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

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**SAFETY ANALYSIS REPORT FOR PACKAGING:
THE ORNL URANIUM-SHIELDED SHIPPING CASK**

J. A. Boulet
J. H. Evans
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0. GENERAL INFORMATION

0.1 Introduction

The ORNL uranium-shielded shipping casks, models L and M, are type B packages for large-quantity radioactive material shipments. There are seven casks altogether: six model L's and one model M. The model L casks are identified by Oak Ridge National Laboratory (ORNL) as 14 UC, Nos. 2, 3, 4, 5, 6, and 7; the model M is identified as 13 UC-1.

Materials to be shipped in the casks are nonfissile radionuclides. The casks are similar, model L being slightly larger than model M. Both casks were fabricated at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky, using the same general fabrication techniques.

The primary purpose of the casks is to provide shielding, containment, and impact and thermal resistance for contents during transport (rail, highway, and water transport) for both normal and accident conditions. The contents for which the casks are designed and evaluated are outlined in Sect. 0.2.2. The containers comply with Energy Research and Development Administration (ERDA) regulations in *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 containers also comply with U.S. Department of Transportation (DOT) regulations in *Code of Federal Regulations*, Title 49, Part 173.³ Calculations, engineering logic, test results, and documents demonstrating compliance are presented in subsequent sections of this report.

The containers may be shipped by rail, highway, and water transport. The casks may be shipped by common carrier unless the internal heat load exceeds 1250 W, in which case they are shipped in a sole-use vehicle as required by DOT regulations.³ Models L and M may be used for a maximum internal heat load of 4000 W.

In this application, models L and M are treated as a single cask so that results and/or analyses of one are conservative and applicable for the other. Separate analyses are performed and presented when differences in the casks preclude selection of an analysis conservative for both.

0.2 Package Description

0.2.1 Packaging

The ORNL uranium-shielded cask, model L, is a right circular cylinder 25-1/2 in. OD with a total height of 39-3/4 in. The inside cavity is 11 in. ID by 17-1/2 in. high. Forty-four 1/4-in.-thick by 3-in.-deep fins extend to 31-1/2 in. diam. The overall diameter is further extended to 35-5/8 in. by four lug plates and bottom support and tie-down plate. The 6.75-in.-thick (minimum) uranium walls of the cylinder and closure lid are clad in 1/4-in. stainless steel. The cask is bolted to a special skid and covered with a personnel heat shield for shipping. Construction drawings of model L are in Appendix A.

The ORNL uranium-shielded cask model M is a right circular cylinder 25 in. OD with a total height of 38 in. The inside cavity is 11 in. ID by 17-1/2 in. high. Thirty-two 1/8-in.-thick by 3-in.-deep heat transfer fins extend to 31 in. diam. The overall diameter is further extended to 35-1/8 in. diam by four lug plates and the bottom support and tie-down plate. The 6.5-in.-thick uranium walls of the cylinder, 6-in.-thick bottom head, and closure lid are clad in 1/4-in. stainless steel. The closure lid is secured to the body with sixteen 300-series stainless steel bolts in the L model and 12 stainless bolts in the M model. For shipment, the cask is attached to a special skid assembly and covered with a personnel heat shield. Model M on the skid is shown in Fig. 0.1; Fig. 0.2 shows model M with both the skid and heat shield attached. Construction drawings of model M are in Appendix A.

The closure gasket for model M is 22 in. ID by 24 in. OD by 1/16 in. thick. For model L, it is 22-1/2 by 24-1/2 by 1/16 in. thick. Material is flat neoprene sheet except when casks are shipped via sole-use vehicles. Silicone rubber is used in these shipments because of its higher service temperature (Table 1.7).

Fig. 0.1. Uranium-shielded cask.

Fig. 0.2. Uranium-shielded cask with heat shield.

Both models L and M are surrounded by an expanded metal heat shield while being transported. This shield is shown in place on Fig. 0.2, and details of the construction and materials are given in the as-built drawings in Appendix A.

Models L and M were fabricated by Union Carbide Corporation, Nuclear Division, Paducah Plant, Paducah, Kentucky, using the same techniques. The cask gross weights are 13,200 lb for model L and 11,600 lb for model M, including skids. Cutaway sketches of models L and M are shown in Fig. 0.3.

An extensive report⁴ was prepared covering the fabrication of model M. A brief summary of the fabrication procedures is given in Sect. 1.1.

0.2.2 Contents of packaging

The radioactive contents of either package will be any nonfissile radioisotope in solid form. Contents of each package are restricted by volume, shape, internal heat load, and external radiation levels allowed by the regulations. All contents of the package are in special form containers or are contained within DOT Specification 2R inner containment (Sect. 1.9).

Total heat load for either cask will not exceed 4000 W and is limited to 1250 W when the casks are shipped by common carrier. When the heat load exceeds 3000 W, the contents will be special form. At heat loads less than 3000 W, inner containers meeting DOT Specification 2R may be used. Metallic gaskets will be used in the inner (2R) container (Fig. 1.36). See Sect. 2.3 for discussion relating to these limitations.

1. STRUCTURAL EVALUATION

1.1 Structural Design

1.1.1 Discussion

As-built drawings for models L and M are shown in Appendix A. Principal structural members of the casks are (1) the cylinders consisting of both the formed, laminated uranium plates and the stainless steel cladding, (2) the closure heads consisting of two pieces of uranium also

Fig. 0.3. Cutaway sketches of models L and M.

clad with stainless steel plate, and (3) the 1-in.-thick stainless steel plates and flanges used to lift the cask, form the closure, and secure the cask to the skid. The 1-in.-thick plates serve as impact limiters, and heat transfer fins also dissipate impact energy. Principal structural members and systems for both casks can be identified on the as-built drawings in Appendix A.

The cylindrical shield was formed by welding a 304L stainless steel cladding cylinder around a finned welding mandrel and by hand-clamping and weld-shrinking successively larger 1/2-in.-thick uranium cylinders over the preassembled section of the shield. This process was shown to produce a high percentage of metal-to-metal contact. The welding mandrel with the partly fabricated cylindrical shield is shown in Fig. 1.1. The fabricator⁴ reported that it was not possible to run a 0.001-in. feeler gage more than a fraction of an inch into a joint. In addition, the model M, the outside stainless steel cladding was type 405 stainless steel plate, and the inside was type 304L stainless steel.

All uranium is clad with 1/4-in.-thick stainless steel. Full penetration welds were made in all cladding welds, followed by dye-penetrant inspection. At an interface of stainless steel and uranium, an alloy with a melting point of around 1450°F can be formed. To circumvent this problem, the stainless steel was flame-sprayed with copper at all interfaces. This prevents the formation of the low-melting eutectic until temperatures in excess of 1750°F are reached.⁴ Because uranium exhibits thermal-cycling growth, a heat-treating procedure⁴ to randomly orient the grain structure was applied to the uranium plates. The effectiveness of this heat treatment has been demonstrated experimentally.⁵ Helium was used to fill the laminar gaps, followed by seal welding to prevent oxidation of the uranium plate.

The uranium, which is clad with stainless steel, is a structural member of the cask. Its minimum yield strength of 25,000 psi is only 5000 psi lower than that for stainless steel.

Fig. 1.1. Welding mandrel with partially fabricated cylinder.

1.1.2 Design criteria

The design of model L and model M was based on proposed regulations⁶ in effect in May 1964 and on the cask designer's guide published at that time.⁷

1.2 Weights and Centers of Gravity

Weights of the packages, their contents, and subassemblies are shown in Table 1.1. Centers of gravity of the packages were determined from Fig. 1 2. Only the containment vessel and its closure were used in each calculation.

Table 1.1 Weights of models L and M casks

Component	Weight (lb)	
	Model L	Model M
Cask (without closure)	8,800	7,400
Closure	2,100	1,900
Personnel heat shield	200	200
Skid	1,900	1,900
Maximum weight of contents	200	200
Total maximum weight	13,200	11,600

1.3 Mechanical Properties of Materials

The mechanical properties for the uranium and stainless steel are summarized in Table 1.2. Figure 1.3 is a dynamic compressive stress-strain curve for stainless steel.⁸

1.3.1 Dynamic properties of uranium

Almost no data concerning the dynamic compressive properties of uranium were found in the literature; however, tensile data were found in references 9-12. As indicated in ref. 4, the uranium in the cask is beta heat treated and oil quenched. Tensile data for this material

ORNL DWG 74-2259-R1

Fig. 1.2. Idealized models for calculating the centers of gravity for the cask.

Fig. 1.3. Stainless steel stress-strain curves.

Table 1.2. Mechanical properties

Properties	Symbol	304L and 405 stainless steel	Uranium ^a
<u>Static</u>			
Yield stress, psi	σ_y	30,000 ^b	25,000 ^c
Ultimate shear strength, psi	τ_u	61,000 ^b	35,000 ^d
Young's modulus, psi	E	30×10^6 ^b	24.7×10^6 ^c
Poisson's ratio	ν	0.3 ^b	0.23 ^c
Weight density, lb/in. ³	γ	0.283 ^b	0.69 ^e
Thermal expansion coefficient, in./in.°F	α	9.6×10^{-6} ^b	8.04×10^{-6} ^f
<u>Dynamic properties</u>			
Specific energy, in.-lb/in. ³	S min	10×10^4 ^g	4×10^4 ^g
	S max	26×10^4 ^g	12×10^4 ^g

^a Beta heat treated and oil quenched.

^b The International Nickel Company, *Mechanical and Physical Properties of Austenitic Chromium-Nickel Stainless Steel at Ambient Temperatures*, 1963.

^c A. N. Holden, *Physical Metallurgy of Uranium*, Addison-Wesley, Reading, Mass., 1958.

^d See Sect. 1.3.2.

^e *Handbook of Chemistry and Physics*, 45th ed., Chemical Rubber Co., Cleveland, 1964.

^f C. R. Herrington and A. E. Ruehle, *Uranium Production Technology*, Van Nostrand, New York, 1959.

^g See Sect. 1.3.1. and Fig. 1.3.

(ref. 12 does not indicate material phase) are plotted in Fig. 1.4. Conservative approximations to these data are shown in Figs. 1.4 and 1.5. Figure 1.5 also shows compressive curves obtained by multiplying the tensile stresses by $(1 + \epsilon)/(1 - \epsilon)$. This assumes the true

Fig. 1.4. Tensile data for uranium.

Fig. 1.5. Uranium stress-strain curves.

stress-strain properties of the material to be the same for tension and compression.

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. The higher value will result in calculated accelerations of greater magnitude than actual. Thus, selected values (Fig. 1.5) of 40,000 psi and 120,000 psi for uranium will effect a conservative solution for the uranium-shielded cask.

1.3.2 Shear strength of uranium

No information on the direct measurement of the ultimate shear strength of uranium was found in the literature; however, ref. 13 indicates that, in general, ultimate shear strength is approximately 70% of ultimate tensile strength. Furthermore, since tensile specimens generally fail along a plane inclined 45° from the specimen axis, the ultimate shear strength

$$\tau_u = \sigma_u \cos 45^\circ ,$$

where

$$\sigma_u = \text{ultimate tensile strength (psi).}$$

A value of 50,000 psi for σ_u is conservative, since Fig. 1.4 indicates a higher ultimate tensile strength. Hence, τ_u for uranium is taken as $(0.7)(50,000) = 35,000$ psi.

1.4 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.

1.4.1 Chemical and galvanic reactions

The casks are fabricated from stainless steel and depleted uranium. The uranium is completely clad with stainless steel plate to prevent oxidation of the uranium. The cask design drawings call for full-penetration welds and dye-penetrant inspection to ensure the integrity of the cladding. In construction of the laminar cylinder, the structure was evacuated and backfilled with helium to prevent oxidation of the uranium. A similar procedure was used in the cladding process. Thus no oxide film should form on the uranium.

Uranium in contact with stainless steel exhibits a tendency to alloy at the interface at a temperature 1450°F. Consequently, all surfaces of the stainless steel which could come in contact with uranium were flame-sprayed with copper. This raises the temperature at which the eutectic occurs to over 1750°F at the interface.

The radioisotope content of the package is in solid form and is singly or doubly encapsulated in special form containers or contained in a DOT Specification 2R container.¹⁴ The containers may be in contact with the stainless steel cladding and will not react. Experience and inspections to date have indicated no chemical, galvanic, or other reaction between the casks and their contents.

1.4.2 Closure

Standards specify that the package be equipped with a positive closure that will prevent inadvertent opening. Both casks are equipped with positive closure devices consisting of 16 bolts on the lid for model L and 12 for model M. In addition, one of the bolts in each cask is drilled and a wire seal is installed to indicate that the lid has not been removed during shipment. Also, the closure bolts are not readily

accessible with the personnel shield in place (see Fig. 0.2). Thus inadvertent opening is prevented, and unauthorized opening may be detected.

1.4.3 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 containers are designed to be lifted by four lugs, spaced symmetrically around the containers, using conventional slings. The heat shield will have to be removed before these lugs can be accessed; therefore, the shield will have no effect on the lifting of the cask. Since it is reasonable to assume that on occasion only two lugs will be used, the lugs will be evaluated on this basis. They are of 304L stainless steel, which has a yield of 30,000 psi, and are loaded as shown in Fig. 1.6. Since the vertical force F on either lug is $F = 1.5W$, and the total tension T in the sling cable is $T = F/\cos \theta$, the maximum cable tension occurs when θ is a maximum. For model L, as shown in Fig. 1.6,

$$\theta_{\max} = \tan^{-1}(3.5/7.25) = 25.8^\circ .$$

Hence,

$$T_{\max} = F/\cos \theta_{\max} = 1.5W/0.9006 = 1.5(13,200)/0.9006 = 22,000 \text{ lb} .$$

For model M,

$$\theta_{\max} = \tan^{-1}(2/3) = 33.7^\circ ,$$

so

$$T_{\max} = 1.5(11,600)/0.8321 = 20,900 \text{ lb} .$$

ORNL DWG 74-8407

ALL DIMENSIONS
GIVEN IN INCHES

Fig. 1.6. Lifting load diagram.

Since the lugs are the same for each model, model L will experience the greater stresses. Assuming a shackle pin diameter of 1-1/8 in., the bearing stress at the hole is

$$\sigma_b = P/Dt ,$$

where

P = applied load (lb),

D = pin diameter (in.),

t = lug plate thickness (in.).

$$\sigma_b = T_{\max}/Dt = 22,000/(1.125)(1) = 19,600 \text{ psi} .$$

Maximum shearing stress τ on the shackle pin in the lug hole is

$$\tau = P/2A = T_{\max}/(2\pi D^2/4) = 2T_{\max}/\pi D^2 ,$$

where

P = applied load (lb)

A = cross-sectional area of pin (in.²),

D = pin diameter (in.).

$$\tau = 2(22,000)/\pi(1.125)^2 = 11,100 \text{ psi} .$$

The lifting lugs conform to the regulations since the stresses generated in them are less than the yield strength of the materials. If under excessive loads the lifting device fails, the damage would be localized in the area above the lifting-lug eyes since this is the weakest point. This area contributes nothing to the function of the container, and failure would not impair the containment or shielding properties of the cask.

1.4.4 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 device or any other system of lifting devices shall conform to the requirements for the package lifting system.

Using a single hole in lifting the lid only for model L, the bearing stress (see Sect. 1.4.3) is

$$\sigma_b = 3W_L / Dt ,$$

where

W_L = weight of lid (lb),
 D = hole diam (in.),
 t = lug thickness (in.).

$$\sigma_b = 3(2100)/(1.125)(1) = 5600 \text{ psi} ,$$

and for model M

$$\sigma_b = 3(1900)/(1.125)(1) = 5070 \text{ psi} .$$

Thus the lids may be safely lifted at any one hold, and the lid-lifting devices comply with the requirements of the regulations since the stresses generated in them are less than the yield strength. Normally, however, both holes would be used to lift the lid.

