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ORNL/ENG/TM-10

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Safety Analysis Report for Packaging: The ORNL In-Pile Capsule Shipping Cask

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ORNL/ENG/TM-10
Dist. Category UC-71

Contract No. W-7405-eng-26

ORNL Engineering

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Date Published: November 1977

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Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

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ABSTRACT

The ORNL in-pile capsule shipping cask is used to transport irradiated experimental capsules and spent fuel elements. The cask was analytically evaluated to determine its compliance with the applicable regulations governing containers in which radioactive materials are transported, and that evaluation is reported. Computational procedures were used to determine the structural integrity and thermal behavior of the cask relative to the general standards for normal conditions of transport and the standards for the hypothetical accident conditions. The results of the evaluation show that the cask is in compliance with the applicable regulations.

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0. GENERAL INFORMATION

0.1 Introduction

When a package containing radioactive or fissile material is shipped from one location to another, the package is subject to regulations governing its structural integrity, shielding, heat dissipating capabilities, containment capabilities, and quality assurance. The governing regulations are set forth in Title 10, Part 71, of the *Code of Federal Regulations;*[1] Chapter 0529 of the Department of Energy (DOE) Manual;[2] and in Title 49, Part 173, of the *Code of Federal Regulations.*[3] Compliance of the package or shipping container with these regulations must be shown by test, experimental, or computational methods to secure approval for shipment of radioactive or fissile materials. The analytical evaluations and supporting experimental data which demonstrate that the ORNL in-pile capsule shipping cask complies with the regulations are reported.

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The cask was designed in 1964 by the Equipment Design Group of Connecticut Advanced Nuclear Engineering Laboratory (CANEL), a division of Pratt and Whitney Aircraft Corporation. Two identical casks were fabricated by National Welding and Manufacturing Company of Newton, Connecticut. The casks were transferred to Oak Ridge National Laboratory in November 1965. Prints of the original fabrication drawings were obtained with the casks and are maintained on file in Building 3525.

The cask will be modified to improve its structural integrity and to enable it to comply with the thermal accident requirements of the regulations. The cask will undergo the modifications upon approval of this SARP by the Oak Ridge Operations Office of the DOE. All analyses and description of the cask, presented here, reflect the modifications to be made.

The fabrication work is to be performed in the ORNL Shops, and "as-built" drawings, including the modifications, of the cask were prepared by the Equipment Design Section of the General Engineering Division at Oak Ridge National Laboratory. These drawings are presented in Appendix A. There are two casks which are identified by DOE Certificate of Compliance No. AEC-OR USA/5907/BLF and ORNL identification numbers 10S16-201 and 10S16-202 respectively. The cask is usually shipped via motor carrier, but it is also usable for rail and water transport.

0.2 Package Description

0.2.1 Cask description

The cask is a horizontal circular cylinder (shown in Figs. 0.1 and 0.2) having an outside diameter of 24 in., length of 83 in., and weight of 17,000 lb including the skid. The cavity dimensions are 4-1/4-in. in diameter by 58-in. long. The cask is lead filled between a stainless steel inside liner and carbon steel outer shell. Biological shielding consists of 9-1/2 in. of lead. Access to the cavity is through a plug on one end (upper cover) and a sliding plug shutter (lower cover) on the other end. These plugs are gasketed and form secondary containment. Primary containment is provided by the cladding or jackets of the fuel elements or capsules or an inner vessel conforming to Department of Transportation (DOT) Specification 2R.[4]

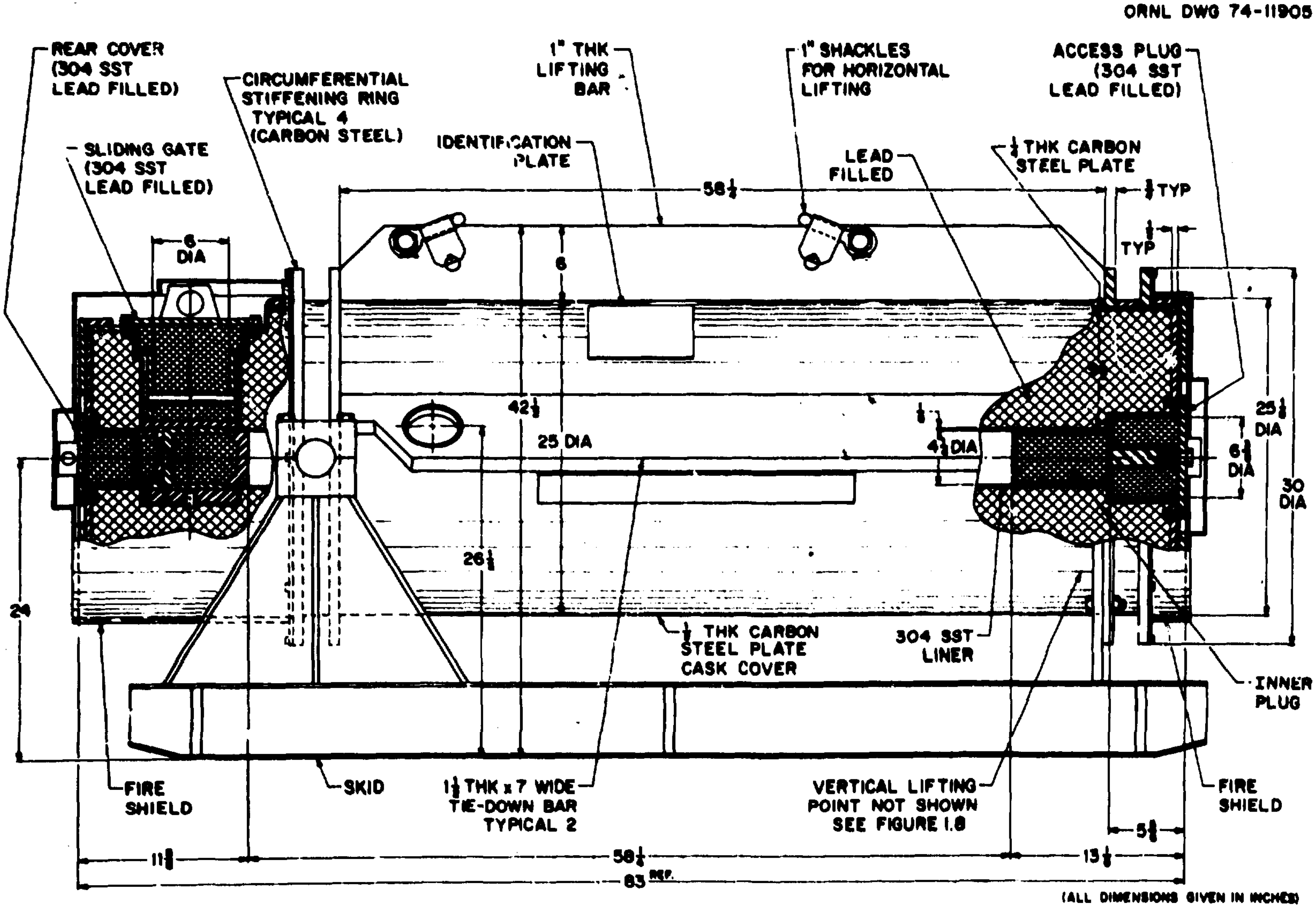

Fig. 0.1. In-pile capsule shipping cask.

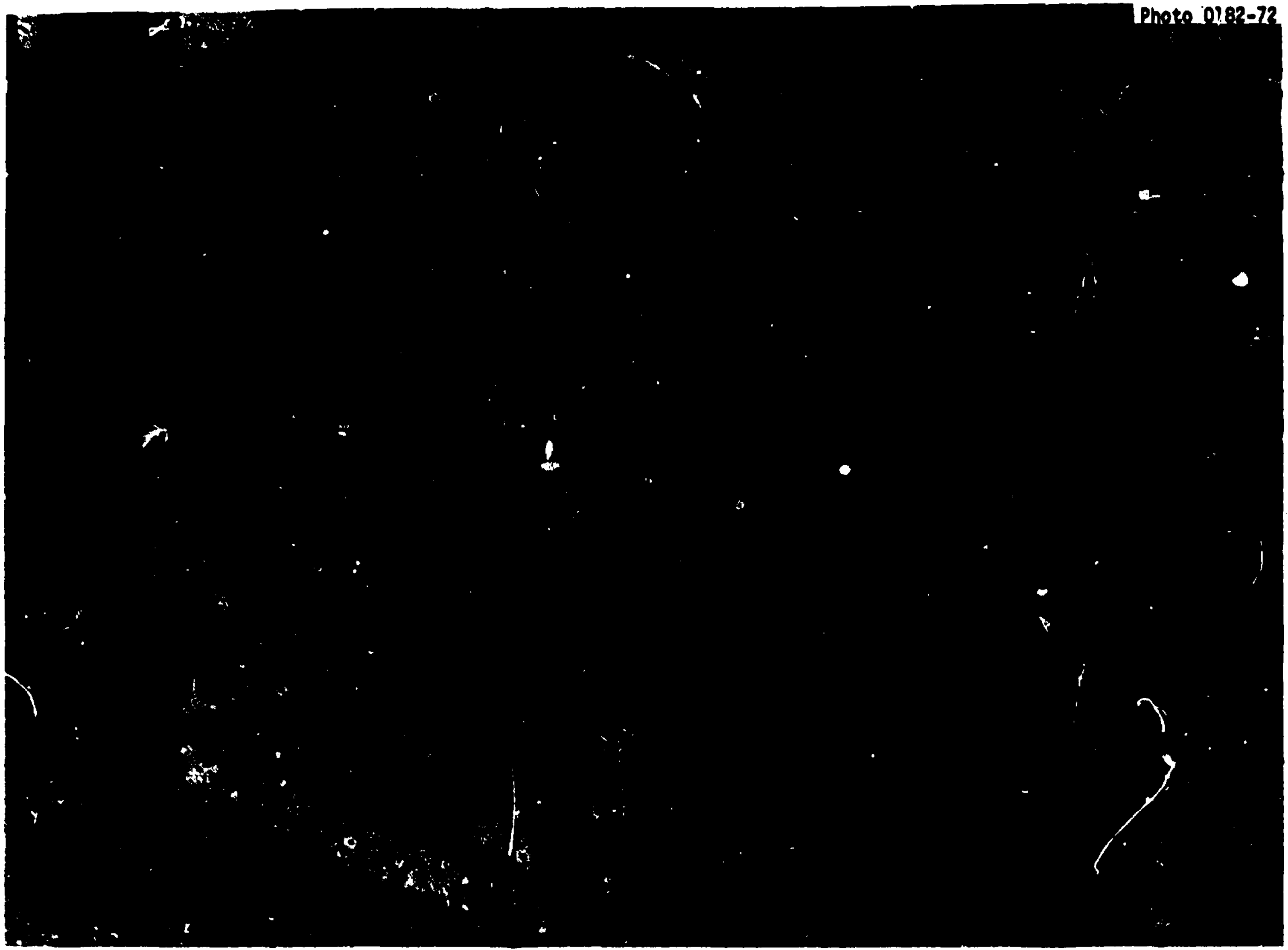
Photo 0182-72

Fig. 0.2. In-pile capsule shipping cask.

The original cask had an exterior shell of 0.25-in.-thick carbon steel. This was modified by placing an additional 0.5-in.-thick carbon steel shell in contact with the original. Both shells are seen in Fig. 0.1. The cask and skid weigh 17,000 lb. The cask, excluding the skid, weighs 16,000 lb, and its center of gravity is approximately at the geometric center. The cask access plug assembly weighs 110 lb, the sliding gate weighs 220 lb, and the gate cover weighs 30 lb. The cask is equipped with fire shields covering each end and is painted with intumescent paint to reduce the quantity of lead which would melt in a fire. The simplified model used in the calculations is illustrated in Fig. 0.3.

0.2.2 Operational features

The cask may be loaded or unloaded in either a horizontal or vertical orientation while in a hot cell, connected to a hot-cell transfer port, or underwater, or by other remote means. Underwater loading and unloading is via the cask access plug with the axis of the cask vertical. Dry loading and unloading is usually accomplished via the sliding gate with the axis horizontal. The cask can be unloaded by connecting a handle to the inner part of the cask access plug and pushing the contents through a port.

The cask is lifted in a horizontal attitude by two shackles attached to the cask lifting bar. When lifted with the axis vertical, a special lifting fixture and the trunnions on the access plug end are used. The cask is secured to transport vehicles by use of tension members as shown in Fig. 0.4. The skid is used for all modes of transport, but may be removed for loading and on-site handling.

0.2.3 Contents

The cask is approved for Type B and large quantities of radioactive materials and Fissile Class I shipments. The contents are limited to solid materials.

Examples of contents are spent reactor fuel, irradiated experiments, and other solid radioactive and fissile materials. Spent fuel examples

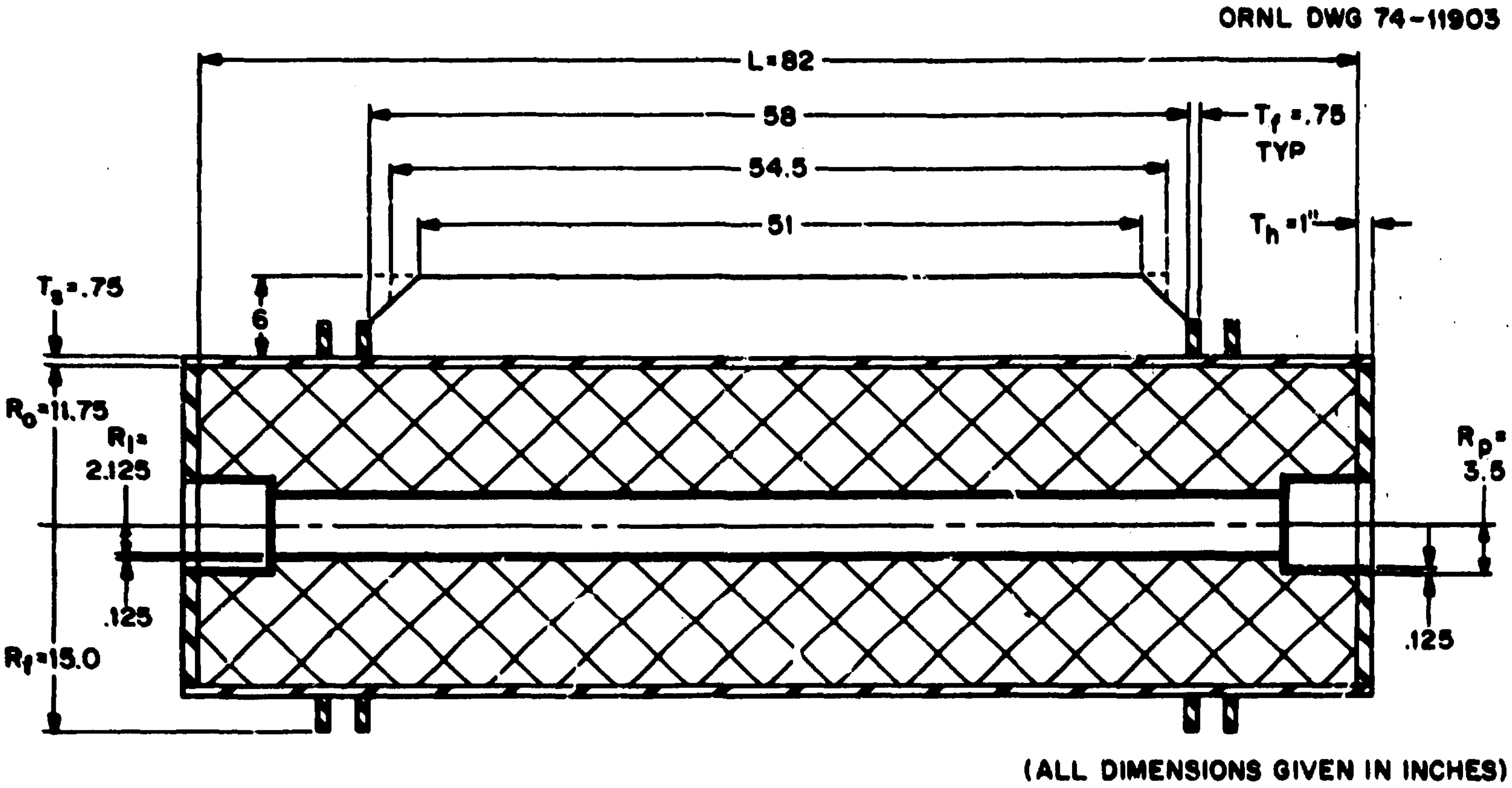

Fig. 0.3. Simplified cask model.

