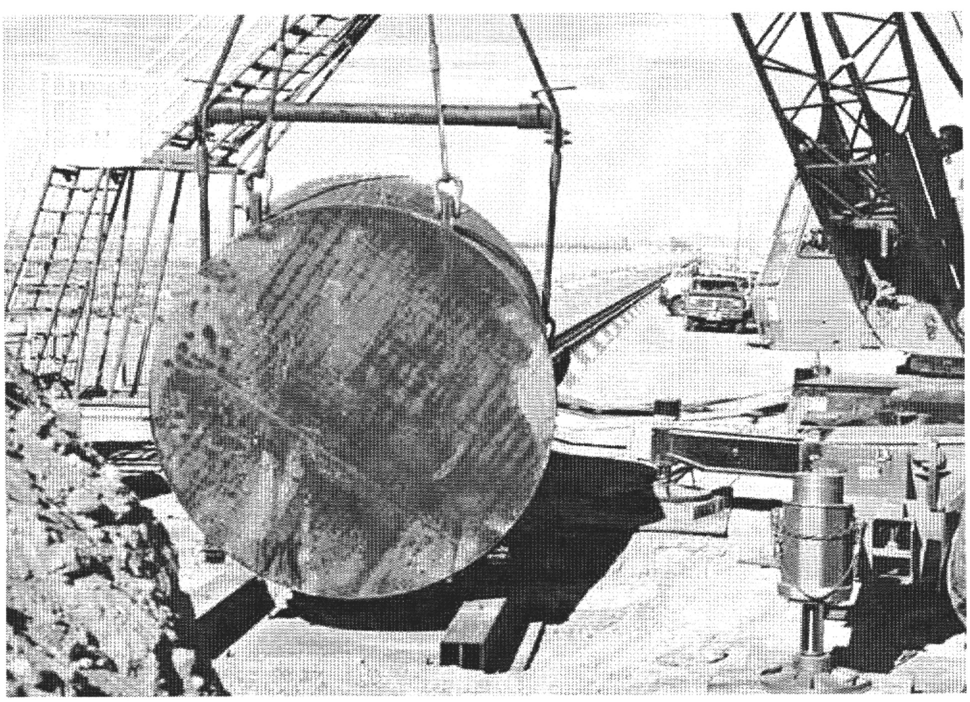

Figure 4.22. PMATP-SO1 Target Rotation.

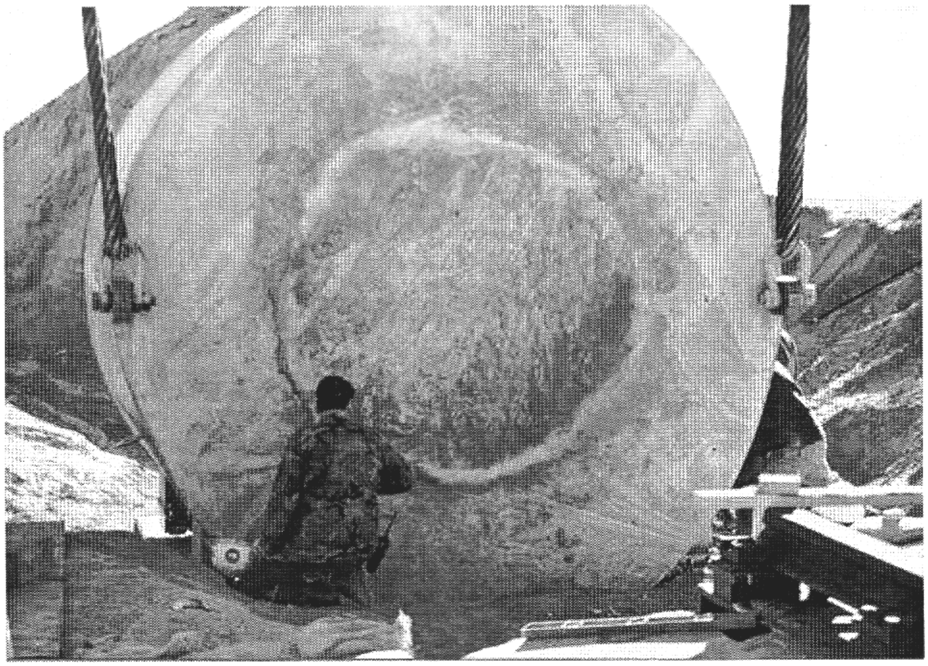

**Figure 4.23. PMATP-SO1 Target in Position.**

The side of the target facing the photometric cameras had one-inch-wide black and white vertical stripes painted on it. A fixed indicator was used to evaluate movement of the target during the impact as shown in Figure 4.24.

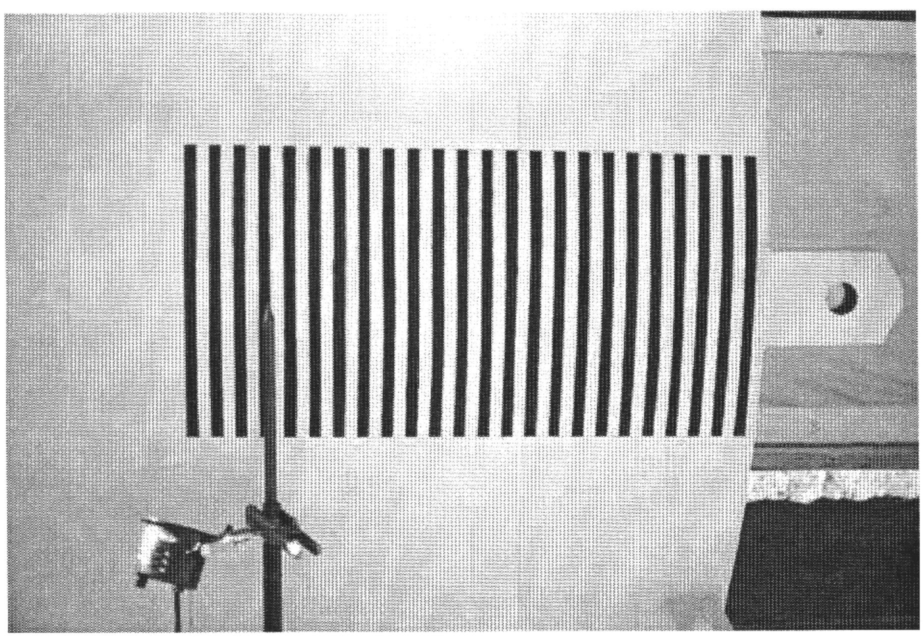

**Figure 4.24. Target Movement Indicator.**

# 4.3 PMATP-SO1 Test Requirements

The PMATP-SO1 test was a side-on impact test into a light-strength target. The desired velocity for this test was 925 ft/s (282 m/s) at impact. To achieve this velocity, the package was accelerated to provide a velocity greater than 1400 ft/s before sled braking and allowing the package to glide to the target for impact at the desired velocity.

The side-on impact test required the package be oriented horizontally across the sled track in order to impact the 0° side of the PMATP-SO1 into the center of the target.

## 4.3.1 Test Facility

The test was conducted at the 10,000-ft rocket sled test facility located at SNL Tech Area III. The area between the rails was filled with water dams of increasing depth to gently slow the first-stage pusher sled. The first-stage pusher sled consisted of the rocket mounting area, pusher saddles, and a water-brake chute as shown in Figure 4.25.

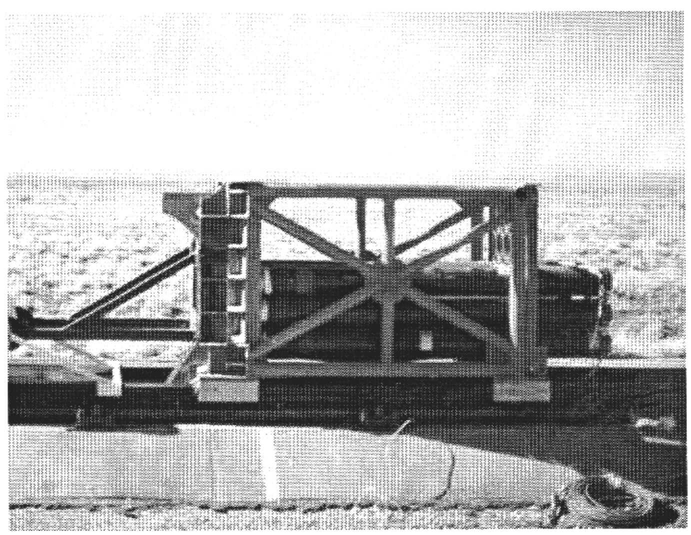

**Figure 4.25. PMATP-SO1 First-Stage Pusher Sled.**

The test unit was supported above the track on a second-stage unpowered expendable sled. This second-stage sled was propelled along the track by a first-stage pusher sled containing 12 Zuni rockets. At burnout of the first-stage rocket motors, the first-stage pusher sled was slowed by water braking, at which time the second-stage sled separated and coasted along the track to the target.

A copper screen and Mylar impact switch were used to determine the moment of impact for this test as shown in Figure 4.26. Timing switches were also installed along the sled track to determine sled velocity as shown in Figure 4.27. The timing switches were cut by the second-stage sled immediately before impact.

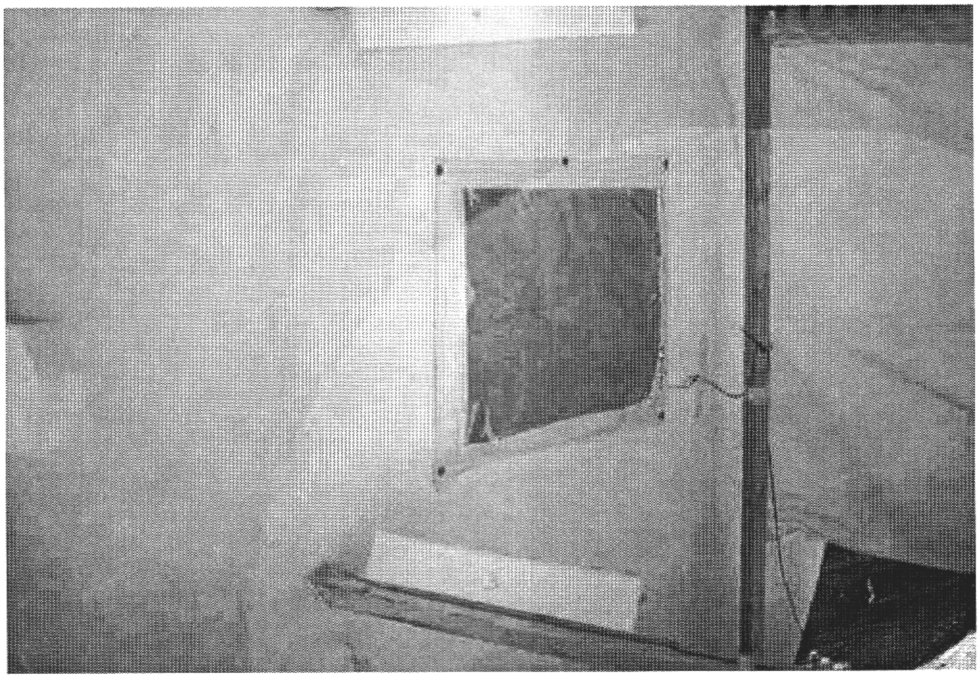

Figure 4.26. PMATP-SO1 Impact Switch.

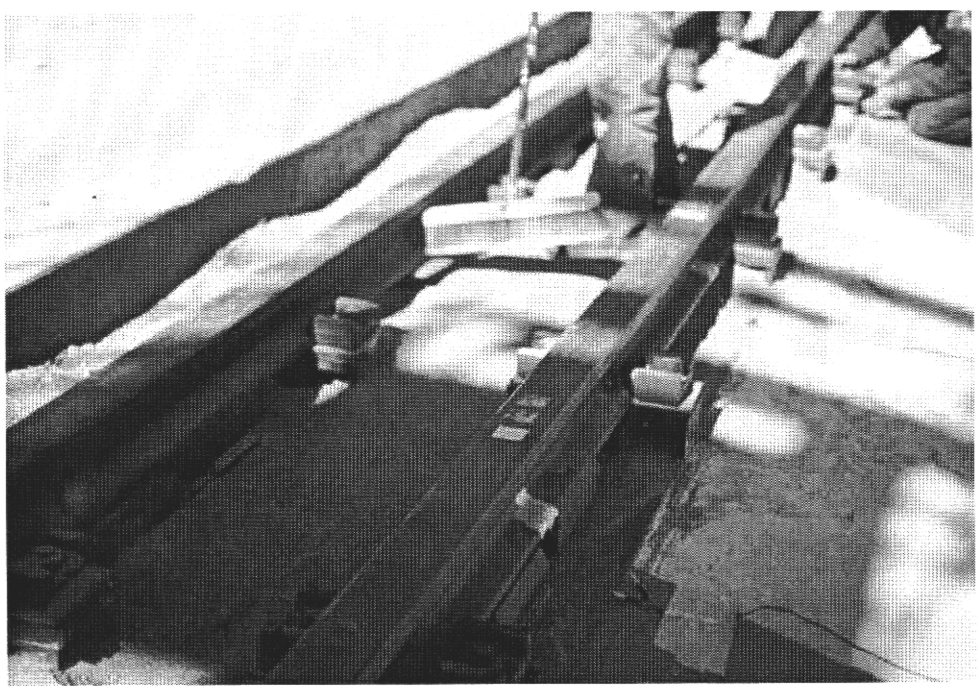

Figure 4.27. PMATP-SO1 Timing Switches.

## 4.3.2 Photometrics

Pre- and post-test documentary photographs were taken. These included 35-mm still photographs of the test site, the equipment, and the instrumentation to be used: fixtures, hardware, and rigging needed for the test. The top, bottom, and all four sides of the test package were photographed before the test and again after the test.

High-speed cameras were positioned for top and side views of the impact area to determine impact velocity and observe package performance throughout the impact. Hand-tracked cameras were used to document the full extent of the test. The camera types, locations, and coverage are shown in Figure 4.28. A total of 12 film and video cameras were used in support of the PMATP-SO1 impact test. This included 13 16-mm film cameras, two high-speed digital cameras, one 70-mm film camera, three super VHS (SVHS) video cameras, and two high-speed slit cameras (image motion [IM]). The relative positions of each of these cameras and the frame rates used by each are included in the camera layout schematic shown in Figure 4.28. The lines with arrows indicate the approximate angle of view for each camera.

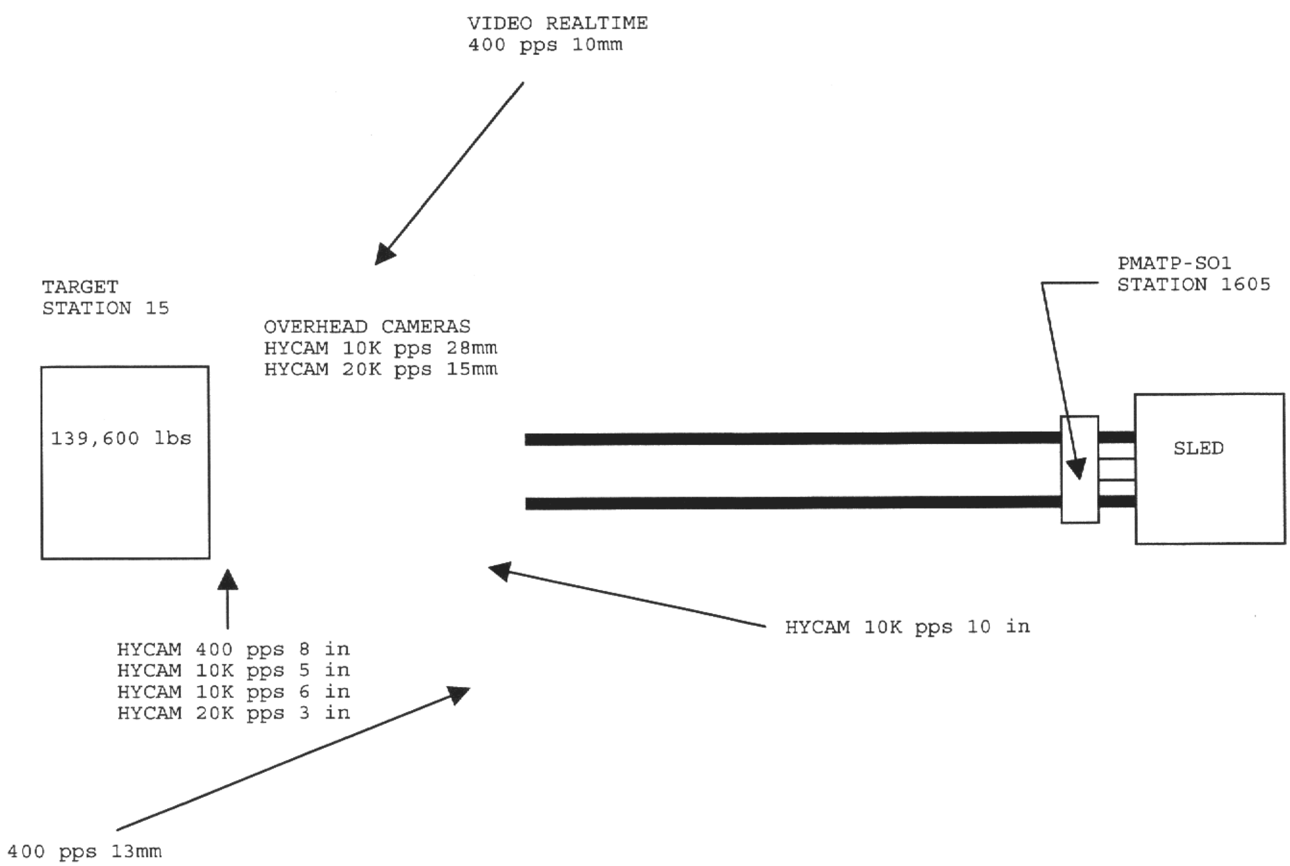


**Figure 4.28. PMATP-SO1 Camera Layout.**

A laser tracker was positioned to track the package during the test for accurate determination of package location and velocity throughout the test. The laser tracker locked onto a reflective marker that was located on the package and followed the package throughout the test, as shown in Figure 4.29. High-speed cameras were mounted on the tracking platform to provide additional photometric test documentation.

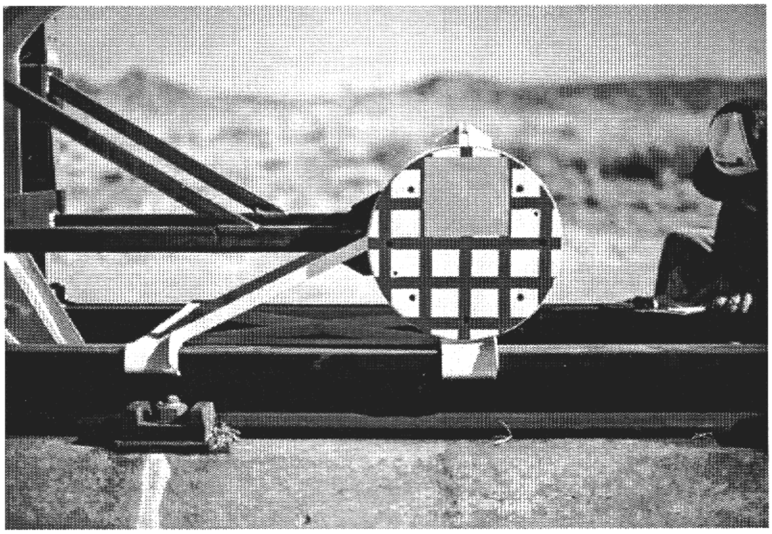

**Figure 4.29. PMATP-SO1 Reflective Marker.**

## 4.3.3 Inspection Measurements

The inner containment vessel was inspected by SNL personnel before assembly for pretest measurements and again after disassembly for post-test measurements. Diameters were measured at 0° – 180°, 45° – 225°, 90° – 270°, and 135° – 315°.

The closure was measured at one location on the largest shoulder diameter. The container body was measured at five locations including the top, midway between top and center, center, midway between center and bottom, and bottom. Lengths were measured every 45° with and without the closure installed.

## 4.3.4 Test Unit Weight Measurements

The weights of various components were documented before each test. The inner containment vessel was weighed when empty and after the steel shot mass was loaded. The overpack body, End Plug 1, and End Plug 2 were weighed before assembly. The total package weight was measured after final assembly.

## 4.4 PMATP-SO1 Test Results

### 4.4.1 Side-On Impact Test

The test article was configured for a side-on impact test of 925 ft/s. The as-tested weight of the test article was 256 lb as shown in Table 4.1. The first-stage pusher sled weighed 1683 lb including rockets, and the total weight of the second-stage sled and test package was 293 lb. The test unit was launched from Station 1605, and the target was placed at Station 15 for a total travel distance of 1620 ft.

**Table 4.1. PMATP-SO1 Weight Measurements (lb)**

| | |
|---|---|
| Containment vessel empty | 17.00 |
| Containment vessel full | 23.00 |
| Overpack body | 189.00 |
| End Plug 1 | 21.7 |
| End Plug 2 | 21.8 |
| Total assembled weight | 256.00 |
| Target weight | 139,600.00 |

Figures 4.30 through 4.33 show the PMATP-SO1 being prepared for the side-on impact test.

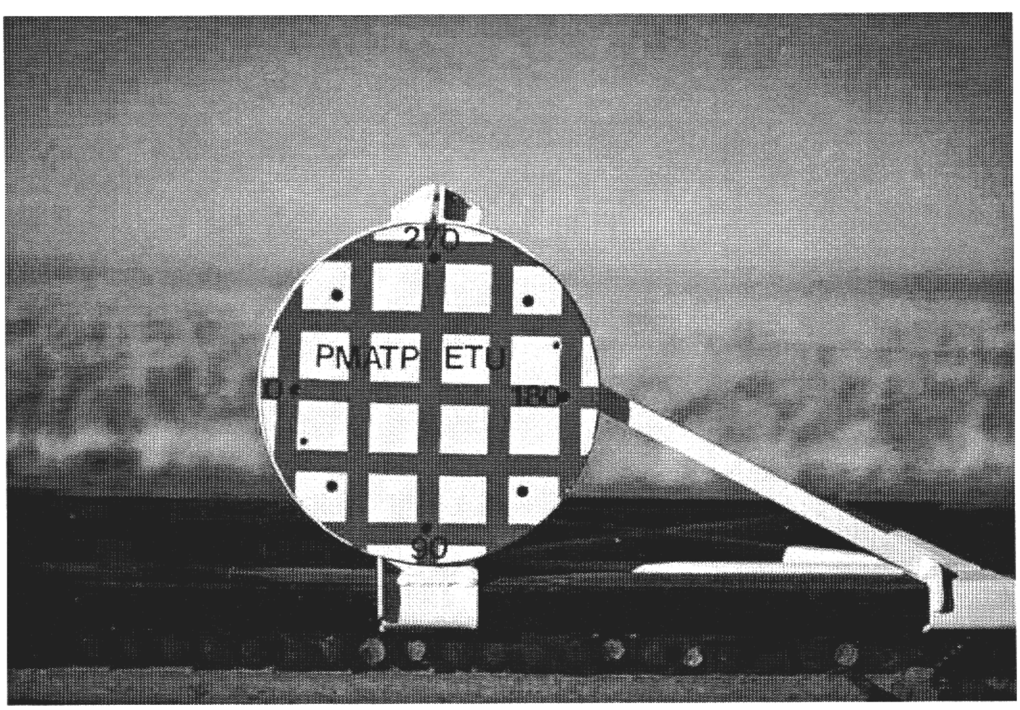


**Figure 4.30. PMATP-SO1 Mounted in Stage 2 Guide Sled.**

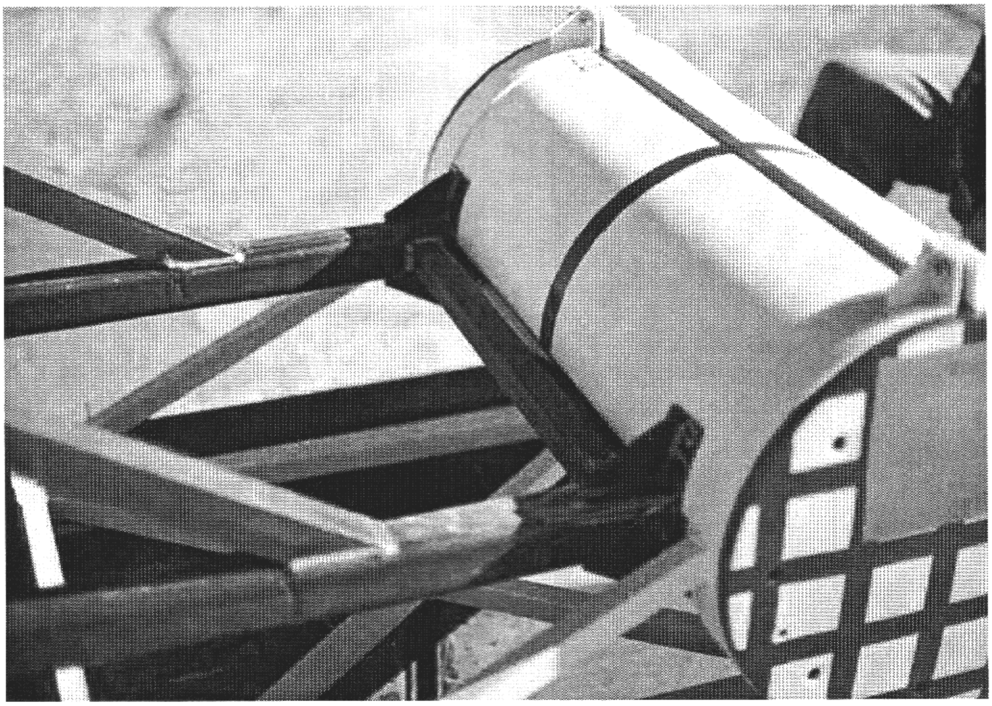

**Figure 4.31. PMATP-SO1 Stage 1 Pusher Sled to Stage 2 Guide Sled Interface.**

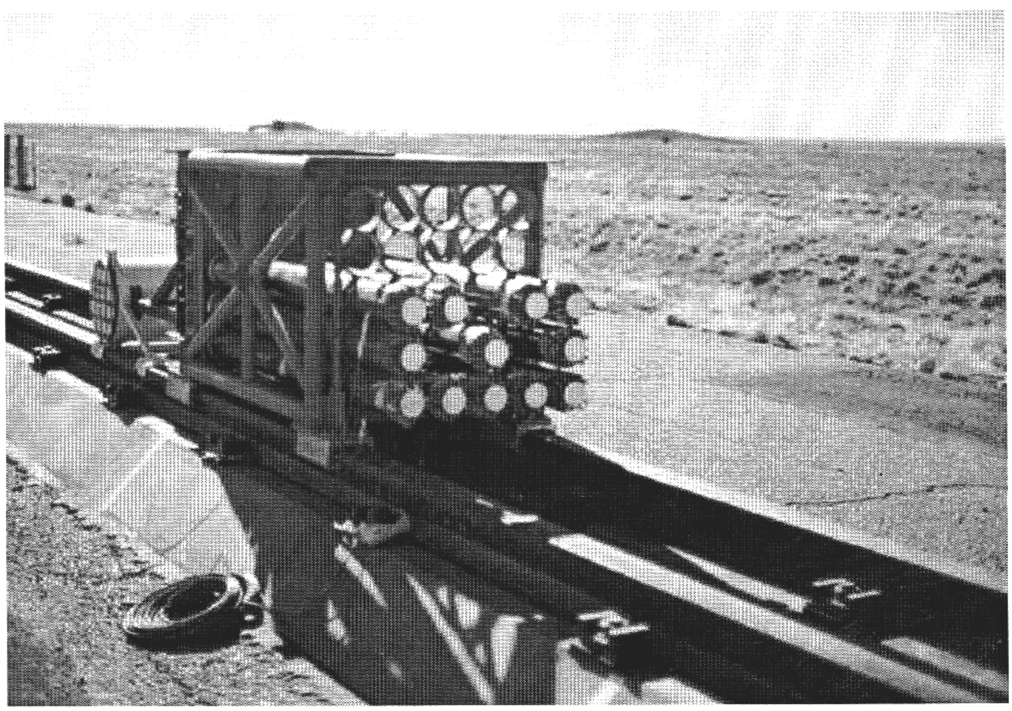

**Figure 4.32. PMATP-SO1 Stage 1 Pusher Sled with 12 Zuni Rockets.**

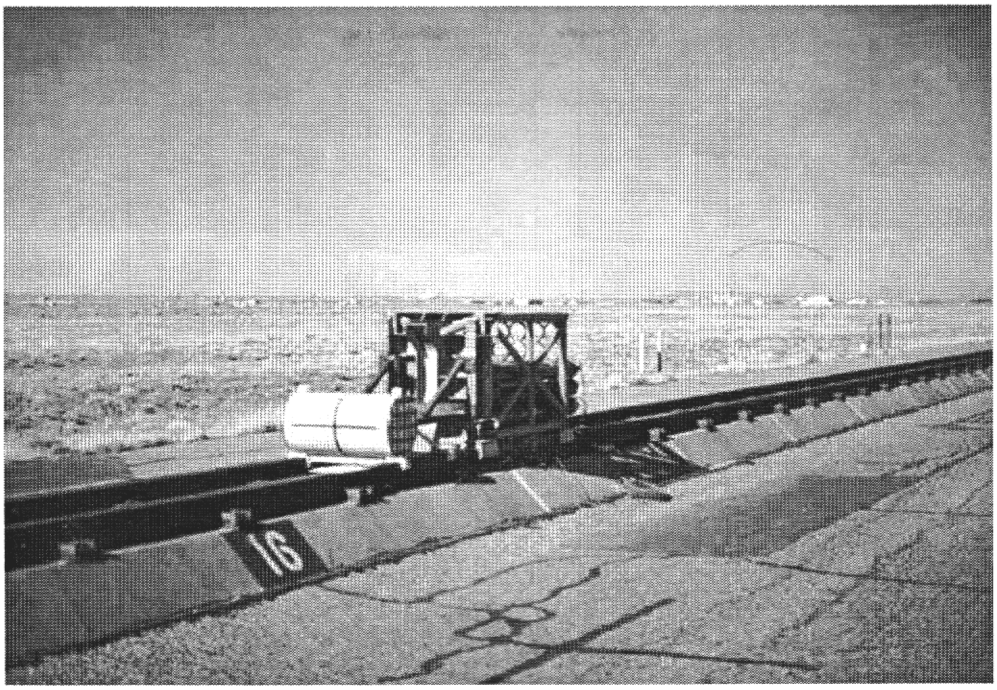


**Figure 4.33. PMATP-SO1 Ready for Test.**

The PMATP-SO1 impact test was performed on January 14, 1999, at 1:58 p.m. MST. The rockets fired as desired, and the first-stage pusher sled accelerated the second-stage guide sled and package as expected. The package impacted in the desired horizontal orientation (parallel to the target) at a velocity of 883 ft/s. Table 4.2 documents the velocity measurement taken by various methods. The most reliable velocity data come from the fixed photometric sources, the IM camera in particular. The IM camera at Station 5 (which is located 20 ft from impact) velocity measured 892 ft/s, and with the calculated nominal deceleration (12 g), this extrapolates to 883 ft/s at impact.

**Table 4.2. Velocity Measurements**

| Method | Velocity (ft/s) |
|---|---|
| Laser tracker (Station 10) | 880 |
| Timing switches (Station 10) | 877 |
| Overhead Hycam (Station 15) | 882.5 |
| Image motion camera (Station 5) | 892 |

Figure 4.34 illustrates the test unit and target following the impact test. The end caps had sheared from the overpack body as shown in Figure 4.35. This was most likely caused by the guide sled hardware. The package rebounded from the target, impacted the end of the sled track, and caused a tear in the overpack skin as shown in Figure 4.36.

