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**Safety Analysis Report for Packaging:
The ORNL Tungsten-Shielded Cask**

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SAFETY ANALYSIS REPORT FOR PACKAGING:
THE ORNL TUNGSTEN-SHIELDED CASK

J. H. Evans
D. L. Levine
R. A. Just

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OAK RIDGE NATIONAL LABORATORY
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SAFETY ANALYSIS REPORT FOR PACKAGING.
THE ORNL TUNGSTEN-SHIELDED CASK

J. H. Evans D. L. Levine R. A. Just

ABSTRACT

The ORNL tungsten-shielded cask was designed and fabricated at the Oak Ridge National Laboratory (ORNL) for the transport of Type B and large quantity nonfissile isotopes. The container was evaluated analytically to determine its compliance with the applicable regulations governing containers in which radioactive and fissile materials are transported, and that evaluation is the subject of this report. Computational methods were employed in a determination of the structural integrity and thermal behavior of the cask relative to the general standards for normal conditions of transport and to the standards for the hypothetical accident conditions. The results of these evaluations demonstrate that the container is in compliance with the applicable regulations.

0. GENERAL INFORMATION

0.1 Introduction

The ORNL tungsten-shielded cask was developed at the Oak Ridge National Laboratory (ORNL) in 1967, and 12 casks were built at the Oak Ridge Y-12 Plant. The design was analyzed in 1974 to demonstrate compliance with the regulations. The results of the analyses are presented in Sects. 1 and 2 of this report. The package was inspected to insure that it was in accordance with the drawing in Appendix A.

The primary use of the container is to provide shielding and impact and thermal resistance for its contents during transport for both normal and hypothetical accident conditions. The package is amenable to rail, highway, air, and water transport for Type B and large-quantity radioactive material shipments. It complies with the Energy Research and Development Administration (ERDA) regulations contained in the *Code of Federal Regulations*, Title 10, Part 71;¹ ERDA Manual Chapter 0529;² and all Immediate Action Directives (IAD) in effect as of this report date. The cask also complies with U.S. Department of Transportation regulations published in the *Code of Federal Regulations*, Title 49, Part 173.³

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Calculations, engineering logic, and all related documents which demonstrate compliance with specifications are presented in subsequent sections of this report. Copies of the approval documents are reproduced in Appendix B.

0.2 Package Description

0.2.1 Container description

The ORNL tungsten-shielded cask is a right circular cylinder with a hemispherical bottom. Its features are illustrated in Fig. 0.1. It has a maximum outside diameter of 16 in. at the base. The cask itself has an outside diameter of 8 in. The overall height is 15-1/4 in. The inner cavity dimensions are 3.120 in. diam by 6-1/2 in. high. The shielding of the cask is composed of isostatically pressed and sintered tungsten alloy containing 95% tungsten, 3.5% nickel, and 1.5% iron, with a 1/4-in. type 304L stainless steel cladding outside and a 1/8-in. type 304L stainless steel cladding inside. The thickness of the tungsten shielding is 2 in., which is approximately equivalent to 4 in. of lead. The as-built drawings of this cask are in Appendix A. The cask weight is 381 lb.

The device for closing the cask consists of a standard 150-lb, 4-in. slip-on welding flange as part of the cask body and a standard 150-lb, 4-in. blind flange as part of the top plug. The stepped design of the cask plug prevents radiation streaming. Securing of the closure is effected by eight 304L stainless steel 5/8-11 UNC studs. Two of these studs are drilled for seal wires.

0.2.2 Operational features

The cask is designed to be lifted and tied down by 3/4-in.-diam holes in the four gusset plates that support the cask. The gussets are welded to a 16-in.-diam base plate which provides stability to the cask. The sintered tungsten alloy shield provides some structural support to the system, but its main value is in its effectiveness as a radiation shield.

Fig. 0.1. Features of ORNL tungsten-shielded cask.

The cask is also designed for easy manipulator loading (via the top opening), transfer into and out of existing hot cells, and decontamination of all interior and exterior surfaces.

0.2.3 Contents

The cask is designed for the shipment of nonfissile radioisotopes in solid form with a total maximal internal heat load of 25 W. All radioactive material will be in special form containers. See Sect. 1.6 for description of special form containers.

1. STRUCTURAL EVALUATION

The package complies with the structural requirements of the regulations.¹⁻³ The calculations, test results, and engineering logic presented in the following sections demonstrate compliance with these performance criteria. Effects of both normal and specified accident conditions on the structural integrity of the package are considered.

1.1 Mechanical Properties of Materials

The properties of the materials used in the cask are listed in Table 1.1. Dynamic properties are not available for the tungsten alloy, but the static values provide a reasonably good approximation to dynamic conditions if care is taken to ensure that the use of static values results in a conservative evaluation. Generally, structural materials exhibit greater strength in a dynamic loading situation than for static loads. Numerous tests on materials having ultimate elongation comparable with the tungsten alloy have demonstrated this. The results reported by the author⁶ are typical of these tests.

Table 1.1. Mechanical properties of cask materials

Property	Symbol	304L stainless steel ^a	W-Fe-Ni ^b alloy
Yield stress, psi	σ_y	30,000	86,500
Ultimate tensile strength, psi	σ_u	75,000	102,400
Modulus of elasticity, psi	E	30×10^6	5.54×10^6
Elongation, %		40.	20.8
Density, lb/in. ³	ρ	0.283	0.661
Maximum allowable shear = $\sigma_y/2$, psi	τ_{max}	15,000	43,250
Coefficient of expansion, in./in.-°F		9.2×10^{-6}	9.4×10^{-6}
Ultimate shear stress, psi	τ_u	61,000	
Poisson's ratio	τ	0.3	

^aStainless steel properties taken from ref. 4.

^bW-Fe-Ni properties taken from ref. 5.

Dynamic material properties are used in the impact analyses in succeeding sections. The computer analysis and hand techniques used in this report are based on two distinctly different principles. The program used for end impact is based on experimentally determined material properties developed and reported⁶ by the author. These same dynamic material properties are also used in the puncture analysis (see Sect. 1.5.2).

Figure 1.1 illustrates the dynamic compressive stress-strain curves for 300-series stainless steel and mild steel and are reproduced from the above work. The polynomial equations of these curves are used in this analysis.

The programs used to estimate the response of the cask impacting on the corner and side are based on the assumption that the cask is constructed of ideally plastic materials. An ideally plastic material is a material which has a constant value of stress for all strains. It is recognized that normally used cask materials do not behave in this manner. However, conservative solutions can be effected if care is used in selecting the material property constant, dynamic yield stress or specific energy, and in interpreting the results. To accomplish this objective, numerical values for ideal dynamic yield stress or specific energy which bound the real stress-strain curve must be selected. The lower value will result in a calculated deformation which is greater than actual. It can be seen from Fig. 1.1 that the selected values of 70,000 psi and 230,000 psi for stainless steel will effect a conservative solution for the tungsten cask. Dynamic properties of tungsten are not used in any of the analysis, since the cask configuration is such that little if any deformation of the tungsten will result from the specified impacts.

1.2 General Standards for All Packages

General standards for all packaging cover chemical and galvanic reaction of the materials of the package, closure of the package, and lifting and tie-down devices for the package. The containers are constructed as shown in the as-built drawing of type 304L stainless steel and a sintered W-Fe-Ni alloy. These containers have been used for eight years

Fig. 1.1. Dynamic compressive stress-strain curves for stainless steel and mild steel.

to transport the contents described in Sect. 0.2.3. Visual examination shows that there has been no evidence of any significant chemical, galvanic, or other reaction between these materials, nor has there been any experience of reaction between these materials of construction and the intended package contents.

1.2.1 Closure

The cask is equipped with a positive closure consisting of eight 5/8-in.-diam studs which secure the lid and prevent inadvertent opening of the cask. Additionally, two of the studs are drilled for a wire seal to discourage tampering with the package during shipment.

1.2.2 Cask-lifting devices

If there is a system of lifting devices that is a structural part of the package, regulations require that this system be capable of supporting three times the weight of the loaded package without generating stress in any material of the package in excess of its yield strength.

The tungsten-shielded cask is designed to be lifted by holes in four gusset plates mounted symmetrically about the cask. These plates are of 1/4-in.-thick type 304L stainless steel. Since it is likely that only two of the four holes will be used for lifting, all calculations will be based on two-hole lifting. The loading configuration is shown in Fig. 1.2. The lifting cables will be within 1° of vertical due to the geometry of the system, so it is reasonable to assume that the load at each hole will be vertical and of magnitude equal to 1.5 times the cask weight.

ORNL DWG 74-8949

Fig. 1.2. Forces on cask during lifting.

The bearing stress at each hole is

$$\sigma_b = P/dt = (1.5)(381)/(3/4)(1/4) = 3050 \text{ psi} ,$$

where

P = vertical load (lb),

d = bolt diameter (3/4 in.),

t = metal thickness (1/4 in.).

This is approximately 10% of the yield stress, and thus the cask-lifting device meets the requirements of the regulation. There are no other significant stresses as a result of lifting. If the lifting device failed under excessive load the failure would be a bearing failure around the hole. A failure of this type would not result in a reduction of the shielding and containment capabilities of the cask. Failure of the lifting sling is more likely than failure of the cask-lifting device.

1.2.3 Lid-lifting device

The regulations require that if there is a system of lifting devices that is a structural part of the lid only, this system shall be capable of supporting three times the weight of the lid and any attachment without generating stress in any material of the lid in excess of its yield strength. It is further required that unless rendered useless for lifting during transport of the package, the lid-lifting or any other system of lifting devices shall conform to the requirements for the package-lifting system.

The approximate weight of the lid is 42.5 lb. The lid-lifting device consists of one eyebolt centrally located with a 3/8-in.-16 UNC-2 thread. The stress area of the bolt is 0.0775 in.² (ref. 7). If this bolt is subjected to an axial load of three times the lid weight, the stress generated will be

$$\sigma = P/A = (3)(42.5)/0.0775 = 1645 \text{ psi} .$$

This eyebolt is thus a safe lid-lifting device; however, it will be removed during transit to avoid the possibility of being used in lifting the entire cask.

Should the single eyebolt be used for lifting the entire cask, the stress in the bolt would be

$$\sigma = P/A = (3)(381)/0.0775 = 14,750 \text{ psi.}$$

Even in this eventuality the stress is less than half the yield point and therefore complies with the requirements of the regulation. If the lid-lifting device failed under excessive load, the failure would be a tensile failure of the eyebolt which would not compromise the shielding or containment capabilities of the cask.

1.2.4 Tie-down devices

If there is a system of tie-down devices that is a structural part of the package, the regulations require that this system be capable of withstanding a static force applied to the center of gravity of the package with a vertical component of two times the weight of the package and its contents, a horizontal component along the direction of travel of ten times the weight of the package and its contents, and a horizontal component in the transverse direction of five times the weight of the package and its contents. This applied force shall not generate stresses in any material of the package in excess of the yield strength of that material. It is also required that any tie-down device that is a structural part of the package shall be so designed that failure of the device under excessive load will not impair the ability of the package to meet other requirements of the regulations.

The cask could be secured to the transport vehicle, as shown in Fig. 1.3, by four tension members attached to the four lifting lugs. For the general case, the notations I, J, K, H, and L of Fig. 1.3 represent the dimensions of the tie-down system. Of these, only the value of H is fixed by the container geometry. For the 10W load, by summation of horizontal forces, $F_x = 5W$. It follows that the horizontal

ORNL DWG 75-12971

Fig. 1.3. Cask tie-down.

resultant in the direction of the tie-down member is $F_R = 5W(K/J)$. Tension in the two rear tie-down members is $T_{10} = 5W(L/J)$. For the 5W transverse load it is $T_5 = 2.5W(L/I)$. The 2W vertical load has a net resultant of W upward and is equally distributed between the four tie-down members. The tension in each member as a result of the upward load is $T_2 = (W/4)(L/H)$. The tension T in the most loaded member is

$$\begin{aligned} T_a &= T_{10} + T_5 + T_2 = 5W(L/J) + 2.5W(L/I) + (W/4)(L/H) \\ &= WL[(5/J) + (2.5/I) + (0.25/H)] . \end{aligned}$$

For the other members,

$$\begin{aligned} T_b &= WL[(5/J) + (0.25/H)] , \\ T_c &= WL(0.25/H) , \\ T_d &= WL[(2.5/I) + (0.25/H)] . \end{aligned}$$

For geometry,

$$\begin{aligned} L &= (K^2 + H^2)^{1/2} ; K = (I^2 + J^2)^{1/2} , \\ L &= (I^2 + J^2 + H^2)^{1/2} . \end{aligned}$$

Values of the dimensions I and J will vary over a considerable range in practice. The practical tie-down geometry will vary from an I to J ratio of 1:1 to 1:2. To demonstrate compliance with the regulations, we will examine the three cases shown in Table 1.2.

