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Plutonium Accident Resistant Container Project

John A. Andersen

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PLUTONIUM ACCIDENT RESISTANT CONTAINER PROJECT*

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ABSTRACT

The PARC (plutonium accident resistant container) project resulted in the design, development, and certification testing of a crashworthy air-transportable plutonium package (shipping container) for certification by the USNRC (Nuclear Regulatory Commission). This PAT-1 (plutonium air transportable) package survives a very severe sequential test program of impact, crush, puncture, slash, burn, and water immersion. There is also an individual hydrostatic pressure test. The package has a payload mass capacity of 2 kg of PuO_2 and a thermal capacity of 25 watts. The design rationale for very high energy absorption (impact, crush, puncture, and slash protection) with residual high-level fire protection, resulted in a reasonably small air-transportable package, advancing the packaging state-of-art. Optimization design iterations were utilized in the areas of impact energy absorption and stress and thermal analysis. Package test results are presented in relation to radioactive materials containment acceptance criteria, shielding and criticality standards.

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PLUTONIUM ACCIDENT RESISTANT CONTAINER PROJECT

Introduction and General

A recent United States Public Law (94-79; August 9, 1975) restricts the air shipment of plutonium. This law reads, in part, that no plutonium (except for very small quantities of material in medical devices) may be air transported until the NRC (U.S. Nuclear Regulatory Commission) ". . . has certified that a safe container has been developed and tested which will not rupture under crash and blast testing equivalent to the crash and explosion of a high-flying aircraft. . . ." Although there were problems of translating the general language of the law to technically meaningful definitions, very severe accident-modeling criteria were developed by the NRC, which also engaged Sandia Laboratories in the development of a transportation package that would acceptably survive the new criteria. The initial tasks were to promulgate criteria and then to design a package to satisfy those criteria. Both the new criteria and the new package have been presented for approval to the Advisory Committee for Reactor Safeguards and the National Academy of Engineering's Ad-hoc Committee on the Air Transport of Plutonium. Results are being, or have been, presented to the U.S. Congress, as originally mandated.

The NRC criteria became a document defining those measures necessary to qualify and certify a package for the air transport of plutonium; hereafter, this will be referred to as the Qualification Criteria. The Qualification Criteria essentially consists of a test program with supporting rationale and stringent acceptance standards. The rationale embodies a maximum credible accident approach, with very severe single-event accident elements applied sequentially to the same package. Also, certain individual tests are included as well as a requirement to conform to existing regulations.

That portion of the program performed at Sandia bears the acronym "PARC" for Plutonium Accident Resistant Container. The PARC project resulted in the development of the PAT-1 (Plutonium Air Transportable) Package. The package was designed concurrently with and in response to the Qualification Criteria and survives the sequential and individual tests of both the new and old criteria and meets the applicable acceptance standards in each case.

The Qualification Criteria are summarized in the next two tables; Table I defines the test program of new sequential and individual tests, and also summarizes the tests of the existing regulations, 10 CFR 71.

TABLE I

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); 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
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
10 CFR 71 Tests	
Normal	Heat, cold, pressure, vibration, water spray, 1.2-m (4 ft) drop, penetration, compression
Accident	9-m (30 ft) drop, puncture, fire, submersion

Table II summarizes the acceptance criteria, essentially comprising three requirements: containment, shielding, and criticality.

In response to the Qualification Criteria a package was designed, analyzed, and developed. The resulting PAT-1 (Plutonium Air Transportable Model 1) package is shown in Figure 1. The package is 62 cm (24-1/2 in.) O.D., 108 cm (42-1/2 in.) in length, and weighs approximately 227 kg (500 lb) when loaded. Externally, it resembles a 65-gallon commercial stainless-steel process vessel. The PAT-1 package comprises an AQ-1 (Air Qualified Model 1) overpack, TB-1 containment vessel, and PC-1 product can, as shown in Figure 2.

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TABLE II

Acceptance Criteria

Containment of Plutonium

-- Release must be < IAEA A2 weekly quantity following test sequence of new criteria

-- "No release" from double containment following 10 CFR 71 normal or accident conditions measured as a leak rate -- ANSI N 14.5: 10^{-7} cm^3/s -- or as actual loss of surrogate: less than 10^{-8} g, by fluorimetry

Shielding

-- Normal transport - 49 CFR 173 requires that external radiation be limited to: 10 mrem/hr at 1 m (3 ft), and 200 mrem/hr at surface

-- Postaccident - 10 CFR 71 requires that external radiation, following the more severe tests of the new criteria, be limited to:
1000 mrem/hr at 1 m (3 ft)

Criticality

-- Undamaged single packages and large arrays must be subcritical per 10 CFR 71

-- Arrays of damaged packages must be subcritical per 10 CFR 71, following the more severe tests of the new criteria

