Design Aspects of Plutonium Air-Transportable Packages*

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INTRODUCTION

Recent worldwide interest in transporting plutonium powders by air has created a need for expanding the packaging technology base as well as improving our understanding of how plutonium air transport (PAT) packagings perform during severe accident tests. Historically it has not been possible to establish design rules for individual package components because of the complex way parts interacted in forming a successful whole unit. Also, computer analyses were only considered valid for very limited portions of the design effort because of large deformations, localized tearing occurring in the package during accident testing, and extensive use of orthotropic materials. Consequently, iterative design and experimentation has historically been used to develop plutonium air-transportable packages. Full-scale prototypes have been tested since scaling of packages utilizing wood as an energy absorber and thermal insulator has not proven to be very successful. This is because the wood grain and dynamic performance of the wood during crush do not always scale. The high cost of full-scale testing of large packages has certainly hindered obtaining additional data and developing new designs.

The testing criteria for PAT packages, as described in the U. S. Nuclear Regulatory Commission's Qualification Criteria to Certify a Package for Air Transport of Plutonium, NUREG-0360, 1978, are summarized in Table 1. This paper will review general performance trends observed during past testing of PAT packages and observed from recent computer models of impact events. Computer modelling techniques have greatly improved over the last ten years, and there are some areas of opportunity for future applications to plutonium air-transportable package design problems. Having developed a better understanding of the performance of current packages, we have the opportunity to make major improvements in new packaging concepts. Each of these areas is explored in further depth to establish their impact on design practices for air-transportable packages.

CURRENT PACKAGE TECHNOLOGY

Two packagings have been designed and certified to meet the NUREG-0360 test criteria. These were both developed about ten years ago by Sandia National Laboratories (SNL) and are: the PAT-1 described in PARC (Plutonium Accident Resistant Container) Program Research, Design, and Development, Andersen et al., Sandia National Laboratories, 1978 and the PAT-2 described in PAT-2 Safety Analysis Report, Andersen et al., Sandia National Laboratories, 1981. They are shown in Fig. 1 and have a gross weight of 227 kg and 34 kg, respectively. Both are heterogeneous designs that primarily rely on wood for energy absorption and thermal insulation. The development of these packages established the basic concept that has been the focus of most subsequent larger package design efforts.

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TABLE 1

NUREG-0360 Plutonium Air Transport Package
Qualification Criteria

Sequential Tests	
Impact	129 m/s (422 fps, 250 KTS) perpendicular to flat unyielding target; most severe orientation.
Crush	310 kN (70,000 lb.) through 5.1 cm (2 in.) wide steel bar; most severe location.
Puncture	227 kg (500 lb.) steel probe dropped 3 m (10 ft.) for packages weighing less than 227 kg. For heavier systems, the package itself is dropped 3 m onto the steel probe; most severe location.
Slash	45 kg (100 lb.) steel angle dropped 46 m (150 ft.); twice onto package tilted at 45°.
Fire	Engulfed in large JP-4 fire for one hour; left to self-extinguish or extinguished after 3 hrs., whichever is worse.
Submersion	Under 1 m (3 ft.) of water for 8 hours.
Individual Tests	
Hydrostatic	4.1 MPa (600 psi) for 8 hours (411 m [1350 ft.] depth)
Terminal Velocity Free Fall	Test required if terminal velocity is more than 250 KTS

The PAT-1 and PAT-2 are a collection of components that combine to form a packaging capable of successfully surviving the tests specified in NUREG-0360. An inner vessel contains the PuO_2 payload. An outer vessel provides the primary containment boundary for the packaging under the normal and accident conditions specified in both 10 CFR 71, as described in the U.S. Nuclear Regulatory Commission's U.S. Code of Federal Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Material" (1983), and NUREG-0360. This outer vessel provides the strength needed for the large forces experienced in a high-speed impact. Metal seals are used to withstand elevated temperatures from the one-hour fire. This vessel and seal assembly must also withstand a high pressure test of 4.1 Mpa in an undamaged condition. This outer containment vessel is surrounded by an initial layer of energy-absorbing material that serves three primary functions: (1) to provide energy absorption or shock mitigation for the containment vessel, (2) to provide backing support (in either the crushed or uncrushed state) for the load spreader, and (3) to provide thermal protection for the containment vessels. Surrounding this inner layer of energy-absorbing material is a metal load spreader that serves four basic functions: (1) to distribute the inertial load of the inner portion of the package over a larger volume of primary energy-absorbing material, (2) to hold the inner wood in place so as to resist relative displacement during impact, (3) to protect the containment vessel and inner energy-absorbing material surrounding the containment vessel from puncture damage, and (4) to provide a barrier to reduce thermal degradation of the wood surrounding the containment vessel which in turn provides protection to the containment vessel seals during a fire. Outside of the load spreader is the primary energy-absorbing material. Finally, all of these components are enclosed in a metal overpack that provides protection for all the internals during normal transport conditions and provides a confinement boundary for preventing relative displacement of the primary energy-absorbing material during impact. For the PAT-1 and PAT-2, redwood and maple were used for the energy-absorbing materials, and steel, titanium, and aluminum were used for the metal components. Finite element computer models were used only for static pressure evaluations of the containment vessels. Energy balance calculations and iterative full-scale development testing were used to establish the package configuration and to size most of the components.