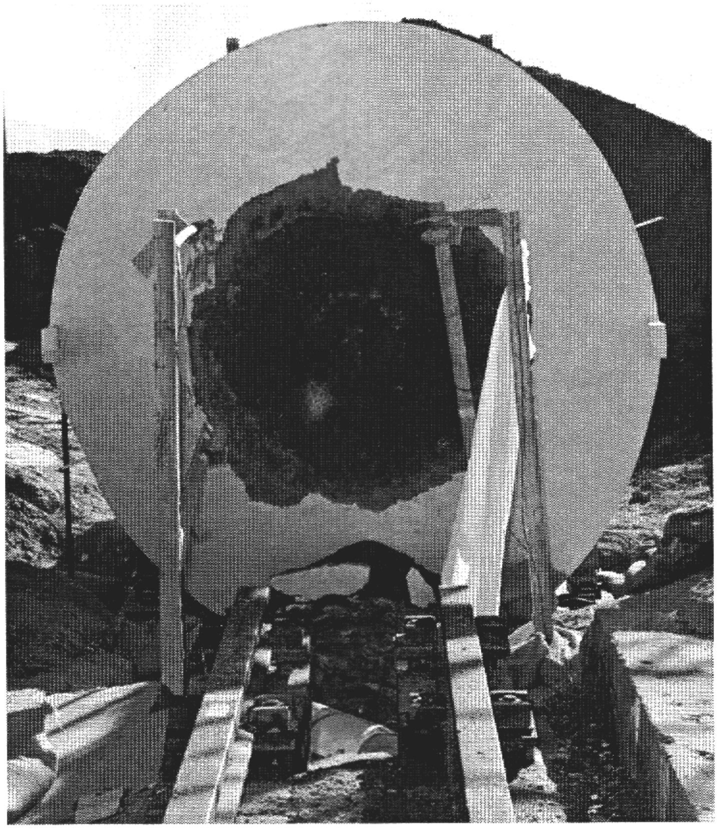

**Figure 4.34. PMATP-SO1 Test Article and Target After Impact Test.**

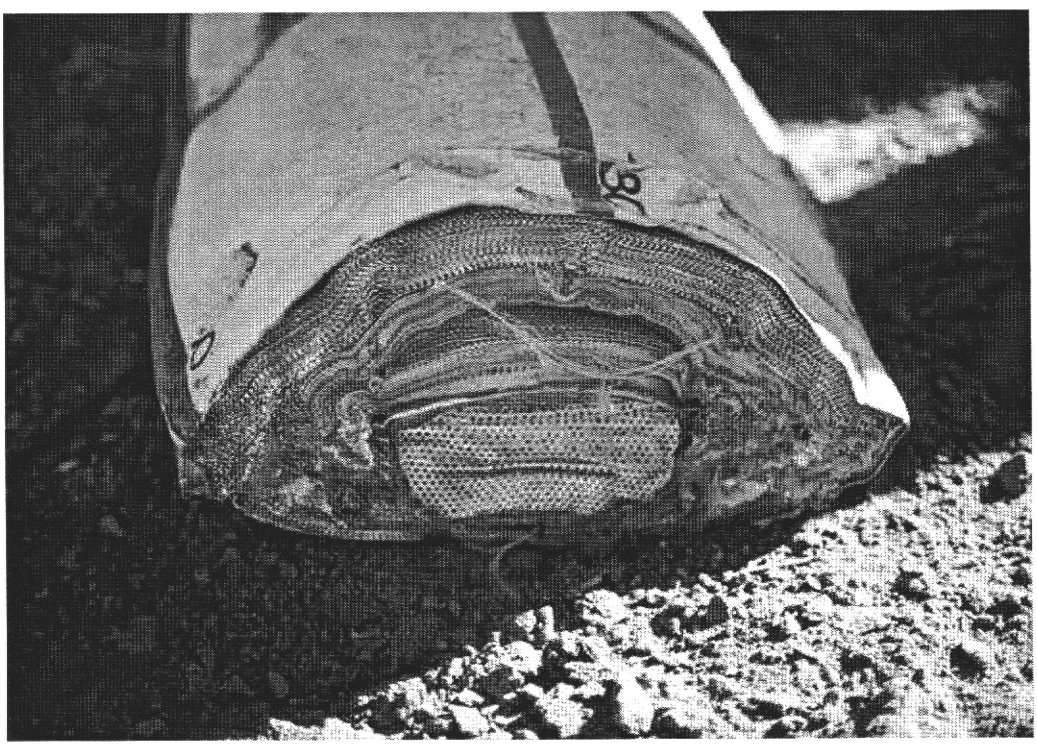

**Figure 4.35. PMATP-SO1 Exposed Ends.**

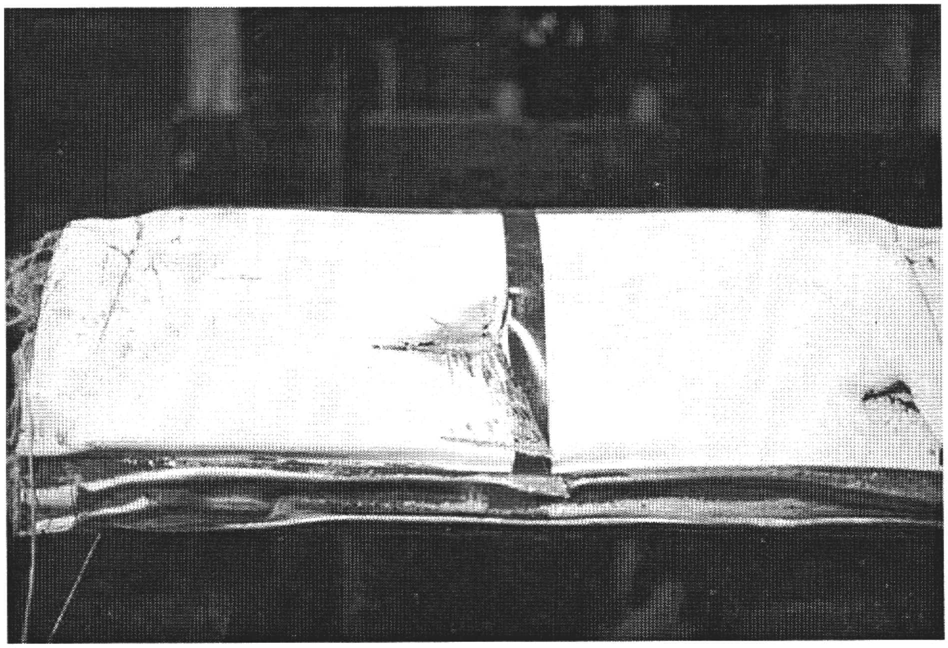

**Figure 4.36. PMATP-SO1 Ruptured Skin.**

A crater was formed at the impact area of the target approximately 72 inches in diameter and 18 inches deep at the center as shown in Figure 4.37. This crater includes most of the repoured concrete of Layer 5. The compressive strength tests of the concrete on the day of the test indicated that Layer 5 (the impact layer) was considerably weaker than anticipated; however, the layers beneath Layer 5 were considerably stronger than desired as shown in Table 4.3.

The test conditions for the side-on calibration test are shown in Table 4.4.

**Figure 4.37. Target After PMATP-SO1 Impact Test.**

**Table 4.3. PMATP-SO1 Concrete Target Compressive Strengths**

| Layer | Compressive Strength Day of Test |
|---|---|
| 1 back end | 3670 psi |
| 2 | 2550 psi |
| 3 | 2410 psi |
| 4 | 3580 psi |
| 5 impact end | 625 psi |

**Table 4.4. Test Conditions for Side-On Calibration Test**

| | |
|---|---|
| Temperature | 49.5° F at 13:58 |
| Lighting | Full sun |
| Wind direction | Out of southwest |
| Wind velocity | 0.2 mph |
| Number of rockets | 12 Zuni rockets |

# 4.5 PMATP-SO1 Disassembly and Evaluation

After the side-on impact test, the PMATP-SO1 was retrieved for disassembly and evaluation.

The inner containment vessel remained intact and within the overpack. The inner containment vessel was removed from the overpack for inspection, initially by cutting through the overpack to locate the inner container as shown in Figure 4.38. A cut was then made along the axis through the overpack and inner container as shown in Figure 4.39. Inspection showed the inner containment vessel deformation, as seen in Figure 4.40. Physical dimensions of the inner containment vessel are documented in Tables 4.5 and 4.6. The D0° – 180° diameter measurements were the only whole diameter measurements. All other diameter measurements were measured across the cut after disassembly. The closure was not removed from the container body; therefore, there are no post-test length measurements without the closure.

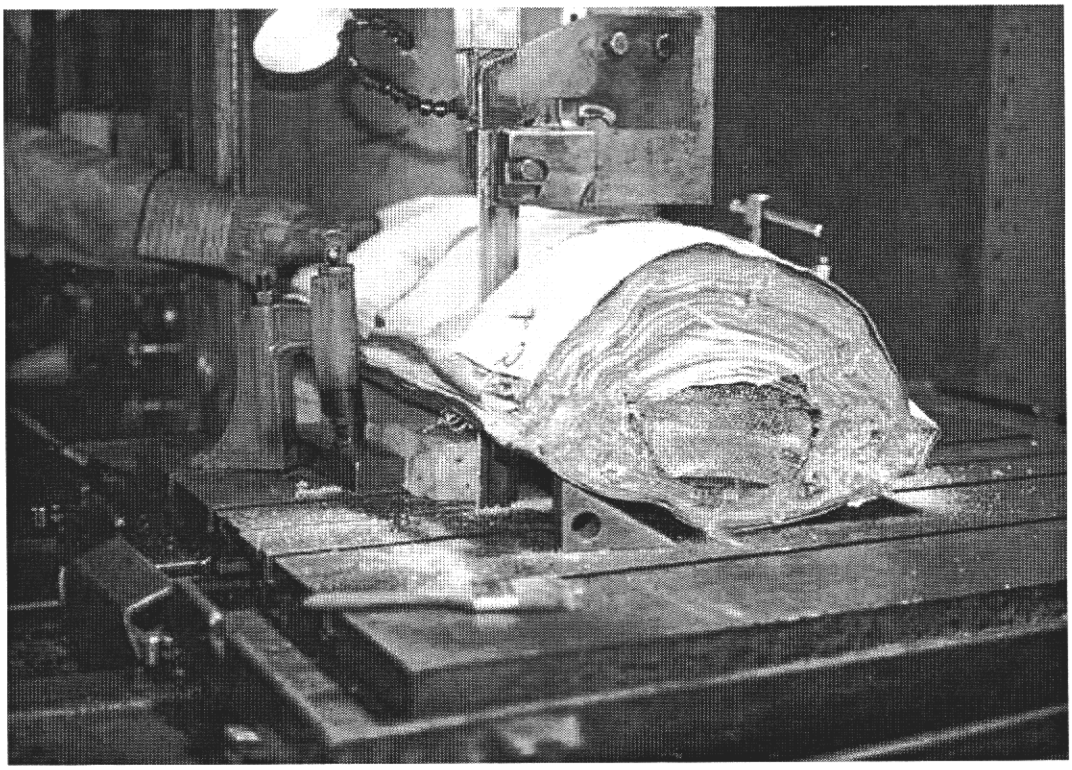

**Figure 4.38. Locating PMATP-SO1 Inner Containment Vessel.**

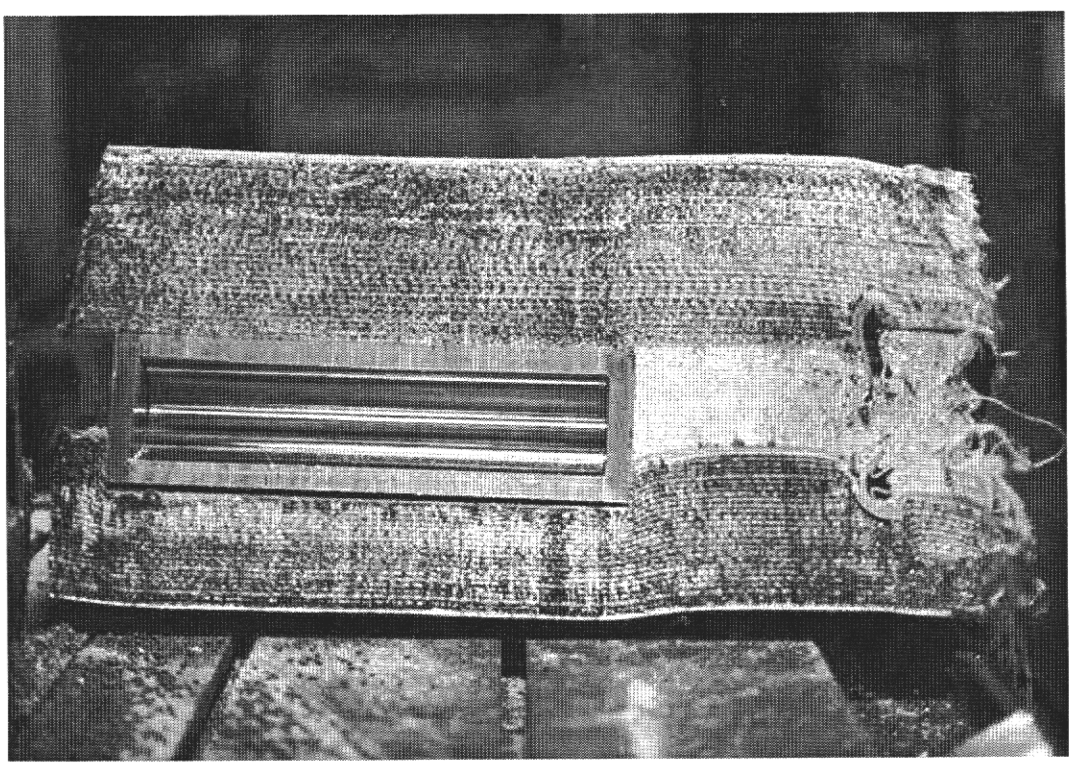

**Figure 4.39. Cutting Through the PMATP-SO1 for Inspection.**

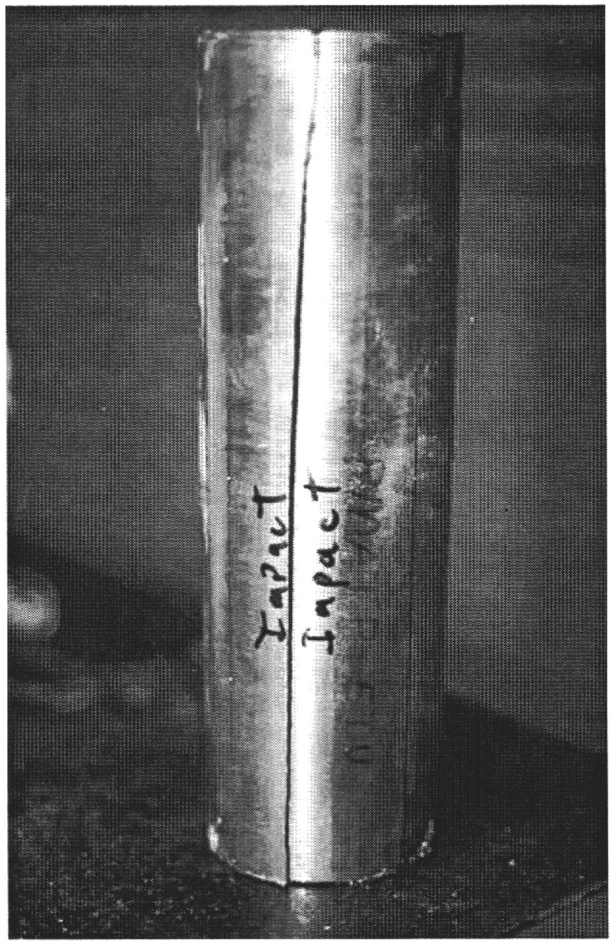


**Figure 4.40. PMATP-SO1 Inner Containment Vessel Deformation.**

**Table 4.5. PMATP-SO1 Inspection Measurement Lengths (inches)**

| | L0° | L45° | L90° | L135° | L180° | L225° | L270° | L315° |
|---|---|---|---|---|---|---|---|---|
| Pre no lid | 11.675 | 11.673 | 11.675 | 11.675 | 11.676 | 11.676 | 11.676 | 11.675 |
| Post no lid | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Difference (no lid) | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Pre w/lid | 11.804 | 11.805 | 11.806 | 11.804 | 11.805 | 11.802 | 11.802 | 11.801 |
| Post w/lid | 11.812 | 11.812 | 11.814 | 11.811 | 11.814 | 11.807 | 11.804 | 11.804 |
| Difference (w/lid) | +.008 | +.007 | +.008 | +.007 | +.009 | +.005 | +.002 | +.003 |

**Table 4.6. PMATP-SO1 Inspection Measurement Diameters (inches)**

| | D0° – 180° | D45° – 225° | D90° – 270° | D135° – 315° |
|---|---|---|---|---|
| Pre closure | 3.495 | 3.496 | 3.498 | 3.496 |
| Post closure | 3.485 | 3.438 | 3.427 | 3.431 |
| Difference (closure) | –.010 | –.058 | –.071 | –.065 |
| Pre body top | 3.495 | 3.496 | 3.496 | 3.495 |
| Post body top | 3.487 | 3.444 | 3.436 | 3.445 |
| Difference (body top) | –.008 | –.052 | –.060 | –.050 |
| Pre body TC (top, center) | 3.497 | 3.497 | 3.497 | 3.496 |
| Post body TC | 3.467 | 3.444 | 3.449 | 3.444 |
| Difference (top, center) | –.030 | –.053 | –.048 | –.052 |
| Pre body center | 3.497 | 3.496 | 3.498 | 3.497 |
| Post body center | 3.456 | 3.443 | 3.457 | 3.443 |
| Difference (body center) | –.041 | –.053 | –.041 | –.054 |
| Pre body CB (center, bottom) | 3.497 | 3.497 | 3.496 | 3.497 |
| Post body CB | 3.471 | 3.445 | 3.446 | 3.445 |
| Difference (center, bottom) | –.026 | –.052 | –.050 | –.052 |
| Pre body bottom | 3.495 | 3.496 | 3.495 | 3.496 |
| Post body bottom | 3.494 | 3.452 | 3.428 | 3.448 |
| Difference (body bottom) | –.001 | –.044 | –.067 | –.048 |

# 4.6 PMATP-SO1 Conclusions

A half-scale plutonium air-transportable package identified as PMATP-SO1 was successfully tested at the Full-Scale Experimental Complex 10,000-ft sled track in the SNL Tech Area III Test Facility. The PMATP-SO1 was subjected to a side-on orientation impact test as specified in the Murkowski Amendment.

The inner containment vessel suffered little deformation. The measured deformation was approximately 0.040 inch from the center diameter, thus indicating that the vessel would remain leak-tight.

Lessons learned from this test include the need to remove the second-stage guide sled hardware before impact and optimization of the overpack design. This test clearly demonstrates the viability of perforated aluminum sheet and Kevlar™ cloth as an excellent energy-absorbing overpack material.

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# 5. PMATP-EO1

## 5.1 PMATP-EO1 Package Description

The PMATP End-on (EO) prototype was a right circular cylinder. The PMATP-EO1 was 15 inches in diameter by 30 inches long and weighed 289 lb. This package had an inner containment vessel 3.5 inches in diameter by 11.8 inches long with a 0.5-inch wall thickness. It was constructed from S13-8 H1100 stainless steel as shown in Figure 5.1. The containment vessel was filled with No. 6 steel shot to simulate mass as shown in Figure 5.2. The PMATP-EO1 was slightly modified from the PMATP-SO1 package. This package incorporated thicker stainless steel (0.120 inch vs. 16 gauge) for all of the end plates of the inner tube and end plugs.

**Figure 5.1. PMATP-EO1 Inner Containment Vessel.**

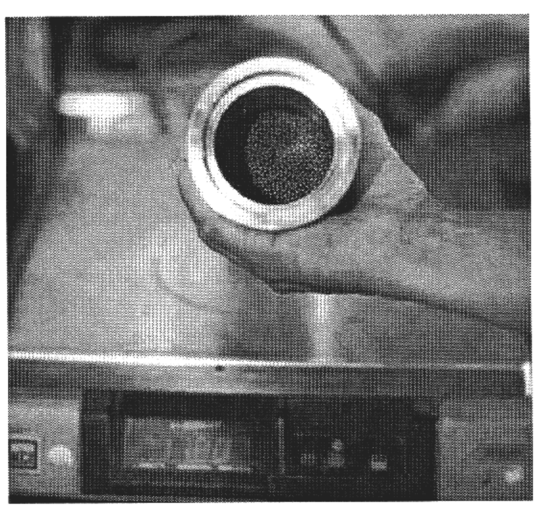

**Figure 5.2. PMATP-EO1 Inner Containment Vessel Loaded with Steel Shot.**

The containment vessel was placed in a two-step, 16-gauge and 0.120-inch 304 stainless-steel inner tube as shown in Figure 5.3. The inner tube was wrapped with perforated aluminum sheet and Kevlar™ cloth as shown in Figure 5.4. The wrap cycles include three wraps of perforated aluminum sheet and two wraps of perforated aluminum with Kevlar™ cloth. The perforated aluminum used was 0.032-inch-thick 3003-H14 with a 51% open space made with 0.115-inch-diameter staggered holes 0.117 inch apart. The Kevlar™ cloth was approximately 0.018-inch thick. The PMATP-EO1 had a 16-gauge 304 stainless-steel outer shell welded to the outer plates of the inner tube as shown in Figure 5.5.

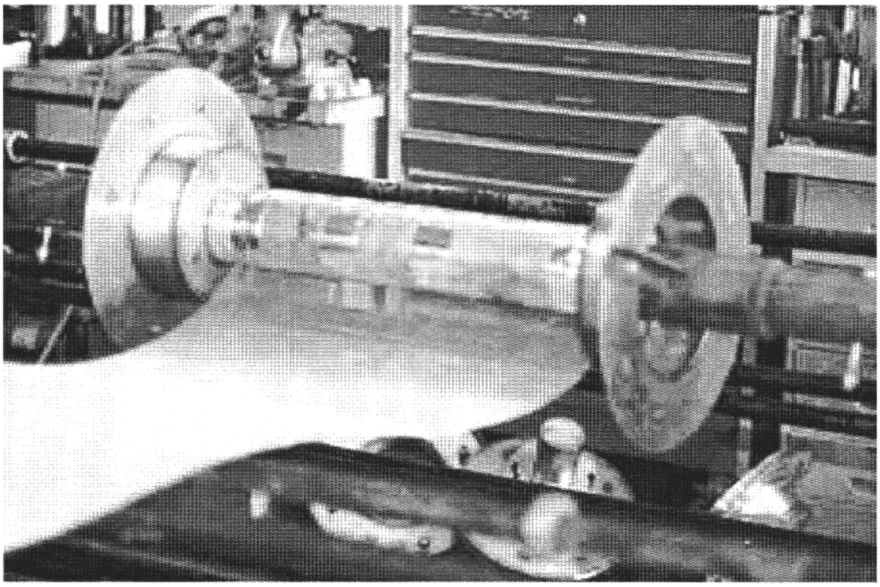

**Figure 5.3. PMATP-EO1 Inner Tube.**

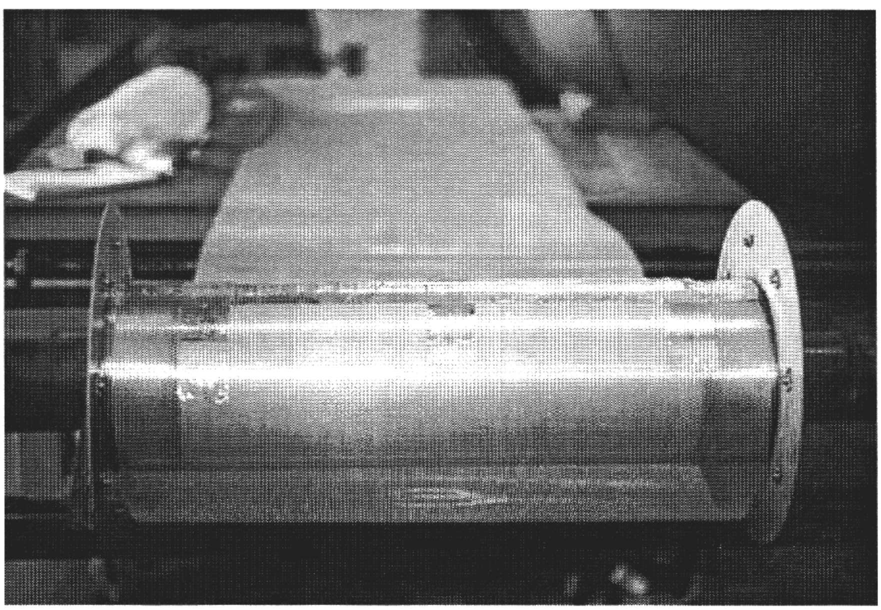

**Figure 5.4. Wrapping of PMATP-EO1 Overpack.**

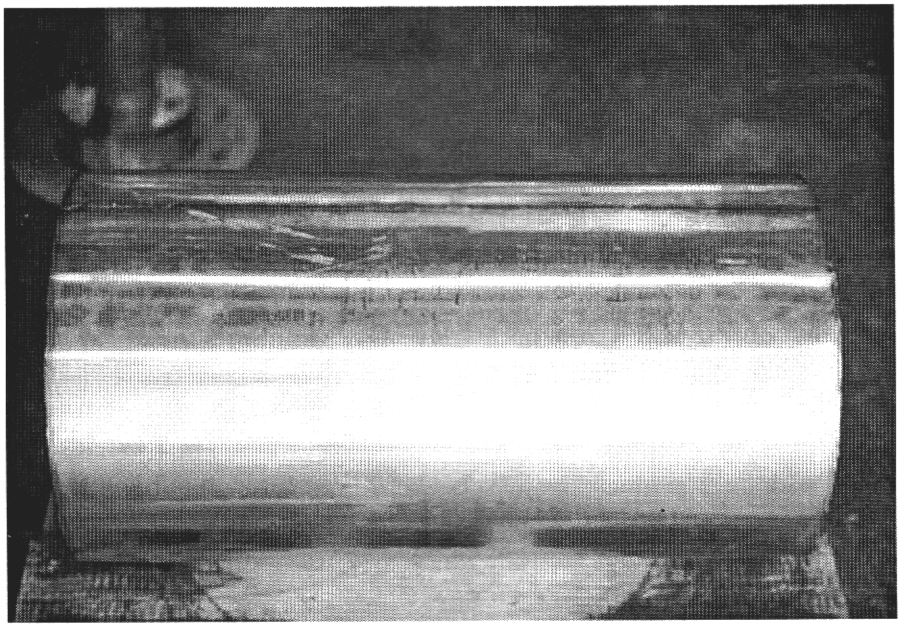

**Figure 5.5. PMATP-EO1 Overpack Body.**

The PMATP-EO1 had two end plugs made of 16-gauge and 0.120-inch 304 stainless steel as shown in Figure 5.6. The end plugs were filled with three diameters of 3003-H14 0.063-inch perforated aluminum discs stacked as shown in Figures 5.7 through 5.9. The two larger diameter discs were stacked with Kevlar™ cloth in the same pattern as the wrapping of the overpack body. The end plugs had a 0.120-inch, 304 stainless-steel outer plate welded to completely enclose the packing materials as shown in Figure 5.10.

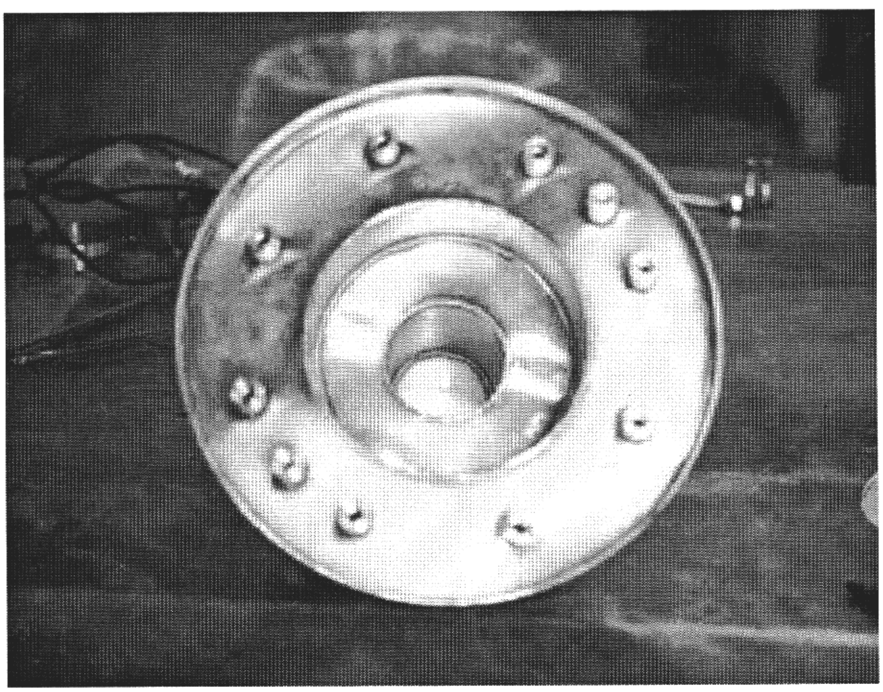

**Figure 5.6. PMATP-EO1 End Plugs.**

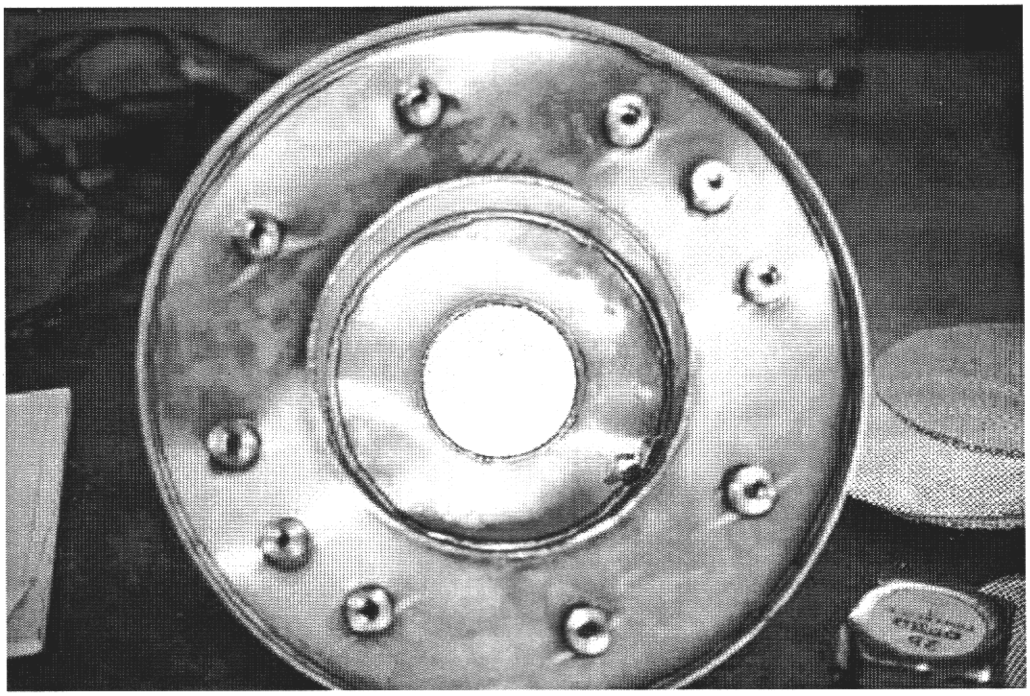

Figure 5.7. PMATP-EO1 Packing of End Plugs (Small Diameter).

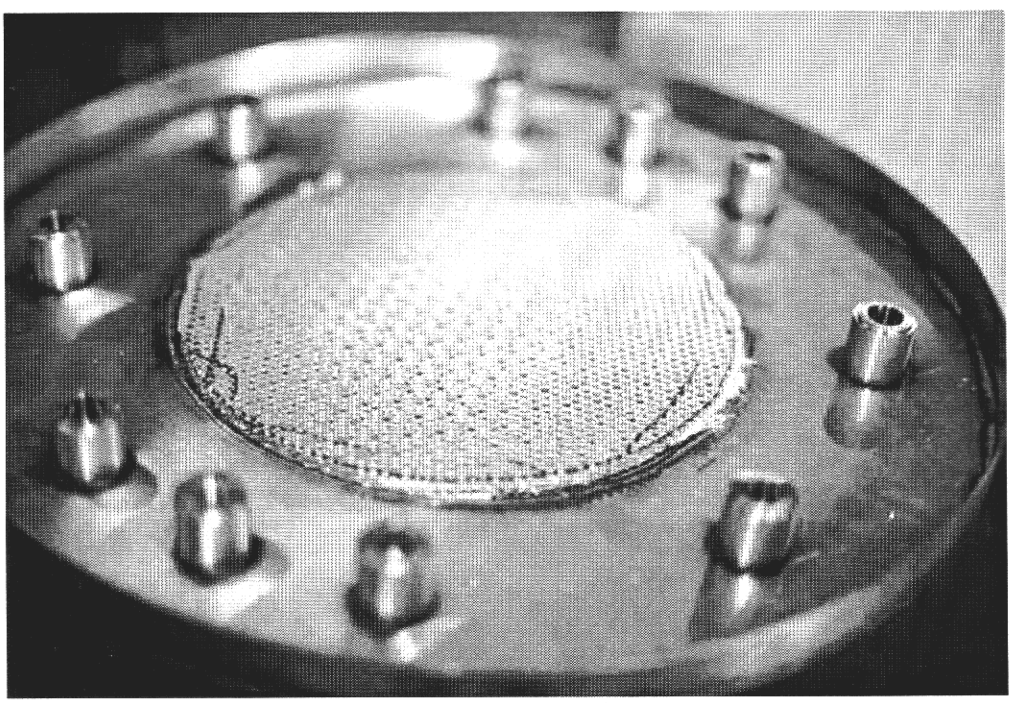

Figure 5.8. PMATP-EO1 Packing of End Plugs (Medium Diameter).

