Plutonium Air Transport Package Development for "Worst-Case" Accident

J.D. Pierce*, D. C. Harding, and J. G. Bobbe
Sandia National Laboratories**
Albuquerque, NM 87185

G. F. Hohnstreiter,
Images of the Southwest,
Albuquerque, NM 87123

T. Kitamura, Y. Ouchi, and T. Ito
Japan Nuclear Cycle Development Institute
4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1184, Japan

Abstract

Sandia National Laboratories (SNL) has developed and tested a package design for air transport of plutonium that can survive a "worst-case" aircraft crash. This work has been performed for the Japan Nuclear Cycle Development Institute (JNC) using technology developed by SNL (US Patent 5,337,917) for the United States Department of Energy. U. S. law requires that air transport of plutonium through U.S. airspace from a foreign origin to a foreign destination must be in a packaging that is able to survive a "worst-case" aircraft crash. As a result, JNC has pursued the development of a design that can meet these stringent requirements.

This report details the design and testing of a new plutonium air transport (PAT) package capable of protecting its contents in "worst-case" accident conditions. A potential "worst-case" accident is prescribed as a 282 m/s (925 ft/s) impact onto a decomposed rock surface. This is expected to be more severe than the current U.S. regulations that require a 129 m/s (422 ft/sec) impact onto a rigid surface. PAT packages currently certified in the U.S. were designed to meet the 129 m/s impact criteria in the U.S. regulations and use redwood as an impact-limiting material. The new design for transport of plutonium dioxide uses a non-flammable layered composite of aluminum perforated sheet and aramid cloth as an overpack to absorb kinetic impact energy and maintain confinement for subsequent fire protection. This design also uses a very robust primary containment vessel with a welded or brazed closure for protection and confinement of the contents. In addition, an outer shell around the energy absorbing material is provided for handling and weather protection. Package performance for end-on and side-on dynamic impact events was studied using 2D and 3D nonlinear finite-element codes. Half-scale models were fabricated and tested at the 3000-m rocket sled track at SNL. Side, end, and center-of-gravity-over-corner impact tests were performed.

Results of these analyses and tests showed that the package design is capable of meeting the "worst-case" accident conditions and is more efficient than the current design as a result of its smaller overall volume and total mass.

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* Author to whom all correspondence should be sent.
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Introduction

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 (Reference 2) has been developed 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) (Reference 3) as described in US Patent No. 5337917 (Reference 4). 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 1. The impact limiting materials have been well characterized and tested (Reference 5) to provide constitutive material properties for finite element analyses that were documented in Reference 1.

This paper describes the design and a series of impact tests that were 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 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 any impact orientation.

The impact tests of the PMATP prototypes were performed at SNL's 3000-m Rocket Sled Track. The tests were performed according to test plans and procedures written by the authors and approved by SNL management and quality assurance personnel. These tests indicate that a full-scale PMATP package would be expected to survive a "worst case" airplane crash under the required conditions.

Background

SNL designed and received certification for two PAT packages in the late 1970's and early 1980's (References 6 and 7). The mass of the PAT-1 is approximately 225 kg and it can contain 2.0 kg of plutonium dioxide. The mass of the smaller PAT-2 is approximately 33 kg and it can carry 15 g of plutonium. Both containers consist of a high-strength bolted containment vessel surrounded by a redwood overpack impact limiter covered by stainless-steel overpack drums. Impact tests at 129 m/s of both containers in various orientations have shown that the primary containment vessel sustained no plastic or permanent deformation after impact, and passed leak-check requirements defined in NUREG-0360 (Reference 8). These containers have been used to ship small quantities of plutonium by air over U.S. and international air spaces in accordance with the more stringent U.S. air transport packaging regulations than those of the International Atomic Energy Agency (IAEA).

JNC has had a joint research and testing program at SNL for over 10 years (Reference 9). The primary thrust of this program has been to assist JNC's development of a larger PAT package designed to ship 7.6 kg of plutonium dioxide, based on the NUREG-0360 accident conditions. The resultant containers were successfully tested in two specific orientations through impact and fire accident conditions at SNL.