Figure 1. PAT-1 Package Exterior

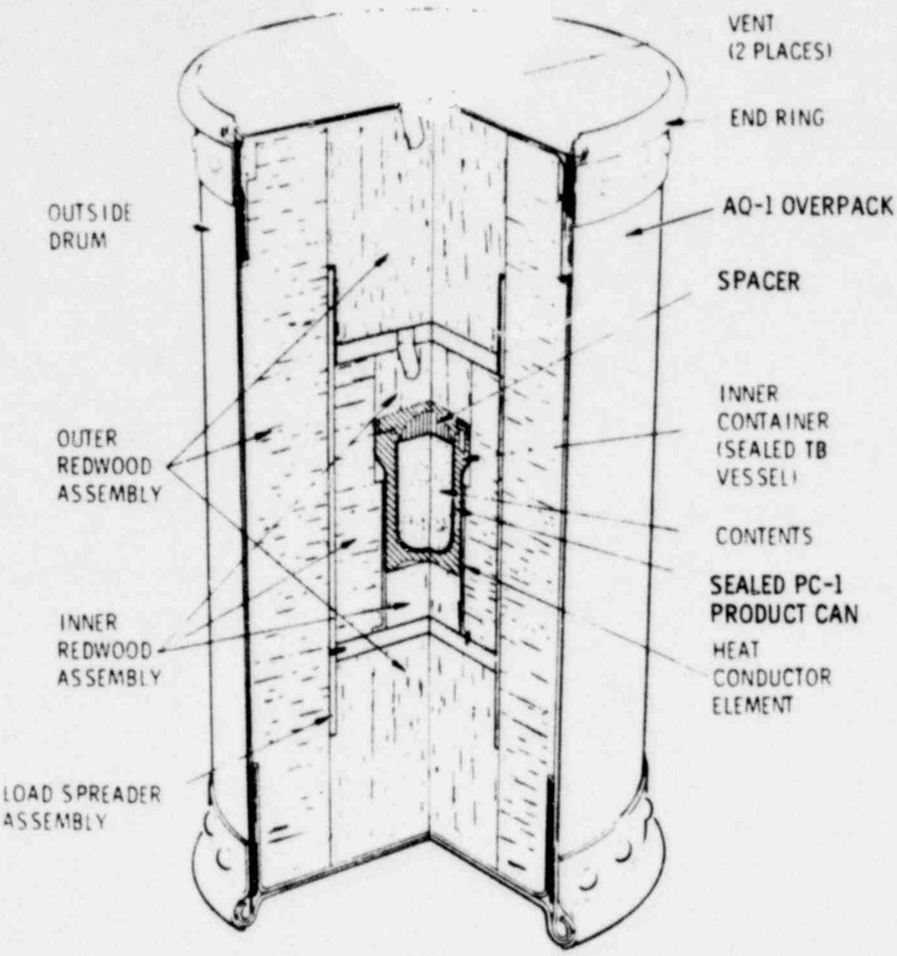

Figure 2. PAT-1 Plutonium Air Transportable Package, Cutaway

Air Qualified Overpack (AQ-1)

The AQ-1 configuration consists of an outside drum, with at least two layers and in some locations five layers of 16 gauge, 304 stainless steel; an outer and inner grain-oriented redwood assembly with an interstitial load spreader assembly; and a heat conductor element.

The outside drum-ends, both top and bottom, are secured in a unique manner, shown in Figure 3, to permit relatively simple access to the container and yet retain the removable parts in a violent crash.

One factor leading to the selection of redwood as the shock mitigator/thermal barrier is its high specific energy absorption capability parallel with the grain, as indicated in Figure 4; redwood outranks most shock mitigators such as elastomeric and rigid foams, aluminum and stainless steel honeycombs, foam-filled honeycombs, and other natural products. This capability was examined relative to density so as to constrain the final package size and weight while maintaining utility as an industrial air transportable package with a practical (although small) internal payload.