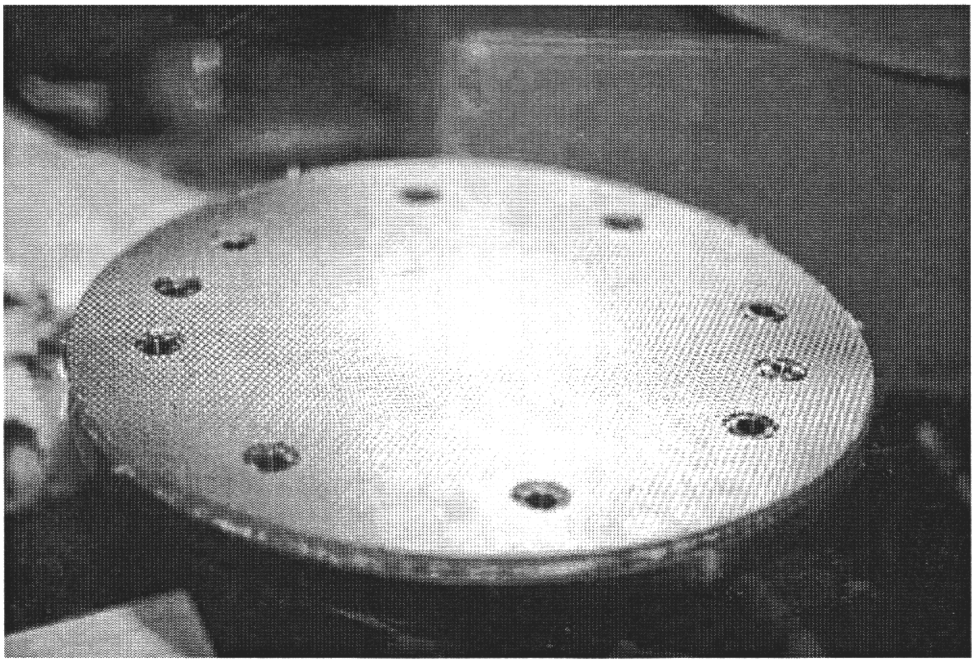

**Figure 5.9. PMATP-EO1 Packing of End Plugs (Large Diameter).**

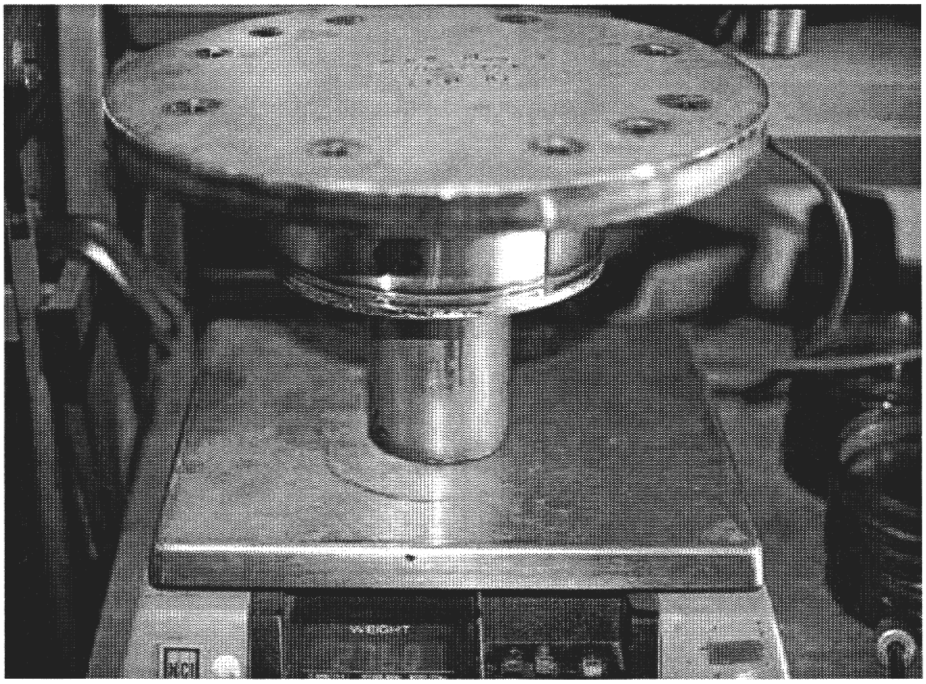


**Figure 5.10. PMATP-EO1 Welded End Plug.**

The inner containment vessel was loaded in the inner tube of the overpack body as shown in Figure 5.11. Each end plug was assembled to the overpack body with four tee slots and buttons as shown in Figure 5.12. The end plug was rotated 15° and locked with eight bolts as shown in Figure 5.13.

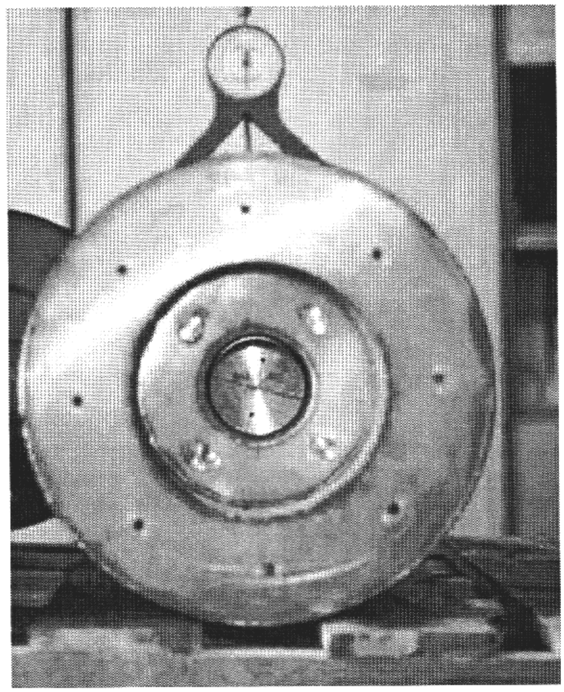

**Figure 5.11. Loading of Inner Containment Vessel.**

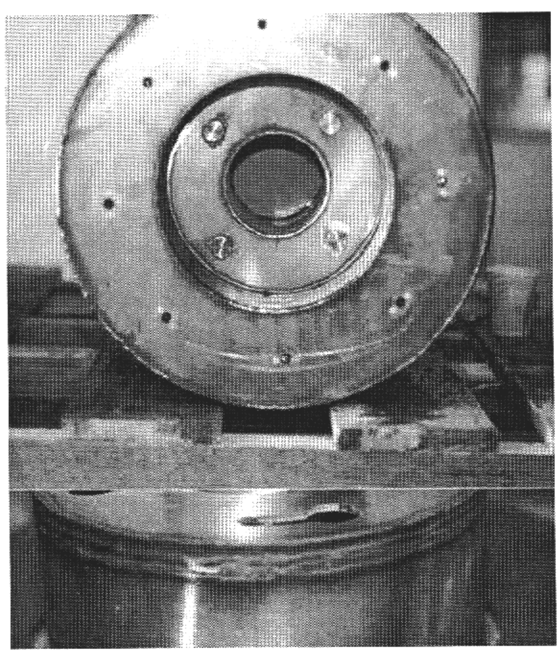

**Figure 5.12. PMATP-EO1 Tee Slots and Buttons.**

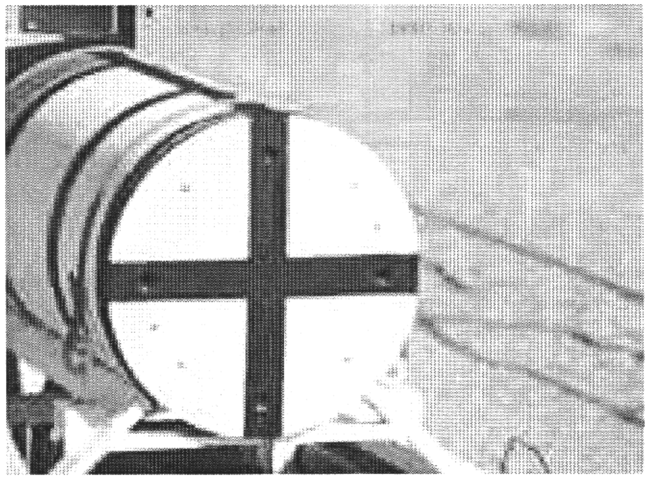

**Figure 5.13. End View of Assembled PMATP-EO1.**

The PMATP-EO1 prototype was painted white with black stripes to ensure good visibility for photometrics. The paint scheme included two-inch black stripes every 90° for the full length of the package, around the circumference at each end of the package, and 12 inches center-to-center centered on the package. Each end of the PMATP-EO1 had two-inch black stripes painted in a cross horizontal and vertical pattern.

# 5.2 PMATP-EO1 Target Description

The target shell for PMATP-EO1 consisted of a 0.5-inch-thick mild steel right circular cylinder with a flat bottom as shown in Figure 5.14. The target shell was filled in the vertical position with light-strength concrete (approximately 1200 psi). The light-strength concrete was a grout-type mixture including only water, washed sand, and cement. Agra Earth & Environmental, Inc., was consulted throughout the design phase of the concrete mixture. Agra formulated and tested concrete design batches to arrive at the appropriate water-to-cement (w/c) ratio to achieve the desired 1200-psi strength in 14 curing days.

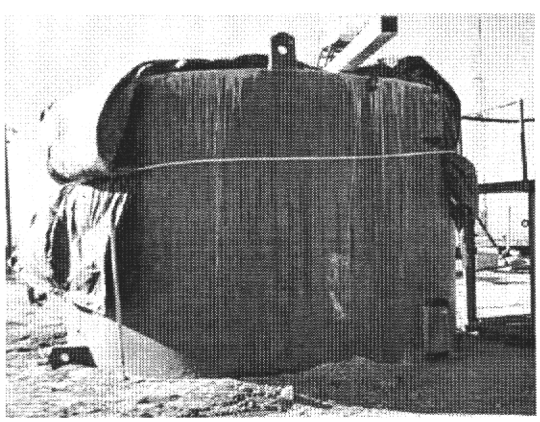

**Figure 5.14. Target Cylinder.**

Agra performed mix design testing to arrive at the appropriate w/c ratio. The results of this study are summarized in Figure 5.15. All results are based on unconfined break strength using 4-inch by 8-inch cast test cylinders. Each data point represents the average from three samples.

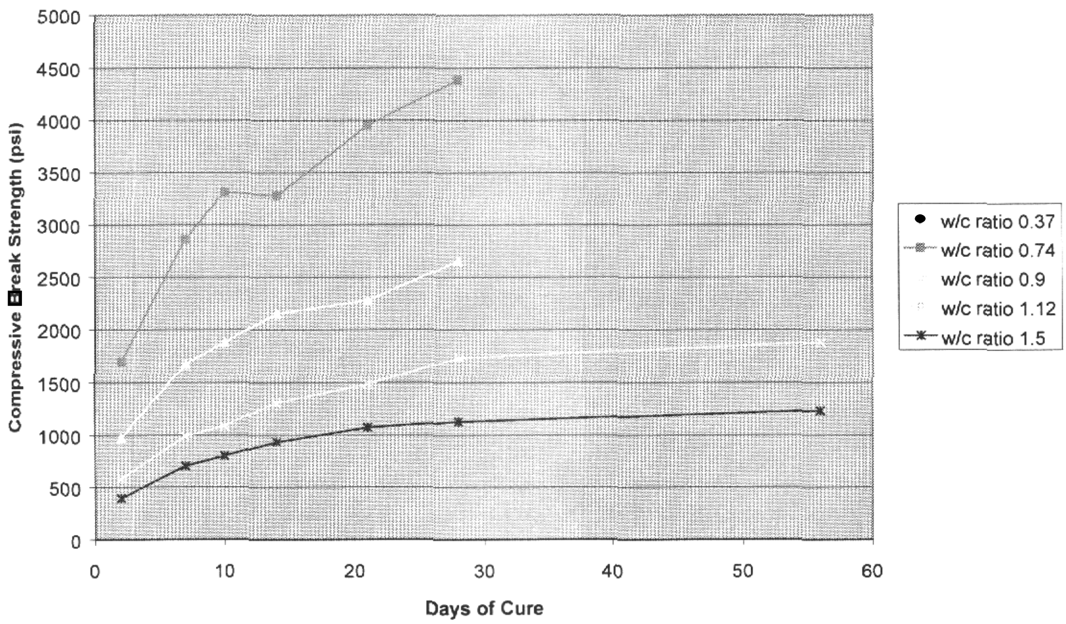


**Figure 5.15. Agra Concrete Mix Design Results for Water-to-Cement Ratios.**

A w/c ratio of 1.2 was selected based on the mix design results. This ratio was expected to produce a compressive strength of 1200 psi after 14 days of curing. Results of the actual concrete strengths from target samples are shown in Figure 5.16. Compressive strength versus the number of cure days are shown for the target samples as vertical bars in the figure; for the mix design samples comprehensive strength versus the number of cure days are shown as solid lines. The target sample strengths are divided into lab and field samples. The lab samples refer to the lab-cured samples (cured at Agra laboratory), and the field samples refer to the samples cured alongside the actual target in the field. The target samples are also divided into bottom – 1/4, 1/4 – 1/2, 1/2 – 3/4, and 3/4 – top, referring to the height location within the target from which the samples are taken. Four trucks were used to fill the target as shown in Figure 5.17, each truck filling approximately one-quarter of the height of the form. Equal numbers of samples were taken from each truck for testing the four sections of the target. As seen in Figure 5.16, the target strength increased considerably more slowly than expected. The 1200-psi strength was not obtained until nearly 42 days. It should be noted that 21 cure days correspond to test day for the PMATP- EO1.

The target was 12 ft in diameter by 8 ft long and weighed approximately 140,000 lb after the concrete had cured as shown in Figure 5.18.

The target was rotated and placed on a steel plate 40 ft from Station 0 and perpendicular to the track. The target was backfilled on three sides with dirt to stabilize the target for impact as shown in Figure 5.19.

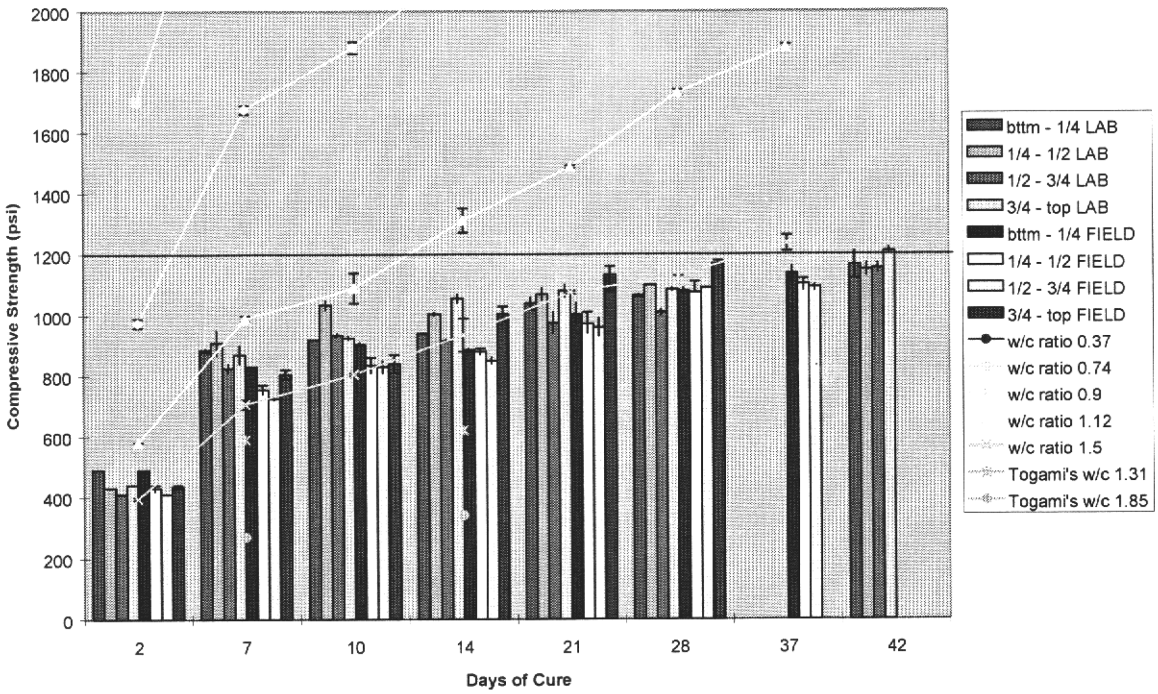


**Figure 5.16. Target Strength as a Function of Cure Days.**

**Figure 5.17. PMATP-EO1 Target Pour.**

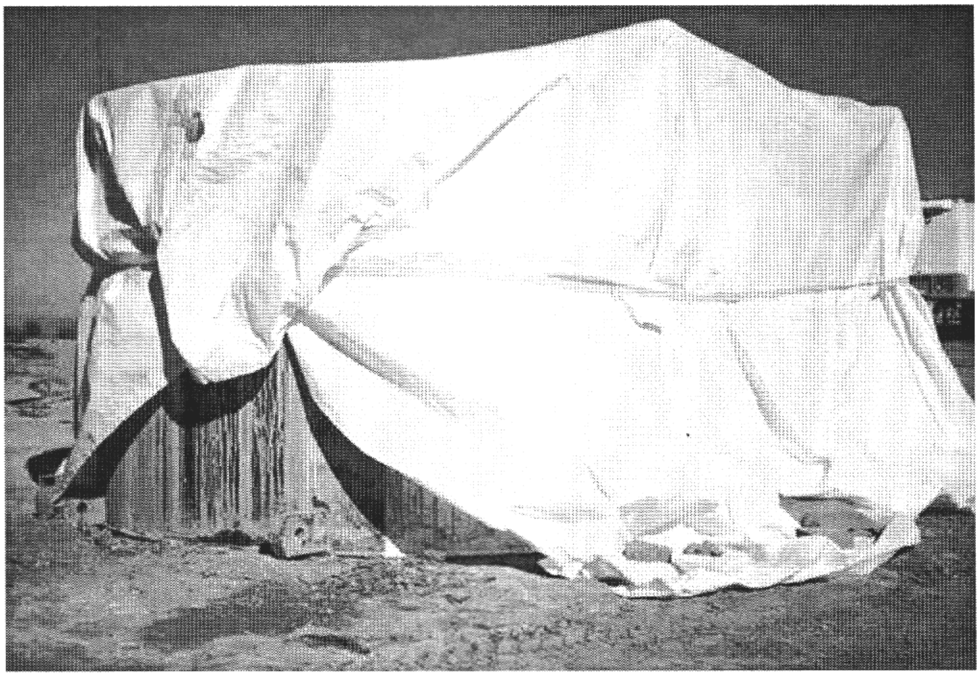

**Figure 5.18. PMATP-EO1 Target Cure.**

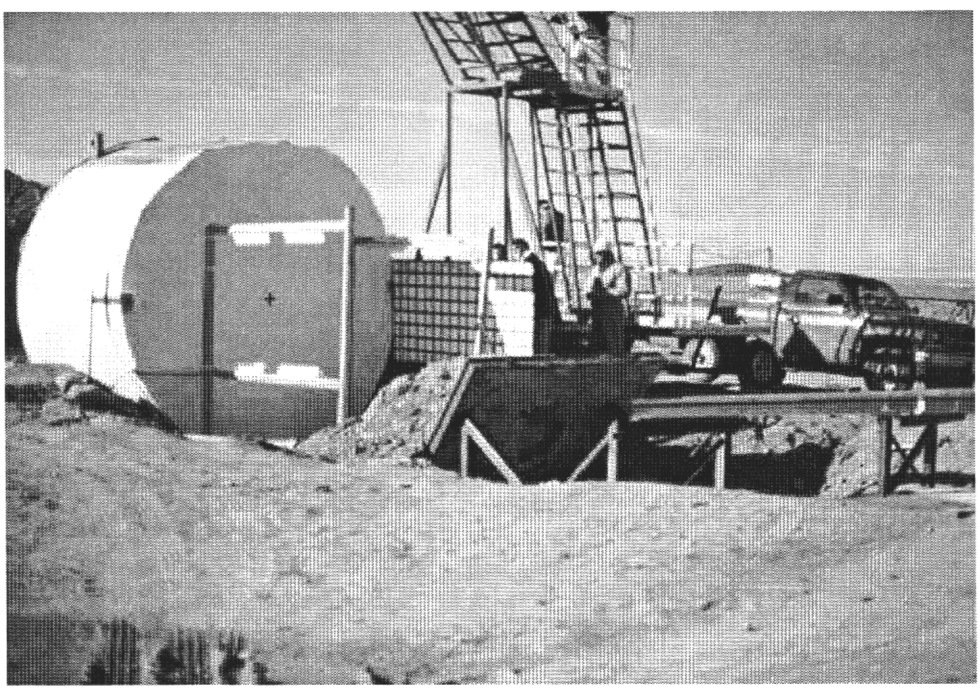

**Figure 5.19. PMATP-EO1 Target in Position.**

Split tensile tests were performed on field-cured target samples on day 21 (which was the test day for PMATP-EO1). These tests were performed on 6-inch by 12-inch cast cylinders taken from all four sections of the target. The results of these tests are shown in Table 5.1. Again, these average values are based on three test samples each.

**Table 5.1. Split Tensile Strengths on Day 21**

| Sample Location Within Target | Average Tensile Strength (psi) | Deviation from Average (psi) |
|---|---|---|
| Bottom – 1/4 | 113 | –3, +7 |
| 1/4 – 1/2 | 127 | –7, +3 |
| 1/2 – 3/4 | 77 | –7, +3 |
| 3/4 – top | 113 | –3, +7 |

Compressive strength samples were cored from the target on day 21, subsequent to the PMATP-EO1 impact. These cored samples were taken from the target in regions around the impact site that appeared to be undamaged. A photograph of the cored target is shown in Figure 5.20. The compressive strengths from each of the five cored samples are shown in Table 5.2. Four of the five cored samples, denoted by asterisks in Table 5.2, had visible cracks before testing.

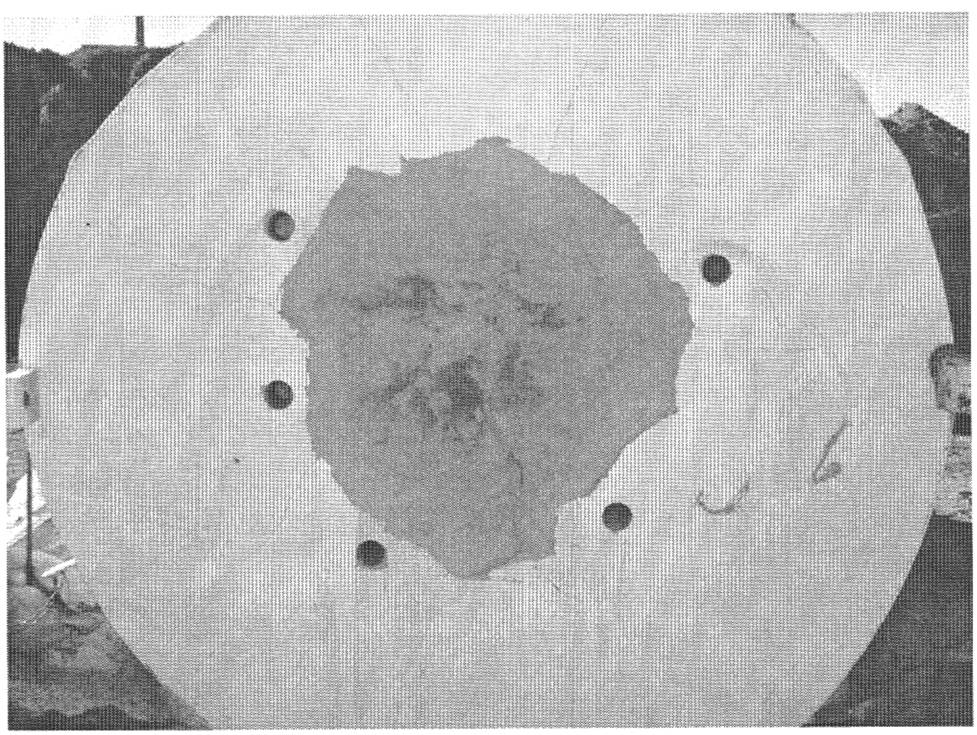

**Figure 5.20. Core Sample Locations.**

**Table 5.2. Post-test PMATP-EO1 Target Core Strengths**

| Core Location | Compressive Strength (psi) |
|---|---|
| Lower left side* | 760 |
| Low center* | 780 |
| Lower right side* | 750 |
| Upper right side* | 800 |
| Upper left side | 870 |

* Core samples had visible cracks before testing.

Triaxial compressive strengths were measured on test samples prepared during the original target pour. These strengths were measured 62 days after the pour date. As a part of this testing process, a single unconfined compressive strength was measured to be 1333 psi. This value appears realistic compared to the trend in strength up to 42 days seen in Figure 5.16. The triaxial strength data are shown in Figure 5.21, along with linear regressions and equations for the data. In triaxial testing, a sample is initially loaded to peak axial failure stress under maximum confining stress. This initial failure stress is referred to as peak strength in Figure 5.21. Once peak failure occurs, the confining stress is stepped down to a lower level and the sample is loaded again to failure. This procedure is repeated until the confining stress approaches zero. The failures subsequent to the initial peak failure define the residual strengths. In one case, a single sample was tested five times (one peak, four residual). Note that failure is defined as a significant drop in the stress-strain loading curve.

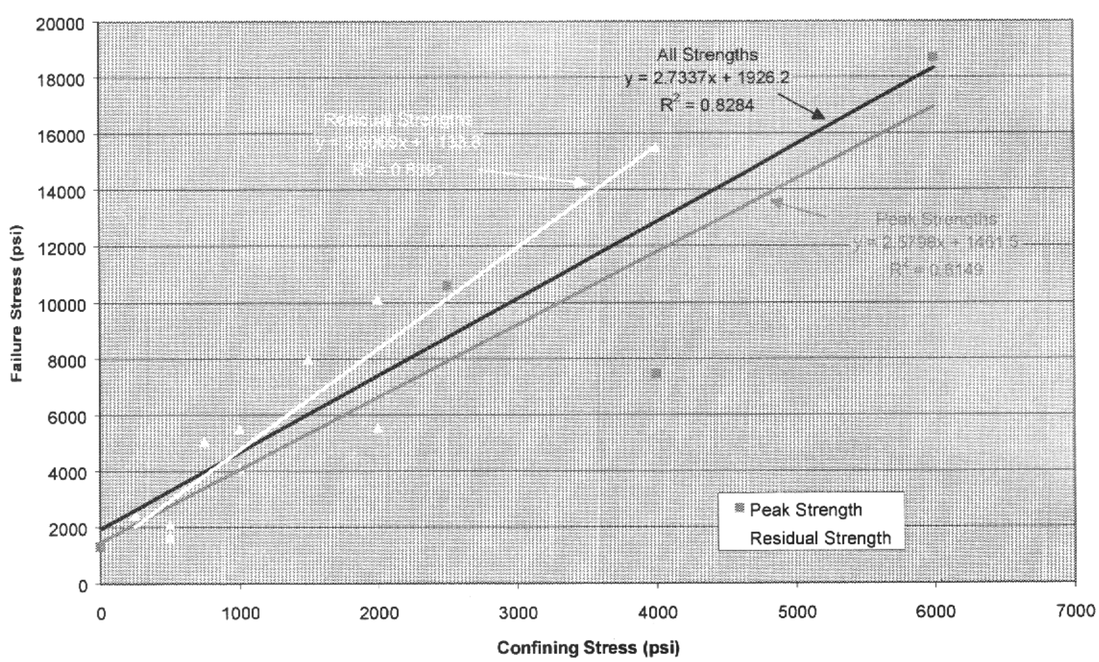


**Figure 5.21. Triaxial Compressive Strength of Target Concrete at 62 Days of Cure.**

The side of the target facing the photometric cameras had a three-inch-wide black cross, painted on the white target. The forward edge of the vertical stripe was 10.5 inches from the front edge of the target. A vertical marker was used as a fixed indictor to evaluate movement of the target during the impact as shown in Figure 5.22.

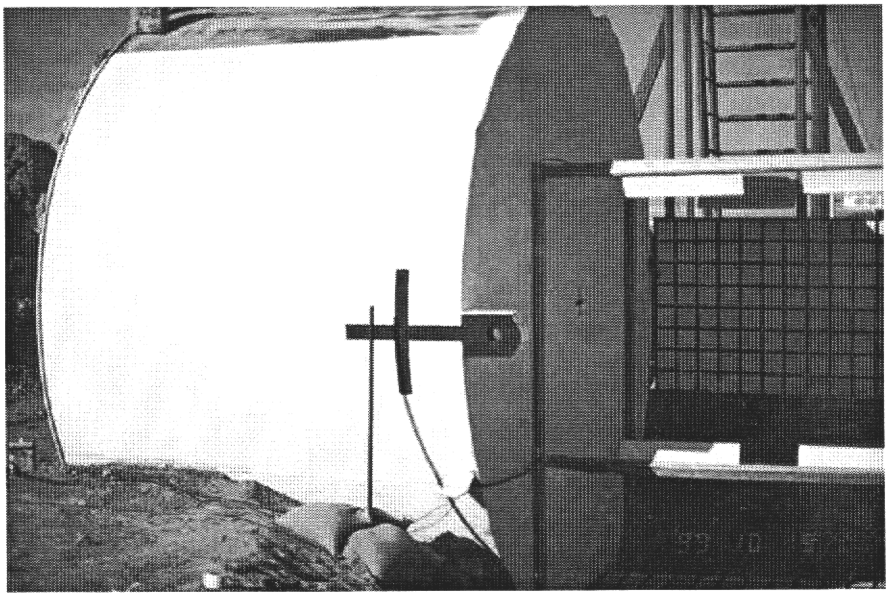

**Figure 5.22. Target Movement Indicator.**

For completeness, the temperatures of the concrete during curing are included in Figure 5.23. This information was collected to note the effect of air temperature on cure rates.

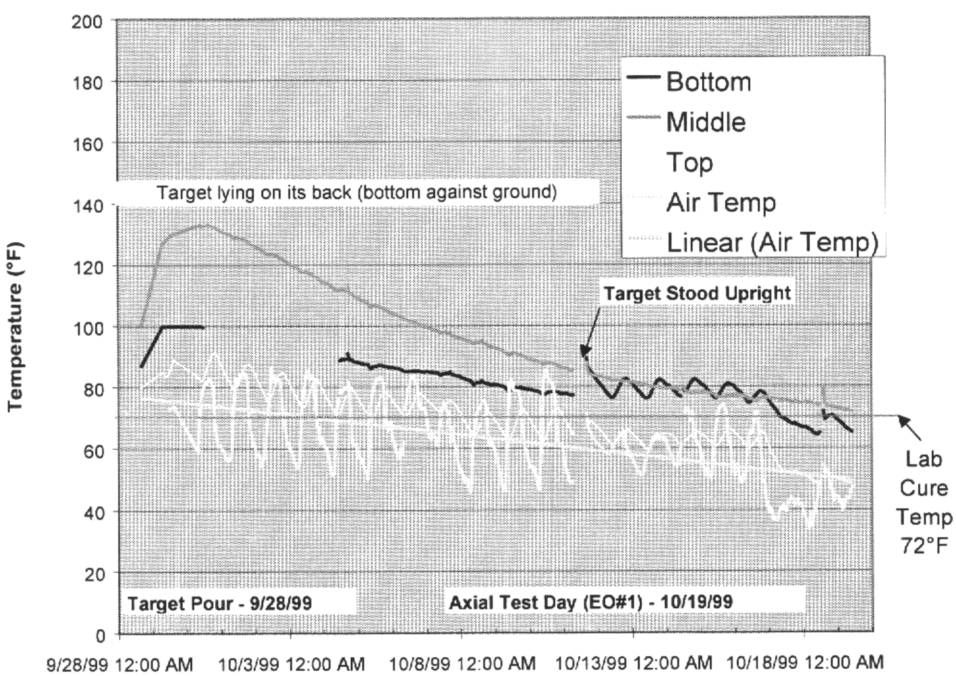


**Figure 5.23. Target Temperatures from Pour Until PMATP-EO1 Test.**

## 5.3 PMATP-EO1 Test Requirements

The PMATP-EO1 test was an end-on impact test into a light-strength concrete target. The desired velocity for this test was 925 ft/s at impact. To achieve this package velocity at the target location, the package was accelerated to a velocity above 1400 ft/s before sled braking.

The end-on impact test required the package be oriented horizontally and parallel to the sled track axis in order to impact the top flat end of the PMATP-EO1 into the center of the target.

### 5.3.1 Test Facility

The track of the 10,000-ft rocket sled test facility at SNL Tech Area III was modified with curved end rails as shown in Figure 5.24. An area between the rails was filled with water dams of increasing depth to sequentially slow the first-stage pusher sled. The test unit was supported above the track on a second-stage unpowered expendable sled. This second-stage sled was propelled along the track by a first-stage pusher sled containing eight Super Zuni rockets as shown in Figure 5.25. The launch position was approximately 2350 ft north of track Station 0 (the south end of the track). At burnout of the first-stage rocket motors, the first-stage sled was decelerated by water braking with separation of the second-stage sled and coasted along the track target at Station 0. Near Station 0, onboard explosive cutters severed the steel cables that held the test unit to the sled. As the sled passed Station 0, it was forced downward by 20-ft-long curved rail extensions that were welded to the existing rails as shown in Figure 5.26. At the end of the 20-ft curved rail section, the second-stage guide sled exited the track and impacted a containment plate approximately 3 ft to the south as shown in Figure 5.27. The containment plate forced the majority of the sled downward and into the ground. The momentum of the test unit carried it in a near-horizontal flight path over the containment plate and onto the concrete target, whose impact face was located 40 ft south of Station 0.

The second-stage guide sled consisted of a horizontal cradle attached by support members to four shoes. Each of the four shoes was made from quarter-inch shoe stock and gusseted to withstand the calculated 270 g uploading during the turning impacted by the curved rail section. This value was based on a 100-lb sled weight and a 1000-ft/s velocity. Details of the sled are shown in Figure 5.28. The first-stage pusher sled was a utility sled designed to carry up to 25 five-inch rocket motors. An adapter was fabricated that would push the test unit sled and is seen in Figure 5.29. A separation distance of 30 inches was used between the sleds to minimize adverse effects of water spray on the test unit during braking and separation of the first-stage sled. Cables used to tie down the test unit can be seen in Figure 5.29, along with the explosive cutters, wrapped in yellow tape, that were used to sever the cables near Station 0.

Timing switches were also installed along the sled track to determine sled velocity as shown in Figure 5.30. The timing switches were cut by the second-stage guide sled immediately before impact.

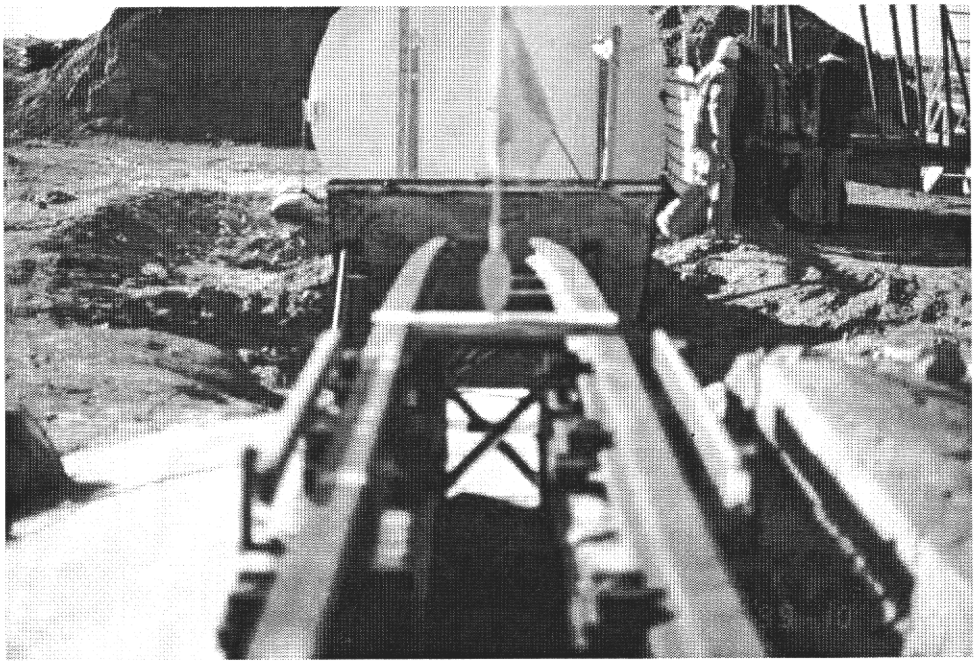

Figure 5.24. Rocket Sled Test Facility.