In 1987 the US government passed Public Law 200-203 (Reference 10), also known as the Murkowski amendment (named for Senator Murkowski of Alaska.) This amendment stipulated that any aircraft carrying nuclear material through US 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 PSA Flight 1771 crash at 282 m/s onto a soft rock (shale and sandstone) surface in California (Reference 2). The kinetic energy of the Murkowski Amendment impact event is almost five times greater than the NUREG-0360 requirement, and although a "yielding" target is specified rather than an unyielding one, the higher-velocity impact condition will most likely be more severe or damaging to most packages. Because all previous PAT packaging were designed to meet NUREG-0360 requirements, a new PAT package may be needed to survive this "worst-case" accident.

The Murkowski Amendment legislation provided a significant enhancement of the then existing regulations concerning air transport of plutonium. The regulations at the time, NUREG 0360, stipulated an impact of 129 m/s. Because of the more difficult conditions and the unavailability of a package that would meet these conditions at that time, JNC resumed sea transport for plutonium oxide shipments from Europe to Japan, while continuing to research air transport methods for future consideration. The testing reported here for the PMATP prototype developed at SNL are significant for JNC because they provide the technical justification for an alternate mode of plutonium oxide shipment. This crash-resistant container utilizes perforated aluminum sheet and aramid cloth as a protective overpack

This recent testing has shown the success of the PMATP in a prototype stage for half-scale models. The experimental results (Reference 11) were predicted by finite-element structural analysis of the PMATP, and analysis has also shown the scalability of the PMATP concept to a full-scale package.

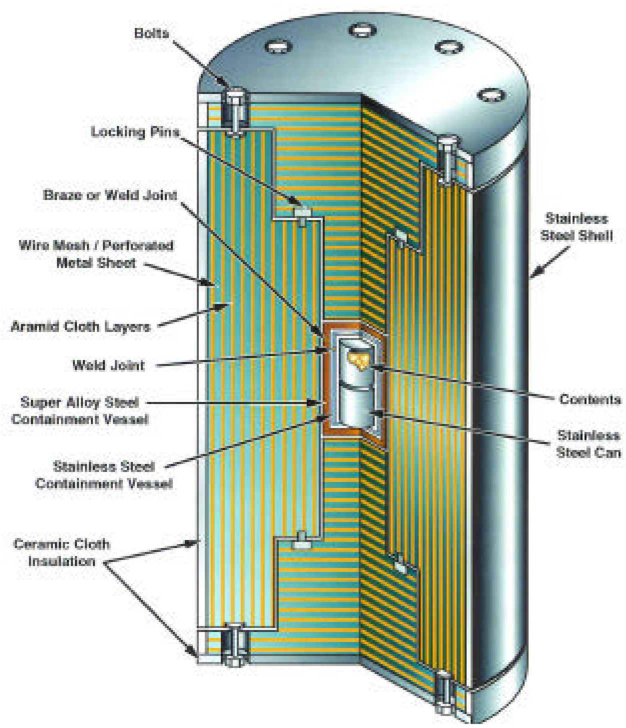

Figure 1. Perforated Metal Air Transportable Package (PMATP) Prototype.

Design

Before conceptual design could begin, the design requirements had to be delineated pertaining to mass or volume of contents, overall package cost, mass and size restrictions, regulatory normal conditions, accident condition restraints, criticality and shielding constraints, handling issues, and materials considerations. One guiding assumption was that the secondary welded containment vessel and internal powder containers be identical to those used in JNC's Common Package Model 1 and Model 2 designs (Reference 9).

The primary design constraint is obviously based on regulatory accident conditions as defined in 10CFR-71 (Reference 12) for U.S. Type B packages and Safety Standards of the IAEA (Reference 13) for international packaging. Accident conditions for plutonium air transport packagings were initially defined in NUREG-0360 and have since been incorporated into 10CFR-71. The Murkowski Amendment as discussed above extends those regulations. Overall package mass and size restrictions were based on the interior volume of a standard ISO container (3 m x 3 m x 2.4 m) and a Boeing 747-400 main floor weight limitation of 4800 kg.

Unlike Type B packages for surface transport of plutonium, air transport package design guides do not exist. Regulatory Guide 7.6 (Reference 14) provides specific requirements on containment vessel stress levels with respect to ASME Boiler and Pressure Vessel Code material stress intensities for Type B packaging. Using finite element analysis, the deformation of the PCV was monitored throughout the dynamic impact events and compared with its failure level to ensure integrity of the PCV for this severe accident condition.

