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CRASHWORTHY SEALED PRESSURE VESSEL FOR PLUTONIUM TRANSPORT

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Synopsis

A rugged transportation package for the air shipment of radioisotopic materials was recently developed. This package includes a tough, sealed, stainless steel inner containment vessel of 1460 cc capacity. This vessel, intended for a mass load of up to 2 Kg PuO_2 in various isotopic forms (not to exceed 25 watts thermal activity), has a positive closure design consisting of a recessed, shouldered lid fastened to the vessel body by twelve stainless-steel bolts; sealing is accomplished by a ductile copper gasket in conjunction with knife-edge sealing beads on both the body and lid.

Design goals are stated as severe accident-modeling tests and stringent acceptance criteria.

Some unsuccessful seal designs that were fabricated and tested are surveyed.

Design features and rationale for the successful pressure vessel and seal are discussed, including high-impact and high-temperature survival. Finite element and other stress analyses were iteratively performed to arrive at a practical design optimization.

The performance of the seal is judged through pre- and post-environmental-test helium mass spectrometer leak rate measurements, and fluorimetry detection measurements for surrogate uranium release. These data demonstrate that the seal remains leaktight per ANSI N14.5 in the 10 CFR 71 Appendix A (normal) and Appendix B (accident) environments, and that the seal limits radioactive material loss to far less than the IAEA "A2" quantity, following the application of the new severe accident criteria.

Follow-on applications of this seal in newer, smaller packages for international air shipments of plutonium safeguards samples, and in newer, more optimized packages for greater payload and improved efficiency and utility, are briefly presented.

SAND-78-1121

CRASHWORTHY SEALED PRESSURE VESSEL FOR PLUTONIUM AIR TRANSPORT

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BACKGROUND AND INTRODUCTION

Plutonium, usually in the form of plutonium oxide, is shipped by air, within and between nations, for reasons of timeliness and perceived advantages in safety, security, and reliability. Activities associated with such shipments include research and development in the nuclear fuel cycle, commercial processing of mixed oxide fuels for power generation, aerospace and technical applications such as radioactive thermal generators and medical applications. Special attention to the problem of plutonium air transport has evolved from reactor analysis samples and safeguards analytical laboratory evaluation samples, which have a timeliness requirement.

Although the risk of transporting plutonium by air has been assessed (1)(2) and was found to be small, the conditions under which plutonium is air transported in the United States began to change as a result of public laws PL94-79 and PL94-187, late in 1975. These laws, directed to the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) (then the Energy Research and Development Agency), generally required new standards of crashworthiness for plutonium air transport packagings and specifically required the development of a new package. The NRC developed new qualification criteria (1) and Sandia Laboratories, under contract to the NRC, developed the PAT-1 package (3), which NRC subsequently certificated (licensed). The pressure vessel that is the subject of this paper is the TB-1 containment vessel within the PAT-1 package. In addition to the internal containment vessel, the PAT-1 package (Fig. 1) comprises an overpack of layers of grain-oriented redwood with an embedded aluminum load spreader and an exterior double-walled stainless steel drum.

The pressure vessel design that evolved (Fig. 2), as described below, has a total internal volumetric capacity of 1.46 litres (3 pints, U.S. liquid), is 171 mm (6.75 in.) in diameter at its largest region, is 217 mm (8.55 in.) in height, has a mass (empty) of 16.8 kg (37 lb), and has been licensed for the air transport of 2 kg of PuO_2 in any isotopic composition not to exceed 25 W thermal activity.

DESIGN CRITERIA

The prevailing design criteria for this sealed pressure vessel are impact resistance, fire resistance, seal integrity under conditions of internal and external pressure, and internal heat capacity. Design satisfaction of these conditions with essentially no release of submicron plutonium oxide particulate matter produced a pressure vessel that satisfied other design criteria of crush, puncture, submersion, low temperature, vibration, penetration, and compression, without specific additional considerations.

Impact

The impact test requirement is 129 m/s (250 knots) minimum velocity, perpendicular to an unyielding target, of the complete package (containment vessel within overpack), in the most damaging orientation. This is a severe test for a package that also is to be bounded by reasonable limits of size and weight for commercially feasible air transport. Therefore, the utilization of an impact limiter of optimum specific energy absorption in the overpack is desired. Any remaining kinetic energy not absorbed in the impact must be accepted as elastic or plastic deformation loads on the pressure vessel. It was desired that the pressure vessel, in the protective overpack, be capable of withstanding small high-velocity armor-piercing projectile attack. It was also desired that the vessel be able to withstand a static compressive load test of 3.1×10^5N (70,000 lbs-force), at any point of application.

Fire Resistance

In sequence, following the above impact and preceding a fire test, the package is required to withstand a 3.1×10^5N (70,000 lbs-force) crush, a puncture (3-m drop of a 227-kg blunt steel spike), and two slash tests (46-m drop of a 45-kg structural steel angle beam).

