Plutonium Air Transportable Package Development Using Metallic Filaments and Composite Materials*

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INTRODUCTION

A new design concept for plutonium air transport packagings has been developed by the Transportation Systems Department and modeled by the Engineering Mechanics and Material Modeling Department at Sandia National Laboratories (SNL). The new concept resulted from an in-depth review (Allen et al., 1989) of existing package design philosophies and limitations. This review indicated a need for a new package which could survive combinations of impact, fire, and puncture environments, and which could be scaled up or down to meet a wide range of requirements for various contents and regulations.

This new design concept uses a very robust primary containment vessel with elastomeric seals for protection and confinement of an inner containment vessel with contents. An overpack consisting of multiple layers of plastically-deformable metallic wire mesh and high-tensile strength materials is placed around the containment vessels to provide energy absorption for the primary containment vessel as well as thermal protection. The use of intermittent layers with high-tensile strength results in a limiter which remains in place during accidental impact events and can be relied upon to provide subsequent puncture and fire protection. In addition, an outer shell around the energy absorbing material is provided for handling and weather protection.

To validate the concept, numerous scoping tests were performed on material samples, wall sections, and partially modeled prototypes. To evaluate various design features, finite element analyses were performed on the package. The finite element analysis required the development of a new constitutive theory for layered composite materials. The effects of neglecting the anisotropic tensile behavior were investigated with a series of dynamic finite element analyses. The model was implemented in both static and dynamic finite element codes and a number of steps were completed to benchmark the model. Uniaxial compression and tension experiments were performed on various candidate materials to obtain appropriate material properties for the model. Scale model packages subjected to side and end impacts were analyzed. Prototype scale model packages were fabricated and subjected to 129 m/s side impact and 200 m/s end impact tests, respectively. Test results indicated that the overpack

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would remain intact throughout a worst case accident, and that structural loads on the containment vessel could be limited to assure integrity of the containment vessel.

DESIGN REQUIREMENTS

A package design was needed that could not only meet but exceed the requirements for a large plutonium air transport package as prescribed in NUREG-0360. The sequential test environments in NUREG-0360 that a package weighing more than 227 kg must be subjected to and not release an A_2 quantity of material in one week are: (1) a 129-m/s perpendicular impact onto a flat unyielding target in the most severe location, (2) a 3-m drop onto a conical steel puncture probe in the most severe location, (3) two slash tests by a 45-kg section of structural steel dropped 46 m onto the package, (4) a fully-engulfing JP-4 fire test for a period of no less than one hour, and (5) a 1-m submersion test in water for a period of 8 hours. Recent U.S. legislation (U.S. Public Law 100-203) also requires that foreign shipments of plutonium through U.S. airspace be able to withstand a worst-case aircraft crash, therefore the requirements for packages used for these applications is expected to be even more severe. An examination of crash data indicated that an impact onto a rigid target at a higher velocity might be a required extrapolation of current impact requirements for future designs. An arbitrary impact velocity of 200 m/s was chosen as a design goal for this study.

The primary goals for the new package design were:

1. the overpack should remain in place after the impact to provide protection for subsequent environments such as crush, puncture, and fire;
2. the overpack should be well characterized and the performance well understood so that computer simulation of hypothetical accident events is possible;
3. the overpack material should perform the same when scaled for large or small applications;
4. the package parameters should be able to be easily changed to meet not only the requirements in NUREG-0360 but also any worst-case accident environment that might be part of future regulations or applications;
5. the overpack should be fabricated out of non-combustible materials to prevent the containment vessels from being subjected to unduly high heat loads in an accident environment; and
6. the package should be cost-effective for large quantities of material.

PACKAGE DESIGN

An in-depth review of existing package design philosophies and their limitations led to the development of a new package concept. This new design concept which met the above criteria consists of only a few basic elements.

1. An inner vessel is provided that is made of titanium, alloy steel, or any other material suitable for providing a containment boundary around the payload. The material and its configuration are chosen depending on the severity of the transportation accident environment to be encountered. The type and condition of the payload also determine the type of seal and method of securing the closure on the inner vessel.

2. Multiple layers of wire mesh are provided for energy absorption. This material may have various wire sizes, various mesh spacings, and may be aluminum, corrosion resistant steel, titanium, or other suitable material depending on the requirements.

3. Layers of high-tensile strength fabric are sandwiched in the wire mesh for confinement of the wire mesh in an impact environment and for puncture protection. This material may be aramid cloth, S-2 glass, graphite, or other suitable cloth depending on the environment.

4. Layers of insulation material are sandwiched in the wire mesh as needed for thermal protection and multiple layers at the external surface for primary thermal protection.