Materials Selection

The overpack and impact mitigating materials selected for the new PAT package design are layered aluminum wire mesh and/or perforated aluminum sheet with aramid cloth. Extensive quasi-static crush testing, constitutive modeling, and high-speed impact testing have been performed at SNL on these composite materials, and they are well characterized (Reference 3). A comparison of engineering compressive stress vs. strain for the two composite overpack materials measured at SNL is shown in Figure 2.

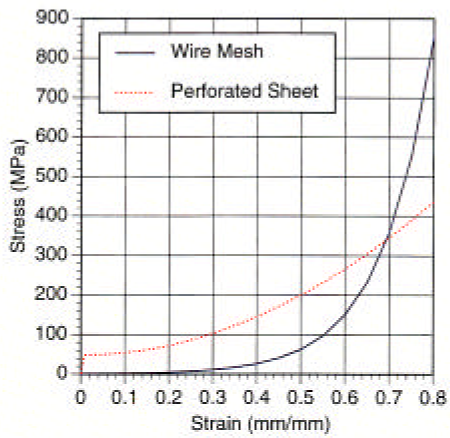

Figure 2. Stress-strain Diagram for Aluminum Wire Mesh And Perforated Sheet.

Unlike previous PAT packages that use heavy bolted closures in their primary containment vessels, the new package design uses a welded or re-brazeable closure. SNL has developed re-brazeable closures and has proven viability of the technology (References 15 and 16). Elimination of the bolted closures provides increased integrity in the seal area, for both the impact and fire accident conditions, and significant reductions in containment vessel mass as a result of the omission of the reinforced flange and bolting required for metal and O-ring seals.

Selection of a primary containment vessel material is based on many criteria. The NRC requires all nuclear material containment vessels to be ASME Code Section III, Class 1 materials. Other important material characteristics for this application are relatively high ductility or fracture resistance, weldability, corrosion resistance, and low density. A survey of all materials listed in the ASME Code referred to above resulted in one superior material, by far outperforming the others listed. AISI Type S13800 is a martensitic, precipitation hardening (maraging) stainless steel with a yield strength almost 60% higher than Ti-6Al-4V, a non-ASME Code approved material. Figure 3 shows true stress vs. strain for 304 stainless steel, Ti-6Al-4V, and S13800. AISI S13800 is also known as Ph13-8Mo and has a proven performance record as a primary containment vessel material in the PAT-1 package as well as in aircraft and nuclear reactor components.

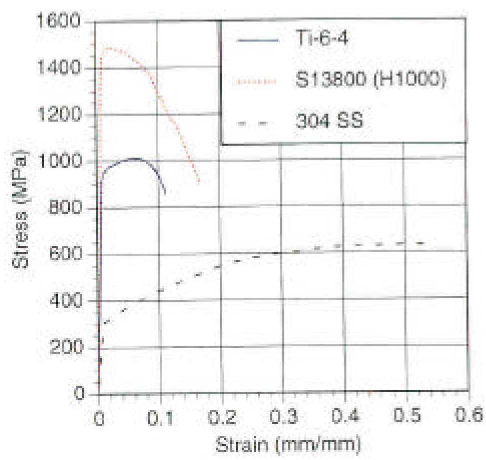

Figure 3. Stress-strain Curves to Failure for Three Containment Vessel Candidate Materials.

Conceptual Design and Analysis

The conceptual design of the new PAT packaging was based on materials and design constraints developed previously, combined with simplified quasi-static analyses to approximate component sizes and dimensions. Because the inner containment vessel and its contents (plutonium dioxide and its containers) are fixed, the primary containment vessel and wire mesh or perforated plate and aramid cloth overpack were the major components requiring design analysis. Previous analyses and tests validated the overpack material's global isotropic behavior, with deformation and impact mitigation response independent of wrap angle or orientation. This simplified the initial analyses for determination of the preliminary overpack design thickness.

For the overpack design in the end-on case, a simplified analytical circular plate bending solution was utilized to determine the thickness of the top and bottom wire mesh or perforated metal plate.

For the side-on impact case, no simplified analytical method could be used to accurately size the side overpack thickness. A linear finite element analysis (FEA) was used to determine the maximum allowable decelerative load applied to the PCV without plastic deformation. Linear FEA was sufficient to approximate the maximum PCV loading because non-linear plastic deformation is undesirable and exceeds the design requirements. Pro/ENGINEER (Reference 17) was used to produce the solid model and generate the approximately 15,700-element tetrahedral finite-element mesh. COSMOS/M Engineer (Reference 18) was used to perform the linear FEA. Von Mises stress results are plotted in the quarter-symmetric deformed mesh model in Figure 4.