These tests, and especially the slash tests, tend to tear open the remaining overpack, increasing the vulnerability of the package to damage by fire. Next, the package must be burned in a large, JP-4 aviation fuel fire for at least one hour. The luminous flames of the fire are required to extend at least 1 m but not more than 3 m beyond the package in all horizontal directions. The fire-test facility is constructed in such a manner as to produce a minimum temperature of 1010°C, at the package level, throughout the burn. In view of these requirements, it is desired to gain thermal protection from the impact limiter materials or from the overpack, even following the damaging results of impact, crush, puncture, and slash. However, if the overall size, mass, and cost of the package are held within practical limits, the overpack cannot provide complete thermal protection for the internal containment vessel, and the vessel itself must have good structural integrity during and following the thermal environment.

Seal integrity

The pressure vessel under normal conditions of use is required to contain plutonium oxide with no release. Maximum normal internal pressure results from the maximized conditions of 3.15 kg PuO_2 powder having 0.5% water content and 25 W decay heat, in conjunction with the insulating properties of the overpack and exposure to high ambient temperature and maximum solar heating. In this case, the vessel rises to 102°C with 240 kPa (34.3 psi) internal pressure; the test requirement is 1-1/2 times this pressure or 350 kPa (54.4 psi). It is desired that the vessel be leaktight $\{\dot{q} \leq 10^{-7}$ cm^3/s helium (4)$\}$ at this condition. Also under normal conditions of use, the vessel is required to withstand a positive external pressure of 0.17 MPa (25 psi) and a negative external pressure of one-half standard atmospheric pressure.

Under accident conditions, the pressure vessel is required to contain plutonium oxide within stringent limits, restricting total release to no more than an IAEA "A2" quantity (5), which would be approximately 2.55 mg of a typical recycled plutonium oxide powder. The maximum credible accident pressure in the vessel is 8.6 MPa (1253 psi) with a corresponding vessel temperature of 582°C (1080°F). In a separate test, the vessel is also required to be watertight at an external hydrostatic pressure of 4.1 MPa (600 psi) for at least eight hours.

Internal heat capacity

Under normal conditions of use, the internal vessel must accommodate 25 W thermal activity of its radioisotopic contents without degrading results to the vessel or to the package. This condition is taken to be on a standard hot day of 54°C (130°F) ambient temperature with 16-hour exposure to direct sunlight.

PRESSURE VESSEL DESIGN

The pressure vessel that evolved from the above principal design criteria is shown in Fig. 2. The vessel consists of a body, a lid secured by bolts, a copper gasket, and an O-ring seal.

Vessel body and closure

The vessel body and lid are fabricated from PH13-8 Mo precipitation-hardened stainless steel in the H1075 temper condition. This material and temper were chosen for high strength and ductility, toughness, good corrosion and stress corrosion resistance, and good high temperature properties. The body and lid are designed with approximately hemispherical end shapes and a cylindrical side wall to resist deformation from both internal and external loads or pressures. In general, the shell thickness is a minimum of 14 mm.

Positive closure of the pressure vessel is provided by twelve 1/2-20 (12.7 mm) socket-head cap screws, or bolts, which fasten the lid to the body of the vessel. The bolts, tightened to a minimum torque of 102 N•m (75 ft-lb), are forged from A-286 stainless steel, with more than 1.3×10^5N (30,000 lb) ultimate tensile strength per bolt. The A-286 material resists corrosion with the PH13-8 Mo stainless-steel body and lid, and provides high-temperature strength to maintain the pressure vessel closure at elevated temperature. The bolts are silver plated to prevent galling of the stainless-steel bolt in the stainless-steel vessel.

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.

An elastostatic finite element analysis of the containment vessel was performed in an effort to optimize the design with regard to stresses resulting from an external hydrostatic pressure load. This analysis generally aided in optimizing the overall shape and thickness of the vessel, striving for a uniformity of stress distribution and a reduction in mass. Vessel mass is a primary threat to the energy absorbing medium of the overpack; conversely, vessel mass is also proportional to vessel strength and structural integrity. This analysis was done using the axisymmetric finite element code TEXGAP (6). The finite element mesh and boundary conditions applied are similar to those shown in Fig. 3. A 34.5 MPa (5,000 psi) hydrostatic pressure was used as an incremental modeling load. Locations of maximum (i.e., tensile) and minimum (compressive) stresses are, as could be expected, in the vicinity of the sharp corner (in actuality, the juncture point inside the vessel, between the body and the lid). Under this loading condition, maximum vessel stress is 4.35 MPa (631 psi) and minimum vessel stress is -294.9 MPa (-42,768 psi), as shown in

Fig. 3. Assuming a compression yield for PH13-8 Mo equal to the tensile strength, the margin of safety is calculated as

$$M.S. = \frac{150,000}{42,768} - 1 = 3.5 - 1 = 2.5.$$

As long as vessel response is in the linear elastic regime, the principle of linear superposition may then be used to evaluate the stress and margin of safety at various other lesser conditions, such as the regulatory requirement (1) for a 4.1 MPa (600 psi) hydrostatic pressure condition.