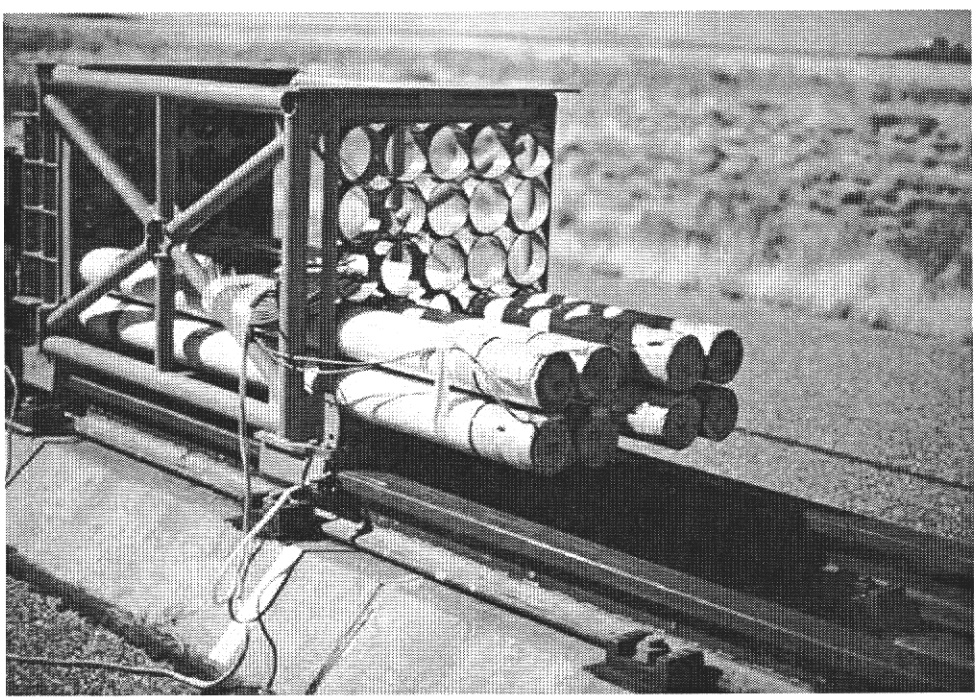

Figure 5.25. PMATP-EO1 First-Stage Pusher Sled.

**Figure 5.26. Curved Rails.**

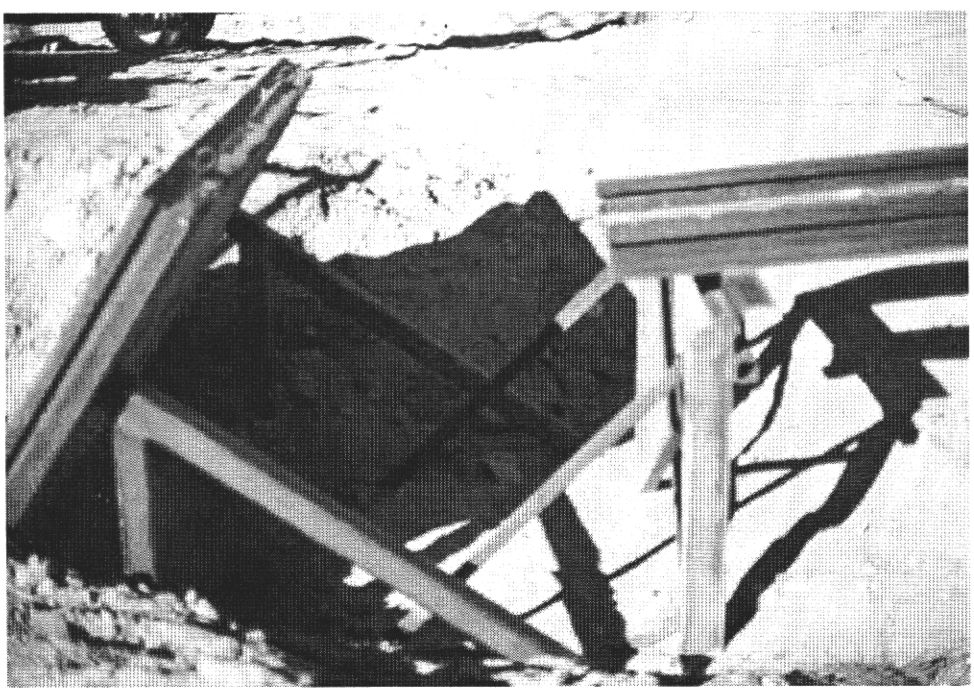

**Figure 5.27. Containment Plate.**

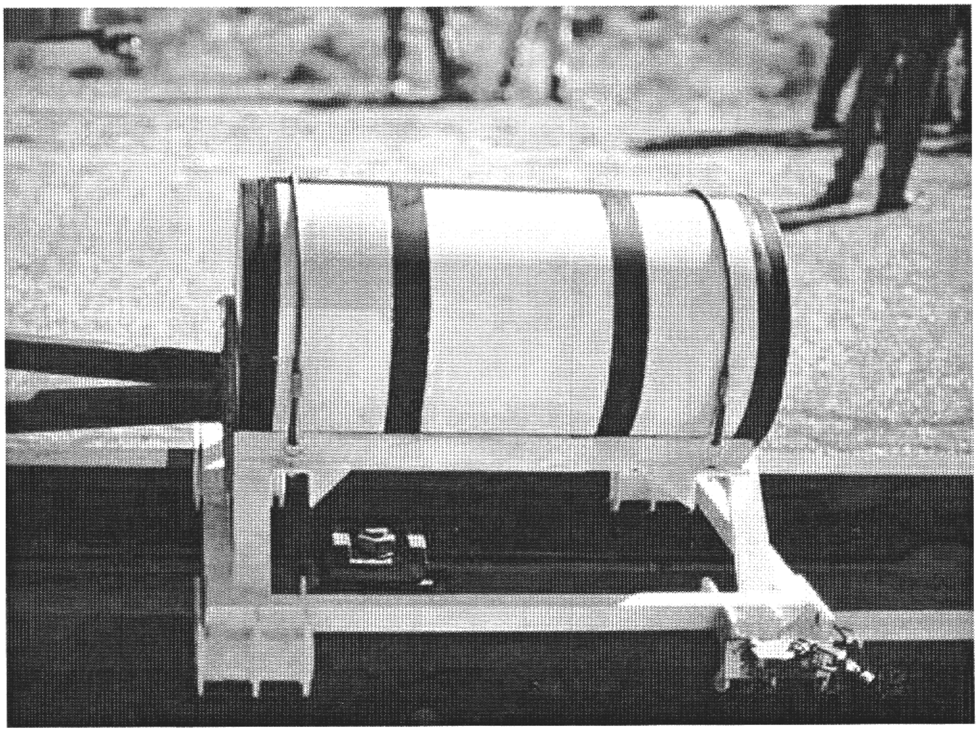

Figure 5.28. PMATP-EO1 Guide Sled.

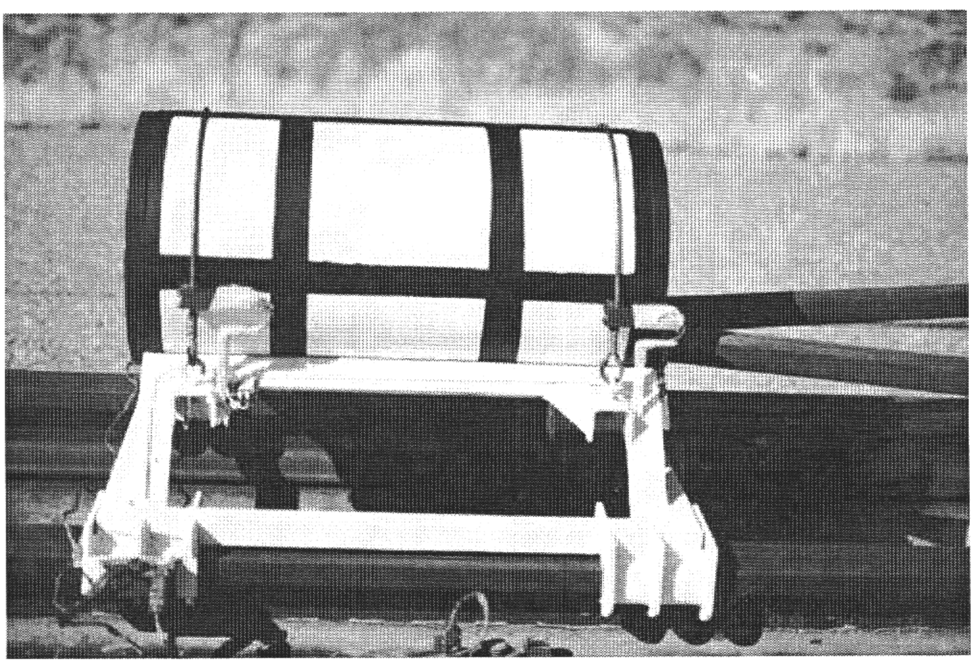

Figure 5.29. PMATP-EO1 Separation Hardware.

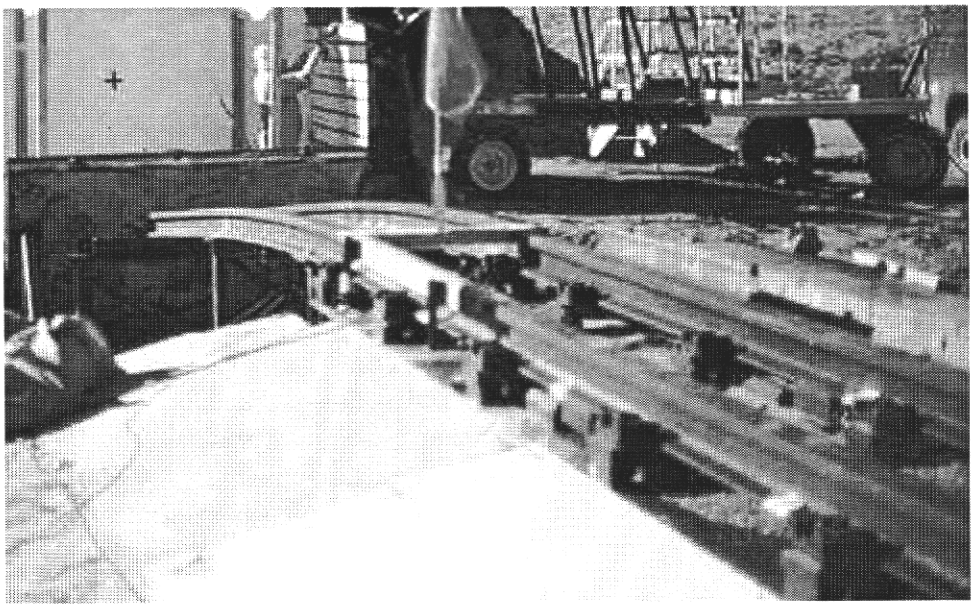

**Figure 5.30. PMATP-EO1 Timing Switches.**

## 5.3.2 Photometrics

Pre- and post-test documentary photographs were taken. These included 35-mm still photographs of the test site, the equipment and instrumentation to be used, fixtures, hardware, and rigging needed for the test. The top, bottom, and all four sides of the test package were photographed before the test and again after the test.

High-speed cameras were positioned for top and side views of the impact area to determine impact velocity and to observe package performance throughout the impact. Hand-tracked cameras were used to document the full extent of the test. The camera types, locations, and coverage are shown in Figure 5.31. A total of 21 film and video cameras were used in support of the PMATP-EO1 impact test. This included 13 16-mm film cameras, two high-speed digital cameras, one 70-mm film camera, three SVHS video cameras, and two high-speed slit cameras (IM). The relative positions of each of these cameras and the frame rates used by each are included in the camera layout schematic shown in Figure 5.31. The dashed lines indicate the approximate field of view for each camera.

A laser tracker was positioned to track the package during the test for accurate determination of package location and velocity throughout the test. The laser tracker locked onto a reflective marker that was located on the package and followed the package throughout the test as shown in Figure 5.32. High-speed cameras were mounted on the tracking platform to provide additional photometric documentation of the test.

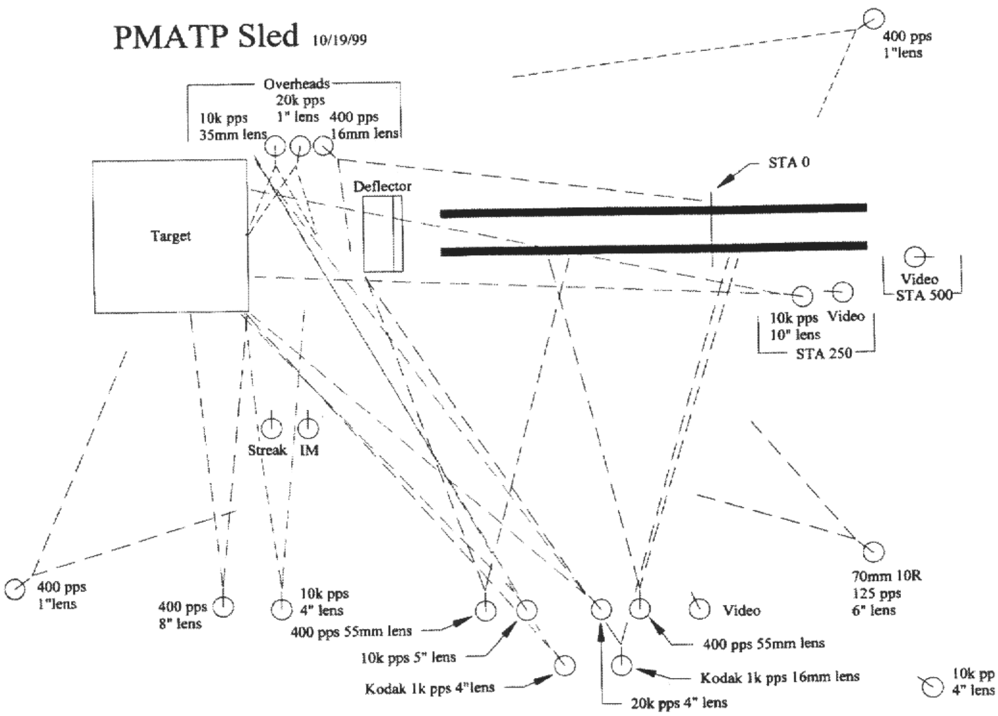


**Figure 5.31. PMATP-EO1 Camera Layout.**

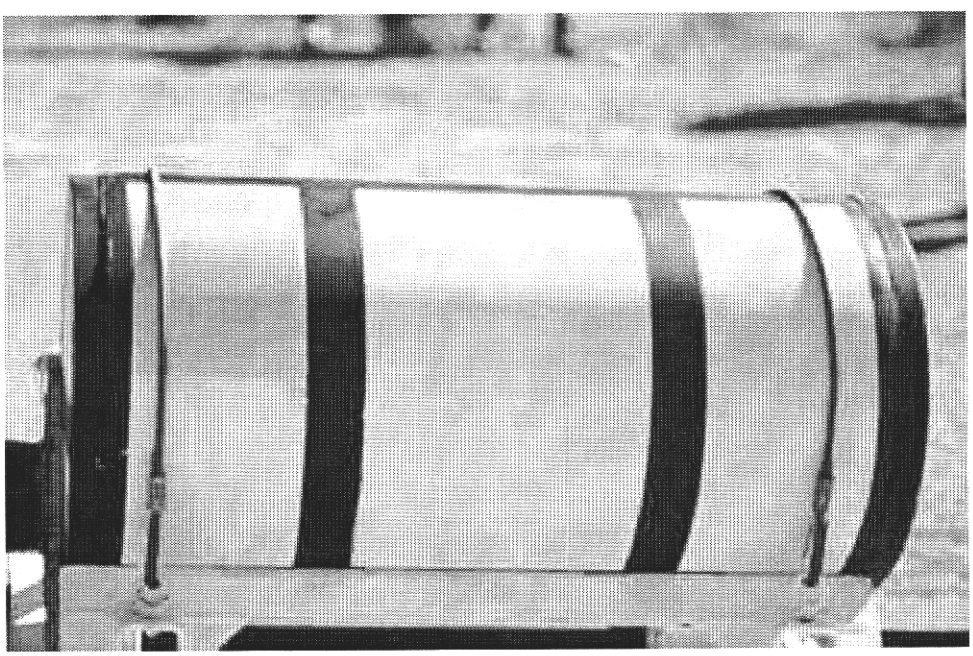

**Figure 5.32. PMATP-EO1 Reflective Marker.**

### 5.3.3 Inspection Measurements

The inner containment vessel was inspected by SNL personnel before assembly for pretest measurements and again after disassembly for post-test measurements. Diameters were measured at 0° – 180°, 45° – 225°, 90° – 270°, and 135° – 315°.

The closure was measured at one location on the largest shoulder diameter. The container body was measured at five locations including the top, midway between top and center, center, midway between center and bottom, and bottom. Lengths were measured every 45° with and without the closure installed.

### 5.3.4 Test Unit Weight Measurements

The weights of various components were documented before each test. The inner containment vessel was weighed when empty and after the steel shot mass was loaded. The overpack body, End Plug 1, and End Plug 2 were weighed before assembly. The total package weight was measured after final assembly.

## 5.4 PMATP-EO1 Test Results

### 5.4.1 End-On Impact Test

The test article was configured for an end-on impact test of 925 ft/s. The as-tested weight of the test article was 289 lb as shown in Table 5.3. The first-stage pusher sled weighed 1595 lb including rockets, and the total weight of the second-stage sled and test package was 360 lb. The test unit was launched from Station 2350 and the target was placed at Station 40 for a total travel distance of 2390 ft.

**Table 5.3. PMATP-EO1 Weight Measurements (lb)**

| | |
|---|---|
| Containment vessel empty | 15.70 |
| Containment vessel full | 22.70 |
| Overpack body | 208.50 |
| End Plug 1 | 27.95 |
| End Plug 2 | 27.60 |
| Total assembled weight | 289.00 |
| Target weight | 142,000.00 |

Figures 5.33 through 5.37 show the PMATP-EO1 being prepared for the end-on impact test.

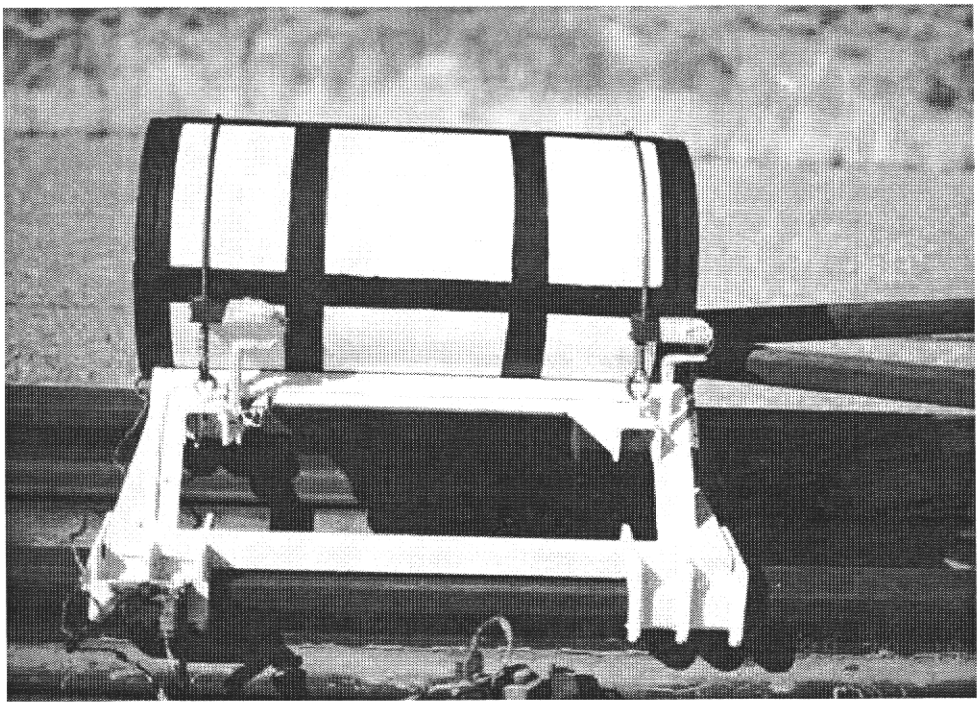

Figure 5.33. PMATP-EO1 Mounted in Stage 2 Guide Sled.

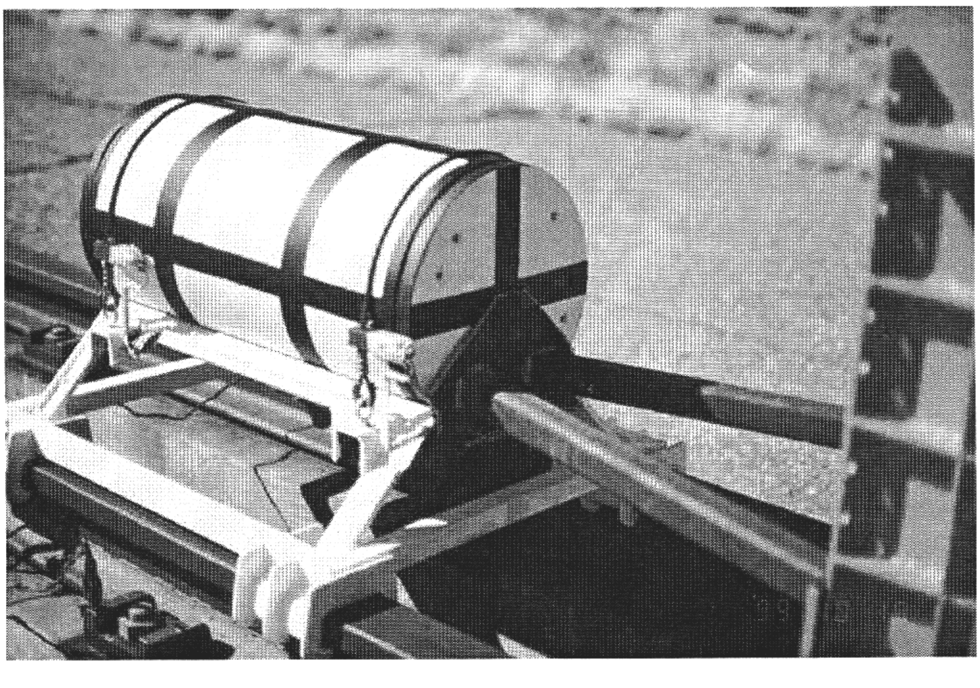

Figure 5.34. PMATP-EO1 Stage 1 to Stage 2 Interface.

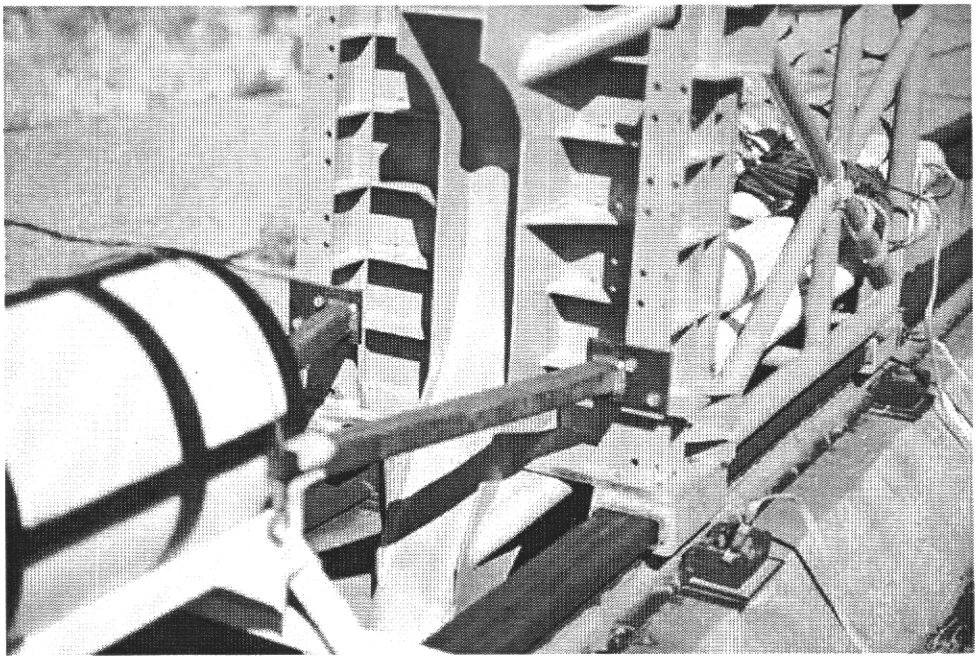

**Figure 5.35. PMATP-EO1 Grounded Sled Ready for Arming.**

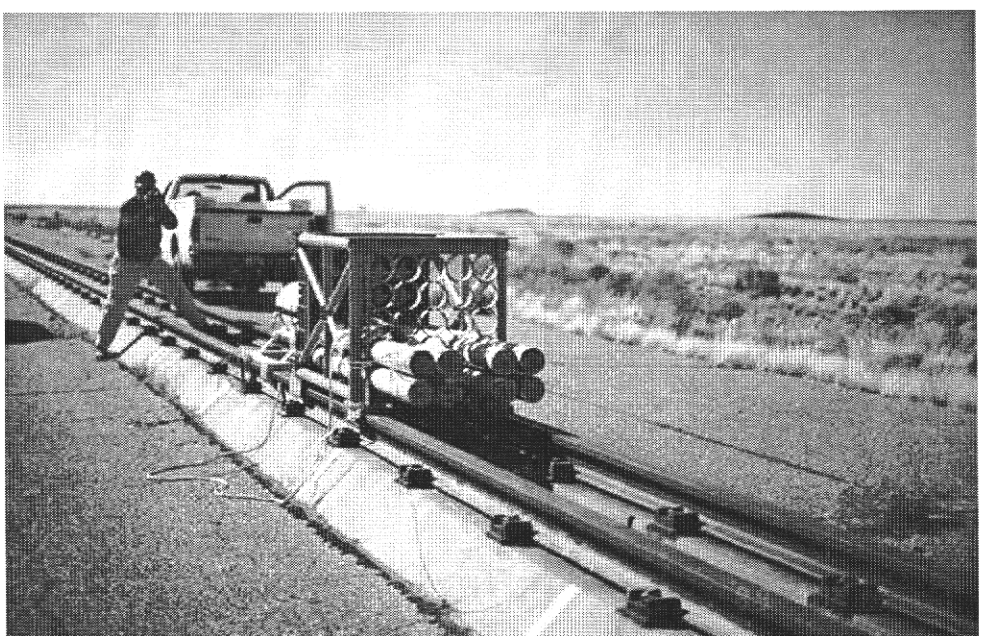

**Figure 5.36. PMATP-EO1 with Eight Super Zuni Rockets.**

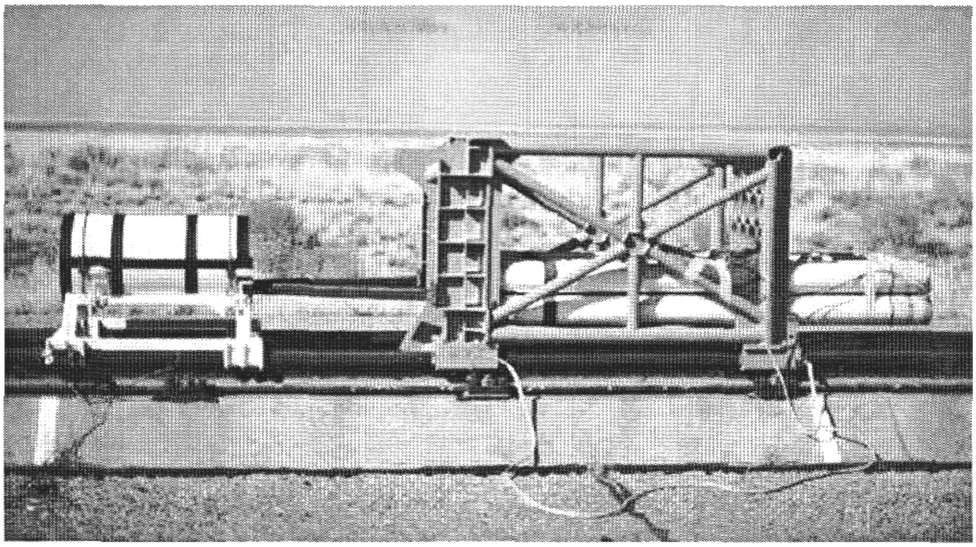

**Figure 5.37. PMATP-EO1 Ready for Test.**

The PMATP-EO1 impact test was performed on October 19, 1999, at 11:30 a.m. MST. The rockets fired as desired, and the first-stage pusher sled accelerated the second-stage guide sled and package as expected. The package impacted in the desired horizontal orientation (perpendicular to the target) at a velocity of 910 ft/s.

The IM camera shown in Figure 5.31 recorded the test unit velocity and was located 7 ft in front of the impact face of the target. The streak camera (an IM turned on its side) was located approximately 5 ft in front of the face of the target. This streak camera measured test unit velocity as well as deceleration of the test unit during impact.

Three pretest trajectories are presented in Figure 5.38 together with post-test data from break wires, laser tracker, and IM cameras. The three pretest trajectories represent engineering estimates for fast, slow, and best-estimate trajectories. The uncertainty in each of these trajectory predictions was the aerodynamic drag of the test unit, the sled holding the test unit, and the first-stage pusher sled, and, more important, the interaction of the airflow between these three bodies. Harold Spahr, of the SNL Aerosciences and Fluid Mechanics Department, provided experimental data for a cylinder in freestream flow. These data were utilized together with the experience gained from the previous PMATP side-on test and the sled calibration test to develop trajectory data at package impact with a velocity span of approximately 60 ft/s. The upper bound of the velocity band was placed at 950 ft/s.

The laser tracker trajectory matched very well with the discrete break wire data points along the track. Data from near the end of the run experienced undesirable fluctuations that were assumed to result from environmental effects rather than actual behavior of the test unit. The IM, streak, and break wire data points all indicated an impact velocity of approximately 910 ft/s compared to 885 ft/s from the laser tracker. This translated into a difference of 3%. It should be noted that the break wire impact velocity is a calculated value based on unit velocity 60 ft before impact and calculated deceleration based on assumed aerodynamic drag coefficients.

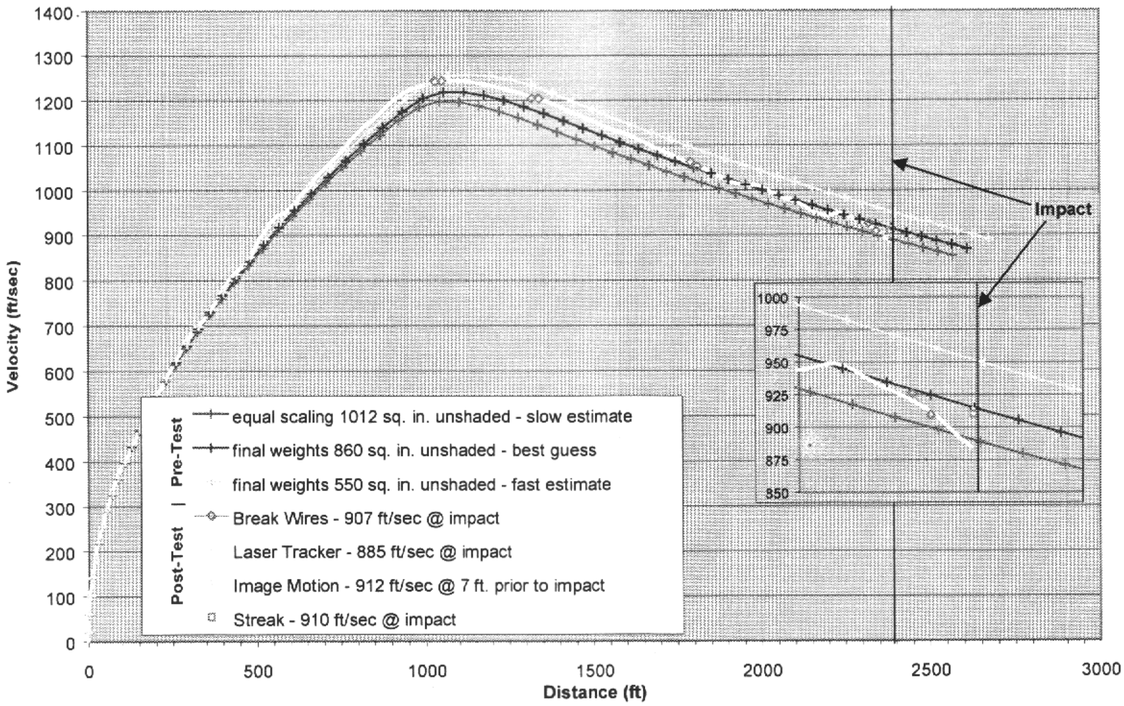


**Figure 5.38. Pretest and Post-test Velocity Trajectories for PMATP-EO1.**

The use of a streak camera in PMATP-EO1 provided a measure of the unit velocity before impact as well as the unit deceleration during impact. The streak camera used was a slit camera like the IM, but with the slit parallel to the direction of travel of the test unit rather than perpendicular. The images in Figures 5.39 and 5.40 are negatives taken from the streak camera and, as such, the black stripes on the unit appear white in the image.