Photo 2439-74

Fig. 0.4. Cask tie-down.

are coated particles of U, Pu, and Th; clad oxide rods of U, Pu, and Th; or solidified molten salt fuels. Examples of other materials which have been shipped are BeO; silicates of Nb, Ti, Ta, and Zr; nitrides of Zr, Nb, Ta, and Ti; carbides of Zr, Nb, Ti, and W; and metallic specimens. All the above are either encased in metal cladding or in a 2R container. The contents may also be special form materials.

Radioactive materials are limited to quantities that will result in radiation levels external to the cask equal to or less than allowed by the regulations.[3] Fissile material is limited to 1250 g per shipment. In addition, if the total quantity of fissile material exceeds 800 g, the distribution of fissile material is limited to 250 g per linear foot. All fissile shipments are Fissile Class I. The decay heat is limited to 350 W when shipment is by common carrier. When shipped by exclusive-use vehicle, the decay heat load is limited to 1000 W. The weight of the contents and the inner containment vessel(s) will not exceed 100 lb.

1. STRUCTURAL EVALUATION

The package complies with the structural requirements of the regulations.[1-3] The calculations, test results, and engineering logic presented in succeeding sections demonstrate compliance with these performance criteria. Additional evaluations, considered pertinent to the safety and operability of the package, are included. The effects of both normal and specified accident conditions on the structural integrity of the package are considered.

1.1 Mechanical Properties of Materials

The cask is constructed of low-carbon or mild steel, type 304 stainless steel, and cast-in-place lead. The steel is specified on the drawings as "steel," "mild steel," "HR steel," etc.; hence there is doubt as to mechanical properties. The properties in Table 1.1 are taken to effect conservative solutions. The static properties of the materials used in the cask are listed in Table 1.1. The stainless steel properties are published by the International Nickel Company.[5] Low-carbon steel and lead properties are taken from *Machine Design*[6] and *Manual of Steel Construction.*[7]

Table 1.1. Static mechanical properties of cask materials

Property	Symbol	304L stainless steel	Low carbon steel	Lead
Yield stress, psi	σ_y	30,000	30,000	1300
Ultimate tensile strength, psi	σ_u	75,000	60,000	2500
Modulus of elasticity, psi	E	29×10^6	29×10^6	2×10^6
Elongation, T	Δ	40	28	45
Density, lb/in.^{3}	ρ	0.283	0.283	0.41
Maximum allowable shear = $\sigma_y/2$, psi	τ_{max}	15,000	15,000	1000
Coefficient of expansion in./in.·°F	α	9.2×10^{-6}	6.5×10^{-6}	16.3×10^{-6}
Ultimate shear stress, psi	τ_u	61,000	45,000	
Allowable bearing stress, psi	σ_b		48,000	

The properties of chemical lead are used to effect a conservative solution. The dynamic properties of chemical lead reported by Evans[8] are used in the impact analyses. 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 one 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. It can then be seen from observation of Fig. 1.1 that the selected values of 6000 and 14,000 psi for lead will effect a conservative solution for the in-pile shipping cask. The volumetric expansion properties of lead as reported by Shappert[9] are used to evaluate the effects of thermal gradients. Figure 1.2 is reproduced from Shappert's report. The dynamic tensile properties of stainless steel and mild steel reported by Clark[10] are reproduced in Figs. 1.3 and 1.4. The dynamic compressive properties reported by Evans,[11] reproduced in Figs. 1.5 and 1.6, were used in the impact analyses. These curves support the selection of 100,000 and 240,000 psi as limits for ideal dynamic yield stress or specific energy for mild steel for those techniques employing this concept, as discussed previously for lead. In all impact analyses, it is assumed that the materials are incompressible.

The dynamic properties of threaded stainless steel fasteners reported by Cannon[12] are used in the impact analysis of the closures. Cannon impact tested commercial stainless steel bolts and cap screws in the size range 3/8 to 1 in. He found that the dynamic yield stress of fasteners was in the range 75,000 to 104,000 psi, and the ultimate stress was in the range 95,000 to 150,000 psi. The wide variation in properties is, to a great extent, due to difference in method of manufacture. The lower values will be used as failure criteria for this analysis.

1.2 General Standards for All Packages

The general standards for all packaging cover the chemical and galvanic reaction of the package materials, closure of the package, and the lifting and tie-down devices for the package. The in-pile capsule

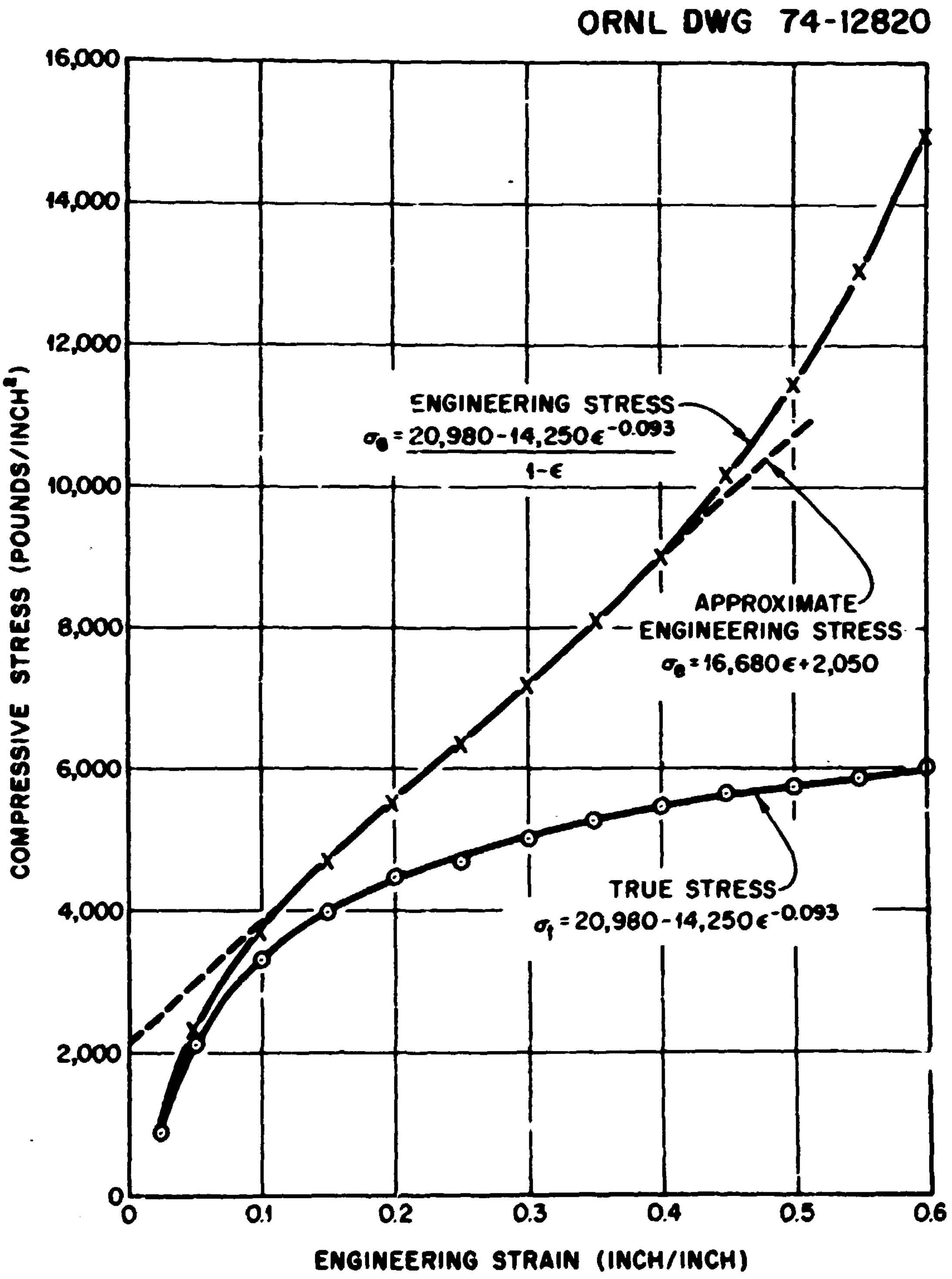

Fig. 1.1. Dynamic compressive stress-strain diagram for lead.

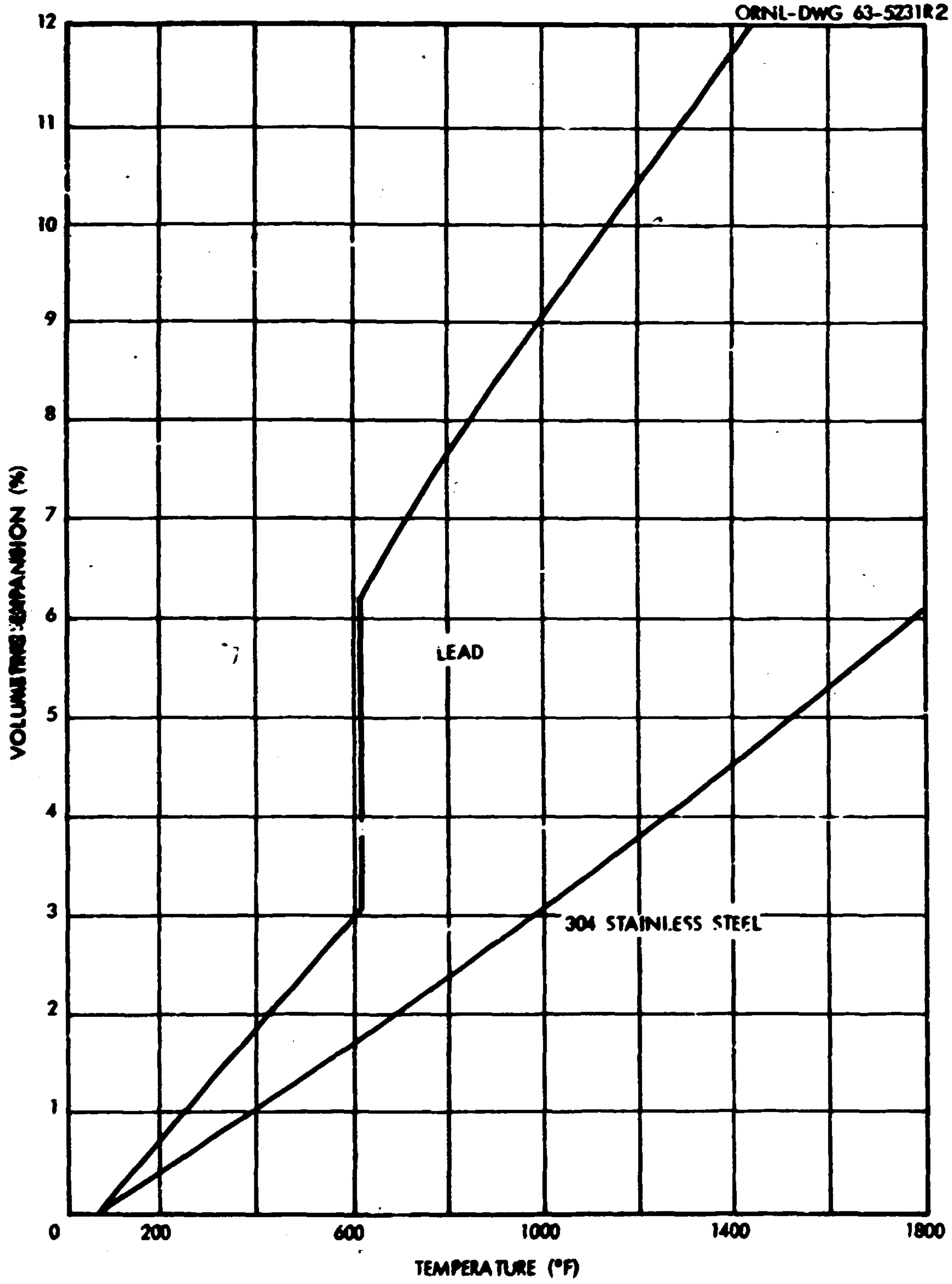

Fig. 1.2. Thermal expansion of lead and stainless steel.

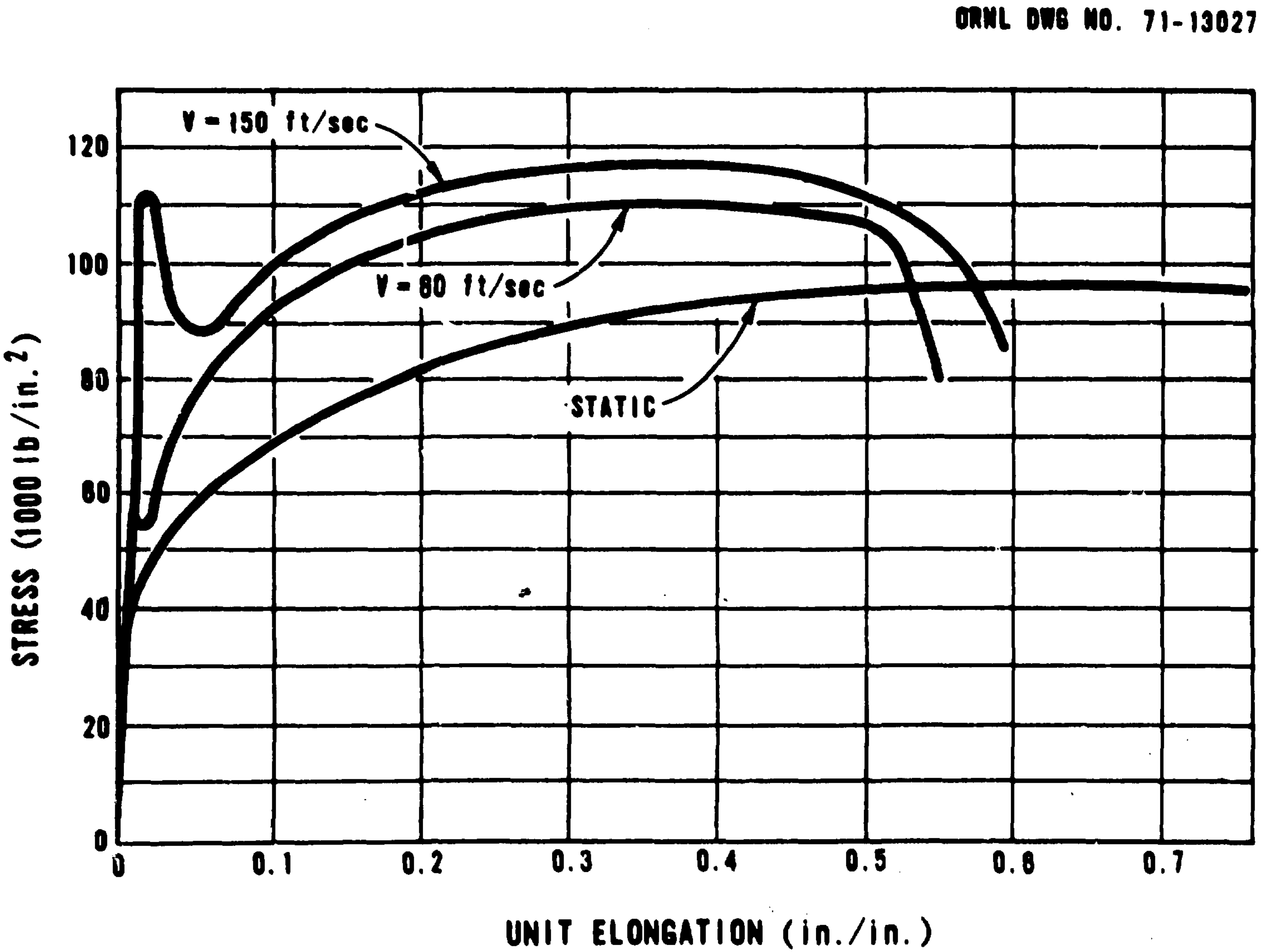

Fig. 1.3. Dynamic tensile properties of stainless steel.