The vessel was also analyzed (3) for internal pressure loads, including the case of maximum credible accident pressure (Fig. 4). Maximum possible internal pressure generates from water content in the PuO_2 powder, becoming a saturated or super-heated vapor, and from volatization of packaging materials such as polyethelene bags and plastic adhesive tape, all being heated due to the fire test on the damaged package. From these conditions, the bounding assessment of internal pressure and temperature is 8.6 MPa (1253 psi) with a corresponding internal temperature of 582^0C (1080^0F). This problem was conservatively analyzed by modeling the vessel as a uniform cylinder with flat ends. Stresses in the cylinder and flat head were found by superposing a number of individual loading cases. At the juncture of the cylinder and the head, the bending moment per unit circumferential length and the transverse shear force per unit circumferential length were determined. The stress field in the cap (conservatively assumed to be flat) was obtained by superposition of stresses due to internal pressure, bending moment, and transverse shear force. The stress field in the vessel body was calculated in a similar manner by superposing stresses due to internal pressure, transverse edge shear force (acting on the end of a long cylinder), and uniform edge moment acting per unit length on the end of a semi-infinite cylinder.

The location of maximum stress in the end cap is on the inner surface near the outer edge of the cap (cap/cylinder intersection); the maximum radial and circumferential stresses, for the 8.6 MPa internal pressure condition, was conservatively calculated to be:

$$\sigma_{rr_{max}} = 0.128 \text{ GPa } (18513 \text{ psi})$$

$$\sigma_{\theta\theta_{max}} = 38.5 \text{ MPa } (5591 \text{ psi})$$

The maximum stresses for the cylinder in hoop and axial directions occur in different locations, the maximum hoop stress occurring at an axial distance of 1.25 radii from the end, and the maximum axial stress occurring near the end cap/cylinder intersection on the inner surface. These stresses, with the 8.6 MPa internal pressure condition, were calculated to be:

$$\sigma_{\theta\theta_{max}} = 39.1 \text{ MPa } (5676 \text{ psi})$$

$$\sigma_{ZZ_{max}} = 129 \text{ MPa } (18751 \text{ psi}) \quad (Z=0)$$

Due to the presence of a biaxial stress state, worst case stresses must be calculated at the same point so that biaxial yielding can be checked using a suitable yield criterion. Since axial stress at Z = 0 is dominant, the hoop stress calculated for this location is then:

$$\sigma_{\theta\theta_{max}} = 6.6 \text{ MPa } (954 \text{ psi})$$

$$\sigma_{ZZ_{max}} = 129 \text{ MPa } (18751 \text{ psi})$$

These stress values are then compared to the minimum yield strength of PH13-8 Mo alloy in the H1075 condition at 582°C (1080°F), which was determined (3) to be:

$$\sigma_y = 641 \text{ MPa } (93{,}000 \text{ psi})$$

Using the Von Mises yield condition

$$\sigma_{eff} = (\sigma_1{}^2 + \sigma_2{}^2 - \sigma_1 \sigma_2)^{1/2}$$

the effective stress in the cylinder was calculated to be

$$\sigma_{eff} = 126.2 \text{ MPa } (18{,}307 \text{ psi})$$

giving a factor of safety of 5.08.

In a similar manner, the effective stress in the end cap was calculated and the factor of safety was 5.65.

Bolt and thread failure of the closure, a possibility with high internal pressure, was analyzed as follows.

The total axial force per bolt is simply the product of the vessel cross section area multiplied by the unit pressure, divided by the number of bolts. For a vessel internal radius of 54mm (2.125 in) and a pressure of 8.6 MPa (1253 psi) and twelve bolts, the load per bolt is 6.6 kN (1481 lb). This load is compared to the ultimate tensile strength of the A286 closure bolts at 582^{0}C (1080^{0}F) of 68 kN (15,327 lb). Bolt tensile failure will not occur and the factor of safety is 10.3.

At failure conditions, thread shearing would occur in the PH13-8 Mo alloy vessel material, because the shear strength of the A-286 alloy bolt material is higher. The shear stress, in the vessel, tending to strip out the threads (1/2-20 thread, 19mm minimum depth of engagement) was calculated to be 8.7 MPa (1257 psi). This shear stress is compared to the shear failure stress, estimated to be one-half the guaranteed minimum tensile ultimate strength at 582^{0}C (1080^{0}F) of 689 MPa (100,000 psi), or 345 MPa (50,000 psi). Thread shearing failure will not occur for the stated accident conditions; the factor of safety is 39.

<u>Vessel seal</u>

Initial design guidance from the regulatory agency requested that the inner vessel approximate the design of an existing package (DOT Specification 6M/2R) which had a single screw-thread closure plug on the inner containment vessel. Thus, early designs attempted to configure and qualify a large screw plug, although prior laboratory experience indicated that a multiple-fastener bolted joint was more likely to be successful. A design with a solid stainless steel lens ring on a "shelf" (Fig. 5) was unsuccessful due to large post-crash leak rates. Another design, with a silver-plated stainless steel C-ring seal on a "shelf", (Fig. 6), was similarly unsuccessful. A tapered copper obturator design (Fig. 7) suffered the same results. Additionally, it was difficult to torque these designs sufficiently tight with practical hand tools to achieve a leak-tight leak rate (4) for normal conditions of use.