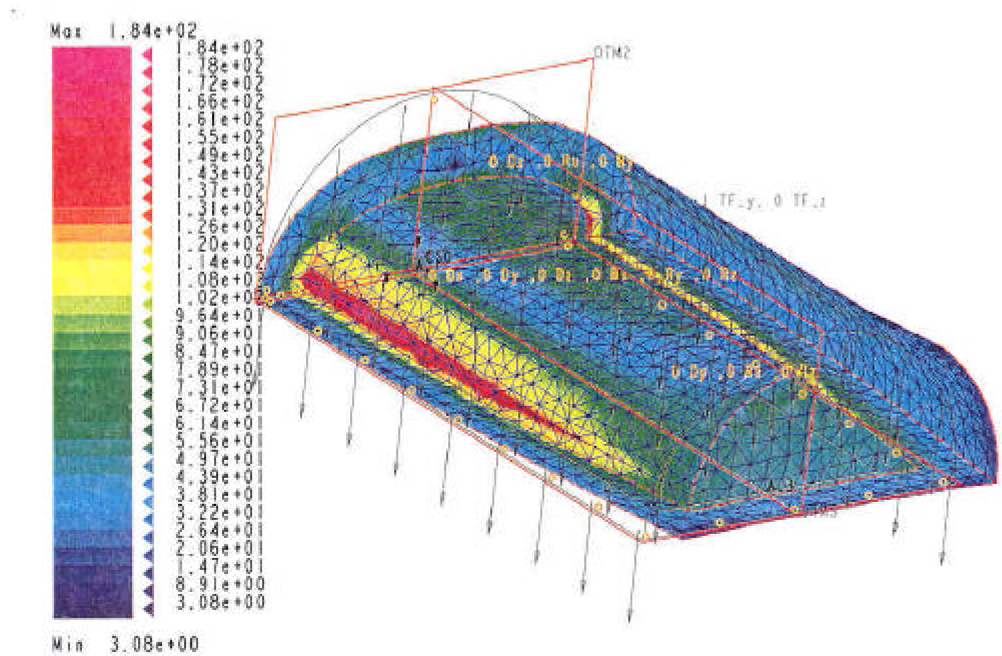

Figure 4. Von Mises Stresses on Quarter-Symmetry Pro/ENGINEER Model and Deformed Finite Element Mesh of the Primary Containment Vessel With Applied Uniform Loading Boundary Conditions.

Detailed Analyses

A series of explicit transient dynamic FEA were performed on the conceptual package designs using SNL's PRONTO 2D and 3D finite element analysis codes (References 19 and 20). End-on and side-on impacts were analyzed onto an unyielding target at 129 m/s as well as onto the Murkowski Amendment soft rock target at 282 m/s. This analysis showed that, although the 282 m/s impact events possess almost five times the kinetic energy of the 129 m/s impacts, peak decelerations are only two to three times greater due to energy absorption of the yielding soft rock target. As expected, peak PCV decelerations were greater during the higher velocity impacts. Figure 5 shows the calculated deformed shape of the perforated overpack package for the 282 m/s impact onto soft rock, and Figure 6 shows the calculated equivalent plastic strain in the primary containment vessel for this case (well below failure level for this material).