5. A thin shell encases the wire mesh, high-tensile strength cloth, and insulation materials for handling protection. This may be corrosion resistant steel, aluminum, resin impregnated cloth materials or other suitable material.

A baseline design capable of carrying 7.8 kg of plutonium was developed (Figure 1). The package utilizes a robust primary containment vessel fabricated from a titanium alloy with a 2.5-cm sidewall that can carry various configurations of inner containment vessels. A cylindrical overpack is provided as shown that has stepped end, caps. The composite wall is radially wrapped in the cylinder and stacked in layers in the end plugs to achieve a wall thickness of 60 cm and 120 cm on the sides and ends respectively. The end plugs are held in place by keyed pins and bolts. The layered wire mesh and cloth materials are encased in a 1.5-mm thick 304 stainless steel shell.

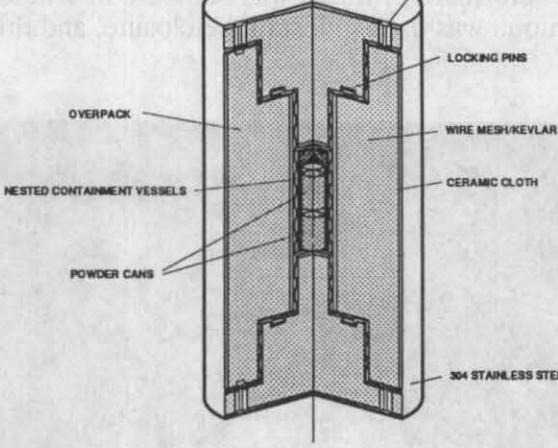

Figure 1. Plutonium Air Transport Package Design Concept

SCOPING TESTS

Many static tests were performed on small samples and wall sections of various wire mesh and high-tensile strength cloth materials. Dynamic tests were then performed on scale model prototypes. The best material for energy absorption for air transport applications was found to be aluminum wire mesh. The high-tensile strength cloth materials had less utility as energy absorbers, but were very necessary to provide confinement of the wire mesh, spread the load from a puncture environment over a much larger area, and provide thermal protection for the contents of the overpack.

Several radial sample wall sections with aramid cloth included at multiple locations in the wire mesh were tested to failure by crushing in the same configuration as a dynamic side impact test. A significant improvement in confinement was observed with the addition of the aramid cloth (approximately a factor of four improvement for the configuration tested).

The data from these tests were used to design and fabricate a simple quarter-scale wire mesh model capable of carrying 8 kg of PuO_2. This model was subjected to a side-impact reverse ballistic test at the 3 km rocket sled track at SNL. A 273-kg steel target mounted to a rocket sled with a catcher box was impacted onto the test model at 129 m/s. The overpack remained completely intact, and the containment vessel, which was fabricated of low carbon steel, sustained minimal (approximately 3% maximum at the center of the cylinder) deformation.

Next, a number of composite wall cross sections comprised of aluminum wire mesh and aramid cloth were assembled and tested statically to determine the performance of the overpack wall during an end impact test. The data from these tests were used to design and fabricate a simple quarter-scale wire mesh model of a package capable of carrying eight kilograms of PuO_2. This model was also subjected to a reverse ballistic test. The steel target impacted onto the test model in an end-on orientation at 129 m/s. The overpack remained completely intact, and the containment vessel, which was fabricated of low-carbon steel, sustained minimal deformation.

Another simple quarter-scale wire mesh model of a package carrying eight kilograms of PuO_2 was fabricated. This model was again subjected to a reverse ballistic test. A steel target mounted to a rocket sled with a catcher box was impacted onto the test model at 129 m/s. The package was impacted in a center-of-gravity over-the-corner orientation. The overpack remained completely intact, and the containment vessel, which was fabricated of low-carbon steel, had local permanent deformation, which was outboard of where the seals would be. A simple retaining ring technique was used to install the closure, and this appeared to work very well.

Figure 2. Section of Overpack Subjected to a Corner Impact

MATERIAL CHARACTERIZATION

The behavior of layers of aluminum wire mesh with and without aramid cloth fabric was characterized with a series of uniaxial compression and confined compression tests. Axial stress versus axial engineering strain curves generated during these tests are shown in Figures 3 and 4. In the first series of tests, samples with various layer orientations were subjected to confined compression (Figure 3). All of the samples used in these tests were manufactured by alternatively stacking 20 layers of aluminum wire mesh and 2 layers of aramid cloth fabric. The undeformed samples all had a cubical shape with an edge dimension of 5.1 cm. The confined compression tests indicated that layer orientation had little effect on the crush strength of the material: thus, the crush strength is nearly isotropic. Also, the crush strength, σ^c, varies exponentially with axial engineering strain ε. The solid line in Figures 3 and 4 represents a best fit to the experimental confined compression test data which is given by the following equation.

$$\sigma^c = 17.0e^{-8.68\varepsilon} \quad (1)$$

Since the lateral displacements are constrained, the axial engineering strain, ε is equal to the engineering volume strain, γ, in these tests.