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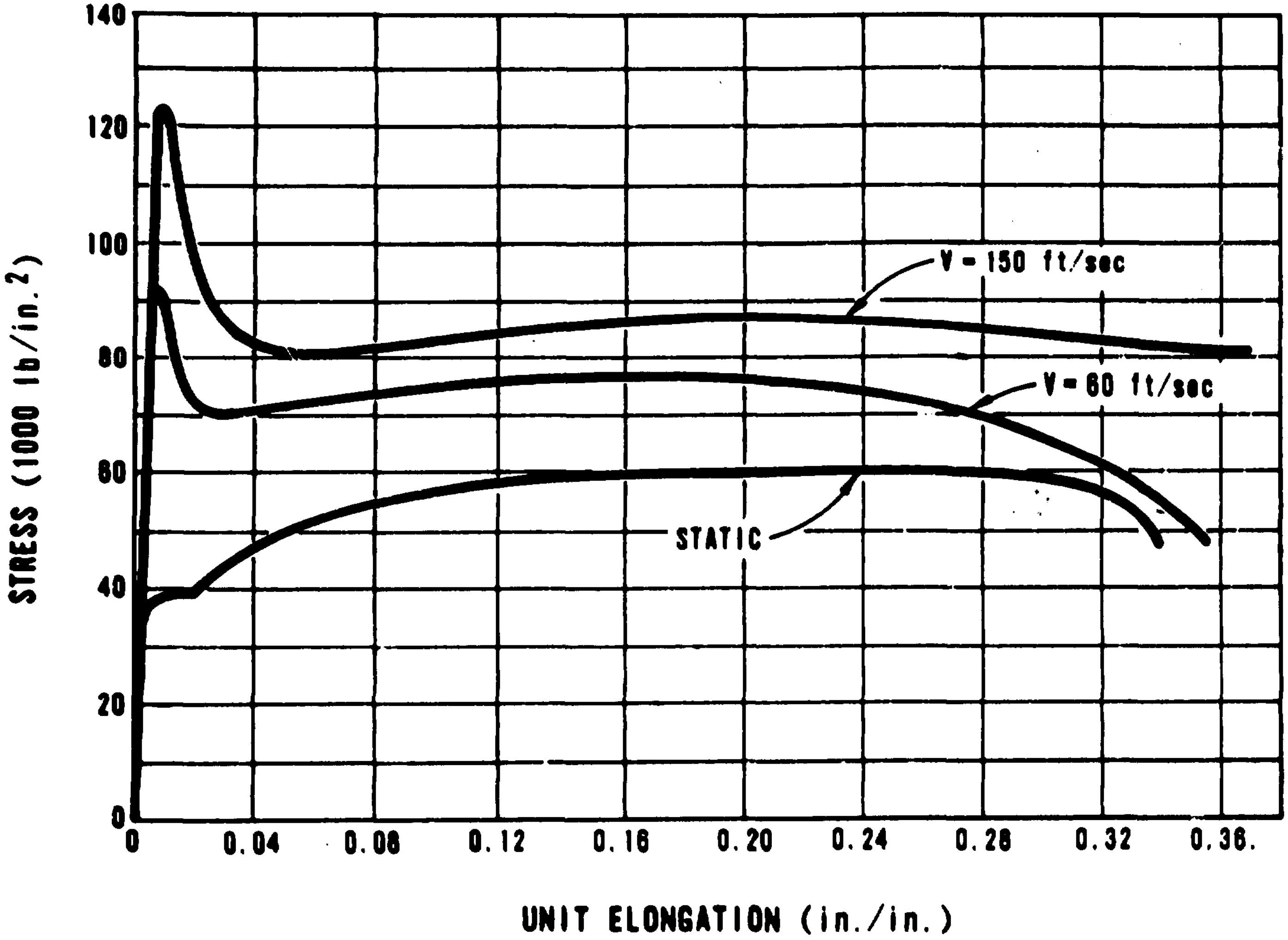

Fig. 1.4. Dynamic tensile properties of mild steel.

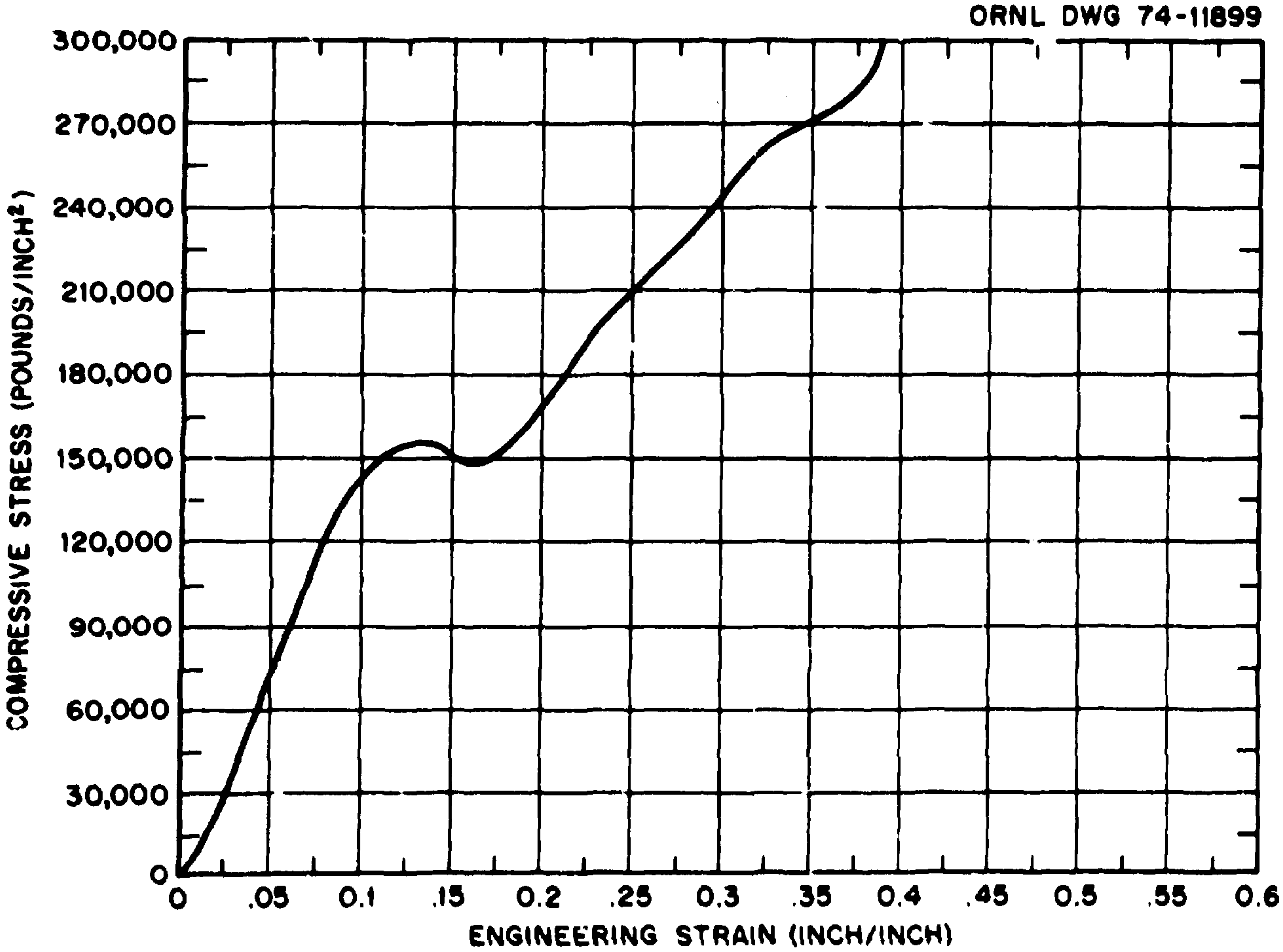

Fig. 1.5. Dynamic compressive properties of stainless steel.

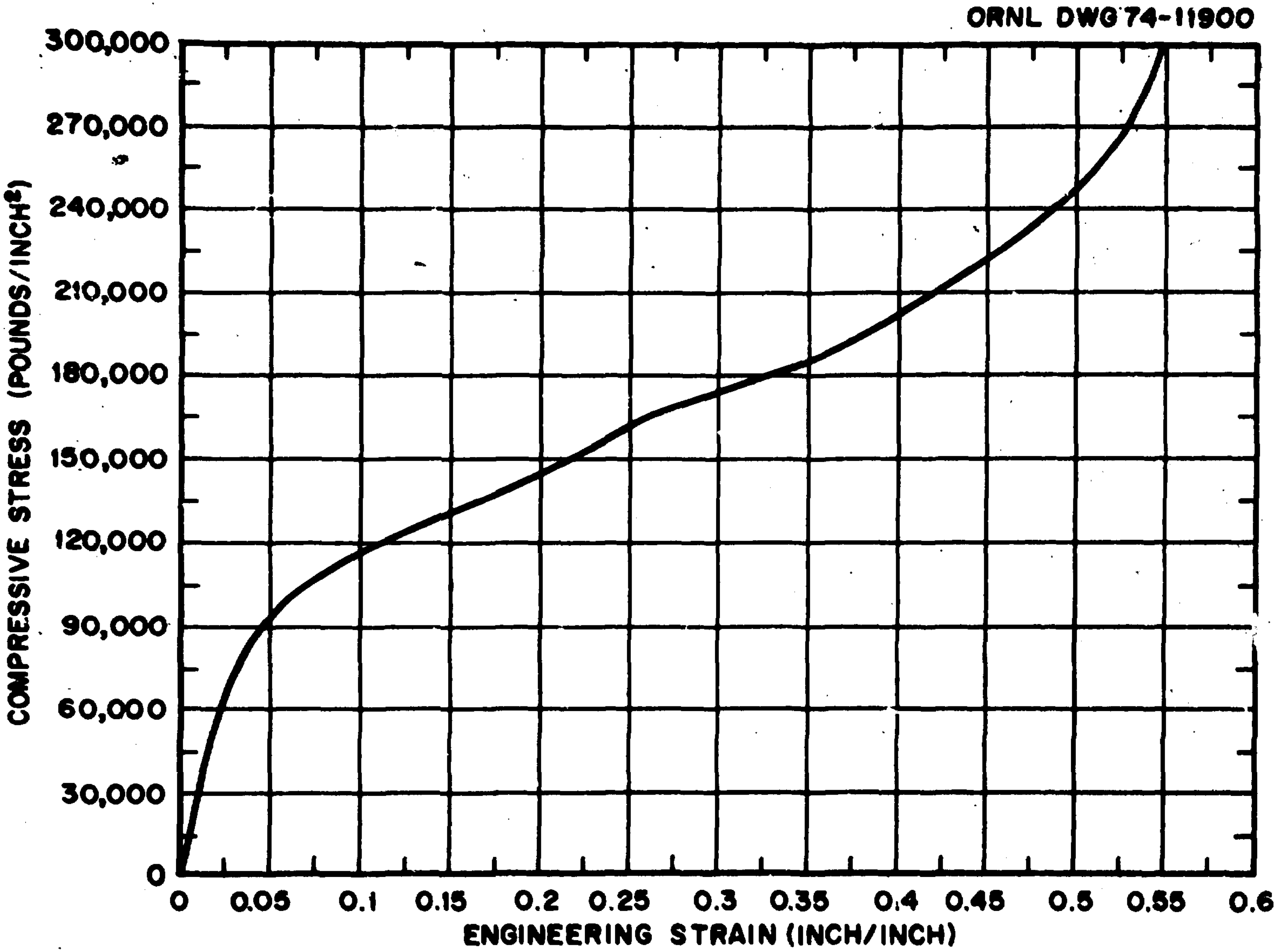

Fig. 1.6. Dynamic compressive properties of mild steel.

shipping cask is constructed of lead, low-carbon steel, and stainless steel. To date, visual inspections indicate there has been no chemical or galvanic reaction between the components of the cask or the cask and its contents.

1.2.1 Closure

The standards specify that the package be equipped with a positive closure that will prevent inadvertent opening. The cask upper cover, lower cover, and gate are all secured with stainless steel bolts which qualify as positive closure.

1.2.2 Cask-lifting device

If there is a system of lifting devices that is a structural part of the package, the 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 the yield strength.

1.2.2.1 Horizontal lift. The cask is normally lifted in the horizontal orientation by a two-legged sling a tached to two 1-in. shackles which are in turn attached to a lifting bar (see Fig. 0.1). The shackles are rated[13] at 8-1/2 tons each and comply by virtue of their rating. We are assuming the sling angle (as measured from the vertical centerline) is at no more than 45°. This assumption will be conservative, since this is the maximum angle used in good rigging practice. The load applied to each lifting device is then

$$P = 1.5W/\cos 45° = 36{,}060 \text{ lb} ,$$

where

W = weight of cask and skid (lb) .