STRUCTURAL DESIGN CONSIDERATIONS BASED ON MORE RECENT EMPIRICAL DATA

A number of conclusions and recommendations have been formulated from empirical data obtained from testing of plutonium air-transportable packages which utilize wood for impact and fire protection. The data have been derived from environmental testing of the PAT-1, PAT-2, and various other larger prototype packages.

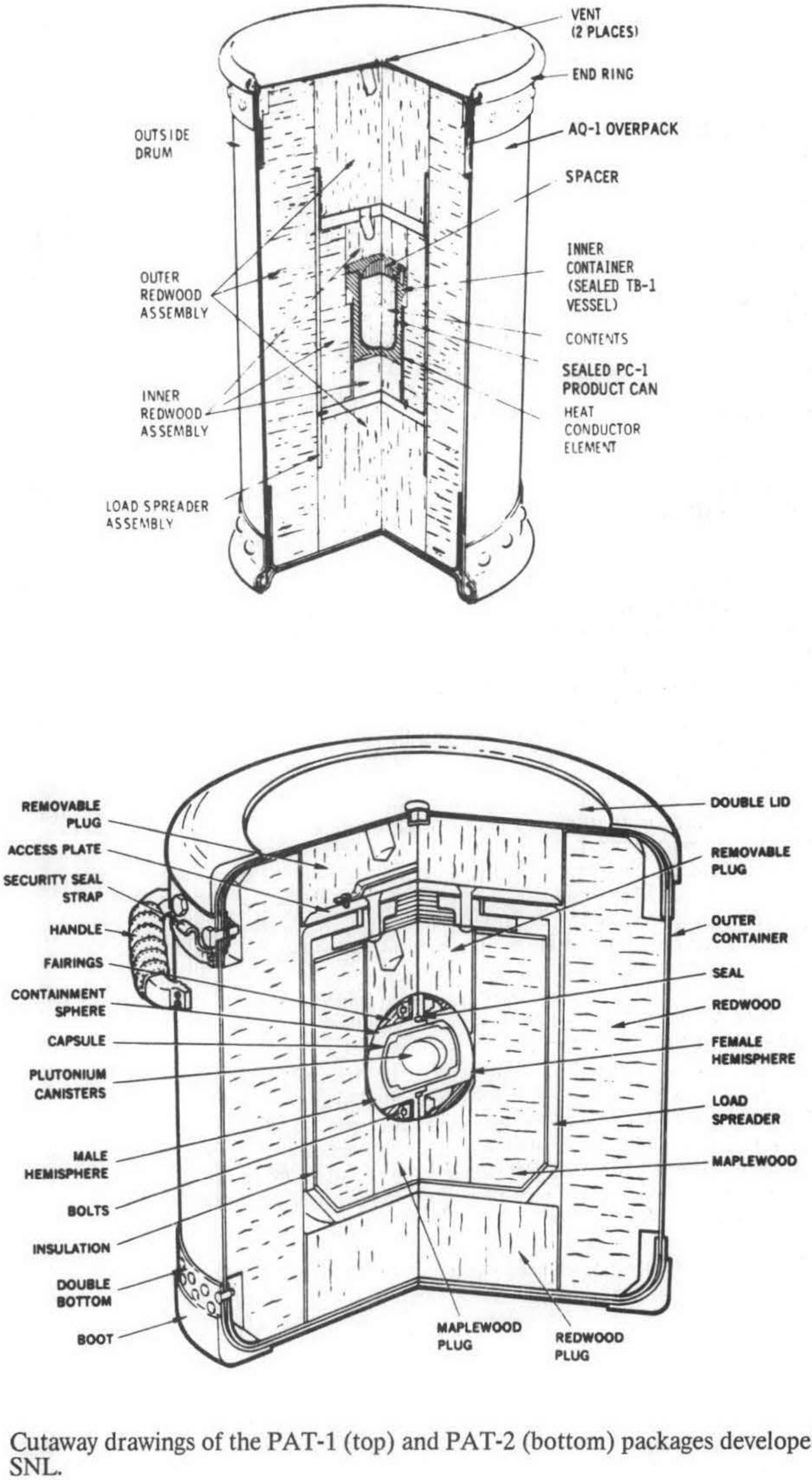

Figure 1. Cutaway drawings of the PAT-1 (top) and PAT-2 (bottom) packages developed by SNL.

Containment Vessel

Spherical and cylindrical containment vessel shapes have performed well in the past. Irregular shapes are the least desirable since higher stress concentrations and bending moments are induced in the vessel during certain impact orientations. The impact performance of an irregular shaped containment vessel can be improved by providing a sleeve of metallic or composite materials so that the object which interacts with the energy-absorbing material is spherical or cylindrical in geometry. The PAT-2 is a good example of this point.

Load spreaders, heat shunts, or mounting hardware should either be decoupled from, or carefully designed to limit high stress concentrations on, the containment vessel. The use of wood, or a relatively softer material, to decouple components whenever possible should enhance performance during an impact environment.

Load Spreader

While load spreaders have been used in all PAT packages to date, there have been significant differences in the details of load spreader design. The PAT-1 utilizes a ductile aluminum load spreader with redwood surrounding the containment vessel and can accommodate very large deformations during impact. The PAT-2, however, utilizes a more rigid titanium load spreader with maple backing and accommodates very little deformation during impact. It is important to recognize and choose an appropriate approach based on performance requirements for a given design. The shape of the PAT-1 load spreader offers several advantages for large packages over other shapes which have been considered: (1) the amount of redwood which can absorb the energy of the load spreader and contents can be increased significantly, (2) the end sections of the tubular load spreader also help to confine the wood for end and corner impacts, and (3) additional energy is absorbed by the crush and buckling of the end sections of the load spreader in end and corner impacts. An important further consideration in the load spreader design is whether the selected configuration acts as a wedge or entraps energy-absorbing material. This hinders or aids the confinement of the surrounding wood.

Adhesives

The use of relatively flexible adhesives to bond wood and metal components is considered to be absolutely essential to confinement of the wood during an impact environment. The adhesives help prevent the wood from slipping at the wood-to-metal interfaces. Slipping can result in lateral displacement of the wood at one or both ends of the wood column before the wood absorbs a sufficient amount of energy.

