Overview of JNC Pu Air Transport Packaging Development

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Abstract

The Power Reactor and Nuclear Fuel Development Corporation (PNC), the former organization of the Japan Nuclear Cycle Development Institute (JNC), transported a shipment of plutonium by sea from France to Japan for use in the experimental Fast Breeder Reactor (FBR) "Joyo." This shipment was made over a period of time from October to November 1984. Since then, research and development has been carried out to provide the option of transporting future shipments of plutonium by air for enhanced physical protection. PNC began Plutonium Air Transport (PAT) package development in 1984 based on a joint research agreement with Battelle Columbus Laboratories until 1988. Since 1988, the PAT development has continued under a joint research agreement with the US Department of Energy (DOE) and Sandia National Laboratories (SNL). Package development was based on technology developed earlier at SNL. The objective was to develop a package that would conform to NUREG-0360 criteria (Ref. 1), which is the technical standard for air transport of plutonium in the US as developed by the US Nuclear Regulatory Commission (NRC). That work resulted in packaging prototypes that were developed and tested that did not release any of their contents following high speed impact, puncture, slash, and one-hour fire tests stipulated by NUREG-0360. These tests, conducted at SNL, demonstrated that the innermost containment vessels of these packages remained leaktight.

The original agreement for cooperation between Japan and the US concerning peaceful uses of nuclear energy required the transport of plutonium only by air, but it was later amended to allow transport by sea under certain conditions. The appropriate package has not been developed at that moment. Based on this, a shipment of plutonium was made by sea from Europe to Japan by the "Akatsuki-Maru" in 1992. PAT package development has been continued, however, in order to provide an option for future shipments.

Concerns in the US Congress about the safety of plutonium shipments through US air space that originate in a foreign nation and are destined for a foreign nation resulted in legislation that required an actual crash test of a cargo aircraft loaded with full-scale packages carrying test material or the execution of an acceptable alternate test. The bill was referred to as the Murkowski Amendment because of the legislation's author, Senator Frank Murkowski of Alaska (Ref. 2). The bill was signed into force as Public Law 100-203 on December 22, 1987. Because this new

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** Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000 requirement entailed test parameters significantly more severe than those required by NUREG-0360, it was recognized that the PAT package developed earlier might need to be enhanced or redesigned to meet the new requirement.

Initially, the goal was to develop a package to meet the NUREG-0360 standard(impact speed: 129 m/s and one hour fire) as defined by the NRC. This paper deals with the ten-year development program to meet the NUREG-0360 requirements. In 1988 PNC requested the NRC to define a technical standard as required by the Murkowski Amendment. As a result, a draft technical standard was developed and published in 1992 (Ref. 3). JNC is currently proceeding with the development of a PAT package based on the requirements stemming from the Murkowski Amendment (impact speed: 282 m/s). A separate paper entitled "Plutonium Air Transport Package Development for Worst-Case Accident" (Ref. 4) reports on the development and testing of a new prototype PAT package capable of meeting the more stringent Murkowski Amendment conditions.

1. Summary

The Japan Nuclear Cycle Development Institute (JNC) of Japan has been active in the development of packaging for air transport of plutonium dioxide powder with plans to use a Boeing 747-400 as the supply aircraft. A fully loaded aircraft could carry 13 large cargo containers holding two PAT packages, or 29 small cargo containers with a single package. Each package is capable of containing 7.6 kg of plutonium dioxide with as much as 150 watts of thermal energy. Because the transport aircraft may be required to land in Alaska and US regulators have established precedents for civilian air shipments of plutonium, this new package is being designed to meet both US and Japanese regulations. The qualification criteria in NUREG-0360 governing plutonium air transport in the United States require that plutonium air transport (PAT) packagings be impact tested at a velocity of 129 m/s onto a flat, rigid surface in an orientation to produce maximum package damage followed by a one-hour fire. Air transport packagings for foreign origin shipments through United States airspace are also required to survive the Murkowski Amendment conditions, also called the "worst-case" accident. JNC wished to use SNL expertise gained from their Plutonium Air Transport Packaging (PAT-1 and PAT-2) programs (Ref. 5 & 6) throughout the development stages of their packaging. JNC had SNL perform several developmental tests of the final designs at SNL facilities.