Both models will have a personnel heat shield attached while in transit. As seen in Fig. 0.2, the lid-lifting holes are not accessible during transport; therefore, the lid-lifting device cannot be used for lifting the entire cask.

1.4.5 Tie-down devices

If there is a system of tie-down devices that is a structural part of the package, 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 personnel heat shield has been modified to render the cask-lifting lugs inaccessible during shipment for tie-down purposes, but accessible for lifting the casks.

Models L and M casks are bolted to a skid by means of sixteen 1.5-in.-diam bolts (see Figs. 0.1 and 0.2). In turn, the skid is attached to the vehicle by means of bolts. Figure 1.2 shows that the casks and their centers of gravity are sufficiently similar that we need consider only the model L loading system shown in Fig. 1.7. Here we idealize model L as a cantilever beam attached to a solid flat plate by the bolts. The stabilizing effect of the cask's weight has been neglected.

Maximum tensile stress in any bolt will be a combination of the tensile stresses caused by each of the applied loads. The L and M models are of such similar construction that maximum stress will certainly occur in the heavier model. Stress in the bolts due to the vertical load is

$$\sigma_v = P / \Sigma A = 2W/16A = (2)(13,200)/(16)(1.405) = 1170 \text{ psi} ,$$

where A is the stress area of the bolts.¹⁵

This stress is the same for all bolts. The maximum tensile stress caused by the longitudinal 10W load is in the bolts at B in Fig. 1.8. As shown,

ORNL DWG 74-8409

Fig. 1.7. Tie-down load diagram.

ORNL DWG 74-8404

ALL DIMENSIONS GIVEN IN INCHES

Fig. 1.8. Tie-down bolt deformation.

$$\Delta_i / x_i = \text{constant} ,$$

where

Δ_i = bolt elongation (in.),

x_i = distance (in x direction) from bolt to A (in.).

Hence,

$$\Delta_i = \Delta_B x_i / x_B .$$

Summing moments about A gives

$$\sum M_A = 0 ,$$

$$2 \sum F_i x_i = 10Wh ,$$

where

F_i = tension in the bolts (lb),

h = vertical distance from A to the center of gravity (in.)

(Fig. 1.7).

By definition,

$$F_i = \sigma_i A ,$$

where

σ_i = stress in the bolts (psi),

A = stress area of a bolt (in.²) .

By Hooke's law,

$$\sigma_i = \epsilon_i E ,$$

where

ϵ_i = bolt strain (in./in.),

E = Young's modulus for the bolt material (psi).

Also by definition,

$$\epsilon_i = \Delta_i/L ,$$

where L is the bolt length.

Hence,

$$2 \sum \Delta_i EA x_i / L = 10Wh ,$$

$$\sum \Delta_i x_i = 5Wh/EA ,$$

$$\sum \Delta_B x_i^2 / x_B = 5Wh/EA ,$$

$$\Delta_B = 5Whx_B / EA \sum x_i^2 ,$$

$$\sigma_B = \Delta_B E / L = 5Whx_B / A \sum x_i^2 .$$

Referring to Fig. 1.8,

$$\sigma_B = 5(13,200)(20.5)(33.26)/(1.405)(3531) = 9670 \text{ psi} .$$

Similarly, the maximum tensile stress caused by the transverse load occurs in the bolts at C, and

$$\sigma_C = \Delta_C E / L = 2.5Why_C / A \sum y_i^2 ,$$

$$\sigma_C = 2.5(13,200)(20.5)(33.26)/(1.405)(3531) = 4540 \text{ psi} .$$

The maximum tensile stress produced by the resultant of the longitudinal and transverse loads occurs in the bolt nearest the resultant's line of action. As shown in Fig. 1.8, the bolt in question is at D. The combined normal stress in this bolt is

$$\sigma = \sigma_V + (\sigma_B x_D / x_B) + (\sigma_C y_D / y_C) ,$$

$$\begin{aligned}\sigma &= 1170 + [(9070)(30.91)/33.26] + [(4540)(26.56)/33.26] \\ &= 13,200 \text{ psi} .\end{aligned}$$

This is the maximum stress experienced by threaded portions of the bolt.

Bolt shanks experience both tensile and shear stresses. The maximum tensile stress is

$$\sigma_s = \sigma A/A_s ,$$

where

$$\begin{aligned}\sigma_s &= \text{tensile stress in bolt shanks (psi)}, \\ A_s &= \text{cross-sectional area of a bolt shank (in.}^2\text{)} .\end{aligned}$$

Thus,

$$\begin{aligned}\sigma_s &= (13,200)(1.405)/(\pi D^2/4) = 13,200(1.405)(4)/\pi(1.5)^2 \\ &= 10,500 \text{ psi} .\end{aligned}$$

The shear stress τ on the bolt shanks is

$$\begin{aligned}\tau &= P/\Sigma A = 11.18W/(16)(\pi D^2/4) = (11.18)(13,200)/4\pi(1.5)^2 \\ &= 5220 .\end{aligned}$$

The maximum principle stress, from Mohr's circle, is given by

$$\sigma_{\max} = (\sigma/2) + [(\sigma/2)^2 + \tau^2]^{1/2} ,$$

where

$$\begin{aligned}\sigma &= \text{tensile stress (psi)}, \\ \tau &= \text{shear stress (psi)} .\end{aligned}$$

This gives

$$\sigma_{\max} = (10,500/2) + [(10,500/2)^2 + (5220)^2]^{1/2} = 12,700 \text{ psi} .$$

Since maximum stresses in the bolts do not approach the yield strength, and since the bolts are the weakest members of the tie-down system, the tie-down system conforms to regulations. If the tie-down system failed under excessive load, the cask would separate from the skid due to failure of the bolts. Since the bolts and skid do not

contribute to the function of the cask, the effectiveness of the container would not be reduced.

1.5 Standards for Type B and Large-Quantity Packaging

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

1.5.1 Load resistance

When regarded as a simple beam supported at its ends along any major axis, the container must be capable of withstanding a static load normal to and uniformly distributed along its length that is equal to five times its full loaded weight without generating stress in any material of the cask in excess of the yield strength of that material. The equivalent cross section of the container analyzed in this study is illustrated in Fig. 1.9.

The maximum bending stress is

$$\sigma = Mc/I ,$$

where

M = maximum moment in the beam = $\omega L^2/8$, where

ω = load per unit length of cask (lb/in.),

L = cask length (in.) (see Appendix A),

c = distance from neutral axis (NA) to outermost fiber of cross section (in.),

I = moment of inertia of cross section = $(\pi/4)(r_o^4 - r_i^4)$ (in.⁴),
where

r_o = outer radius of cross section (in.),

r_i = inner radius of cross section (in.).

As shown in Fig. 1.9, $\omega = 5W/L$, where W is the cask weight excluding skid.

For these calculations only the outer uranium cylindrical lamination will be considered — a very conservative approach. Combining the above formulas,

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(a) CONTAINER AS SIMPLE BEAM (b) EQUIVALENT CROSS SECTION OF CONTAINER

Fig. 1.9. Container idealized as a simply supported beam.

$$\sigma = (5W/L)(L^2/8)(r_o)/(\pi/4)(r_o^4 - r_i^4) = 5WLr_o/2\pi(r_o^4 - r_i^4) .$$

For model L,

$$\sigma = 5(11,300)(39.75)(12.75)/2\pi(12.75^4 - 12.25^4) = 1166 \text{ psi} .$$

For model M,

$$\sigma = 5(9700)(38)(12.5)/2\pi(12.5^4 - 12.0^4) = 997 \text{ psi} .$$

From ref. 16, the maximum shear stress in the beam is

$$\tau = 4V/3A ,$$

where

V = maximum shear force in the beam (lb),

$$= \omega L / (2 - 2.5W) ,$$

A = cross-sectional area = $\pi(r_o^2 - r_i^2)$ (in.²).

Hence,

$$\tau = 4(2.5W)/3\pi(r_o^2 - r_i^2) = 10W/3\pi(r_o^2 - r_i^2) .$$

For model L,

$$\tau = 10(11,300)/3\pi(12.75^2 - 12.25^2) = 960 \text{ psi} .$$

For model M,

$$\tau = 10(9700)/3\pi(12.5^2 - 12.0^2) = 840 \text{ psi} .$$

The maximum principle stress, from Mohr's circle, is given by

$$\sigma_{\max} = (\sigma/2) + [(\sigma/2)^2 + \tau^2]^{1/2} ,$$

For model L,

$$\sigma_{\max} = (980/2) + [(980/2)^2 + 960^2]^{1/2} = 1568 \text{ psi} .$$

For model M,

$$\sigma_{\max} = (865/2) + [(865/2)^2 + 840^2]^{1/2} = 1377 \text{ psi} .$$

These stresses indicate that when regarded as a simply supported beam, the cask conforms to regulations since the yield stress is greater than the stresses generated in the material.

1.5.2 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.

Considering only the 1/4-in.-thick stainless steel cladding as a thin wall structure, the critical buckling pressure P_{cr} is given by the lesser value resulting from the solution of the expressions¹⁷

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

for axisymmetric buckling or

$$P_{cr} = \left| \frac{1.345E}{(1 - \nu^2)^{3/4}} \right| \left| \frac{(t/r_m)^{5/2}}{1.57(L/r_m) - (t/r_m)^{1/2}} \right|$$

for lobar buckling,

where

E = modulus of elasticity (psi),

ν = Poisson's ratio,

t = wall thickness (in.),

r_m = midwall radius (in.),

L = length (in.).

Thus,

$$P_{cr} = 2(30 \times 10^6)(0.25/12.5)^2/[3(1 - 0.3^2)]^{1/2} = 8400 \text{ psi and}$$

$$P_{cr} = \left| \frac{1.345(30 \times 10^6)}{(1 - 0.3^2)^{3/4}} \right| \left| \frac{(0.25/12.5)^{5/2}}{1.57(28/12.5) - (0.25/12.5)^{1/2}} \right| = 725 \text{ psi .}$$

Thus the cask meets the requirements of the regulations since the critical buckling pressure is much greater than the required 25 psi.

External pressure would load the flat ends of the stainless steel cladding. The external container structure and the massive uranium shields provide sufficient support to prohibit significant deflection of the flat ends due to external pressure. Gaskets have been used at differential pressures significantly greater than 25 psig and have been found to satisfy the requirements.

1.6 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 gasses 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.

1.6.1 Heat

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. A computer program, HEATING-3,¹⁸ was used to compute the steady-state temperature distribution in the cask and its contents under

the specified conditions. The models are shown in Figs. 2.1 and 2.2 and the input constants in Appendix B. The computed temperatures at locations of concern are outlined in Table 2.3. These temperatures will not adversely affect the containers. The physical properties of the materials of construction do not change to the extent that the integrity of the cask is compromised. The maximum allowable temperatures for various gasket materials and the calculated temperature at these points are discussed in Sect. 1.9 and tabulated in Table 1.7. The cask is able to withstand the calculated pressures (Sect. 1.6.3).

The DOT regulations³ further stipulate that the temperature of any accessible surface shall not exceed 122°F when the package is in the shade in still air and at ambient temperature. An exception to this is allowed by the regulation when packages are shipped in a sole-use vehicle, in which case the maximum accessible surface temperature can be 180°F. This evaluation is discussed in Sect. 2.3.2.

1.6.2 Cold

The shipping package must be able to withstand an ambient temperature of -40°F in still air and shade. Taking $T_1 = -40^\circ\text{F}$ (420°R) and assuming no internal heat load, the final or maximum pressure P_2 in any cavity sealed at a pressure of 14.7 psia and a temperature of 70°F (530°R) is

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

The resulting pressure differential is less than the 25-psig external pressure of Sect. 1.5.2. A temperature of -40°F is within the operating temperature range of the cladding, structural components, fasteners, and seals. Brittle fracture of these components under the stipulated cold condition is not likely since type 304L stainless steel retains most of its ductility at -40°F. The International Nickel Company reports¹⁹ that tensile strength and yield strength of type 304L stainless steel increase above room temperature and that ultimate elongation is in excess of 55% at -40°F. The notch toughness brittle-to-ductile transition temperature

of the ferritic type 405 stainless steel is reported in *Metals Handbook*²⁰ to be near room temperature. Data for type 405 is not specifically reported, but the similar type 430 retains about 30% of its room temperature Izod energy at -40°F. The -40°F Izod energy is about 10 ft-lb. A failure of the type 405 stainless steel liner of the model L cask would not compromise the containment nor the shielding of the cask.

Holden⁹ reported that the ductile-to-brittle transition temperature of uranium is close to room temperature. He also reported that a -40°F uranium has an ultimate elongation of 5%. Furthermore, the uranium could reach -40°F only if the cask were empty. These two facts imply that brittle fracture of the uranium is unlikely. Additionally, since the cask is a laminated structure, it is unlikely that flaws in material (where any cracking would occur) would line up; thus loss of shielding effectiveness would not occur.

The above considerations indicate that the stipulated cold conditions will not reduce the effectiveness of the packaging, and the container conforms to the requirements for the cold condition of normal transport.

1.6.3 Pressure

The regulations for normal conditions of transport specify that the package be able to withstand an atmospheric pressure of 0.5 times the standard atmospheric pressure, or 7.35 psia.

When the model is under full heat load, trapped air in all sealed cavities will expand and exert internal pressures. Assuming assembly at 70°F and 14.7 psia, the resultant pressure of any trapped air is

$$P_2 = P_1 T_2 / T_1 = 14.7 T_2 / 530 ,$$

where

P_1 = assembly pressure (psia),

T_2 = temperature under heat load (°R),

T_1 = assembly temperature (°R).

The pressures shown below were calculated by the above formula and refer to the model shown in Fig. 1.10, which is based on Fig. 2.1 and the information given in Table 2.3 and Sect. 2.3.4 for a heat load of 4000 W.

$$P_B = 22.6 \text{ psia} , \text{ where } T_2 = 354^\circ\text{F},$$

$$P_C = 24.9 \text{ psia} , \text{ where } T_2 = 436^\circ\text{F},$$

$$P_D = 29.2 \text{ psia} , \text{ where } T_2 = 592^\circ\text{F},$$

where

P_B = pressure in Cavity B,

P_C = pressure in Cavity C,

P_D = pressure in Cavity D.

As prescribed by the regulations, atmospheric pressure is $P_A = 7.35$ psia.

The pressure differential between the inner cavity and the cask body will cause no significant deformation of the cavity walls because these are supported by uranium. Considering the pressure differential between the cask body and the outside, the end plates are the weakest areas. The weakest end plate is the lid of model M because its lug plate structure is smallest. However, the pressure differential is greater at the cask bottom. For a conservative analysis, we consider the bottom-outside pressure differential applied to the lid of model M.

The model shown in Fig. 1.11b was used to approximate the stiffness of the 90° sector of the cask cover shown in Fig. 1.11a. Each section was treated as a plane section with length equal to its actual arc length. For Sect. A-A, Fig. 1.11b, the location of the neutral axis is

$$\begin{aligned}\bar{Y}_{AA} &= 3.14(0.25)(0.125) + 2(1)(1 + 0.25)/3.14(0.25) + 2(1) \\ &= 0.933 \text{ in} .\end{aligned}$$

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A

A

Fig. 1.10. Average cavity temperatures for pressure calculations.

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(a) PLAN VIEW, ACTUAL SECTOR

SECT. A-A
TYPICAL
SECTION

(b) PLAN VIEW, EQUIVALENT SECTOR

ALL DIMENSIONS GIVEN IN INCHES

Fig. 1.11. Equivalent cross section, end plates.