Table 1.2. Tie-down analysis

Case	I	J	H	L	T_a	T_b	T_c	T_d
1	1	1	1	1.73	13.42W	9.09W	0.43W	4.76W
2	4	4	1	5.74	12.21W	8.62W	1.44W	5.03W
3	4	8	1	9.00	13.5W	7.88W	2.25W	7.88W

It can be seen that variation in tension in the most loaded member varies little due to the variations in tie-down geometry. To determine if any additional forces are required to prevent tipping, the forces in the Z direction are calculated:

$$F_{za} = \frac{13.5W}{9} = 1.5W ,$$

$$F_{zb} = \frac{7.88W}{9} = 0.88W ,$$

$$F_{zc} = \frac{2.25W}{9} = 0.25W ,$$

$$F_{zd} = \frac{7.88W}{9} = 0.88W ,$$

$$F_n = \Sigma F_z - W = 2.51W .$$

Summing moments about m-m:

$$\curvearrowright + \Sigma M_{m-m} = 0 ,$$

$$F_n X = (F_{za} + F_{zb})(4.25) + (F_{zc} + F_{cd})(4.25) = 0 ,$$

$$F_n X = (F_{za} + F_{zb} - F_{zc} - F_{zd})(4.25) ,$$

$$2.51WX = (1.25)(4.25)W ,$$

$$X = 2.12 \text{ in.}$$

Summing moments about n-n:

$$\curvearrowright + \Sigma M_{n-n} = 0 ,$$

$$F_n Y + (F_{zb} - F_{za} - F_{zd} + F_{zc})(4.25) = 0 ,$$

$$F_n Y = (F_{za} + F_{zd} - F_{zb} - F_{zc})(4.25) ,$$

$$2.51WY = (1.25)(4.25) ,$$

$$Y = 2.12 \text{ in.}$$

These values show the normal force to be within the cask's skid. Therefore no additional tension forces are present to prevent tipping. The maximum force F applied to the tie-down is 13.5W or 5150 lb. This load would produce a shearing stress T in the gusset tending to shear as shown in Fig. 1.3(a) of

$$T = R/A = \frac{5150}{(1.0 + 0.75)(0.25)} = 11,800 \text{ psi} .$$

The force produces a bearing stress at the hole equal to

$$\sigma_b = P/dt = (5150)/(0.75)(0.25) = 27,200 \text{ psi} .$$

Although various tie-down geometries are possible, the most likely tie-down geometry was used in the analysis. The analysis showed that normal stresses are less than the yield point, 30,000 psi, for stainless steel; and shear stresses are less than the allowable shear stress. If under extreme load the tie-down device fails, damage will be localized to the area of the tie-down lug. This area of the container does not contribute to the function of the shipping container. Failure would not impair the containment or shielding properties of the overall package.

1.3 Standards for Type B and Large-Quantity Packaging

The structural standards for large-quantity packaging cover load resistance of the packaging and the external pressure which the package must withstand. Compliance of the ORNL tungsten-shielded cask with these requirements is discussed in the following subsections.

1.3.1 Load resistance

When regarded as a simple beam supported at its ends along any major axis, the container must be able to withstand a static load normal to and uniformly distributed along its length that is equal to five times its fully loaded weight without generating a stress in any material in the cask in excess of the yield strength of that material.

The equivalent cross section of the container used for the simple beam calculation is illustrated in Fig. 1.4.

Fig. 1.4. Simple beam-loading model.

The cross section of the container is made up of the inner and outer stainless steel shells and the tungsten alloy shield between them. The outer shell alone will be considered as constituting the beam for the purposes of the stress calculation since stress conditions within it would be more critical. For a thin shell, the moment of inertia about its center is

$$I = \pi r_m^3 t,$$

where

r_m = midwall radius,
 t = shell thickness.

Neglecting the effect of the tungsten alloy and the inner shell, the moment of inertia is

$$I = \pi t_0 r_m^3 = (\pi)(0.25)(3.9)^3 = 46.58 \text{ in.}^4 .$$

The maximum bending stress is

$$\begin{aligned} \sigma &= Mc/I = \omega L^2 r_0 / 8I = 5\omega L r_0 / 8I \\ &= (5)(381)(13.53)(3.9)/(8)(46.58) = 270 \text{ psi} , \end{aligned}$$

where

M = moment around center of mass (in.·lb),
 c = distance from the neutral axis to the extreme fiber (in.),
 ω = load per unit length (lb/in.),
 L = length (in.),
 I = moment of inertia (in.⁴).

This stress is significantly less than the yield stress of the material, and the bending stress criterion is met.

1.3.2 External pressure

Regulations require that the shipping package be adequate to ensure that the containment vessel will suffer no loss of contents if subjected to an external pressure of 25 psig.

One potential consequence of the external pressure is buckling of the outer cylindrical shell and its hemispherical end cap. The model to be considered in the buckling calculations is shown in Fig. 1.5.

The necessary expressions for calculation of the buckling stresses are given by Faupel.⁸ The critical pressure for buckling of the hemispherical end cap is

ORNL DWG 74-8953

Fig. 1.5. Pressure calculations model.

$$P_{cr} = 2Et/r_m [3(1 - \nu^2)]^{1/2} ,$$

where

E = modulus of elasticity (psi),

t = thickness (in.),

r_m = midwall radius (in.),

ν = Poisson's ratio.

$$\begin{aligned} P_{cr} &= (2)(30 \times 10^6)(0.25)/(3.9)[3(1 - 0.3^2)]^{1/2} \\ &= 2.32 \times 10^6 \text{ psi} . \end{aligned}$$

The critical pressure for buckling of the cylindrical shell is

$$\begin{aligned}
 P_{cr} &= Et^3/4r_m^3(1 - \nu^2) \\
 &= (20 \times 10^6)(0.25)^3/(4)(3.9)^3(1 - 0.3^2) \\
 &= 2100 \text{ psi} .
 \end{aligned}$$

The limiting pressure for failure of the end plate is

$$\begin{aligned}
 P_{cr} &= 4\sigma_y t_p^2/3r_i^2 \\
 &= (4)(30,000)(0.92)^2/(3)(3.9)^2 \\
 &= 2230 \text{ psi} ,
 \end{aligned}$$

where

$$\begin{aligned}
 t_p &= \text{thickness of plate (in.)}, \\
 r_i &= \text{inside radius of plate (in.)}.
 \end{aligned}$$

Since all three limiting pressures are far greater than 25 psi, the shell will withstand the pressure condition.

The silicone rubber gaskets, which are used for considerably higher pressures, would not be damaged by the 25-psig external pressure.

1.4 Compliance with Standards for Normal Conditions of Transport

Regulations for normal conditions of transport for a single package require that the effectiveness of the package will not be substantially reduced by normal conditions of transport and that there will be no release of radioactive material from the containment vessel. The contents of the container are limited such that there will be no gases or vapors in the package that could reduce the effectiveness of the packaging. There is no circulating coolant other than atmospheric air, and there is no mechanical cooling device required or provided. The shield and inner container(s) are so designed that the contents will not be vented to the atmosphere under normal conditions of transport. These normal conditions include the effects of heat, cold, pressure, free drop, and penetration.

1.4.1 Heat

The package must be able to withstand direct sunlight at an ambient temperature of 130°F in still air without any reduction in the effectiveness of the packaging. A computer program, HEATING-3,⁹ modified to evaluate phase change of materials, was used to predict the steady-state temperature distribution in the cask and its contents, which were treated as a concentrated source under the specified conditions. Results of this evaluation are presented in Sect. 2. Temperatures which would exist will not affect the containers adversely, since the materials do not suffer significant loss of physical properties at these temperatures. The continuous operating temperature limit of the silicone rubber gaskets is 450°F,¹⁰ which is above the calculated seal temperature. The calculated internal pressure (see Sect. 1.4.3) will not damage the cask.

Department of Transportation (DOT) regulations³ stipulate that the temperature of any accessible surface of the fully loaded shipping package shall not exceed 122°F with the package in the shade in still air at an ambient temperature. For this evaluation, the ambient temperature was assumed to be 100°F, and the modified HEATING-3 computer program⁹ was used to compute the maximum container surface temperature loaded with a concentrated internal heat load of 25 W. Results of this evaluation are presented in Sect. 2. The maximum calculated surface temperature is 114°F, which occurred close to the bottom of the vessel.

The possibility of large thermal stresses arising and causing damage to the casks as a result of the allowable heat loads is not very great because the stainless steel and the tungsten alloy have very similar thermal expansion coefficients.

1.4.2 Cold

The container must be able to withstand an ambient temperature of -40°F (420°R) in still air and shade. Assuming no internal heat load, the final or maximum pressure (P_2) in any cavity sealed at a pressure of 14.7 psia (P_1) and a temperature of 70°F (530°R) is

$$P_2 = P_1 T_2 / T_1 = 11.65 \text{ psig} .$$

The resulting pressure differential is not significant by comparison with the 25-psig external pressure considered in Sect. 1.3.2. A temperature of -40°F is within the operating temperature range of the materials of the container. Brittle fracture of the type-304L-stainless-steel cask cladding under the stipulated cold condition is not likely because the operating temperature is above the ductile-to-brittle transition temperature of this material.¹¹ The low-temperature properties of the tungsten alloy which forms the shielding are not known. However, a brittle failure of the shielding during normal transport at -40°F is not likely since the loads on the shielding are very low and since it is supported by the cladding.

Data published by Parker Seal Company show that the continuous temperature operating range for static sealing with silicone rubber gaskets is -135°F to 450°F . The stipulated cold condition will not reduce the effectiveness of the packaging, and the cask conforms to the requirements for the cold condition of normal transport.

1.4.3 Pressure

Regulations for normal conditions of transport specify that the package be able to withstand a reduction in atmospheric pressure to 0.5 atm (the resulting pressure being 7.35 psia) at the 130°F ambient temperature condition. If the inner housing were at atmospheric pressure at 70°F (530°R), then the final pressure at -220°F (680°R) (see Table 2.2) is

$$P_2 = (14.7)(780)/(530) = 18.86 \text{ psia} .$$

With the reduction in external pressure to 0.5 atm, the pressure differential across the stainless steel shell is $18.86 - 7.35 = 11.51$ psi. This would generate a hoop stress in the stainless steel inner shell of

$$\sigma_h = Pr/t = (11.51)(1.56)/(0.25) = 72 \text{ psi} ,$$

where r is radius. This low stress level cannot reduce the effectiveness of the packaging.

Consider the stress generated in the stainless steel cladding of the cask plug, assuming no support from the tungsten shielding. An expression from Timoshenko¹² gives the maximum stress in a uniformly loaded round flat plate with clamped edges as

$$\sigma_{\max} = 3PR^2/4t^2 ,$$

where

P = inside pressure (psi),

R = plate radius (in.),

t = plate thickness (in.).

For the 1/8-in.-thick by 3.125-in.-diam plug plate,

$$\sigma_{\max} = (3)(11.5)(1.560)^2/(4)(0.125)^2 = 1340 \text{ psi} .$$

Thus the stress generated will not compromise the integrity of the tungsten cask.

1.4.4 Vibration

Vibration encountered in transport has not reduced the integrity of this packaging in five years of transport experience. All welds are full penetration and thus should not suffer any damage from vibration. The lid, which is bolted with lock washers, will not loosen with vibration; and thus the possibility of release of contents is precluded.