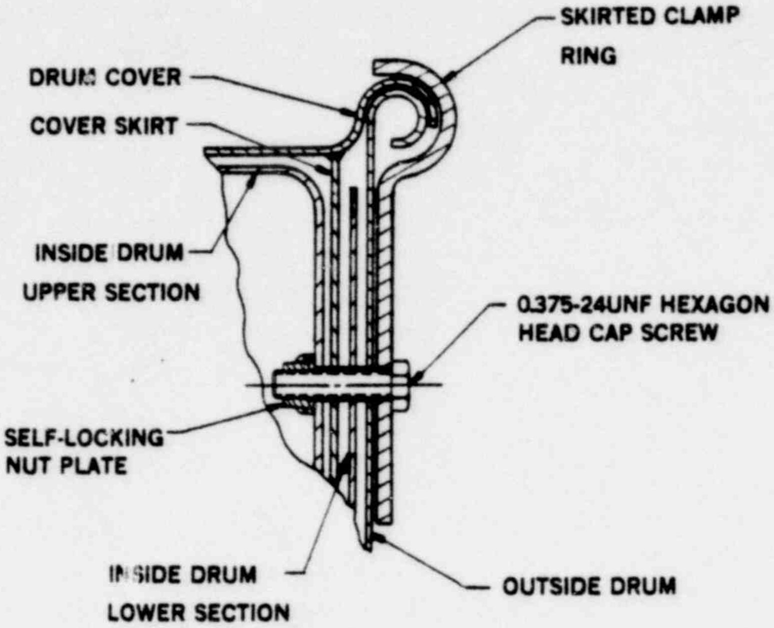

Figure 3. AQ-1 Closure

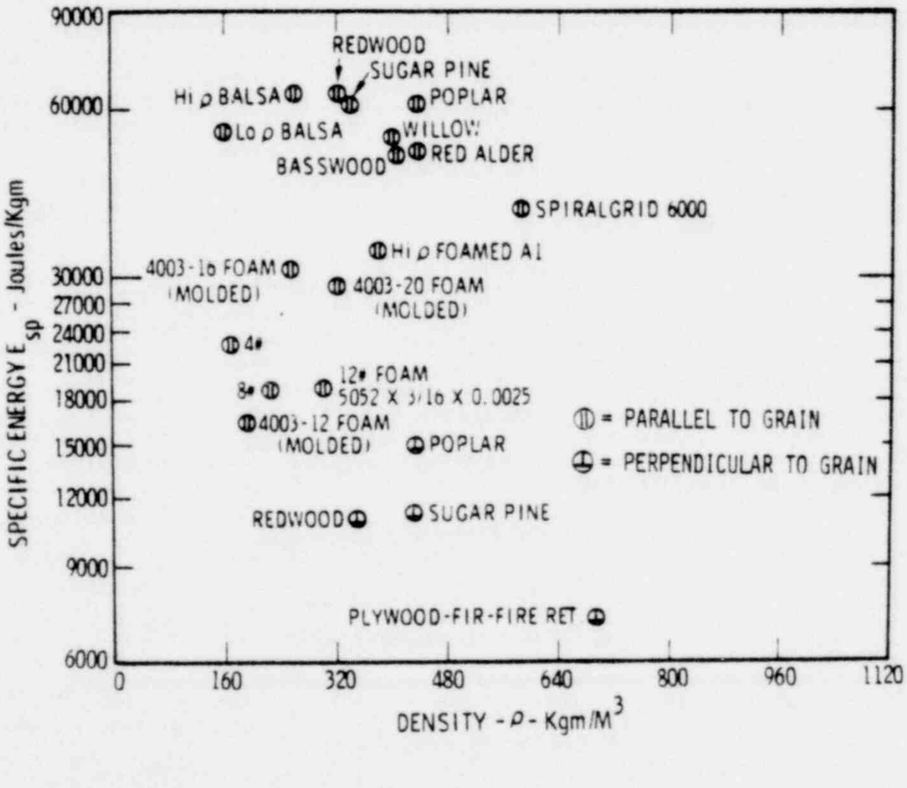

Figure 4. Accident Resistant Container Materials Evaluation

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Thermal barrier or char performance was the other principal characteristic leading to the choice of redwood. As indicated in Figure 5, redwood char performance compares favorably with other high energy absorbers, even outperforming some fire-retardant-treated materials which were not as efficient. Although balsa and some rigid foams slightly outperformed redwood in this regard, the former was too bulky for air transportable design and the latter were not as efficient in energy absorption.

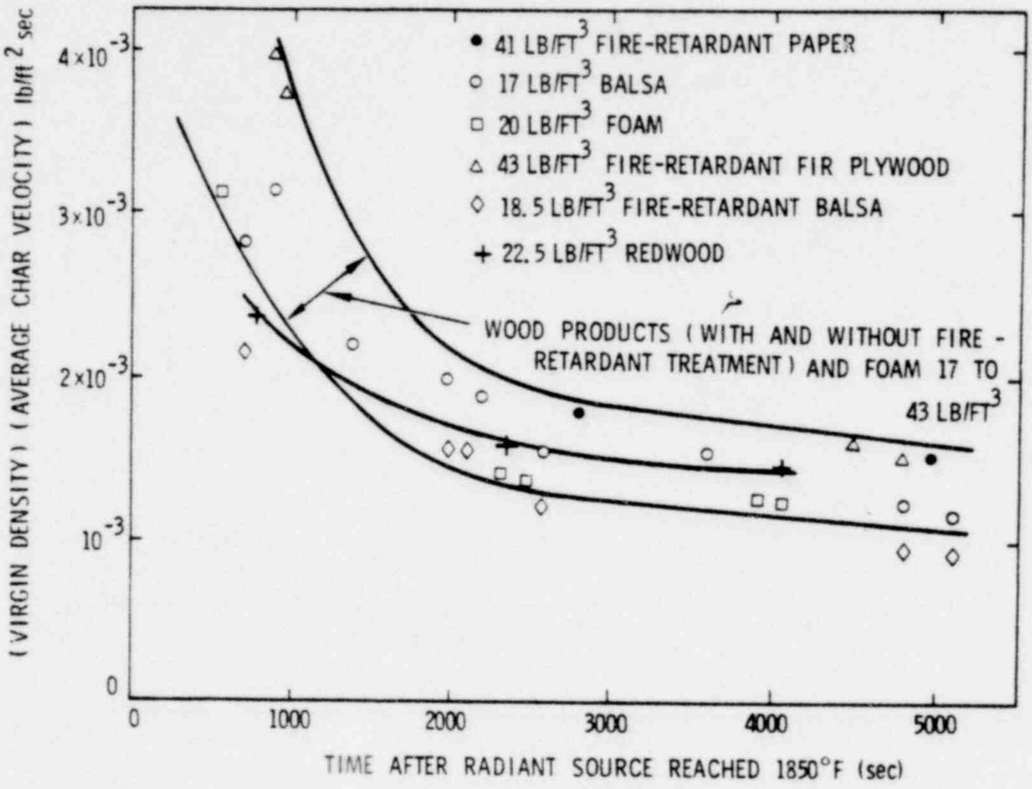

Figure 5. Char Performance

New redwood strength data, Figure 6, were generated to support design analysis across an appropriate broad temperature range. An impact energy balance analysis, Figure 7, was iterated to optimize the design application of the inner and outer regions of redwood and the interstitial aluminum load spreaders.

Aluminum was chosen for the load-spreader assembly because of its favorable mass, strength, modulus, thermal conductivity, cost and availability. Load spreaders were found to be essential to distribute dynamic inertial compressive loading from the relatively small area loading of the containment vessel within the package, to a larger area of the shock-absorbing material. In a side or lateral impact, the tube is the principal load spreader; in an end or longitudinal impact, the discs are the principal load spreaders. Referring to Figure 2, the extended region of the tube, beyond the discs, deforms inward in a severe corner impact, constricting possible passage of the discs and containment vessel in an outward direction.