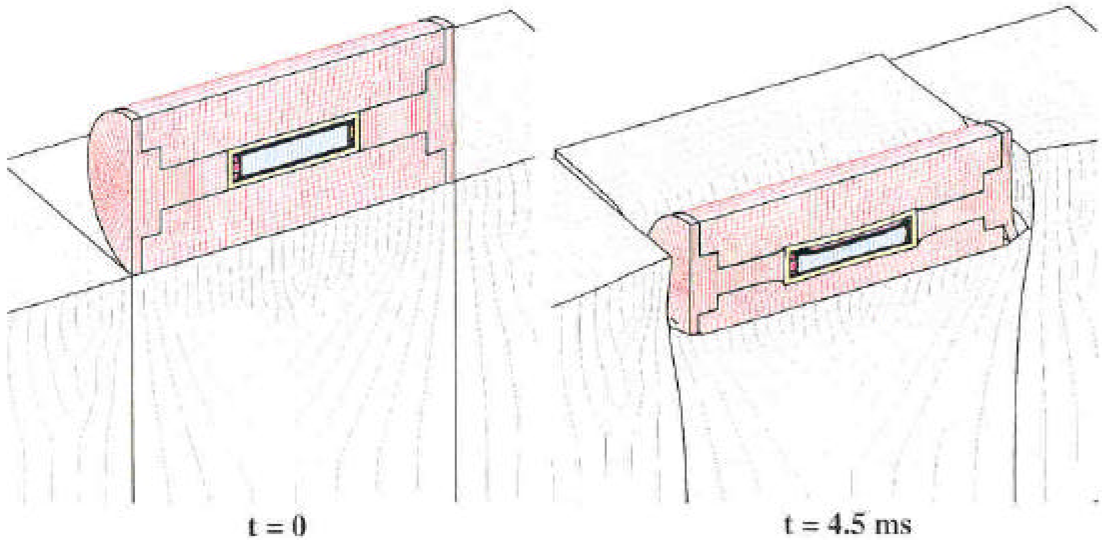

Figure 5. Deformed Shape of Perforated Plate Overpack Package After 282 m/s Side-on Impact Onto Soft Rock.

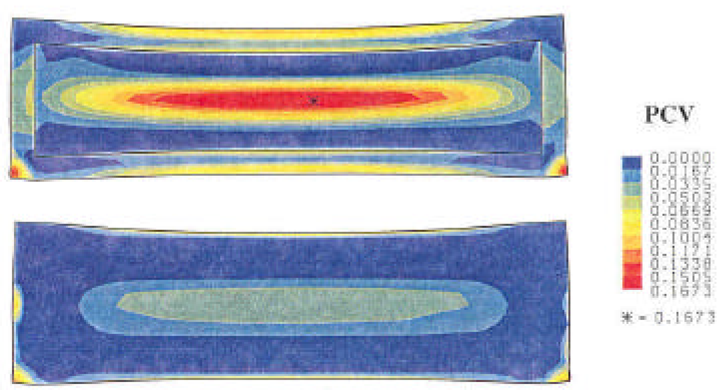

Figure 6. Equivalent Plastic Strain in Primary Containment Vessel (PCV) After 282 m/s Side-on Impact of Perforated Plate Overpack Package Onto Soft Rock.

Although structural accident conditions drove the overpack designs in the preliminary analyses, normal transport and thermal accident conditions may also affect containment vessel and overpack design. Previous analyses and tests of the wire mesh composite overpack in fuel fire accident conditions have proven its excellent insulating performance (Reference 21). The thermal effects on the welded or re-brazeable containment vessels are greatly alleviated because of the elimination of elastomeric seals with their more stringent thermal requirements.

Testing

A series of four impact tests on half-scale prototype models of the new Perforated Metal Air Transportable Package design, were conducted at SNL's 3000-m Rocket Sled Track (Reference 11). These impact tests were in the side, end-on, and center-of-gravity-over-corner orientations at velocities close to 282 m/s onto a concrete 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 result of these tests was that the half-scale PMATP performed very well under the "worst-case" aircraft-crash conditions, and these tests, together with analyses, indicated that a full-scale PMATP utilizing this overpack concept and impact-limiting design would survive these crash conditions.

The location of the PSA crash was a severely weathered sandstone hillside. For the testing program, engineered concrete targets were used. Typical concretes have much higher strength than the weathered sandstone, so an altered concrete target structure was designed and developed. Important target parameters that were used to model the high-speed impact testing for the designed crushable target are density, shear strength (defined by the deviatoric yield surface), hydrostatic crush behavior, and degree of confinement. During an impact onto an actual rock target, the surrounding rock provides nearly perfect confinement of the material being impacted. For this reason, it was necessary to have a target significantly larger than the package being tested and to confine the edges of the target. Targets utilized were cast into a 3.6 m diameter by 2.4 m deep steel vessel. The steel around and in back of this target structure provided excellent confinement and simulated the boundary conditions provided by the semi-infinite real target. In order to obtain the matching target material parameters, a concrete mix with the following proportions was designed: sand 1060 kg, cement 213 kg, air entrainment 0.48 kg, and water 170 kg. 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. Extensive investigations were conducted on the correct concrete mixtures and curing times for the proper simulation.