The successful seal and vessel design is shown in Fig. 8. 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; bolt tightening embeds the knife-edges into the copper, effecting a hermetic seal ($\dot{q} < 10^{-10} cm^3/s$ helium) under normal conditions of use. The sealing surfaces are arranged to afford handling protection to the knife-edge sealing beads. The pilot diameter of the lid, where it fits down within the inside diameter of the vessel, is equipped with a fluorocarbon 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 under conditions of normal use and as an assembly aid (e.g., rapid capture of intentionally-added helium tracer gas).

PERFORMANCE AND EVALUATIONS

Results from required tests

Performance of the sealed pressure vessel was judged by these acceptance standards: (a) no release of radioactive material from the sealed containment vessel following the normal and accident condition tests of 10 CFR 71 (7) [a "leak-tight" ($\dot{q} < 10^{-7}$ cm^3/s) leakrate per ANSI N14.5 (4) qualifies as "no release"] and (b) release of no more than an A_2 quantity of plutonium in one week from the containment vessel following the tests prescribed in the qualification criteria (1). An A_2 quantity is defined in Table VII of the International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Materials (IAEA Safety Series No. 6) (5).

Verification of compliance with these performance specifications was achieved through two complementary methods: (a) Following the tests, a direct measurement was made to detect if any surrogate contents (UO_2) had escaped.* The measurement procedure involved submitting standard health physics swipe samples to analysis with a fluorimeter which was capable of

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*The surrogate UO_2 powder utilized had a 3 micron median particle size, with 53% of the particle population being $<$1 micron. By comparison, a fine PuO_2 powder had 28 micron median particle size and no particles $<$ 6 microns.

detecting $\geq 10^{-8}$ grams of uranium. This was accomplished both prior to and following all test sequences. (b) Gas leakage across the seal was measured. During assembly, the TB-1 containment vessels were backfilled with helium at ambient temperature and pressure and checked with a mass spectrometer helium leak detector for leaktightness. The helium leak rate test was repeated after all test sequences. This gas leakage measurement was then used to perform bounding analytical and experimental correlations to establish the potential for PuO_2 powder loss.

For the 10 CFR 71 series of both normal and accident tests (which included 9 meter drops and a JP-4 jet fuel fire) post-test helium leakage of the seal was undetectable (spectrometer capability of detection $\geq 10^{-10}$ cm^3/s). Helium detection at the time of disassembly confirmed that helium had remained in the vessel. Also, no uranium dioxide was detected external to the seal (detectable limit $\geq 10^{-8}$ g uranium). These results demonstrate that the containment vessel and its seal remained leaktight throughout the normal and accident conditions of transport per 10 CFR 71.

Following the severe test sequence of the NUREG-0360 criteria (impact, crush, puncture, slash, fire, immersion), the direct uranium surrogate detection measurement and the gas leakage measurement were both used to verify that the performance specifications were achieved. Specifically,

(a) the post-test leakage measurement across the seal indicated, through correlation with experiments involving PuO_2 powder, that a very conservative bounding magnitude on the potential for PuO_2 leakage from the TB-1 was less than 6.0×10^{-1} *mg in one week* (~ 10^{-1}x *typical* A_2 *quantity*) and (b) the uranium detection measurement confirmed that no release of surrogate contents had occurred. The observed air leakage rates are shown in Table 1.

The sealed pressure vessel was subjected to a required 4.1 MPa (600 psi) hydrostatic pressure by water for 25 hours; no leakage occurred. The helium leak rate of the vessel was $< 10^{-10}$ cm^3/s both before and after hydrostatic testing.

Results from engineering development tests and overtests

The pressure vessel was hydrostatically tested at 34.5 MPa (5,000 psi) external pressure, with no water leakage, no change in helium leaktightness ($\dot{q} < 10^{-10}$ cm^3/s), and no permanent deformations.

High internal pressure overtesting was thermally induced, with a large fraction of water inside the vessel; the seal and vessel remained leaktight up to a condition of 18 hours at 22.9 MPa (3330 psi) internal pressure at 538°C (1000°F), at which point some relaxation of the seal occurred. Upon cool-down, the vessel was leaktight. In sequential testing (the required series of impact, crush, puncture, slash, fire, immersion, with the overpack) the vessel repeatedly attained

Table I

Post-Test Sealed-Vessel Leakage Rates

Package* Impact Orientation	Air Leakage Rate (cm^3/s)**
Top End (0^o)	$< 4.5 \times 10^{-6}$
Top Corner (30^o)	$< 4.5 \times 10^{-5}$
Side (90^o)	1.4×10^{-6}
Bottom Corner (150^o)	$< 5.5 \times 10^{-6}$
Bottom End (180^o)	1.9×10^{-6}