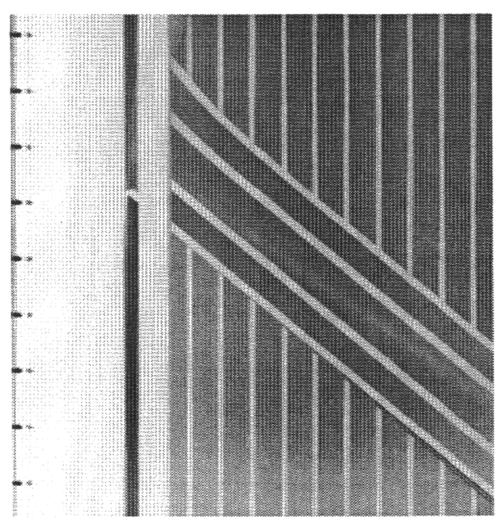

**Figure 5.39. Image from Streak Camera without Visual Aids.**

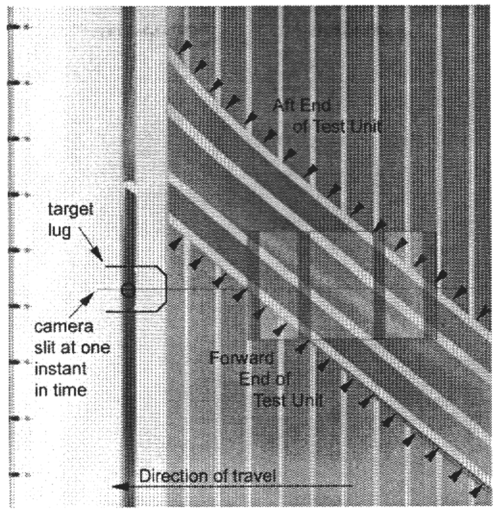


**Figure 5.40. Image from Streak Camera with Visual Aids.**

In the images, the test unit moves from right to left while the film moves from top to bottom. The vertical black stripes on the test unit are observed on the film as diagonal white lines as a result of the combined motion of the unit and the film. The forward stripe on the unit corresponds to the bottom diagonal line, and the aft stripe on the unit corresponds to the top diagonal line. The vertical white lines in the image correspond to the portion of vertical black lines on the target board backdrop that line up with the slit in the camera. The fact that they appear as lines is because the film sweeps past the camera slit. These lines appear straight and vertical because they remain stationary as the film sweeps past the camera slit.

One-millisecond timing marks are seen on the left-hand vertical edge of the image. The length scale in the image was obtained by comparing the length of the test unit to the horizontal distance between the forward end of the unit and the aft end of the unit in the image. The distance-time information can be differentiated to obtain velocity and change of velocity of the unit. For instance, the relatively straight appearance of the diagonal line representing the forward end of the unit indicates a near-constant velocity of the forward end of the unit. The curved nature of the diagonal line representing the aft end of the unit, particularly in the upper left portion of the image, indicates that the aft end of the test unit was decelerating as the unit impacted the target.

The image in Figure 5.40 had visualization aids added for clarity. The slit in the streak camera was located physically at the height of the lifting hole in the lug on the east side of the target. A representation of the lug has been included in Figure 5.40 showing where the hole appears in the image as a vertical black line. The forward end of the test unit can actually be seen in this vertical black line at a position above where the lug is drawn, i.e., at a later point in time, as the unit passed behind the lug before impact. A ghost image of the test unit has been drawn in Figure 5.40 to show how the diagonal white lines line up with the corresponding black lines on the test unit.

The velocity data shown in Figure 5.41 represent the velocity of the aft end of the test unit as calculated from the streak camera data in Figure 5.40. The data trace in Figure 5.41 represents a five-point running average of the change in raw position data divided by the change in time over approximately 50-microsecond intervals. The computed trace represents the time derivative of a two-piece regression to the raw position-time data. The time scale for each of the plots is time in milliseconds with an arbitrary reference point. Impact of the test unit is seen in Figure 5.41 to occur near a time value of 6 milliseconds where the unit's velocity sharply decreased from 910 ft/s.

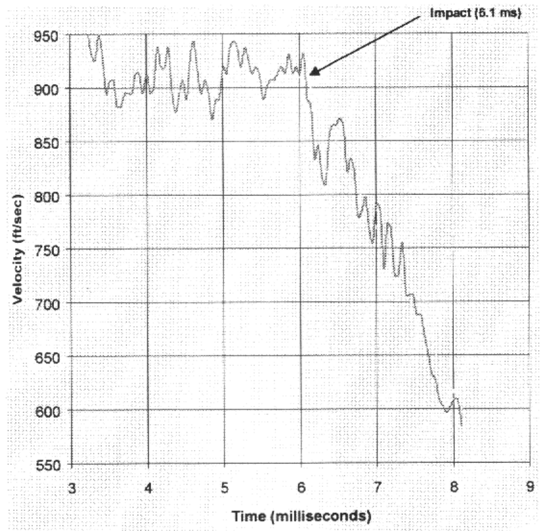


**Figure 5.41. PMATP-EO1 Aft End Velocity.**

The acceleration data in Figure 5.42 are the time derivative of the velocity data in Figure 5.39. The deceleration of the aft end of the unit is a constant –4765 g's (–153,433 ft/sec$^2$). This constant deceleration is based on the second-order regression of the nonlinear portion of the position-time data from Figure 5.40.

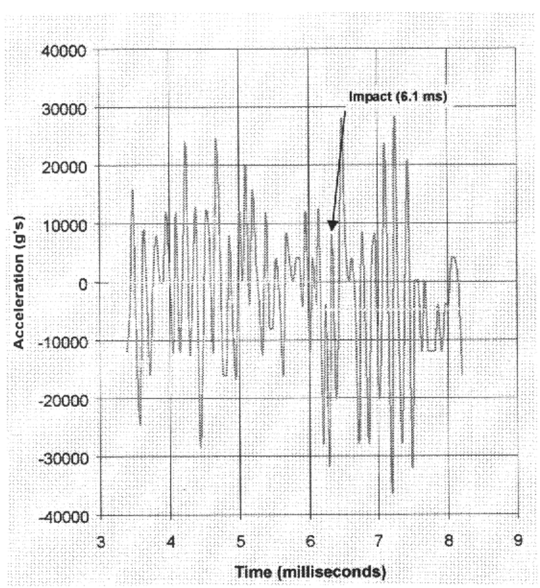


**Figure 5.42. PMATP-EO1 Aft End Deceleration.**

Orthogonal views of the test unit were obtained on 16-mm film for PMATP-EO1. However, these images were not digitized to allow calculation of impact angle. Calculations performed by freezing video frames indicated that the test unit had approximately one-degree nose-down angle of attack near impact and approximately three degrees of yaw.

Figure 5.43 illustrates the test unit entering the target during the impact test. The PMATP-EO1 outer shell crushed as expected in an accordion-like manner as shown in Figure 5.44. The bottom cover sheared from the package, thus exposing the overpack perforated aluminum and Kevlar™ cloth as shown in Figure 5.45. The containment vessel remained confined in the over-pack. The package rebounded from the target and landed 75 ft north of the target and 38 ft west of the track.

A crater was formed at the impact area of the target approximately 60 inches in diameter and 16 inches deep at the center as shown in Figure 5.46. Compressive strength tests the day of the test indicated the target was in the desired range to simulate the PSA crash site as shown in Table 5.4.

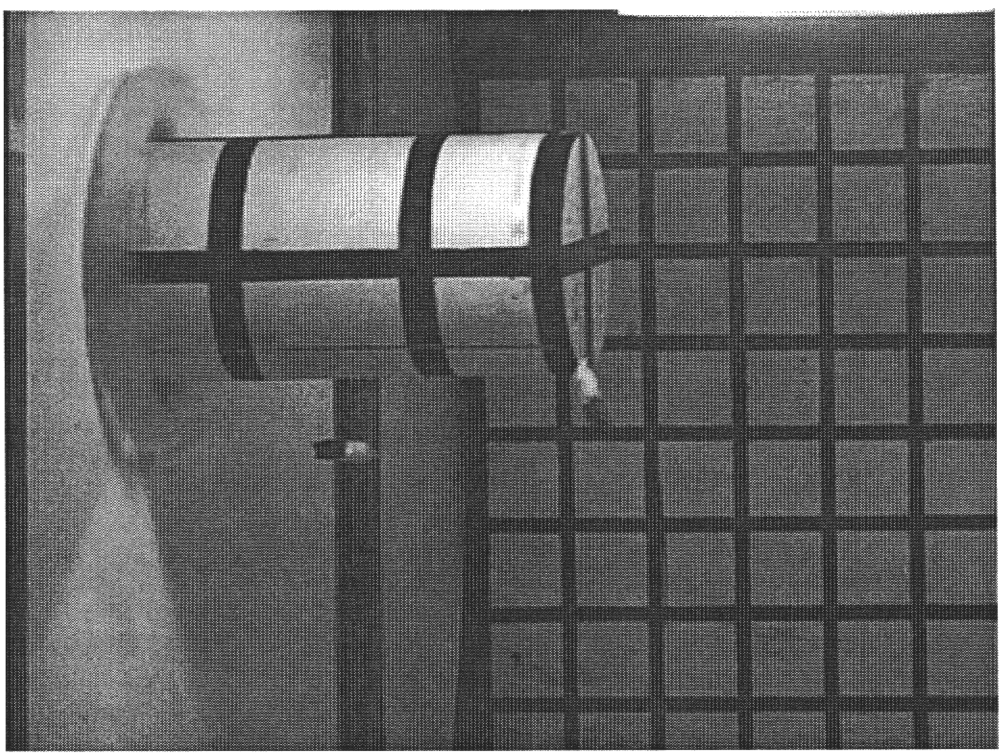

**Figure 5.43. PMATP-EO1 Test Article and Target During Impact Test.**

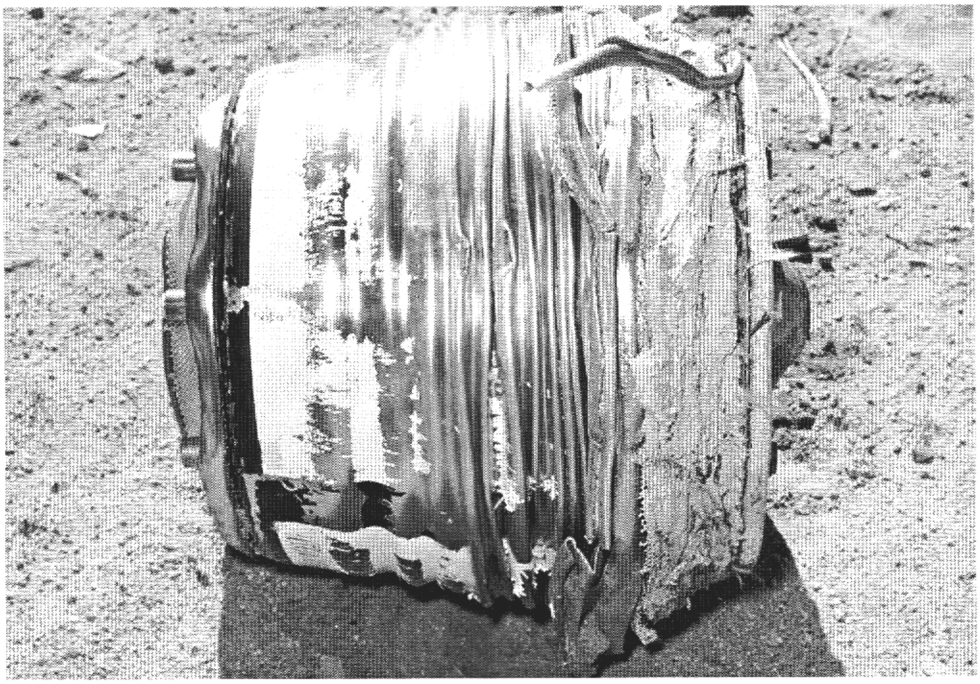

Figure 5.44. PMATP-EO1 Expected Crush.

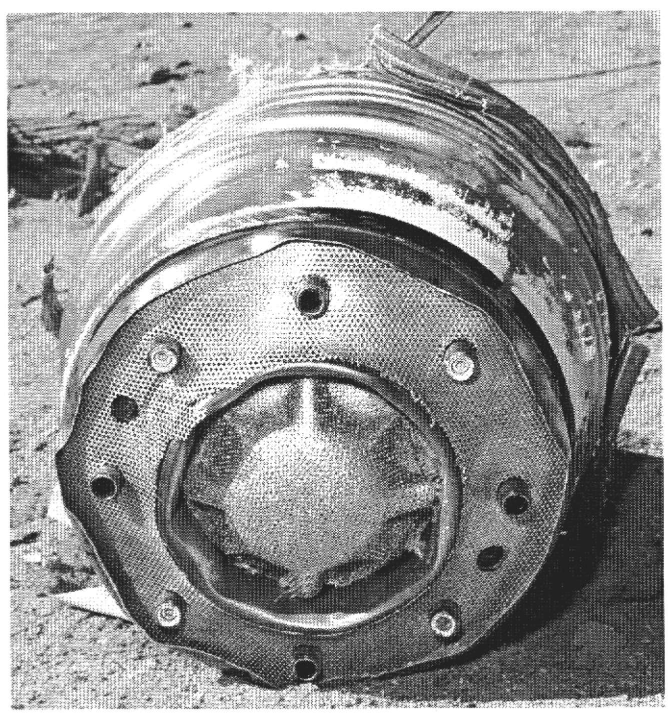

Figure 5.45. PMATP-EO1 Exposed Bottom End.

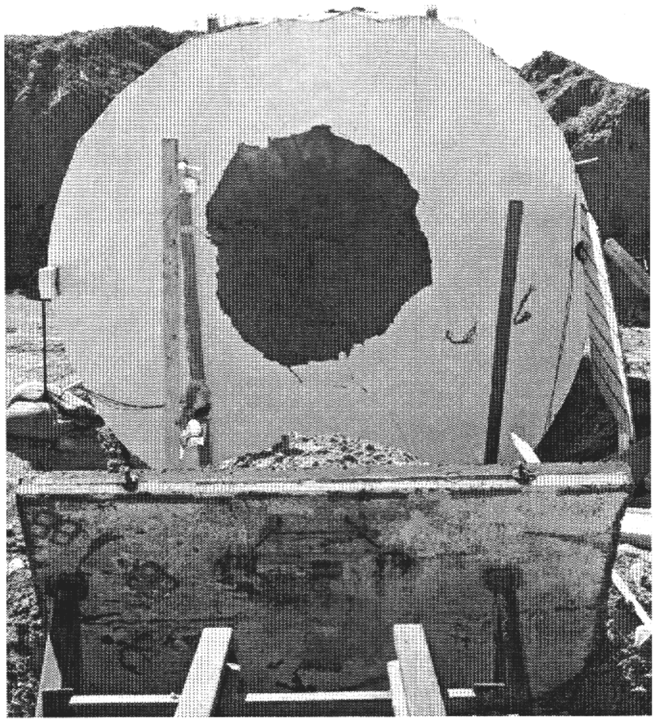

**Figure 5.46. Target After PMATP-EO1 Impact Test.**

**Table 5.4. PMATP-EO1 Concrete Target Compressive Strengths**

| Layer | Compressive Strength Day of Test |
|---|---|
| 1 back end | 1040 psi |
| 2 | 1070 psi |
| 3 | 980 psi |
| 4 impact end | 1080 psi |

The test conditions for the PMATP-EO1 test are depicted in Table 5.5.

**Table 5.5. Test Conditions for End-On Impact Test**

| | |
|---|---|
| Temperature | 53°F at 11:30 |
| Lighting | Full sun |
| Wind direction | Out of east |
| Wind velocity | <5 mph |
| Number of rockets | 8 Super Zuni rockets |

## 5.5 PMATP-EO1 Disassembly and Evaluation

After the end-on impact test, the PMATP-EO1 was retrieved for disassembly and evaluation.

The inner containment vessel remained intact and within the overpack. The inner containment vessel was removed from the overpack for inspection. Deformation of the overpack was located in the inner container as shown in Figure 5.47. The test article was cut along the axis through the overpack and inner container as shown in Figure 5.48. The inner containment vessel deformed as shown in Figure 5.49. Physical dimensions of the inner containment vessel are documented in Tables 5.6 and Table 5.7. Only one-half of the containment vessel was removed for evaluation. There were no post-test diameter measurements taken. The closure lid was deformed approximately 0.067 inch at the center, and its threads were sheared. The container body wall had less than 0.002-inch deformation along the full length.

## 5.6 PMATP-EO1 Conclusions

A half-scale plutonium air-transportable package test unit identified as PMATP-EO1 was successfully tested at the Full-Scale Experimental Complex 10,000-ft sled track in SNL's Tech Area III Test Facility. The PMATP-EO1 was subjected to an end-on orientation impact test as specified in the Murkowski Amendment.

The inner containment vessel suffered little damage. The measured deformation was approximately 0.002 inch from the center diameter of the container body. The closure lid suffered more damage than anticipated, including deformation of approximately 0.067 inch and shear failure of the closure threads. Further evaluation has determined this damage resulted from the improper fit of the closure lid on the container body shoulder.

Lessons learned from this test include optimizing the overpack design with more perforated aluminum sheet and Kevlar™ cloth in the overpack end plugs and reducing tolerances of the inner containment vessel to assure good contact between the closure lid and containment body. This test clearly demonstrated the viability of perforated aluminum sheet and Kevlar™ cloth as an excellent energy-absorbing overpack material.

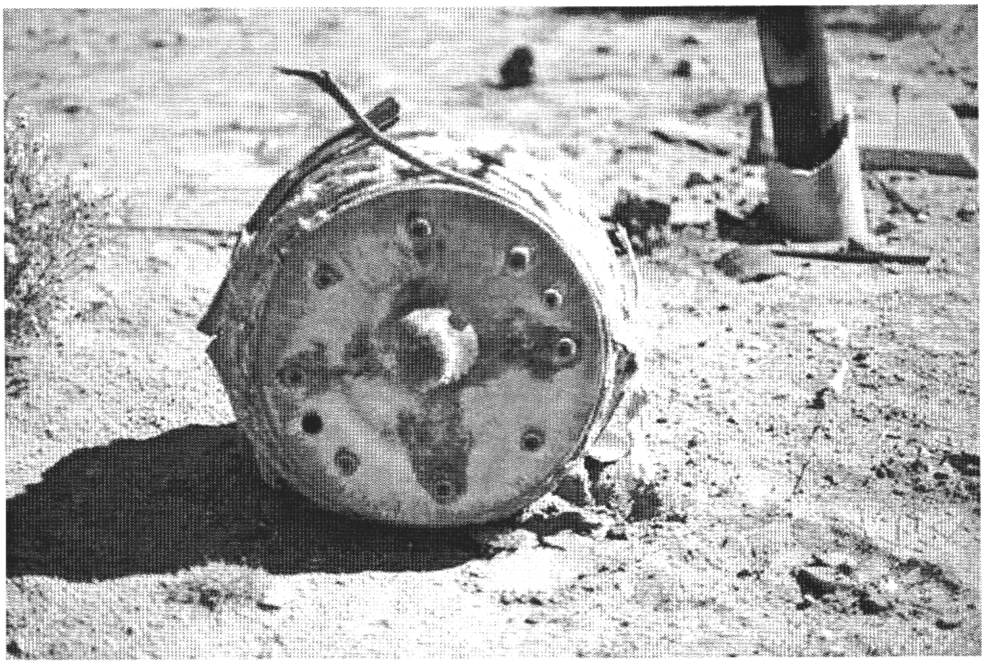

**Figure 5.47. Locating PMATP-EO1 Inner Containment Vessel.**

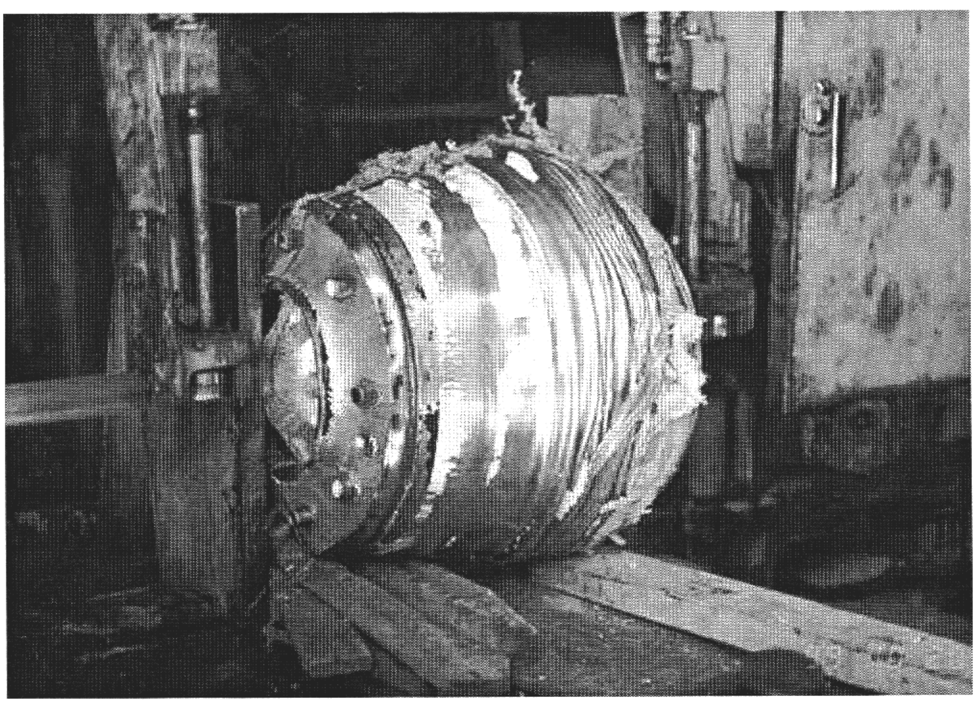

**Figure 5.48. Cutting Through the PMATP-EO1 for Inspection.**

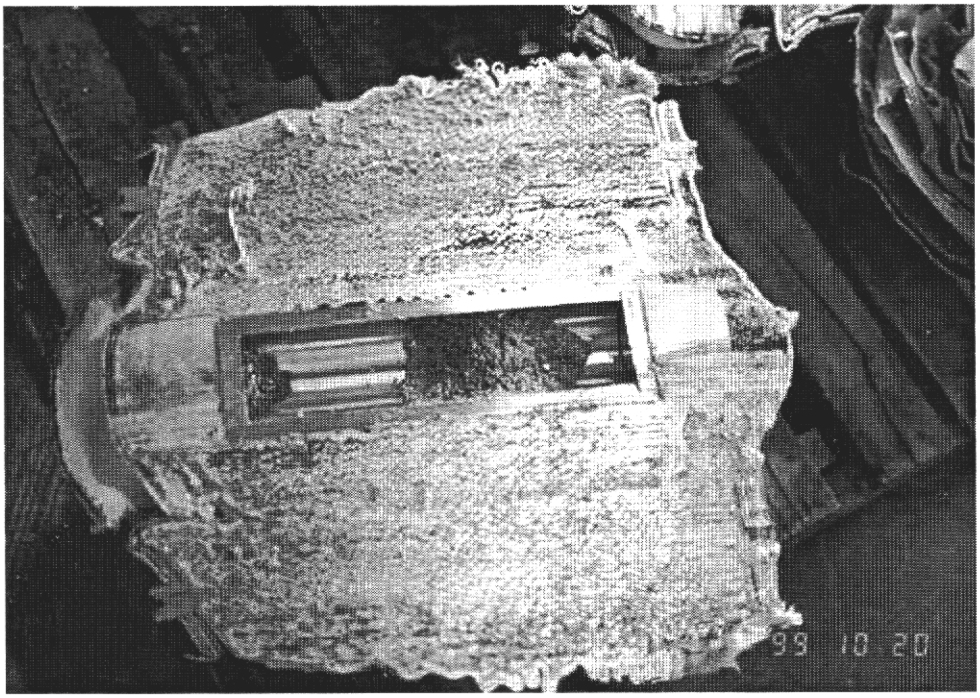


**Figure 5.49. PMATP-EO1 Inner Containment Vessel Deformation.**

**Table 5.6. PMATP-EO1 Inspection Measurement Lengths (inches)**

| | L0° | L45° | L90° | L135° | L180° | L225° | L270° | L315° |
|---|---|---|---|---|---|---|---|---|
| Pre no lid | 11.677 | 11.678 | 11.677 | 11.677 | 11.679 | 11.678 | 11.679 | 11.677 |
| Post no lid | N/A | 11.675 | 11.674 | 11.676 | 11.677 | N/A | N/A | N/A |
| Difference (no lid) | N/A | –.003 | –.003 | –.001 | –.002 | N/A | N/A | N/A |
| Pre w/lid | 11.798 | 11.798 | 11.798 | 11.800 | 11.800 | 11.800 | 11.798 | 11.798 |
| Post w/lid | N/A | 11.790 | 11.790 | 11.798 | 11.800 | N/A | N/A | N/A |
| Difference (w/lid) | N/A | –.008 | –.008 | –.002 | .000 | N/A | N/A | N/A |

**Table 5.7. PMATP-EO1 Inspection Measurement Diameters (inches)**

| | D0° – 180° | D45° – 225° | D90° – 270° | D135° – 315° |
|---|---|---|---|---|
| Pre closure | 3.503 | 3.502 | 3.502 | 3.502 |
| Post closure | N/A | N/A | N/A | N/A |
| Difference (closure) | N/A | N/A | N/A | N/A |
| Pre body top | 3.504 | 3.503 | 3.503 | 3.502 |
| Post body top | N/A | N/A | N/A | N/A |
| Difference (body top) | N/A | N/A | N/A | N/A |

**Table 5.7. PMATP-EO1 Inspection Measurement Diameters (inches) (continued)**

| | D0° – 180° | D45° – 225° | D90° – 270° | D135° – 315° |
|---|---|---|---|---|
| Pre body TC (top, center) | 3.504 | 3.504 | 3.504 | 3.504 |
| Post-body TC | N/A | N/A | N/A | N/A |
| Difference (top, center) | N/A | N/A | N/A | N/A |
| Pre-body center | 3.502 | 3.504 | 3.503 | 3.503 |
| Post-body center | N/A | N/A | N/A | N/A |
| Difference (body center) | N/A | N/A | N/A | N/A |
| Pre-body CB (center, bottom) | 3.507 | 3.506 | 3.507 | 3.507 |
| Post-body CB | N/A | N/A | N/A | N/A |
| Difference (center, bottom) | N/A | N/A | N/A | N/A |
| Pre-body bottom | 3.507 | 3.508 | 3.507 | 3.507 |
| Post-body bottom | N/A | N/A | N/A | N/A |
| Difference (body bottom) | N/A | N/A | N/A | N/A |

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# 6. PMATP-CGOC1

## 6.1 PMATP-CGOC1 Package Description

The PMATP center-of-gravity over corner (CGOC) prototype is a right circular cylinder. The PMATP-CGOC1 was 15 inches in diameter by 32 inches long and weighed 307.5 lb. This package had an inner containment vessel that was 3.5 inches in diameter and 11.675 inches long, and had a wall thickness of 0.5 inch. It was constructed from S13-8 H1100 stainless steel as shown in Figure 6.1. The containment vessel was filled with No. 6 steel shot to simulate mass as shown in Figure 6.2. The PMATP-CGOC1 was slightly modified from the PMATP-EO1 package. The overpack package was made from 16-gauge 304 stainless steel except that the tee slot and button locking plates were 0.120-inch 304 stainless steel. The end caps were also modified to add one inch more of the perforated aluminum with Kevlar™ cloth energy-absorbing packing.

The containment vessel was placed in a two-step 16-gauge 304 stainless-steel inner tube as shown in Figure 6.3. The inner tube was wrapped with perforated aluminum sheet and Kevlar™ cloth as shown in Figure 6.4. The wrap cycles included three wraps of perforated aluminum sheet and two wraps of perforated aluminum with Kevlar™ cloth. The perforated aluminum was 0.032-inch-thick 3003-H14 with a 51% open space made with 0.115-inch-diameter staggered holes 0.117 inch apart. The Kevlar™ cloth was approximately 0.018 inch thick. The PMATP-CGOC1 had a 16-gauge 304 stainless-steel outer shell welded to the outer plates of the inner tube as shown in Figure 6.5.

The PMATP-CGOC1 had two end plugs made of 16-gauge and 0.120-inch 304 stainless steel as shown in Figure 6.6. The end plugs were filled with three diameters of 3003-H14 0.063-inch perforated aluminum discs stacked as shown in Figures 6.7 through 6.9. The two larger diameter discs were stacked with Kevlar™ cloth in the same pattern as the wrapping of the overpack body. The end plugs had a 16-gauge 304 stainless-steel outer plate welded to completely enclose the packing materials as shown in Figure 6.10.

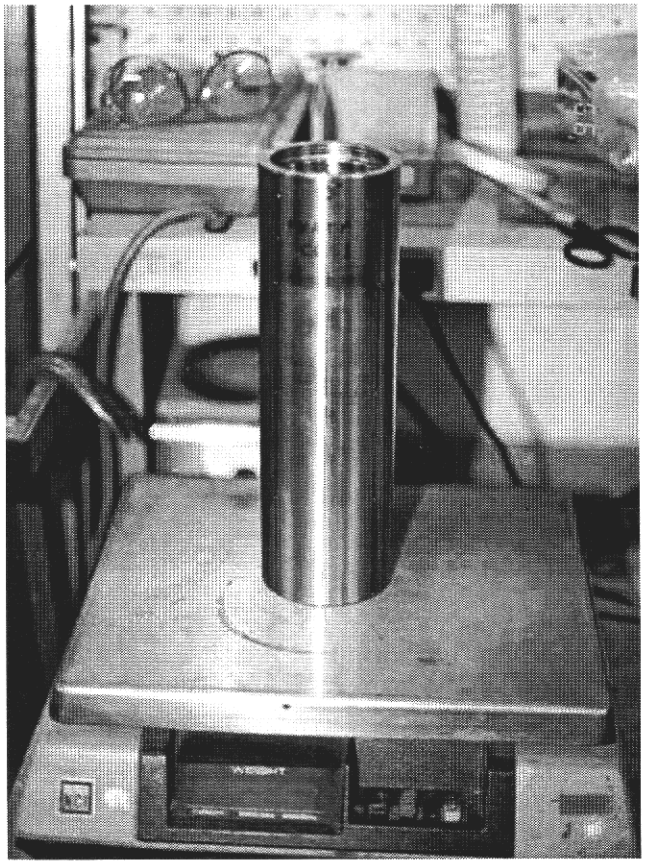

**Figure 6.1. PMATP-CGOC1 Inner Containment Vessel.**

**Figure 6.2. PMATP-CGOC1 Inner Containment Vessel Loaded with Steel Shot.**

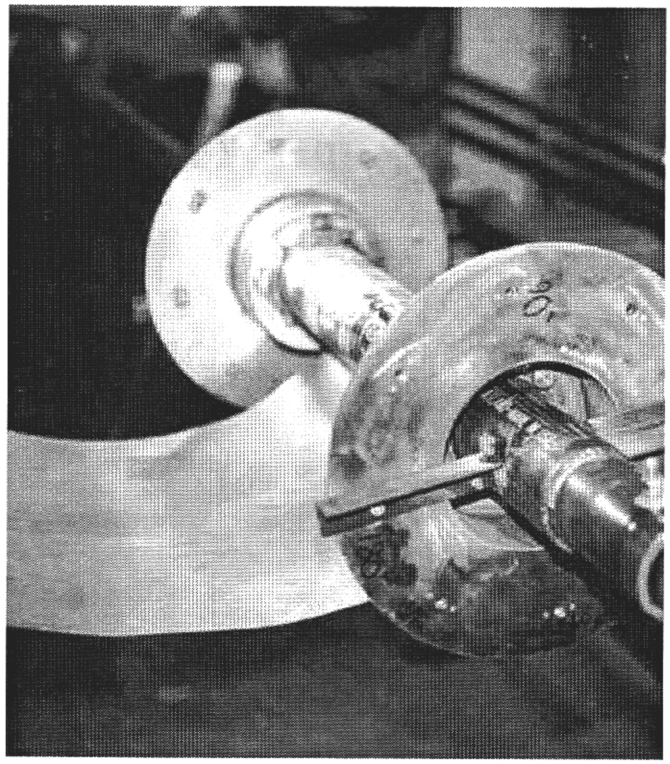

Figure 6.3. PMATP-CGOC1 Inner Tube.

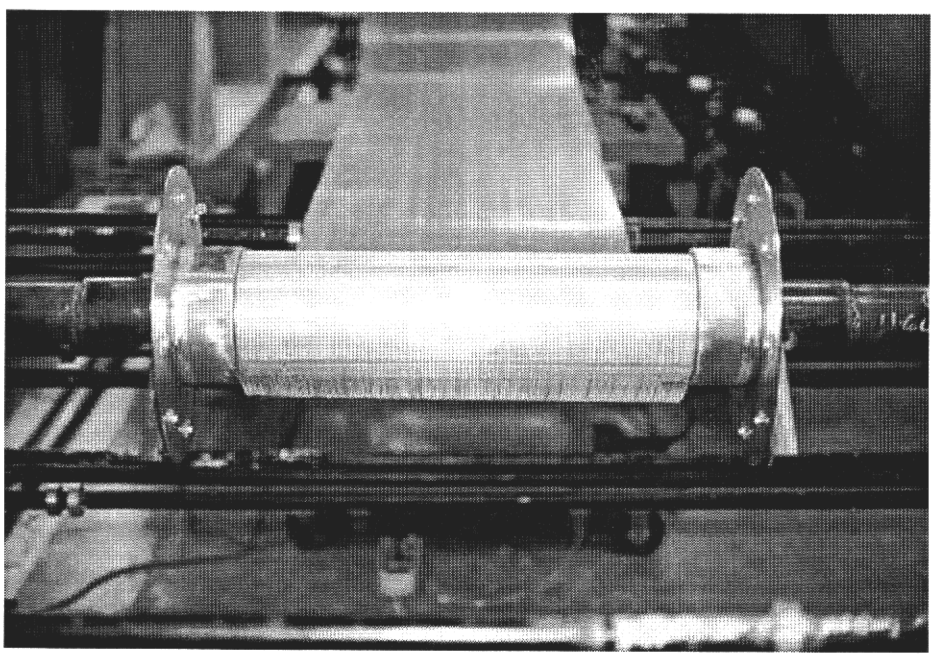

Figure 6.4. Wrapping of PMATP-CGOC1 Overpack.

