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Radiant Heat Test of Perforated Metal Air Transportable Package (PMATP)

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Radiant Heat Test of Perforated Metal Air Transportable Package (PMATP)

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Abstract

A conceptual design for a plutonium air transport package capable of surviving a “worst case” airplane crash has been developed by Sandia National Laboratories (SNL) for the Japan Nuclear Cycle Development Institute (JNC). A full-scale prototype, designated as the Perforated Metal Air Transport Package (PMATP) was thermally tested in the SNL Radiant Heat Test Facility. This testing, conducted on an undamaged package, simulated a regulation one-hour aviation fuel pool fire test. Finite element thermal predictions compared well with the test results. The package performed as designed, with peak containment package temperatures less than 80°C after exposure to a one-hour test in a 1000°C environment.

This work was supported by the Japan Nuclear Cycle Development Institute (JNC) under contract DE-F104-88AL5272, Appendix A-15, Statement of Work, and Section 1.2, Land Transport Emergency Response Technology.

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Executive Summary

A conceptual design for a plutonium air transport package capable of carrying 7.6 kg of plutonium oxide and surviving a “worst-case” airplane crash was 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 U. S. Department of Energy (DOE) as described in U. S. Patent No. 5337 917.

In a variety of investigations, SNL has conducted extensive computer modeling and experimental testing on the PMATP conceptual package to verify its ability to satisfy the stringent requirements of the “worst-case” accident conditions as stipulated by the Murkowski Amendment. These investigations include laboratory tests on the component materials, field impact tests on half-scale models, and thermal analyses of the package in both undamaged and a suite of post-impact states.

This report presents results from a thermal test of the full-scale package in its undamaged condition and compares these test measurements with finite element simulations. The test is intended to simulate a one-hour aviation fuel fire.

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Nomenclature

DOE	U. S. Department of Energy
JNC	Japan Nuclear Cycle Development Institute
MST	Mountain Standard Time
NUREG	Nuclear Regulatory Commission
PMATP	Perforated Metal Air Transportable Package
PSA	Pacific Southwest Airlines
SNL	Sandia National Laboratories
TC	thermocouple

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1. Background and Scope

A conceptual design for a plutonium air transportable package capable of carrying 7.6 kg of plutonium oxide and surviving a “worst-case” airplane crash was developed by Sandia National Laboratories (SNL) for the Japan Nuclear Cycle Development Institute (JNC).¹ The package is based on technology developed by SNL for the U. S. Department of Energy (DOE) as described in U. S. Patent No. 5337 917.²

The U. S. government passed Public Law 100-203, also known as the Murkowski Amendment (named for U. S. Senator Frank Murkowski of Alaska).³ This amendment stipulated that any aircraft carrying nuclear material through U. S. airspace would have to ensure that, in a worst-case crash, no spillage or release of nuclear material would ensue. Worst-case crash conditions for this legislation are based on the crash of Pacific Southwest Airlines (PSA) Flight 1771, on December 7, 1987, and are technically defined as an impact at a velocity of 282 m/s onto a severely weathered sandstone hillside target.

The radiant heat tests reported here for the PMATP prototypes are significant for JNC because they provide the thermal justifications, in aircraft crash test conditions, for the ability of this package to survive the worst-case accident as stipulated in the Murkowski Amendment.

In a variety of investigations, SNL has conducted extensive computer modeling and experimental testing on the PMATP conceptual package to verify its ability to satisfy the stringent requirements of the “worst-case” accident conditions as stipulated by the Murkowski Amendment. These investigations include laboratory tests on the component materials, field impact tests on half-scale models, and thermal analyses of the package in both undamaged and a suite of post-impact states.^{4, 5}

This report presents results from a thermal test of the full-scale package in its undamaged condition and compares these test measurements with finite element simulations. The test is intended to simulate a one-hour aviation fuel fire.

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2. PMATP Description

As shown in Figure 2.1, the PMATP consists of a substantial stainless-steel primary containment vessel within an overpack of layered perforated aluminum and Aramid cloth, encased in a thinner stainless steel shell, and thermal insulation. The full-scale package is 1.6-m long by 0.8-m diameter and weighs approximately 850 kg.

The containment vessel dimensions are 0.1778-m outer diameter by 0.5842-m long with 0.0254-m thick stainless-steel walls. The Aramid cloth (Kevlar®*) is 0.0004318-m thick, and the perforated aluminum is 20 gauge. The layering sequence is aluminum, aluminum, aluminum, Kevlar, aluminum, Kevlar, aluminum for the cylindrical body as well as the end plugs.

Figure 2.1. Perforated Metal Air Transportable Package (PMATP).

* Kevlar® is a Dupont registered trademark.