The 1-in.-thick lifting bar is reinforced at the holes where the shackles are attached, and the thickness at these points is 1-5/8 in. (see Fig. 1.7). Thus the bearing stress in the gusset when two shackles are used is

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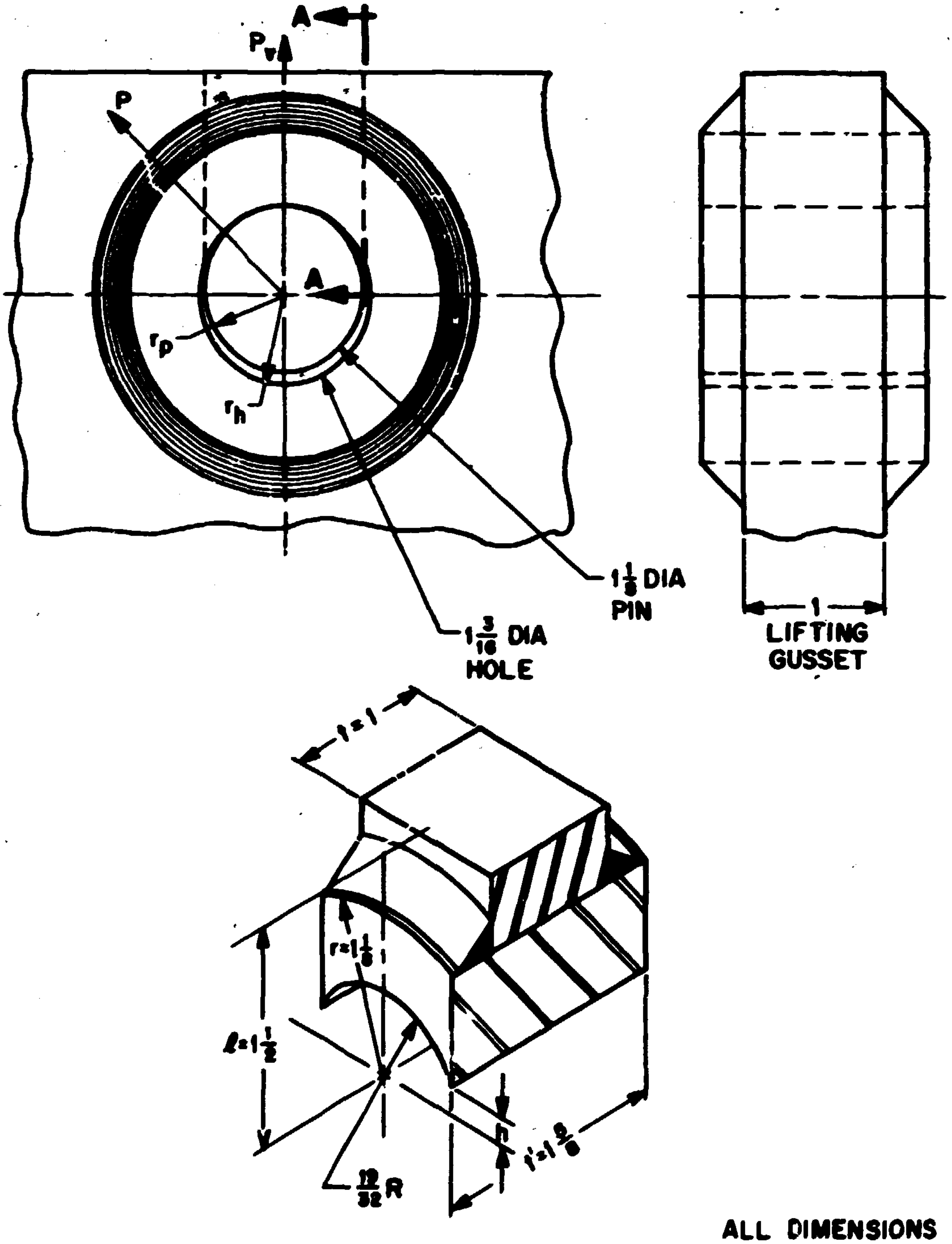

ALL DIMENSIONS GIVEN IN INCHES

SECTION A-A

Fig. 1.7. Horizontal orientation lifting device.

$$S_b = \frac{P}{dt} = \frac{(36,060)}{(1.125)(1.625)} = 19,700 \text{ psi} ,$$

where

t = thickness at the hole = 1.625 in.,

d = shackle pin diameter = 1.125 in.

The clearence is

$$h = (r_h^2 - r_p^2)^{1/2} = \left((0.594)^2 - (0.563)^2\right)^{1/2} = 0.189 \text{ in.}$$

The shearing stress at A-A is

$$T = \frac{P_V}{2A} = \frac{1.5W}{2[r - h)t' + (\ell - r)t]}$$

$$= \frac{25,500}{2[(1.25 - 0.189)1.625 + (1.5 - 1.125)1]} = 6720 \text{ psi} ,$$

where

W = weight of cask and skid (lb) .

The stress (σ) in the gusset-to-container skin weld is

$$\sigma = \frac{P}{A} = \frac{3W}{A}$$

$$= \frac{51,000}{58} = 880 \text{ psi} ,$$

where

A = weld area.

Therefore the bearing stress and shearing stresses are less than the allowable. If, under extreme loading, either cask lift device failed, damage would occur in the area adjacent to the lifting device. This would not impair the function of the cask. Hence the horizontal lift device complies with the regulations.

1.2.2.2 Vertical lifting. The cask is lifted in the vertical orientation by using the two 3-in.-diam trunnions on the plug end of the cask (see Fig. 1.8). These devices will be used to rotate the cask from the horizontal orientation to vertical. The maximum load will result from a vertical lift, since for turning, a portion of the cask's weight is supported by the rear trunnions, which are used to secure the cask to the skid. The vertical load, P_y, on each trunnion will be 1.5W = 24,000 lb. For the vertical lift, the cask is lifted without the skid; however, for calculation purposes it shall be included.

At plane m-m, the maximum bending stress is

$$\sigma = \frac{M}{Z} = \frac{P_y k}{\pi D^3/32} = \frac{32(25{,}500)(1.25)}{\pi(3)^3} \doteq 12{,}000 \text{ psi} ,$$

where

M = moment (in.·lb),

Z = section modulus (in.^{3}).

For vertical lifting, the sling angle will not exceed 45° in practice. The horizontal component, P_x, is also 1.5W = 24,000 lb. The compressive stress, σ_c, on the trunnion is

$$\sigma_c = \frac{P_x}{A} = \frac{25{,}500}{\pi(1.5)^2} = 3600 \text{ psi} .$$

The maximum stress, σ_{max}, is

$$\sigma_{max} = \sigma_b + \sigma_c = 12{,}000 + 3600 = 15{,}600 \text{ psi} .$$

The shearing stress is

$$\tau = \frac{P}{A} = \frac{P_y}{\pi D^2/4} = \frac{24{,}000}{4} \cdot \underline{(3)^2} = 3400 \text{ psi}$$

at plane n-n. The location of the neutral axis (see Sect. A-A, Fig. 1.8) is

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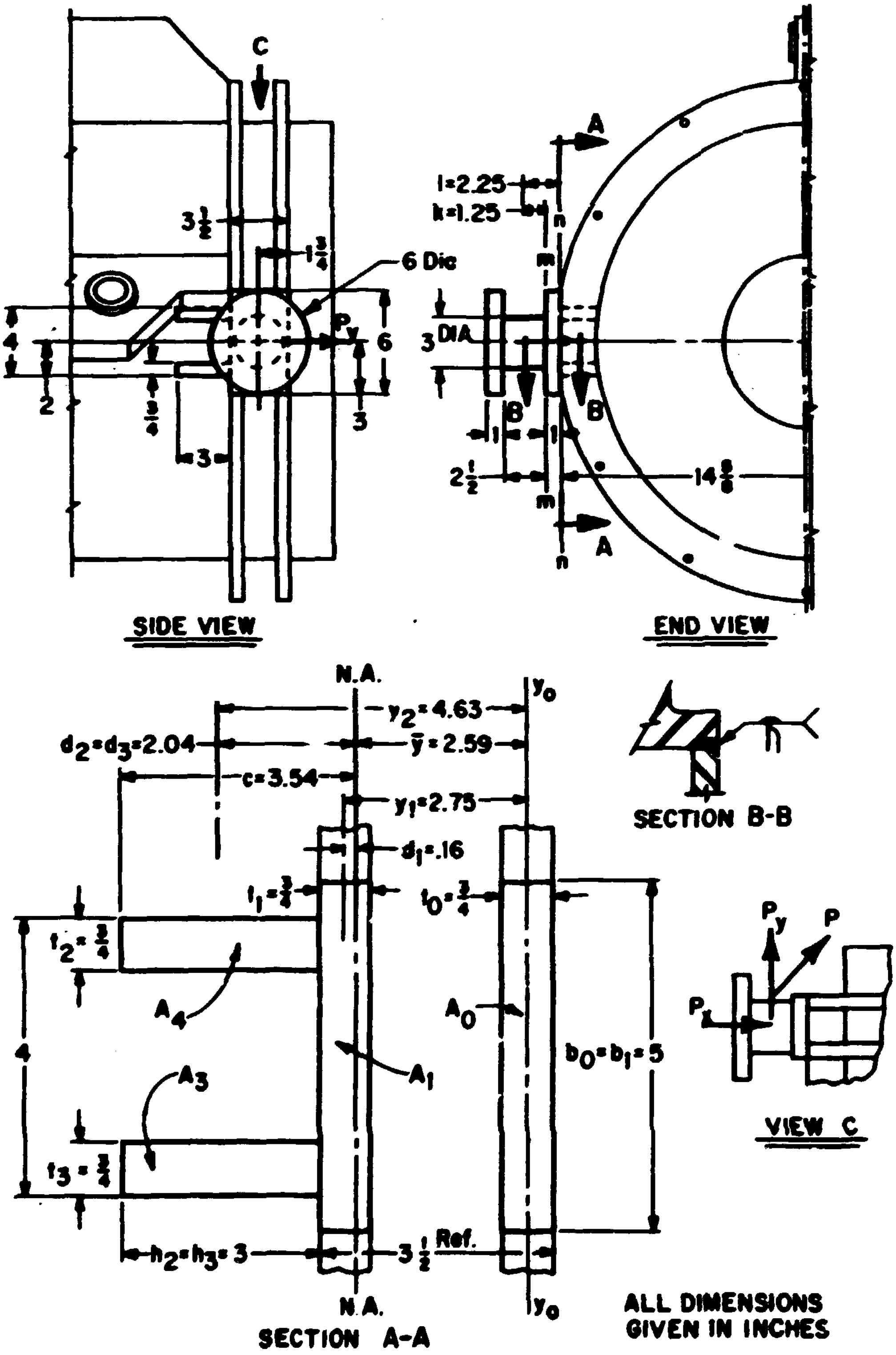

Fig. 1.8. Vertical orientation lifting device.

$$\bar{y} = \frac{A_0 y_0 + A_1 y_1 + A_2 y_2 + A_3 y_3}{A_0 + A_1 + A_2 + A_3} ,$$

where A is cross-section area;

$$\bar{y} = \frac{5(3/4)0 + 5(3/4)(2.75) + 2(3)(3/4)(4.63)}{2(5)3/4 + 2(3)(3/4)} = 2.59 \text{ in.}$$

The moment of inertia by the transfer axis theorem is

$$I = \Sigma(I_0 + Ad^2) ,$$

where

I_0 = moment of inertia of the individual parts, about their centroid (in.^{4}),

A = area of the individual parts (in.^{2}),

d = distance from the neutral axis to the centroid of the individual parts (in.).

Since $I_0 = I_1$, $I_2 = I_3$, $A_2 d_2{}^2 = A_3 d_3{}^2$, and $A_0 = A_1$,

$$I = 2I_0 + A_0(d_0{}^2 + d_1{}^2) + 2I_2 + 2A_2 d_2{}^2$$

$$= \frac{2(t_0{}^3)b}{12} + (t\ b\ (d_0{}^2 + d_1{}^2) + \frac{2(h_2{}^3)t_2}{12} + 2(t_2 h_2)d_2{}^2 ,$$

$$I = \frac{2(0.75)^3(5)}{12} + (0.75)(5)(2.59^2 + 0.16^2) + \frac{2(3^3)0.75}{12}$$

$$+ 2(0.75)(3)2.04^2 = 47.7 \text{ in.}^4 ,$$

and the bending stress is

$$\sigma_b = \frac{Mc}{I} = \frac{P_y \ell c}{I} = \frac{24{,}000(2.25)(3.54)}{47.7} = 4000 \text{ psi} .$$

The compressive stress is

$$\sigma_c = \frac{P_x}{A} = \frac{24{,}000}{12} = 2000 \text{ psi} ,$$

$$\sigma_{max} = \sigma_b + \sigma_c = 4000 + 2000 = 6000 \text{ psi} .$$

The shearing stress is

$$\tau \frac{P}{A} = \frac{24,000}{2[(0.75)(5) + 0.75(3)]} = 2000 \text{ psi} .$$

The calculated normal stresses are less than yield, and the shearing stresses are less than the allowable shearing stress. It is concluded that the cask-lifting devices comply with the regulations.

1.2.3 Lid-lifting devices

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

The package has three plugs which fit the definition of lids. These are shown in place in Fig. 0.1. The calculated weights of the upper cover, lower cover, and gate are 110, 30, and 220 lb respectively.

1.2.3.1 Upper cover. The upper plug is normally lifted either by the two handles or by the two lifting lugs shown in Fig. 1.9. Consider the case where the lid is lifted by the two handles. The load on each handle would be as shown in Fig. 1.9. Note that if the load was not centrally located, there would be a tendency for the plug to rotate and bind in the hole, so the centrally located force will be considered in this calculation. The handle top bar could reasonably be treated as a rigid frame, using formulas published by Griffel:[14]

$$M_1 = M_4 = \frac{PL}{8\,[2 + (I_b/I_c)(h/L)]} = \frac{(1.5)(110)(3\text{-}11/16)}{8\,[\,2 + (1)(1\text{-}1/16/3\text{-}11/16)]} = 34 \text{ in.}\cdot\text{lb} ,$$

where

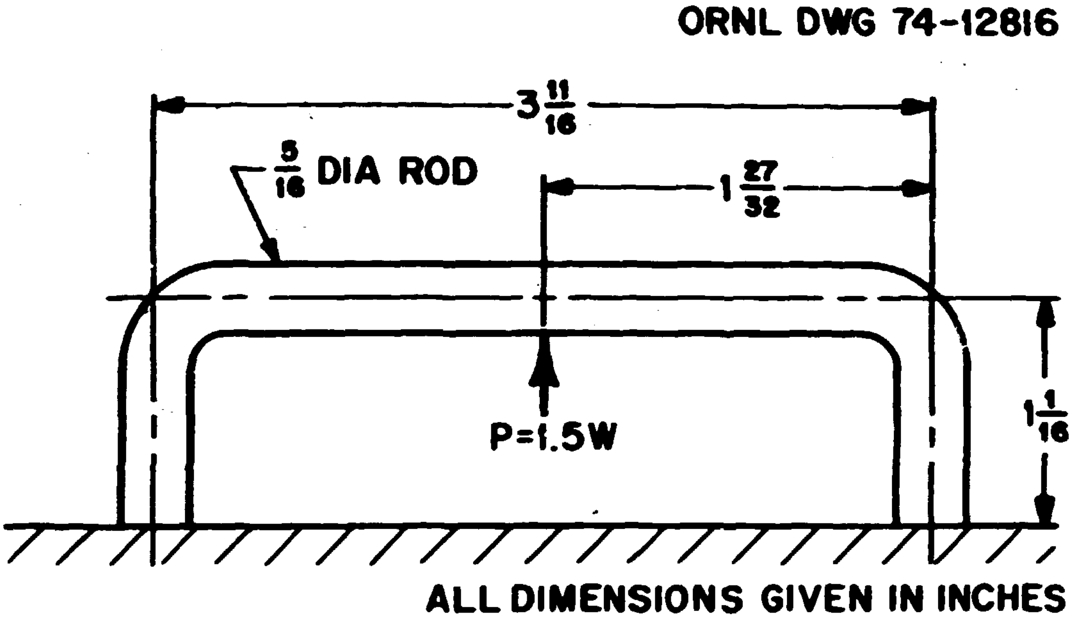

Fig. 1.9. Upper cover-lifting device.