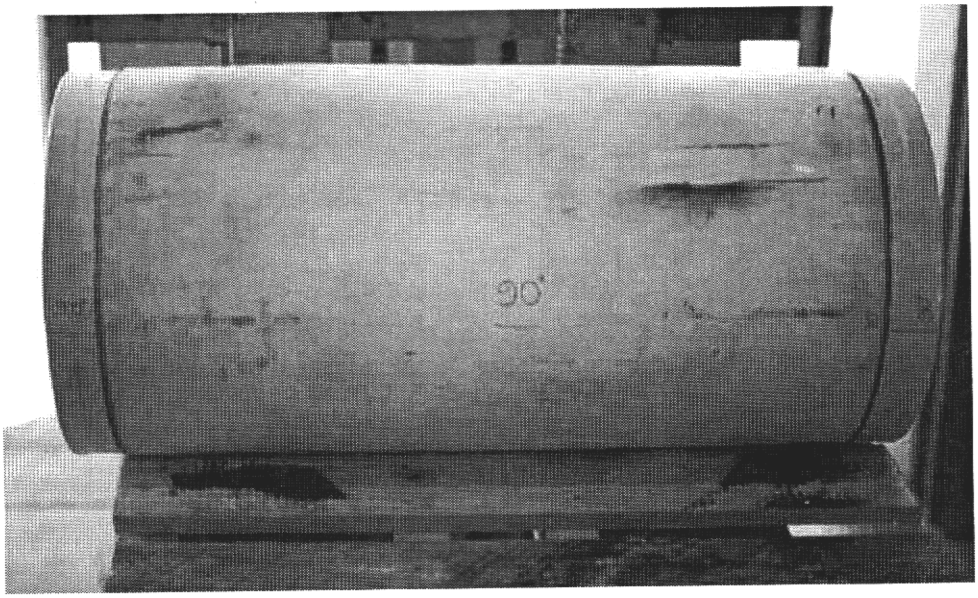


**Figure 6.5. PMATP-CGOC1 Overpack Body.**

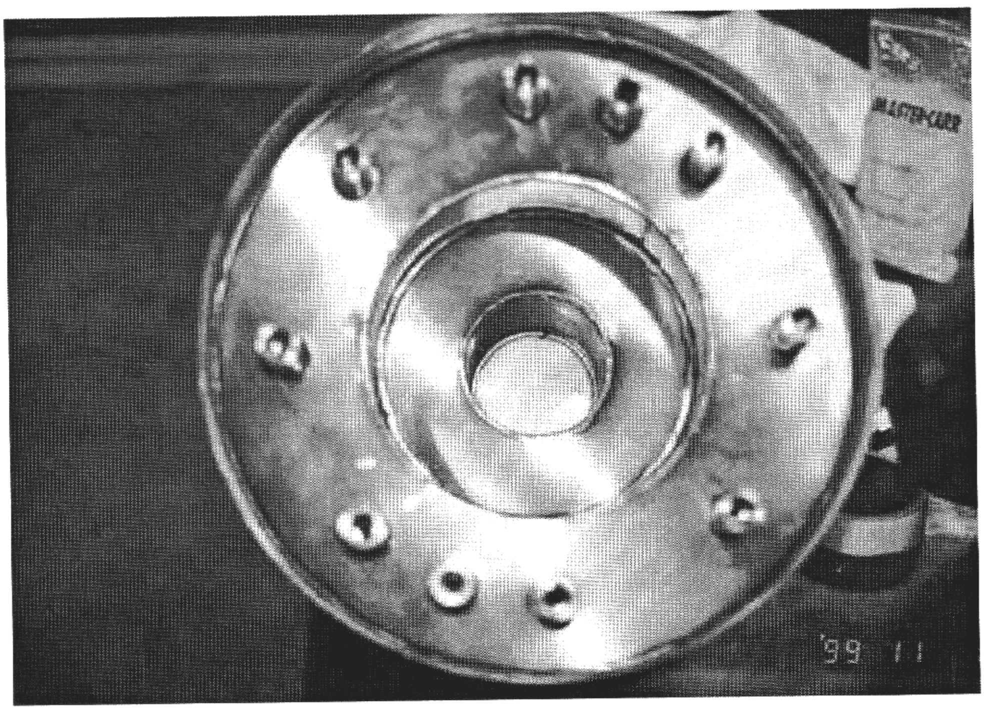

**Figure 6.6. PMATP-CGOC1 End Plugs.**

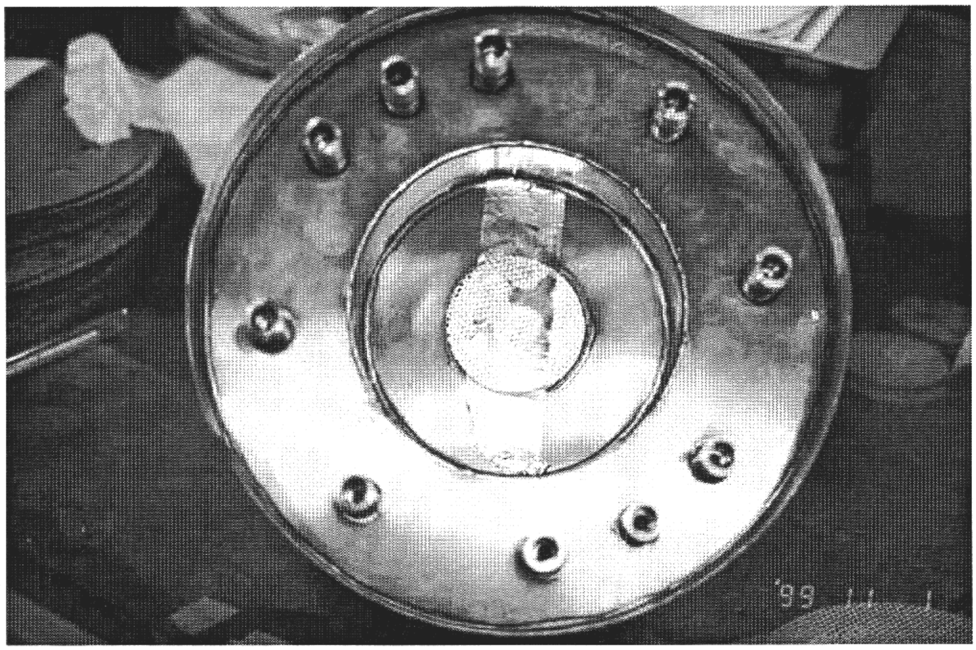

**Figure 6.7. PMATP-CGOC1 Packing of End Plugs (Small Diameter).**

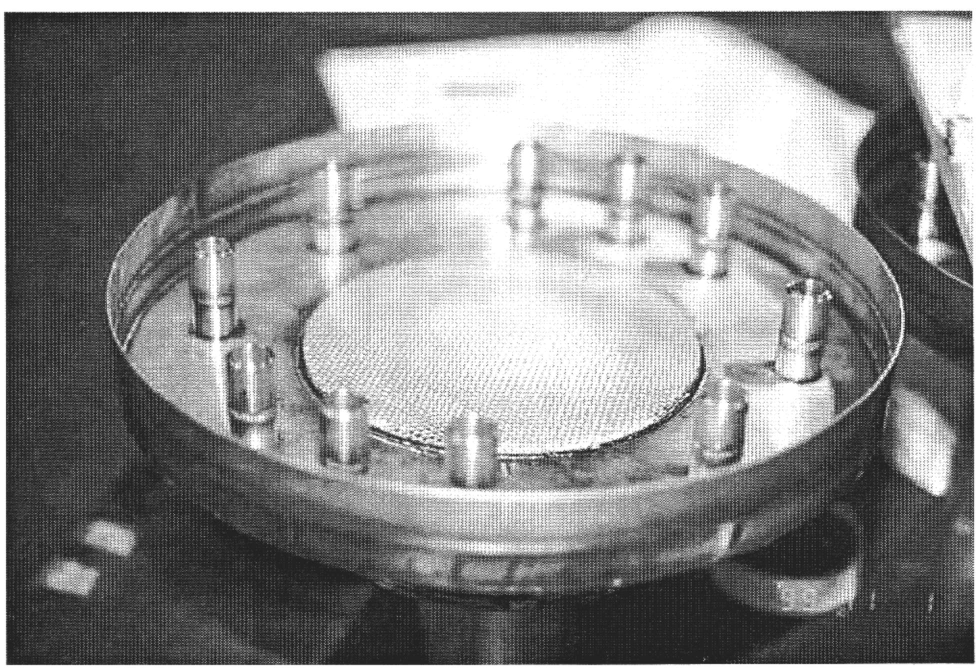

**Figure 6.8. PMATP-CGOC1 Packing of End Plugs (Medium Diameter).**

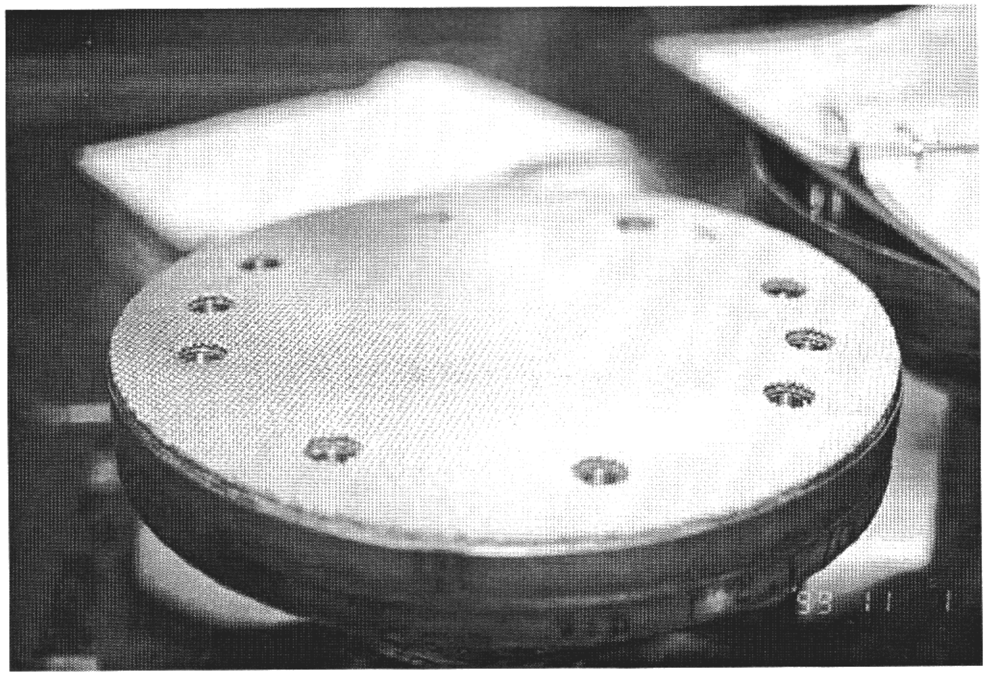

**Figure 6.9. PMATP-CGOC1 Packing of End Plugs (Large Diameter).**

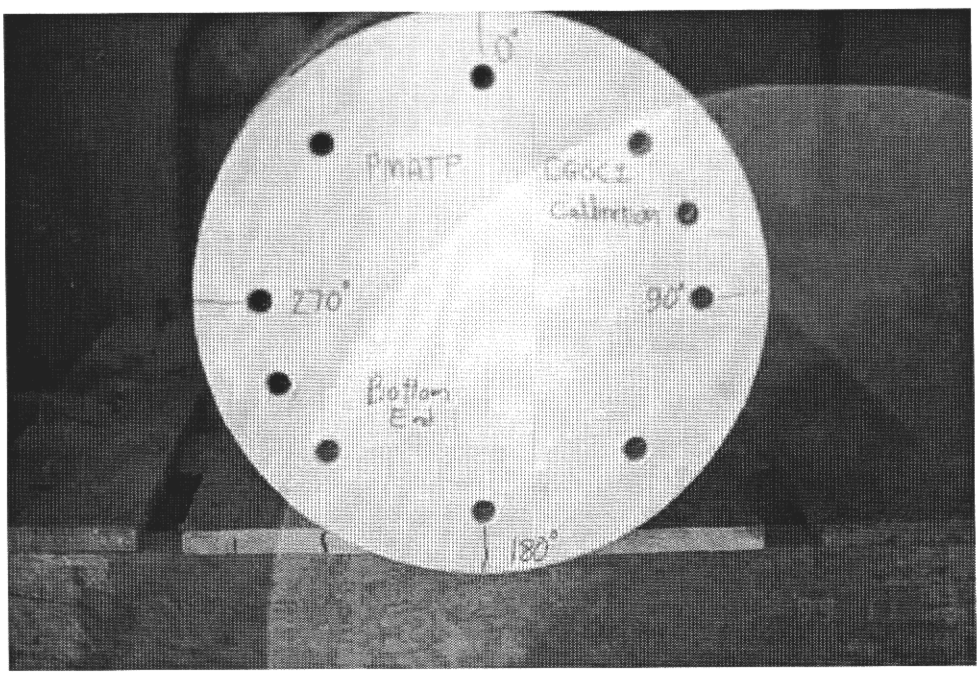


**Figure 6.10. PMATP-CGOC1 Welded End Plug.**

The inner containment vessel was loaded in the inner tube of the overpack body as shown in Figure 6.11. Each end plug was assembled to the overpack body with four tee slots and buttons as shown in Figure 6.12. The end plug was rotated 15° and locked with eight bolts as shown in Figure 6.13.

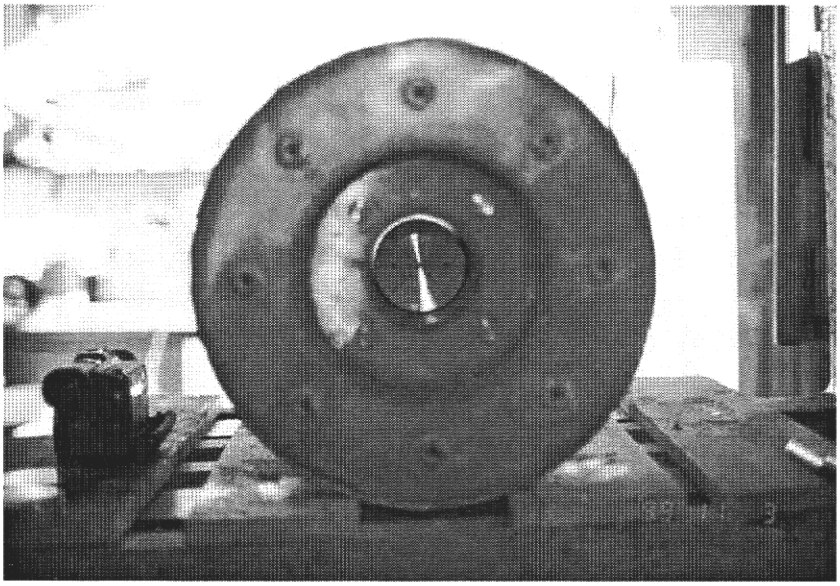

**Figure 6.11. Loading of Inner Containment Vessel.**

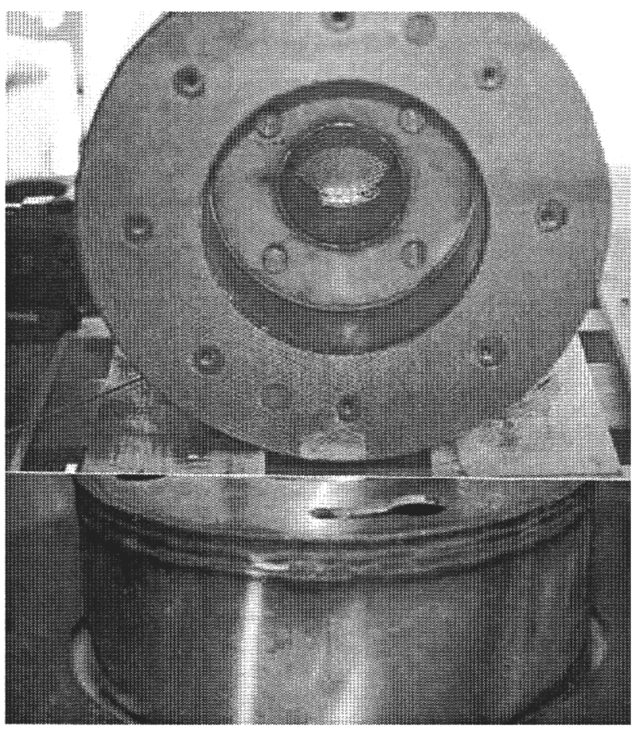

**Figure 6.12. PMATP-CGOC1 Tee Slots and Buttons.**

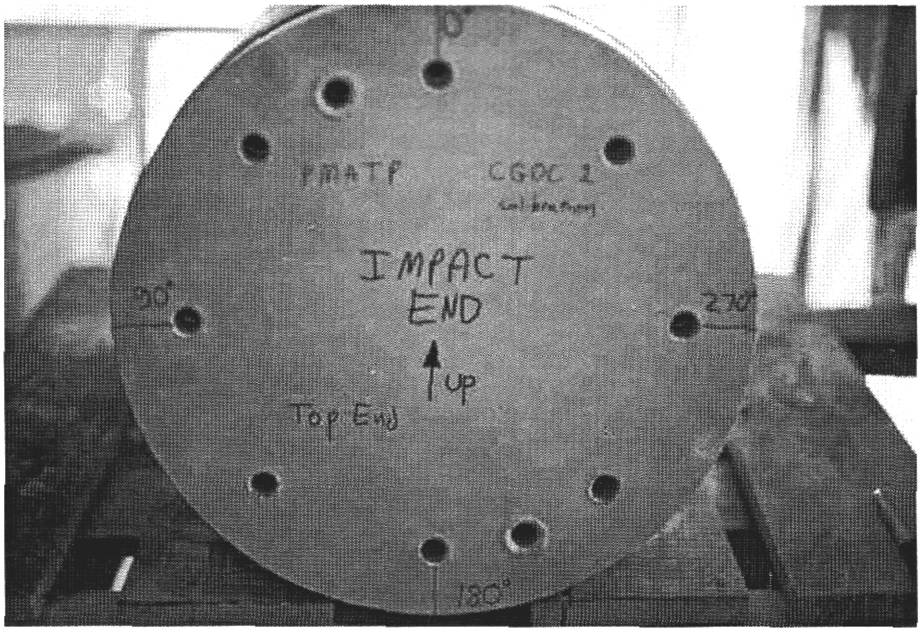


**Figure 6.13. End View of Assembled PMATP-CGOC1.**

The PMATP-CGOC1 prototype was painted white with black stripes to ensure good photometrics. The paint scheme included two-inch black stripes at 0° and 90° for the full length of the package, and it had a three-inch black stripes around the circumference at each end of the package with another at the package center. Each end of the PMATP-CGOC1 had two-inch black stripes painted in a cross horizontal and vertical pattern.

# 6.2 PMATP-CGOC1 Target Description

The target shell for the PMATP-CGOC1 consisted of a 0.5-inch-thick mild steel right circular cylinder with a flat bottom as shown in Figure 6.14. The target shell was filled in the vertical position with light-strength concrete (approximately 1200 psi). The light-strength concrete was a grout-type mixture including only water, washed sand, and cement.

Agra Earth & Environmental, Inc. was consulted throughout the design phase of the concrete mixture. Agra formulated and tested concrete design batches to arrive at the appropriate w/c ratio to achieve the desired 1200-psi strength in 14 curing days.

The top 24 inches of the PMATP-EO1 target were removed in the impact area for the PMATP-CGOC1 impact test as shown in Figure 6.15. This exposed the 1/2 – 3/4 sections of the target to the PMATP-CGOC1 impact. This represents a 37-day cure of the target for day of test.

Agra performed mix design testing to arrive at the appropriate w/c ratio. The results of this study are summarized in Figure 6.16. The results are based on unconfined break strength using 4-inch by 8-inch cast test cylinders. Each data point represents the average from three samples.

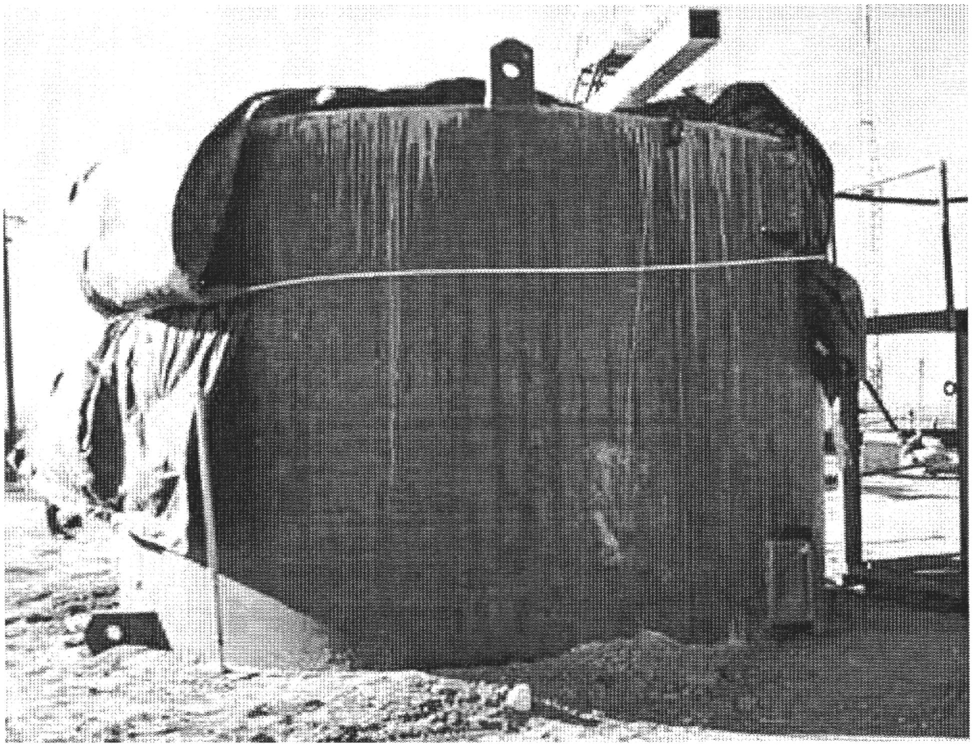

Figure 6.14. Target Cylinder.

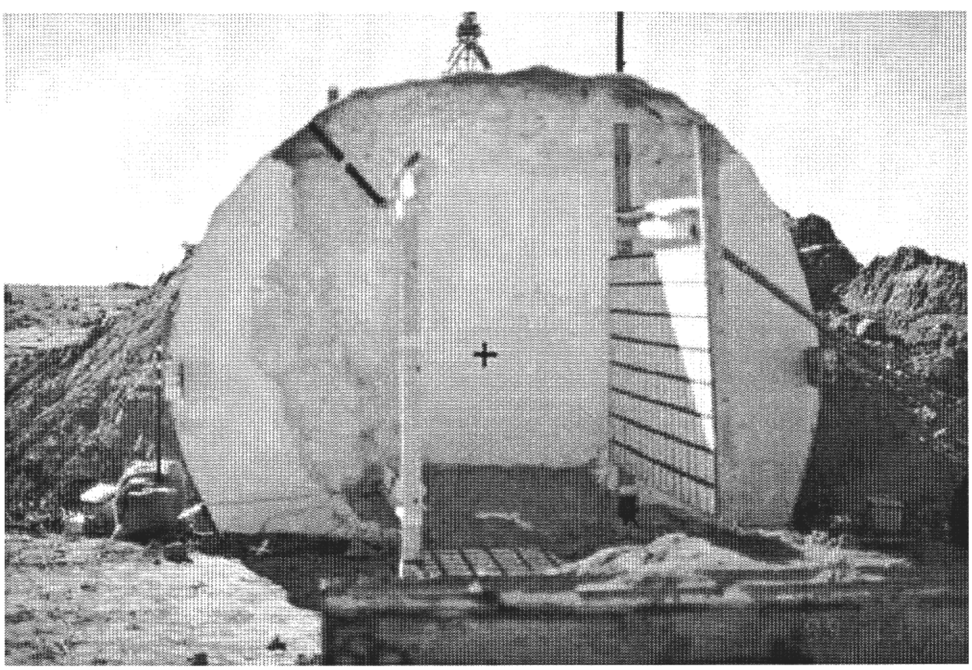

Figure 6.15. PMATP-CGOC1 Impact Target.

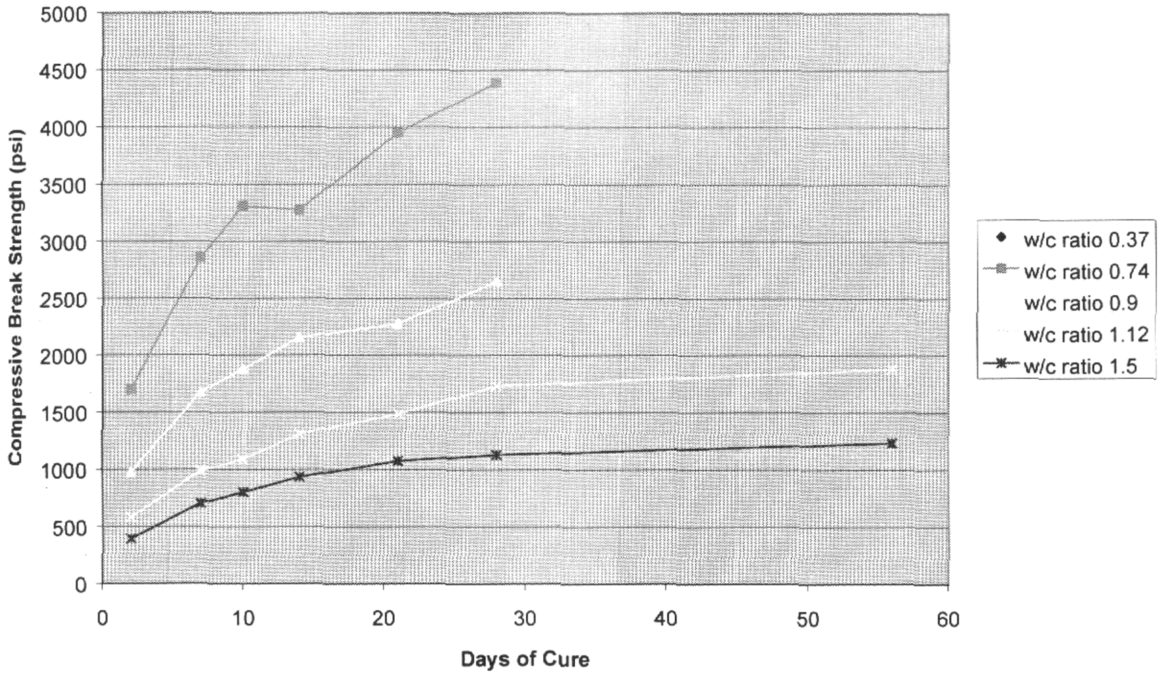


**Figure 6.16. Agra Concrete Mix Design Results for Water-to-Cement Ratios.**

A w/c ratio of 1.2 was selected based on the mix design results. This ratio was expected to produce a compressive strength of 1200 psi after 14 days of cure. Results of the actual concrete strengths from target samples are shown in Figure 6.17. Compressive strength versus the number of cure days are shown for the target samples, shown as vertical bars in the figure, and for the mix design samples, shown as solid lines. The target sample strengths are divided into lab and field samples. The lab samples refer to the lab-cured samples (cured at Agra laboratory), and the field samples refer to the samples cured alongside the actual target in the field. The target samples are also divided into bottom – 1/4, 1/4 – 1/2, 1/2 – 3/4, and 3/4 – top, referring to the height location within the target from which the samples are taken. Four trucks were used to fill the target, each truck filling approximately one-quarter of the height of the form. Equal numbers of samples were taken from of each truck for testing the four sections of the target. As seen in Figure 6.17, the target strength increased considerably more slowly than expected. The 1200-psi strength was not obtained until nearly 42 days. It should be noted that 37 cure days correspond to test day for the PMATP-CGOC1.

The target was 12 ft in diameter by 8 ft long and weighed approximately 140,000 lb after the concrete had cured, minus the material removed from the impact area. The target was backed on three sides with dirt for stabilizing the target.

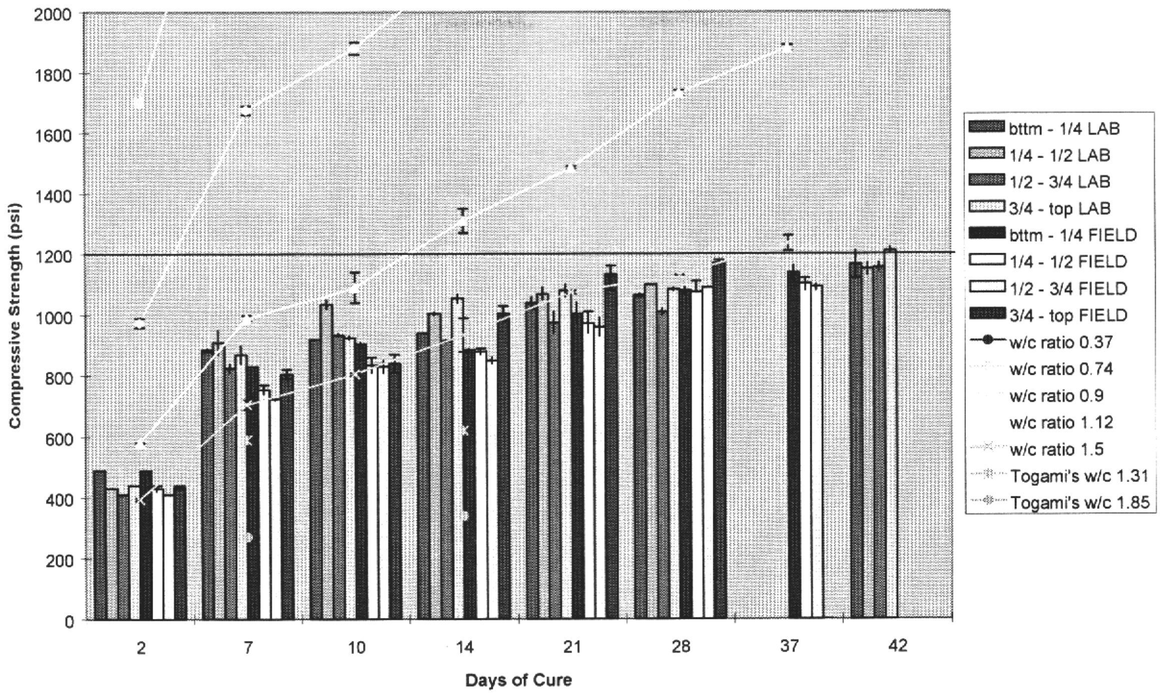


**Figure 6.17. Target Strength as a Function of Cure Days.**

Triaxial compressive strengths were measured on test samples prepared during the original target pour. These strengths were measured 62 days after the pour date. As a part of this testing process, a single unconfined compressive strength was measured to be 1333 psi. This value appears realistic compared to the trend in strength up to 42 days seen in Figure 6.17. The triaxial strength data are shown in Figure 6.18, along with linear regressions, and equations, for the data. In triaxial testing, a sample is initially loaded to peak axial failure stress under maximum confining stress. This initial failure stress is referred to as peak strength in Figure 6.18. Once peak failure occurs, the confining stress is stepped down to a lower level and the sample is loaded again to failure. This procedure is repeated until the confining stress approaches zero. The failures subsequent to the initial peak failure define the residual strengths. In one case, a single sample was tested five times (one peak, four residual). Note that failure is defined as a significant drop in the stress-strain loading curve.

The side of the target facing the photometric cameras had a series of vertical and horizontal one-inch-wide black stripes painted on the white target. A vertical marker was used as a fixed indictor to evaluate movement of the target during the impact as shown in Figure 6.19.

For completeness, the temperatures of the concrete during curing are included in Figure 6.20. This information was collected to note the effect of air temperature on cure rates.