This paper provides an overview of the many technical areas researched over a period exceeding ten years of development effort. These include design considerations of the original package, the testing program to demonstrate regulatory compliance, analyses conducted on the packaging, analysis and wind-tunnel testing for terminal-velocity considerations in a free-fall event, analysis into multiple-package effects in the case of an aircraft crash, packaging susceptibility to engine part impacts resulting from possible jet-engine failure, and analysis and test to investigate possible airframe mitigation for crash conditions.

As a result of this decade of design, analysis, research, and testing experience, a design has been developed capable of meeting the NUREG-0360 requirement.

2. Design

JNC produced two slightly different designs for the load spreader and overpack for the plutonium air transport packaging. These are the Common Package Model 1 (Kobe) and the Common Package Model 2 (JSW). The Kobe package, shown in Figure 1, is 1.2 m in diameter, 2.3 m long, and weighs 2551 kg. The JSW series, shown in Figure 2, is 1.16 m in diameter, 2.6m long, and weighs 2830 kg. Each package has the same two 304 stainless-steel plutonium-dioxide powder cans, a welded 304 stainless-steel inner containment vessel (AA303), a threaded 304 stainless-steel outer containment vessel (AA227), a double-bolted (630 stainless-steel bolts) titanium-alloy primary containment vessel, and a carbon-fiber spacer. The Model 1 packaging uses a layer of maple wood between the spacer and a titanium load spreader, followed by thick grain-oriented redwood and thin 304 stainless-steel shells and end covers. The Model 2 package uses a Nitronic 50 load spreader surrounding the primary containment vessel, carbon-fiber spacer, and maple wood, followed by thick grain-oriented redwood and thin 304 stainless steel outer shells and end covers. Rubber end caps are located on both ends of the Model 1 package.

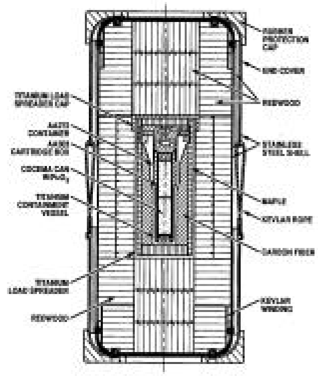


Figure 1. JNC Common Package Model 1 (Kobe)

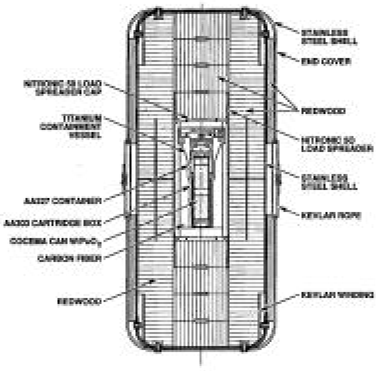


Figure 2. JNC Common Package Model 2 (JSW)

Figure 3 shows the orientation of the dual-packaging configuration within the cargo container and placement of the cargo containers within the 747-400 aircraft.

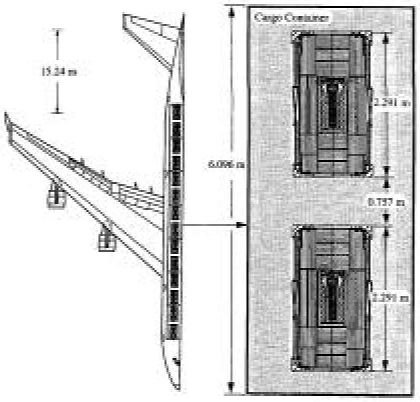


Figure. 3. Orientation of plutonium Packaging Within the Cargo Aircraft.

3. Testing

Internationally, all packagings that transport radioactive materials are required to meet the IAEA regulatory requirements for structural and thermal accident conditions (Ref. 7). The US additionally requires that packages for transport of plutonium by aircraft meet more stringent accident conditions. These conditions, originally defined in NUREG-0360 have been incorporated into 10CFR-71 (Ref. 8). PAT packagings must withstand a series of six sequential test environments: (1) a 129 m/s impact onto an unyielding target in the most damaging orientation for the package, (2) a static crush load of 32 ton, (3) a drop of the package from a height of 3 m onto a 20.3 cm diameter mild-steel conical puncture probe with a 2.5 cm diameter flat tip, (4) two slash loads to the packaging skin from a 45 kg steel angle dropped from 46 m, (5) a 60 minute fully-engulfing jet-fuel fire, and (6) immersion of the package in water to a depth of at least 0.9 m for 8 hours.