Similarly,

$$\begin{aligned}\bar{Y}_{BB} &= 0.666 \text{ in.}, \\ \bar{Y}_{CC} &= 0.532 \text{ in.}, \\ \bar{Y}_{DD} &= 0.451 \text{ in.}\end{aligned}$$

For Section A-A, the moment of inertia is

$$\begin{aligned}I_{AA} &= 1(2)^3/12 + 3.14(0.25)^3/12 + 2(1.25 - 0.933)^2 \\ &\quad + 3.14(0.25)(0.933 - 0.125)^2 = 1.384 \text{ in.}^4\end{aligned}$$

Similarly,

$$\begin{aligned}I_{BB} &= 1.988 \text{ in.}^4, \\ I_{CC} &= 2.305 \text{ in.}^4, \\ I_{DD} &= 2.492 \text{ in.}^4\end{aligned}$$

For this analysis, the equivalent thickness of a given cross section is the thickness of a rectangular cross section having the same moment of inertia as the given cross section. For a rectangular cross section,

$$I = bh^3/12 ,$$

where

b = length of the base of the rectangle (in.),

n = height of the rectangle (thickness of the cross section) (in.).

Solving for h,

$$h = [\sqrt[3]{12I/b}]^{1/3} .$$

Hence, for Sect. A-A the equivalent thickness

$$h_{AA} = [\sqrt[3]{12(1.384)/3.14}]^{1/3} = 1.74 \text{ in.}$$

Similarly,

$$h_{BB} = 1.40 \text{ in.},$$

$$h_{CC} = 1.25 \text{ in.},$$

$$h_{DD} = 1.15 \text{ in.}$$

According to Timoshenko,²¹ the maximum stress in a uniform circular plate subjected on one side to a uniformly distributed pressure is

$$\sigma_{\max} = 3qa^2/4h^2 ,$$

where

q = applied pressure (psig),

a = plate radius (in.),

h = plate thickness (in.).

Since the stress varies inversely with the square of the plate thickness, it is conservative to consider the cask lid as a uniform circular plate of thickness less than any of the equivalent thicknesses calculated above. Taking the lid thickness as 1.15 in. and the applied gage pressure $q = P_C - P_A$ (24.9 - 7.35) psig, then

$$\sigma_{\max} = 3(17.55)(12.75)^2/4(1.15)^2 = 1618 \text{ psi} .$$

For bending in the lid between two lug plates, Roark²² gives an expression for the maximum stress:

$$\sigma_{\max} = 0.24\omega a^2/t^2 ,$$

where

ω = applied pressure (psig),

a = plate radius (in.),

t = plate thickness (in.).

Thus,

$$\sigma_{\max} = 0.24(17.55)(12.75)^2/(0.25)^2 = 10955 \text{ psi} .$$

Neither of the above stresses would damage the cask since they are less than the yield stress.

1.6.4 Vibration

The containers are of welded construction and all weld designs call for complete penetration; therefore, transport vibrations are not expected to affect the integrity of the container weldment. All fasteners are equipped with lockwashers and will not loosen from vibrations. Properly installed pipe fittings generally do not loosen due to transport vibrations.

Furthermore, an extensive experimental evaluation was made of a considerably larger shipping cask manufactured from the same material.²³ This cask was shipped both by rail and by truck between Oak Ridge, Tennessee, and Paducah, Kentucky. The maximum acceleration rate even under heavy impact loading conditions during railcar switching was 6. The maximum by motor freight was 3. No damage was detected. Accelerations of this magnitude are of no concern structurally for either model. Many years of use have resulted in no damage from vibrations.

1.6.5 Water spray

The containment capabilities of the casks are not compromised by water spray since all external surfaces are stainless steel. The closure seal is an elastomer which is impervious to water.

1.6.6 Free drop

Regulations for normal conditions of transport require that a package weighing more than 10,000 lb be capable of withstanding a free drop through a distance of 3 ft onto a flat, essentially unyielding, horizontal surface, striking the surface in a position in which maximum damage is expected to result. Because the most damaging free drop orientation is not evident by inspection, several orientations are considered below.

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.

For top, bottom, and side impacts with the lug plates striking squarely, an existing ORNL computer (1014 CASK) program based on experimentally derived compressive stress-strain curves⁸ was used to calculate the resulting maximum accelerations and deformations as shown in Table 1.3 (input constants, typical program listing, and derivations of pertinent equations are presented in Appendix B). For this calculation only the model L cask is analyzed since it is the heavier cask and greater deformation will result.

Table 1.3 Maximum deformation and maximum acceleration experienced by ORNL uranium cask in 3-ft free drop

Orientation	Maximum deformation (in.)	Maximum acceleration (g's)
Bottom	0.140	450
Top	0.170	400
Side	0.300	235

Comparing the calculated deformations with the dimensions of the lug plates reveals that the lug plates are capable of absorbing all the available energy, and no plastic deformation of the cask body is expected to occur. Calculated time histories of acceleration deformation for these drops are shown in Figs. 1.12, 1.13, and 1.14.

Corner drop orientation was analyzed by another existing ORNL computer program also based on plastic deformation theory (Appendix B). The program assumes a diagonal axis of impact along the cask and assumes that all the energy is dissipated in plastic deformation of the cask.

Fig. 1.12. Three-ft top impact.

Fig. 1.13. Three-ft bottom impact.

Fig. 1.14. Three-ft side impact.

Because of the uncertainty of the dynamic properties of uranium, the program was used to examine several impacts, each using a different value for the specific energy of uranium ranging from 40,000 to 120,000 in.·lb/in.³ (Fig. 1.5 and Sect. 1.3.1). The greatest deformation and acceleration resulting from these calculations are 1.17 in. at a specific energy of 40,000 in.·lb/in.³ and 124 g's at a specific energy of 120,000 in.·lb/in.³, respectively. A deformation of this order would leave approximately 11 in. of uranium shielding at the corner. This amount of shielding is greater than the radial shielding thickness of the undamaged cask; therefore, the shielding effectiveness of the cask would not be reduced. Accelerations of this order would not damage the cask. Calculated time histories of acceleration vs deformation for this drop are presented in Figs. 1.15 and 1.16.

If model L were dropped with its axis horizontal and impacted along a line parallel to and midway between two lug plates (Fig. 1.17), some of the kinetic energy of the cask would be absorbed in deforming cooling fins. Davis²⁴ studied the deformation of cooling fins of various heights impacted at various angles. Reproduction of the curve for 3.5-in. fins at 0° inclination and the curves for 4-in. fins at 10°, 20°, 30°, and 40° inclination (Davis' Figs. 5.1-5.5) are shown in Fig. 1.18. Interpolation of these curves yielded the other curves shown, which are for the angles encountered in the impacts of these casks.

As used by Davis,

$$M_p = \sigma_y b t^2 / 4 ,$$

where

M_p = static plastic moment of specimen (in.·lb),

σ_y = yield stress of specimen (psi),

b = length of specimen (in.),

t = thickness of specimen (in.).

$$M_p = (30,000)(22.0625)(0.25)^2 / 4 = 10,340 \text{ in.·lb} .$$

Fig. 1.15. Three-ft corner impact.

Fig. 1.16. Three-ft corner impact.

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Fig. 1.17. Side impact between lug plates.

Fig. 1.18. Cooling fin energy absorption.²⁰ Curves for 0°, 10°, 20°, 30°, and 40° were experimentally obtained. Other curves were obtained by interpolation.

Davis' results²⁴ show that fins impacted at angles less than 10° fold into an s-shape or double-hinge mode so that their minimum deformed height is approximately three times their thickness. If it is assumed that the fin at $\alpha = 0$ is deformed so that its deformed height is $3t$, as shown in Fig. 1.17, then the deformation δ_α for any deformed fin is

$$\delta_\alpha = R + H - (R + 3t/\cos \alpha) ,$$

where

H = undeformed fin height (in.),

t = fin thickness (in.),

R = cask radius (in.),

α = angle made by fin and vertical.

Calculations of deformation times 100 divided by original height, as specified on the ordinate of Fig. 1.18, give the values of absorbed energy divided by plastic moment as shown in Table 1.4.

Table 1.4. Cooling fin energy absorption for model L

Angle ($^\circ$)	Deforma- tion (in.)	$(\delta/H)100$	Energy absorbed per fin/ plastic moment	No. of fins for angle	Energy absorbed/ plastic moment
0.0	2.25	75.0	33.5	1	33.5
7.5	2.13	71.1	23.6	2	47.2
15.0	1.77	59.1	12.9	2	25.8
22.5	1.14	37.9	4.0	2	8.0
30.0	0.16	5.4	0.6	2	1.2
					$\Sigma = 115.7$

Summing these values and multiplying by plastic moment gives the absorbed energy (A.E.). Thus,

$$A.E. = M_p \Sigma$$

where

Σ = sum of last column in Table 1.4,

M_p = plastic moment, (in.·lb),

A.E. = absorbed energy, (in.·lb).

$$A.E. = (115.7)(10,340) = 1.20 \times 10^6 \text{ in.·lb.}$$

The available kinetic energy is $(36)(11,300) = 4.07 \times 10^5 \text{ in.·lb.}$ Hence, the fins can absorb all the available energy of the 3-ft drop, and the body of the cask is not expected to be significantly deformed.

If model M were dropped with its axis horizontal and impacted along a line parallel to and midway between two lug plates (Fig. 1.17), some of the cask's kinetic energy would be dissipated in deforming the circular flanges near each end of the cask (Fig. 1.19). An existing ORNL computer program was used to analyze this impact (program listings and derivations of pertinent equations are presented in Appendix B). The program utilizes the plastic deformation theory for stainless steel material. This concept was discussed in Sect. 1.3.1 for the dynamic properties of uranium. The program uses specific energy values of 100,000 and 260,000 in.·lb/in.³ for stainless steel to obtain a bracketed solution (Fig. 1.3 and Table 1.2). Calculated time histories of acceleration vs deformation for these drops are shown in Figs. 1.20 and 1.21. The maximum calculated deformation and acceleration are 0.22 in. for a specific energy of 100,000 in.·lb/in.³ and 430 g's for a specific energy of 260,000 in.·lb/in.³, respectively. Since the flanges protrude 1-5/16 in. from the cask body, the shielding will not be deformed. Neglecting the energy dissipated in deforming cooling fins contributes to the conservatism of this analysis from the standpoint of cask damage or deformation. No loss of shielding or damage would result from the acceleration caused by a 3-ft drop onto the side.

1.6.7 Penetration

The 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

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Fig. 1.19. Side impact between lug plates, model M.

Fig. 1.20. Three-ft side impact between lug plates, model M.

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Fig. 1.21. Three-ft impact between lug plates, model M.

1-1/4 in. diam, 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 was performed on the cask with no damage to the cask.

1.6.8 Compression

Since the weight of both packages, including skid, exceeds 10,000 lb, no calculations are necessary.

1.7 Compliance with Standards for Hypothetical Accident Conditions

The 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 will not be sufficient to increase the external radiation dose rate to more than 1000 mR/hr at a distance of 3 ft from the outside surface of the package, no radioactive material will 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.

1.7.1 Free drop

The first in the sequence of hypothetical accident conditions to which the cask must be subjected is a free drop through a distance of 30 ft onto a flat, essentially unyielding, horizontal surface, striking the surface in a position in which maximum damage is expected to occur. Because the most damaging free-drop orientation is not evident by inspection, several orientations were considered.

Demonstration of compliance with this requirement by analytical methods is difficult because experimentally verified analytical techniques do not exist, and 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.

For top, bottom, and side impacts with the lug plates striking squarely, an existing ORNL computer program (1014 CASK) was used to calculate the resulting maximum accelerations and deformations as shown in Table 1.5 for the model L cask (Appendix B). The results are considered conservative for the model M cask.

Table 1.5 Maximum deformation and maximum acceleration experienced by ORNL uranium cask in 30-ft free drop

Orientation	Maximum deformation (in.)	Maximum acceleration (g's)
Bottom	0.52	980
Top	0.63	840
Side	1.17	460

Comparing the calculated deformations with the dimensions of the lug plates reveals that the lug plates absorb all the available energy and no plastic deformation of the cask body occurs. Calculated histories of acceleration vs deformation for these drops are shown in Figs. 1.22, 1.23, and 1.24.

Corner drop orientation was analyzed by another existing ORNL computer program (1001 CASK) (Appendix B). The program assumes a diagonal axis of impact along the cask and assumes that all the energy is absorbed in the cask in plastic deformation. Because of the uncertainty of the dynamic properties of uranium (Sect. 1.3.1), the program examines several impacts, each using a different value for the specific energy of uranium ranging from 40,000 to 120,000 in. $\cdot$ lb/in.³ (Fig. 1.5). The greatest deformation and acceleration resulting from these calculations are 2.96 in. for specific energy of 40,000 in. $\cdot$ lb/in.³ and 479 g's for a specific energy of 120,000 in. $\cdot$ lb/in.³, respectively. Calculated

Fig. 1.22. Thirty-ft bottom impact.

Fig. 1.23. Thirty-ft side impact.

Fig. 1.24. Thirty-ft top impact.

histories of acceleration vs deformation for this drop are presented in Figs. 1.25 and 1.26. Deformations and accelerations of these magnitudes will not affect the cask's ability to provide shielding (Sect. 4.1).

If model L were dropped 30 ft with its axis horizontal and impacted along a line parallel to and midway between two lug plates (Fig. 1.17) some of the kinetic energy of the cask would be absorbed in deforming cooling fins. As in Sect. 1.6.6, the total energy dissipated by the fins up to the beginning of cask body deformation is 1.20×10^6 in.·lb. The total energy available is $(360)(11,300) = 4.07 \times 10^6$ in.·lb. The remaining energy, 2.87×10^6 in.·lb, would be dissipated in deforming the cask body. (Energy dissipated in further deformation of fins is ignored for conservatism and calculational simplicity.) An existing ORNL computer program was used in analyzing this drop (Appendix B). Calculations were made using several values for the specific energy of uranium ranging from 40,000 to 120,000 in.·lb/in.³ (Fig. 1.5). Calculated histories of acceleration vs deformation for this drop are shown in Figs. 1.27 and 1.28. The maximum calculated deformation and acceleration are 0.4 in. for a specific energy of 40,000 in.·lb/in.³ and 1770 g's for a specific energy of 120,000 in.·lb/in.³, respectively. The thickness of the uranium shielding is thus reduced by no more than 0.4 in., leaving 6.35 in. of shielding intact.

As discussed in Sect. 1.6.6, a side drop of model M would deform the circular flanges near the ends of the cask (Fig. 1.19). An existing ORNL computer program was used to analyze a drop of this type from 30 ft (Appendix B). Calculated histories of acceleration vs deformation are shown in Figs. 1.29 and 1.30. The maximum calculated deformation and acceleration are 1.1 in. for a specific energy of 260,000 in.·lb/in.³ and 940 g's for a specific energy of 100,000 in.·lb/in.³, respectively. Since the flanges protrude 1-5/16 in. from the cask body, the shielding will not be significantly deformed. Neglecting the energy dissipated in deforming cooling fins contributes to the conservatism of this analysis.

Separation of the lid from the rest of the cask was considered for the side and corner drops. The maximum acceleration experienced by the casks in any drop discussed above is 1770 g's for model L and 940 g's

Fig. 1.25. Thirty-ft corner impact.

Fig. 1.26. Thirty-ft corner impact.

Fig. 1.27. Thirty-ft side impact between lug plates, model L.

Fig. 1.28. Thirty-ft side impact between lug plates, model L.

Fig. 1.29. Thirty-ft side impact between lug plates, model 11.