M_1, M_4, h, and L are as labeled in Fig. 1.12,

$P = 1.5W$,

I_b/I_c = ratio of moments of inertia, beam to column.

The moment in either corner joint is

$$M_2 = M_3 = -2M_1 = -2(34) = -68 \text{ in.}\cdot\text{lb} .$$

The moment at the load P is

$$M_p = \frac{PL}{4} + M_2 = \frac{1.5(110)(3\text{-}11/16)}{4} -68 = 84 \text{ in.}\cdot\text{lb} .$$

The horizontal force at the bottom of each column is

$$H = \frac{3M_1}{L} = \frac{3(34)}{1\text{-}1/16} = 96 \text{ lb} .$$

The bending and tensile stresses at the load point are

$$S_b = \frac{Mc}{I} = \frac{(84)(5/32)}{\pi(5/32)^4/4} = 28{,}000 \text{ psi} ,$$

$$S_T = \frac{\text{tension}}{\text{area}} = \frac{96}{\pi(5/32)^2} = 1251 \text{ psi} .$$

For an extreme fiber at the top of the beam, the stresses are both tension and additive. Thus,

$$S_{max} = S_b + S_T = 28{,}000 + 1251 = 29{,}251 \text{ psi} .$$

Thus the lifting handles are adequate for the loading condition.

The alternative means of lifting this plug is with the two lifting eyes made of 3/8-in. plate each having 3/4-in.-diam holes. The loading on each eye is shown in Fig. 1.10. For these calculations, it will be assumed that a 5/8-in.-diam pin is inserted through the hole for lifting. The bearing stress is

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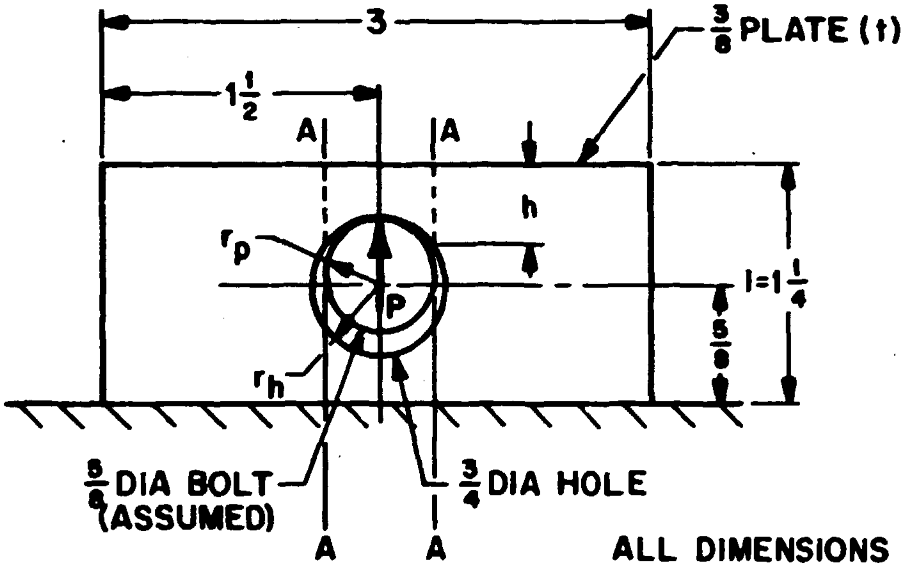

ALL DIMENSIONS GIVEN IN INCHES

Fig. 1.10. Alternate upper cover-lifting device.

$$\sigma = \frac{P}{dt} = \frac{165}{(0.625)(0.375)} = 704 \text{ psi} ,$$

where

P = load = 1.5W = 165 lb,
d = pin diameter (in.),
t = thickness of plate (in.).

The shearing stress, τ, along plane A-A is

$$\tau = \frac{P}{2A} = \frac{P}{2th} ,$$

where

$$h = \text{length of plane A-A}$$

$$= \ell/2 - a = \ell/2 - \left(r_h^2 - r_p^2\right)^{1/2} = 0.625 - \left((0.375)^2 - (0.312)^2\right)^{1/2}$$

$$= 0.417 \text{ in.}$$

Therefore the shearing stress is

$$\tau = \frac{165}{2(0.375)(0.417)} = 527 \text{ psi} .$$

Since these are below the allowable stresses, the eyes comply with the regulations. The lower cover weighs 30 lb and has two lifting eyes made of 1/4-in.-thick plate. Each has a 1-in. hole as shown in Fig. 1.11. The load per eye, P, to be used in calculating stresses is 1.5 times the cover weight or 45 lb. Using the same method of calculation, the bearing stress, σ, and shearing stress, τ, are

$$\sigma = \frac{P}{dt} = \frac{45}{(0.875)(0.250)} = 205 \text{ psi} ,$$

$$h = \ell/2 - \left(r_h^2 - r_p^2\right)^{1/2} = 0.750 - \left(0.5^2 - 0.438^2\right)^{1/2} = 0.508 \text{ in.} ,$$

$$\tau = \frac{P}{2ht} = \frac{45}{2(0.508)(0.25)} = 177 \text{ psi} .$$

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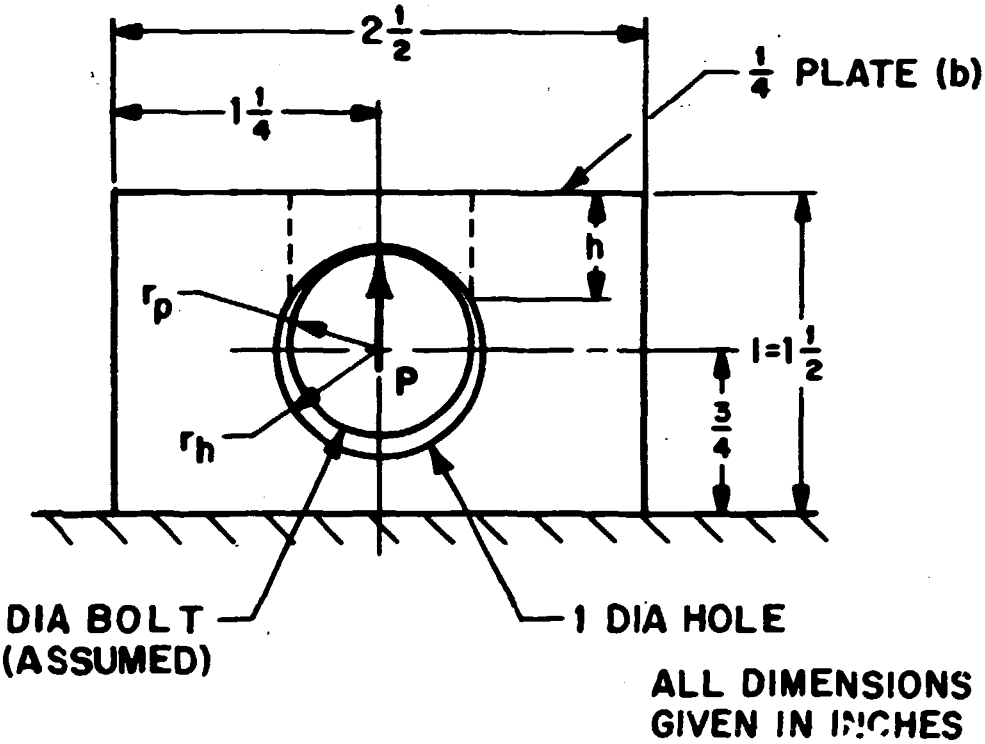

Fig. 1.11. Lower cover-lifting device.

These stresses are less than the allowable; hence they comply with the requirements of the regulations.

The gate or shutter lid plug is lifted by a single ear made from a 1/4-in.-thick plate with a 2-in.-diam hole. The plug weight is 220 lb, so the load which must be supported is 3 x 220 = 660 lb. The primary concern for the plug-lifting device is bending when a small pin is inserted in the 2-in.-diam hole. To find the bending stress in the lifting eye, assume that the eye has the dimensions of the dotted model as shown as an overlay in Fig. 1.12. This will be conservative in comparison because the model has both a longer horizontal beam and columns of less stiffness. The rigid-frame formulas have been published by Griffel:[14]

$$M_1 = M_4 = \frac{PL}{8\,[\,2 + (I_b/I_c)(h/L)]}$$

$$= \frac{3(220)(2.62)}{8\,[\,2 + (0.5^3/0.62^3)(1.75/2.62)]} = 92 \text{ in.}\cdot\text{lb} \ ,$$

where

M_1, M_4, h, and L are as labeled in Fig. 1.12,

P = three times the actual 220 lb weight,

I_b/I_c = ratio of moments of inertia, beam to column, in this case the cube of the depth ratio.

The moment in either corner joint is

$$M_2 = M_3 = -2M_1 = -2(92) = -184 \text{ in.}\cdot\text{lb} \ .$$

The moment at the load P is

$$M_p = \frac{PL}{4} + M_2 = \frac{3(220)(2.62)}{4} - 184 = 248 \text{ in.}\cdot\text{lb} \ .$$

The horizontal force at the bottom of each column is

$$H = \frac{3M_1}{h} = \frac{3(92)}{1.75} = 158 \text{ lb} \ .$$

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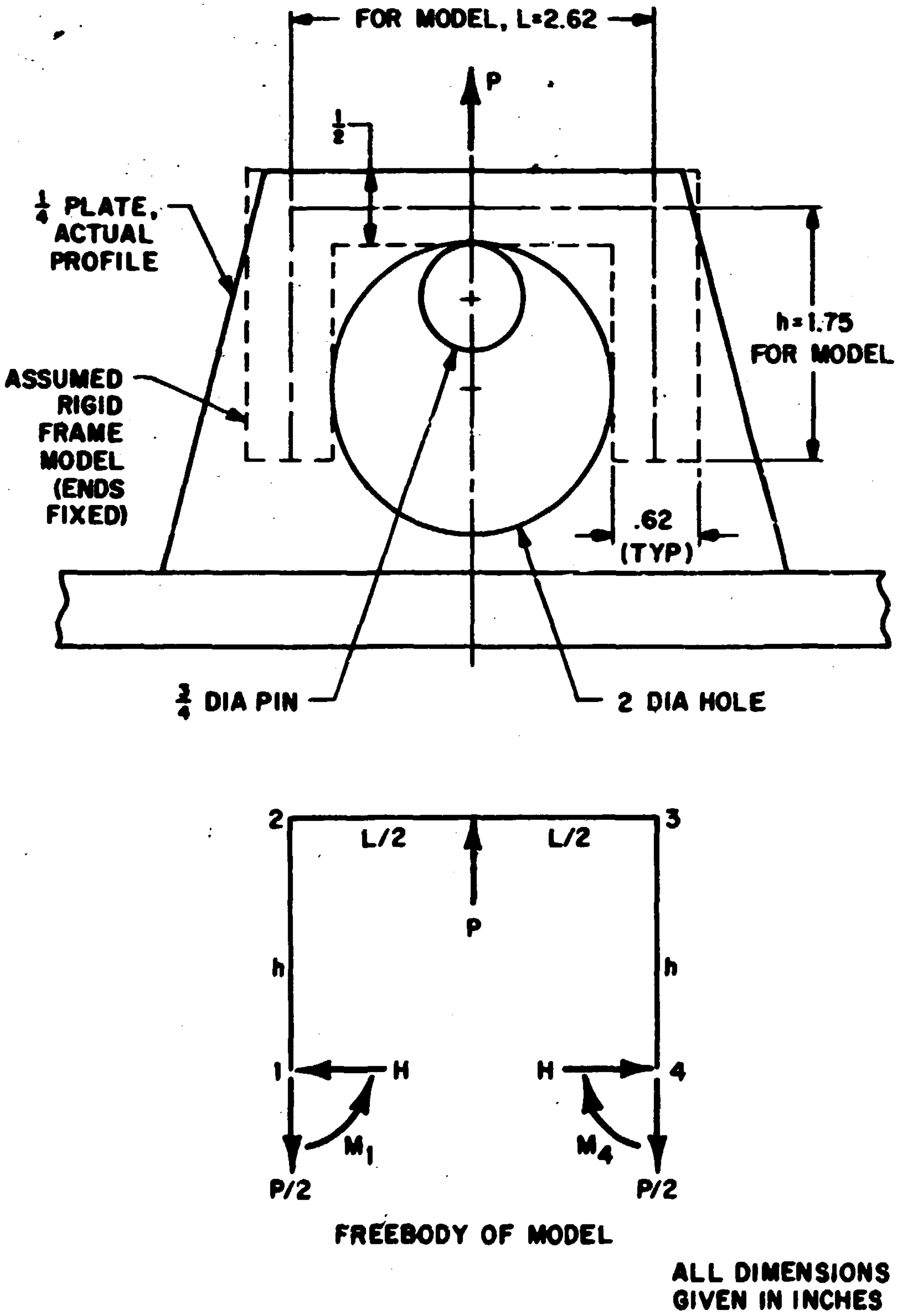

Fig. 1.12. Sliding gate-lifting device.

The bending and tensile stresses at the load point are

$$S_b = \frac{Mc}{I} = \frac{248(0.25)12}{(0.25)(0.5)^3} = 23{,}800 \text{ psi} ,$$

$$S_T = \frac{\text{tension}}{\text{area}} = \frac{158}{(0.25)(0.5)} = 1260 \text{ psi} .$$

For an extreme fiber at the top of the beam, the stresses are both tension and additive. Thus,

$$S_{max} = S_b + S_T = 23{,}800 + 1260 = 25{,}100 \text{ psi} .$$

These stresses are less than the yield stress, and the plug-lifting device complies with the regulations.

1.2.4 Tie-down devices

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

The cask is designed to be secured to the transport vehicle, as shown in Figs. 0.4 and 1.13, by four tension members attached to the four tie-down lugs. For the general case, the notations I, J, K, H, and L of Fig. 1.13 represent the dimensions of the tie-down system. Of these, only the value of H is fixed by the container geometry. For the 10W load, by summation of horizontal forces (see Fig. 1.13), $F_x = 5W$.