1.4.5 Water spray

The container exterior is constructed of type 304L stainless steel, a highly resistant alloy which should show no visible evidence of corrosion in the water spray test. The silicone rubber gaskets are impervious to water and would allow no water to enter the cask during this test.

1.4.6 Free drop

The regulations for normal conditions of transport require that a package weighing less than 10,000 lb be capable of withstanding a free drop through a distance of 4 ft onto a flat, essentially unyielding, horizontal surface, striking the surface in a position in which maximum damage is expected to occur.

The free drop was examined analytically by means of two existing computer programs (1014 CASK and 1001 CASK listed in Appendices C and D, respectively) developed by the authors. These programs determine maximum deformation and acceleration for three different cask angular orientations with respect to the impact surface. The situations considered to be most critical included flat impact on the cask top, impact on the top corner with the center of mass directly over the corner, and impact at an angle which would put the maximum shear load on the cask closure bolts (side drop). Cask geometry constrains the angle for maximum shear on the bolts to approximately 74° with respect to the longitudinal axis of the cask (Fig. 1.6).

Fig. 1.6. Impact angles in cask corner drops.

These orientations are more severe than the other possible impact orientations of bottom, side, bottom corner, and oblique angle other than 74° for the reasons outlined below. The bottom and side of the cask are protected by the base plate and gusset structure. In the bottom, bottom corner, and side orientation the closure is not in the impact area. Oblique angles other than 74° would result in less load on the closure bolts.

Demonstration of compliance with this requirement by analytical methods is difficult because experimentally verified analytical techniques do not exist and because all the necessary material properties data are not available. Drop tests have not been performed on the cask configuration under consideration. The following analyses are presented to conservatively characterize cask response and so demonstrate compliance with the regulations. It is concluded that the cask is adequate to sustain the hypothetical conditions. A conservative analysis results from the conservative selection of material constants (see Sect. 1.1).

1.4.6.1 Impact on top. Computer program 1014 CASK calculates the response of a cask equipped with an energy absorber if the latter fails in pure compression. The eight 5/8-in. steel nuts and lock washer assemblies which protrude above the top flange comply as such an energy absorber. The simplified model of eight hexagonal extensions measuring 15/16 in. across the flats by 45/64 in. long is assumed (see ref. 13). The effect of the steel protruding above the nut is neglected.

The computer program calculations for a drop height of 48 in. predict a maximum deceleration of 1875 g's and a maximum deformation of 0.053 in. (see Fig. 1.7). Maximum compressive stress in the tungsten alloy shielding can be evaluated by considering a body having a unit cross section and length of 12.53. This is equivalent to the maximum length of the tungsten measured normal to the impact surface. The compressive stress at the base of this column is

$$\begin{aligned}\sigma &= F/A = \frac{Wa}{gA} = \frac{\rho l a}{gA} \\ &= \frac{0.661(12.53)1875}{g(1)} = 15,530 \text{ psi} ,\end{aligned}$$

where

σ = stress (psi),

F = force (lb),

a = acceleration (g's),

W = weight (lb),

A = cross sectional area (in.²),

ρ = density (lb/in.³).

Fig. 1.7. Acceleration vs deformation for end impact, 4-ft drop.

Since this is less than the yield stress for the tungsten alloy, it can be concluded that the tungsten will not crack and that shielding integrity will be maintained. The impact would be less severe than the special form free-fall test² since primary containment would be maintained. The impact would result in damage to the closure studs which would require replacement of the studs prior to additional use.

1.4.6.2 Top corner impact. A homogeneous model made of a single material having an ideal dynamic compressive stress-strain relationship is assumed in the corner impact program, 1001 CASK. The cask top corner approximates this model and will give conservative results with the proper choice of a specific energy relationship.

The corner impact program predicts a maximum deformation of 0.3028 in. for a specific energy of 70,000 in.·lb/in.³ and a maximum acceleration of 597 g's for a specific energy of 230,000 in.·lb/in.³. A discussion of the validity of this specific energy range is included in Sect. 1.1. Figures 1.8 and 1.9 show acceleration vs deformation as predicted by the computer program for stainless steel specific energies of 70,000 and 230,000 in.·lb/in.³, respectively. Under these conditions, there would be considerable permanent deformation of the lid in the vicinity of the impact. The accelerations are of less magnitude than for the top impact; hence there will be no permanent deformation of the shielding. It is concluded that containment will be maintained by comparison with the special form test sequence.² The cask closure bolts will not shear by comparison with Sect. 1.5.1.2.

1.4.7 Compression

It is required that packages weighing less than 10,000 lb be capable of withstanding a compression load of five times the container weight or 2 psi distributed uniformly across the top and bottom, whichever is greater. In this instance, five times the weight is considerably greater than 2 psi. The compressive stress generated in the stainless steel outer shell with axial loading is

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Fig. 1.8. Acceleration vs deformation for corner impact, 4-ft drop, 70,000 in.·lb/in.³

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Fig. 1.9. Acceleration vs deformation for corner impact, 4-ft drop, 230,000 in.·lb/in.³

$$\sigma_c = P/A = 5W/\pi D_o t = (5)(381)/(\pi)(8.048)(0.25) = 301 \text{ psi} .$$

This stress is small compared with the yield stress.

1.4.8 Penetration

Regulations for normal conditions of transport also stipulate that the package be capable of withstanding the impact of the hemispherical end of a vertical steel cylinder which weighs 13 lb, has a diameter of 1-1/4 in., and is dropped from a height of 40 in., normally onto the exposed surface of the package that is expected to be the most vulnerable to puncture. This test would only result in a very minor dent in the stainless steel shell and would have no effect on the function of the container.

1.5 Compliance with Standards for Hypothetical Accident Conditions

Standards for the hypothetical accident conditions stipulate that a package used for the shipment of fissile or a large quantity of radioactive material shall be so designed and constructed and its contents so limited that if it is subjected to the specified free drop, puncture, thermal, and water immersion conditions, the reduction in shielding would not be sufficient to increase the external radiation dose to more than 1000 millirem/hr at a distance of 3 ft from the outside surface of the package. No radioactive material would be released from the package except for gases containing total radioactivity not to exceed 0.1% of the total radioactivity of the contents of the package, and the contents must remain subcritical.

1.5.1 Free drop

First in the sequence of hypothetical accident conditions to which the package must be subjected is a free drop through a distance of 30 ft onto a flat, essentially unyielding, horizontal surface, striking that surface in a position for which the maximum damage is expected to occur.

Demonstration of compliance with this requirement by analytical methods is difficult because experimentally verified analytical techniques do not exist and because all the necessary material properties data are not available. Drop tests have not been performed on the cask configuration under consideration. The following analyses are presented to conservatively characterize cask response and so demonstrate compliance with the regulations. It is concluded that the cask is adequate to sustain the hypothetical conditions.

Existing ORNL computer programs (1014 CASK and 1001 CASK listed in Appendices C and D, respectively) were used with appropriate modifications for end-impact and corner-impact analyses, respectively.

1.5.1.1 End impact. The end-impact program (1014 CASK, previously discussed in Sect. 1.4.6.1) calculations for a drop height of 30 ft predicts a maximum deceleration of 3360 g's and a maximum deformation of 0.176 in. Figure 1.10 shows acceleration vs deformation for the 30-ft drop, end impact. The majority of the cask's kinetic energy would be dissipated in plastic deformation of the studs and nuts. This conclusion is based on comparison of the cross sections of studs and nuts protruding above the flange with cross sections at other locations on the cask. The calculated deformation of 0.176 in. is a fraction of the length available of 0.703 in.

The maximum stress in the tungsten alloy shielding can be calculated using the equation

$$\sigma = \frac{pla}{gA} = \frac{(0.661)(12.58)3360}{g(1)}$$

$$= 27,940 \text{ psi}$$

from Sect. 1.4.6.1. Since the calculated stress is less than the yield stress (see Sect. 1.1), it is concluded that there will be no failure or permanent deformation of the shielding.

The calculated acceleration would not be as severe as in the special form test sequence. Hence it is concluded that the special form encapsulation would not be breached and containment would be maintained. The impact would not impair the heat transfer capabilities of the cask.

Fig. 1.10. Acceleration vs deformation for end impact, 30-ft drop.

1.5.1.2 Top corner impact. In the 30-ft drop case, the corner-impact program (1001 CASK) predicts a maximum deformation of 0.69 in. for a specific energy of 70,000 in.-lb/in.³ and a maximum acceleration of 2050 g's for a specific energy of 230,000 in.-lb/in.³ Figures 1.11, 1.12, and 1.13 show acceleration vs deformation for this drop as predicted by the program for stainless steel specific energies of 70,000 and 230,000 in.-lb/in.³, respectively. There would be no chance of removal of the cask lid at impact. The integrity of the closure and of the welds would be maintained.

This force acts along line 2 in Fig. 1.6. The component of the force F which acts perpendicular to the closure studs is given by

$$F_s = F \cos(90^\circ - 74^\circ) = 332,600 \text{ lb} .$$

This shearing force must be resisted by the closure in the event of a 30-ft drop on the cask side.

For the purposes of design calculations, an ultimate shear stress on the closure material can be taken as 61,000 psi.⁸ Based on this design stress, the area necessary to resist the shear load F_s must be greater than

$$A_g = 332,600/61,000 = 5.45 \text{ in.}^2 .$$

The load bearing area of the closure studs is

$$A_g = (8)(\pi)(r^2) = (8)(\pi)(5/16)^2 = 2.454 \text{ in.}^2 .$$

A shear ring is welded to the plug flange as shown in Fig. 1.14. This retaining ring has an effective shear area A_g (which is half the total area) of

$$A_g = \pi(4.875^2 - 4.5^2)/2 = 5.52 \text{ in.}^2 .$$

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Fig. 1.11. Acceleration vs deformation for corner impact, 30-ft drop, 70,000 in.·lb/in.³

Fig. 1.12. Acceleration vs deformation for corner impact, 30-ft drop, 230,000 in. $\cdot$ lb/in.³

Fig. 1.13. Acceleration vs absorbed energy, top corner, 30-ft drop.

Fig. 1.14. Cask closure.

The weld sealing the plug cladding to the top flange has a shear area A_s of

$$A_s = 2\pi r t = 2\pi(2.125)(0.125) = 1.67 \text{ in.}^2 .$$

Thus, it can withstand the shear forces which would exist in this condition. Also, since this is the most severe condition of load on the cask head, an ability to withstand it means that the cask will survive all other impact conditions with no possibility of release of contents.

1.5.2 Puncture

The second in the sequence of hypothetical accident conditions to which the cask must be subjected is a free drop through a distance of 40 in. to strike, in a position in which maximum damage is expected, the top end of a vertical mild steel bar mounted on an essentially unyielding horizontal surface. The mild steel bar shall have a diameter of 6 in. with the top horizontal and its edge rounded to a radius of not more than 1/4 in., and the bar shall be of such length that it will cause maximum damage to the cask but shall be not less than 8 in. long. The long axis of this bar shall be normal to the surface of the cask upon impact.

To analyze the puncture accident, a rather conservative model can be used which considers that all the energy absorbed by the cask is absorbed only by the outer stainless steel shell, with no consideration given to the sintered tungsten-alloy shield.

The energy of impact will be absorbed by the 6-in.-diam mild steel bar and the 1/4-in.-thick cask outer shell. Figure 1.15 illustrates the configuration for this computation model.

Fig. 1.15. Model for puncture analysis.

The absorbed energy $U = Wh = (381)(40) = 15,240 \text{ in.}\cdot\text{lb}$, and

$$\begin{aligned}
 U = Wh = U_{SS} + U_{MS} &= \int_0^{\Delta_{SS}} F_{SS} d\delta = \int_0^{\Delta_{MS}} F_{MS} d\delta = \int_0^{\Delta_{SS}} \sigma_{SS} A_{SS} d\delta_{SS} \\
 &+ \int_0^{\Delta_{MS}} \sigma_{MS} A_{MS} d\delta_{MS} ,
 \end{aligned} \tag{1}$$

where

- U = energy (in. $\cdot$ lb),
- W = weight of cask (lb),
- h = drop height (in.),
- F = force (lb),
- Δ = deformation (in.),
- $d\delta$ = incremental deflection,
- σ = stress (psi),

A = undeformed cross-section area of member (in.²),

ϵ = strain (in./in.),

L = undeformed length of member (in.),

SS = subscript for stainless steel,

MS = subscript for mild steel.