Outer Energy Absorber

The outer energy absorber consists of both wood and a metal or composite material system (also includes the outer skin called the "overpack") that confines the wood during the impact and allows it to efficiently crush. Frequently, the major design issue is the effectiveness of the confinement system rather than the wood itself. Redwood and maple have been used as the wood for all packages developed to date.

Methods of stabilizing the wood for the impact environment need to be pursued by the designer. Shorter sections of wood behave better when crushed than long sections. Thin metal or composite plates used between each short wood section and coupled with a flexible adhesive should enhance the performance of the end sections during an end or corner impact. For designs using thick sections of wood, a thin shell spaced equidistant between the load spreader and the outer shell should stabilize the wood in the radial direction as well as increase the level of confinement for part of the radial wood.

The position of the bolts attaching the closure for the confining overpack is very important to its survivability. These bolts can be accurately located by using computer analyses to assure they are not located in a high stress area. An overpack closure utilizing a ring clamp and a skirt with multiple bolts, such as was used on the PAT-1, appears to be the best design for large packages.

Adequate void space needs to be provided at the corners of the overpack. This will allow the overpack shell to corrugate properly without interference with the wood. A thin layer of Kevlar could be added around the wood in the void space region which would help confine the wood during crush without interfering with the corrugation of the overpack shell. The ends of the overpack should be shaped to assure that corrugation is initiated easily without overstressing the shell. The PAT-1 type of closure also performed this function very well.

Vents

A considerable amount of discussion has also been generated regarding the necessity of vent holes for the overpack shells. The PAT-1 and PAT-2 included vent holes; however, their necessity has not been totally proven. During the development of these packages, vents were added in conjunction with other structural design changes to improve the package performance. When the package performance was improved, credit was given to the presence of vent holes as well as the structural changes. There was not, however, any conclusive evidence that the vents were responsible for the improved package performance. Recent work at SNL indicates that vents may not be necessary. Vents may in fact be detrimental to package performance since tearing of the overpack metal skin usually initiates at the vent holes, and the vents also allow additional oxygen to enter the package during the fire test.