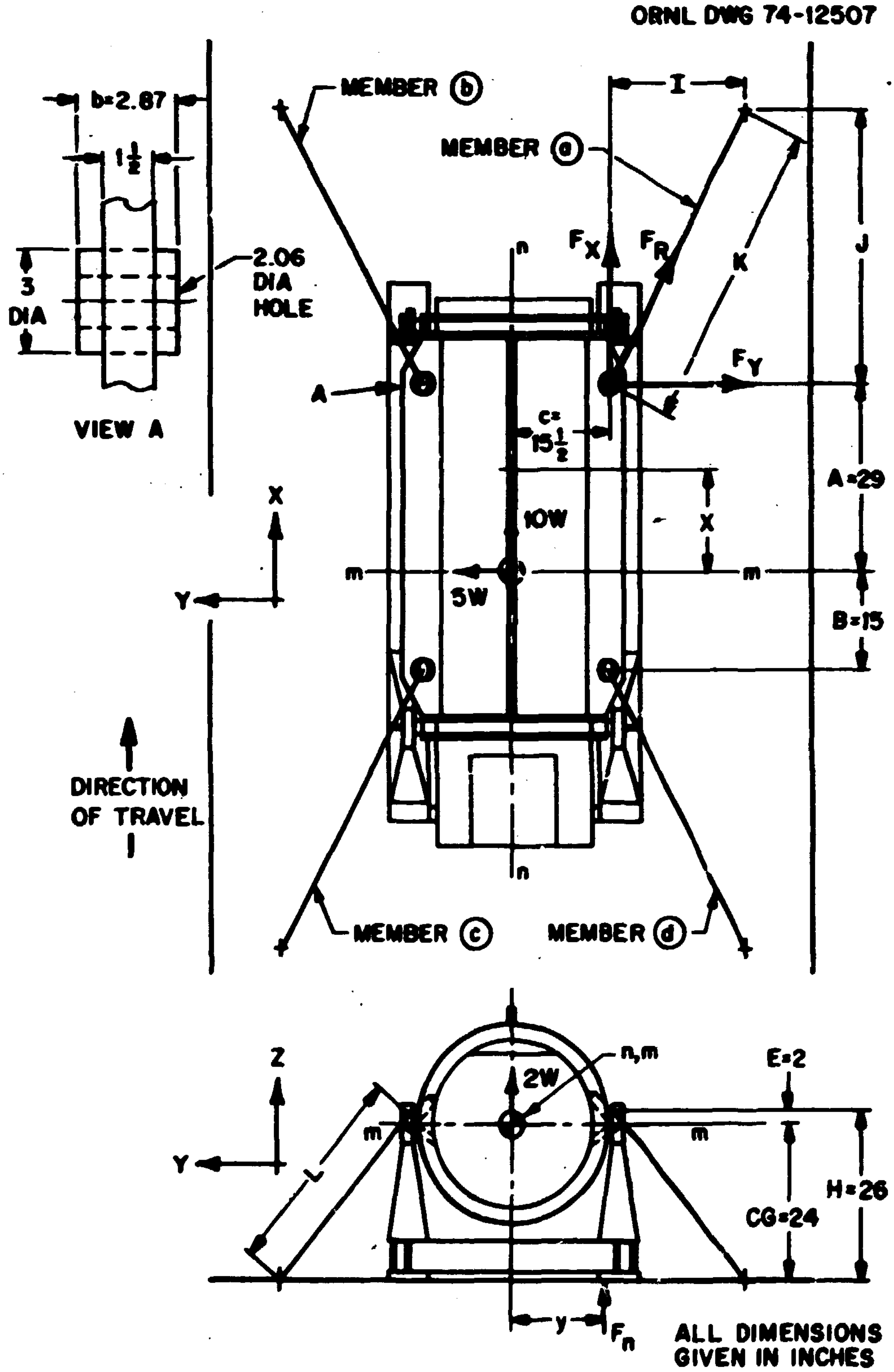

Fig. 1.13. Cask tie-down.

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

$$T_a = T_{10} + T_5 + T_2 = 5W(L/J) + 2.5W(L/I) + (W/4)(L/H)$$

$$= WL(5/J + 2.5/I + 0.25/H) .$$

The values of the dimensions I and J will vary over a considerable range in practice. Ratios of I to J will be in the range 1/1 to 1/2. For highway trailers, the most likely mode of transport for the casks, an I to H ratio of near 1/1 is likely. These ratios are selected to demonstrate compliance with the tie-down requirements. For $I/J = 1$, $H = 1$, $K = 3^{1/2}$, and $T_a = W(3)^{1/2}(5 + 2.5 + 0.25) = 13.42W$. For the I/J ratio of 1/2, $H = 1$, $K = (5)^{1/2}$, $L = (6)^{1/2}$, and

$$T_a = W\ (6)^{1/2}\left(\frac{5}{2} + \frac{2.5}{1} + \frac{0.25}{1}\right) = 12.86W .$$

The I to J ratio of 1/1 results in the largest loads in the tie-down lugs, and the evaluation will be made on this basis.

The tensile forces and component loads in the members are

$$T_a = 13.42W ,$$

$$T_b = W(3)^{1/2}(5 + 0.25) = 9.093W ,$$

$$T_c = W(3)^{1/2}\ (0.25) = 0.433W ,$$

$$T_d = W(3)^{1/2}\ (2.5 + 0.25) = 4.763W ,$$

$$F_{za} = T_a H/L = \frac{13.42W}{(3)^{1/2}} = 7.75W \ ,$$

$$F_{zb} = \frac{9.093W}{(3)^{1/2}} = 5.25W \ ,$$

$$F_{zc} = \frac{0.433W}{(3)^{1/2}} = 0.25W \ ,$$

$$F_{zd} = \frac{4.763}{(3)^{1/2}} = 2.75W \ ,$$

$$F_n = \Sigma\, F_z - W = 15W \ .$$

It is possible that the tension members carry additional loads to prevent tipping. To evaluate this possibility, the point at which the resultant force (F_n) acts must be located.

Summation of moments about axis m-m yields

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

$$F_n X - 10WE - (F_{za} + F_{zb})A + (F_{zc} + F_{zd})B = 0 \ ,$$

$$X = \frac{[10E + (7.75 + 5.25)A - (0.25 + 2.75)B]W}{15W}$$

$$= \frac{E + 1.3A - 0.3B}{1.5} = \frac{2 + 37.7 - 4.6}{1.5} = 23.4 \text{ in.}$$

Summation of moments about axis n-n yields

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

$$F_n y - 5We + (-F_{za} + F_{zb} + F_{zc} - F_{zd})C = 0 \ ,$$

$$y = \frac{5WE + (7.75 - 5.25 - 0.25 + 2.75)WC}{15W}$$

$$= \frac{E + C}{3} = \frac{2 + 15.5}{3} = 5.8 \text{ in.}$$

If the direction of travel were reversed, the dimension y would be as calculated above. The equation for X would become

$$X = \frac{E + 0.3A - 1.3B}{1.5} = \frac{2 + 8.7 - 19.8}{1.5} = -6.07 \text{ in.}$$

The negative sign means X is located on the opposite side of the axis. Since these dimensions are located within the cask skid, the tension members do not carry additional loads to keep the cask from tipping.

The load in the most loaded member is

$$T_a = 13.42W = 13.42(17{,}000) = 2.28 \times 10^5 \text{ lb.}$$

The load is applied essentially normal to the tie-down lug. The bearing stress is

$$\sigma_B = \frac{T_a}{db} = \frac{2.28 \times 10^5}{(2.9)(2)} = 39{,}300 \text{ psi} \,,$$

where

b = width of lug,
d = diameter of hole.

The bearing stress is less than the allowable bearing stress (see Table 1.1) of 48,600 for mild steel. It can be determined by inspection that welds securing the tie-down bar to the cask are adequate. Failure under extreme load would occur in the tie-down lug. This would not impair the function of the container. It is concluded that the cask tie-downs conform to the requirements of the regulations.

1.3 Standards for Type B and Large-Quantity Packaging

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

1.3.1 Load resistance

When regarded as a simple beam supported at its ends along any major axis, the cask must be capable of withstanding a static load normal to and uniformly distributed along its length that is equal to five times its fully 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. 1.14. The effect of the original 0.250-in.-thick outer shell is neglected.

The cross section of the container is composed of the outer steel shell, the lead, and the inner stainless steel shell, as shown in Fig. 1.14. Since these components are symmetrical about the same axis, the moment of inertia of the composite section is the sum of the equivalent moments of inertia of the individual components. For a thin shell, the moment of inertia about its diameter is

$$I_s = \int y^2 \, dA = 4\int_{\theta=0}^{\theta=\pi/2} (r_m{}^2 \sin^2 \theta) t r_m \, d\theta = \pi r_m{}^3 t \ ,$$

where r_m is the mean radius and t is the thickness. Neglecting the effect of the lead, the moment of inertia of the composite section is

$$I = \pi(r_0{}^3 t_0 + \quad {}^3 t_i) = \pi \left[(12.25^3)(0.5) + (2.188^3)(0.125)\right] = 2890 \text{ in.}^4 \ .$$

The maximum bending stress is

$$\sigma = \frac{Mc}{I} = \frac{w(L)^2 \cdot c}{8I} = \frac{964(83)^2(12.5)}{8(2890)} = 3600 \text{ psi} \ ,$$

which is far below the allowable stress.

1.3.2 External pressure

The regulations require that the shipping package be adequate to assure that the containment vessel will suffer no loss of contents if subjected to an external pressure of 25 psig. For calculational purposes, it will be assumed that the lead cavities are at atmospheric pressure.

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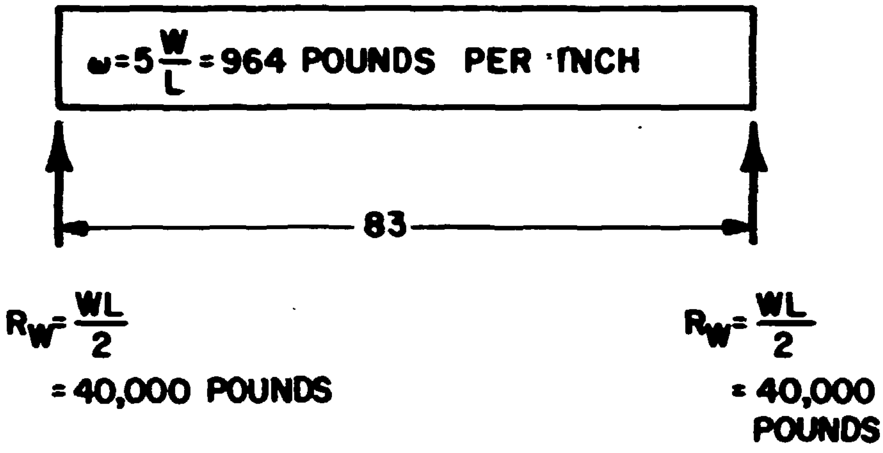
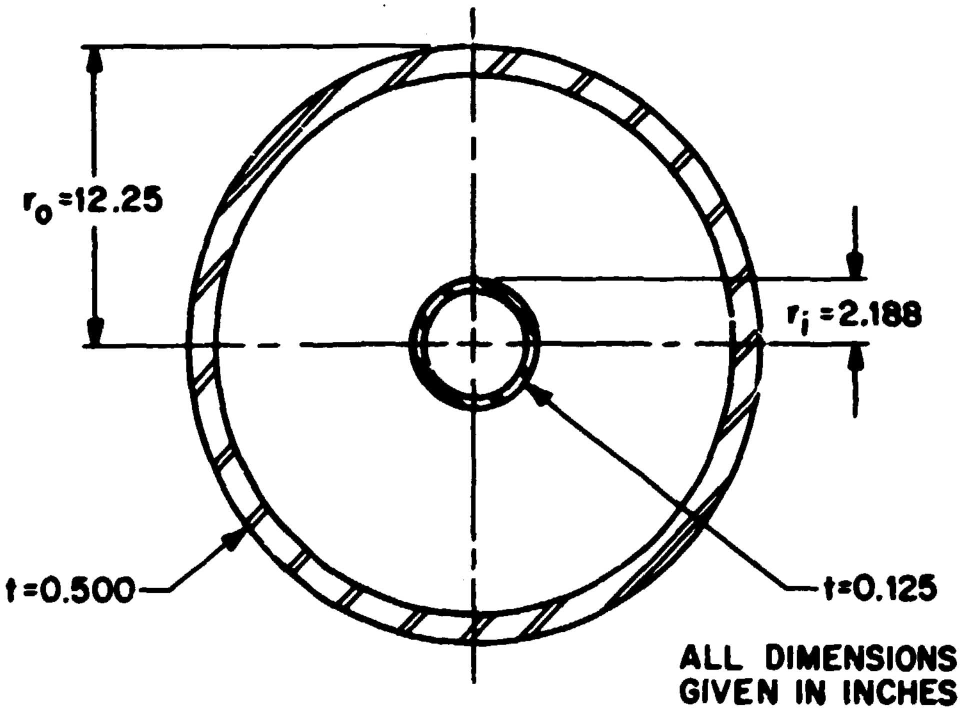


(a) CONTAINER AS SIMPLE BEAM



(b) EQUIVALENT CROSS SECTION OF CONTAINER

Fig. 1.14. Cask as a simple beam.

A potential consequence of external pressure is buckling of the cylindrical shells. The outer shell of the vessel or body is probably the most vulnerable shell from a buckling standpoint. Assuming the simplified model of a right circular cylinder 25 in. in outside diameter by 83 in. long by 0.5 in. in wall thickness with closed ends, the cricial (buckling) pressure is determined using equations published by Faupel.[15] As before, the effect of the original shell is neglected. For axisymmetric (bellows type) buckling, the critical pressure is

$$P_{cr} = \frac{2E(t/R)^2}{[3(1 - \mu^2)]^{1/2}} = \frac{2(29 \times 10^6)(0.500/12.25)^2}{[3(1 - 0.3^2)]^{1/2}} = 58{,}480 \text{ psig} .$$

For lobar buckling the critical pressure is

$$P_{cr} = \frac{1.345E}{(1 - \mu^2)^{3/4}} \cdot \frac{(t/R)^{5/2}}{1.57(L/R) - (t/R)^{1/2}}$$

$$= \frac{1.345(29 \times 10^6)}{(1 - 0.3^2)^{3/4}} \cdot \frac{(0.5/12.25)^{5/2}}{1.57(83/12.25) - (0.5/12.25)^{1/2}} = 1350 \text{ psig} .$$

Since the critical buckling pressure of 1350 psig is greater than 25 psig, the shells will not buckle.

External pressure would also load the flat-plate-type ends of the cask. These plates have a central hole concentric with the vessel axis. Both the inner and the outer perimeter of each plate are welded to supporting parts so that edge moments will be developed if the plate is deflected by a pressure differential. In calculating stresses for these plates (with outer radius to inner radius of only 24/7), it will be conservative to neglect the edge moments. Thus, from Roark,[16] the maximum stress is

$$s_r = \frac{\beta w a^2}{t^2} = \frac{0.348(25)(12)^2}{(0.5)^2} = 5012 \text{ psi} ,$$

where

β = coefficient interpolated from Roark's work,

w = pressure differential (psi),

a = outer radius (in.),

t = plate thickness (in.).

Thus the actual stress will be a small part of the yield stress, and the plate will not fail.

Primary and secondary containment will withstand the 25 psig external pressure as outlined below. The 2R container heads will withstand 25 psig external pressure, since they are tested (see Sect. 1.7) at 1.5 times the design pressure of 20 psig. Comparison of the ratios of t/R and L/R raised to the appropriate powers for the 2R containers with those preceding for the outer shell of the shield demonstrates the adequacy of the cylindrical shells of the 2R containers. The ability of "special form" encapsulations to withstand the external pressure is obvious by comparison of geometry with the above and consideration of the prescribed tests.[1,2]

1.4 Compliance with Standards for Normal Conditions of Transport

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

1.4.1 Heat

The package must be able to withstand direct sunlight at an ambient temperature of 130°F in still air without reducing the effectiveness of the packaging. A computer program, HEATING-3,[17] modified to evaluate phase change of materials, was used to compute the steady-state temperature distribution in the cask and its contents under the specified conditions (see Sect. 2). The calculatory model is shown in Fig. 2.1 and the input constnats in Table 2.1. The computed temperatures at locations of concern are outlined in Table 2.2.

These temperatures will not adversely affect the casks. The materials of construction do not suffer significant change in physical properties at these temperatures. The continuous operating temperature limit[18] of the O-rings in the 2R container is 500°F, which is above the calculated seal temperature. The calculated pressures (see Sect. 2.3.4) will not adversely affect the containers (see Sects. 1.7 and 1.9).