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*Each package subjected to impact, crush, puncture, slash, fire, and submersion tests

**The measurements with a < sign include gases from redwood decomposition products (trapped in bolt holes), cleaning solution, and water vapor, all generated exterior to the containment vessel. Wide-spectrum gas spectrometer leak rate tests identified the presence of other gases, which was expected considering the combustion processes that took place adjacent to the vessel in the fire test, and indicated smaller fraction helium leaks. However, the helium-only mass spectrometer readings reported above are used as a conservative judgement of seal performance. The helium leak rates are converted to air leak rates as a standard, because the pressure vessel, in normal use, is sealed with an ambient air atmosphere, not with helium.

previously described condition of 8.6 MPa (1253 psi) internal pressure at 582°C (1080°F) without any detectable loss of uranium contents.

During development, impact testing of the package onto the side, at impact velocities in excess of 129 m/s (422 f/s) perpendicular to the unyielding target, was identified as the condition that produced the greatest containment vessel plastic deformation. In one case, an impact of 151 m/s (495 f/s) produced a noticeable out-of-round condition in the region of the seal, but with a resultant leak rate on the order of only 10^{-8} to $10^{-7} cm^3/s$. This may be compared with the leak rates measured after the entire sequential series of required tests, Table I. In the development program, it was observed that the principle influence on vessel leaktightness was the combined effect of the impact test (mechanical strain), the slash test (reduction of overpack thermal protection), and the fire test (thermal strain), and not just the impact test alone.

As another engineering evaluation, the sealed pressure vessel, without the protective overpack, was directly subjected to the 3.1×10^5N (70,000 lb) crush test, applied through a 50mm-wide steel bar, onto the lid, onto the vessel side in the region of the seal, onto the midpoint of the vessel side and onto the side near the bottom end. All strains remained in the elastic region and there was no change in vessel leaktightness.

As another engineering evaluation, the sealed pressure vessel, without the protective overpack, was directly subjected to the puncture test, on the lid and at the midpoint on the side. This test consists of a 3-m (10 ft) drop of a 227 kg (500 lb) blunt steel spike onto the vessel. The tip of the blunted steel spike is a 25.4 mm (one in.) diameter circular flat. This testing did not penetrate or rupture the pressure vessel, although an impression of the spike tip was coined into the vessel body and lid. The side test did not influence the leaktightness of the vessel; the lid test did induce a measurable helium leak rate. Since, in the complete required test series of impact, crush, puncture (this test), double slash, fire, and immersion, the protective overpack is never removed from the containment vessel, this direct puncture test was not an official requirement and was done for engineering evaluation only. No rupture occurred and there was no loss of contents.

The entire package, including the sealed containment vessel, was subjected to evaluation testing for resistance to small arms attack. Armor-piercing 30 cal. rounds (ammunition) were fired at close range, with muzzle velocities up to 853 m/s, along a centerline of the package, so as to maximize the possible penetration of the inner vessel (projectile impact perpendicular to a tangent line of the circular section of the pressure vessel side, thus reducing ricochet). Only shallow nicking or indentation occurred; there was no rupture and no change in vessel leaktightness.

A summary of containment vessel integrity is presented as Table II.

Evaluations

The pressure vessel as a constituent element of the PAT-1 package was evaluated by the following authoritative bodies: the Advisory Committee on Reactor Safeguards (ACRS); the ad hoc Committee on the Transportation of Plutonium by Air, Aeronautics and Space Engineering Board, Assembly of Engineering, National Academy of Sciences (U.S.) (8); and by the U.S. Nuclear Regulatory Commission (USNRC) (9). These bodies all concurred in the suitability and acceptability of the vessel for its intended purposes.

The USNRC endorsed the PAT-1 package to the U.S. Congress (10), as was required by law (11), and then issued a Certificate of Compliance (12) or "license" for its use.

TABLE II

SUMMARY OF CONTAINMENT VESSEL INTEGRITY

Internal Pressure, including high temperature

Maximum Credible Accident Environment: 582°C (1080°F)
(Bounding Assessment) 8.6 MPa (1253 psi)

Margin of Safety ≈ 4

Maximum normal Operating Pressure: 102°C (215°F)
0.254 MPa (34.3 psi)

Margin of Safety ≈ 306

External Pressure

Hydrostatic Requirement: 4.1 MPa (600 psi)

Margin of Safety ≈ 20

IMPACT

Survives all required impact tests, within the protective overpack, at high velocity (≥ 129 m/s), perpendicular to an unyielding target

Crush

Survives crush test without overpack

Puncture

Survives puncture test without overpack. Survives small arms gunfire within protective overpack.

CONCLUSION

It was determined that the sealed pressure vessel remains leaktight ($\dot{q} < 10^{-7} cm^3/s$) under many conditions of external threat (impact, crush, puncture, fire) and under high levels of internal and external pressure. Although severe levels of assault produce a measurable air leak (on the order of 10^{-5} to 10^{-7} cm^3/s), the seal labrynth is still intact to such a degree that particulate nuclear material $< 1\mu$ dia. does not escape ($\geq 10^{-8}$ gram detection level). Thus, all design goals were met or exceeded.