The high-speed impact test and the fire test typically impart the most severe loading on the containment vessels of the packaging. After sequential testing, the containment vessel must not be ruptured and the package must provide a sufficient degree of containment to restrict the accumulated loss of plutonium contents to not exceed an A_2 quantity per week.

JNC contracted with the Department of Energy (DOE) to perform development testing on the Common Package Prototypes. This program required the use of unique SNL test facilities located in Albuquerque, NM. To verify package design, an environment that simulated the crash and explosion of a high-flying aircraft was needed. SNL's Aerial Cable Test Facility provided the high-speed impact environment. Other tests in the required sequence were also performed at SNL, with the thermal fire test being conducted at the Large Pool Fire Test Facility.

Four high-speed impact tests were conducted on the Common Packages. At the Aerial Cable Test Facility, each package was connected to a rocket sled with towing cables, accelerated, and impacted onto an essentially unyielding armored target. The target was a 9.1E+5 kg monolith of highly-reinforced concrete and steel. After impact testing, all test packagings were subjected to the remaining tests of slash, puncture, and the one-hour fire test.

The impact-test configurations for the Common Packages were as follows:
Common Package Model 1 (Kobe 1): Side impact configuration.
Common Package Model 1 (Kobe 2): Center-of-gravity-over-top-corner impact configuration.
Common Package Model 2 (JSW 1): Side impact configuration.
Common Package Model 2 (JSW 2): Center-of-gravity-over-top-corner impact configuration.

Additional testing was performed on terminal velocity models, jet-engine fragment impacts on one-dimensional models, and tests for aircraft mitigation effects. These latter tests are discussed in later sections.

All units were successfully impact tested at the SNL test facilities in 1989 with post-test inspections completed by 1990. In general, although the overpack was severely damaged and the primary containment vessel was fractured and no longer leak tight, the inner containment vessel (AA303) remained leak tight following testing for all units. The Model 2 version performed better than the Model 1 units in impact testing because of increased redwood volume and redwood confinement as a result of its cup-shaped load-spreader design. As a result of this testing, a number of design improvements have been developed to improve compliance with the NUREG-0360 test requirements.

4. Design Enhancements

Numerous detailed analyses and tests have been performed by SNL toward the goal of assisting JNC with the development of a new NUREG-0360 certifiable PAT packaging. Analytical models at SNL can now accurately predict package performance in high-speed impacts, including general redwood behavior and material failure. Conclusions from these analyses and tests are compiled as follows: provide additional lightweight internal spacers, utilize a thicker aramid-cloth outer cover to withstand high tensile loading and provide redwood confinement, use the cup-shaped load spreaders that had performed well, provide additional redwood impact-limiting material with an increase of 30% radial thickness combined with additional circumferential aramid cloth confinement boundaries, provide drag enhancements to limit terminal velocity, and selectively place the packagings to avoid fragment impingement in case of a jet-engine failure.

5. Package Impact Analysis

A series of analyses (Ref. 9), including three-dimensional finite-element models of a complete package, were performed to evaluate the effects of impact onto a rigid target in various orientations with impact velocity of 129 m/s. These three-dimensional analyses provided an opportunity to gain a better understanding of impact-limiter behavior. Analyses were also performed to evaluate the value of adding internal package spacers for better protection in the end-impact tests. The result was effective designs that were beneficial for bottom and top impact tests with little weight penalty. Axisymmetric analyses were also performed to correlate experimental results with results from the numerical models, and were investigated with regards to the buckling observed on the AA303 box container. It was found that, for proper alteration for strain-rate effects in the AA303 box container and the AA227 container, buckling in these containers could be eliminated. The three-dimensional simulations identified the need for aramid layers to enhance redwood containment, and these analyses provided engineering specifications for the thickness, placement, and number of layers required.

For the impact analyses, the PAT package materials were simulated using a variety of constitutive theories and material parameters. The metals and the carbon fiber were simulated using a von Mises plasticity theory. This constitutive theory has been used extensively to describe the behavior of metals and other materials that exhibit only deviatoric plasticity. Material parameters for the metals and the carbon fiber are summarized in Table 1.