In a second set of tests, layers of wire mesh and wire mesh with aramid cloth fabric were subjected to cyclic, unconfined uniaxial loads. In these tests, the load was always applied in a direction normal to the layers (0 degrees) but the number of aramid cloth layers and the sample size was allowed to change. In the first test, a sample with a length of 15.2 cm, a width of 17.8 cm and a height of 2.54 cm was used. In the remaining three tests, samples with lengths and widths of 5.1 cm inches and heights of 2.54 cm were used. In the first two uniaxial compression tests, the layering was identical to the layering used in the confined compression tests; but, in the last two tests, the aramid cloth layers were eliminated. Results from these tests indicated that inclusion of the aramid cloth fabric had little effect on the response of the material to uniaxial compression. Also, these tests indicated that the lateral strains generated by uniaxial compression are negligible. This means that the material has a Poisson's ratio that is nearly equal to zero. Furthermore, any plasticity theory that is developed to capture the behavior of this material should predict no lateral strains when the material is loaded in the plastic regime. The solid line in Figure 3 represents a best fit to the confined compression test data (Equation 1). Results from the limited number of uniaxial compression tests indicates that Equation 1 also represents the uniaxial compression data reasonably well.

In tension, the wire mesh material exhibits widely varying behavior. For example, when the material is loaded in tension in a direction parallel to the layers, the wire mesh has a tensile strength of approximately 158 newtons/cm of width per layer and the aramid cloth fabric has a tensile strength of 1922 newtons/cm of width per layer. However, when the material is loaded in a direction normal to the fabric layers the material exhibits essentially no strength as the layers are separated. The wire mesh has a wire diameter of 0.27 mm and the aramid cloth fabric has a thickness of 0.43 mm.

ANALYSIS

A review of existing constitutive theories indicated that no existing theory could adequately simulate the response of the layered composite materials. Thus, a new plasticity theory which captures the layered material behavior exhibited during the uniaxial and confined compression tests was developed (Neilsen and Pierce, 1992). This new plasticity theory is similar in many respects to a plasticity theory that was developed for polyurethane foam (Neilsen et al., 1987).

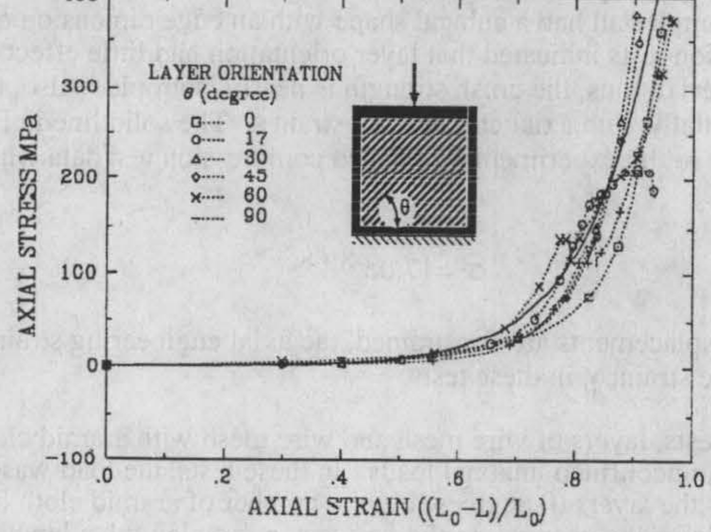

Figure 3. Confined Material Test Data

The new theory has yield functions which describe intersecting planes in principal stress space:

$$\left|\sigma^i\right| - Ae^{\beta\gamma} \qquad i= 1, 2, 3 \qquad (2)$$

$$\left|\sigma^i\right| - c \qquad i= 1, 2, 3 \qquad (3)$$

where σ^i is a principal stress and A, β, and c are material parameters. The first yield function (Equation. 2) is used when the principal stress is compressive and the second yield function (Equation. 3) is used when the principal stress is tensile. Material parameters A and β are selected based on the results from the uniaxial and confined compression tests. Material parameter c is a measure of the tensile strength of the material and is independent of the compressive response. This new plasticity theory uses associated flow rules.