ACKNOWLEDGMENTS

Finite element stress analysis was performed by C. M. Stone; other stress analyses were done by T. A. Duffey. Metallurgical engineering was by C. H. Maak.

References

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(2) U.S. Nuclear Regulatory Commission 'Final environmental statement on the transportation of radioactive material by air and other modes', NUREG-0170 December 1977.

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(4) American National Standards Institute 'Leakage tests on packages for shipment of radioactive materials', ANSI Standard N14.15 1974 1430 Broadway New York NY 10018.

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(6) BECKER, E. B. and DUNHAM, R. S. 'TEXGAP - the Texas grain analysis program', TICOM Report 73-1 August 1973 The Texas Institute for Computational Mechanics The University of Texas at Austin.

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(8) Aeronautics and Space Engineering Board, Assembly of Engineering 'Review of criteria for packaging plutonium for transport by air', 1978 National Academy of Sciences Washington D.C.

(9) U.S. Nuclear Regulatory Commission 'Plutonium air transportable package model PAT-1 safety analysis report', NUREG-0361 June 1978.

(10) HENDRIE, J. M., letter to the U.S. Congress Concerning NUREG-0360, NUREG-0361, and the PAT-1 package, August 4 1978.

(11) U.S. Congress 'Nuclear regulatory commission appropriation authorization', Public Law 94-79, 94-1 Congress August 9 1975 Washington D.C.

(12) U.S. Nuclear Regulatory Commission 'Certificate of compliance for radioactive materials package', Certificate No. 0361, Package ID Number USA/0361/B( )F September 5 1978.

Figures

Tables

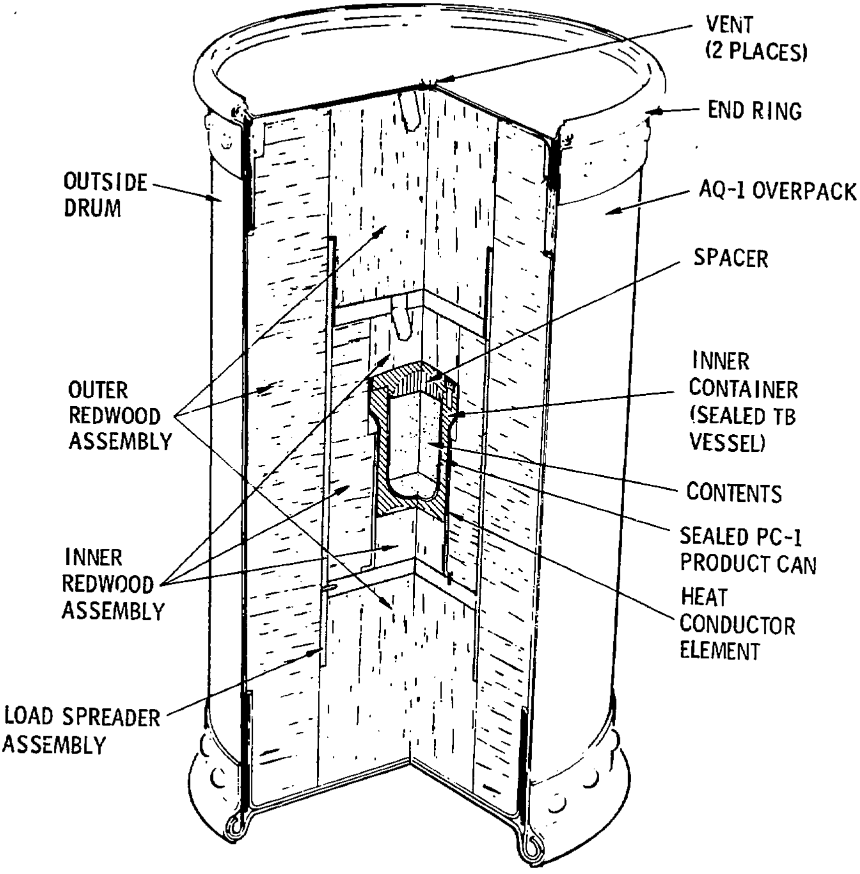

VENT (2 PLACES)
END RING
OUTSIDE DRUM
AQ-1 OVERPACK
SPACER
INNER CONTAINER (SEALED TB VESSEL)
OUTER REDWOOD ASSEMBLY
CONTENTS
SEALED PC-1 PRODUCT CAN
INNER REDWOOD ASSEMBLY
HEAT CONDUCTOR ELEMENT
LOAD SPREADER ASSEMBLY