The regulations[3] set forth by DOT further stipulate that the temperature of any accessible surface of the fully loaded shipping package shall not exceed 122°F when the package is in the shade in still air at an ambient temperature. Assuming an ambient temperature of 100°F and an inner container heat load of 350 W, the maximum accessible surface temperature was found to be 120°F.

1.4.2 Cold

The shipping package must be able to withstand an ambient temperature of -40°F in still air and shade. At -40°F, pressure (p) in any cavity sealed at a pressure of 14.7 psia and a temperature of 70°F (530°R) is

$$p = \frac{p_1 T_2}{T_1} = \frac{(14.7)(420)}{(530)} = 11.65 \text{ psia} .$$

The resulting pressure differential is not significant by comparison to the 25 psig external pressure of Sect. 1.3.2. A temperature of -40°F is within the operating temperature range of the materials of the cask. Brittle fracture of the primary containment vessel (2R container or cladding) under the stipulated cold condition is not credible, since the ductile-to-brittle transition temperature of the materials[29] from which the vessel is constructed is below -40°F. The same is true of all threaded fasteners and the cask inner cavity. The cask outer shell, flat heads, lifting and tie-down devices, and support structure are fabricated from low-carbon steel. The transition temperature of this material is above -40°F; hence these members would undergo a loss of ductility. They operate under very small loads during normal conditions, and failure is not likely. If a failure did occur, primary containment would be maintained, and the shielding capability of the cask would not be compromised. A failure would be detected by routine inspection and repairs made before further use of the cask.

1.4.3 Pressure

The regulations for normal conditions of transport specify that the package be able to withstand an atmospheric pressure 0.5 times the standard atmospheric pressure, the resulting pressure being 7.35 psia. This reduced atmospheric pressure is additive to the internal pressures attributable to the elevated temperatures resulting from the content's decay heat and atmospheric conditions (see Sect. 2.3.2). The pressure differential between any part of the cask body or plug and atmosphere will not exceed 7.35 + 4.75 = 12.1 psig. The hoop stress in the outer lamination of the shell is

$$\sigma = \frac{pr}{t} = \frac{12.1(12)}{0.5} = 290 \text{ psi} .$$

The gaskets are adequate for a differential of 12.1 psi.

By comparison with the 25 psig external pressure conditions (see Sect. 1.3.2), it can be seen that the stresses in the flat heads of the cask body will not approach the yield stress. It can be determined by inspection that the stresses in the plug cladding are less than those in the body shells. The reduced atmosphere would ot affect the primary containment vessel unless secondary containment failed. If this did happen, the resulting pressure differential, which is the sum of the reduced atmosphere and the maximum in container pressure from Sect. 2.3.4, is 7.35 + 11.5 = 19.85 psig, less than the design pressure for the vessel (see Sect. 1.7). It is concluded that the cask complies with the reduced atmospheric pressure requirement.

1.4.4 Vibrations

The regulations require packages to withstand the vibrations normally incident to transport.

The containers are of welded construction. Transport vibrations have not affected the integrity of the cask. All fasteners are equipped with lock washers and will not loosen due to transport vibrations.

1.4.5 Water spray

It is required that the cask withstand a water spray sufficiently heavy to keep the entire exposed surface, except the bottom, continuously wet for a period of 30 min. The exposed surfaces of the cask are of painted steel and will be unaffected by water spray.

1.4.6 Free drop

The regulations for normal conditions of transport require that a package weighing between 10,000 and 20,000 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 the position in which maximum damage is expected to result. It cannot be determined by inspection which orientation would result in maximum damage. Therefore, impact orientations of (1) corner, (2) end with the axis of the cask vertical, (3) on top of the cask on the lifting bar with the axis of the cask horizontal, and (4) with the axis of the cask horizontal, impacting between the lifting bar and tie-down lugs, are 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. Therefore, the following analyses are intended to conservatively characterize cask response and to demonstrate compliance with the regulations.

1.4.6.1 Corner impact. If the cask impacted on a corner, the kinetic energy would be dissipated in both elastic and plastic deformation of the lead and steel near the point of impact. An unpublished ORNL computer program, 1001 CASK, was used to estimate the response of the cask to a corner impact. The derivation of the equations used in the program and a program listing are in Appendix C. The program is based on a cylindrical model made from a single ideally plastic material. The model assumed for calculation purposes has a radius of 12.5 in., a length of 84 in., and a weight of 16,000 lb. The assumed material has a dynamic yield stress in the range of 6000 to 14,000 psi. The deformation calculated using the lower value is greater than actual, and the acceleration calculated with the higher value is greater than actual. A report by Shappert and Evans[19] supports the validity of the stress range selected (see Sect. 1.1 for a discussion of this approach). The calculated acceleration-deformation histories of the cask are shown in Figs. 1.15 and 1.16 for the smallest and largest dynamic yield stress values used.

The calculated deformation will be a maximum when the lower value of dynamic yield stress is used. The calculated deformation is 1.98 in. (see Fig. 1.15). The acceleration will be a maximum when the upper value of dynamic yield stress is used. The calculated maximum acceleration is 62g's (see Fig. 1.16).

The calculated maximum deformation will not result in radiation dose rates in excess of those allowed by the regulations.[1-3] This conclusion is reached, since the thickness of shielding in the corner after the accident is greater than the original radial thickness.

Fracture or cracking of the welds joining the heads to the shells is not likely. If a crack did occur, it would be detected by routine inspections and appropriate repairs made. The rear sliding gate, the rear cover, or the cask plug could be jammed. If this occurred, the cask could be unloaded via the undamaged end. After unloading, repairs would be made. The impact would place the bolts securing the plugs and gate in tension. The vectorial fraction of the acceleration which loads the bolts is $A = A_{max} \cdot \cos\theta = (62) \cos 16.6 = 59.5g$, where $\theta = \tan^{-1}$ (cask diameter/cask length) = 16.6°.

The stress in the bolts, σ, for the 110-lb cask access plug, which is secured by eight 1/2-13NC stainless steel cap screws, is

$$\sigma = \frac{F}{A} = \frac{wa}{gNA_b} = \frac{(110)(59.5)g}{g(8)(0.14)} = 5850 \text{ psi} ,$$

where

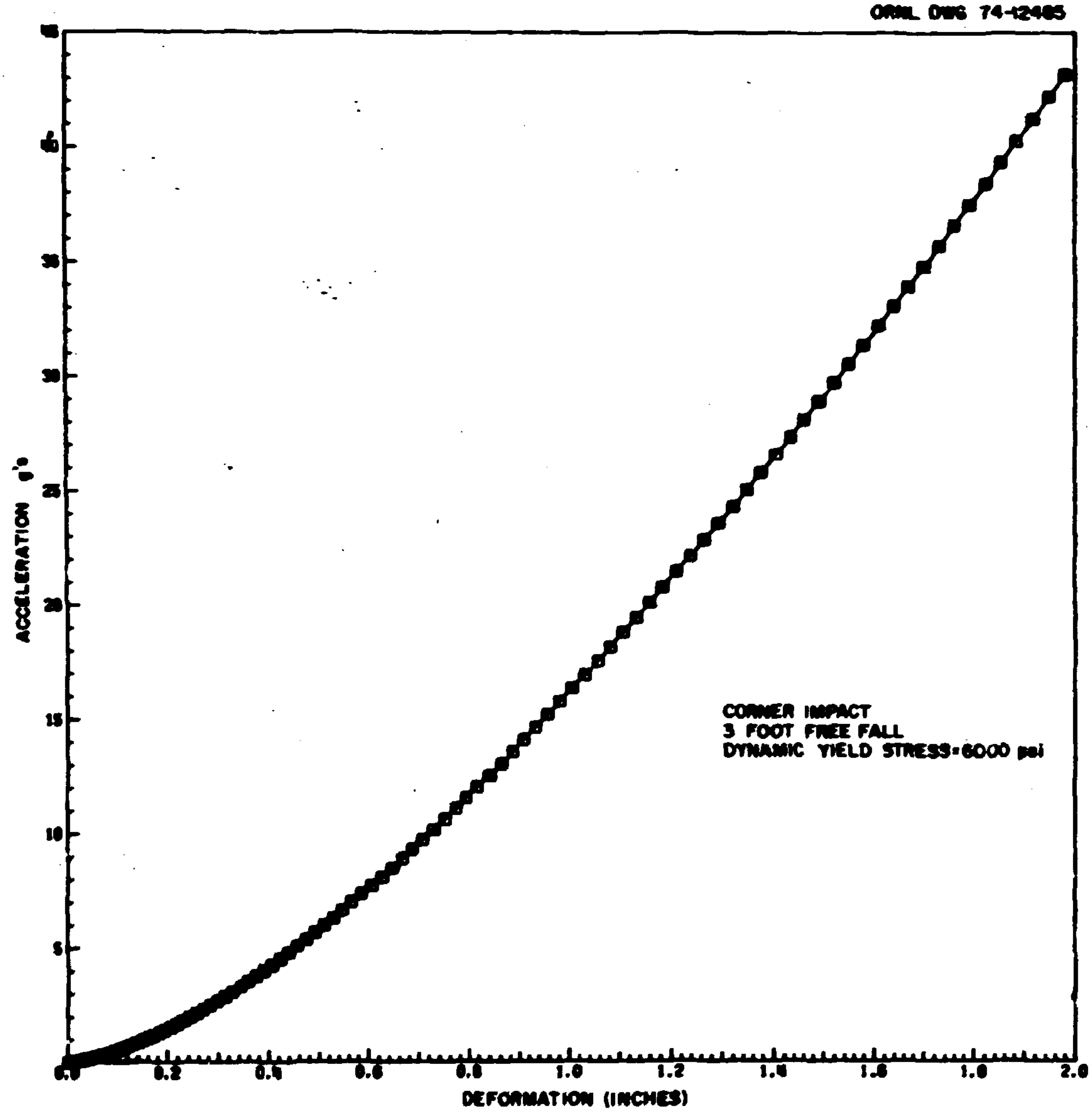


Fig. 1.15. Corner impact — dynamic yield stress = 6000 psi.

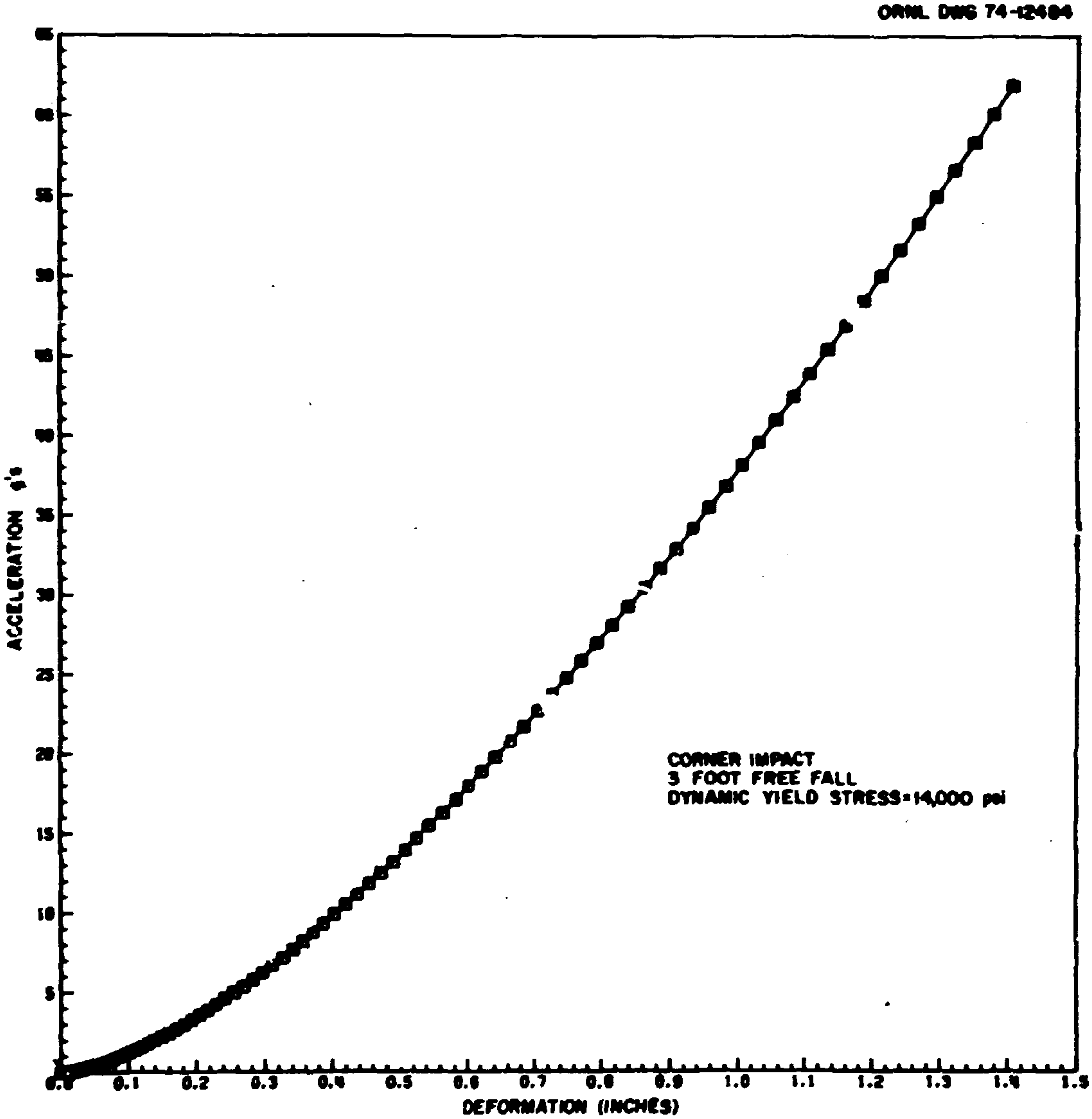


Fig. 1.16. Corner impact — dynamic yield stress = 14,000 psi.

F = force (lb),
w = weight of the plug (lb),
a = acceleration (g's),
g = gravitational constant,
N = number of bolts,
A_b = stress area[20] of one bolt (in.^{2}).

If the cask impacted on the sliding-gate end, the inner plug of the cask access plug would place in tension the modified bolt which secures it. This bolt is a standard 3/4-10NC bolt which has been modified to receive a tool handle. The cross section of the bolt is reduced in the thread area by a 7/16-in.-diam axial hole. The resulting cross section, A, is

$$A = A_s - \frac{\pi d^2}{4} = 0.334 - \frac{\pi}{4}(0.438)^2 = 0.184 \; ,$$

where

A_s = stress area of the unmodified bolt (in.^{2}) (see ref. 20),
d = diameter of the drilled hole (in.).

The resulting tensile stress, σ, is

$$\sigma = \frac{\text{force}}{\text{area}} = \frac{aW_p'}{gA} = \frac{(59.5)(40)g}{g(0.184)} = 12{,}940 \text{ psi} \; ,$$

where

W_p' = weight of the inner plug (lb), and the other notation is as above.

The lower cover is also secured by eight 3/8-16NC stainless steel cap screws and weighs 30 lb. As above,

$$\sigma = \frac{W_c}{gNA_b} = \frac{30(59.5)g}{g(8)(0.078)} = 2900 \text{ psi} \; .$$

Since these stresses are less than the yield, the plugs will remain in place.