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Fig. 1.30. Thirty-ft side impact between lug plates, model M.

for model M. These occur in 30-ft side drops when the lids are oriented as shown in Fig. 1.31. The maximum force experienced by the lid is

$$F = ma$$

where

m = mass of the lid, slugs,

$$= \Sigma \gamma v / g,$$

a = maximum acceleration experienced by the lid (ft/sec²),

in which,

γ = weight density of material (lb/in.³),

v = volume occupied by material (in.³),

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

The densities of stainless steel and uranium (Table 1.2), are 0.283 and 0.69 lb/in.³, respectively; since the applicable mass is only that which is above the shearing plane (Fig. 1.31), $m_L = 55.63$ slugs and $m_M = 38.28$ slugs, then

$$F_L = (55.63)(1770)(32.2) = 3.17 \times 10^6 \text{ lb} ,$$

$$F_M = (38.28)(940)(32.2) = 1.16 \times 10^6 \text{ lb} .$$

For model L, the area of metal being sheared by this force includes the base area of the 1/4-in. "V" weld and the 1/4-in. fillet weld (Fig. A.4) all the way around in the stainless steel, the base area of the 1/2-in. bevel weld all the way around in the uranium, and the shear area of the 16 stainless steel closure bolts.¹⁵ These areas are

$$A_{sst} = \pi(25.125)(0.500) = 39.47 \text{ in.}^2 ,$$

$$A_u = \pi(10.125)(0.500) = 15.90 \text{ in.}^2 ,$$

$$A_B = 16(.334) = 5.34 \text{ in.}^2 ,$$

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Fig. 1.31. Lid-shearing diagram.

where

$$\begin{aligned} A_{sst} &= \text{shear area of stainless steel welds (in.}^2\text{),} \\ A_u &= \text{shear area of uranium weld (in.}^2\text{),} \\ A_B &= \text{shear area of closure bolts (in.}^2\text{).} \end{aligned}$$

The total load-bearing capacity of these areas is

$$F_{\max} = A_{sst} \tau_{sst} + A_u \tau_u + A_B \tau_B ,$$

where

$$\begin{aligned} \tau_s &= \text{ultimate shear strength of stainless steel (psi),} \\ \tau_u &= \text{ultimate shear strength of uranium (psi),} \\ \tau_B &= \text{ultimate shear strength of stainless steel bolts (psi)} \\ &\quad (\text{Table 1.2}). \end{aligned}$$

$$\begin{aligned} F_{\max} &= (39.47)(61,000) + (15.9)(35,000) + (5.34)(61,000) \\ &= 3.29 \times 10^6 \text{ lb .} \end{aligned}$$

Since $F_{\max}$ is greater than the applied load, the cover of model L will remain attached to the cask, and the contents will remain in the cavity.

For model M, the area stressed is in the four lug plates and the 1/4-in.-thick cladding

$$A = (24.375)(0.25)\pi + (4)(1)(1.5) = 25.14 \text{ in.}^2 .$$

The stress on this area is

$$\sigma = F_M/A = (1.16 \times 10^6)/25.14 = 46,100 \text{ psi .}$$

Since this stress is below the ultimate shear strength of type 304L stainless steel (Table 1.2), the lid will remain attached to the cask, and the contents will remain in the cavity.

The shielding capability of the cask would be reduced if the shielding were deformed so that its thickness at any point were less

than that required for adequate shielding. As shown by Fig. 1.32a, if the cask impacted squarely, the S dimension could deform so that the shielding was no longer of the required thickness. For this to occur, the compressive stress in the shielding would have to equal or exceed the yield point of uranium, which is 25,000 psi (Table 1.2). Considering a column of shielding material with a 1-in.² cross section as shown in Fig. 1.32b, the stress at the bottom of the column is

$$\sigma = P/A = P/1 = P ,$$

where

P = load on the bottom of the column (lb),

A = the cross-sectional area of the column (in.²).

From Newton's second law,

$$P = ma = AL\gamma a/g ,$$

where

m = mass of column, slugs,

a = acceleration of column (ft/sec²),

γ = weight density of uranium (lb/in.³),

L = length of column of uranium for model L (in.),

A = cross-sectional area of column (in.²),

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

Hence,

$$\sigma = AL\gamma a/g .$$

The worst case for this type of deformation will be vertical impact on the cask bottom. Taking the maximum acceleration from Table 1.5 and the weight density of uranium from Table 1.2,

$$\sigma = (1)(27.69)(0.69)(980)g/g = 18,720 \text{ psi} .$$

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Fig. 1.32. Shielding deformation, bottom impact.

Since the yield point of uranium is not reached, there will be no plastic deformation, and no reduction of shielding capability will occur for end impact.

For corner impact, the most damaging case is impact on one of the top corners. Although the shielding is thinner at the bottom, the lug plate structure at the bottom is sufficient to prevent significant deformation of the shielding. In this case, the uranium is 6.8125 in. thick in the wall and 8.5 in. thick in the lid. For the top corner of model L (Fig. 1.33), the length L is

$$L = (8.5/\cos \alpha) + [(6.8125 - 8.5 \tan \alpha)(\sin \alpha)] - \delta ,$$

where

α = impact angle,

δ = calculated deformation (in.) (Fig. 1.33).

Since the axis of impact is along the cask diagonal,

$$\alpha = \tan^{-1} d/h ,$$

where

d = cask diameter (in.),

h = cask height (in.).

Referring to Fig. 1.33,

$$\alpha = \tan^{-1}(25.5/33.75) = 37.1^\circ .$$

Hence,

$$\begin{aligned} L &= (8.5/\cos 37.1^\circ) + (6.8125 - 8.5 \tan 37.1^\circ)(\sin 37.1^\circ) - 2.96 \\ &= 7.89 \text{ in.} \end{aligned}$$

This is thicker than the undeformed shielding thickness of the cask wall, and therefore sufficient shielding remains after the accident.

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ALL DIMENSIONS GIVEN IN INCHES

Fig. 1.33. Uranium shielding deformation, corner impact, model L.

1.7.2 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 to the top end of a vertical, cylindrical mild steel bar mounted on an essentially unyielding horizontal surface. The mild steel bar shall have a diameter of 6 in. with its 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.

The energy resulting from a 40-in. free drop and impact with the surface of the cask to the 6-in.-diam bar will be absorbed through plastic compression of the mild steel bar and the 1/4-in.-thick stainless steel cladding. It may be said that

$$\begin{aligned}
 U = Wh = 5.28 \times 10^5 &= U_{ss} + U_{ms} = \int_0^{\Delta_{ss}} F_{ss} d\delta_{ss} + \int_0^{\Delta_{ms}} F_{ms} d\delta_{ms} \\
 &= \int_0^{\Delta_{ss}} \sigma_{ss} A_{ss} d\delta_{ss} + \int_0^{\Delta_{ms}} \sigma_{ms} A_{ms} d\delta_{ms},
 \end{aligned}$$

where

U = energy (in.·lb),

W = weight of cask (lb),

h = drop height (in.),

F = force (lb),

Δ = deflection (in.),

$d\delta$ = incremental deflection,

σ = stress (psi),

A = original cross-sectional area of member undergoing deformation (in.).

ss = subscript denoting stainless steel,

ms = subscript denoting mild steel.

It is known that stress is a function of strain, that is,

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

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

where

ϵ = strain (in./in.),

L = original length (in.).

The author has published these relationships for mild steel and stainless steel.⁶

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

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

Substituting these relationships into the integral equation for energy absorption,

$$U = \int_0^{\Delta_{ss}} (6.42 \times 10^5 \frac{\delta_{ss}}{L_{ss}} + 50,300) A_{ss} d\delta_{ss} \\ + \int_0^{\Delta_{ms}} (3.45 \times 10^5 \frac{\delta_{ms}}{L_{ms}} + 73,000) A_{ms} d\delta_{ms} .$$

Note that the area of the stainless steel cladding involved is the same as the area of the piston. The length of the piston is assumed to be 8 in. since this will maximize acceleration.

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

$$F_{ss} = F_{ms} ,$$

$$\sigma_{ss} A_{ss} = \sigma_{ms} A_{ms} ,$$

but

$$A_{ss} = A_{ms} ;$$

therefore,

$$\sigma_{ss} = \sigma_{ms} ,$$

and

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

$$\Delta_{ss} = 0.537 \frac{\Delta_{ms}}{8.0} (.25) + 0.03536 (.25) ,$$

$$\Delta_{ss} = 0.0168 \Delta_{ms} + 0.00884 .$$

Substituting back into the equation for absorbed energy,

$$\begin{aligned} \frac{U}{A} &= 1.28 \times 10^6 (0.0168 \Delta_{ms} + 0.00884)^2 \\ &+ 50,300 (0.0168 \Delta_{ms} + 0.00884) + 2.16 \times 10^4 \Delta_{ms}^2 \\ &+ 73,000 \Delta_{ms} . \end{aligned}$$

Simplifying this quadratic equation and solving using the quadratic formula,

$$\Delta_{ms} = 0.22888 \text{ in. ,}$$

and

$$\Delta_{ss} = 0.0168(0.22888) + 0.00884 \text{ ,}$$

$$\Delta_{ss} = 0.01267 \text{ in. ,}$$

since

$$F = A\sigma = A_s [f(\epsilon)],$$

$$F_{ss} = [\pi(3)^2](6.42 \times 10^5 \frac{\Delta_{ss}}{L_{ss}} + 50,300),$$

$$F_{ss} = 28.27(82,837),$$

$$F_{ss} = 2,341,790 \text{ lb.}$$

From Newton's second law of motion, the peak acceleration is

$$a_{\max} = \frac{F}{m} = \frac{2.41 \times 10^6}{11,300} = 207 \text{ g .}$$

Since this acceleration is less than that associated with the 30-ft impact on the side, it is concluded that containment will be maintained and that shielding will be adequate.

1.8 Special Form

The ORNL Radioisotopes Department of Operations Division certifies that a material conforms to the special form requirements of Appendix D of 10 CFR 71.¹ 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. 1.34 and 1.35.

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Fig. 1.34. Special form inner container.

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Fig. 1.35. Special form inner container.

1.9 Inner Container Design

Typical inner 2R containers used at ORNL are shown in Fig. 1.36. Materials and bolting are limited to that given in Table UHA 23 of the *ASME Boiler and Pressure Vessel Code*.²⁵ Design temperature is taken as 800°F, which is the maximum temperature for which an allowable stress is listed for type 304L stainless steel in Table UHA-23.²⁵ This is a conservative design temperature for the inner container since the maximum temperature for normal conditions of transport for the 3000 W case is 660°F (Table 2.3). Assuming assembly at 70°F and 14.7-psia air pressure, a temperature of 800° will produce a pressure of

$$P_2 = P_1 T_2 / T_1 = 14.7(800 + 460) / (70 + 460) = 34.95 \text{ psia}$$

in the container. Assuming the least external pressure experienced to be 0.5 atm (see Sect. 1.6.3), the greatest gage pressure experienced is $34.95 - 7.35 = 27.6$ psig. Hence, design pressure is established conservatively as 30 psig. Design stress is 9000 psi, which is the minimum listed in the tables for 800°F.²⁵

For use with the uranium-shielded cask, the containers will have the minimum head and wall thicknesses given in Table 1.6. These dimensions are based on the requirements of Specification 2R¹⁴ and of Sect. VIII of the *ASME Boiler and Pressure Vessel Code*,²⁵ whichever is greater. The applicable equations for sizing shells and heads are for the shell, Eq. (1), para aph UG 27,

$$t = PR / (SE - 0.6P)$$

and for the top and bottom heads, Eq. (1), paragraph UG 34,

$$t = d(CP/S)^{1/2} ,$$

$$d_h = d + 0.375 .$$

Fig. 1.36. 2R container.

Table 1.6 Dimension schedule for specification 2R containers
(Fig. 1.36)

d	t_s	t_f	t_h	t_a	Bolts	
					Number	Size
2	3/32	3/16	3/16	3/8	4	1/4 - 20
3	1/8	1/4	1/4	3/8	6	1/4 - 20
4	1/8	1/4	1/4	3/8	8	1/4 - 20
5	1/8	1/4	1/4	3/8	8	5/16 - 18
6	1/8	3/8	1/4	3/8	8	5/16 - 18
8	1/4	3/8	3/8	3/8	8	3/8 - 16
10	1/4	1/2	3/8	1/2	12	3/8 - 16
12	1/4	1/2	1/2	1/2	16	3/8 - 16

The stress in the bolts due to the pressure in the container is

$$\sigma = pA/nA_s = p\pi d^2/4nA_s ,$$

where

p = internal gage pressure (psi),

n = number of bolts,

A = area of container lid exposed to internal pressure (in.²),

A_s = stress area of bolts (in.²),

d = diameter of container lid (in.).

The greatest stress on the 1/4 - 20 bolts (Table 1.6) will occur for the greatest value of d^2/n which corresponds to $d = 4$ in., $n = 8$ bolts.

$$\sigma = 30\pi 4^2/4(8)(0.0317) = 1490 \text{ psi} .$$

For the 5/16 - 18 bolts, the worst case is

$$\sigma = 30\pi 6^2/4(8)(0.0522) = 2030 \text{ psi} .$$

For the 3/8 - 16 bolts, the most damaging case is

$$\sigma = 30\pi 12^2 / 4(16)(0.0773) = 2740 \text{ psi} .$$

The bolting is increased beyond that required for pressure to ensure leak tightness in the accident. Some dimensions are increased beyond the calculated values or those required by specification 2R to facilitate fabrication.

Metal O-rings can be used in all 2R containers. As calculated in Sect. 2.3.2 and presented in Table 2.1, a heat load of 3000 W produces no temperatures greater than 800°F, which is the maximum allowable operating temperature for metallic (Inconel 600) O-rings. See Table 1.7 for the complete description of various gasket material applications in the uranium cask.

Fabrication will be in accordance with ORNL quality assurance procedures. Applicable approved ORNL welding procedures will be used for welding. All welds will be appropriately inspected in accordance with approved ORNL weld inspection procedures. All containers shall be leak tested using vacuum bubble techniques²⁶ or helium leak detection methods.

1.10 Thermal Expansion Stresses

The linear coefficient of thermal expansion for stainless steel is 9.6×10^{-6} in./in.°F (Table 1.2); that for uranium is 8.04×10^{-6} in./in.°F. Hence, the steel shell will expand more than the uranium. Since thermal expansion of the uranium will be unrestricted, there will be no induced stresses due to thermal expansion.

1.11 Thermal Stresses

The results of the heat transfer analysis indicate that the most severe thermal gradients occur across the cylindrical uranium slabs in the plug and the bottom of the cask (Fig. 0.3). The most damaging of these is a 44°F temperature difference across the upper base slab (between points H and I from Table 2.3) for the 4000 W case in the shade.

Table 1.7. Maximum allowable and calculated temperatures for normal conditions for various gasket materials

Material	Maximum heat load (W)	Maximum allowable continuous temp. (°F)	Calculated temperature at maximum heat load for normal conditions of transport ^a	Calculated temperature at maximum heat load for thermal accident conditions ^b
Closure gaskets	1250	300 ^c	230	900
Neoprene			(interpolated)	
Silicone rubber	4000	450 ^c	292	986
2R Container gaskets	3000		627	780
Metallic O-rings				(interpolated)
Inconel 600		800 ^d		
Inconel X-750		1300 ^d		

^aTable 2.3.

^bFig. 2.4 and Sect. 2.1.

^cParker Seal Company, *Seal Compound Manual*, C5702, Cleveland, Ohio, 1971.

^dUnited Aircraft Products, Inc., *United Metallic O-Rings*, No. 7111.

A comparison of the gradient across this slab for the accident condition and the 4000 W shade case also supports the selection of 4000 W shade case as the most severe condition. Harvey²⁷ gives an expression for the maximum stress σ in this situation as

$$\sigma = E\alpha(T_2 - T_1) ,$$

where

E = Young's modulus,

α = coefficient of thermal expansion ($^{\circ}\text{F}^{-1}$),

T_2 = temperature at the hotter face ($^{\circ}\text{F}$),

T_1 = temperature at the cooler face ($^{\circ}\text{F}$).

Referring to Table 1.2 for E and α and noting that $T_2 - T_1 = 44^{\circ}\text{F}$,

$$\sigma = (30 \times 10^6)(8.04 \times 10^{-6})(44) = 10,612 \text{ psi} .$$

This stress is well below the yield stress of the material.