It is known that stress is a function of strain, i.e.,

$$\sigma = f(\epsilon) ,$$

$$\epsilon = \frac{\delta}{L} .$$

Then Eq. (1) becomes

$$U = \int \sigma A(\epsilon_{SS} L_{SS}) . \quad (2)$$

For plastic deformation of stainless steel and mild steel, simple stress-strain relations can be written as⁶

$$\sigma_{SS} = (6.42 \times 10^5) \epsilon_{SS} + 50,300 \quad (3)$$

and

$$\sigma_{MS} = (3.45 \times 10^5) \epsilon_{MS} + 73,000 . \quad (4)$$

Substituting these relationships into Eq. (1),

$$U = \int_0^{A_{SS}} \left[(6.42 \times 10^5) \frac{\delta_{SS}}{L_{SS}} + 50,300 \right] A_{SS} d\delta_{SS} \\ + \int_0^{A_{MS}} \left[(3.45 \times 10^5) \frac{\delta_{MS}}{L_{MS}} + 73,000 \right] A_{MS} d\delta_{SS} .$$

Note that the area of stainless steel cladding involved is the same as the area of the piston. The length of the stainless steel involved is the thickness of the cladding, 1/4 in. Rearranging terms and integrating,

$$\frac{U}{A} = \frac{6.42 \times 10^5 \Delta_{SS}^2}{2(.25)} + 50,300 \Delta_{SS} + \frac{3.45 \times 10^5 \Delta_{MS}^2}{2(8.0)} + 73,000 \Delta_{MS} ,$$

$$\frac{U}{A} = 1.28 \times 10^6 \Delta_{SS}^2 + 50,300 \Delta_{SS} + 2.16 \times 10^4 \Delta_{MS}^2 + 73,000 \Delta_{MS} .$$

From basic statics, F_{SS} is equal to F_{MS} ; then

$$\sigma_{SS} A_{SS} = \sigma_{MS} A_{MS} ,$$

$$\text{but } A_{SS} = A_{MS} ;$$

$$\text{therefore, } \sigma_{SS} = \sigma_{MS}$$

and

$$6.42 \times 10^5 \frac{\Delta_{SS}}{L_{SS}} + 50,300 = 3.45 \times 10^5 \frac{\Delta_{MS}}{L_{MS}} + 73,000 ,$$

$$\Delta_{SS} = 0.537 \frac{\Delta_{SS}}{8.0} (.25) + .03536(.25) ,$$

$$\Delta_{SS} = 0.0168 \Delta_{MS} + .00884 .$$

Substituting back into the equation for absorbed energy,

$$\begin{aligned} \frac{U}{A} &= 1.28 \times 10^6 (0.0168 \Delta_{MS} + .00884)^2 + 50,300 (0.0168 \Delta_{MS} + .00884) \\ &\quad + 2.16 \times 10^4 \Delta_{MS}^2 + 73,000 \Delta_{MS} . \end{aligned}$$

Simplifying this equation and solving using the quadratic formula,

$$\Delta_{MS} = 7.48 \times 10^{-5} ;$$

therefore,

$$\Delta_{SS} = 8.84 \times 10^{-3} .$$

Substituting these values back into Eqs. (3) and (4) yields

$$\sigma = 73,000 .$$

From Newton's second law, the peak acceleration is

$$a_{\max} = F/m = Fg/W = \sigma Ag/W = (73,000)(\pi)(3)^2(g)/(381) \\ = 5417 \text{ g} .$$

This acceleration is greater than that associated with the end impact resulting from the 30-ft free drop discussed in Sect. 1.5.1.1. Using the equation from Sect. 1.4.6.1, we find the stress.

$$\sigma = \frac{pla}{gA} = \frac{0.661(12.58)5388 \text{ g}}{g(1)} = 44,800 \text{ psi}.$$

Since this is less than the yield stress for the tungsten alloy, it is concluded that shielding will not be permanently deformed.

The stainless steel outer shell will deform plastically; however, because of the support from the tungsten alloy, it would not rupture. As before, the calculated acceleration is less than that which would result from the special form tests. Based on this fact, it is concluded that the special form encapsulation will be intact and that containment of the material will be maintained.

1.6 Special Form

The ORNL Radioisotopes Department of Operations Division certifies that a material conforms to the special form requirements of MC-0529, Annex 4.² The tests prescribed have been performed on a number of capsule designs. When a design is similar in size, mass-wall thicknesses, materials, weld design, etc., to a capsule previously tested, the design is certified as special form based on previous test results. If this similarity does not exist, it is required that a prototype be tested as prescribed. Typical examples of special form capsules are illustrated in Figs. 1.16 and 1.17.

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Fig. 1.16. Example of special form capsule.

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Fig. 1.17. Typical example of special form capsule.

2. THERMAL EVALUATION

2.1 Discussion

The package must be able to withstand direct sunlight at an ambient temperature of 130°F in still air without reducing the effectiveness of the packaging. The DOT regulations³ also stipulate that the temperature of any accessible surface of the fully loaded shipping package shall not exceed 122°F when the package is in the shade in still air at an ambient temperature of 100°F.

The third in the sequence of hypothetical accident conditions specified by the regulations to which the cask must be subjected is exposure for 30 min within a source of radiant heat having a temperature of 1475°F and an emissivity coefficient of 0.9 or equivalent. For calculational purposes, it shall be assumed that the package has an absorption coefficient of 0.8. The package shall not be cooled artificially until after the 30-min test period has expired and the temperature at the center of the package has begun to fall. A computer program, HEATING 3,⁹ modified to evaluate phase change of materials, was used to determine the temperature distribution, quantity, and location of material which had undergone a change of phase when exposed to these thermal environments.

It was assumed that the container was loaded with the maximum permissible decay heat load of 25 W. The temperature distribution resulting from a steady-state analysis under a 100°F ambient condition was input as starting temperatures for the accident (fire) calculation.

2.2 Thermal Properties of Materials

The thermal properties of materials used to compute the temperature distribution and material phase change are listed in Table 2.1.

2.3 Thermal Evaluation for Normal Conditions of Transport

2.3.1 Thermal model

The computational model representing the tungsten-shielded cask is illustrated in Fig. 2.1. The contents are modeled as a homogeneous cylinder, with the decay heat generation uniformly distributed. This body is

Table 2.1. Material properties used in thermal analysis

Temperature (°F)	Thermal conductivity (Btu/hr·ft·°F)	Density (lb/in. ³)	Heat capacity (Btu/lb·°F)
Type 304L stainless steel ^a			
32.0	8.5	0.2824	0.12
260.3	9.8		
440.3	10.6		
620.3	11.4		
752.0			
800.3	12.2		0.135
980.3	13.0		
1160.0	13.8		
Tungsten ^b			
50.0	39.53	0.6568	0.0341
100.0	43.53		0.0344
200.0	45.00		0.0349
300.0	46.08		0.0355
400.0	46.94		0.0360
500.0	47.74		0.0365
600.0	48.38		0.0371
700.0	48.96		0.0376
800.0	49.54		0.0381
900.0	50.04		0.0386
1000.0	50.41		0.0392
1100.0	50.83		0.0397
1200.0	51.12		0.0402
1300.0	51.48		0.0408
1400.0	51.70		0.0413
1500.0	51.98		0.0418
Air ^c			
32.0	0.014	4.69 x 10 ⁻⁵	0.240
100.0	0.015	4.11 x 10 ⁻⁵	0.240
200.0	0.017	3.47 x 10 ⁻⁵	0.241
300.0	0.019	3.01 x 10 ⁻⁵	0.243
400.0	0.021	2.66 x 10 ⁻⁵	0.245
500.0	0.023	2.38 x 10 ⁻⁵	0.247
600.0	0.025	2.16 x 10 ⁻⁵	0.250
700.0	0.027	1.97 x 10 ⁻⁵	0.253
800.0	0.029	1.82 x 10 ⁻⁵	0.256
900.0	0.030	1.68 x 10 ⁻⁵	0.259
1000.0	0.032	1.57 x 10 ⁻⁵	0.262
1500.0	0.040	1.17 x 10 ⁻⁵	0.276

^aType 304L stainless steel properties are taken from refs. 14, 15, and 16.

^bTungsten properties are taken from ref. 17.

^cAir properties are taken from ref. 18.

Fig. 2.1. Heat map for tungsten-shielded cask.

separated from the inner wall of the container by an air gap as shown. The gussets were treated as fins.

$$\begin{aligned} A_{\text{fin}} &= 0.476(12.281) + (1/2)(3.976 - 0.476)(12.281) \\ &= 27.34 \text{ in.}^2 \text{ (see Fig. 2.2).} \end{aligned}$$

The significant length L' required to calculate the convective heat transfer coefficient for the fin is determined from the average height of the fin as follows:

$$\begin{aligned} L' &= \frac{A_1 L + A_2 (L/2)}{A_1 + A_2}, \\ &= \frac{0.476(12.281)(12.281) + (1/2)(3.976 - 0.476)(12.281)(12.281)}{0.476(12.281) + (1/2)(3.976 - 0.476)(12.281)} \\ &= 7.45 \text{ in.} \end{aligned}$$

From McAdams¹⁹ for a vertical plane,

$$h = 0.29 (\Delta T / L_{\text{ft}})^{0.25} \text{ Btu/hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}.$$

Assuming $\Delta T = 22^\circ\text{F}$ and $L_{\text{ft}} = 7.45 \text{ in.} = 0.6211 \text{ ft.}$

$$\begin{aligned} h &= 0.29 (22/0.6211)^{0.25} = 0.7075 \text{ Btu/hr} \cdot \text{ft}^2 \cdot ^\circ\text{F} \\ &= 8.19 \times 10^{-5} \text{ Btu/min} \cdot \text{in.}^2 \cdot ^\circ\text{F}. \end{aligned}$$

Using L' and the fin thickness ($t = 0.25 \text{ in.}$) to calculate the perimeter P ,

$$\begin{aligned} P &= 2L' + 2t = 2(7.45) + 2(0.25) \\ &= 15.40 \text{ in.} \end{aligned}$$

Also, the fin cross-sectional area, A_c , can be calculated from

$$\begin{aligned} A_c &= L't = 7.45(0.25) \\ &= 1.86 \text{ in.} \end{aligned}$$

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Fig. 2.2. Fin model.

In the calculation of the fin effectiveness, it was assumed that the effect of the gussets could be modeled as an enhancement of the heat transfer coefficients of the outer surface with the gussets replaced by rectangular fins. In other words, the heat transfer coefficients for the outer surface are multiplied by the calculated enhancement factor (see below) to give a larger effective heat transfer coefficient.

$$\eta = \tanh(mL)/mL ,$$

where

η = fin efficiency,

$$m = (hP/kA_c)^{1/2} \text{ (see ref. 20),}$$

where

h = convective heat transfer coefficient

$$= 8.23 \times 10^{-5} \text{ Btu/min}\cdot\text{in.}^2\cdot^\circ\text{F},$$

P = length of perimeter = 15.104 in.,

k = thermal conductivity of fin's material

$$= 0.01 \text{ Btu/min}\cdot\text{in.}^2\cdot^\circ\text{F},$$

$$A_c = \text{fin's cross-sectional area} = 1.86 \text{ in.}^2;$$

$$m = [(8.23 \times 10^{-5})(15.104)/(0.01)(1.825)]^{1/2} = 0.261,$$

$$L = \text{mean conductive length} = 2.226 \text{ in.}$$

$$\eta = \tanh(0.5805)/0.5805 = 0.90 .$$

$$\text{Enhancement} = (A_s + \eta A_f)/A_s ,$$

where

$$A_s = \text{surface area of the outer surface} = 304.19 \text{ in.}^2,$$

$$A_f = \text{surface area of four fins} = 214.25 \text{ in.}^2.$$

$$\text{Enhancement} = [(304.19) + (0.90)(214.25)]/304.19 = 1.634 .$$

After a solution for the above model was attained, the volume of the heat generating region was reduced to a 1-in.-long cylinder so that the effect of concentrating the heat generation at the bottom of the cask could be determined.