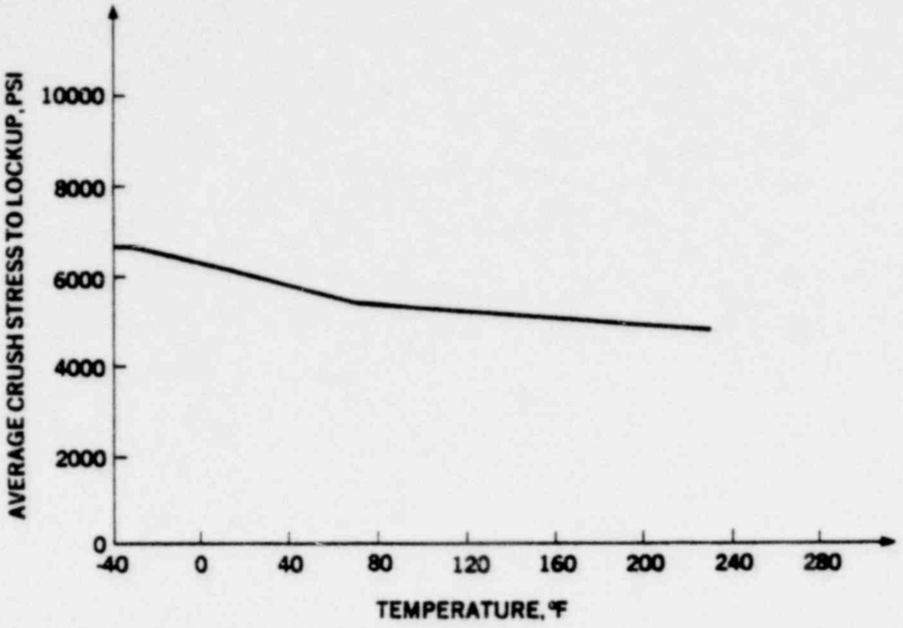

Figure 6. Average Crush Stress for Redwood as a Function of Temperature

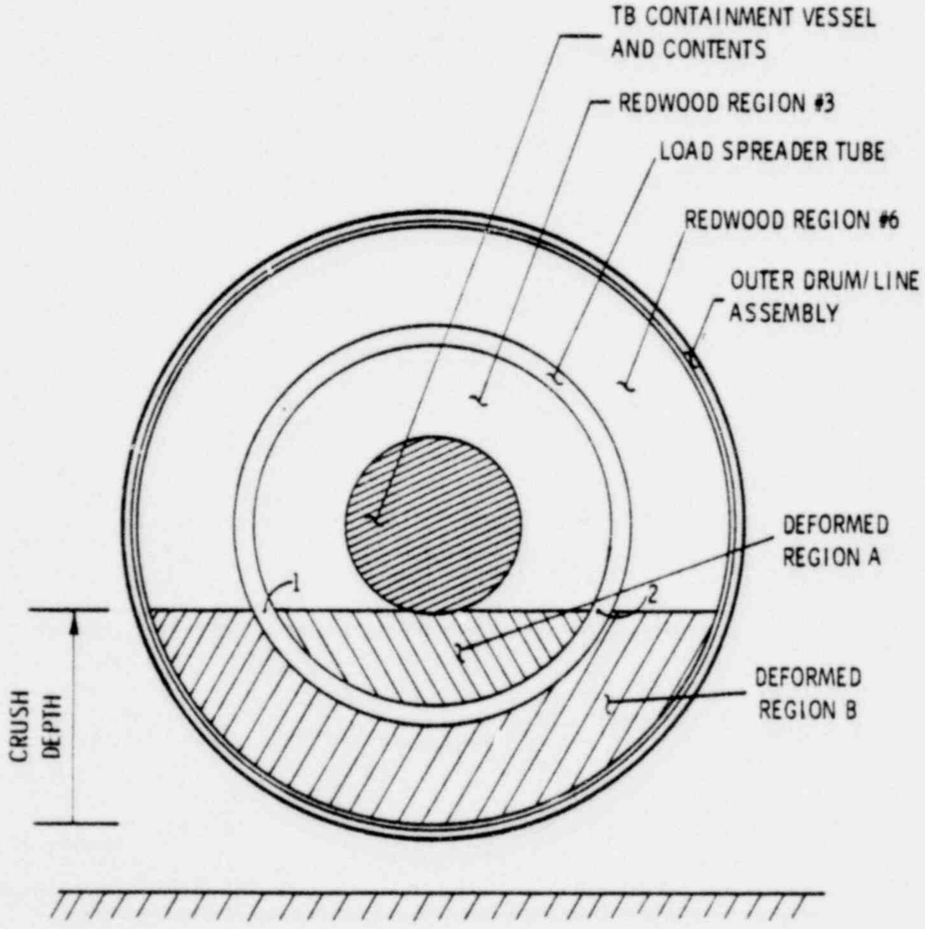

Figure 7. Impact Energy Balance

This deformation/constriction action also occurs in side and end impacts. Additionally, as shown in Figure 8, load spreader deformational energy is also accounted for in the impact energy balance, again for design optimization to restrict package weight and size while retaining great toughness.

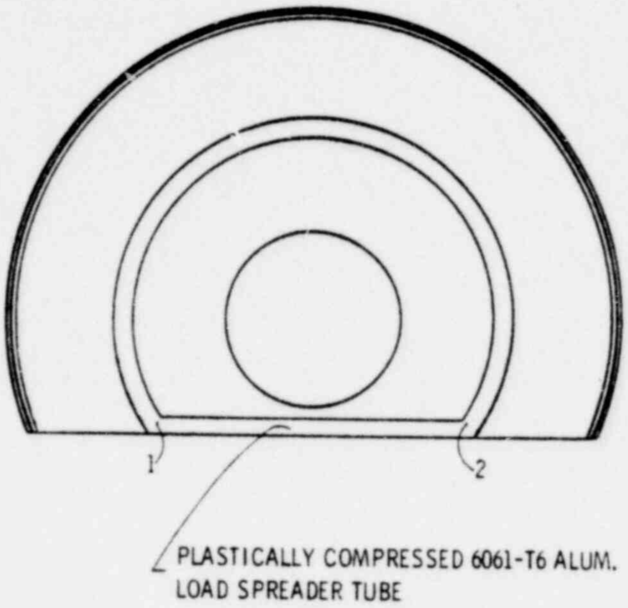

Figure 8. Impact Energy Balance

A photograph, Figure 9, of the resulting package cross-section shows the double-walled outside drum, the radial grain orientation of the outer and inner annuli of redwood, the load spreader tube, and the containment vessel. The non-removable elements of this assembly are permanently bonded together with a polyester-flexibilized epoxy adhesive which has resilience over a wide temperature range. When impact forces cause deformations, this bond acts in unison with the wooden elements and their adjacent metal elements.