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 regulations³ set forth by DOT further stipulate that the temperature of any accessible surface of the fully loaded shipping package shipped by common carrier shall not exceed 122°F or being transported on a sole-use vehicle shall not exceed 180°F when the package is in the shade in still air at an ambient temperature. For this evaluation, ambient temperature was assumed to be 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 heating 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 3 hr after the 30-min test period has expired unless it can be shown that the temperature at the center of the package has begun to fall in less than 3 hr.

A computer program, HEATING-3,¹⁸ was used to determine the temperature distribution. Analyses were performed for the container loaded with (1) the maximum permissible heat load of 4000 W, (2) the limit for shipment via common carrier, 1250 W, and (3) the heat load of 3000 W, the lower limit of heat load for which special form is required (Table 2.1). The temperature distributions from 100°F ambient conditions with 4000 W internal heat load were input as starting temperatures for the accident (fire) calculation. In addition, a fire case for 600 W case was run, but the results were used only for interpolation purposes to anticipate the temperatures for the 1400 W and the 3000 W cases in a fire.

Table 2.1 Cases examined

Decay heat load (W)	100°F shade	130°F solar	Fire
1250	x		
3000		x	
4000	x	x	x

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 2.2.

2.3 Thermal Evaluation for Normal Conditions of Transport

2.3.1 Thermal model

The models used for the heat transfer computations are shown in Figs. 2.1 and 2.2. The contents are modeled as a uniform body, nominally

Table 2.2 Material properties used in thermal analysis

Material	Temperature (°F)	Thermal conductivity (Btu/hr·ft·°F)	Density (lb/in. ³)	Heat capacity (Btu/lb·°F)
Cast uranium ^{a,b,c}	32	15.6	0.6879	
	80	15.9		
	170	16.5		
	200			0.0278
	260	17.1		
	400			0.0295
	440	18.3		
	600			0.0326
	620	19.6		
	800	21.0		0.0366
	980	22.4		
	1000			0.0410
	1100			0.0433
	1160	23.9		
	1200			0.0464
	1340	25.4		
	1520	26.8		
	1700	28.3		
Laminated uranium ^{b,d}	200		0.6879	0.0278
	244	5.4		
	339	6.2		
	400			0.0295
	600			0.0326
	800			0.0366
	1000			0.0410
	1100			0.0433
	1200			0.0464
Stainless steel ^{a,e}	32	8.5	0.286	0.120
	80	8.7		
	170	9.4		
	260	10.2		
	350	10.2		
	440	10.6		
	620	11.4		
	752			0.135
	800	12.2		
	980	13.0		
	1160	13.8		
	1340	14.6		
	1520	15.4		
	1700	16.2		
	2000			0.160

Table 2.2 (continued)

Material	Temperature (°F)	Thermal conductivity (Btu/hr·ft·°F)	Density (lb/in. ³)	Heat capacity (Btu/lb·°F)
Air ^f	32	0.0140	4.69×10^{-5}	0.240
	100	0.0154	4.11×10^{-5}	0.240
	200	0.0174	3.47×10^{-5}	0.241
	300	0.0193	3.01×10^{-5}	0.243
	400	0.0212	2.66×10^{-5}	0.245
	500	0.0231	2.38×10^{-5}	0.247
	600	0.0250	2.16×10^{-5}	0.250
	700	0.0268	1.97×10^{-5}	0.253
	800	0.0286	1.82×10^{-5}	0.256
	900	0.0303	1.68×10^{-5}	0.259
	1000	0.0319	1.57×10^{-5}	0.262
	1500	0.0400	1.17×10^{-5}	0.276

^aThe thermal conductivity values for stainless steel and cast uranium were obtained from Y. S. Touloukian, *Thermal Conductivity*, Plenum, New York, 1970.

^bThe density and heat capacity values for uranium were obtained from M. M. El-Wakil, *Nuclear Heat Transport*, International Text Book, Scranton, Pa., 1971.

^cApproximate emissivity values:

Material	ϵ
Stainless steel	0.6
Sandblasted stainless steel	0.7
Uranium	0.6

^dThe thermal conductivity values for laminated uranium was based upon experimental data taken from C. B. Clifford, *Design and Fabrication of a Prototype Laminated Uranium Metal Shipping Cask for Large Shipments of Cobalt-60*, Report KY-521, April 3, 1967.

^eThe density and heat capacity values for stainless steel were obtained from *A Compilation of Thermal Property Data for Computer Heat-Conduction Calculations*, UCRL-50589.

^fAll air properties were obtained from F. Krieth, *Principles of Heat Transfer*, International Text Book, Scranton, Pa., 1958.

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Fig. 2.1. Heat transfer model 1.

Fig. 2.2. Heat transfer model 3.

with physical properties of stainless steel, with the decay heat evenly distributed throughout. The cask contents applicable to heat loads at or approaching the maximum load of 4000 W would consist of special form encapsulated material in a tightly packed array such that the cavity would be essentially full. The model will result in higher contents temperatures since the assumed bottom contact area of the inner container with the cask is significantly less than actual, and no contact with the cavity wall was assumed in the model (Fig. 2.1). The cask contents applicable to a heat load of 1250 W would vary in shape from shipment to shipment. A parametric study based upon a maximum decay heat rate of 0.1 W/cm^3 was made to determine the length-radius characteristics of the contents that would result in the maximum contents temperature for a given decay-heat load. The contents configuration resulting in the maximum contents temperature for a decay-heat load of 1250 W is shown in Fig. 2.2. The detailed fin geometry was not included in the model. However, the effect of the fins was accounted for by the use of a modified heat transfer coefficient for the fin region. To effect a conservative solution, end effects were neglected in the calculations.

Except for the fins, the heat transfer calculations were a straightforward application of the computer code. The fins were treated as longitudinal fins with no heat loss from the end. The nominal fin dimensions are $19-7/8$ by 3 by $1/8$ in. spaced 10° apart for model M. For model L the fins are $22-11/16$ by 3 by $1/4$ in. spaced $7-1/2^\circ$ apart. Using the model M fin dimensions for both models will result in a conservative analysis for model L. The expression for the efficiency of these fins is

$$\eta = (\tanh mb)/mb, \quad (1)$$

where

b = fin height (in.),

$m = (wh/k\delta)^{1/2},$

in which

k = fin conductivity (Btu/hr·ft·°F),

w = fin thickness (in.),

h = convection coefficient (BTU/hr·ft²·°F).

For air as the cooling fluid, h can be approximated as²⁸

$$h = 0.29(\Delta T/L)^{0.25} \text{ Btu/hr·ft}^2\text{·°F} , \quad (2)$$

where L is fin length (19.875 in.). For normal condition temperatures, k is approximately equal to 9 Btu/hr·ft·°F. Thus, it turns out that

$$mb = 0.5834 \Delta T^{0.125} . \quad (3)$$

By definition,

$$\eta = \frac{\text{Actual heat dissipated by fin}}{\text{Heat dissipated if entire fin surface operated at the fin root temperature}} . \quad (4)$$

Define $\bar{h}$ and $\bar{A}$ as the convective coefficient and area to be input to HEATING-3, respectively; then

$$\bar{h} \bar{A} \Delta T = \eta(hA_{\text{fin}} \Delta T) + (hA_{\text{surface}} \Delta T) , \quad (5)$$

where

A_{fin} = actual fin area,

h = convection coefficient for vertical plates and cylinders (Btu/hr·ft²·°F),

A_{surface} = actual outer surface area (in finned section) not covered by fins (ft²),

ΔT = temperature difference between the fin base and the air (°F).

The numerical values for these parameters are obtained as follows:

$$\bar{A} = 2\pi rL = 2\pi(12.75)(19.875)/144 = 11.06 \text{ ft}^2 ,$$

where

L = the fin length,

r = the root radius of the fins (radius used by HEATING-3),

$$A_{fin} = 2bLn = 2(d/12)(19.875/12)(32) = 26.50 \text{ ft}^2,$$

where

L = the fin length,

b = the fin depth,

N = the number of fins,

$$A_{surface} = 2\pi rL - NL\delta = 2\pi(12.75/12)(19.875/12) - 32(19.875/12)(0.125),$$

$$A_{surface} = 10.50 \text{ ft}^2.$$

The expression for $\bar{h}$, the effective heat transfer coefficient, can now be written as

$$\bar{h} = (\eta h A_{fin} + h A_{surface}) / \bar{A}, \quad (6)$$

$$\bar{h} = (\eta h(26.50) + h(10.50)) / 11.06,$$

or

$$\bar{h} = h(2.40\eta + 0.95). \quad (7)$$

In the HEATING-3 analysis of casks, the convection coefficients, such as h , are routinely treated as functions of the surface-to-ambient ΔT . This functional dependence was used in Eq. (7), along with the same type of dependence exhibited by η to develop a ΔT -dependent surface heat transfer coefficient for the finned region, which was subsequently used in HEATING-3 as the boundary condition for the finned region.

For the purposes of radiant heat transfer, the finned region was treated as a cavity radiator. The effective emissivity for such is given by

$$\bar{\epsilon} = 1 / \{1 + (\delta/s) [(1/\epsilon) - 1]\} \text{ (Ref. 7) },$$

where

δ = face-to-face distance between fins (in.),

$s = \delta + 2b$.

The fins are spaced at 10° circumferentially with a 12.75-in. root radius. Thus

$$\delta = 12.75(2\pi)(10/360) = 2.33 \text{ in.},$$

$$s = 2.23 + 2(3) = 8.23 \text{ in.},$$

$$\bar{E} = 1/[1 + (2.23/8.23)(1/0.7 - 1)] = 0.8961.$$

The effective conductivity of the laminated uranium sheets was estimated from the experiments and data presented in ref. 4. This estimation was based on measured temperatures at two different known heat loads. The result was an effective conductivity in the radial direction that was about 30% of that for solid, pure uranium metal. This decrease in effective conductivity is due to the air gaps between the laminated uranium sheets.

In calculating the steady state temperatures for the 130°F environment in direct sunlight, it was assumed that a solar heat influx of $144 \text{ Btu/hr}\cdot\text{ft}^2$ was incident upon the cask. The fraction of the incident solar flux that is absorbed by the cask is equal to the absorptivity of the cask, estimated to be 0.7. Based upon an approximate absorptivity of 0.7 for sandblasted stainless steel and an actual total top and side area of the cask, the solar heat flux into the cask is $100.8 \text{ Btu/hr}\cdot\text{ft}^2$. 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

Temperatures at points of interest throughout the cask are given in Table 2.3. Data are presented for the 130°F ambient-solar load of $144 \text{ Btu/hr}\cdot\text{ft}^2$ incident on the cask and 100°F ambient environments.

The maximum accessible surface temperature for the 100°F ambient temperature case is based on experimental tests reported by Clifford.⁴ Figure 2.3 and Table 2.4 reproduce the reported surface temperature

Table 2.3. Calculated temperatures during normal conditions of transport for various internal heat loads

Point ^a		Temperature (°F)			
		100°F shade (1250 W)	100°F shade (4000 W)	130°F solar (3000 W)	130°F solar (4000 W)
A	Contents maximum temperature	579	747	660	777
B	Contents midplane edge	532	697	627	728
C	Inner surface uranium plates	194	407	396	453
D	Radial midpoint, uranium plates	184	327	336	373
E	Outer surface, uranium plates	179	287	307	335
F	Cask outer surface and midplane	179	285	305	332
G	Closure seal	151	239	278	292
H	Inner surface of lid	177	331	341	382
I	Axial midpoint of lid	164	287	313	341
J	Top surface of lid	157	260	294	313
K	Interior of lower plug				436

^aSee Figs. 2.1 and 2.2.

data. The tests were conducted with an internal heat load of 4090 W indoors (no solar load) at an ambient temperature of 76°F and at a heat load of 2405 W with a 75°F ambient temperature. Linear extrapolation of the temperature differences was used to estimate the personnel shield temperature for the case of 4000 W with a 100°F ambient and of 1400 W with a 100°F ambient. These temperatures, also presented in Table 2.2, indicate that the package complies with DOT surface temperature regulations.³ The maximum surface temperature applicable to 4000 W, the limit for a sole-use vehicle, is 163°F as compared with the allowable of 180°F. The maximum personnel-shield surface temperature for 1250 W load is 122°F, the allowable limit.

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Fig. 2.3. Schematic representation of temperature measurement locations for Clifford's data.

Table 2.4 Surface temperatures

Temperature measuring point ^a	Temperature (°F)		
	Experimental (4090 W, 76°F)	Extrapolated (4000 W, 100°F) (1250 W, 100°F)	
1	140	163	122
2	212	233	147
3	107	130	111
4	207	228	146
5	95	119	107
6	280	300	170
7	86	110	103
8	264	284	164
9	101	124	109
10	217	238	148

^aRefer to Fig. 2.3 for location of these points.

2.3.3 Minimum temperatures

Reduced or zero heat loads would lower temperatures throughout the container. This would not be expected to affect the integrity of the cask. There is no material present whose properties are drastically altered by the lowered temperatures (Sect. 1.6.2).

2.3.4 Maximum internal pressure

The pressure in the central cavity, contents, and gap region above the uranium plates will increase after the cask is loaded and sealed. This is due to the heat source in the contents raising the gas temperature in these regions. If ideal gas behavior and constant gas volume are assumed and if the gas regions were assumed initially to be at 70°F

(530°R) and 14.7 psia when the cask was sealed, the resulting pressure P is given by

$$P = 14.7T/530 ,$$

where T is the elevated gas temperature.

The following pressures correspond to temperatures at the 130°F ambient-solar case for a decay heat rate of 4000 W.* For gas in the upper shielding cavity, $T = 354^{\circ}\text{F}$,

$$P = 14.7(814)/530 = 22.6 \text{ psia} .$$

For gas in the lower shielding cavity, $T = 436^{\circ}\text{F}$,

$$P = 14.7(896)/530 = 24.9 \text{ psia} .$$

For air in the central cavity, $T = 592^{\circ}\text{F}$,

$$P = 14.7(1052)/530 = 29.2 \text{ psia} .$$

For gas in the special form or 2R container, $T = 777^{\circ}\text{F}$,

$$P = 14.7(1237)/530 = 34.3 \text{ psia} .$$

See Sect. 1.6.3 for the effects of pressure on the cask for normal conditions of transport. See Sects. 1.8 and 1.9 for discussion of inner container design.

2.4 Hypothetical Thermal Accident Evaluation

Damage from the free drop and puncture portions of the hypothetical accident is not expected to adversely affect the thermal performance of the container.

* Temperatures used are representative of the various regions.

2.4.1 Thermal accident analysis

Effects of the hypothetical thermal accident were analyzed using the same geometric model in a HEATING-3 computer calculation that was used for the normal conditions analysis. Boundary condition parameters were adjusted to include the 1475°F radiant environment for the 30-min thermal exposure. Surface convection parameters were modified to account for the elevated surface temperature.

2.4.2 Thermal model

The computer models discussed in Sect. 2.4.1 were used to determine the temperature distribution within the container during the 30-min thermal exposure and postexposure cooldown period. Steady-state temperature distribution for 100°F ambient temperature for the 4000 W case was used to start the calculations. The postexposure period was considered over a time span sufficient to allow all cask temperatures to begin decreasing with time. No special cooling was assumed, only normal radiation and natural convection transfer to the 100°F environment.

2.4.3 Maximum temperatures

The temperature-time history of several points of interest is given in Fig. 2.4. (See Fig. 2.1 for explanation of these point locations.) The computer calculation predicts the maximum centerline temperature to be 937°F for a decay heat load of 4000 W. Maximum temperature of the closure seal is predicted to be 986°F for a decay heat load of 4000 W; thus this seal will fail in the thermal incident.

2.4.4 Maximum pressures

The central cavity pressure increase will not be calculated since the primary seal has been predicted to fail. Since such a seal could fail over some significantly broad range of temperatures, an arbitrary maximum temperature at failure could be postulated, and the pressure increase could be calculated as in Sect. 2.3.4. For the other two gas

Fig. 2.4. Cask time-temperature history for 4000 W thermal accident.

regions, contents, and above uranium plates, the pressure increase was calculated using the method of Sect. 2.3.4 as follows:

For 4000 W,

contents: $P = 14.7(1397)/530 = 38.7 \text{ psia} = 24.0 \text{ psig}$;

uranium plates: $P = 14.7(1260)/530 = 34.9 \text{ psia} = 20.2 \text{ psig}$.