As stated above, four impact tests were conducted at the SNL rocket sled track test facility. These were:

PMATP-CTU1:	A calibration test in the side-on configuration
PMATP-SO1:	Side-on configuration test.
PMATP-EOl:	End-on configuration test.
PMATP-CGOC1:	Center-of-gravity-over-corner test.

The PMATP side-on prototype, typical of all units tested, was a right circular cylinder, 38.1 cm in diameter and 76.2 cm long. The inner containment vessel, constructed from S13-8 H1100 stainless steel, was 8.9 cm diameter and 30 cm long with a 1.27 cm wall thickness. It was filled with Number 6 steel shot to simulate the mass of the plutonium dioxide. The containment vessel was placed in a two-step 16-gauge 304 stainless-steel inner tube. The inner tube was wrapped with perforated aluminum sheet and aramid cloth. The wrap cycles include three wraps of perforated aluminum sheet and two wraps of perforated aluminum with aramid cloth. The perforated aluminum was 0.81 mm thick 3003-H14 with a 51% open space made with 2.97 mm diameter staggered holes 3.0 mm apart. The aramid cloth was approximately 0.46 mm thick. The outer shell and the ends were constructed from 16-gauge 304 stainless steel welded to the outer plates of the inner tube. The two end plugs were filled with three perforated aluminum disks. Total assembled weight of the PMATP-SO1 package was 116.1 kg, and the concrete target weight was 63,300 kg. The package, shown in Figure 7, was propelled to the target by a pusher sled containing 12 Zuni rockets. The package impacted the target for this test at a velocity of 269 m/s. A crater was formed at the impact area of the target approximately 1.83 m in diameter and .46 m deep.

Figure 7. PMATP-SO1 and Pusher Sled Prior to Test

On post-test analysis of the package, it was determined that the inner containment vessel of the PMATP-SO1 suffered only 1.0 mm deformation over its length, thus indicating that the vessel would remain leak-tight. This test clearly demonstrated the viability of the perforated aluminum sheet and aramid cloth as an excellent energy absorbing overpack material. The SNL photometrics group provided extensive optical measurements, including streak camera and laser-tracker coverage. The PMATP-EO1 impact test was performed on October 19, 1999. The package impacted in the desired end-on configuration at a velocity of 277 m/s, as shown in Figure 8 at the moment of impact.

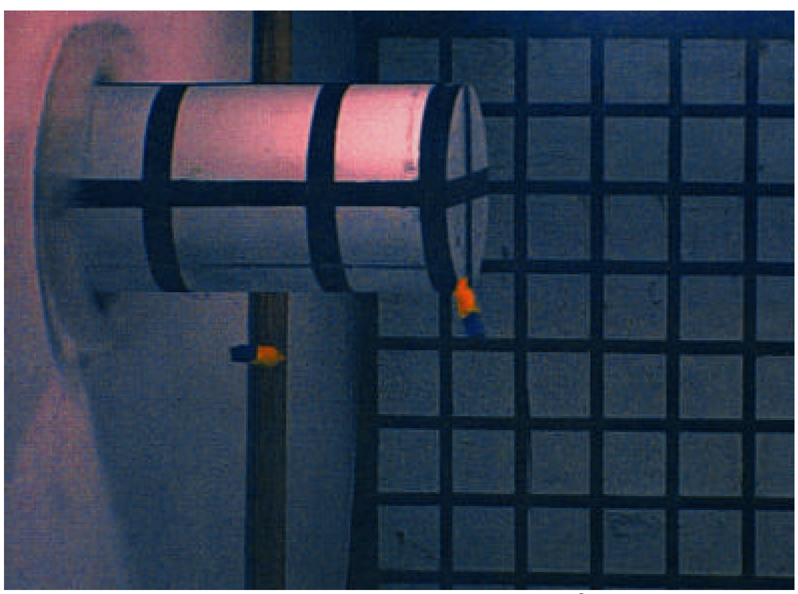
Figure 8. PMATP-EO1 at moment of impact.