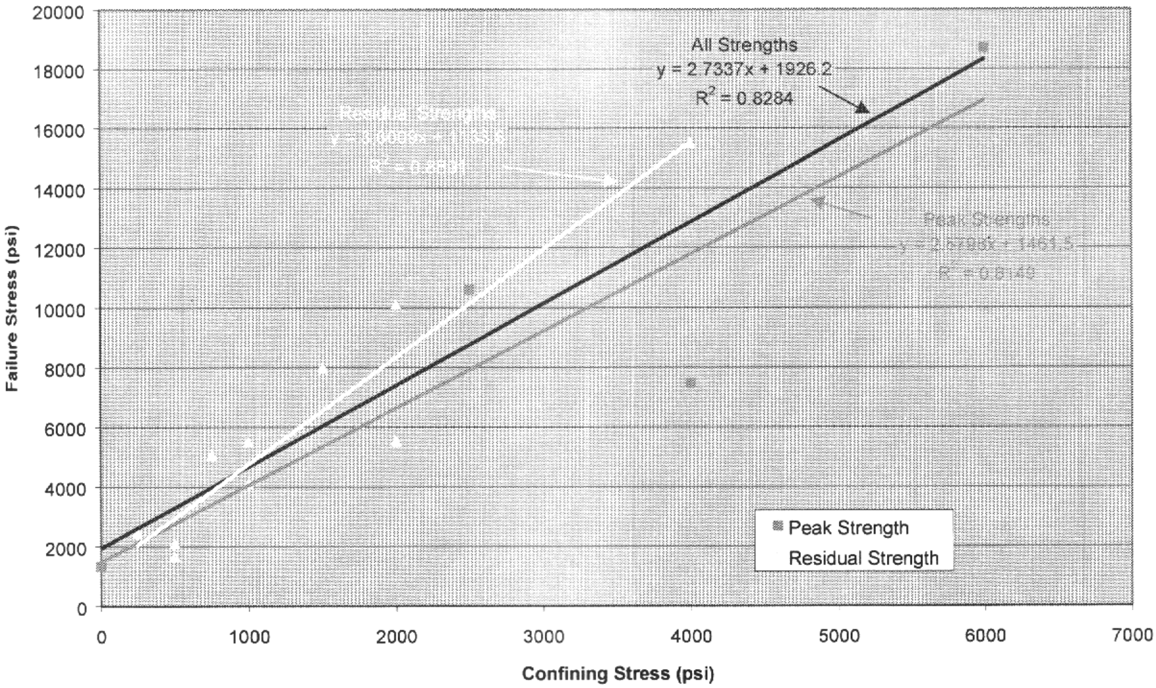


**Figure 6.18. Triaxial Compressive Strength of Target Concrete at 62 Days of Cure.**

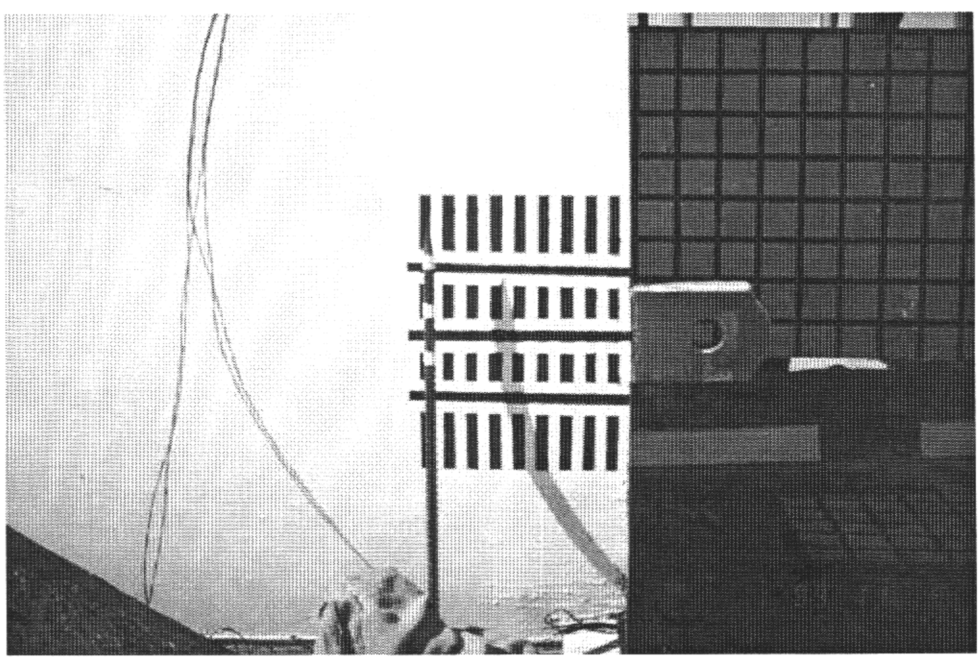

**Figure 6.19. Target Movement Indicator.**

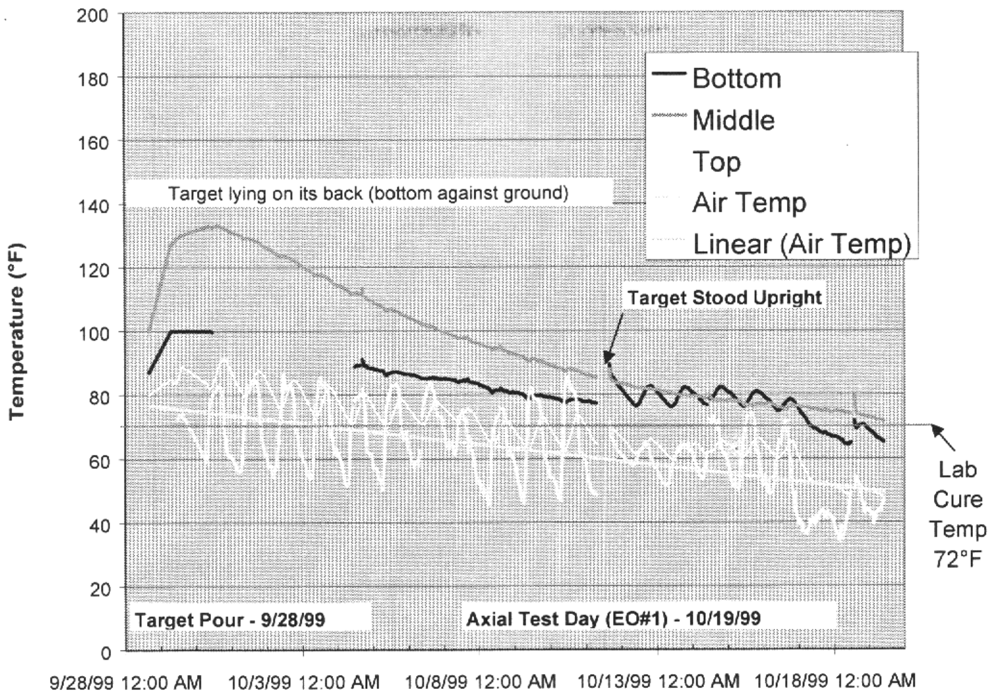


**Figure 6.20. Target Temperatures from Pour until October 19, 1999.**

# 6.3 PMATP-CGOC1 Test Requirements

The PMATP-CGOC1 test was a CGOC impact test into a light-strength concrete target. The desired velocity for this test was 925 ft/s at impact. To achieve this velocity, the package accelerated to a velocity above 1400 ft/s before sled braking.

The CGOC impact test required the package be oriented 25° top end up from horizontal and in parallel with the sled track in order to impact the top end of the PMATP-CGOC1 onto the center of the target.

## 6.3.1 Test Facility

The 10,000-ft rocket sled test facility located at SNL Tech Area III was used for this test, and the target was aligned at the end of the curved section of rails as shown in Figure 6.21. The area between the rails was filled with water dams of increasing depth to sequentially slow the first-stage pusher sled. The test unit was supported above the track on a second-stage unpowered expendable sled. This second-stage sled was propelled along the track by a first-stage pusher sled containing eight Super Zuni rockets as shown in Figure 6.22. Launch occurred approximately 2130 ft north of track Station 0 (the south end of the track). At burnout of the first-stage rocket motors, the first-stage sled slowed by water braking, at which time the second-stage guide sled separated and coasted along the track toward Station 0. Near Station 0, onboard explosive cutters severed the steel cables that held the test unit to the sled. As the second-stage

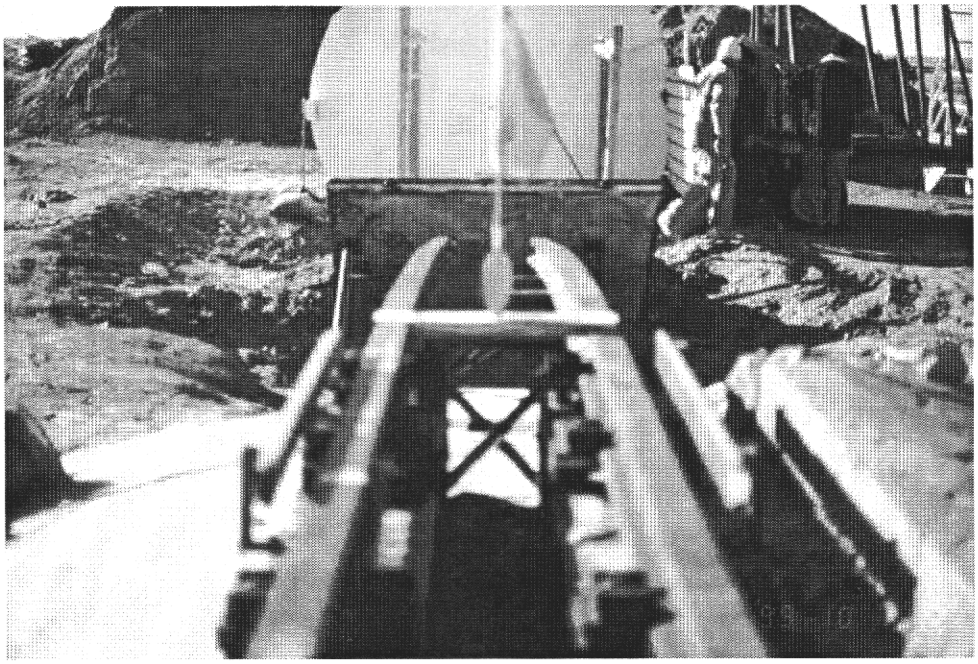

**Figure 6.21. End of Rails and Target Alignment.**

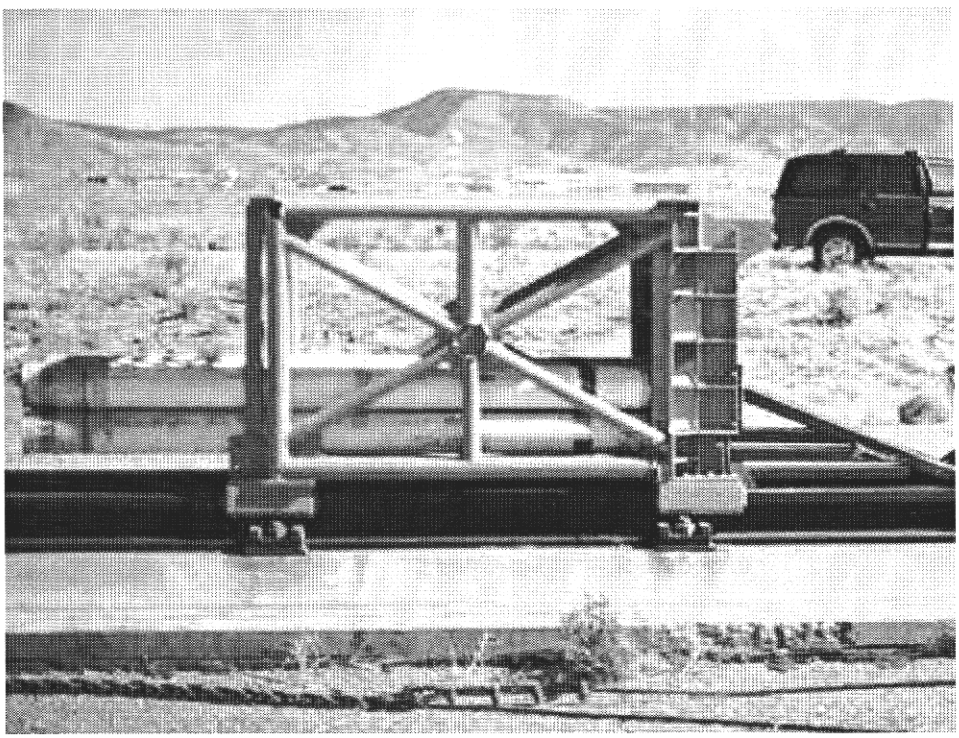

**Figure 6.22. PMATP-CGOC1 First-Stage Pusher Sled.**

guide sled passed Station 0, it was forced downward by 20-ft curved rail extensions that were welded to the existing rails at Station 0 as shown in Figure 6.23. At the end of the 20-ft curved rail section, the sled exited the track and impacted a containment plate approximately 3 ft to the south as shown in Figure 6.24. The containment plate forced the majority of the sled downward and into the ground. The momentum of the test unit carried it in a near-horizontal flight path over the containment plate and onto the concrete target, whose impact face was located 40 ft to the south of Station 0.

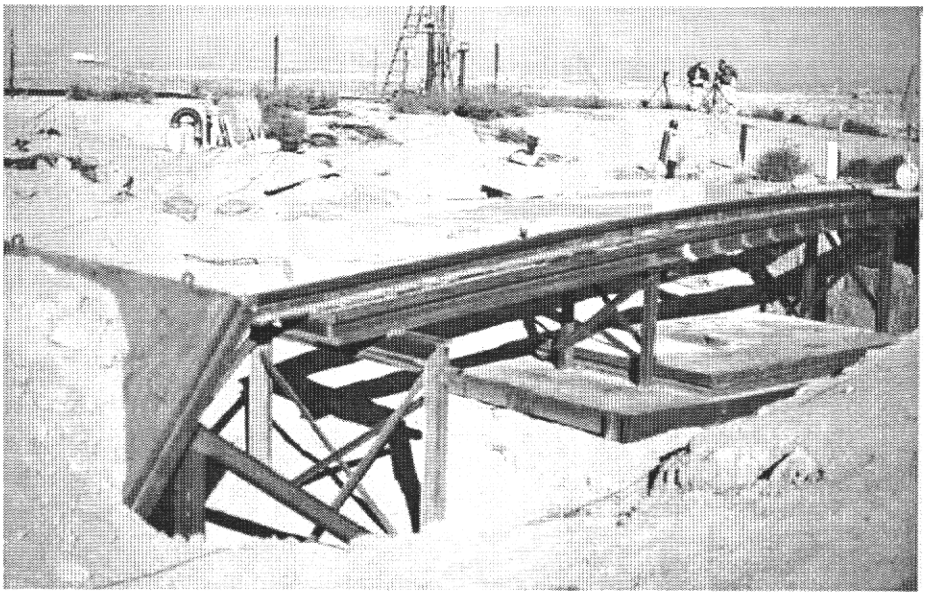

**Figure 6.23. Curved Rails.**

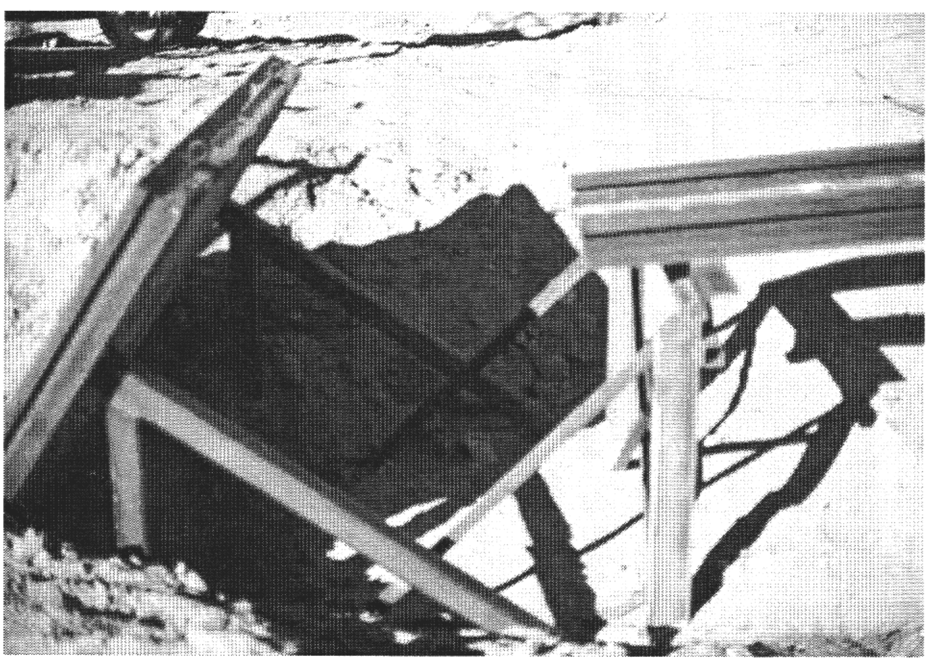

**Figure 6.24. Containment Plate.**

The second-stage guide sled consisted of a horizontal cradle attached by support members to four shoes. Each of the four shoes was made from quarter-inch shoe stock and gusseted to withstand the calculated 270-g uploading during the turning impacted by the curved rail section. This value was based on a 100-lb sled weight and a 1000-ft/s velocity. Details of the sled are shown in Figure 6.25. The first-stage pusher sled was a utility sled designed to carry up to 25 five-inch rocket motors. An adapter was fabricated to push the test unit sled and is seen in the Figure 6.25. A separation distance of 30 inches was used between the sleds to minimize adverse effects of water spray on the test unit during braking and separation of the first-stage sled. Cables used to tie down the test unit can be seen in Figure 6.26, along with the explosive cutters, wrapped in yellow tape, that were used to sever the cables near Station 0. The explosive cutters were positioned to symmetrically sever the hold-down cables and were attached with a lanyard to the hold-down cables.

Timing switches were also installed along the sled track to determine sled velocity as shown in Figure 6.27. The timing switches were cut by the second-stage guide sled immediately before impact.

### 6.3.2 Photometrics

Pre- and post-test documentary photographs were taken. These included 35-mm still photographs of the test site, the equipment and instrumentation to be used, fixtures, hardware, and rigging needed for the test. The top, bottom, and all four sides of the test package were photographed before the test and again after the test.

High-speed cameras were positioned for top and side views of the impact area to determine impact velocity and observe package performance throughout the impact. Hand-tracked cameras were used to document the full extent of the test. The camera types, locations, and coverage are shown in Figure 6.28. A total of 21 film and video cameras were used in support of the PMATP-CGOC1 impact test. This included 13 16-mm film cameras, two high-speed digital cameras, one 70-mm film camera, three SVHS video cameras, and 1 high-speed slit camera (IM). The streak camera was not used in this test because the target pan obscured the aft end of the test unit at impact. The relative positions of each of these cameras and the frame rates used by each are included in the camera layout schematic shown in Figure 6.28. The dashed lines indicate the approximate field of view for each camera.

A laser tracker was positioned to track the package during the test for accurate determination of package location and velocity throughout the test. The laser tracker locked onto a reflective marker that was located on the package and followed the package throughout the test as shown in Figure 6.29. High-speed cameras were mounted onto the tracking platform to provide additional photometric documentation of the test.

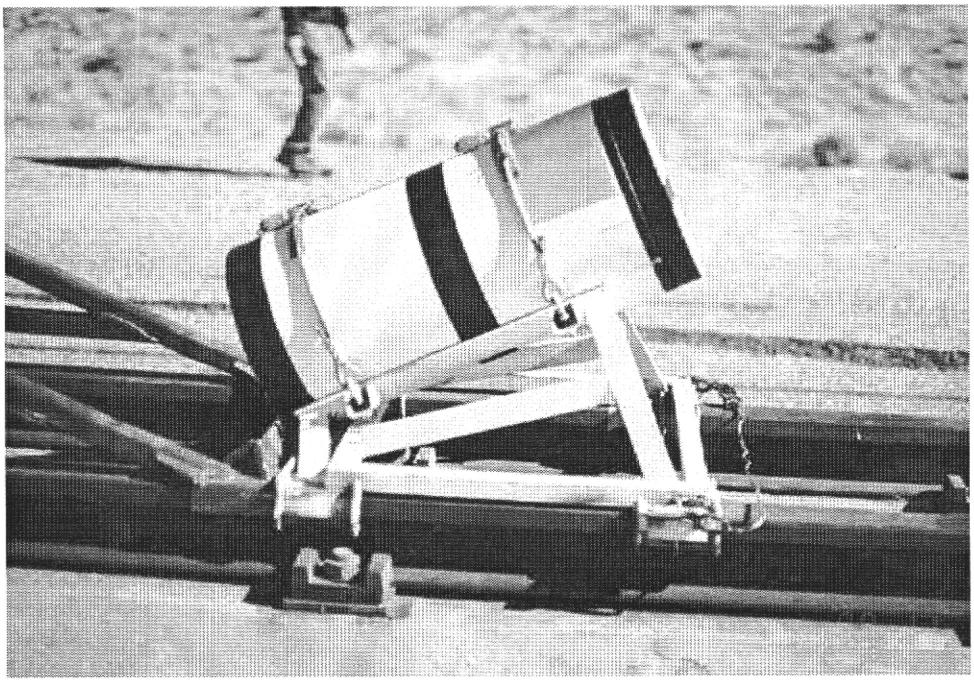

Figure 6.25. PMATP-CGOC1 Guide Sled.

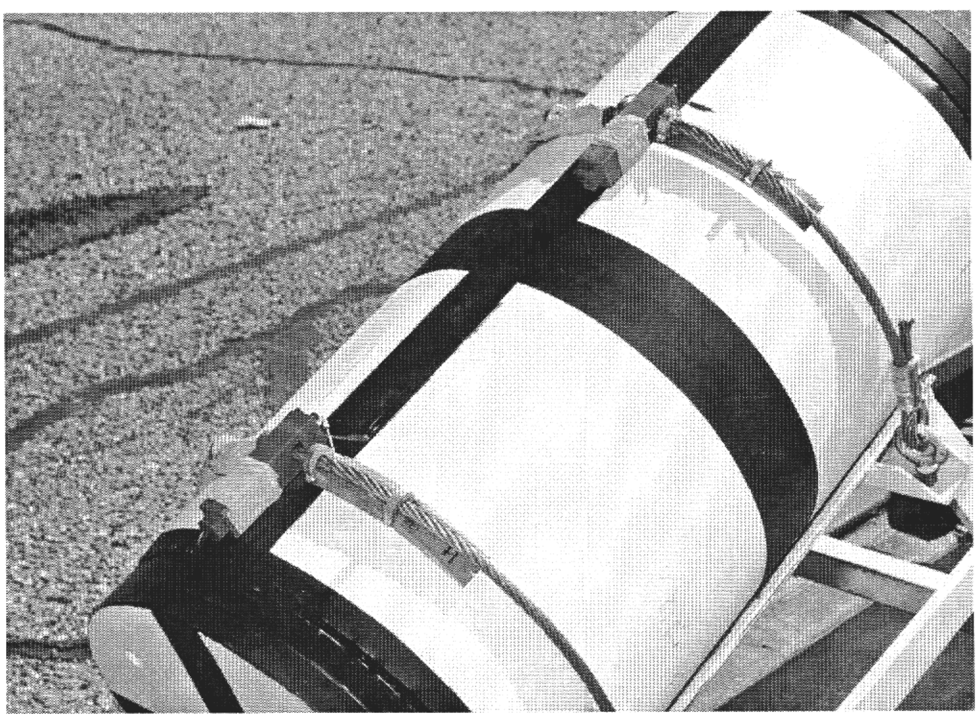

Figure 6.26. PMATP-CGOC1 Separation Hardware.

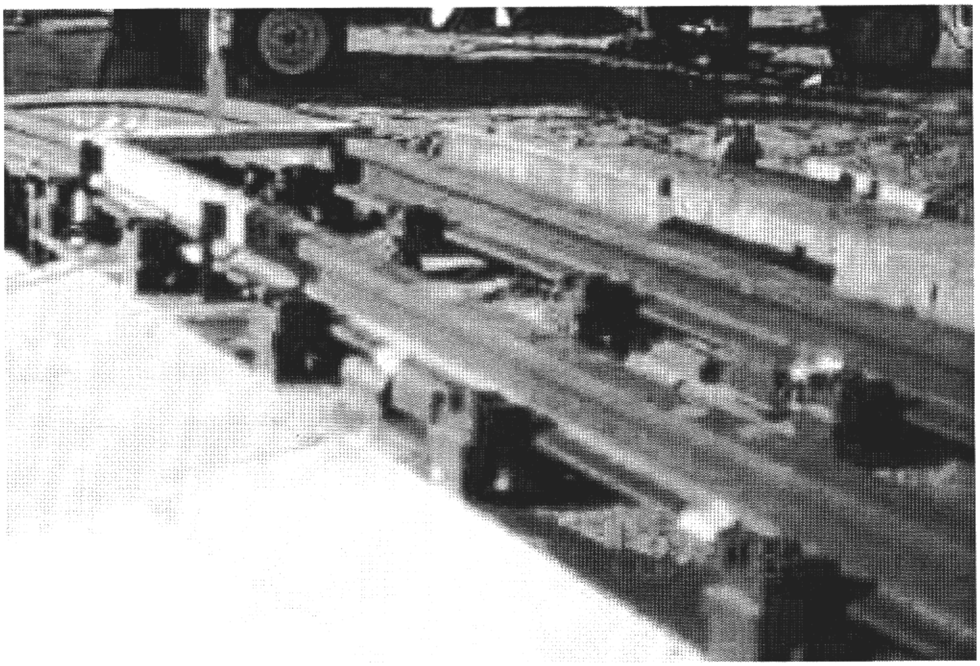

Figure 6.27. PMATP-CGOC1 Timing Switches.

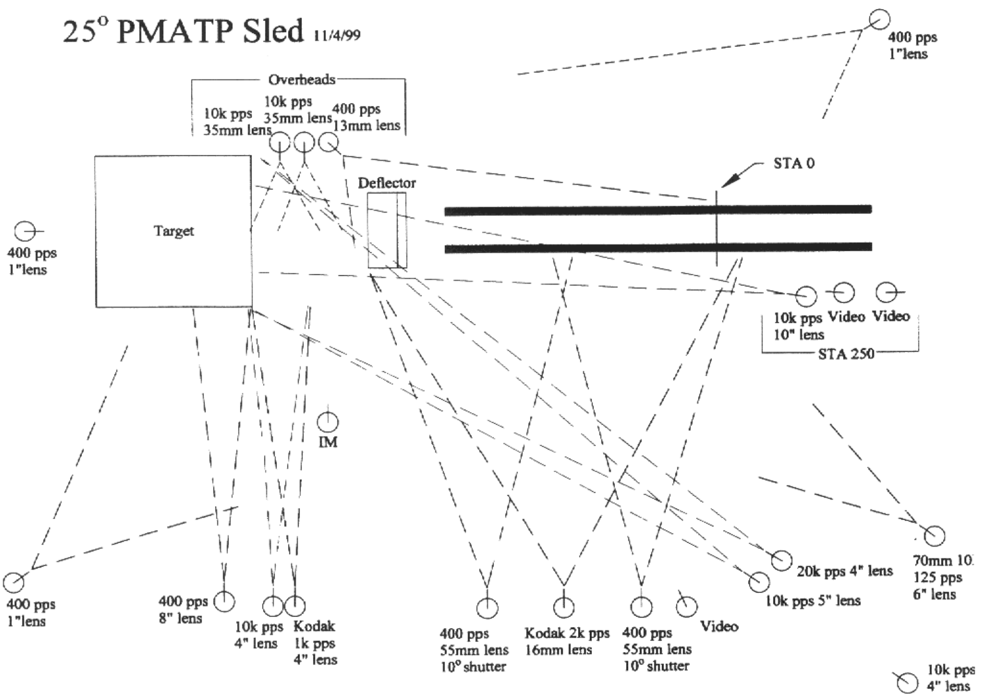


Figure 6.28. PMATP-CGOC1 Camera Layout.

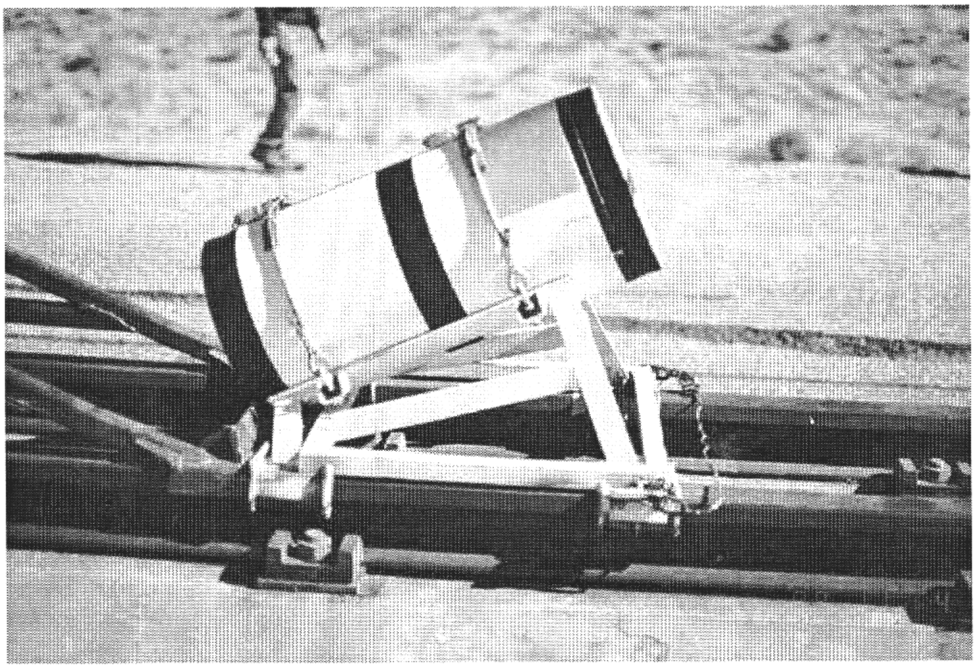

Figure 6.29. PMATP-CGOC1 Reflective Marker.

### 6.3.3 Inspection Measurements

The inner containment vessel was inspected by SNL personnel before assembly for pretest measurements and again after disassembly for post-test measurements. Diameters were measured at 0° – 180°, 45° – 225°, 90° – 270°, and 135° – 315°.

The closure was measured at one location on the largest shoulder diameter. The container body was measured at five locations including the top, midway between top and center, center, midway between center and bottom, and bottom. Lengths were measured every 45° with and without the closure installed.

### 6.3.4 Test Unit Weight Measurements

The weights of various components were documented before the test. The inner containment vessel was weighed when empty and after the steel shot mass was loaded. The overpack body, End Plug 1, and End Plug 2 were weighed before assembly. The total package weight was measured after final assembly.

## 6.4 PMATP-CGOC1 Test Results

### 6.4.1 Center-of-Gravity Over Corner (CGOC) Impact Test

The test article was configured for a CGOC impact test of 925 ft/s. The as-tested weight of the test article was 307.5 lb as shown in Table 6.1. The first-stage pusher sled weighed 1565 lb including rockets, and the total weight of the second-stage guide sled and test package was 380 lb. The test unit was launched from Station 2130, and the impact face of the target was placed at Station 42 for a total travel distance of 2172 ft.

**Table 6.1. PMATP-CGOC1 Weight Measurements (lb)**

| | |
|---|---|
| Containment vessel empty | 15.60 |
| Containment vessel full | 22.65 |
| Overpack body | 218.00 |
| End Plug 1 | 31.80 |
| End Plug 2 | 32.00 |
| Total assembled weight | 307.50 |
| Target weight | 140,000.00 |

Figures 6.30 through 6.34 show the PMATP-CGOC1 being prepared for the CGOC impact test.