This new constitutive theory was implemented into a static finite element code, SANTOS (Stone, 1992) and into dynamic finite element codes, PRONTO-2D (Taylor and Flanagan, 1987) and -3D (Taylor and Flanagan, 1987). The material characterization tests were numerically simulated to ensure that the new constitutive theory was properly implemented and that the new theory accurately captured the material behavior exhibited during these tests. Next, a number of impact tests were simulated to further benchmark the model. In some of these analyses, individual layers with alternating amounts of tensile strength were used to investigate the effect of layer separation. These analyses indicated that simulation of layer separation was not needed to generate accurate package response predictions. The response of the layered composite material during a hypothetical accidental impact event was adequately captured by the new isotropic plasticity theory.

Finally, the response of a baseline package subjected to side and end impact velocities of 129 m/s and 200 m/s was numerically simulated. Typical deformed shapes of the package predicted by these simulations are shown in Figure 4. Results from these simulations indicated that the primary container would be deformed only a small amount during a 200 m/s impact event and that the amount of predicted deformation would depend on the response of the contents.

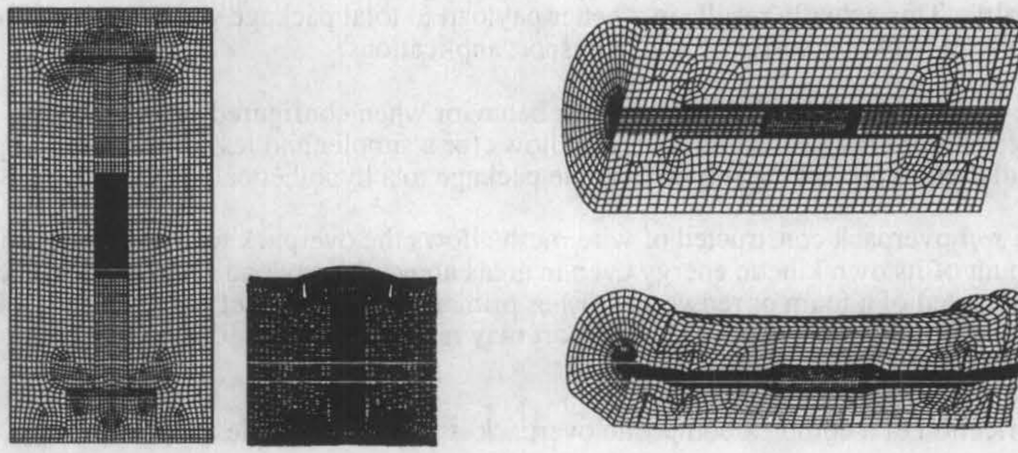

Figure 4. Deformed Shape of Baseline Package for End and Side Impacts Predicted by a Numerical Simulation of a 200 m/s Impact

THERMAL

A series of thermal tests was performed at the Radiant Heat Facility. A partial one-dimensional test article with the same composite makeup as an actual prototype was fabricated for each test. The test articles were subjected to a thermal environment for 30 minutes and 60 minutes to establish the preliminary thermal properties for the material. Samples are also being evaluated by use of a thermal compactor and a guarded hot plate to establish more accurate thermal data. The results of these tests will be used in a 3-D model currently under development. Initial results indicate that, depending on the heat load generated by the contents, the inner containment vessels will remain below the maximum allowable temperatures. Analyses performed on a package with approximate dimensions of only one fourth those for this package indicate temperatures would be below the allowable temperatures for elastomeric seals in a 30 minute fire. The results were conservative and do not account for heat flow through the shell, however they are an indication that temperature rise in a fire should not be a major design problem as long as the container remains surrounded by the composite material.

CONCLUSIONS

Experiments and analyses to date have verified and demonstrated several key points:

1. Although materials have not been optimized, aluminum wire mesh may be used as an overpack material with desirable and predictable results.

2. This concept allows a composite wall to be easily fabricated which can incorporate wire mesh for energy absorption, high-tensile strength cloths for puncture and intermediate thermal protection (i.e., aramid cloth, fiberglass, or graphite) and insulation material (i.e., ceramic cloth) for primary thermal protection. This allows the design to be easily tailored for a variety of applications.

3. Although the aluminum wire mesh has a higher density than redwood, other major components for confinement that previously designed packages required are not needed. Components such as full load spreaders and heavy outer shells inflict a severe weight penalty. This actually results in a better payload to total package weight ratio (efficiency) than with redwood designs for air transport applications.

4. The wire mesh exhibits global isotropic behavior when configured as a multilayer overpack for energy absorption. This allows for a simpler and less expensive computer simulation to predict the response of the package to a hypothetical accident event.

5. The *soft* overpack constructed of wire mesh allows the overpack to absorb a significant amount of its own kinetic energy even in areas above the payload. A *rigid* overpack constructed of a foam or redwood crushes primarily at the contact point. This is a key factor since the overpack for air transport may represent 80% to 95% of the total mass of the package.

6. Fabrication of a complex composite overpack is relatively simple and inexpensive.

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