In calculating the steady-state temperatures for the 130°F environment in direct sunlight, it was assumed that a solar heat flux of 144 Btu/hr·ft² was incident upon the cask. This is based on information from *Cask Designer's Guide*.²¹ The fraction of the incident solar flux that is absorbed by the cask is equal to the absorptivity of the cask, estimated to be 0.6. Based upon an absorptivity of 0.6 and an actual total top and side area of the cask, the solar heat flux into the cask is 86.4 Btu/hr·ft². It was assumed that this heat flux would be uniformly applied over the actual area of the top and the sides of the cask. The bottom of the cask is hidden from the sun in normal transport.

2.3.2 Maximum temperatures

The maximum temperatures for both models are presented in Table 2.2 for the 100°F-in-the-shade environment. The temperatures for the system represented in Fig. 2.1 for the environment of 130°F in direct sunlight are also shown.

Table 2.2. Cask temperatures in normal transport

Location	<u>Maximum temperature (°F)</u>	
	130°F air in sunlight	100°F air in shade
Contents at centerline	264	204
Inner cavity at midpoint	177	113
Inner cavity at bottom on centerline	180	116
Midpoint of region 18	177	113
Mid elevation on outer surface	177	113
Bottom of region 24 at centerline	179	115
Top of cask at centerline	177	112
Upper gasket	176	112
Midpoint of region 4	176	112
Lower gasket	176	113
Cavity air temperature	220	159

2.3.3 Thermal stress

There are no thermal gradients sufficient to cause significant thermal stresses in metallic members.

2.4 Hypothetical Thermal Accident Evaluation

The damage from the free drop and puncture portions of the hypothetical accident would not adversely affect the performance of the container in the hypothetical thermal accident. Hence the undamaged configuration was assumed.

2.4.1 Thermal accident analysis

The computational model used in the steady-state analysis (Sect. 2.3.1) was also used for the thermal analysis under accident conditions. The modified HEATING-3 computer program⁹ was used to determine the temperature distribution in the cask that would result from the prescribed 30-min thermal exposure, and the material constants given in Table 2.1 were used as computer input. The steady-state temperature distribution computed for the heat condition of normal transport was taken as the starting point, and internal heat generation was included in the transient analysis.

At the conclusion of the calculations, the temperature of the contents was dropping at the rate of 15.3°F/min. The maximum temperature of the contents was less than the test temperature (1475°F) specified for special form material. Therefore, the actual thermal environment is less severe than that specified for special form material. The cladding would not fail and primary containment would be maintained. The cask gasket temperature was calculated to be greater than 1350°F, and thus it was concluded that the gasket would not survive the thermal exposure and secondary containment would be lost.

The maximum air temperature in the shielding cavity was used in evaluation for structural integrity due to internal pressure condition. In the fire, the air in the cavity will reach 1400°F (see Fig. 2.3). The resulting pressure P_2 is calculated by the ideal gas laws:

$$P_2 = (14.7)(1400 + 460)/(530) = 51.6 \text{ psia} = 36.9 \text{ psig} .$$

Hoop stress in the outer cylindrical shell is

$$\sigma_n = Pr/t = (36.9)(3.75)/(0.250) = 553 \text{ psi} .$$

The stress in the lower plate of the cask plug is calculated using the equation in Sect. 1.4.3 from Timoshenko¹²:

$$\sigma_{\max} = 3Pr^2/4t^2 = (3)(36.9)(1.560)^2/4(0.125)^2 = 4310 \text{ psi} .$$

The stress in the closure studs is

$$\sigma = P\pi r_g^2/N_s A_s = 36.9\pi(1.9)^2/(8)(0.226) = 231 \text{ psi} ,$$

where

r_g = mean gasket radius (in.),

N_s = number of studs,

A_s = stress area of one stud (in.²) (see ref. 13).

In the above analysis of the closure studs, it is assumed that the gaskets had not failed. This assumption results in a conservative analysis since the gaskets would leak at a lower temperature.

TUNGSTEN SHIPPING CASK

ORNL DWG 74-6946

Fig. 2.3. Temperature vs time profiles for the fire test.

These stresses are less than the yield stress of stainless steel at the maximum cask temperature of 1475°F, which is ~12,000 psi.¹³ It is therefore concluded that the cask will not fail due to pressurization; hence, shielding will be maintained.

2.4.2 Cask temperatures

The temperature distribution within the container with respect to time is illustrated in Fig. 2.3. It is noted that at the end of the fire test the lowest temperature in the container was about 1350°F, while the

highest temperature was about 1470°F. Under the fire test condition, the tungsten cask will maintain its shape, shielding capability, and structural integrity; however, the silicon gaskets would not survive the 1470°F temperature extreme, and thus containment of gases from the cask's central cavity would not be maintained. The gases will not be contaminated since the special form containers within the cask used for all shipments are designed to withstand these temperature extremes; thus no release of package contents in a fire is expected under the imposed accident fire conditions.

3. CONTAINMENT

The tungsten-shielded cask constitutes the secondary line of containment in the system, while primary containment may be one of various encapsulations classified as special form.

Adequacy of primary containment for both normal and accident conditions is demonstrated by special form tests and requirements. Adequacy of secondary containment for normal condition temperatures and pressures is discussed in Sect. 1.4. Adequacy of containment under accident conditions is discussed in Sect. 2.

The lines of containment can be routinely inspected for leaks by means of a mass spectrometer or vacuum-leak detection technique.

4. SHIELDING

The shielding¹⁷ is made of 2-in.-thick tungsten alloy, the equivalent of 4 in. of lead shielding. The alloy is composed of approximately 95.29% tungsten, 3.16% nickel, and 1.45% iron and is produced by liquid-phase sintering of metal powders which have been blended in the right proportions and isostatically pressed at 30,000 psi. Because the alloy is sintered, there are numerous voids of 0.010 in. diam which may give some slight internal density variations; however, typical densities are better than 99% of the theoretical values.

The shielding effectiveness of the cask was tested by loading it with 17 sealed sources containing a total of 250 Ci of ⁹⁰SrTiO₃. Radiation readings of 110 mR/hr were obtained at the cask surface. Cask contents will be limited to the loading that will not exceed the allowable radiation dose limitations of the DOT regulations.³

The shielding effectiveness would not be reduced by the hypothetical 30-ft drop accident. The sintered tungsten alloy fractures in an intergranular manner, providing a labyrinthine pathway for radiation and allowing no possibility of radiation streaming.

5. CRITICALITY

Since no fissile materials are to be transported, a criticality evaluation is not necessary for this container.

6. QUALITY ASSURANCE

6.1 Fabrication, Inspection, and Acceptance Tests

The majority of the fabrication work on these containers was performed prior to the requirements for a formal quality assurance program. The fabrication was performed in 1967 at the Y-12 Plant shops in accordance with normal shop fabrication procedures. The material specified on the original drawings was type 304L stainless steel. The material used conforms to the requirements of ASTM specifications, since Y-12 stores stock is purchased by these specifications. These specifications are listed in note II of ORNL drawing M-11575 EM 001, which is included in Appendix A.

The existing containers were inspected by ORNL Inspection Engineering Department personnel for conformance to the as-built drawings and quality of workmanship. In the opinion of the inspecting personnel, the containers were in accordance with the drawings.

For casks to be made in the future, all welds will be made in accordance with the specified WPS specifications and inspected as specified. Required leak tests will be performed to verify the integrity and leak tightness of the cask. Dimensional inspections of the completed container will be performed. Weld and dimensional inspection reports and leak test reports will be prepared. Manufacturer's material certification will be provided.

6.2 Operating Procedures and Inspection

The ORNL Operations Division has established routine operating and inspection procedures and standard checklists to ensure that all shipments

are safe and comply with all ERDA and ORNL regulations. A copy of the routine packaging and inspection procedures are presented in Appendix E.

6.3 Periodic Maintenance and Inspection

The design of the container is such that there are no periodic inspections required in addition to those outlined in Appendix E. Maintenance will be required only when routine inspections indicate damage. There are no time-degradable materials used in the construction of the containers.

REFERENCES

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Appendix A

AS-BUILT DRAWINGS

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Fig. A.2. As-built drawing of the open, two-station-shielded tank.

Appendix B

APPROVAL DOCUMENTS

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INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

November 20, 1974

TC 74-12

To: J. H. Evans, R. W. Schaich

From: Transportation Committee

Subject: Approval of SARP for the ORNL Tungsten Shielded Cask

The ORNL Transportation Committee has reviewed your submission of the subject SARP to fulfill the requirements (internal review) of paragraph B of AEC Immediate Action Directive 5201-3. Particular attention was given the five areas of structural integrity, thermal resistance, radiation shielding, nuclear criticality safety, and quality assurance.

The results of the evaluation show that the container meets the requirements of AECM 0529 and the SARP is approved for submission to the AEC for request of a Certificate of Compliance for approval of the cask for use for offsite shipments of fissile and radioactive materials.

E. M. King

E. M. King, Chairman
Transportation Committee

EMK:bb

cc: Transportation Committee

Form AEC-418
(12-73)
10 CFR 71
AECM3281

U.S. ATOMIC ENERGY COMMISSION
CERTIFICATE OF COMPLIANCE
For Radioactive Materials Packages

1a. Certificate Number	1b. Revision No.	1c. Package Identification No.	1d. Page No.	1e. Total No. Pages
USA/5597/BL(ERDA-3B)	1	USA/5597/BL(ERDA-3B)	1	2

2. PREAMBLE

- 2a. This certificate is issued to satisfy Sections 173.393, 173.394, 173.395, and 173.396 of the Department of Transportation Hazardous Materials Regulations (43 CFR 170-189 and 14 CFR 103) and Sections 146-19-10a and 146-19-100 of the Department of Transportation Dangerous Goods Regulations (16 CFR 146-149), as amended.
- 2b. The packaging and contents described in item 5 below, meets the safety standards set forth in Subpart C of Title 10, Code of Federal Regulations, Part 71, "Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions."
- 2c. This certificate does not relieve the consignor from compliance with any requirement of the regulations of the U.S. Department of Transportation or other applicable regulatory agencies, including the government of any country through or into which the package will be transported.

3. This certificate is issued on the basis of a safety analysis report of the package design or application.

(1) Prepared by (Name and address):

Oak Ridge National Laboratory
Post Office Box 2
Oak Ridge, Tennessee 37830

(2) Title and identification of report or application:

Safety Analysis for the 100L
Tungsten-Shielded Cask, Report
No. ORNL/ENG/TM-3

(3) Date:

October 1977

4. CONDITIONS

This certificate is conditional upon the fulfilling of the requirements of Subpart D of 10 CFR 71, as applicable, and the conditions specified in item 5 below.

5. Description of Packaging and Authorized Contents, Model Number, Fissile Class, Other Conditions, and References

a. Packaging

- (1) Model: Tungsten Shielded Cask
(2) Description:

The packaging consists of a right circular cylinder with a hemispherical bottom. It has a maximum outside diameter of 16-in. at the base. The cask itself has an outside diameter of 8-in. The overall height is 15-1/4 in. Inner cavity dimensions are 3.125-in. diam. by 6-1/2-in. high. Shielding is composed of 1/2" thickness of isostatically pressed and sintered tungsten alloy containing 95% tungsten, 3.5% nickel, and 1.5% iron, with a 1/4-in. type 304L stainless steel cladding outside and a 1/8-in. type 304L stainless steel cladding inside. The gasket lid consists of a 150-lb. flange to which the top shield plug is attached and is held in place by eight 5/8-in. studs and bolts.

(3) Drawings:

The packaging is as described and fabricated in accordance with Oak Ridge National Laboratory Drawings No. M-11575-EM-001-B-Rev. 1 and No. C-EM-2495.

b. Contents

- (1) Type and form of material:

(cont'd next page)

6a. Date of Issuance	APR 18 1977	6b. Expiration Date	
FOR THE U.S. ATOMIC ENERGY COMMISSION			
7a. Address of AEC Issuing Office:	7b. Signature, Name, and Title of AEC Approving Official:		
U. S. Energy Research & Development Adm. Post Office Box E Oak Ridge, Tennessee 37830 Oa	William E. Travis, Director Safety and Environmental Control Div.		