Table 1: Material Parameters Used to Describe the Metals and Carbon Fiber

MATERIAL	YOUNG'S MODULUS N/m^2 (psi)	POISSON'S RATIO	YIELD STRENGTH N/m^2 (psi)	HARDENING MODULUS N/m^2 (psi)	DENSITY kg/m^3 (lbm/in^3)
SUS304	2.00×10^{11} (29.0×10^{6})	0.26	2.07×10^{8} (30.0×10^{3})	7.76×10^{8} (112.5×10^{3})	8660. (0.313)
SUS 630	1.97×10^{11} (28.5×10^{6})	0.30	12.0×10^{8} (174.0×10^{3})	4.83×10^{8} (70.0×10^{3})	7775. (0.281)
Ti - 6Al - 4V	1.17×10^{11} (17.0 x 106)	0.30	8.96×10^{8} (130.0×10^{3})	4.05×10^{8} (58.8×10^{3})	4820. (0.174)
Carbon Fiber	655×10^{10} (9.5×10^{6})	0.20	6.90×10^{8} (100.0×10^{3})	6.21×10^{8} (90.0×10^{3})	1700. (0.0613)
SUS304: Powder Cans, AA303 Box, AA227 Container, Outer Shells, Cover					
SUS630: Bolts in Primary Container					
Ti-6Al-4V: Primary Container, Load spreader, Spacer Outside Primary					

The maple, redwood, and honeycomb were simulated using an orthotropic plasticity theory that was originally developed to describe the behavior of honeycomb materials. The behavior of redwood was experimentally investigated at SNL. Like most impact-limiting materials, the redwood has a plateau regime in which the load required to compress the material is nearly constant. This plateau region is followed by a densification regime wherein the load transmitted by the limiting material to the inner containers increases rapidly. The predicted response of the redwood during a uniaxial compression test with the redwood compressed along its grain axis is shown in Figure 4. The material parameters for the redwood and maple are summarized in Table 2.

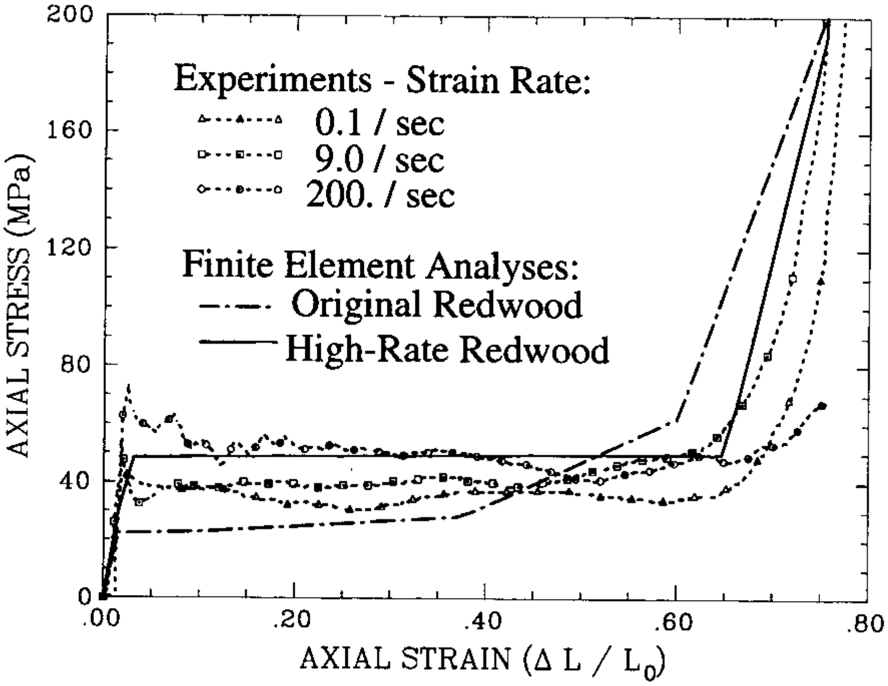


Figure 4. Behavior of Redwood Subjected to Uniaxial Compression Along the Grain Axis