Containment Vessel (TB-1)

The containment vessel, TB-1, Figure 10, consists of a body, a lid secured by bolts, a copper gasket, and an O-ring. The vessel body and lid are fabricated from PH13-8Mo precipitation hardened stainless steel. The H1075 temper enhances ductility while preserving high strength from low to high temperatures. The TB body and lid are designed with approximately hemispherical end shapes and cylindrical side wall shapes to resist deformation from either external or internal loads or pressures. The lid is hermetically sealed to the body by the use of a ductile copper gasket in conjunction with knife edge sealing beads on both the body and lid, and a pattern of bolts, as shown in Figure 11. The sealing surfaces are arranged to afford handling protection to the knife edge sealing beads. The lid has a pilot diameter region of great structural shear strength which fits closely into the mating internal diameter of the body. This closely limits any possible radial motion between these parts, especially motion that would be induced from deformations resulting from accidental crash, crush, or puncture loads. This pilot diameter is also equipped with an O-ring in a groove, as a secondary seal to supplement the upper copper gasket and double knife edges, for containment of contents within the TB-1 containment vessel.

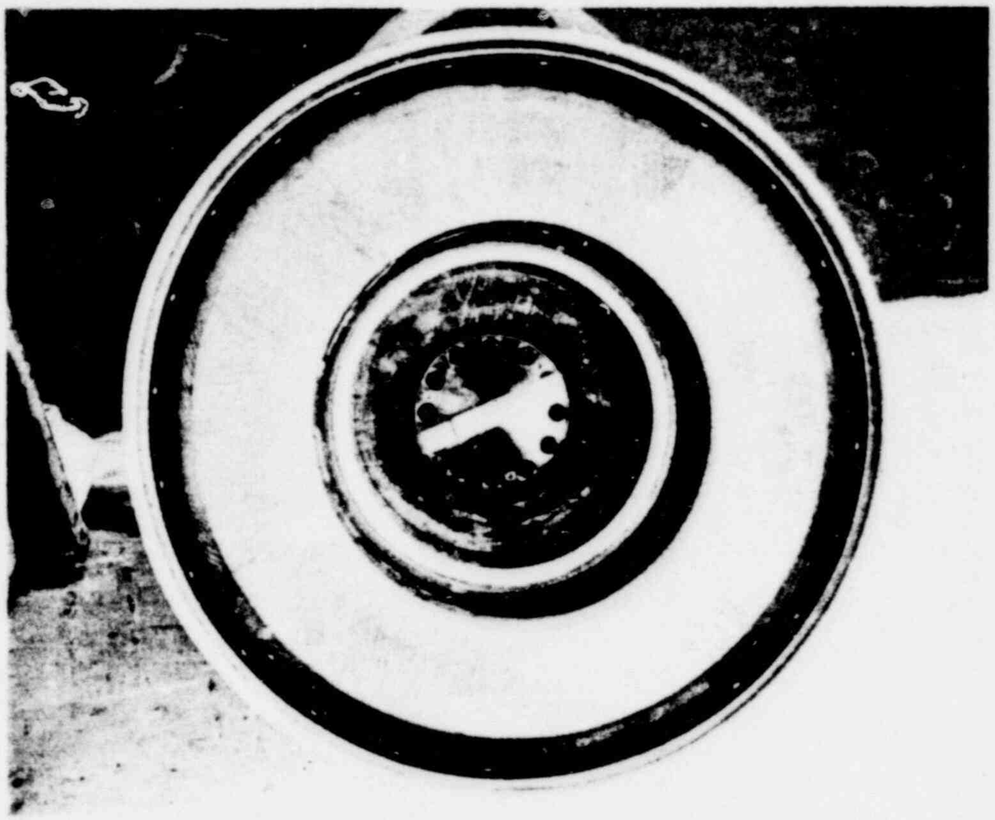

Figure 9. PAT-1 Package Interior

The twelve TB-1 closure bolts, 1/2-in. in diameter, shown in Fig. 10, are forged from A-286 stainless steel, with over 30,000 lb ultimate tensile strength per bolt. This material resists corrosion in conjunction with the stainless steel TB-1 body and lid, and provides high temperature strength to maintain the TB-1 seal at elevated temperatures. The bolts are silver plated to prevent galling of the stainless steel bolt in the stainless steel vessel.

A shock mitigation spacer within the TB-1 containment vessel is fabricated from aluminum honeycomb (see Fig. 10) with axial cell orientation. This honeycomb spacer prevents the flat end of the PC-1 product can from entering into the hollow hemispheric lid in the case of severe impact loads in the axial directions. This spacer also serves as a thermal conductor for heat generated by certain PuO_2 contents.