FIG. 1

7 dy
1-4

76-0387/3152-1

80%

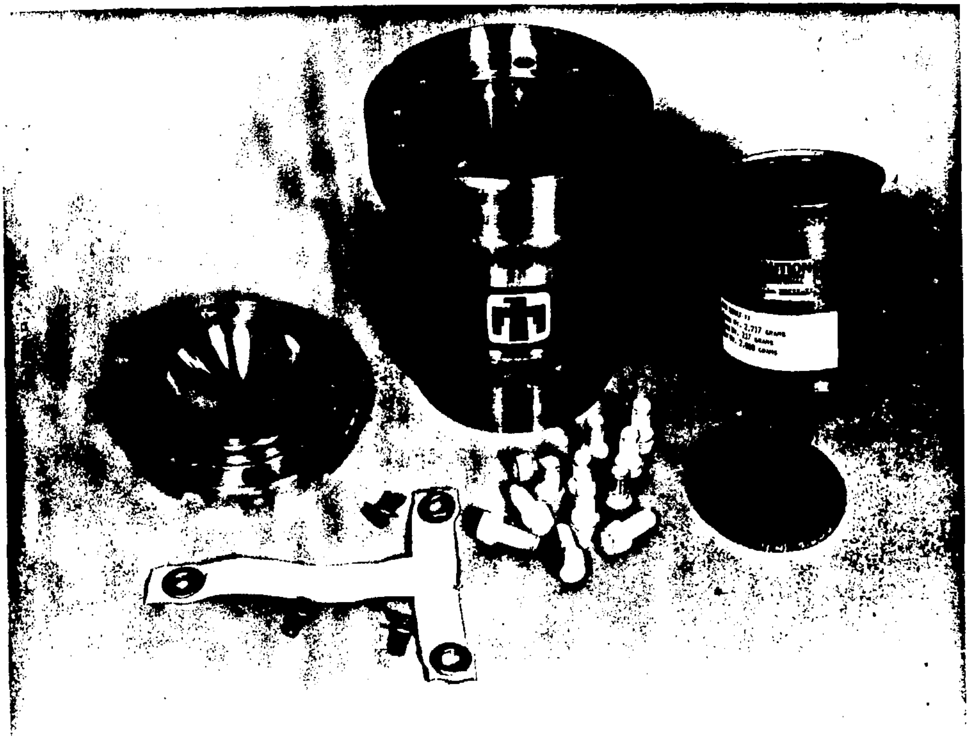
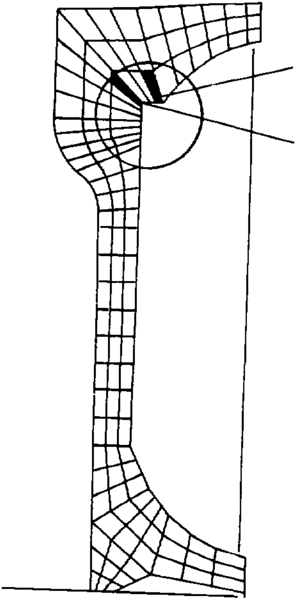