THERMAL DESIGN CONSIDERATIONS BASED ON MOST RECENT EMPIRICAL DATA

Many radioactive material packages use wood or other combustible materials for protection during the hypothetical impact, puncture, and thermal accident conditions. Since the sequential nature of the regulatory tests dictates thermal testing of structurally damaged packages, extensive damage to the outer skin of the package, resulting in sufficient oxygen access and heat exposure, can lead to extended burning of the combustible material.

Wood discolors and chars at temperatures above 200 to 250 °C, and the physical structure begins to break down rapidly at temperatures above 300 °C. This is first apparent on the surface when cracks appear in the char perpendicular to the direction of the grain which permit volatiles to escape easily through the surface from the wood pyrolysis zone. The cracks will gradually widen as the depth of char increases, leading to the characteristic "crazed" pattern. The complexity of wood makes it difficult to analytically interpret the burning behavior of wood, but empirical methods have been developed. In the enclosed fire test of PAT packages at SNL, average flame temperatures of approximately 1000 °C are achieved. This average flame temperature corresponds to a black body radiation of 150 kW/m^2, which could result in wood burning rates as high as 2.9 mm/min (An Introduction to Fire Dynamics, Drysdale and Dougal, 1985). Therefore, the 60-minute fire test could theoretically provide enough thermal input to consume 17 cm of the outer wood layer.

In addition, redwood, like several other woods and organic foams, will form a solid carbonaceous char which can smolder (i.e., continue to burn slowly) even after the cessation of flaming. A substantial amount of the total heat of combustion of the material is associated with the char, approximately 30 percent in the case of redwood. In general, glowing combustion will only continue if heat is conserved at the reacting surface. As packages become larger and if the initial fire is long and hot enough to have a large thermal input to the package, it appears to be easier for them to conserve heat from smoldering. As demonstrated in the fire test of larger PAT packages conducted at SNL, glowing combustion continues for several days due to the ability of the package to conserve its heat energy. The outer layers of char form a insulating barrier and do not allow the smoldering wood to cool. The residual fire does not self-extinguish and, thus, propagates. Thus, if the combustible material continues to burn long after the fire, it provides for a potentially greater thermal load to the package seals.

ANALYTICAL TOOLS FOR PERFORMANCE EVALUATION OF PLUTONIUM PACKAGES USING WOOD FOR ENERGY ABSORPTION

As stated earlier, most plutonium air-transportable package concepts pursued to date have relied on wood as an energy absorber to limit damage to the containment vessel during severe accidents. Because of the complex nature of impact events with wooden components and the lack of good dynamic wood data, earlier computer models have been unable to yield detailed predictions needed to design these packages. However, improvements in both computer hardware and software now provide an opportunity for using analytical tools to model the severe accident environment found in NUREG-0360. The following is a description of a new computer method developed by SNL that predicts detailed behavior of wood crushing under impact conditions.

Redwood and maple have historically been the materials of choice and should be oriented so that the direction of crush is parallel to the grain of the wood. The orthotropic nature of wood requires that an analysis account for any change in wood strength associated with wood grain orientation. Crush strength in the direction perpendicular to the grain is approximately five times less than in the parallel direction. Packages containing wood are particularly difficult to model because of complicated splitting, folding, and relative slipping of the wood inside the metallic skin which also bends and folds severely.

An accurate wood crush model is required for analyzing package designs. Wood crushes at nearly a constant load until it reaches a point known as lockup. Beyond lockup, the pressure required for further volume crush increases rapidly. If wood in a PAT package is crushed beyond lockup, then the force transmitted by the wood can be quite large.

A new finite element technique that models the orthotropic crush and folding of wood has been developed. The new technique uses alternating layers of hard and soft crushable materials to produce the directional behavior observed in wood. The alternating layers are locally isotropic but when assembled, behave globally orthotropic, hence, the name Local Isotropic/Global Orthotropic, LIGO, as described in "A Local Isotropic/Global Orthotropic Finite Element Technique for Modeling the Crush of Wood," S. W. Attaway, Sandia National Laboratories, 1988. The LIGO technique accounts for the grain orientation effects on the wood's crush strength as well as produces the complex behavior observed when wood buckles under compressive loading.