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3. Test Design

As suggested in NUREG-0360, the most severe likely aviation fuel fire environment can be simulated as a black-body radiation source at 1010°C for a one-hour duration.⁶ Because the maximum temperature at interior points within the package may occur after the fire is extinguished, temperatures were monitored well beyond the one-hour heating period. Plutonium acts as an internal power source (approximately 150 watts) for the 7.6 kg loading. Due to the insulating properties of the PMATP, this heat will cause internal temperatures to rise above ambient. Calculations indicate that at steady state, these will reach a peak value of 134°C.⁵

To thermally validate the package design to satisfy the fire test environment, a full-scale test unit was constructed and instrumented with thermocouples. Figures 3.1 through 3.3 are photographs of the test unit during construction. Figure 3.4 shows the thermocouple locations within the unit. Table 3.1 lists coordinates of the thermocouples. More detailed specifications of the test unit and instrumentation are given by J. Nakos.⁷ Note that the containment vessel is empty (air-filled) for this test.

Figure 3.1. Inner Structure of PMATP Before Wrapping.

Figure 3.2. View of PMATP Showing Perforated Aluminum Wrap.

Figure 3.3. Instrumented PMATP Containment Vessel.

Figure 3.4. PMATP Test Unit Thermocouple Locations.

Table 3.1. PMATP Thermocouple Locations

(Origin of coordinates is at centroid of containment vessel.)

TC No.	Location	X [m]	Y [m]	Z [m]
1	Inner tube, 0 degrees	0	0	0.095123
2	Inner tube, 90 degrees	-0.095123	0	0
3	1 st Kevlar Wrap Interface, 0 degrees	0	0	0.206248
4	1 st Kevlar Wrap Interface, 90 degrees	-0.206248	0	0
5	2 nd Kevlar Wrap Interface, 0 degrees	0	0	0.33401
6	2 nd Kevlar Wrap Interface, 90 degrees	-0.33401	0	0
7	3 rd Kevlar Wrap Interface, 0 degrees	0	0	0.381
8	3 rd Kevlar Wrap Interface, 90 degrees	-0.381	0	0
9	Top end plug	0	0.739648	0
10	Top end plug	0	0.6477	0
11	Top end plug	0	0.530098	0
12	Top end plug	0	0.390525	0
13	Top end plug	0	0.3048	0
14	Containment vessel, 90 degrees, inside wall	-0.0635	0	0
15	Containment vessel	0	0	0
16	Containment vessel, 0 degrees, inside wall	0	0	0.0635
17	Containment vessel	0	-0.264668	0
18	Containment vessel, 90 degrees, inside wall	-0.0635	-0.264668	0
19	Containment vessel, 0 degrees, inside wall	0	-0.264668	0.0635
20	Containment vessel, 90 degrees, outer wall	-0.0889	0	0
21	Containment vessel, 90 degrees, outer wall	-0.0889	-0.290068	0
22	Containment vessel, 0 degrees, outer wall	0	-0.290068	0.0889
23	Containment vessel, 0 degrees, inside wall	0	0	0.0889
24	Containment vessel	0	-0.290068	0
25	Bottom end plug	0	-0.3048	0
26	Bottom end plug	0	-0.390525	0
27	Bottom end plug	0	-0.530098	0
28	Bottom end plug	0	-0.6477	0
29	Bottom end plug	0	-0.739648	0

The prescribed environment for the test was to increase air temperature from ambient to 1000°C in four minutes, hold at 1000°C for one hour, and then monitor the package cooling for at least 24 hours. Uniform heating around the circumference, reflective heating on the top, and no direct

heating of the bottom were deemed adequate. No internal heat sources were included; thus the package was initially at ambient temperature.

An extensive description of the Radiant Heat Test Facility, shown in Figure 3.5, is provided by J. Nakos.⁷ Heating is generated by 24 panels of quartz lamps, oriented as 12 on the top and 12 on the bottom, as shown in Figure 3.6. Figure 3.7 is an elevation view of the array, and Figure 3.8 is a plan view of the concentric array. Each lamp can draw up to 6.4 kw of electric power. The total number of lamps used was 456, so the entire array could draw up to 2736 kw.

The panels were electrically connected into six independent channels for temperature control. Each channel controlled two top panels and two bottom panels. In order to control the test temperature more accurately, the lamps did not heat the test unit directly. Rather, a thin stainless steel shroud painted black on both sides was positioned between the heater array and the test unit. The lamp panels heat the shroud, which was controlled and monitored by thermocouples to the desired temperature. The shroud then re-radiated heat to the test unit. The shroud environment approximated a gray-body with an emissivity 0.85. The shroud was directly heated only on the sides. The top was not heated, but was insulated to provide a partial heat source. The bottom of the shroud was open. Figure 3.9 is a photograph of the test unit inside the heater array, and Figure 3.10 is a photograph with the shroud in place.