Figure 9 shows the test unit with the outer shell crushed as expected in an accordion-like manner. The bottom cover sheared from the package thus exposing the overpack perforated aluminum and aramid cloth. The containment vessel remained confined in the overpack. The package rebounded from the target and landed 23 m north of the target and 12 m west. A crater was formed at the impact area of the target approximately 1.52 m in diameter and .4 m deep at the center. Lessons learned from this test include optimizing the overpack design with more material, and assuring proper tolerances of the inner containment vessel to assure good contact between the closure lid and the containment body. These modifications were made for the last test in this series, the center-of-gravity-over-corner test. The end-on test also clearly demonstrated the viability of the new design concept.

Figure 9. PMATP-EO1 Package After 277 m/s Impact Showing Expected Crush.

The PMATP-CGOC1 test was conducted on November 4, 1999. This center-of-gravity-over-corner test configuration is shown in Figure 10.

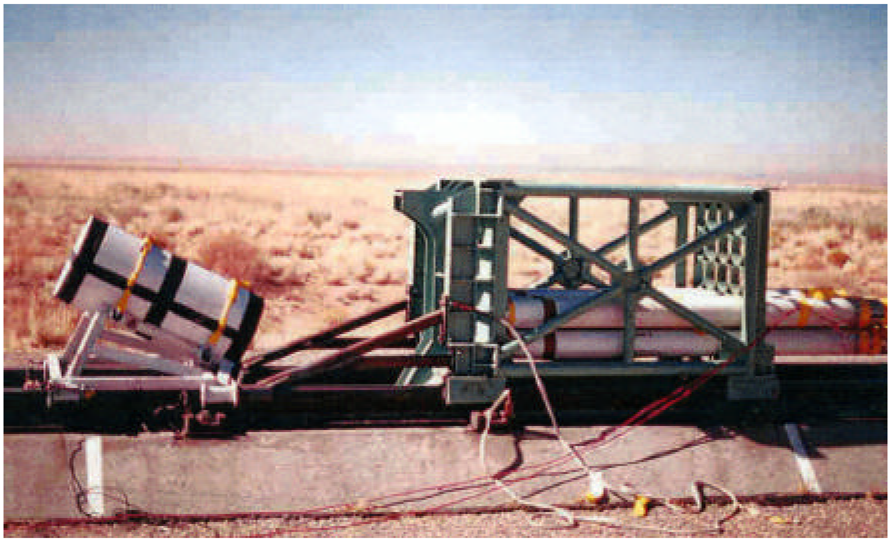

Figure 10. PMATP-CGOC1 Package and Pusher Sled With Zuni Rockets

Figure 11 shows the moment of impact of the PMATP-CGOC1 package onto the target. The structure in front of the target area was used for the photometrics equipment.

Figure 11. PMATP-CGOC1 at Moment of Impact With Impact Velocity of 271 m/s.

The post-test inspection of the test unit for PMATP-CGOC1 showed that the inner containment vessel had suffered little damage: the measured deformation was approximately 0.05 mm at the center diameter of the container body. The closure lid did not suffer any measurable damage, and the closure threads remained intact. This test also demonstrated viability of the perforated aluminum sheet and aramid cloth as an excellent energy absorbing overpack material.

Conclusion

A comprehensive series of engineering tests were conducted for the Japan Nuclear Cycle Development Institute (JNC) at the Sandia National Laboratories (SNL) 3000-m rocket sled track on a prototype plutonium air transport (PAT) package design developed by SNL. This prototype PAT package, called the Perforated Metal Air Transportable Package (PMATP), is a half-scale PAT package designed to carry 7.6 kg of plutonium dioxide and survive the "worst case" air crash conditions as stipulated by the Murkowski Amendment. These conditions are to survive a 282 m/s impact onto a defined weathered sandstone target so as 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 a several-year analytical and testing sequence to determine the appropriate parameters to meet the severe crash conditions required. Extensive finite-element structural analyses combined with constitutive material properties were used to evaluate stresses and deformations. Substantial testing was conducted previously to determine conceptual feasibility of the design.

In this latter testing program, four tests were conducted to demonstrate the feasibility of the PMATP in this 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 NRC. These engineering tests were performed to determine the ability of the PMATP to survive impacts in side-on, end-on, and center-of-gravity-over-corner orientations.

Extensive forensic analysis of the test articles after testing showed excellent results. Little deformation of the inner containment vessel was observed posttest. 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 center-of-gravity over corner 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 results from this series of PMATP tests are conclusive demonstrations of the viability of both the concept as well as the underlying engineering basis for design.

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