Table 2. Material Parameters For the Impact Limiting Materials

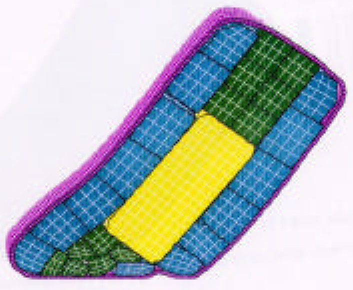
MATERIAL	ELASTIC MODULUS N/m^2 (psi)	SHEAR MODULUS N/m^2 (psi)	YIELD STRENGTH N/m^2 (psi)	HARDENING MODULUS N/m^2 (psi)	DENSITY kg/m^3 (lbm/in^3)
REDWOOD Strong	1.90×10^9 (2.80×10^5)	4.80×10^8 (7.00×10^4)	2.20×10^7 (3200.0)	F (volume strain) see Figure 4	473. (0.0171)
REDWOOD Transverse	9.65×10^8 (1.40×10^5)	4.80×10^8 (7.00×10^4)	5.52×10^6 (800.0)	F (volume strain)	473. (0.0171)
MAPLE Strong	1.30×10^{10} (1.92×10^6)	3.30×10^9 (4.80×10^5)	1.38×10^7 (2000.0)	1.24×10^8 (18.0×10^3)	567. (0.0205)
MAPLE Transverse	6.60×10^9 (9.6 x 105)	3.30×10^9 (4.80×10^5)	6.90×10^6 (1000.0)	1.24×10^8 (18.0×10^3)	567. (0.0205)
HONEYCOMB 1/8-5052-0.002	2.41×10^9 (3.50×10^5)	1.21×10^9 (1.75×10^5)	5.17×10^6 (750.0)	0.0 (0.0)	130. (0.00469)

The plutonium dioxide powder is simulated using a constitutive plasticity theory. The material parameters are provided in Table 3:

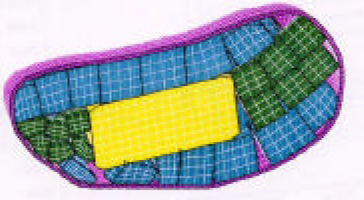
Table 3. Material Parameters for Plutonium Dioxide

MATERIAL	ELASTIC MODULUS N/m^2 (psi)	POISSON'S RATIO	DEVIATORIC YIELD STRENGTH N/m^2 (psi)	DENSITY kg/m^3 (lbm/in^3)
PuO_2 POWDER	1.46×10^9 (212.0×10^3)	0.40	6.90×10^6 (1.0×10^3)	2135. (0.0772)

To illustrate the many analyses performed by finite element methods for these packages, one example is given: To evaluate the effectiveness of an aramid cloth fabric outer shell, a finite-element analysis was performed for a 25.4 mm thick aramid cloth fabric outer shell with the 304 stainless-steel outer layer removed. Figure 5 shows the predicted deformations for a corner impact at a velocity 129 m/s in a direction 30 degrees from horizontal.



a. 5 msec. After Impact



b. 12 msec After Impact

Figure 5. Deformed Package Shape With 25.4 mm Aramid Cloth Fabric Outer Shell During a 129 m/s Comer Orientation Impact

6. Terminal Velocity Studies

The plutonium packaging considered would be transported on a dedicated Boeing 747-400 aircraft that cruises at a maximum altitude of 12.2 km (40,000 ft) Mean Sea Level (MSL) with a horizontal velocity of 268 m/s. The packaging will be contained in rectangular cargo containers. In the unlikely event that the aircraft suffers a catastrophic accident in flight, the plutonium air-transportable packaging may exit the aircraft during flight. In such a case, the survivability of the packaging may depend on the subsequent ground impact velocity. The packages were designed to withstand an impact velocity of at least 129 m/s onto an unyielding target. To determine the impact velocity of the package after ejection from the carrier aircraft, the aerodynamics and flight dynamics of the package configuration had to be well defined. If the impact velocity were expected to exceed 129 m/s, attaching drag enhancements to reduce the impact velocity below the 129 m/s value would be more practical than redesigning the packaging to withstand higher impact velocities. Analyses were performed to investigate analytical solutions for the terminal velocity of this packaging under these flight conditions. In addition, experimental evaluations were carried out at the vertical and horizontal subsonic wind tunnels at the U.S. Army Chemical Research, Development, and Engineering Center (CRDEC) in Edgewood, Maryland on the flight dynamics and aerodynamics of potential PAT drag-enhancement designs. The vertical wind tunnel was used to evaluate the free-fall flight dynamic behavior of various drag-enhancement designs and to approximate the terminal velocities of these containers. Initial conditions, such as tumbling or spinning, could not be adequately evaluated by the use of this tunnel. However, the overall dynamic stability could be determined. Since side-on was the most desirable flight orientation for producing drag, a large number of configurations were screened in the vertical tunnel primarily on the basis of their ability to maintain side-on stable flight. The aerodynamics of potential drag-enhancement designs was then determined in the horizontal tunnel. Using data obtained from this wind-tunnel testing, point-mass trajectories were computed using SNL codes for an assumed flight behavior of the containers.