In addition to correctly modeling wood crush, finite element codes used for impact analysis must account for: (1) large strains, (2) large rotations, (3) large displacements, (4) nonlinear material behavior, (5) large volumetric crush, (6) inertial effects, and (7) contact conditions. The detail required to model package impacts generates very large finite element meshes. The nonlinear aspects of the problem require many thousands of time steps be used in the solution. The problem's large size and dynamic nature make explicit finite element codes, such as DYNA, as described in User's Manuals for DYNA3D and DYNAP, Nonlinear Dynamic Analysis of Solids in Three Dimensions, J. O. Hollquist, 1981, and PRONTO as described in "PRONTO 2D: A Two-Dimensional Transient Solid Dynamics Program," L. M. Taylor and D. P. Flanagan, Sandia National Laboratories, 1987, the most economically attractive.

As an analysis example, a 137 m/sec end-on impact of the PAT-2 package was evaluated using the LIGO technique in the finite element code PRONTO-2D. The PAT-2 containment vessel was treated as a solid sphere with the density corrected to account for the actual contents. The Ti alloy load spreader and the stainless steel outer cover were modeled using a bilinear elastic-plastic constitutive relation. Contact surfaces were used between the redwood, maple, outer cover, load spreader, and containment vessel.

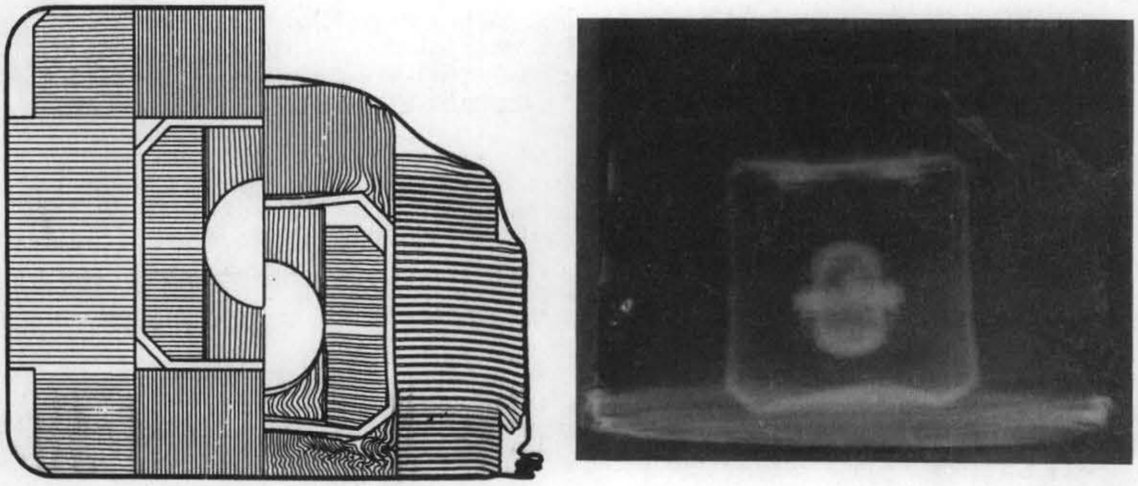

Figure 2. End-on impact of PAT-2 at 450 ft/sec. Comparison between predicted deformed shape from a dynamic analysis of an axisymmetric model (left) and a post-test radiograph (right) taken during the PAT-2 development. The right half of an axisymmetric model is shown deformed, with the left half showing the undeformed package.

The impact analysis predicted the deformed shape in Fig. 2. The left portion of the figure shows the undeformed axisymmetric view of the package, and the right portion shows the deformed shape as the package starts to rebound off the unyielding target. The finely spaced lines in the figure represent the alternating hard and soft materials.

A post-test radiograph of the PAT-2 package tested during the development program is also shown in Fig. 2 for comparison. The comparison between the test results and the finite element results is good. The analysis predicts 0.286 m (11.25 in.) of total displacement from the top of the package to the bottom, while 0.292 m (11.5 in.) was measured in the development test. Both the test and the analysis show four folds in the outer skin. The bending mode of the load spreader is similar in the test and analysis. The analysis indicated that neither the redwood nor the maple would crush beyond lockup during the impact event.

Fig. 3 shows the deformation predicted when a larger package impacts an unyielding target. An important phenomena is observed when a larger package geometry is analyzed using the LIGO technique. The analysis reveals two phases of wood crush. During the initial crush phase, the redwood crushed without rotating. A second phase of crush occurred when the wood became unstable and rotated to form buckle-like folds in the wood. These folds are clearly visible in Fig. 3. The second phase of wood crush requires much less force since the wood grain is rotated with respect to the crush direction. Since less crush force is required, the amount of energy absorbed during the crush stroke is much less than would be predicted by an isotropic assumption for the wood behavior.