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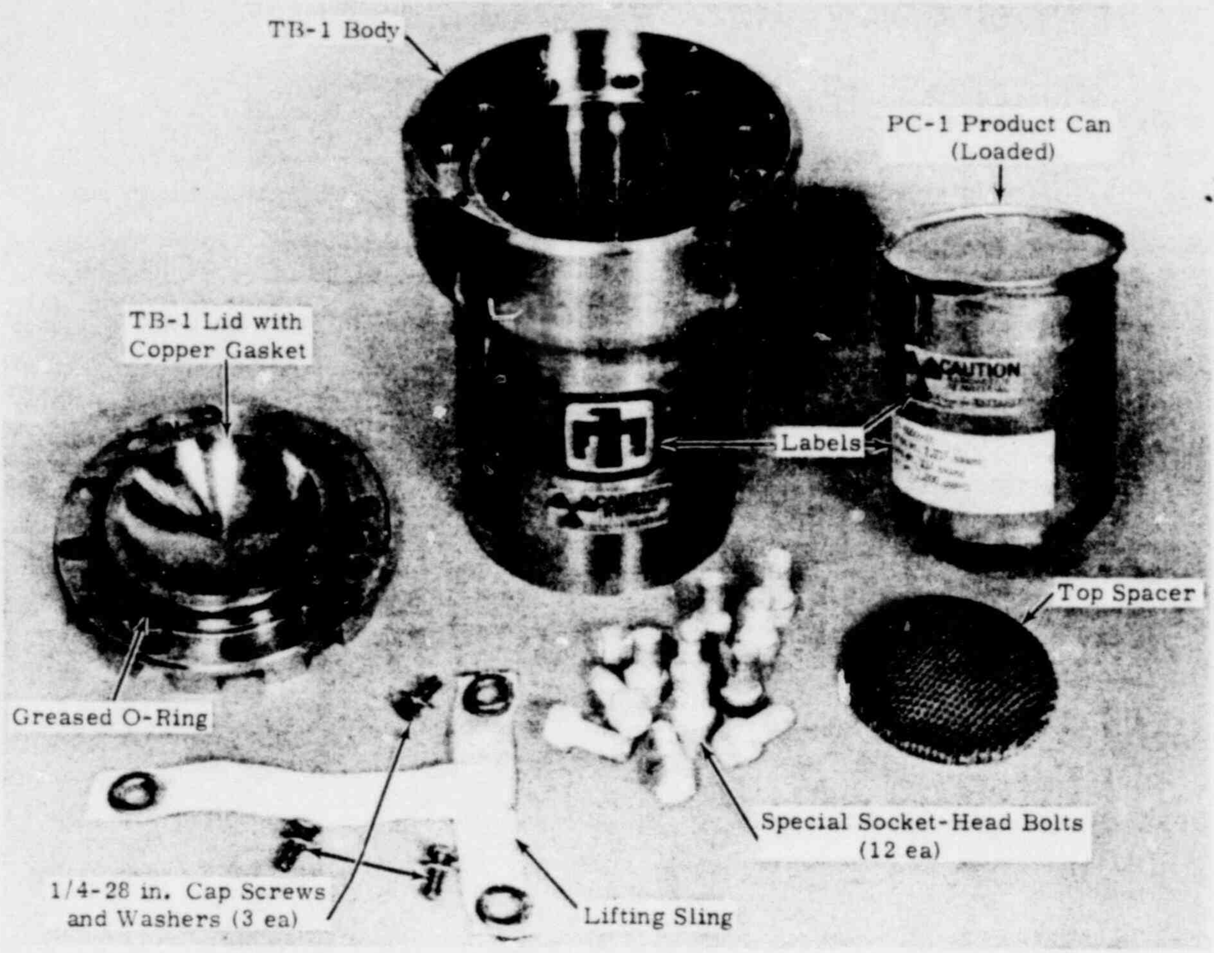

Figure 10. TB-1 Containment Vessel with PC-1 Product Can

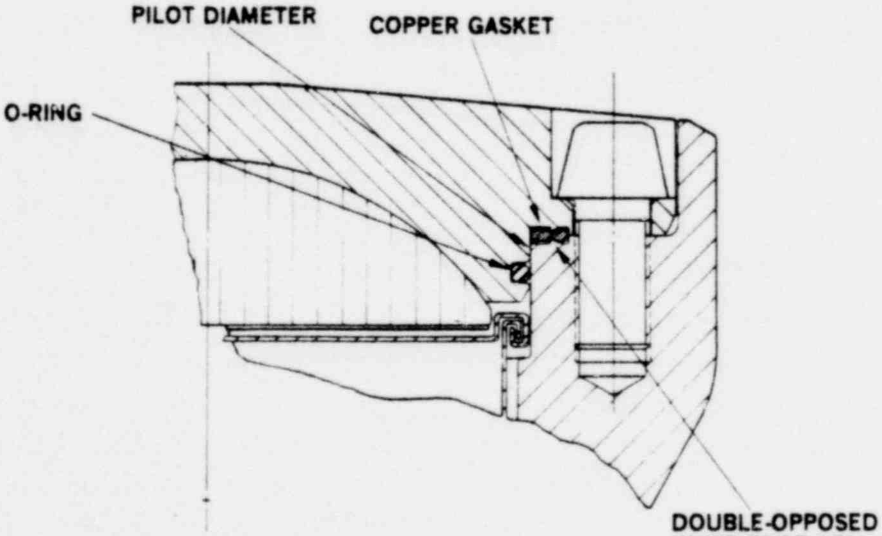

Figure 11. Containment Vessel Seal

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Finite element stress analysis (Fig. 12) was used to define the containment vessel design, leading to optimization of vessel mass, itself a threat to the surrounding shock mitigation material. The vessel was designed to directly accept impact and puncture threat, including armor piercing ballistic attack.

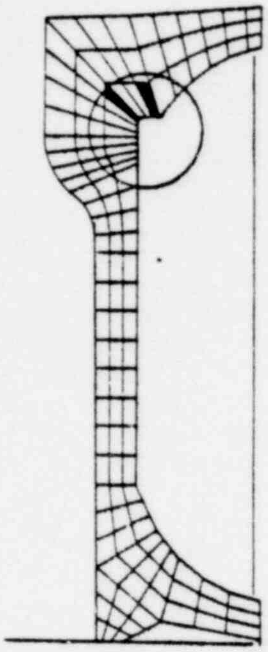

Figure 12. Containment Vessel Finite Element Stress Analysis

The TB-1 inner container is highly resistant to sea water corrosion and will withstand the hydrostatic pressures specified in the NRC Qualification Criteria.