All tested scale-model drag-enhancers were conceived to be as rigid as possible and designed to withstand free-fall aerodynamic loads with no initial spin rates. The design's ability to survive a catastrophic accident during an in-flight accident was not evaluated.

A design, called the PC-10 drag enhancement model using axial strakes and end caps (Fig. 6), proved to be dynamically stable (side-on) based on the wind-tunnel testing, with a calculated impact velocity and spin rate of 120 m/s and 560 rpm, respectively. This impact velocity is less than the 129 m/s impact conditions specified in NUREG-0360. Rotational kinetic energy at impact would be approximately 4% of the translational kinetic energy. Although this design may impart a small amount of additional rotational energy upon impact, its robust design is advantageous. This design was highly recommended as a drag-enhancement design.

Figure 6. Vertical Wind Tunnel Model PC-10a

7. Multiple Package Crush

A fully loaded cargo aircraft can hold 29 standard cargo containers, as described above, on its main cargo deck, each with one PAT packaging, or 13 large containers each holding one packaging. The multiple crush analysis was conducted for the single-package-per-container configuration. A fully loaded aircraft is desirable from an efficiency and risk basis to minimize the number of dedicated aircraft flights. The purpose of this investigation was to evaluate the inertial crush effects the kinetic mass of loaded containers aft would place on the forward-located containers in the rare event of a severe crash. NUREG-0360 states "Plutonium packages must be stowed aboard aircraft on the main deck in the aft-most location that it is possible for cargo of their physical size and weight. No other type cargo may be stowed aft of plutonium packages."

Numerous analyses (Ref. 10) have been performed to understand the effects of multiple-package crush in an aircraft severe accident. These studies typically neglect tie-down devices and other transport structures because they were not considered likely to contribute significant energy dissipation. Studies were initially performed on linear spring-mass models, using non-linear force/deflection curves as spring "constants" derived from theoretical constitutive stress/strain relations with bilinear elastic-plastic force/deformation curves. Additional studies were conducted on package spacing, package number sensitivity, and package orientation. The spring-mass modeling provided simplicity for parametric studies and qualitative predictions of end-on multiple package crush forces. However, a detailed finite-element model was developed to both validate the spring-mass modeling results and provide more accurate quantitative data for the end-on multiple package crush environment. The impact analyses were performed using the transient-dynamics finite-element code PRONTO2D (Ref. 11). Modeling four packages required over 58200 elements and 71500 nodes. Over 100 contact surfaces were used in the model.

Additional elements were used at the bottom corners of the package because deformation was greater in that location. Figure 7 shows a finite-element result for a three-package end-on impact.