USA/5597/BL(ERDA-OR)

Non-fissile radioactive materials as solid and in special form.

- (2) Maximum quantity of material per package may be a large quantity and not to exceed 25 watts of thermal decay energy.

Appendix C

LISTING OF END-IMPACT PROGRAM

Program 1014 CASK
Derivation of Equations

The model shown in Fig. C-1 illustrates the general case of a cask equipped with an energy absorber which deforms in pure compression. If the force-deformation curve for the absorber is taken as shown in Fig. C-2, the expression

$$\Delta U_n = F_n(X_n - X_{n-1}) = \bar{F}_n \delta_n$$

represents the energy expended as the cask moves from X_0 to X_n and deforms the absorber an amount δ_n . It follows that

$$U_n = \sum_{n=0}^{n=n} \Delta U = \sum_{n=0}^{n=n} F \delta .$$

The summation may be simplified by taking δ constant and satisfying the expression

$$N\delta = X_n .$$

The deformation X_n may be written

$$X_n = \epsilon_n L = N\delta .$$

Solving for ϵ_n , we have

$$\epsilon_n = N\delta/L .$$

There is an expression $\sigma_1 = f(\epsilon_1)$, where σ = stress (psi) and ϵ = strain (in./in.), for the material from which the energy absorber is constructed. The force F can then be determined from the following expression:

$$F = \sigma A ,$$

where A = original cross-sectional area of the energy absorber (in.²).

Fig. C.1. Cask model.

Fig. C.2. General force-deformation diagram.

These relationships form the basis for the attached computer program. The absorber deformation is increased in steps of constant magnitude. Strain, stress, and force are computed for value of deformation and the energy for the step determined. The energy is added to the sum of that from previous steps and compared with the cask potential energy. When the dissipated energy equals the potential energy, the computations are complete.

The program is currently supplied with stress-strain equations

$$\sigma = f(\epsilon)$$

for stainless steel and mild steel. The program can be used for absorbers having any cross-sectional shape. It is equipped to compute the area for rectangular toroidal absorbers (see Fig. C-3a) and for rectangular absorbers (see Figs. C-3b and C-3c) having a constant thickness. In the case of the toroidal absorber, the radius and thickness depth must be inserted in statement numbers 70, 71, and 72. For a rectangular absorber, the thickness, depth, and length must be inserted as statement numbers 71, 72, and 73. For absorbers of other geometry, the area must be computed by hand, in input in statement 74. Those statements not applicable must be left as 0.0. In addition, the cask weight in pounds must be input in statement 80, the drop material height in inches in statement 81, and the material in statement 88. The material in input is SST for 300 annealed series stainless steel and STL for mild steel. If a finer or coarser mesh is desired, the value of DE in statement 60 may be decreased or increased. The 100 format should be altered to identify the cask.

Fig. C.3. Energy absorber configurations.

**FTN.L.N.E.O.A.

C PROGRAM 1014 CASK
 C THIS PROGRAM COMPUTES THE RESPONSE OF A RIGID CASK EQUIPPED WITH AN ENERGY-
 C ABSORBER WHICH DEFORMS IN PURE COMPRESSION. THE AXIS OF THE CASK IS
 C VERTICAL. CODED BY JOHN EVANS PE. OAK RIDGE NATIONAL LABORATORY, JUNE 1974

C GLOSSARY OF TERMS

C AMATL=MATERIAL ABSORBER IS MADE OF
 C WT =WEIGHT OF CASK
 C TLEN =LENGTH OF ABSORBER
 C RAD =RADIUS OF ABSORBER
 C THK =THICKNESS OF ABSORBER
 C DEPH =DEPTH OF ABSORBER
 C DL =INCREMENTAL CHANGE IN ABSORBER DEPTH
 C AREA =AREA OF ABSORBER BEFORE IMPACT
 C END DROP TUNGSTEN CASK

C
C

C DIMENSION DE(200),S(200),DEF(200),DU(200),FUNC(200),ENER(200),

2 ACC(200)

DO 25 I=1,2

DO 7 I=1,200

DE(I)=0.0

S(I)=0.0

DEF(I)=0.0

DU(I)=0.0

FUNC(I)=0.0

ENER(I)=0.0

7 ACC(I)=0.0

STL=2.0

SST=1.0

60 EE=.000

DS=0.0

C INPUT MATERIALS

99 AMATL=SST

C INPUT CASK WEIGHT

WT=381.

C INPUT ABSORBER DIMENSIONS

IF(Z.EQ.2) GO TO 66

TLEN=0.0

DEPH=.733

THK=0.0

GO TO 67

66 CONTINUE

67 CONTINUE

RAD=0.0

74 AREA=6.09

DL=EE*DEPH

PHI=3.14159265

IF(RAD .GT. 0.) AREA=2.*RAD*PHI*THK

IF(TLEN .GT. 0.) AREA=TLEN*THK

IF(AMATL.NE.2.0) GO TO 6

C MILD STEEL COEFFICIENTS

A=-4.35337724E+02

B=3.52674712E+06

C=-5.34344912E+07

D=8.44752790E+08

E=-1.00797838E+10

```

F=4.32201260E+10
G=-4.42375304E+11
H=1.50645044E+12
Q=-3.25535392E+12
P=4.31730272E+12
C=-3.20497894E+12
H=1.01910654E+12
AA=0.0
AD=345000.
AC=73000.

```

5 CONTINUE

C IF (AMAL.NF.1.0) GO TO 5
STAINLESS STEEL COEFFICIENTS

```

A=-6.60046924E+22
B=3.27844320E+06
C=-1.74300776E+08
D=5.7629072E+00
E=-9.29116095E+13
F=8.46307045E+11
G=-4.79173290E+12
H=1.75750146E+13
Q=-4.20115552E+13
P=6.33574650E+13
C=-5.40412764E+13
H=2.07901540E+13
AA=0.15
AB=642000.
AC=50300.

```

5 CONTINUE

C ALUMINIUM TYPE 6061-TO COEFFICIENTS
IF (AMAL.NF.3.0) GO TO 12

```

A=-2.3732992E+02
B=8.7722216E+05
C=-2.10335034E+07
D=7.92320975E+04
E=-1.19710415E+10
F=9.24522723E+10
G=-4.2076405E+11
H=1.21914694E+12
Q=-2.224033424E+12
P=2.51113450E+12
C=-1.00332052E+12
H=4.43256444E+11
AA=0.05
AB=209100.
AC=27000.

```

12 CONTINUE

C SELECT JUMP HEIGHT

DO 20 N=1,2

IF=48.0

IF (MT02.10000.) MT=36.0

IF (MT02.20000.) MT=24.0

IF (MT02.30000.) MT=12.0

IF (N2.2) MT=360.0

U=4T0MT

SUMU=0.0

DS=0.


```

DO 1 I=1,200
DE(I)=DS
DEF(I)=L(I)*DEPH
IF(DS.GT.44) GO TO 21
S(I)=A+(J*DS)+(C*DS*DS)+(D*(DS**3.))+(E*(DS**4.))+(F*(DS**5.))+
1 (G*(DS**6.))+(H*(DS**7.))+(U*(DS**8.))+(P*(DS**9.))+
2 (Q*(DS**10.))+(R*(DS**11.))
GO TO 22
21 CONTINUE
S(I)=(4)*DS+AC
22 CONTINUE
FORC(I)=L(I)*AREA
ACC(I)=FORC(I)/WT
DJ(I)=FORC(I)*DL
SUMU=SUMU+DJ(I)
ENER(I)=SUMU
DS=DS+EE
IF(ENER(I).GE.UT) GO TO 2
1 CONTINUE
2 CONTINUE
J=I
WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1001)
WRITE (5,1000)
WRITE (5,1001)
WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1001)
WRITE (6,1003)
WRITE (5,1001)
WRITE (6,1004)
WRITE (5,1001)
WRITE(6,1005),RAD,THK,DEPH,FLCN,AREA
WRITE (5,1001)
WRITE (5,1002)
WRITE (5,1001)
WRITE (5,1006)
WRITE (5,1001)
WRITE (5,1007)
WRITE (5,1001)
WRITE (5,1008)*T,MT,UT
WRITE (5,1001)
WRITE (6,1002)
WRITE (5,1002)
WRITE (5,1001)
WRITE (5,1009)
WRITE (5,1001)
WRITE (5,1010)
WRITE (5,1001)
DO 10 I=1,200
WRITE(5,1011),ACC(I),DEF(I),FORC(I),S(I),DE(I),ENER(I)
IF(I.GE.J) GO TO 11
10 CONTINUE
11 CONTINUE
WRITE (6,1001)
WRITE (5,1001)

```

```

WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1002)
WRITE (5,1001)
WRITE (5,1001)
1000 FORMAT(1H,9X,'MODEL CASE FOR PROGRAM DEMONSTRATION.
1      IMPACT ON SIDE')
1001 FORMAT(1H0)
1002 FORMAT(1H ,1X,49H*****
1      55H*****
2      14H*****
1003 FORMAT(1H ,23X,24HENERGY ABSORBER GEOMETRY)
1004 FORMAT(1H ,12X,6HRAJ15,3X,9HTHICKNESS,3X,5HDEPTH,4X,6HLENGTH,5X,
1      4HAREA)
1005 FORMAT(1H ,F13.3,4F10.3)
1006 FORMAT(1H ,16X,33HCLASK GEOMETRY AND TEST CONDITIONS)
1007 FORMAT(1H ,12X,11HCLASK WEIGHT,3X,11HDROP HEIGHT,3X,9HPOTENTIAL,
1      X, 6HENERGY)
1008 FORMAT(1H ,F21.1,F14.1,F17.1)
1009 FORMAT(1H , 1X,12HACCELERATION,2X,11HDEFORMATION,6X,5HFORCE,6X,
1      6HSTRESS,6X,6HSTRAIN,7X,6HENERGY)
1010 FORMAT(1H , 3X,3HX 3,10X,6HINCHES, 9X,4HMBBS,7X,4HMPSI, 9X,
1      5HIN/IN,7X,5HMB-IN)
1011 FORMAT(1H ,F11.1,F13.3,F16.1,F12.1,F11.3,F12.1)
      CALL JWKPL(DEF,ACC,J,'LINEAR','J.H.EVANS')
      CALL JWKPL(DEF,ENER,J,'LINEAR','J.H.EVANS')
      CALL JWKPL(ACC,ENER,J,'LINEAR','J.H.EVANS')
20 CONTINUE
25 CONTINUE
STOP
END

```

Appendix D

LISTING OF CORNER-IMPACT PROGRAM

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Program 1001 CASK
Derivation of Equations

When a cask constructed of single ideally plastic material impacts on its top corner, the major portion of the kinetic energy will be dissipated through displacement of material in the impact areas. An ideally plastic material is a material which has a stress-strain relationship which is represented by a horizontal line.

The expression

$$dU = S dV,$$

where

U = total energy absorbed (in.·lb),

S = quantity of energy required to displace a unit volume of material or stress divided by strain per above (in.·lb/in.³),

V = displaced volume of material (in.³),

can be used as a basis for determining the effect of the top corner impact. The lack of an accurate numerical value of S necessitates a conservative estimation of its value.

With reference to the computational diagram illustrated in Fig. D-1, it may be said that

$$dV = (XY/2) dZ,$$

where, by trigonometry,

$$X = R(\cos B - \cos A),$$

$$Y = X \tan \alpha = R(\cos B - \cos A) \tan \alpha,$$

$$dZ = R \cos B dB.$$

It follows that

$$dU = (SXY/2) dZ$$

Fig. D.1. Cask model.

and

$$U = \sum dU = \sum (SXY/2) dZ .$$

This expression can be readily solved using a computer. A value for the angle A can be assumed and B incremented from -A to A or from 0 to A if the result is multiplied by 2 and the energy required for the assumed deformation computed. A is started small, incremented, and the energy required is compared with the potential energy of the cask. In this manner a calculated impact history is produced. The program also computes other variables using the expressions below:

Maximum deformation:	$\Delta = R(\sin \alpha)(1 - \cos A)$
Applied force:	$F = dU/d\Delta$
Acceleration:	$a = Fg/W$

The velocity at any increment is found from the kinetic energy relationship

$$\Delta KE = U = \frac{M}{Z} (V_0^2 - V^2)$$

or

$$V = [V_0^2 - 2(U/M)]^{1/2} = [(2g/W)(Wh - U)]^{1/2} ,$$

where

V_0 = initial velocity (ft/sec),

m = cask mass (lb·sec²/ft),

W = weight (lb),

h = drop height (ft),

g = gravitational constant (ft·lb_m/lb_f·sec²).