Figure 3.5. Radiant Heat Test Facility.

Figure 3.6. Quartz Lamp Panels.

Figure 3.7. Elevation View of Radiant Heat Test Configuration.

Figure 3.8. Plan View of Radiant Heat Test Configuration.

Figure 3.9. PMATP on Stand Before Test.

Figure 3.10. Shroud in Place Before Test.

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4. Conduct of Tests

Two calibration tests were conducted using an 18-inch-diameter steel pipe as a dummy test unit to verify that the power supply and temperature control were satisfactory.

The actual test was conducted on September 12, 2002, and began at approximately 9:30 a.m. MST. Figure 4.1 is a photograph taken during the active heating phase. Some aluminum melted and leaked from the bottom of the package during the test. This was expected because the temperature near the skin of the package was expected to exceed the melting point of aluminum during the one-hour test, and the bottom seams of the test unit were not continuously welded. Figure 4.2 shows the leakage.

Figure 4.1. Heating Phase.

Figure 4.2. Melted Aluminum Leaked from Bottom of Test Unit.

Figure 4.3 shows temperatures recorded on the bottom ring of the shroud thermocouples. The thermocouples were labeled by azimuth in degrees and B for bottom (refer to Figures 3.7 and 3.8 for position). Feedback from six of these (B15, B72, B108, B195, B216, and B252) was used to control the heating on the six independent channels.

Figure 4.4 shows the recorded temperatures on the top-level thermocouples. The labeling convention is T for top followed by the azimuth in degrees. Figure 4.5 shows the recorded temperatures at two locations on the stand supporting the test unit. Figure 4.6 compares averages for the top level, bottom level, and support stand. The average top-level temperatures drifted approximately 50°C below the target value during the heating phase. This was because all the feedback controls were located on the bottom level. Uncertainty in the recorded temperatures was estimated to be -21°C to $+8^{\circ}\text{C}$.⁵

Figure 4.3. Bottom Ring Shroud Thermocouples (continued on next page).

Figure 4.3. Bottom Ring Shroud Thermocouples (concluded).

Figure 4.4. Top Ring Shroud Thermocouples (continued on next page).

Figure 4.4. Top Ring Shroud Thermocouples (concluded).

Figure 4.5. Stand Thermocouples.

Figure 4.6. Average of Thermocouple Data.

Figures 4.7 through 4.9 show the temperatures recorded within the test unit itself, with the thermocouple locations given in Figure 3.4 and Table 3.1. The thermocouples were positioned to depict temperature variation versus radius, axial position, and throughout the containment vessel. Figure 4.7 shows the measured temperatures versus time at various radii from the centroid of the containment vessel. Thermocouples with the same radial and axial distances from the centroid but different azimuths are cross-plotted. The peak temperature decreased from nearly 1000°C at the outer surface to less than 80°C at the containment vessel. Figure 4.8 shows the measured temperatures versus time at various axial distances from the centroid of the containment vessel. Thermocouples with the same axial distance are cross-plotted. Figure 4.9 shows the measured temperatures versus time at various locations within the containment vessel.

Uncertainty in the temperature measurements on the test unit itself are reported to vary from $\pm 0.9^\circ\text{C}$ at 100°C to $\pm 8^\circ\text{C}$ at 1000°C .⁷ The recorded temperatures decreased rapidly with distance from the unit's exterior and that the peak temperature at the containment vessel was limited to 80°C.

Figure 4.7. PMATP Thermocouples Along Radius from Centroid (continued on next page).

Figure 4.7. PMATP Thermocouples Along Radius from Centroid (concluded).

Figure 4.8. PMATP Thermocouples Along Vertical Axis (continued on next page).

Figure 4.8. PMATP Thermocouples Along Vertical Axis (continued on next page).

Figure 4.8. PMATP Thermocouples Along Vertical Axis (concluded).

Figure 4.9. PMATP Thermocouples on Containment Vessel (continued on next page).

Figure 4.9. PMATP Thermocouples on Containment Vessel (concluded).

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5. Post-Test Sectioning

The PMATP test unit was sectioned after cooling to provide post-test examination to evaluate interior damage; Figure 5.1 shows half of the unit after sectioning (with the containment vessel and surrogate contents removed). Figure 5.2 shows a region of oxidized overpack material near the side-wall exterior. It is the opinion of the authors that this surface oxidation layer was actually beneficial because it lowered the thermal conductivity and improved the insulating capacity of the package. Figure 5.3 shows a region near the corner of the bottom end plug, where some of the melted aluminum flowed from the test unit. The surrounding material was oxidized.