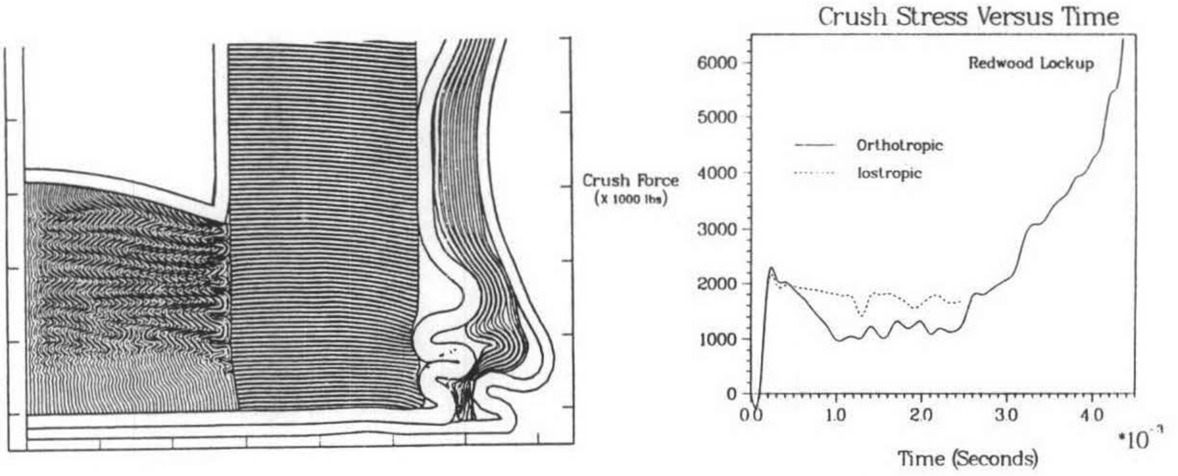

Figure 3. Wood deformation in a large transport package impacting at 137 m/sec and the associated force versus time curve.

The force required to crush the wood in this larger package is also shown in Fig. 3. Also plotted in this figure is the force predicted from an impact analysis assuming isotropic material properties. The onset of the second phase of crush starts at approximately 0.5 msec., which corresponds with the drop in the wood crush force shown on the plot.

An analogy for this two-phase crush is the buckling behavior of a beam on an elastic foundation. A small wood strip from the center of the impact limiter may be viewed as a beam with the surrounding wood viewed as an elastic foundation. If the wood beam is short, then the beam will deform plastically before it can buckle. If the wood surrounding the wood strip is thin, then a high buckling load would be expected since the equivalent beam foundation would be stiffer. Since the dynamic buckling strength of a beam is different from the static buckling strength, rate dependent behavior would be observed for the wood strip.

The LIGO technique predicts both rate and geometric dependent behavior for wood impacting at high speeds. These rate and geometric dependent behaviors translate to poor scaling laws for scale model testing of air transport packages. Impact simulation gives a good understanding of the mechanisms of wood crush and provides a cost effective means of reducing the number of prototype tests required in air transport package designs.

NEW TECHNOLOGY GOALS

The goals of the present work are to improve our understanding of how plutonium air transport packages perform during severe accident tests and to develop new, improved concepts. Our work to date indicates that the following items need to be addressed:

1. The packages are relatively hard--e.g., the payload must be able to withstand very high decelerations even for impacts at speeds much less than the NUREG-0360 test criteria.

2. The packages are relatively complex, heterogeneous structures. Given the complex interaction between parts, it is difficult to develop definitive design theories as to the actual importance of a given part.

3. The package scaling laws are not known.

4. The packages contain a considerable amount of combustible material.

5. The constraints on the energy-absorbing overpack, rather than constraints on the contents, seem to drive the overall package design.

Sandia personnel are evaluating some completely new concepts to address the above weak areas. The development and implementation of new technology for plutonium packages continues to be an SNL transportation base technology goal.

CONCLUSIONS

Recent interest in the development of new and larger plutonium air transport packages has resulted in an improved understanding of the performance of wood-based packages.

New computer models have been developed that can serve as design tools for these packages in the future. This information gives us an optimistic outlook on the ability to design plutonium air-transportable packages that can survive severe aircraft accidents.

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