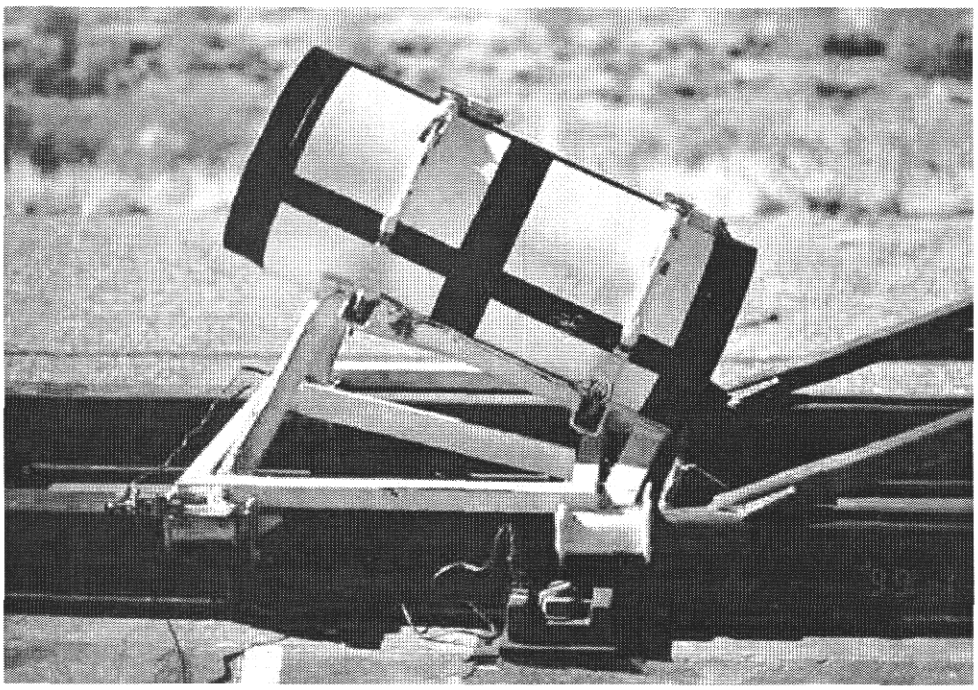

**Figure 6.30. PMATP-CGOC1 Mounted in Stage 2 Guide Sled.**

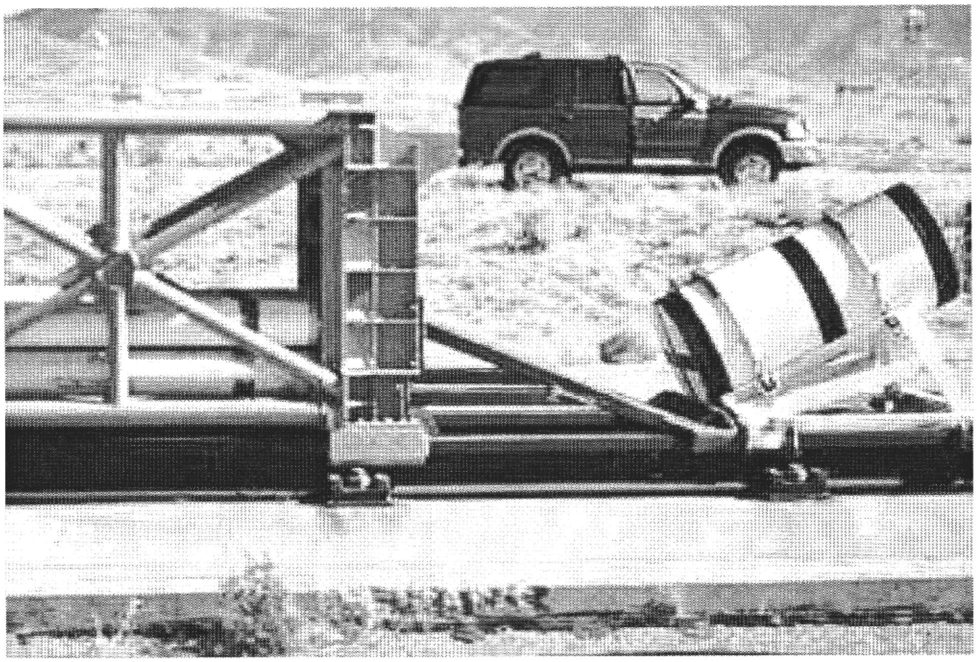

**Figure 6.31. PMATP-CGOC1 Stage 1 to Stage 2 Interface.**

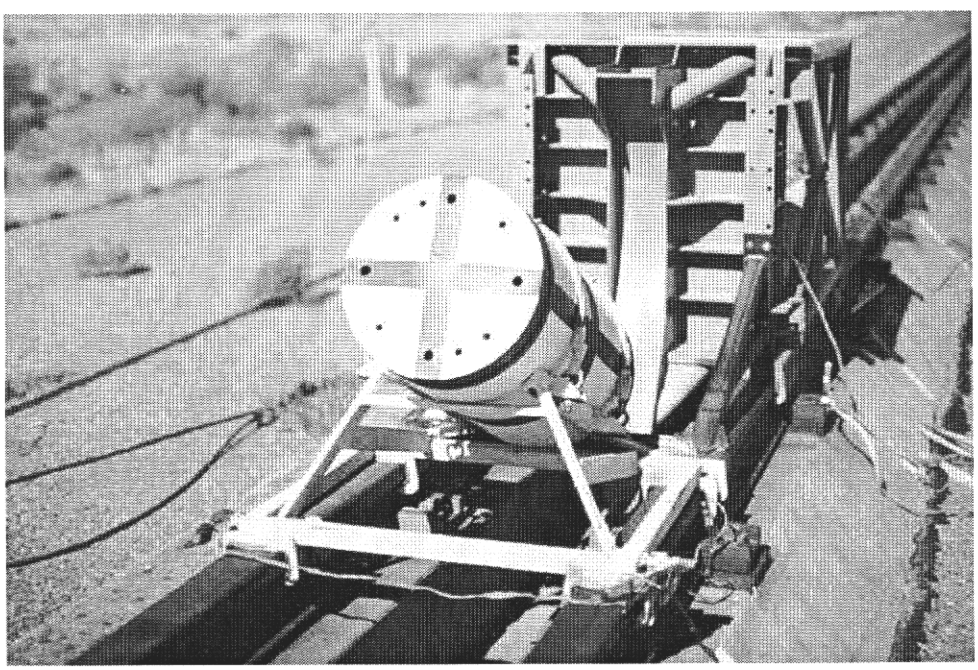

**Figure 6.32. PMATP-CGOC1 Grounded and Ready for Arming.**

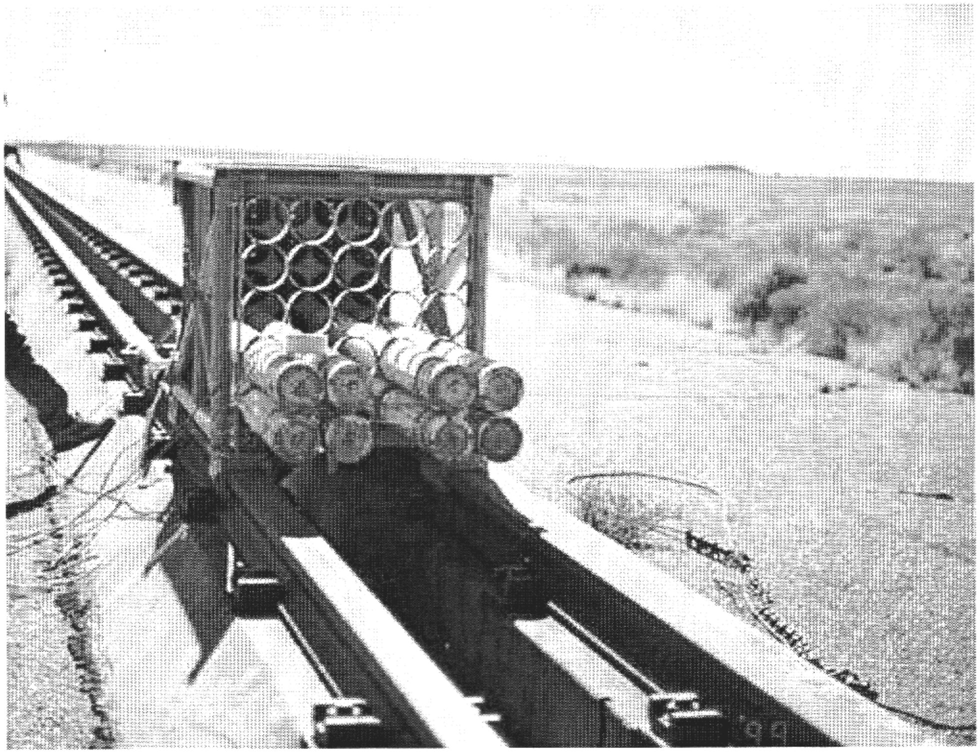

**Figure 6.33. PMATP-CGOC1 Stage 2 Guide Sled**

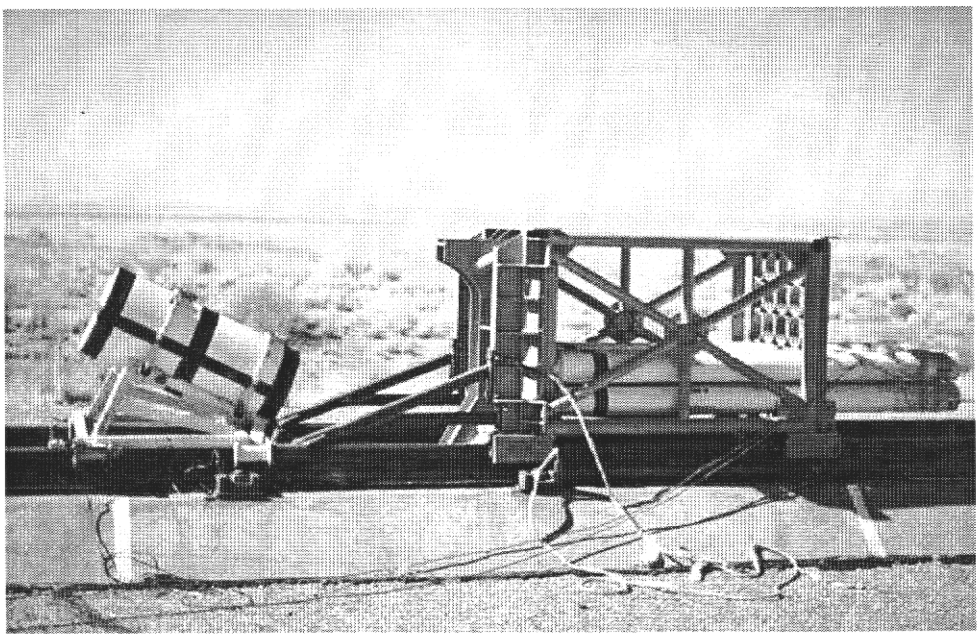

**Figure 6.34. PMATP-CGOC1 Ready for Test.**

The PMATP-CGOC1 impact test was performed on November 4, 1999, at 12:32 p.m. The rockets fired as desired, and the first-stage pusher sled accelerated the second-stage guide sled and package as expected. The package impacted in the desired 25°, nose-up orientation (perpendicular to the target) at a velocity of 890 ft/s.

The IM camera shown in Figure 6.28 recorded the test unit velocity and was located 7 ft in front of the impact face of the target.

Three pretest trajectories are presented in Figure 6.35, together with post-test data from break wires, laser tracker, and IM cameras. The uncertainty in velocity trajectory was greater for this configuration because of the lack of historical drag information on which to base estimates. Harold Spahr again provided drag coefficients for the 25°-cylinder configuration in freestream flow. The necessary hardware to support the cylinder in this configuration, however, significantly disrupted freestream conditions on the cylinder. This together with the uncertainty of the shadowing effect by the test unit onto the pusher sled made velocity predictions unreliable. From Figure 6.35 it is seen that the break wire data and the IM are in good agreement, indicating an impact velocity of approximately 890 ft/s. Once again, the laser tracker value is approximately 3% low at 865 ft/s.

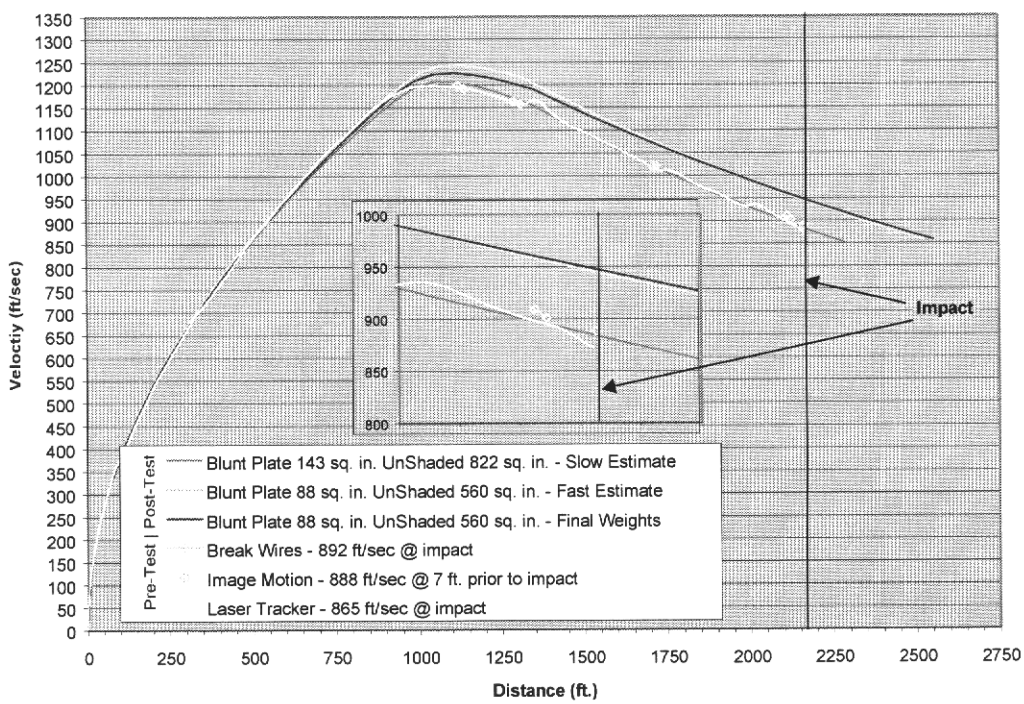


**Figure 6.35. Pretest and Post-test Velocity Trajectories for PMATP-CGOC1.**

The photograph in Figure 6.36 was digitized from the orthogonal viewing 10k fps (frames per second) camera. The backboard in the photograph was precisely leveled before the test to provide a horizontal reference. Straight lines were aligned with sides of the unit and are shown in the figure at 25.6° and 25.0°. The intended impact angle was 25.1° for the CGOC configuration.

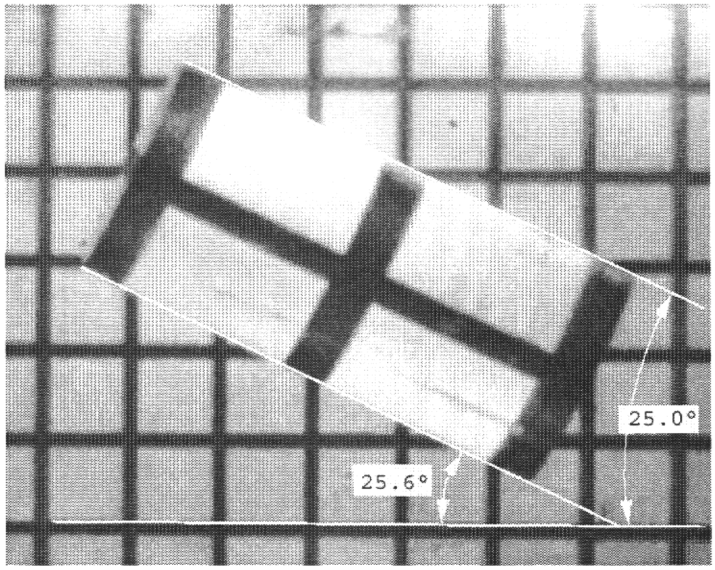


**Figure 6.36. Pitch of PMATP-CGOC1.**

A frame from the 10 k fps overhead camera was digitized and is shown in Figure 6.37. The yaw angle from this image is measured to be between 2.0° and 3.9°. The large discrepancy in the values from one side of the test unit to the other indicates there may be a perspective issue that is not well defined.

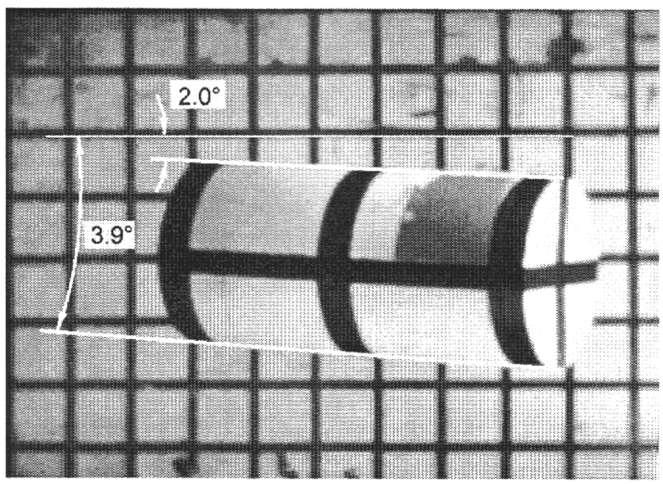


**Figure 6.37. Yaw of PMATP-CGOC1.**

Figure 6.38 illustrates the test unit impacting the target during the impact test. The PMATP-CGOC1 outer shell crushed as expected as shown in Figure 6.39. The bottom cover sheared from the package and exposed the overpack perforated aluminum and Kevlar™ cloth as shown in Figure 6.40. The top of the overpack body skin sheared from the top end to the bottom end exposing perforated aluminum and Kevlar™ cloth as shown in Figure 6.41. The inner containment vessel remained confined in the overpack. The package rebounded from the target and landed 140 ft north of the target and 10 ft east of the track.

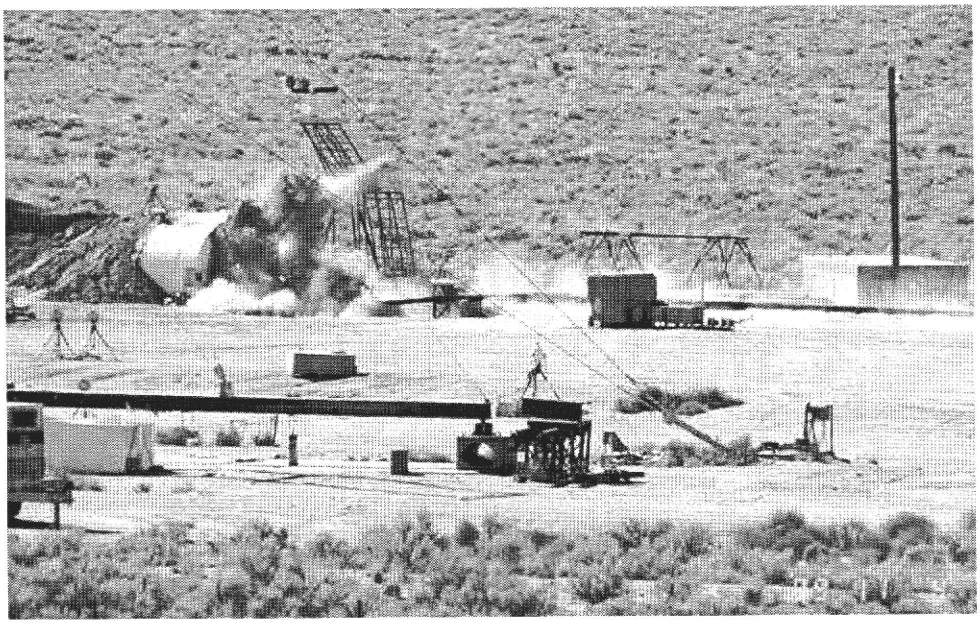

Figure 6.38. PMATP-CGOC1 Test Article and Target During Impact Test.

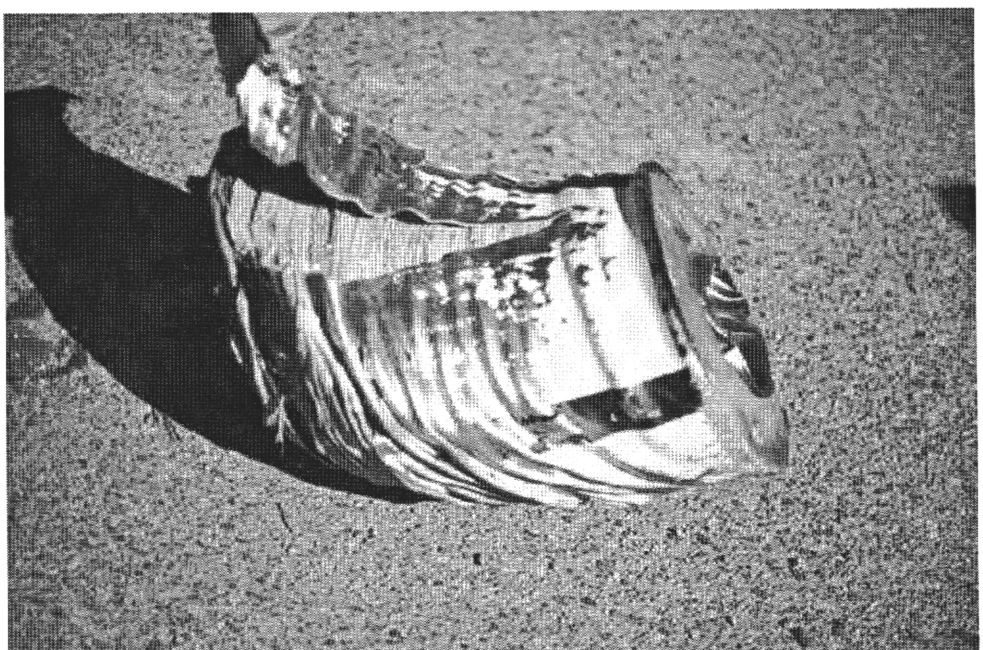

Figure 6.39. PMATP-CGOC1 Crush.

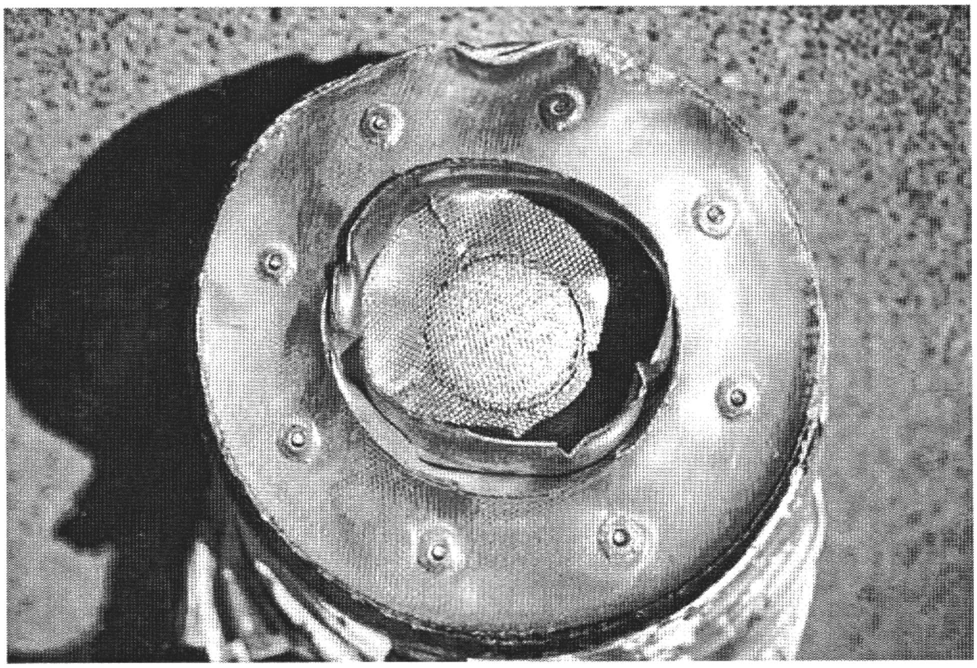

Figure 6.40. PMATP-CGOC1 Exposed Bottom End.

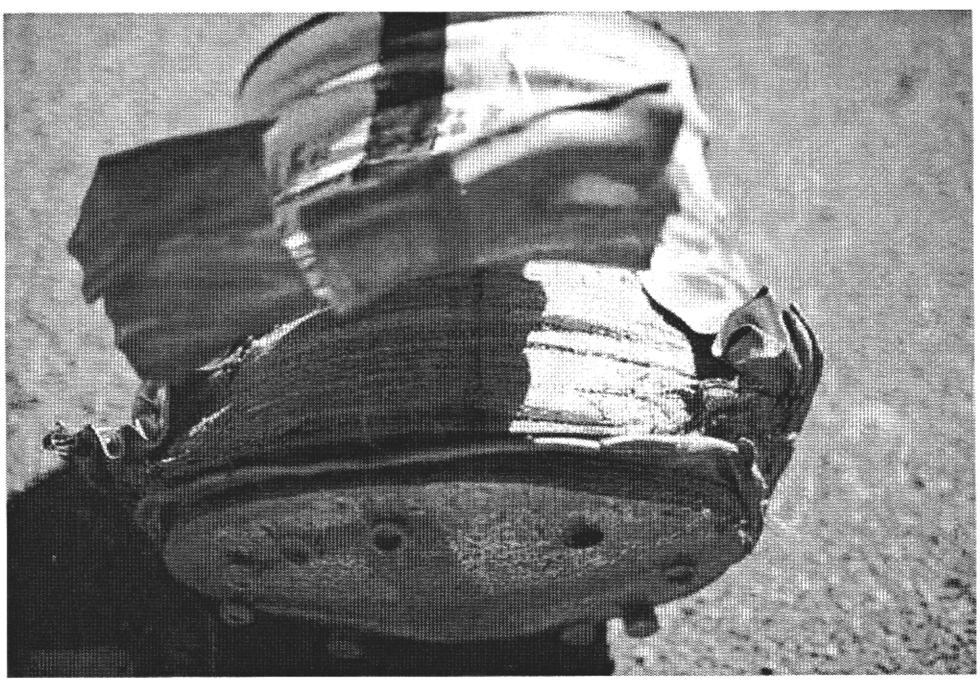

Figure 6.41. PMATP-CGOC1 Exposed Overpack Body.

A crater was formed at the impact area of the target approximately 67 inches tall, 51 inches wide, and 14 inches deep at the center as shown in Figure 6.42. Compressive strength tests the day of the test indicate the target was in the desired range to simulate the PSA crash site as shown in Table 6.2.

Table 6.3 depicts the environmental conditions for the PMATP-CGOC1 impact test.

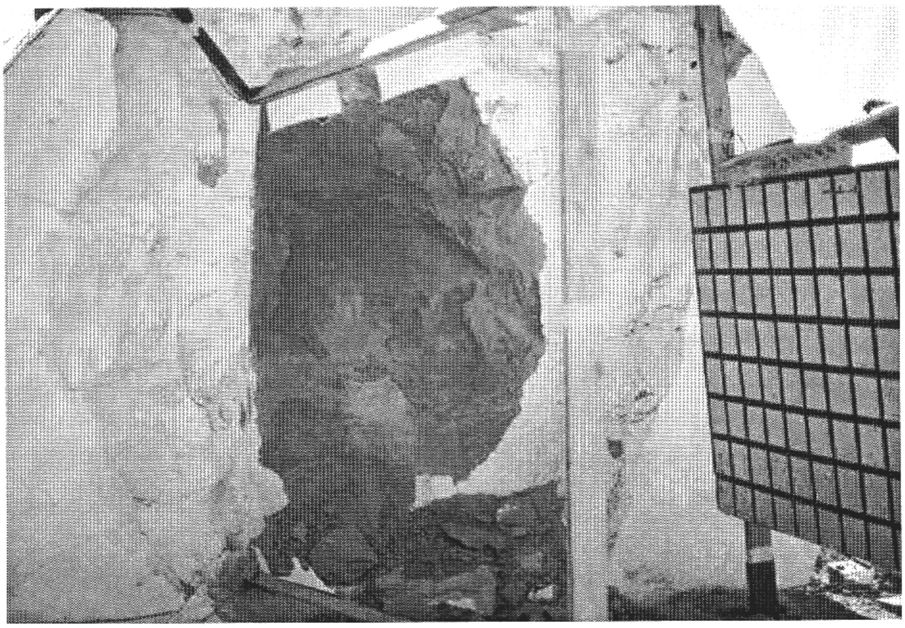

**Figure 6.42. Target after PMATP-CGOC1 Impact Test.**

**Table 6.2. PMATP-CGOC1 Concrete Target Compressive Strengths**

| Layer | Compressive Strength Day of Test |
|---|---|
| 1 back end | 1338 psi |
| 2 | 1103 psi |
| 3 impact end | 1093 psi |
| 4 N/A | N/A |

**Table 6.3. Test Conditions for PMATP-CGOC1 Impact Test**

| | |
|---|---|
| Temperature | 63°F at 12:32 |
| Lighting | Full sun |
| Wind direction | Out of west |
| Wind velocity | <2 mph |
| Number of rockets | 8 Super Zuni rockets |

# 6.5 PMATP-CGOC1 Disassembly and Evaluation

After the CGOC impact test, the PMATP-CGOC1 was retrieved for disassembly and evaluation.

The inner containment vessel remained intact and within the overpack. The inner containment vessel was removed from the overpack for inspection by cutting along the axis through the overpack and inner container as shown in Figure 6.43. The inner containment vessel had no visible deformation as shown in Figure 6.44. Physical dimensions of the inner containment vessel are documented in Tables 6.4 and 6.5. Only one-half of the containment vessel was removed for evaluation. There were no post-test diameter measurements taken; however, there was no visible deformation of the cylinder along the length and only half of the post-test length measurements were recorded. The closure lid was not deformed and the threads appeared to be intact. The container body wall deformed less than 0.002 inch along the full length.

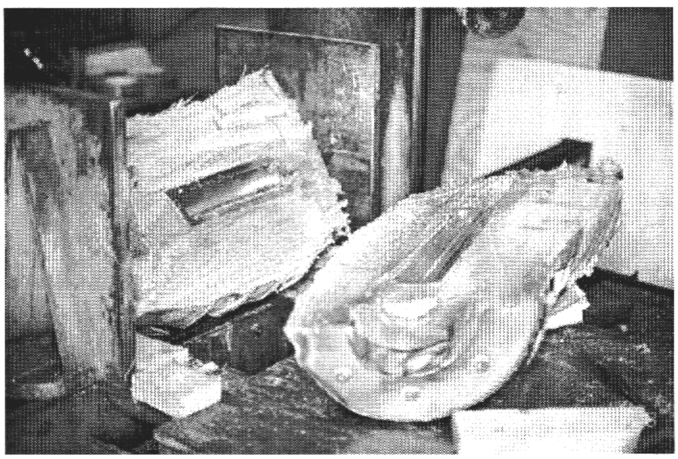

**Figure 6.43. Cutting Through the PMATP-CGOC1 for Inspection.**

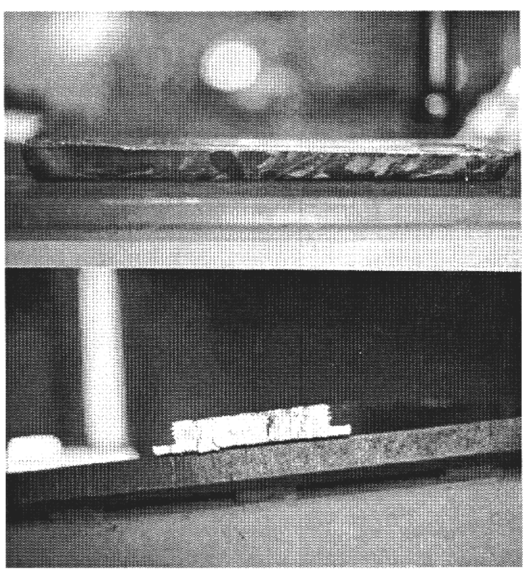

**Figure 6.44. PMATP-CGOC1 Inner Containment Vessel Deformation.**

**Table 6.4. PMATP-CGOC1 Inspection Measurement Lengths (inches)**

| | L0° | L45° | L90° | L135° | L180° | L225° | L270° | L315° |
|---|---|---|---|---|---|---|---|---|
| Pre no lid | 11.548 | 11.547 | 11.548 | 11.547 | 11.548 | 11.547 | 11.548 | 11.548 |
| Post no lid | 11.547 | 11.546 | 11.547 | 11.546 | N/A | N/A | N/A | N/A |
| Difference (no lid) | –.001 | –.001 | –.001 | –.001 | N/A | N/A | N/A | N/A |
| Pre w/lid | 11.673 | 11.672 | 11.673 | 11.673 | 11.676 | 11.677 | 11.675 | 11.674 |
| Post w/lid | 11.672 | 11.672 | 11.673 | 11.673 | N/A | N/A | N/A | N/A |
| Difference (w/lid) | –.001 | .000 | .000 | .000 | N/A | N/A | N/A | N/A |

**Table 6.5. PMATP-CGOC1 Inspection Measurement Diameters (inches)**

| | D0° – 180° | D45° – 225° | D90° – 270 | D135° – 315° |
|---|---|---|---|---|
| Pre closure | 3.499 | 3.500 | 3.499 | 3.500 |
| Post closure | N/A | N/A | N/A | N/A |
| Difference (closure) | N/A | N/A | N/A | N/A |
| Pre body top | 3.503 | 3.503 | 3.502 | 3.504 |
| Post body top | N/A | N/A | N/A | N/A |
| Difference (body top) | N/A | N/A | N/A | N/A |
| Pre body TC (top, center) | 3.502 | 3.502 | 3.505 | 3.501 |
| Post body TC | N/A | N/A | N/A | N/A |
| Difference (top, center) | N/A | N/A | N/A | N/A |
| Pre body center | 3.505 | 3.504 | 3.504 | 3.504 |
| Post body center | N/A | N/A | N/A | N/A |
| Difference (body center) | N/A | N/A | N/A | N/A |
| Pre body CB (center, bottom) | 3.505 | 3.504 | 3.504 | 3.505 |
| Post body CB | N/A | N/A | N/A | N/A |
| Difference (center, bottom) | N/A | N/A | N/A | N/A |
| Pre body bottom | 3.506 | 3.507 | 3.506 | 3.506 |
| Post body bottom | N/A | N/A | N/A | N/A |
| Difference (bottom) | N/A | N/A | N/A | N/A |

# 6.6 PMATP-CGOC1 Conclusions

A half-scale plutonium air-transportable package test unit identified as PMATP-CGOC1 was successfully tested at the Full-Scale Experimental Complex 10,000-ft sled track in SNL's Tech Area III Test Facility. The PMATP-CGOC1 was subjected to a CGOC orientation impact test as specified in the Murkowski Amendment.

The inner containment vessel suffered little damage. The measured deformation was approximately 0.002 inch at the center diameter of the container body. The closure lid did not suffer any measurable damage, and the closure threads remained intact.

Lessons learned from this test include minor design changes to the overpack end cap design to provide protection from shearing with the perforated aluminum sheet and Kevlar™ cloth overpack. This test clearly demonstrated the viability of perforated aluminum sheet and Kevlar™ cloth as an excellent energy-absorbing overpack material.

# 7. Conclusion

A comprehensive series of engineering tests was conducted for the Japan Nuclear Cycle Development Institute (JNC) at SNL's 10,000-ft rocket sled track on a prototype plutonium air transport (PAT) package by SNL. This prototype PAT package, the PMATP, is a half-scale PAT package designed to carry 7.6 kg of plutonium oxide and survive the "worst-case" air crash conditions as stipulated by the Murkowski Amendment. These conditions are a 282-m/s impact onto a defined weathered sandstone target to match the crash parameters experienced by the PSA Flight 1771 crash.

This prototype design was developed for the JNC plutonium air transport program. The prototype design was preceded by, and developed from, a multi-year analytical and testing sequence to determine the appropriate parameters to meet the severe crash conditions required. Extensive finite-element structural analysis modeling combined with constitutive material properties were used to evaluate stresses and deformations pre-test. Substantial testing previously was carried out to determine conceptual feasibility of the design.

In this testing program, four tests were conducted to demonstrate the feasibility of this PMATP in a prototype design phase of development. One calibration test and three engineering design tests on prototype configurations of the PMATP were conducted. Test conditions and engineering standards employed were similar to certification tests required by the Nuclear Regulatory Commission (NRC). The engineering tests were conducted to determine the ability of the PMATP to survive impacts in side-on, end-on, and CGOC orientations.

Extensive forensic analysis of the test articles after testing showed excellent results. Little deformation of the inner containment vessel was observed post-test in all tests. In the one test that did show more deformation than the others, the end-on configuration, a modification of the end plug and inner containment vessel was indicated. To demonstrate this experimental finding, on the CGOC test following the end-on test, one inch of additional end-plug thickness was added and proved effective for that test. The experimental results were predicted by finite-element structural analysis of the PMATP, and that analysis has also shown the scalability of the PMATP concept to a full-scale package.

The full-scale prototype, the next step in this research, will need to optimize the overpack shell and inner containment vessel design. The overpack shell will need to be modified to better protect the end plug during impact. The inner containment vessel may be modified also with a welded closure or a metal seal.

The results from this series of PMATP tests are clearly conclusive demonstrations of the viability of both the concept and the underlying engineering basis for design. The next step is to design, construct, and test a full-scale prototype for engineering feasibility. The NRC should be informed and aware of this progress so that a certification program procedure can be established if JNC wishes to pursue the option of possible future development of PAT packaging.

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