Product Can (PC-1)

The PC-1 product can, right side of Figure 10, is fabricated from stainless steel. It is closed by crimping in a canning machine and is also sealed with an epoxy material. The close fit of the TB-1 containment vessel limits product-can deflection or permanent change of shape under severe impact loads. The product can provides double containment under the normal and accident conditions of transport performance tests as specified by 10 CFR 71.42. This product can may be loaded to a maximum weight of 2 kg PuO_2 contents, not to exceed a maximum of 25 W thermal activity, of PuO_2 of various isotopic composition.

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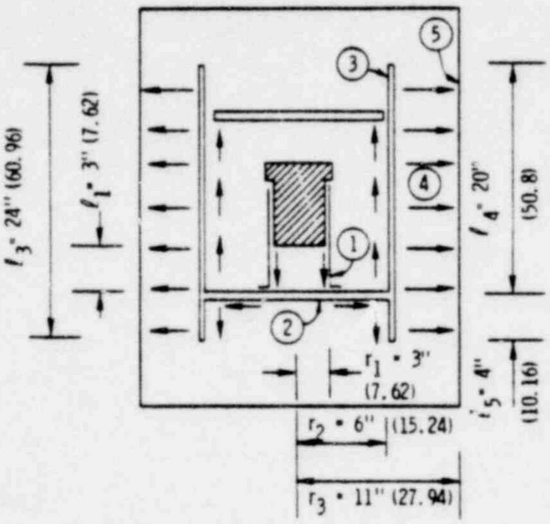
Thermal Analysis

Thermal analyses of the PAT-1 package included finite difference modeling for internal heat load capacity (Fig. 13), leading to the 25-W limitation on thermally active radioisotopic contents; the limiting consideration here was long-term protection of the redwood for preservation of known performance factors. Finite difference thermal modeling was also used in the case of externally applied heat such as the standard hot day conditions (Fig. 14), and to predict package performance in the 1010°C (1850°F) large JP-4 jet fuel fire environment.



1 COPPER CYLINDER: $k_c = 220$ (0.91) δ = THICKNESS INCHES (cm)
$\delta = 0.25$ (0.63) k = CONDUCTIVITY $\frac{\text{Btu}}{\text{hr. ft. °F}} \left(\frac{\text{cal}}{\text{cm. s. °C}}\right)$

2 ALUMINUM PLATE: $k_A = 90$ (0.37)
$\delta = 1"$ (2.54)

3 ALUMINUM TUBE: $k_A = 90$ (0.37)
$\delta = 0.5"$ (1.27)

4 REDWOOD LINER: $k_w = 0.31$ @ 200° F (0.0013)

5. STAINLESS WALL: $k_s = 10$ (0.04)

Figure 13. Finite Difference Internal Heat Model

Test Program

Test activities are best shown by a motion picture, "Plutonium Air Transportable Project," Sandia Laboratories, March 1978. Table III summarizes these tests and also indicates results. This table indicates that five PAT-1 packages were subjected to a similar sequential test series, with the initial impact test oriented so as to encompass the five different principle threat orientations of top, top corner, side, bottom corner, and bottom. The crush, puncture, slash, fire,

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and immersion tests that follow are essentially identical for all packages, with the application point of each test being chosen to produce the most damaging cumulative effect on each package.

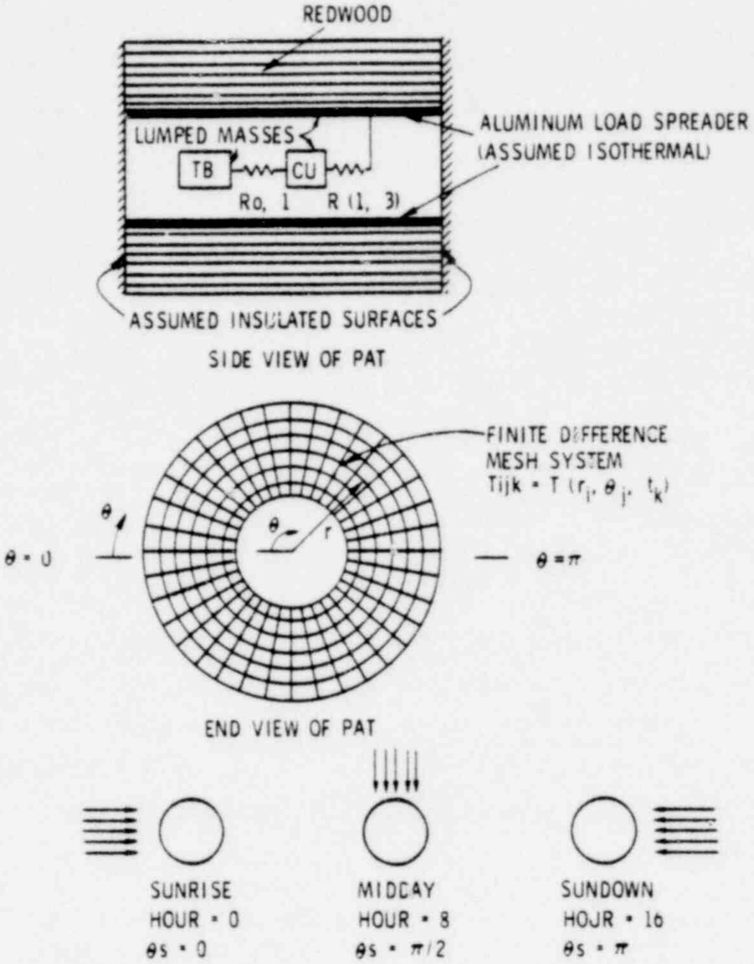

Figure 14. Finite Difference External Heat Model

Table III includes the individual hydrostatic test required by the Qualification Criteria, and high and low temperature engineering development impact tests, applied as the first test in a sequential series.