Figure [illegible] 2. TB-1 ~~Disassembled~~ Containment Vessel



σ_{MAX} = 631 PSI

σ_{MIN} =-42768 PSI

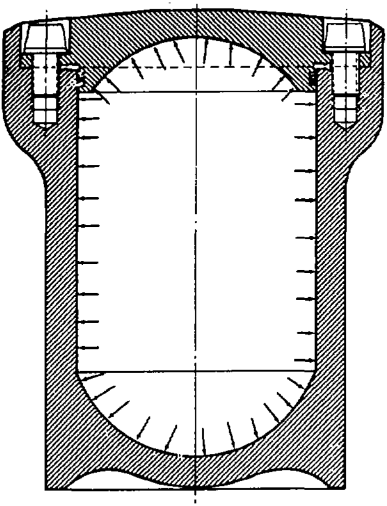
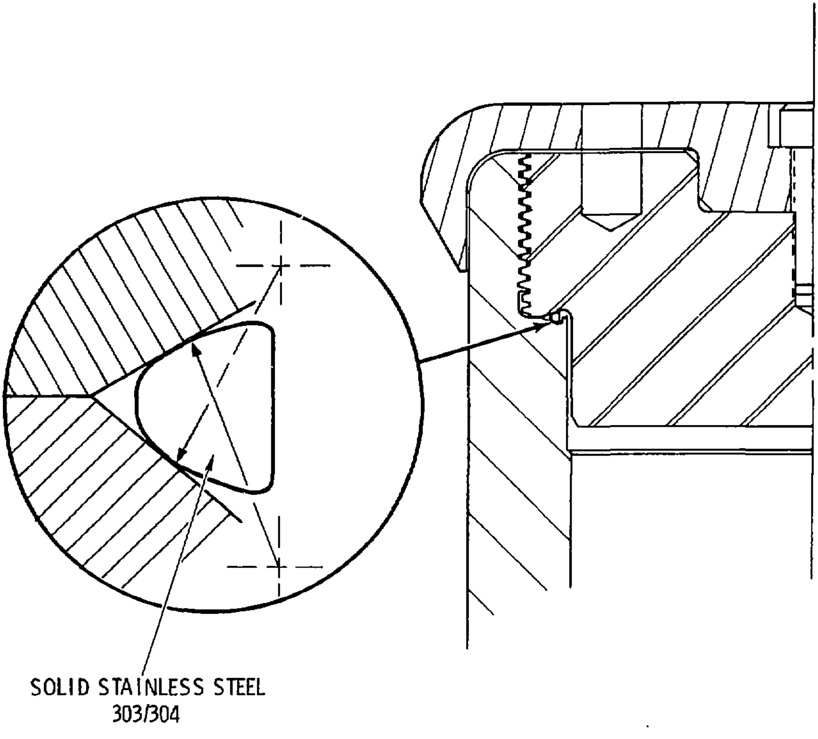
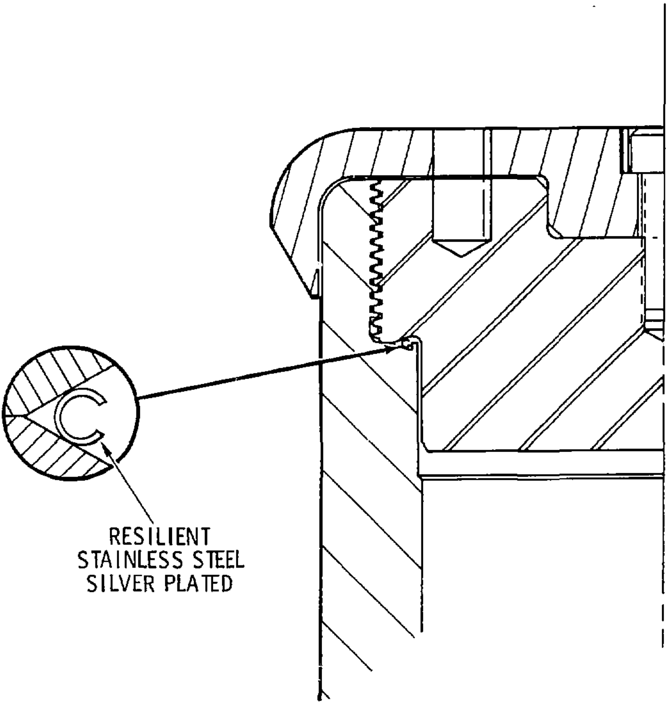
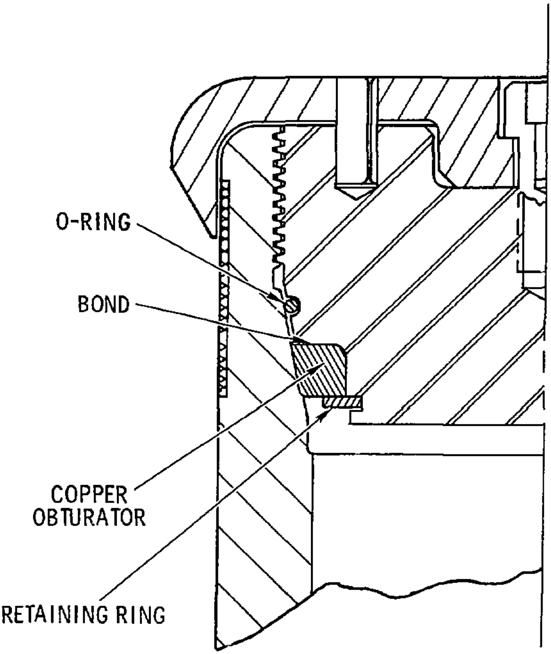


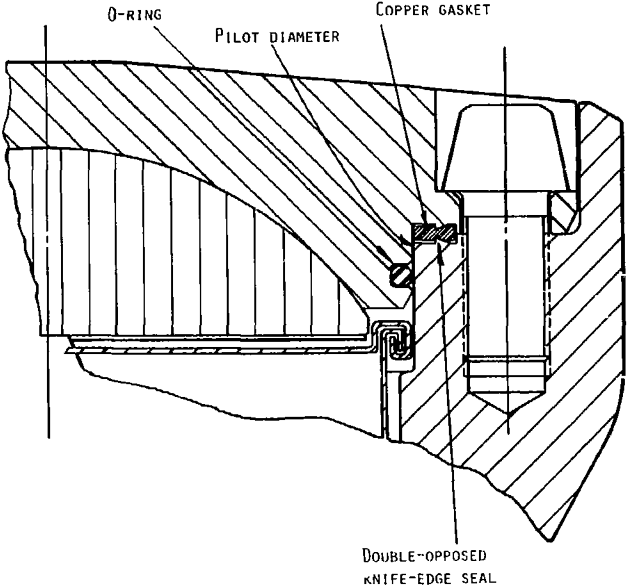
FIG. 4



SOLID STAINLESS STEEL
303/304


RESILIENT
STAINLESS STEEL
SILVER PLATED


O-RING
BOND
COPPER OBTURATOR
RETAINING RING


O-RING
PILOT DIAMETER
COPPER GASKET
DOUBLE-OPPOSED
KNIFE-EDGE SEAL