The time is computed from the relationship

$$a = dV/dt \text{ or } dt = dv/a$$

and summary techniques.

***INCL.00.

C PROGRAM NUMBER 1001-CASK - MODIFIED
 C THIS PROGRAM COMPUTES THE RESPONSE OF A CASK HAVING RIGHT CYLINDRICAL
 C GEOMETRY IN THE INITIAL IMPACT ON ITS CORNER. THIS PROGRAM ASSUMES
 C THE CASK IS MADE OF A HOMOGENEOUS MATERIAL HAVING AN IDEAL STRESS-
 C STRAIN RELATIONSHIP. THE IMPACT SURFACE IS ASSUMED TO BE AN INFINITELY
 C HARD UNYIELDING SURFACE WITH AN INFINITELY HIGH COEFFICIENT OF FRICTION
 C WITH THE CASK.
 C BY JOHN EVANS P.E., GENERAL ENGINEERING DIVISION, OAK RIDGE NATIONAL LAB.

C GLOSSARY OF NOTATION
 C R=RADIUS OF CASK
 C C=CASK LENGTH
 C S=YIELD STRESS OR FLOW PRESSURE
 C H=CASK HEIGHT
 C H=DROP HEIGHT
 C J=ANGLE BETWEEN AXIS OF CASK AND VERTICAL
 C THETA=ANGLE BETWEEN VERTICAL AND IMPACT PT-C.G.
 C ZETA=THE CHANGING THETA ANGLE AFTER IMPACT
 C J=ENERGY
 C F=F/ACE
 C T=TIME
 C A=ACCELERATION
 C JT=TOTAL ENERGY
 C V=VELOCITY
 C X=DEFORMATION
 C AN=ANGLE IN CONTACT / THE SURFACE

C CORNER DROP TUNGSTEN CASK

C DIMENSION V(750),AN(750),F(750),U(750),T(750),AN(750),
 I X(750),A(750),ZETAU(750)
 C PI=3.141592654
 S=0.0
 ANA = 0.0
 C INPUT CASK GEOMETRY
 C #381.
 C=14.45
 R=3.679
 DO 20 Z=1.2
 U=PI/6.
 IF(Z.EQ.2) GO TO 13
 GO TO 17
 19 CONTINUE
 U=ATAN(2.*R/C)
 19 CONTINUE
 C SELECT DROP HEIGHT
 DO 40 NV=1.2
 H=48.0
 IF(NV.EQ.1)H=36.0
 IF(NV.EQ.2)H=24.0
 IF(NV.EQ.3)H=12.0
 IF(NV.EQ.2)H=300.0
 C INPUT ANGLE INCREMENTS
 37 UU=.01
 AA=.01


```

DO 326 KC=1.2
S=40030.
IF(KC.EQ.2)S=120000.
WRITE (51.1002)
WRITE (51.1002)
WRITE (51.1010) H
1010 FORMAT(1H,3X,'LMFAK CASK. JUMP HT.=',5X,F8.2)
WRITE (51.1002)
WRITE (51.1002)
C ZERO SUBSCRIPTED VARIABLES
DO 14 I=1.750
AN(I)=0.0
AG(I)=0.0
V(I)=0.0
X(I)=0.0
T(I)=0.0
F(I)=0.0
J(I)=0.0
AR(I)=0.0
14 CONTINUE
C ZERO NONSUBSCRIPTED VARIABLES
TA=0.0
AE=0.0
A=0.0
TX=0.0
XX=0.0
XA=0.0
UC=0.0
C THE FOLLOWING CALCULATES THE AMOUNT OF ENERGY ADSORBED ON
C INITIAL IMPACT FOR A PERFECTLY PLASTIC CASE
GRAV=32.2*12.
XMASS = W/GRAV
XIMASS=(XMASS/12.)*(3.*R**2.+C**2.)
JPOTEN=0.0H
C PDIST IS THE DISTANCE FROM IMPACT POINT TO CG
PDIST=SQRT((C/2.)**2.+R**2.)
C THETA IS THE ANGLE OF THE CG WITH RESPECT TO VERTICAL
THETA=0-ATAN(2.*R/C)
C CALCULATE VELOCITY BEFORE IMPACT
VEL1=GRAV*SQRT(2.*H/GRAV)
C CALCULATE ANGULAR AND VECTOR VELOCITY AFTER IMPACT
JMEGA2=XMASS*VEL1*SIN(THETA)*PDIST/(XMASS*PDIST**2.+XIMASS)
VEL2=JMEGA2*PDIST
C CALCULATE KINETIC ENERGY REMAINING AFTER IMPACT
UKINT2=(XMASS*VEL2**2.)/2.+(XIMASS*JMEGA2**2.)/2.
C CALCULATE ENERGY ADSORBED ON INITIAL IMPACT
UT=JPOTEN-UKINT2
VV=SQRT((64.*H)/12.)
DO 1 I=1.750
C INCREMENT ANGLE A WHICH IS THE ADVANCING ANGLE OF CONTACT
9 A=A+AA
IF(A.GE.PI) A=PI
CA=COS(A)
C DEFINE UC AS THE DEFORMATION AFTER THE ENTIRE
C END OF THE CASK HAS CONTACTED SURFACE.
UC=UC+.25
IF (A.LT.PI) UC = 0.0

```

```

C   DEFINE ANGLE J AS THE SUPPLEMENT OF ANGLE A
      J=PI-A
      H=C.0
      IF (A.LE.3.14) GO TO 70
      AE=0.0
      SUMU=0.0
      DO 2 J=1.75
C   INCREMENT ANGLE B WHICH IS USED TO INTEGRATE THE VOLUME DISPLACED
      AS ANGLE A ADVANCES
      B=B+HB
      CR=COS(B)
C   CALCULATE VOLUME DISPLACED
      AS ANGLE A EXCEEDS 90 DEG THE DEFINITION FOR THE DIFFERENTIAL
      VOLUME WILL CHANGE WHEN B IS GREATER THAN ANGLE U
      WHICH IS NOW LESS THAN 90 DEG. THE CROSS-SECTION OF THE
      DIFFERENTIAL VOLUME IS TRAPAZOIDAL RATHER THAN TRIANGULAR
      WHEN B IS GREATER THAN U. ANGLE B IS INTEGRATED FROM
      0 DEG TO ANGLE A OR 90 DEG WHICHEVER IS THE LEAST.
      IF (B.GE.0) GO TO 50
      11 CC=(CJ-CA)
      SY=TAN(J)*R*CC
      SX=R*CC
      12 JZ=4*(SIN(B)-SIN(L-UB))
      JU=BY*BX*.02*S
      50 IF (U.LE.J) GO TO 51
      JX=2*R*CD
      YBAX=TAN(J)*(-R*CA)
      JZ= R*(SIN(B)-SIN(B-JB))
      JU= 2*JX*YBAX*.02*S
C   CALCULATE ENERGY ASSUMED
      51 SUMU=SUMU+J
C   CALCULATE AREA
      13 JA=2.*BX*.027/COS(U)
      AE=AE+JA
      IF (J.GE. 3.14/2) GO TO 3
      IF (B.GE.4) GO TO 3
      2 CONTINUE
      3 J(1)=SUMU
      70 IF (A.LE.3.14) J(1)=SUMU+5*DC*PI*H**2
      AR(1)=AE
C   CALCULATE FORCE
      F(1)=AR(1)*S
C   CALCULATE VELOCITY
      IF (U(1).GE.UT) GO TO 16
      5 VA =SQRT((64./(12.*S))*(UT-J(1)))
      16 IF (U(1).GE.UT) VA=0.0
C   CALCULATE ACCELERATION
      AV(1)=F(1)/M
C   CALCULATE DEFORMATION
      XA = COS(U)*(DC+(R-H*CA)*TAN(U))
      X(1)=XA
C   CALCULATE TIME
      TX=(XA-XX)/((VV+VA)*S)
      7 TA=TA+TX
      T(1)=TA*1000.
      XX=XA
      6 V(1)=VA

```

```

9 VV=VA
  AN(1)=A*57.3
  IF(U(1).GT.FUT) GO TO 4
1 CONTINUE
4 CONTINUE
C THIS SECTION CALCULATES ANGULAR ACCELERATION AND ANGULAR
C POSITION WITH RESPECT TO TIME
  TIME = TA
  ALPHA = OMEGA2/TIME
  JJ=1.1
  ZETA = T*ETA *(ALPHA/2.)*(T(JJ)/1000.)*2.
  ZETAD(JJ) = ZETA*57.3
171 CONTINUE
C OUTPUT-WRITE LOOP
  K=1
  WRITE (51,1002)
  WRITE(51,1004)
1004 FORMAT (14, 9X,37HCASK GEOMETRY AND MATERIAL PROPERTIES)
  WRITE (51,1002)
  WRITE(51,1005)
1005 FORMAT (14, 4X,6HMAJUS,8X,6HLENGTH,10X,6HHEIGHT,6X,
1 15H5SPECIFIC ENERGY,7X,15HENERGY ABSORBED,6X,16HPOTENTIAL ENERGY)
  WRITE(51,1006)
1006 FORMAT (14, 4X,6HINCHES,9X,6HINCHES,10X,6HPOUNDS,8X,
1 13HLB-IN/CO, 14, 6X,6HIN.LB.,14X,6HIN.LB.)
  WRITE(51,1002)
1002 FORMAT(1H0)
  WRITE(51,1007) R,C,M,S,UT,UPOTEN
1007 FORMAT (F11.3,F14.3,F16.1,F16.1,F16.1,F22.1)
  WRITE(51,1002)
  WRITE(51,1000)
1000 FORMAT (14, 4X,11HDEFORMATION,4X,6HVELOCITY,7X,4HTIME,13X,6HFORCE,
1 10X,6HENERGY,5X,12HACCELERATION,10X,5HANGLE,5X,13HCONTACT AVGL)
  WRITE(51,1001)
1001 FORMAT (14, 6X,6HINCHES,7X,6HFT./SEC.,4X,12H1111SECONDS,6X,
1 6H1111S,10X,6HIN-IN,10X,3H1111,12X,7HDEGREES,8X,7HDEGREES)
  WRITE(51,1002)
  DO 15 I=1,K
  WRITE(51,1003) X(I),V(I),T(I),F(I),U(I),AG(I),ZETAD(I),AN(I)
1003 FORMAT(14, F14.4,F13.2,F16.5,F15.2,F16.2,F12.2,F16.2,F16.5)
  15 CONTINUE
  CALL QWKPL(X,AG,K,'LINEAR','J.H.EVANS')
126 CONTINUE
90 CONTINUE
20 CONTINUE
STOP
END

```

Appendix E

ROUTINE PACKING AND INSPECTION PROCEDURES

OPERATIONS DIVISION
RADIOISOTOPE DEPARTMENT

Proc. No. 1
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Date 2/17/77

OAK RIDGE NATIONAL LABORATORY
RADIOISOTOPE PACKAGING AND SHIPPING PROCEDURE

OPERATIONS DIVISION

PROCEDURE FOR APPROVAL TO SHIP RADIOACTIVE MATERIAL

1. All requests to ship radioactive material are first referred to the SS Materials Management Department or to the Isotopes Sales Office for approval [reference: *Isotopes Sales Operating Manual* and the *Nuclear Materials Management Manual*, ORNL-2800 (Revised)].
2. Radioactive Materials Packaging Form (UCN-12301) is completed by the requester and attached to the Special Works data sheet (UCN-1784) or the SS Accountability document (UCN-2681). The supervisor of the Radioisotope Packing and Shipping operation reviews the information provided and flags all shipping documents for shipments requiring Type "B" shipping containers.
3. Documentation of requests for shipping radioactive materials with half-lives >14 days is submitted two full working days before the scheduled shipping date to give adequate time for review of package documentation and approval of the shipment.
4. Documentation of requests for shipment of radioactive material with a half-life of <14 days must be submitted by 1:00 PM on the day before the scheduled shipping date.
5. The review of packaging documentation follows the procedure established in ORNL-TM-2769, *ORNL Isotopes Division Guide for the Packaging of Radioactive Materials for Transport*, and *Nuclear Materials Management Manual*, ORNL-2800 (Revised).
6. A Radioactive Materials Packaging Form (UCN-12301) is required for all returnable container shipments (empty or full) and for all shipments containing >1 mCi alpha or >3 Ci beta-gamma.