Figure 5.1. Sectioned Test Unit.

Figure 5.2. Oxidization Near Overpack Side-wall Surface.

Figure 5.3. Oxidization and Void from Melted and Oxidized Aluminum Near Bottom-end Corner.

6. Numerical Simulations

The NLFlex finite element code was used to simulate this test.⁸ The finite element model used for previous thermal simulations of the PMATP in both its undamaged and post-impact conditions⁵ was adapted to this test by replacing the plutonium simulant with air and by reducing the package length to match the test unit dimensions. Both 2D axisymmetric and 3D models were used in previous investigations. For this test, the 2D axisymmetric model was adopted. The boundary conditions were also modified to more closely match test conditions.

Details of the finite element model are given by J. Mould et al.⁵ An anisotropic homogenized representation of the overpack was developed based on the thermophysical properties described by C. Lopez et al.⁹ Handbook values of conductivity and specific heat were used for the stainless steel. The specific heat and conductivity were assumed to vary with temperature, but phase changes due to melting of metal or charring of Kevlar® were not modeled. Outside the temperature range of data, bounding values were assumed.

The convection boundary condition was removed because of the proximity of the shroud. The average of top shroud thermocouple measurements at 3/4 height (see Figure 3.8) was used to drive radiation boundary conditions for the top half circumference of the unit. The average of bottom shroud thermocouples (TCs) (at 1/4 height) was used to drive the radiation boundary conditions for the bottom half circumference of the unit. The exterior PMATP measurements at the top center (TC 9) and bottom center (TC 29) were applied directly as imposed temperatures over the entire top and bottom surfaces of the unit respectively.

Figure 6.1 shows the calculated temperature distribution within the test unit at the end of the one-hour heating period. The peak temperature was approximately 980°C, and, as shown in Figure 6.2, it decays rapidly with distance from the exterior surface. The actively heated circumference was the hottest. The top of the shroud was insulated but not actively heated, so the temperature there was lower. The unheated bottom of the test unit was open, and it was therefore cooler.

The peak temperature calculated in the containment vessel was approximately 82°C, and occurred nearly 24 hours after the beginning of the test. Temperature distribution within the package at this time is shown in Figures 6.3 and 6.4.

Figures 6.5 and 6.6 compare calculated and measured temperatures throughout the test unit. Overall, the correlation was quite good. Some of the interior thermocouples (e.g., TC 1 and TC 2) registered a non-smooth temperature increase during the heating phase that does not appear in the calculation. This is small (less than 10°C) and was probably a result of heat propagation along the instrumentation wires as well as noise. This heat path was not modeled in the simulation and would not exist in an actual package. This heat conduction may partially explain why the TC measurements at the interior rose and fell slightly earlier than the simulated results. The imposed temperatures in the model were based on available TC measurements with a fairly coarse sampling. For example, the temperature over the bottom half of the circumference was not likely to be constant during the cooling phase.

Figure 6.1. Computer Model and Calculated Temperature Distribution (degrees Celsius) at One Hour.

Figure 6.2. Calculated Temperature Distribution at One Hour.

Figure 6.3. Computer Model and Calculated Temperature Distribution (degrees Celsius) at 24 Hours.

Figure 6.4. Calculated Temperature Distribution at 24 Hours.

Figure 6.5. Calculated and Measured Temperatures at Points Along Radius, Where i and j are Radial and Axial Mesh Coordinates (continued on next page).

Figure 6.5. Calculated and Measured Temperatures at Points Along Radius (concluded).

Figure 6.6. Calculated and Measured Temperatures at Points Along Axis (continued on next page).

Figure 6.6. Calculated and Measured Temperatures at Points Along Axis (continued on next page).

Figure 6.6. Calculated and Measured Temperatures at Points Along Axis (continued on next page).

Figure 6.6. Calculated and Measured Temperatures at Points Along Axis (concluded).

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7. Summary and Conclusions

Sandia National Laboratories has designed a crash-resistant container, the Perforated Metal Air Transportable Package (PMATP) for the air transport of plutonium. This package was designed to be capable of surviving a worst-case plane crash including both impact and subsequent fire.

This work reports results from a thermal test simulating a one-hour aviation fuel fire and compares these results with numerical finite-element simulations. The PMATP performed as designed, limiting peak containment vessel temperatures to less than 80°C when subjected to a 1000°C environment for a one-hour radiant heat test. This benchmark test used a full-scale PMATP without an internal heat source and was compared to numerical simulations that also excluded the internal heating from the plutonium for the comparison. The numerical simulations correlated well with the test results, thus increasing confidence in both the consistency of the test results and the validity of the numerical simulations used to evaluate thermal performance in post-impact damaged states.

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