The results of this contents pressure on containment is discussed in Sect. 3.3. This pressure in the uranium plate cavity will not compromise the integrity of the cask since the gage pressure is not significantly greater than the gage pressure for the reduced atmospheric pressure condition for normal conditions as calculated in Sect. 1.6.3. There were no critically stressed members calculated for that condition.

2.4.5 Evaluation of package performance

Temperatures and pressures resulting from the hypothetical thermal accident will cause a loss of the secondary seal integrity. No melting of either cask or contents is expected. The thermal accident is not believed to reduce the shielding effectiveness of the cask. Primary containment is expected to be maintained during the thermal accident.

3. CONTAINMENT

3.1 Containment Boundaries

Containment boundaries for the shipping options available with this package are described below.

3.1.1 Special form shipments

For all special form shipments the welded encapsulation serves as primary containment. See Figs. 1.34 and 1.35 for examples of special form encapsulations and Sect. 1.8 for description of ORNL special form certification. If the material is doubly encapsulated, the outer welded capsule forms secondary containment. These lines of containment are routinely leak checked using mass spectrometer or vacuum leak test detection techniques.²⁵ The cask forms an additional line of containment.

Casks are equipped with gasketed closures which are leak tight during normal transport. An accident would result in leakage from the cask cavity of some coolant (air), but the contents would remain in the cavity (Sect. 1.7).

3.1.2 Other shipments

All materials shipped which do not conform to special form are contained in a Specification 2R container (Sect. 1.9), which forms primary containment. Typical examples of ORNL 2R containers are illustrated in Fig. 1.36. These containers are designed to be leak tight to the extent that water will not leak from the container at the anticipated pressure and room temperature. The container shown in Fig. 1.36d is designed to be leak checked and will be leak tight to the extent that leaks are not detectable by vacuum-bubble or time-pressure drop techniques. All powders and other dispersables will be shipped in 2R containers which are leak checked. The cask forms secondary containment.

3.2 Requirements for Normal Conditions of Transport

The test sequence for special form is more severe than the normal conditions of transport; hence there will be no release of radioactive material from the containment vessel(s). Pressure rises encountered during normal conditions of transport will be less than those experienced in the special form thermal test. There will be no loss of primary coolant (air). The 2R containers are designed (Sect. 1.9) for pressures and temperatures in excess of those encountered in normal transport; hence there should be no release of radioactive material or loss of coolant (air).

3.3 Containment Requirements During the Hypothetical Accident

The test series for special form demonstrates that special form encapsulation will not fail nor leak contents as the result of the free falls. The tests required for special form certification demonstrate this. The special form thermal test results in temperatures in excess of those applicable to the contents during the specified thermal

exposure (Chapter 2); hence there will be no release during the thermal exposure. The water immersion test for special form is identical to the hypothetical accident condition specified.

Tests (Appendix C) of Specification 2R containers indicate that they conform to the 30-ft free-fall regulations. As shown in Sect. 1.9, the 2R container is acceptable for the ASME pressure code calculations for the design temperatures of 800°F. The expected accident condition temperature is only 850°F for the 3000 W case as interpolated between the 4000 W fire test as shown in Fig. 2.4 and a 600 W fire test that is discussed in Sect. 2.1. Since the accident temperature is very close to the design temperature, no catastrophic failure of the 2R container is anticipated. As seen in Table 1.7, the metallic O-ring gaskets used in 2R containers will not reach their maximum allowable temperature; therefore, the gaskets will not fail and containment is maintained.

4. SHIELDING EVALUATION

4.1 Discussion and Results

Gamma shielding in the model L cask is effected by depleted uranium fabricated in solid billet or laminated form and the stainless steel cladding. The minimum thickness of the shielding is 6-3/4 in. of uranium and 1/4 in. of stainless steel with the closure providing additional shielding of 8-1/2 in. of depleted uranium. Model M has similar shielding with a thickness of 6-1/2 in. of uranium for the cylinder. The bottom flat head provides 6 in. of uranium shielding, and the closure provides 8-1/4 in. of uranium shielding.

A requirement of the operating procedures is a mandatory radiation survey prior to shipment with radiation levels limited to those set forth in the regulations. No neutron emitting material is shipped in these casks.

A radiation survey for model M was reported by Clifford.⁴ The model M cask was loaded with 204,590 Ci of ⁶⁰Co. Results of the radiation survey are presented below.

<u>Location</u>	<u>Gamma radiation (Millirad/hr)</u>
Background	6
Between fins (surface)	14
1 ft from side of cask	11
2 ft from side of cask	10
3 ft from side of cask	8
4 ft from side of cask	6.5

From these results it is concluded that a very effective gamma shielding is provided in both model L and model M casks. In Sect. 1.7.1, it is demonstrated that for end impact there is no reduction of shielding thickness (Fig. 1.32); for side impact the maximum reduction is 0.4 in. leaving a minimum wall thickness of 6.35 in.; and for corner impact the minimum shielding thickness is that of the undeformed cask wall (Fig. 1.33). The dose rate as a result of this reduction will not increase over a factor of 4. Thus it is concluded that the requirements of the regulations are met.

5. QUALITY ASSURANCE

5.1 Fabrication, Inspection, and Acceptance Tests

Fabrication of these containers was performed in Paducah Gaseous Diffusion Plant shops in accordance with normal shop fabrication procedures. Material was specified on the original drawings as "304L SST." Material was withdrawn from stores stock. The material used conforms to the requirements of note 1 of the as-built drawing since stores stock is purchased by these specifications. The casks were inspected by Paducah Inspection Department personnel for conformance to the as-built drawing's quality of workmanship and compliance with welding requirements when fabricated. In the opinion of the inspecting personnel, the weldments were in accordance with the drawings and specifications. The casks have operated for seven years with only minor weld failures which have been repaired and recertified. The routine operating inspection procedures specify periodic dye-penetrant weld inspections to verify weld integrity.

5.2 Operating Procedures and Routine Inspection

The ORNL Radioisotopes Department of Operations Division has established operating and routine inspection procedures and standard checklists to ensure that all shipments are safe and comply with DOT and ERDA regulations¹⁻³ and with all ORNL procedures and regulations. A copy of the procedures and the checklists is presented in Appendix D.

5.3 Periodic Maintenance and Inspection

The design of the container is such that there is a six-month inspection required in addition to those performed prior to each shipment as outlined in the preceding pages. Maintenance will be required only when routine inspections indicate damage. There are no time-degradable materials used in the construction of the containers.

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Appendix A
AS-BUILT DRAWINGS

Fig. A.1. Drawing no. M-11572-EM-010-E.

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Fig. A.2. Drawing no. M-11572-EM-011-E.

Fig. A.3. Drawing no. M-11572-EM-014-E.

Fig. A.4. Drawing no. M-11572-EM-012-E.

Fig. A.6. Drawing no. M-11572-EM-002-E.

Fig. A.7. Drawing no. M-11572-EM-003-E.

Fig. A.8. Drawing no. N-11572-EM-001-E.

Appendix B

COMPUTER PROGRAM LISTINGS AND DERIVATIONS

Derivations and FORTRAN Listings

- A. Impact squarely on rectangular energy absorber (1014 CASK)
- B. Corner impact on cask body (1001 CASK)
- C. Side impact on cask body (1005 CASK)

Program 1014 CASK

Derivation of Equations

The model shown in Fig. B.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. B.2, the expression

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

represents the energy expended as the cask moves from X_{n-1} to X_n and deforms the absorber on 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 as constant and satisfying the expression

$$N\delta = X_n .$$

The deformation S_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

$$\sigma_1 = f(\epsilon_1) ,$$

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Fig. B.1. Sketch of the general case of the compression energy absorber.

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DEFORMATION X

Fig. B.2. Force deformation diagram.

where

σ = stress,

ϵ = strain

for the material from which the energy absorber is constructed. Then the force F can be determined from

$$F = \sigma A ,$$

where A is the original cross sectional area of the energy absorber.

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 is 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 (Fig. B.3a) and for rectangular absorbers (Figs. B.3b and B.3c) having a constant thickness. In the case of the toroidal absorber, the radius and thickness depth must be inserted in statement nos. 70, 71, and 72. For a rectangular absorber, the thickness, depth, and length must be inserted as statement nos. 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 height in inches in statement 81, and the material in statement 88. The material in input is stainless steel 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

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Fig. B.3. Typical compression-energy absorber.

be decreased or increased. The 1000 format should be altered to identify the cask.

Input constants for
ORNL uranium-shielded cask (model L)

Top impact

Absorber length (TLEN) = 54.0 in.*
Absorber width (THK) = 1.0 in.
Absorber depth (DEPH) = 3.0 in.
Absorber material (AMATL) = stainless steel
Cask weight (Wt) = 11,300 lb

Bottom impact

Absorber length (TLEN) = 142.5 in.
Absorber width (THK) = 1.0 in.
Absorber depth (DEPH) = 3.0 in.
Absorber material (AMATL) = stainless steel
Cask weight (Wt) = 11,300 lb

Side impact

Absorber length (TLEN) = 31 in.
Absorber width (THK) = 1.0 in.
Absorber depth (DEPH) = 5.065 in.
Absorber material (AMATL) = stainless steel
Cask weight (Wt) = 11,300 lb

* Taken as maximum value to effect a maximum acceleration.

**FTN.L.N.E.G.A.

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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  ANATL= 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 GRAMMUM CASK
C
C  DIMENSION DE(200),SI(200),DEF(200),DU(200),FORC(200),ENER(200),
2  ACC(200)
  DO 25 Z=1,2
  DO 7, I=1,200
    DE(I)=0.0
    SI(I)=0.0
    DEF(I)=0.0
    DU(I)=0.0
    FORC(I)=0.0
    ENER(I)=0.0
  7  ACC(I)=0.0
    SI=2.0
    SST=1.0
60  EE=.005
    DS=0.0
C  INPUT MATERIALS
20  ANATL=SST
C  INPUT CASK WEIGHT
  WT=11300.
C  INPUT ABSORBER DIMENSIONS
  IF(2.E0.2) GO TO 66
  TLEN=142.5
  DEPH=3.0
  THK=1.0
  GO TO 67
66  CONTINUE
  TLEN=54.0
  THK=1.0
  DEPH=3.0
67  CONTINUE
  RAD=0.0
74  AREA=0.0
  DL=EE*DEPH
  PHI=3.14159265
  IF(RAD.GT.0.) AREA=2.*RAD*PHI*THK
  IF(TLEN.GT.0.) AREA=TLEN*THK
  IF(ANATL.NE.2.0) GO TO 6
C  MILD STEEL COEFFICIENTS
  A=-6.36337724E+02
  B=3.52674012E+06

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C=-5.84344912E+17
D=8.44752080E+08
E=-1.00760838E+10
F=8.32241264E+10
G=-4.42875884E+11
H=1.50685404E+12
O=-3.25535392E+12
P=4.31754272E+12
Q=-3.20427884E+12
R=1.01910658E+12
AA=0.5
AB=345000.
AC=73000.
6 CONTINUE
IF (MATL.NE.1.0) GO TO 5
C STAINLESS STEEL COEFFICIENTS
A=-6.60046824E+C2
B=3.27884020E+06
C=-1.74360076E+C8
D=5.78280072E+C5
E=-9.29116050E+10
F=8.46505048E+11
G=-4.79173780E+12
H=1.75760140E+12
O=-4.20115552E+13
P=6.33579650E+13
Q=-5.48432768E+13
R=2.07901540E+13
AA=0.35
AB=642000.
AC=50300.
5 CONTINUE
C ALUMINIUM TYPE 6061-T6 COEFFICIENTS
IF (MATL.NE.3.0) GO TO 12
A=-2.37529952E+C2
B=8.77222210E+05
C=-2.10395908E+C7
D=7.92526970E+C8
E=-1.19710810E+10
F=9.28522720E+10
G=-4.24576490E+11
H=1.21915694E+12
O=-2.22403420E+12
P=2.51118460E+12
Q=-1.60332062E+12
R=4.43286180E+11
AA=0.5
AB=209000.
AC=27900.
12 CONTINUE
C SELECT DRIP HEIGHT
DO 20 N=1,2
HT=48.0
IF (WT.GE.10000.0) HT=36.0
IF (WT.GE.20000.0) HT=24.0
IF (WT.GE.30000.0) HT=12.0
IF (N.EQ.2) HT=36.0

```

```

UT=WT*HT
SUMU=0.0
DS=0.
DO 1 I=1,200
DE(I)=DS
DEF(I)=DE(I)*DEPH
IF(DS.GT.AA) GO TO 21
S(I)=A*(B*DS)*(C+DS*SI)+(D*(DS*43.))+(E*(DS*44.))+(F*(DS*45.))+
1 (G*(DS*46.))+(H*(DS*47.))+(I*(DS*48.))+(J*(DS*49.))+
2 (K*(DS*50.))+(L*(DS*51.))
GO TO 22
21 CONTINUE
SI(I)=(AB*DS)+AC
22 CONTINUE
FORC(I)=SI(I)*AREA
ACC(I)=FORC(I)/WT
DUX(I)=FORC(I)*DL
SUMU=SUMU+DUX(I)
ENER(I)=SUMU
DS=DS+EE
IF(ENER(I).GE.U1) GO TO 2
1 CONTINUE
2 CONTINUE
J=I
WRITE (6,1002)
WRITE (6,1002)
WRITE (6,1001)
WRITE (6,1000)
WRITE (6,1001)
WRITE (6,1002)
WRITE (6,1002)
WRITE (6,1001)
WRITE (6,1003)
WRITE (6,1001)
WRITE (6,1004)
WRITE (6,1001)
WRITE(6,1005),RAD,BHK,DEPH,TLEN,AREA
WRITE (6,1001)
WRITE (6,1002)
WRITE (6,1001)
WRITE (6,1006)
WRITE (6,1001)
WRITE (6,1007)
WRITE (6,1001)
WRITE (6,1008)WT,HT,UT
WRITE (6,1001)
WRITE (6,1002)
WRITE (6,1002)
WRITE (6,1001)
WRITE (6,1009)
WRITE (6,1001)
WRITE (6,1010)
WRITE (6,1010)
DO 10 I=1,200
WRITE(6,1011),ACC(I),DEF(I),FORC(I),S(I),DE(I),ENER(I)
IF(I.GE.J) GO TO 11
10 CONTINUE

```