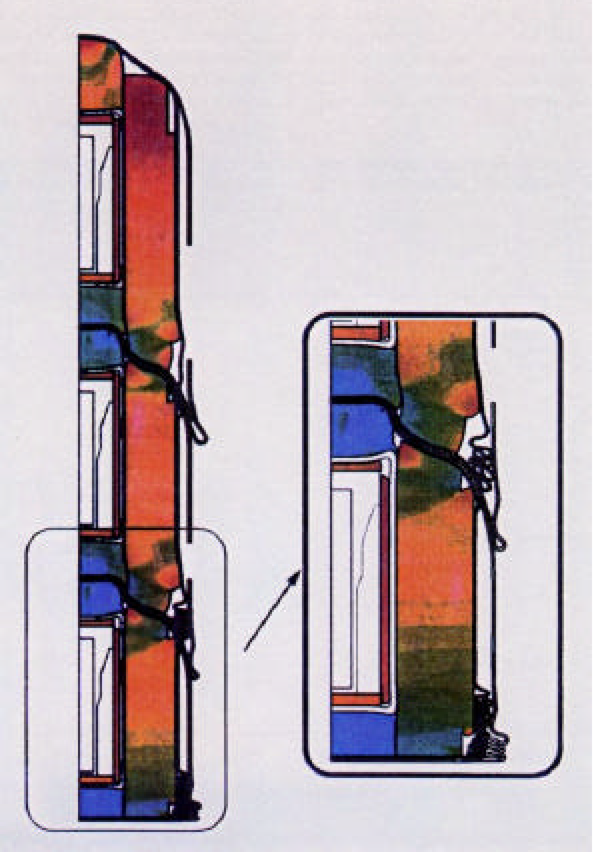


Figure 7. Package Crush At End of Third-Package Impact as Predicted by Finite-Element Analysis

Primary conclusions that were reached by these analyses are 1) that multiple-package crush produces higher compressive forces in the load spreader and containment vessel than a single package impact. These compressive forces are larger than the inertial force for the load spreader and less than the inertial force for the primary containment vessel, and 2) that a two-package impact produces compressive forces on the load spreader nearly as large as an impact with a greater number of packages. A number of mitigating concepts, including spacers and impact-limiting devices have shown to be of significant advantage in reducing inertial forces on the leading package. The next section discussed aircraft mitigation effects for severe crash conditions.

8. Aircraft Mitigation and Impact Analysis

The behavior of multiple plutonium shipping packages in a severe aircraft crash onto a hard target is a difficult phenomenon to predict. A program of analysis, material testing, prototyped testing, and iterative design modification was conducted to enable survivability in this severe environment. To better understand the phenomenology, a full-scale finite-element model (Ref. 12) of the aircraft with cargo containers loaded with plutonium packages was developed using the PRONTO3D (Ref. 13) nonlinear transient dynamic program. A typical graphics result of this code is shown in Figure 8, for an impact velocity of 283 m/s onto a hard target with friction. Although this velocity is much greater than the NUREG-0360 requirement of 129 m/s, these analyses were conducted for the "worst case" conditions.

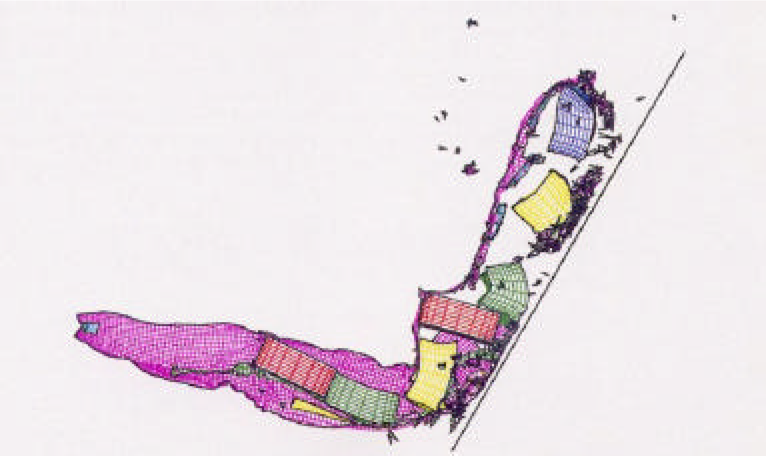


Figure 8. Deformed Shape of a Boeing 747-0400 Model With PAT Packages In Containers at the Time of Closest Approach of Container 4 (0.15 s) With Friction Coefficient of 0.3

Using detailed analyses of the loaded aircraft, it was determined that the crush and fragmentation of the airframe provided negligible energy dissipation and could be neglected in any future container design considerations. For testing airframe, cargo, and target interactions, it is necessary to include only the main floor in the experimental setup. The rest of the airframe has a negligible effect. Future design efforts for air transportation should include integrating the actual plutonium containment package with the cargo container to provide the optimum energy mitigating system.

Based on this analysis, a high-speed 1:5 scale-model impact test of an aircraft main floor and model plutonium packages was conducted. The test was performed on the 3 km long rocket-sled track at SNL on January 18, 1994. This reverse-ballistic test was performed for an impact velocity of over 275 m/s to investigate effectiveness of the aircraft structure in mitigating the impact environment to the packaging. A schematic of the test is shown in Figure 9.