Before the tests, each package was loaded with a finely divided surrogate UO_2 powder and helium gas. The results show that no uranium oxide escaped as indicated by a fluorimetric test with a detection capability of 10^{-8} g. Also, only very small helium leak rates were induced through the containment vessel seals.

TABLE III

Summary of Qualification Tests, PAT-1 Package

Impact Orientation	Impact Vel. ⊥ to Unyielding Target (fps)	Crush 70,000 (lb)	Puncture 5000 (ft-lb)	Slash 15,000 (ft-lb)	Fire 2200°F 60 Minutes	Immersion	Uranium Detection $\geq 10^{-8}$ g	Post-Test Air Leakage (cm^3/s)
Top 0°	442	√	√	√	√	√	none	$< 4.6 \times 10^{-6}$
Top Corner 30°	451	√	√	√	√	√	none	$< 4.5 \times 10^{-5}$ probably $\sim 1.7 \times 10^{-7}$
Side 90°	445	√	√	√	√	√	none	1.4×10^{-6}
Bottom Corner 150°	443	√	√	√	√	√	none	5.5×10^{-6}
End 180°	466	√	√	√	√	√	none	1.8×10^{-6}

Individual Test: 600 psig hydrostatic; 8 hours - No detectable water leakage; $< 10^{-10}$ cm^3/s

Other Requirements: Impact at -40°F -- 2.4×10^{-6} cm^3/s
Impact at 200°F -- 7×10^{-8} cm^3/s

Experimental work with actual PuO_2 was conducted under NRC sponsorship at another laboratory (Ref. 10), to correlate the observed helium leak rates with conservative bounding estimates of worst-case possible plutonium loss (again, no surrogate powder escaped). These conservative bounding assessments of plutonium loss were compared to IAEA "A2" quantities, Table IV, by the NRC staff. These assessments demonstrated successful performance of the PAT-1 package, satisfying the criteria for plutonium containment.

TABLE IV

Allowable Release Masses-IAEA "A2" Quantities

Normal Conditions of Transport (µg/hr)	Accident Conditions of Transport (mg/wk)	
0.000176	^{238}Pu	0.176
0.032	^{239}Pu	32.2
0.0087	^{240}Pu	8.7
0.0009	^{241}Pu	0.9
0.77	^{242}Pu	770.0

Typical Mixture: 2.55 mg Pu/wk

Other

Other analyses conducted to determine package conformance to the Qualification Criteria and to 10 CFR 71 and 49 CFR 173 involve calculations for shielding and criticality. These results are summarized in Table V.

TABLE V

Shielding and Criticality

Shielding

Normal Transport	--	PAT-1 Package Provides Sufficient Shielding (49 CFR 173) Required -- < 10 mrem/hr 3 ft from surface Calculated -- 2 mrem/hr 3 ft from AQ-1[*] Required -- < 200 mrem/hr at surface Calculated -- 33 mrem/hr at surface of AQ-1[*]
Postaccident	--	Containment Vessel (TB-1) Provides Sufficient Shielding (10 CFR 71) -- This permits AQ-1 overpack to be discounted Required -- < 1000 mrem/hr 3 ft from surface Calculated -- 4 mrem/hr 3 ft from surface of TB-1[*]

Criticality

Normal Transport	--	Undamaged Infinite Array $K_{eff} \sim 0.3$
Postaccident	--	Damaged Infinite Array $K_{eff} \sim 0.4$ Single Water-Flooded and Reflected TB-1 $K_{eff} \sim 0.6$ (K_{eff} = effective neutron multiplication factor)

[*] Using 13.5 year-old Hanford-type plutonium as a conservative source model.

Table VI summarizes the results from testing the PAT-1 package to the requirements of the present regulations, 10 CFR 71.

The integrity of the inner containment vessel, determined by both analysis and test, is summarized in Table VII.

TABLE VI

Results of 10 CFR 71 Qualification Tests, PAT-1 Package

Normal Conditions of Transport: **Heat, cold, internal pressure, vibration, water spray, drop (4 ft), penetration, compression**

- -- No Effect on Shielding
- -- No Effect on Criticality
- -- No Release: Leaktight (leakrate $< 10^{-10}$ cm^3/s) Containment Vessel
  No Release ($<10^{-8}$ g) of UO_2 Surrogate from Product Can
- -- Double Containment (product can and containment vessel both meet requirements)

Accident Conditions of Transport: Drop (30 ft), **puncture, fire, immersion**

- -- No Effect on Shielding
- -- No Effect on Criticality
- -- No Release: Leaktight (leakrate $< 10^{-10}$ cm^3/s) Containment Vessel
  No Release ($< 10^{-8}$ g) of UO_2 Surrogate from Product Can
- -- Double Containment (product can and containment vessel both meet requirements)

TABLE VII

Containment Vessel Integrity

Internal Pressure

-- Maximum Credible Accident Environment -- 1080°F, 1253 psi (Bounding Assessment)

Tested to: 1000°F, 3330 psi, 18 hrs
Many tests at ~1080°F, ~1253 psi

Analysis 18,300 psi stress
93,000 psi strength
At 1080°F and 1253 psi, Margin of Safety ≃ 4

-- Maximum Normal Operating Pressure -- 215°F, 34.3 psi

Analysis 455 psi stress
140,000 psi strength
At 215°F and 34.3 psi, Margin of Safety ≃ 306

External Pressure

-- Hydrostatic Requirement -- 600 psi

Tested to: 5,000 psi: No leak

Analysis 5,000 psi load produces -43,000 psi stress
150,000 psi strength gives Margin of Safety ≃ 2.5
Margin of Safety ≃ 20 at 600 psi

Conclusion

The PAT-1 package, developed in the PARC program, survives the severe accident-modeling test threats of the Qualification Criteria, meets the acceptance criteria for containment, shielding, and criticality, and provides a safe means for air transport of plutonium.

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