```

11 CONTINUE
   WRITE (6,10C1)
   WRITE (6,10C1)
   WRITE (6,10C2)
   WRITE (6,10C2)
   WRITE (6,10C2)
   WRITE (6,10C2)
   WRITE (6,10C2)
   WRITE (6,10C2)
   WRITE (6,10C1)
   WRITE (6,10C1)
1000 FORMAT(1H,8X,'MODEL CASE FOR PROGRAM DEMONSTRATION.
1      IMPACT ON SIDE ')
1001 FORMAT(1H0)
1002 FORMAT(1H,1X,40H*****.
1      55H*****.
2      14H*****.)
1003 FORMAT(1H,23X,24HENERGY ABSORBER GEOMETRY)
1004 FORMAT(1H,12X,6HADIUS,3X,9H THICKNESS,3X,5HDEPTH,4X,6HLENGTH,5X,
1      4HAREA)
1005 FORMAT(1H,16.3,4F10.3)
1006 FORMAT(1H,16X,33HCASE GEOMETRY AND TEST CONDITIONS)
1007 FORMAT(1H,12X,11HCASE HEIGHT,3X,11HDROP HEIGHT,3X,9HPOTENTIAL,
1      X, 6HENERGY)
1008 FORMAT(1H,1F21.1,1F14.1,1F17.1)
1009 FORMAT(1H,1X,12HACCELERATION,2X,11HDEFORMATION,6X,5HFORCE,6X,
1      6HSTRESS,6X,6HSTRAIN,7X,6HENERGY)
1010 FORMAT(1H,5X,3H X G,10X,6HINCHES,9X,4H LBS,7X,4HPSI,9X,
1      5HIN/IN,7X,5H LBS-IN)
1011 FORMAT(1H,1F10.1,1F13.3,1F16.1,1F12.1,1F11.3,1F12.1)
      CALL 3WIKPL(DEF,ACC,J,'LINEAR','J.H.EVANS')
      CALL 3WIKPL(DEF,ENER,J,'LINEAR','J.H.EVANS')
      CALL 3WIKPL(ACC,ENER,J,'LINEAR','J.H.EVANS')
20 CONTINUE
25 CONTINUE
STOP
END

```

Program 1001 CASK
Derivation of Equations

When a cask constructed of single ideally plastic material impacts on its corner, the major portion of the kinetic energy will be dissipated through displacement of material in the impact area.

The expression

$$dU = S dV ,$$

where

U = energy dissipated in deforming the cask,

S = specific energy,

V = displaced volume of material,

can be used as a basis for determining the effect of the top-corner impact.

With reference to the computational diagram illustrated in Fig. B.4, it may be said that

$$dV = xy dz/2 ,$$

$$x = r(\cos B - \cos A) ,$$

$$y = x \tan \alpha = \tan \alpha r(\cos B - \cos A) ,$$

$$dZ = r[\sin B - \sin(B - dB)] .$$

When A exceeds 90° and B exceeds $(90^\circ - A)$, then

$$x = 2r \cos B ,$$

$$\bar{y} = -\tan \alpha (r \cos A) ,$$

$$dZ = r[\sin B - \sin(B - dB)] ,$$

$$dV = x\bar{y} dZ ,$$

$$dU = S dV ,$$

and

$$U = \Sigma dU = \Sigma S dV .$$

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Fig. B.4. Computational diagram for corner impact.

This expression can be readily solved using the computer. A value for the angle A can be assumed, and B can be 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 is computed. If A exceeds 90°, B is incremented from 0 to 90°. A is started small, incremented, and the energy required is compared with the potential energy of the cask. Angle A cannot exceed 180°, after which the surface area in contact does not increase. In this manner a calculated impact history is produced. The program also computes other variables using the expressions below:

$$\text{maximum deformation: } \Delta = R(\sin \alpha)(1 - \cos A) + (\cos d)DC ,$$

$$\text{applied force: } F = dU/d\Delta ,$$

$$\text{acceleration: } a = Fg/W ,$$

where DC is deformation along cask length after A = 180°.

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

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

or

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

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 $a = dV/dT$ or $dt = dv/a$ and summary techniques.

This derivation is valid regardless of the angle at which the cask impacts the surface. If the impact is directed through the center of gravity, the drop is a CG drop, and all energy will be dissipated on the

initial impact. If the drop angle is other than this angle, the cask will retain a portion of its potential energy as kinetic energy and revolve about the impact point. This kinetic energy will be dissipated on secondary impact. This cask can be calculated from basic theory of impulse and momentum. Beer and Johnston¹³ present a very similar case, and their approach will be used in this analysis.

To use the program it is necessary to input the cask's outside radius R , weight W , and outside length C , drop heights H , and the limits of ideal yield stress S as indicated in the following program listing. If an impact angle ϕ other than encountered in a CG drop is considered, it must be included in the input data. The angle increments, AA and BB , may be adjusted to effect a finer or coarser grid at the user's option. Representative values for the lower and upper bounds of ideal dynamic yield stress S for leak-shielded casks clad with ferrous metal are 6000 and 14,000 psi. For solid steel or stainless steel casks, the ranges for S are 100,000 to 240,000 psi. For clad uranium-shielded casks, the range of S is 40,000 to 120,000 psi.

Applying the principles of impulse and momentum, it can be seen that the only impulsive forces external to the cask are impulsive reactions F and friction R .

Taking the moments about the impact point Q ,

$$m\bar{v}_1(\sin \theta)p + 0 = m\bar{v}_2p + \bar{I}\omega_2 .$$

The cask is rotating about point Q ; therefore, $\bar{v}_2$ is $\bar{v}_2 = p\omega_2$. Substituting this into the above equations gives

$$m\bar{v}_1(\sin \theta)p = mp\omega_2p + \bar{I}\omega_2 .$$

Therefore,

$$\omega_2 = m\bar{v}_1(\sin \theta)p/(mp^2 + \bar{I}) ,$$

and

$$\bar{V}_2/p = \bar{m}\bar{v}_1(\sin \theta)p/(\bar{m}p^2 + \bar{I}) \text{ ,}$$

$$\bar{V}_2 = \bar{m}\bar{v}_1(\sin \theta)p^2/(\bar{m}p^2 + \bar{I}) \text{ .}$$

The kinetic energy of the cask after impact is

$$KE_2 = \frac{1}{2}\bar{m}\bar{v}_2^2 + \frac{1}{2}\bar{I}\omega_2^2 \text{ .}$$

It can be concluded that the energy absorbed on the initial impact is the difference between the initial potential energy at the drop height and the kinetic energy in the system after impact. This is shown as

$$U \text{ absorbed initially} = W(H) = -KE_2 \text{ .}$$

These formulations have been coded into FORTRAN and are a part of the code.

Input data for corner drop from 36 in. and
360 in. for ORNL uranium-shielded cask (model L)

Cask weight (W) = 11,300 lb

Cask length (C) = 35.75 in.

Cask radius (R) = 12.75 in.

Impact angle (θ) = 37.07°

Specific energy range = 40,000 psi to 120,000 psi

**FTN.L.E.G.

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 W=CASK WEIGHT
 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 U=ENERGY
 C F=FORCE
 C T=TIME
 C AG=ACCELERATION
 C UT=TOTAL ENERGY
 C V=VELOCITY
 C X=DEFORMATION
 C AN=ANGLE IN CONTACT / THE SURFACE

C CORNER DROP URANIUM CASK
 C
 C

C DIMENSION V(750),AR(750),F(750),U(750),T(750),AN(750),
 I(750),AG(750),ZETA(750)
 C P=3.14159254
 C S=0.0
 C ANA = 0.0
 C INPUT CASK GEOMETRY
 C W=11300.
 C C=33.75
 C R=12.75
 C DO 20 Z=1.2
 C O=1/6.
 C IF(Z.EQ.2) GO TO 18
 C GO TO 19
 C 18 CONTINUE
 C O=ATAN(2.*O/C)
 C 19 CONTINUE
 C SELECT DROP HEIGHT
 C DO 90 NY=1,2
 C H=48.0
 C IF(W.GE.10000.)H=36.0
 C IF(W.GE.20000.)H=24.0
 C IF(W.GE.30000.)H=12.0
 C IF(NY.EQ.2)H=36.C
 C INPUT ANGLE INCREMENTS
 C 30 OB=.01
 C AA=.01

```

DO 326 KC=1.2
S=40000.
IF((C.E)-2)S=12000.
WRITE (51.1C02)
WRITE (51.1C02)
WRITE (51.1C1C) M
1010 FORMAT(1H,30X,'LMFBR CASK, D (OP MT. =',5X,F9.2)
WRITE (51.1C02)
WRITE (51.1C02)
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
U(I)=0.0
AR(I)=0.0
14 CONTINUE
C ZERO UN+SUBSCRIPTED VARIABLES
TA=0.0
AE=0.0
A=0.0
T=0.0
X=0.0
XA=0.0
DC=0.0
C THE FOLLOWING CALCULATES THE AMOUNT OF ENERGY ABSORBED ON
C INITIAL IMPACT FOR A PERFECTLY PLASTIC CASK
GRAV=32.2*12.
XMASS = W/GRAV
XMASS=(XMASS/12.)*(3.0R**2.+C**2.)
UPJ TEN=W*H
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(2.0R/C)
C CALCULATE VELOCITY BEFORE IMPACT
VEL 1=GRAV*SQRT(2.0H/GRAV)
C CALCULATE ANGULAR AND VECTOR VELOCITY AFTER IMPACT
OMEGA2=XMASS*VEL1*SIN(THETA)*PDIST/(XMASS*PDIST**2.+XMASS)
VEL 2=OMEGA2*PDIST
C CALCULATE KINETIC ENERGY REMAINING AFTER IMPACT
UKINT2=(XMASS*VEL2**2.)/2.+(XMASS*OMEGA2**2.)/2.
C CALCULATE ENERGY ABSORBED ON INITIAL IMPACT
JT=UPJ TEN-UKINT2
VV=SQRT((64.0H)/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 DC AS THE DEFORMATION AFTER THE ENTIRE
C END OF THE CASK HAS CONTACTED SURFACE.
DC=DC+.05
IF (A.LT.PI) DC = 0.0

```



```

C   DEFINE ANGLE Q AS THE SUPPLEMENT OF ANGLE A
      Q = 180 - A
      S = 0.0
      IF (A.EQ.PI) GO TO 70
      AE = 0.0
      SUMU = 0.0
10  DO 2 J=1,750
C   INCREMENT ANGLE B WHICH IS USED TO INTEGRATE THE VOLUME DISPLACED
C   AS ANGLE A ADVANCES
      B = B + DB
      CB = COS(B)
C   CALCULATE VOLUME DISPLACED
C   AS ANGLE A EXCEEDS 90 DEG THE DEFINITION FOR THE DIFFERENTIAL
C   VOLUME WILL CHANGE WHEN B IS GREATER THAN ANGLE Q
C   WHICH IS NOW LESS THAN 90 DEG. THE CROSS-SECTION OF THE
C   DIFFERENTIAL VOLUME IS TRAPEZOIDAL RATHER THAN TRIANGULAR
C   WHEN B IS GREATER THAN Q. ANGLE Q IS INTEGRATED FROM
C   0 DEG TO ANGLE A OR 90 DEG WHICHEVER IS THE LEAST.
      IF (B.GE.Q) GO TO 50
11  CC = (CB - CA)
      BY = TAN(Q) * CC
      BX = 2 * CC
12  DZ = 2 * (SIN(B) - SIN(B - BB))
      DU = BY * BX * DZ * S
50  IF (B.LT.Q) GO TO 51
      CB = 2 * CA
      YBA = TAN(Q) * (-R * CA)
      DZ = 2 * (SIN(B) - SIN(B - BB))
      DU = 2 * BX * YBA * DZ * S
C   CALCULATE ENERGY ABSORBED
11  SUMU = SUMU + DU
C   CALCULATE AREA
13  DA = 2 * BX * DZ / COS(Q)
      AE = AE + DA
      IF (B.GE.PI/2) GO TO 3
      IF (B.GE.A) GO TO 3
2  CONTINUE
3  U(I) = SUMU
70  IF (A.EQ.PI) U(I) = SUMU + 500 * PI * R * R
      AR(I) = AE
C   CALCULATE FORCE
      F(I) = AR(I) * S
C   CALCULATE VELOCITY
      IF (U(I).GE.UT) GO TO 16
      VA = SQRT((64. / (12. * B)) * (UT - U(I)))
16  IF (U(I).GE.LT) VA = C.0
C   CALCULATE ACCELERATION
      AG(I) = F(I) / B
C   CALCULATE DEFORMATION
      XA = COS(Q) * (DC * (R - R * CA) * TAN(Q))
      X(I) = XA
C   CALCULATE TIME
      TX = (XA - XX) / (VV + VA * B.)
7  TA = TA + TX
      T(I) = TA * 1000.
      XX = XA
6  V(I) = VA

```

```

      8 VV=VA
      AN(1)=A*57.3
      IF(U(1).GE.LT) 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
      DO 101 JJ=1,1
      ZETA = TIME*TA*(ALPHA/2.)*PI*(JJ/100.)*PI.
      ZETAD(JJ) = ZETA*57.3
101 CONTINUE
C OUTPUT-WRITE LOOP
      K=1
      WRITE(51,1002)
      WRITE(51,1004)
1004 FORMAT(11,9X,37HCA SK GEOMETRY AND MATERIAL PROPERTIES)
      WRITE(51,1002)
      WRITE(51,1005)
1005 FORMAT(1H,4X,6HRA DI US,8X,6HLENGTH,10X,5HWEIGHT,6X,
1 15HSPECIFIC ENERGY,7X,15HENERGY ABSORBED,6X,15HPOTENTIAL ENERGY)
      WRITE(51,1006)
1006 FORMAT(1H,4X,6HINCHES,8X,6HINCHES,10X,6HPOUNDS,8X,
1 13HLB-IN/CL,1H,8X,6HIN LB,14X,6HIN LB.)
      WRITE(51,1002)
1002 FORMAT(1H0)
      WRITE(51,1007) R,C,W,S,UT,UPOTEN
1007 FORMAT(F11.3,F14.3,F16.1,F18.1,F19.1,F22.1)
      WRITE(51,1002)
      WRITE(51,1000)
1000 FORMAT(1H,4X,11HDEFORMATION,4X,6HVELOCITY,7X,4HTIME,13X,5HFORCE,
1 10X,6HENERGY,5X,12HACCELERATION,10X,5HANGLE,5X,13HCONTACT ANGLE)
      WRITE(51,1001)
1001 FORMAT(1H,6X,6HINCHES,7X,6HFT./SEC,4X,12HMILLISECONDS,8X,
1 6HPOUNDS,10X,6HLB-IN,10X,3HMG,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(1H,F14.4,F13.2,F16.5,F15.2,F16.2,F12.2,F16.2,F16.5)
15 CONTINUE
      CALL SUBRPL(X,AG,K,'LINEAR',*J,4,EVANS*)
326 CONTINUE
90 CONTINUE
20 CONTINUE
STOP
END

```

Program 1005 CASK

Derivation of Equations

When a cylindrical cask fabricated from a homogenous material impacts on its side, the deformation can be approximated as shown in Fig. B.5. The volume V of material displaced, shown shaded in Fig. B.5, is expressed as

$$V = LR^2/2(2\theta - \sin 2\theta) ,$$

$$V = R^2L(\theta - \sin \theta \cos \theta) .$$

For this derivation it is assumed that the cask is fabricated from an ideal plastic material, that is, a material which has a stress-strain relationship which can be represented by a horizontal line. For such a material the product of the specific energy S (the quantity of energy required to displace a unit volume of material) and the volume displaced is equal to the absorbed energy U as below:

$$U = SV = SR^2L(\theta - \sin \theta \cos \theta) .$$

This equation can be solved by trial and error by assuming values of θ and calculating until $U = Wh$, where W is the cask weight and h is the drop height. For the deflection X , $X = R(1 - \cos \theta)$. For the area A at the surface, $A = 2LR \sin \theta$. It follows that for the force F , $F = SA$, and for the acceleration a , $a = F/M = Fg/W$.

A computer program can be written to solve these equations for increasing values of θ until the deformation is sufficient for U to equal the cask's potential energy Wh . In this fashion an acceleration-deflection energy history of the impact can be calculated. Also velocity V can be computed from the kinetic energy relationship $U = \Delta KE$, and the lapsed time from the relationship $dt = dv/a$.

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Fig. B.5. Cask model.

***FN.L.D.E.G.A.

PROGRAM NUMBER 1005-CASK

THIS PROGRAM ANALYZES THE IMPACT OF A CASK HAVING RIGHT
CYLINDRICAL GEOMETRY, IMPACTING WITH ITS AXIS HORIZONTAL, CODED BY
JOHN EVANS P.E., GEN. ENGR. DIV. ORNL, JUNE 1973.

GLOSSARY OF NOTATION

X=DEFLECTION(INCHES)
U=ENERGY(LB-INCHES)
P=FORCE(POUNDS)
AG=ACCELERATION(G'S)
V=VELOCITY(FT/SEC)
W=WEIGHT OF THE CASK(POUNDS)
H=DROP HEIGHT(INCHES)
C=CASK LENGTH(INCHES)
R=CASK RADIUS(INCHES)
O=ANGLE SUBTENDED BY THE DEFORMED AREA(RADIANS)
UT=TOTAL POTENTIAL ENERGY OF THE CASK (LB-INCHES)
T=SHELL THICKNESS (IN.)
TH=HEAD THICKNESS, PLUG END (IN.)
TAH=HEAD THICKNESS, BOTTOM END (IN.)
W=CASK WEIGHT (POUNDS)
SL=SPECIFIC ENERGY OF SHIELDING MATERIAL (IN-LB/CU.IN.)
SC=SPECIFIC ENERGY OF CLADDING IN COMPRESSION (IN-LB/CU.IN.)
OO=INCREMENT OF ANGLE O
TH=TIME (SEC.)
G=ACCELERATION (FT/SEC/SEC)
VL=VOLUME OF SHIELDING DISPLACED (CU.IN.)
UH=ENERGY DISSIPATED IN DEFORMING THE HEADS (IN-LB.)
UL=ENERGY DISSIPATED IN DISPLACING SHIELDING (IN-LB.)
ZZ=ENERGY DISSIPATED IN DEFORMING COOLING FINS (IN-LB.)

SIDE DROP URANIUM CASK

DIMENSION U(100),M(1000),P(1000),V(1000),AG(1000),TH(1000)
I,A(1000),VL(1000)
ZZ=1246100.5
C INPUT CASK GEOMETRY
TH=2.5
TAH=.25
T=.25
W=11300.
R=12.75
CL=33.75
C SELECT DROP HEIGHT
OO 99 44=1.2
H=48.0
IF(W.GE.10000.)H=36.0
IF(W.GE.20000.)H=24.0
IF(W.GE.30000.)H=12.0
IF(44.EQ.2)H=36.0