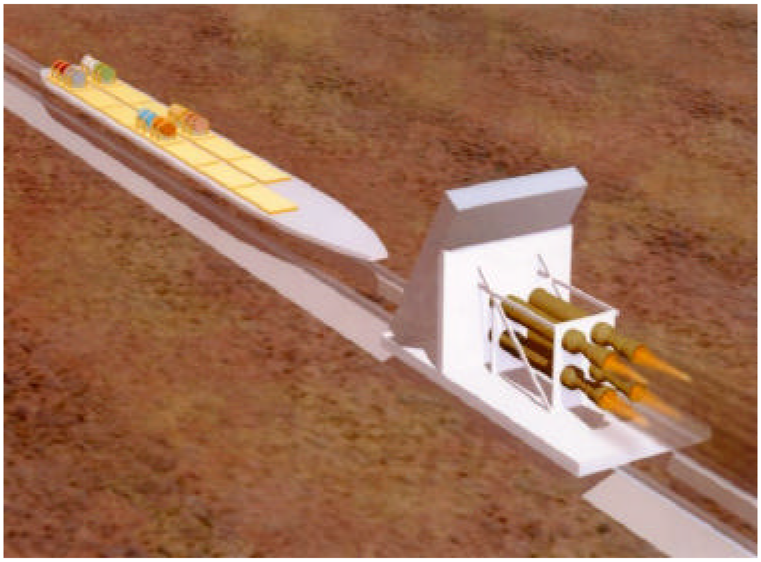


Figure 9. Schematic of Airframe and Packaging Impact Test

The results of this testing showed how the tie-down bolts connecting the container skids to the floor and the structures connecting the packages to the container skids failed and demonstrated the package to package interactions. Even if the floor of the aircraft were effective at mitigating impact energy, the failure of the containment attachments to the floor and the vertical package supports would have prevented significant impact mitigation. Based on how ineffective the aircraft and shipping container skids were at mitigating energy, and the reduced damage observed in the rear packages in the group of four, the recommendation was to use more impact-limiting material in front of each packages to ensure that all packages experience impact conditions similar to the rear packages in this experiment.

9. Jet Engine Failure

Uncontained, high-energy gas-turbine engine fragments are a potential threat to plutonium packages carried aboard jet aircraft. Probability analyses and penetration testing were used to evaluate the effect of this threat. A risk-assessment approach was taken, so that probability analyses were combined with quantitative penetration tests to yield an overall probability of severe containment vessel damage due to uncontained fragments. This resultant probability value is no greater than one such event in 778,000,000 flights, assuming 14-hour flights of a fully-loaded aircraft. This very low probability is primarily due to the low release rate for these uncontained, hazardous jet engine fragments.

Finite element analyses and testing was conducted with the conclusion that only large fan-disk sections have the potential to penetrate a packaging primary containment vessel. The tests performed included air gun and rocket sled tests on one-dimensional models, based on available literature and knowledge of jet-engine failure modes. This analysis and testing concluded that only a bladeless 134-degree fan rotor disk section impacting at redline translational velocity has sufficient energy and size to penetrate the packaging for the conservative one-dimensional models tested. The very small containment vessel damage probability is reducible to virtually zero simply by omitting six Common Packages from each flight that would be located in the paths of fan rotor fragments. Instead of package removal, the use of relatively small, high-strength deflector plates was also suggested to aid in protecting these six packages.

10. Conclusion

JNC has supported a program at SNL for over a decade on analysis, design, and testing for the purpose of developing a PAT package capable of meeting the NUREG-0360 requirements in order to provide an alternate mode for plutonium transport between Europe and Japan. As a result of this multi-year effort, the JNC Common Packages, as modified by SNL recommendations, should be capable of meeting the regulatory requirements. Extensive analysis has been performed to better understand the original design and to suggest design improvements. A comprehensive program was carried out at SNL for impact/crash, puncture, slash, and fire testing for four separate design prototype models. All tests were carried out successfully. Substantial analysis and testing was also performed on ancillary topics such as design enhancements, terminal velocity mitigation, multiple package crush, aircraft mitigation and impact parameters, and jet-engine fragment impacts.

All of this considerable body of work has led to a package design to meet the NUREG-0360 regulations. A separate study addresses a new design concept for plutonium air transport to meet the more stringent requirements of the Murkowski Amendment.

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