PACKING AND SHIPPING PROCEDURE

1. The supervisor of the Radioisotope Packing and Shipping Operation (RPSO) receives approved shipping documents (UCN-2775) from the SS Materials Management and Isotopes Sales Group by 1:00 PM on the day before the shipment is scheduled to leave ORNL.
2. The RPSO supervisor reviews each shipping document and the Radioactive Materials Packaging Form and reports any discrepancies to the Process Group Leader for action. In the absence of the Group Leader, discrepancies in the documentation are reported to the Radioisotope Department Superintendent for action.

Approved: _____

Supervisor

Process Group Leader

FEB - 6 1977

Date

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3. All shipping documents flagged as Type "B" are separated by the RPSO supervisor and handled on a personal basis until the unit is properly loaded on the transporting vehicle. He then signs the Radioactive Materials Packaging Form (UCN-12301) and immediately returns all completed documents to the Process Group Leader for a final review.
4. In the absence of the RPSO supervisor, the relief supervisor brings all shipping documents to the Process Group Leader for review and identification of shipments that require special attention of the relief supervisor.

GENERAL REGULATIONS

1. Short half-life materials (<14 days) are shipped on Tuesday and Friday of each week. Special schedules can be arranged for holiday weeks. Medical isotopes are shipped when required.
2. Long half-life materials (>14 days) are shipped on Wednesday and Thursday of each week. Shipments weighing greater than 300 lbs are shipped on Friday unless special arrangements are made.
3. All packages received at Building 3038 Packing and Shipping Room must meet ORNL *Health Physics Manual* Chapter 4.2 requirements concerning internal transfers of radioactive materials and must meet DOT shipping regulations for external radiation (<200 mrem/hr at the surface and 10 mrem/hr at 3 feet). The RPSO supervisor must be notified by the originator of the shipment when he delivers his package to Building 3038.
4. For each package, bottle of product, source, target, or other form of radioactive material taken to Radioisotope Packing and Shipping, a copy of the Special Work Order or a note must be attached to the container with the following information:
 - A. Quantity of radioactivity actually being shipped.¹
 - B. Chemical form.
 - C. Concentration of radionuclide in solution, mCi/ml.
 - D. Volume or product weight.
 - E. Specific activity¹ (list as "C.F." for carrier free where applicable).
 - F. Assay date and time.¹

Approved: _____

Supervisor

Process Group Leader

FEB 28 1977

Date

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G. Normality of solutions of acids and bases.

H. Radiochemical purity.²

¹Unprocessed reactor and cyclotron targets are not assayed; therefore, quantity of radioactivity is calculated in these cases. Cyclotron target strip solutions should be analyzed for quantity of product radioisotope prior to shipment.

²In the case of short-lived radioisotopes, radiochemical purity assay results may be furnished after the shipment is made.

In the case of partial shipments of products listed on the Special Work Order a copy of the Special Work Order must be furnished with each partial shipment, and the items on the Special Work Order not being shipped must be marked out.

An Isotope Product Card (attached Form UCN-6216) must be filled out for every radioisotope product solution. In the case of product solutions loaded in shipping containers outside of Radioisotope Packing and Shipping, a completed copy of this form must be submitted with the product container to the Packing Supervisor with a copy to the Isotopes Sales Office.

5. The packaging and shipment of radioisotopes shall follow the Procedures for packaging and Shipment of Radioactive Materials Building 3039 and ORNL-TM-2769, ORNL Isotopes Division Guide for the Packaging of Radioactive Materials for Transport.

Approved:

Supervisor

Process Group Leader

FEB 28 1977

Date

OAK RIDGE NATIONAL LABORATORY RADIOACTIVE MATERIALS PACKAGING INFORMATION

THIS FORM IS REQUIRED FOR ALL SHIPMENTS GREATER THAN 100 LBS. FOR ALL MODES OF TRANSPORTATION OF RADIOACTIVE LIQUID, OR GAS AND ALL EMPTY REFILLABLE CONTAINERS

GENERAL INFORMATION

1. Origin (Division)	2. Destination
3. Method of Transport	4. Weight
5. Special Instructions	
Special Instructions Completed by	

RADIOACTIVE CONTENTS

1. All major activities in terms and/or grams	
2. Specify (a) ☐ Normal Form (b) ☐ Special Form	Special Form No.
(c) ☐ Fissile (d) ☐ Non-Fissile	
3. Radioactive Material Form: ☐ Solid ☐ Liquid ☐ Gas	
4. Heat Load (watts): Calculated Estimated By	

SHIPPING CONTAINER

1. Certificate of Compliance No. USA-	
2. DOT Specification No.	3. Nuclear Safety Review No.
4. Container determined proper for contents by	Date

INTERNAL CONTAINER

1. Internal Container: ☐ Glass Bottle ☐ Plastic Bottle ☐ "2R" ☐ Canseal ☐ Welded Capsule (specify capsule material)	
☐ Other (explain)	
2. Contamination level on internal container: Estimated	Measured
3. Radiation level from internal container: Measured	Calculated
4. Gaskets or seals (valves) properly installed	By
5. Leak tests of internal container	By

EXTERNAL CONTAINER

1. Moderator and neutron absorber present for fissile material?	☐ Yes ☐ No	By
2. External container examination	☐ Yes ☐ No	By
3. Gaskets or seals properly installed	☐ Yes ☐ No	By
4. Leak test	☐ Yes ☐ No	By
5. Bolts torqued to	ft. lbs.	By
6. Tie down to skid, checked	☐ Yes ☐ No	By
7. Tamper seal installed	☐ Yes ☐ No	By
8. Lid eye bolt removed and wired to the outside of the carrier	☐ Yes ☐ No	By

RADIATION SURVEY

1. Surface contamination level: Alpha	dpm/100 cm ²	dpm
2. External radiation level		from 10 ft. contact
3. Domestic shipments		from 10 ft. 1 ft. from surface
4. Foreign shipments		from 10 ft. 1 meter from center
5. Health Physics Surveyor		Date

TRUCK TIE-DOWN AND SHORING

1. Tie-down and shoring in accordance with SARP and Designed Layout checked by	
(Inspection Engineering)	
Shipment Approved By	Date

**OPERATIONS DIVISION
RADIOISOTOPE DEPARTMENT**

**BUILDING 3029
SOURCE DEVELOPMENT LABORATORY
QUALITY ASSURANCE PROCEDURE
FOR TYPE B SHIPPING CONTAINERS**

PROC. NO. 26
PAGE 1 OF 4
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Incoming Type B Containers

1. Container is opened under the supervision of the Packing Foreman and a representative of the Health Physics Division. Radiation readings and smear levels on the external and internal surfaces are recorded. These records are stored in the auditable Quality Assurance (QA) files in Buildings 3029 and 3037 by container number.
2. If container is contaminated externally or internally, it is cleaned to ORNL smear tolerances of 500 dis/min beta-gamma or 30 dis/min alpha. The final smear level is recorded by Health Physics and placed in the container's QA files.
3. If the radiation level internally or externally is greater than 1 mR/hr beta-gamma or 500 dis/min alpha, the container is to be decontaminated to the above tolerance. If decontamination efforts fail, the container is tagged out of service and the Department Head is notified in writing of the status. A copy of the notification is placed in the container's QA files. EXCEPTION: Uranium carriers may read up to 10 mrem/hr internally or externally.
4. **Fire Shields**

The RSPD Foreman will visually inspect all fire shields for cracks in the wood, protective coatings, foam glass, and/or steel covers. Defects in these items are to be recorded in the container's QA files and a blanket work order issued immediately to repair same. A copy of the blanket work order and the copy of the completed work order are to be placed in the container's QA files. An inspection of the repair work is to be made by the RSPD Foreman and a record of acceptance placed in the container's QA files.

Outgoing Type B Containers

1. Shielded Containers

- a. Vacuum leak test will be performed by operating personnel and recorded in the container's QA files in Buildings 3029 and 3037 before the container can be used for loading encapsulated radioactive material.
- b. An Inspection Engineering report on the internal weld dye penetrant inspection is valid for 6 months prior to shipment. If inspection is over 6 months old, a new dye penetrant inspection of the internal welds must be made and the results recorded in the QA files. All repairs will be inspected and approved by Inspection Engineering and recorded in the QA files.

APPROVED

SUMMIT	PROD. PRO. LEAD	DATE 5/17/77
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**OPERATIONS DIVISION
RADIOISOTOPE-DEPARTMENT**

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- c. Gaskets will be changed every 6 months and recorded in the container's QA files. Gasket material from storage containers is recorded in the store stock number.

2. Fire Shields

Fire shield lids and bolting devices will be inspected before shipment by the Packing Foreman to insure proper fit of the locking mechanism to hold the lid securely in place during transit. A record of this inspection is to be placed in the container's QA files. All repairs are to be made before shipment and the blanket work order with its completed form is to be filed in the container's QA files.

APPROVED

SUPERVISOR

[Signature]

PROCESS GROUP LEADER

[Signature]

DATE

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1. Chokers for cask handling and lid removal checked for proper loading value and certification by Inspection Engineering _____
by _____
2. Vacuum leak test _____
by _____
3. Inspection Engineering report date (If over 6 months since last report, re-inspect) _____
by _____
4. Planned radioactive heat load _____ watts
a. Neoprene gasket for <1400 W installed _____
b. Silicone rubber gasket for >1400 W installed _____
by _____
by _____
5. Cavity and lid smear level _____
S-Y _____ dpm
a _____ dpm
by _____
6. Outside cask surface smear level _____
S-Y _____ dpm
a _____ dpm
by _____
7. Lid closure cap screws, lockwashers, and nuts (16 required), checked for burrs and proper operation _____
by _____
8. Skid studs and nuts checked for burrs and proper alignment _____
by _____

1. Outside cask surface smear level (clean to ORNL smear tolerance for shipping)	_____	β-γ _____ dpm
	_____	α _____ dpm
		hy _____
2. Lid closure cap screws free of burrs or damage from in-cell loading	_____	by _____
3. Lid cap screws torqued to 150 ft.-lb	_____	by _____
4. Tamper seal installed	_____	by _____
5. Loaded onto skid	_____	hy _____
6. Skid nut torqued to 300 ft.-lb	_____	by _____
7. Personnel heat shield installed	_____	by _____
8. Packaging Information Form (UCN-12301) completed	_____	by _____
9. Notification to Packing and Shipping Foreman	_____	hy _____

Date _____

SUPERVISOR <i>[Signature]</i>	PHOTOGRAPH LEADER <i>[Signature]</i>	DATE JUN 1971
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OPERATIONS DIVISION
RADIOISOTOPE DEPARTMENT
BUILDING 3029
SOURCE DEVELOPMENT LABORATORY
CONTAINER INSPECTION SHEET

PROC. NO. 26
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Date _____ Container Number _____

EXTERNAL INSPECTION

By _____

Smeared _____ dpm By; _____ dpm alpha

Condition Good ☐ Fair ☐ Poor ☐

Repairs Needed _____

Action Taken _____

INTERNAL INSPECTION

By _____

Smeared _____ dpm By; _____ dpm alpha

Decontaminated: Yes ☐ No ☐ By _____CONTAINER TESTING

Vacuum Test _____ Caskets _____

Weld Dye Check _____ Bolts & Lock Washers _____

Repairs Made _____

RE-TESTING

Vacuum Test _____

Weld Dye Check _____

CONTAINER CERTIFIED FOR SHIPMENT - Date _____

By _____

APPROVED

SUPERVISOR
[Signature]

PROCESSOR/LEADER

[Signature]

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