```

C   CALCULATE CASK POTENTIAL ENERGY
    UT=U*M - ZZ
C   INPUT INCREMENT OF ANGLE .0
    OO=.01
C   INPUT WATL. PROPERTIES
    DO 90 M=1,2
      SL=40000.
      SC=100000.
      IF(1.E2.1) GO TO 51
      SL=120000.
      SC=240000.
91 CONTINUE
C   ZERO SUBSCRIPTED VARIABLES
    DO 1 I=1,1000
      X(I)=0.0
      U(I)=0.0
      VM(I)=0.0
      G(I)=0.0
      P(I)=0.
      AG(I)=0.0
      AP(I)=0.0
      VE(I)=0.0
1 CONTINUE
C   ZERO NONSUBSCRIPTED VARIABLES
    UL=0.0
    UM=0.0
    DT=0.0
    TS=0.0
    PU=0.0
    VV=0.0
    UU=0.0
    PP=0.0
    XX=0.0
    C=0.0
    V(1)=SQRT((24.*M/12.))
    VV=V(1)
    DO 2 I=1,1000
      IF(1.E2.1) GO TO 21
      O=O+OO
      SO=SIN(O)
      SD=SIN(2.*O)/2.
      CO=COS(O)
C   CALCULATE VOLUME OF SHIELDING DISPLACED
C   EQUATION 1
      VL=(R*R*CL*(O-SOO))
C   CALCULATE ENERGY DISSIPATED IN DISPLACING SHIELDING
C   EQUATION 2
      UL=SL*VL
C   EQUATION 6
      OO=O-SOO
C   EQUATION 12
      VM=(TH+TAN)*R*R*OO
C   EQUATION 13
      UM=SC*VM
      AR_=2.*O*SD*CL
      FORL=AR_*SL
      ARM=2.*O*SD*(TH + TAN)

```



```

1000 FORMAT ( 1H , 4X, 11HDEFORMATION, 4X, 8HVELOCITY, 7X, 4HTIME, 13X, 5HFORCE,
1          10X, 6HENERGY, 5X, 12HACCELERATION)
1001 FORMAT ( 1H , 6X, 6HINCHES, 7X, 8HFT./SEC., 4X, 12HBILLISECONDS, 8X,
1          6HPOUNDS, 10X, 6HLB-IN., 10X, 3HX G)
1003 FORMAT( 1H , F12.4, F13.2, F15.4, F18.2, F16.2, F12.2)
1002 FORMAT( 1HC)
1004 FORMAT( 1H , 30X, 13HCASK GEOMETRY)
1005 FORMAT ( 1H , 4X, 6HRAJ[LS, 9X, 6HLENGTH, 9X, 10HSHELL THK., 5X,
1          9HHEAD THK., 5X, 9HHEAD THK., 7X, 5HWEIGHT, 5X,
2          15HSPECIFIC ENERGY)
1006 FORMAT ( 1H , 4X, 6HINCHES, 9X, 6HINCHES, 9X, 6HINCHES, 9X, 6HINCHES,
1          8X, 6HINCHES, 8X, 6HPOUNDS, 7X, 11HIN-LB/ CU IN)
1007 FORMAT( 1H , F10.3, 4F15.3, F15.1, F12.0)
1008 FORMAT( 1H, 25X, 'MODEL CASK FOR PROGRAM DEMONSTRATION' )
1009 FORMAT( 1H, X, 49H'*****',
1          55H'*****',
2          14H'*****')
      CALL QWIKPL( X, AG, J, 'LINEAR', 'J.H. EVANS')
      CALL QWIKPL( U, AG, J, 'LINEAR', 'J.H. EVANS')
      CALL QWIKPL( X, U, J, 'LINEAR', 'J.H. EVANS')
20 CONTINUE
90 CONTINUE
59 CONTINUE
77 CONTINUE
STOP
END

```


Appendix C

TEST RESULTS FOR SPECIFICATION 2R CONTAINERS

Test Results for Specification 2R Containers

On August 21, 1974, two each Specification 2R containers, as illustrated in Figs. C.1 and C.2, were drop tested at ORNL to establish the adequacy of this type of container as the primary containment vessel for radioactive materials. This type of container is extensively used at ORNL in conjunction with various shielded casks. Normally, the containers are assembled using forged caps for both end closures. Frequently, one cap is welded to the pipe nipple, enhancing its structural integrity. Both steel and stainless steel pipe and caps have been used. For this test the cast steel (malleable) caps were used at one end due to a temporary shortage of forged caps. In all the tests below, the forged cap is nearest the point of impact. The cast cap is not considered a part of the test except to facilitate leak testing.

Both containers were air-soap bubble leak tested at 10 psig prior to testing. There were no detectable leaks. The first container was filled with tap water placed in an existing steel casing (Fig. C.2) and dropped from 30 ft onto the ORNL pad, impacting at an angle of approximately 17.3° . The angle of impact was calculated from the deformation dimensions of the casing. The casing was used to simulate the protection afforded by the cask. The second container was also filled with tap water, then placed in the casing and dropped as above on its end. The containers were drained and soap-bubble tested at 10 psig. There were no detectable leaks.

Both containers were then refilled with water. The first container was dropped from 30 ft onto the pad without any outer protection. It impacted at a very flat, oblique angle. No leakage of water was observed. There were significant leaks at both threaded joints when air-soap bubble tested at 10 psig. The second container was dropped as above such that the plane containing the point of impact and the center of gravity was essentially vertical. Again, there was no visible loss of water. A 10-psig air-soap bubble test revealed significant leakage around the lower (nearest to the point of impact) threaded joint.

It is concluded that a 2R container made of threaded stainless or carbon steel pipe and forged steel or stainless steel caps is adequate

Fig. C.1. 2R model (photo).

ORNL DWG 74-8940

Fig. C.2. 2R model (drawing).

to provide primary containment when inside a cask. It is also concluded that such a container is not adequate without some external protection. It is obvious that the accelerations experienced by the test containers in the steel casing were of greater magnitude than would be experienced in a shipping cask.

Appendix D
ROUTINE PACKAGING AND INSPECTION PROCEDURES

OPERATIONS DIVISION
RADIOISOTOPE DEPARTMENT

Proc. No. 1
Page 1 of 3
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: Edmond Johnston R. W. Schuch
Supervisor Process Group Leader
Date FEB 18 1977

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RADIOISOTOPE DEPARTMENTProc. No. 1
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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: Edmond Johnston Process Group Leader FEB 28 1977
Supervisor Process Group Leader 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 UCH-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 3008* and ORNL-TM-2769, *ORNL Isotopes Division Guide for the Packaging of Radioactive Materials for Transport*.

Approved: _____

Supervisor

Process Group Leader

FEB 22 1977

Date

OAK RIDGE NATIONAL LABORATORY RADIOACTIVE MATERIALS PACKAGING INFORMATION

THIS FORM IS REQUIRED FOR ALL SHIPMENTS GREATER THAN 1 MILLICURIE ALPHA OR 3 CURIES BETA/GAMMA SOLID, LIQUID, OR GAS AND ALL EMPTY RETURNABLE CONTAINERS

GENERAL INFORMATION

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

Special Instructions Complied by _____

RADIOACTIVE CONTENTS

1. All major activities in curies 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- _____	3. Nuclear Safety Review No. _____
2. DOT Specification No. _____	Date _____
4. Container determined proper for contents by _____	

INTERNAL CONTAINER

1. Internal Containment: ☐ Glass Bottle ☐ Plastic Bottle ☐ "2R" ☐ Conoseal ☐ Welded Capsule (specify capsule material) _____	
☐ Other (explain) _____	
2. Contamination level on internal container: Estimated _____ Smeared _____	
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	☐ By _____
2. External container examination _____ ☐ Yes	☐ By _____
3. Gaskets or seals properly installed _____ ☐ Yes	☐ By _____
4. Leak test _____ ☐ Yes	☐ By _____
5. Bolts torqued to _____ ft. lbs.	☐ By _____
6. Tie down to skid checked _____ ☐ Yes	☐ By _____
7. Tamper seal installed _____ ☐ Yes	☐ By _____
8. Lid eye bolt removed and wired to the outside of the carrier ☐ Yes	☐ By _____

RADIATION SURVEY

1. Surface contamination level: Alpha _____ dpm, β - γ _____ dpm
2. External radiation level _____ mrem/hr @ contact
3. Domestic shipments _____ mrem/hr @ 3 ft from surface
4. Foreign shipments _____ mrem/hr @ 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
DATE 8/1/77

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 arem/hr internally or externally.

4. Fire Shields

The RSPO 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 RSPO 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

SUPERVISOR

JCN-12590A (3-4-75)

PRODUCTION LEADER

DATE

AUG 1 1977

OPERATIONS DIVISION
RADIOISOTOPE DEPARTMENTPROC. NO. 26
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-
- c. Gaskets will be changed every 6 months and recorded in the container's QA files. Gasket material from stores stock must be verified by 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

PROCESS GROUP LEADER

DATE

AUG 1 1977

OPERATIONS DIVISION
RADIOISOTOPE DEPARTMENT
BUILDING 3029
SOURCE DEVELOPMENT LABORATORY
CONTAINER INSPECTION SHEET

PROC. NO. 26
PAGE 4 OF 4
DATE 8/1/77

Date _____ Container Number _____

EXTERNAL INSPECTION

By _____

Smear dpm By; _____ dpm alpha

Condition Good ☐ Fair ☐ Poor ☐

Repairs Needed _____

Action Taken _____

INTERNAL INSPECTION

By _____

Smear 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]

PROCESS LEADER

[Signature]

DATE

206 1/1/77

URANIUM CASK PACKING PROCEDUREPre-Loading Check

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) _____
4. Planned radioactive heat load _____ watts
 - a. Neoprene gasket for <1400 W installed _____ by _____
 - b. Viton gasket for >1400 W installed _____ by _____
5. Cavity and lid smear level _____ B-γ _____ dpm

_____ α _____ dpm

by _____
6. Outside cask surface smear level _____ B-γ _____ dpm

_____ α _____ 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 _____

Post Loading Checks

1. Outside cask surface smear level (clean to ORNL smear tolerance for shipping) _____ B-γ _____ dpm

_____ α _____ dpm

by _____
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 _____ by _____
6. Skid nut torqued to 300 ft.-lb _____ by _____
7. Personnel heat shield installed _____ by _____
8. Packaging Information Form (Tx-4623) completed _____ by _____
9. Notification to Packing and Shipping Foreman _____ by _____

Supervisory Approval by _____

Date _____

Appendix E
APPROVAL DOCUMENTS

November 20, 1974

To: J. H. Evans, R. W. Schaich
From: Transportation Committee
Subject: Approval of SARP for the ORNL Uranium-Shielded
Shipping Casks

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

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Form AEC-618
(12-73)
10 CFR 71
AECM 1201

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

1a. Certificate Number USA/5595/BL (ERDA-OR)	1b. Revision No. 1	1c. Package Identification No. USA/5595/BL (ERDA-OR)	1d. Page No. 1	1e. Total No. Pages 2
--	------------------------------	--	--------------------------	---------------------------------

2. PREAMBLE

2a. This certificate is issued to satisfy Sections 173.303a, 173.304, 173.305, and 173.306 of the Department of Transportation Hazardous Materials Regulations (49 CFR 170-199 and 14 CFR 163) and Sections 146-19-10a and 146-19-10b of the Department of Transportation Dangerous Cargo Regulations (49 CFR 146-148), 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 consignee from compliance with any requirements 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:	(2) Title and Identification of report or application:	(3) Date:
Oak Ridge National Laboratory Post Office Box X Oak Ridge, Tennessee 37830	Safety Analysis Report for Packaging for the ORNL Uranium-Shielded Shipping Casks Report No. ORNL/ENG/TM-4	November 1977

4. CONDITIONS

This certificate is conditioned 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, F-code, Test, Other Conditions, and References:

(a) Packaging:

(1) Model(s): L and M

(2) Description:

Type B Packaging for large quantities of nonfissile radioactive material. The inner containment vessel which consists of a vessel meeting either special form or DOT Specification 2R, is determined by heat load as follows:

Heat Load (Watts)	Inner Containment Vessel
< 3000	DOT Spec 2R*
> 3000	Special Forms

*Metallic gasket required.

The inner containment vessels are positioned within rigid circular cylinders of 1/4 inch thick stainless steel-clad depleted uranium having a plug-type, bolted and gasketed top lid closure.

6a. Date of Issuance August 30, 1977	6b. Expiration Date
--	---------------------

FOR THE U.S. ATOMIC ENERGY COMMISSION

7a. Address of Issuing Office:	7b. Signature, Name, and Title of Approving Official:
U. S. Energy Research & Development Adm. Post Office Box E Oak Ridge, Tennessee 37830	<i>William H. Travis</i> William H. Travis, Director Safety & Environmental Control Division

(a) (2) - Description (continued):

Details of the two Models are as follows:

	<u>Model L</u>	<u>Model M</u>
<u>Cavity</u>		
I.D. (in.)	11	11
Height (in.)	17 1/2	17 1/2
<u>Outside Dimensions</u>		
O.D. (in.)*	25 1/2	25
Height (in.)	39 3/4	38
Bottom Lug Plate		
O.D. (in.)	35 5/8	35 1/8
*Excluding 3 in. deep fins		
<u>Minimum U Shield Thickness (in.)</u>	6 3/4	6
<u>Gross Weight** (lbs.)</u>	13,200	11,600
**Including Skid		

Each cask is mounted on a skid and covered with a personnel heat shield.

(3) Drawings

The packagings are as described and fabricated in accordance with the following Union Carbide Corporation, Nuclear Division, Paducah Plant Drawings:

Model L - M-11572-EM-001- through -003-E

Model M - M-11572-EM-010-E through -014-E

(b) Contents(1) Type and Form of Material

Nonfissile radioactive materials in solid form.

- (2) Maximum quantity of radioactive Material limited by the volume and shape of the internal cavity of each cask, internal heat load, and external radiation levels prescribed in DOT Regulations, Title 49 CFR.
- (3) Maximum decay heat load not to exceed 4000 watts; however, when the heat load exceed 1250 watts transport will be made by exclusive-use vehicle.