1.4.6.2 Impact on end. If the cask impacted on its end with the axis of the cask vertical, the kinetic energy would be dissipated by deforming the lead shielding, stretching the outer shell, and deforming the plug. This would be true for an impact on either end. A program, CEIR,[21] applicable to the end impact of a steel-clad, lead-shielded cask was used to calculate the response of the cask. The measured and observed response of casks dropped from 30 ft have been compared[19] with the response calculated using CEIR. The calculated response (from CEIR) of the cask is shown in Fig. 1.17. The calculated deformation of the shielding was 0.308, and the maximum acceleration was 7.5g's. This acceleration would not damage the contents, and the loss of shielding would not result in radiation levels in excess of those allowed by the regulations. The plug(s) would be jammed and would require considerable effort to remove. Some repair of the cask would be required in the plug (closure) areas.

1.4.6.3 Impact on top. If the cask impacted on its top, that is, with the axis of the cask horizontal, the cask lifting bar would contact the impact surface first. The bar would either behave like a heat transfer fin and buckle in an S-curve or fail in compression. Davis[22] tested heat transfer fins. He reported the peak failure load for fins impacted normal to the fin axis as a function of the ratio of fin height to fin thickness (L/t). Figure 1.18 is a reproduction of Davis's Fig. 5.10. The curve has been extrapolated as indicated to the (L/t) value of 6, which is the geometry applicable to the lifting bar. The extrapolated curve indicates the peak failure of dynamic buckling load would be 150,000 psi, and a strain of 0.22 in./in. (see Fig. 1.16) is reached. Prior to and during this failure, the bar would apply load to the shell, and the shell would load and locally deform the shielding.

The body would deform similarly to the side impact of an unprotected clad, lead-shielded cask. In the case at hand, the end effects would be less significant than those of end plates in a cask. An unpublished ORNL program based on plastic deformation theory has been written and used to predict the response of casks in a side impact. The program

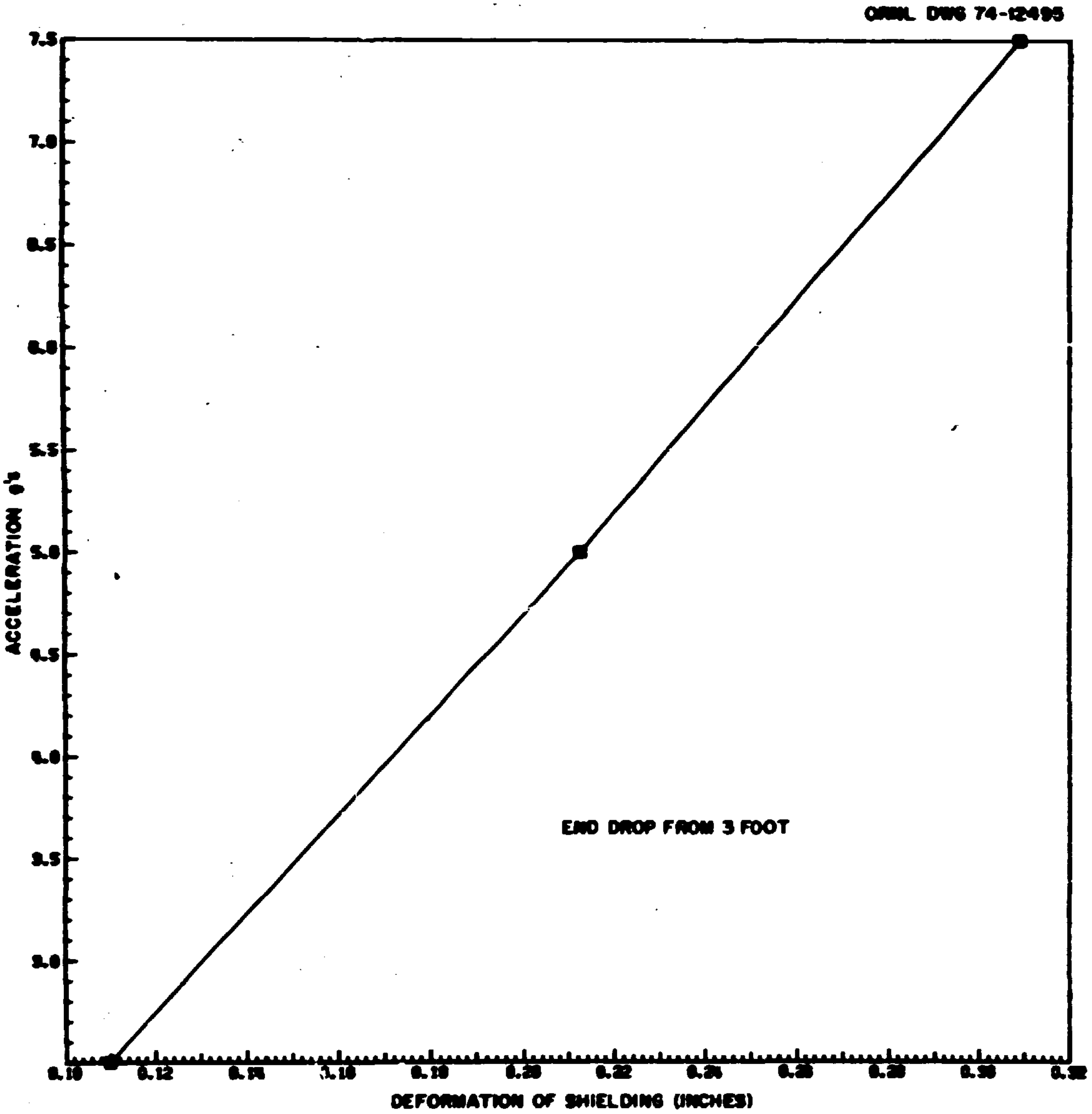


Fig. 1.17. End impact — shielding deformation vs acceleration.

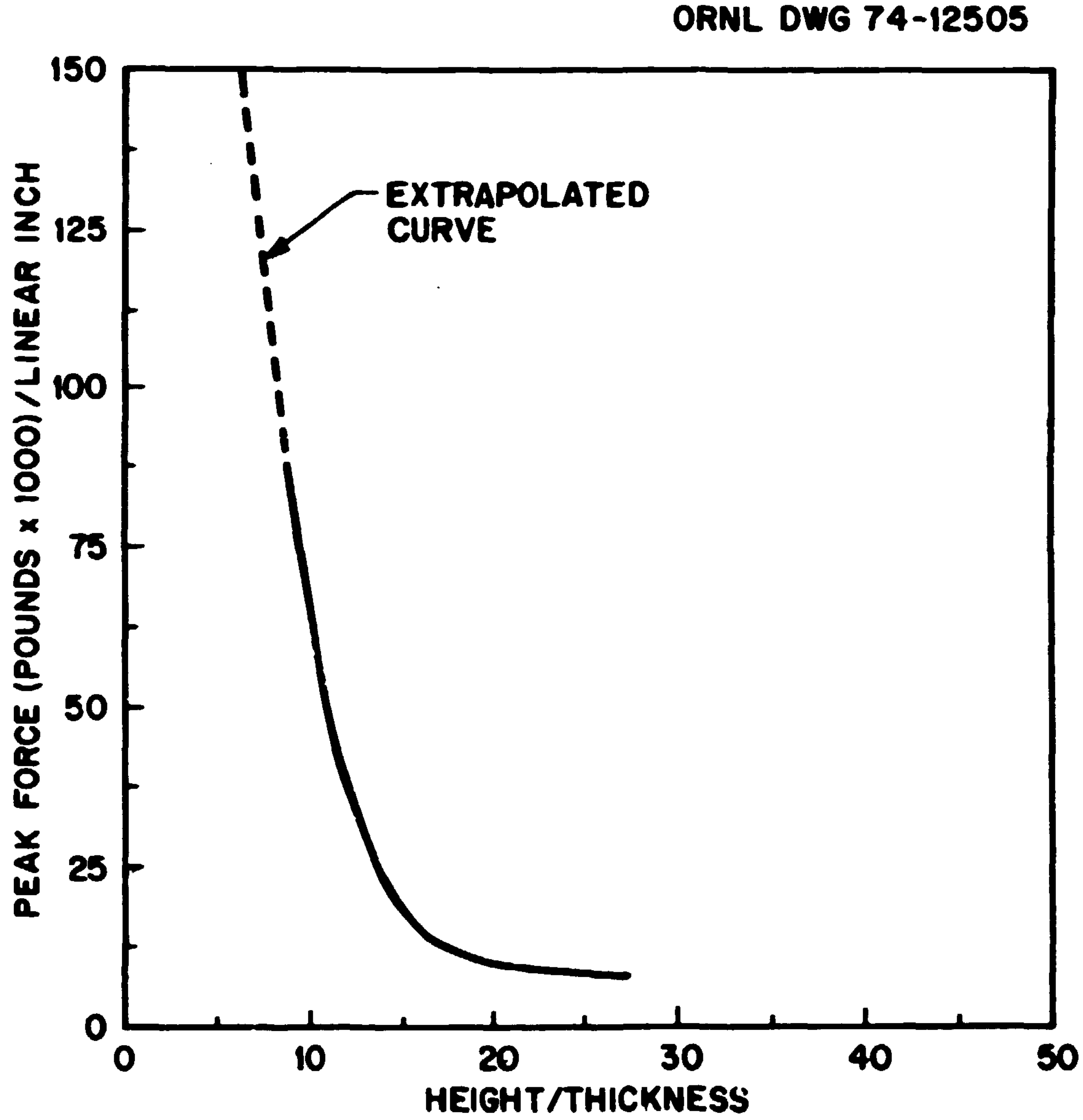


Fig. 1.18. Fin peak force per linear inch vs height-to-thickness ratio.

assumes ideally plastic materials for the shielding and end plates and neglects the energy dissipated in bending the shell. This program, 1005 CASK (see Appendix C for derivation of equations and program listing), was used to estimate the energy absorbed in the lead. It was modified to neglect the end plates. The lower limit of 6000 psi and the upper limit of 14,000 psi dynamic yield stress were again used.

A second existing program, 1014 CASK (see Appendix C for derivations and program listing), was used to calculate the energy absorbed in the bar and the contribution of the bar to the cask response. This program is based on experimentally determined dynamic material properties previously stated in the report. The program is applicable to energy absorbers which fail in compression. The bar complies with this requirement if the strain does not exceed 0.22 in./in., that is, deformation does not exceed 1.32 in.

These programs can be used to determine the response if the cask is assumed to accelerate as a unit. Figures 1.19 and 1.20 are the calculated acceleration-energy responses of the cask body for the lower and upper limits of dynamic yield stress. Figure 1.21 is the corresponding curve for the lift bar. It can be determined by trail and error when the cask's kinetic energy has been absorbed in the lift bar and the body. For the case where the dynamic yield stress is taken as 6000 psi, the acceleration reaches a peak of 99g's. From Fig. 1.19 it can be seen that about 5.05 x 10^5 in.·lb of energy is absorbed in the cask body and from Fig. 1.21 that about 0.72 × 10^5 in.·lb is absorbed in the lift bar. The calculated shielding deformation is 0.475 in. (see Fig. 1.22), and the calculated lift bar deformation is 0.06 in. (see Fig. 1.23). For the case where the dynamic yield stress in the cask body is 14,000 psi, the acceleration reaches a peak of 167g's. It can be seen that 3.72 × 10^5 in.·lb is absorbed in the cask body and that 2 × 10^5 in.·lb is absorbed in the lift bar (see Figs. 1.20 and 1.21). From Fig. 1.23, the deformation in the lift bar is 0.011 in.

Accelerations of this magnitude will not adversely affect the containment vessels. The contents have structural rigidity or support to withstand the accelerations without significant deformation. The

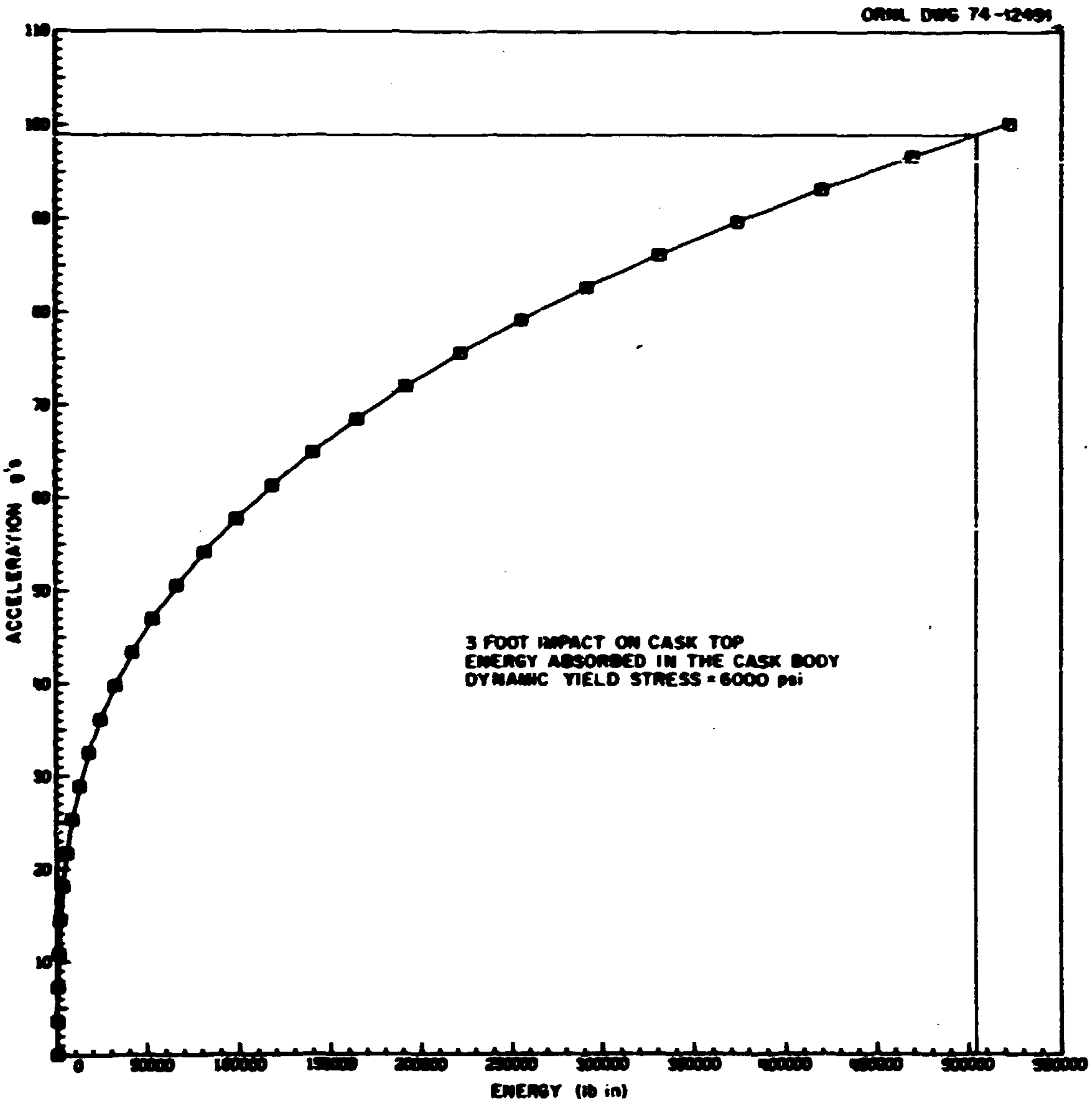


Fig. 1.19. Top impact — energy absorbed in the cask body; dynamic yield stress = 6000 psi.

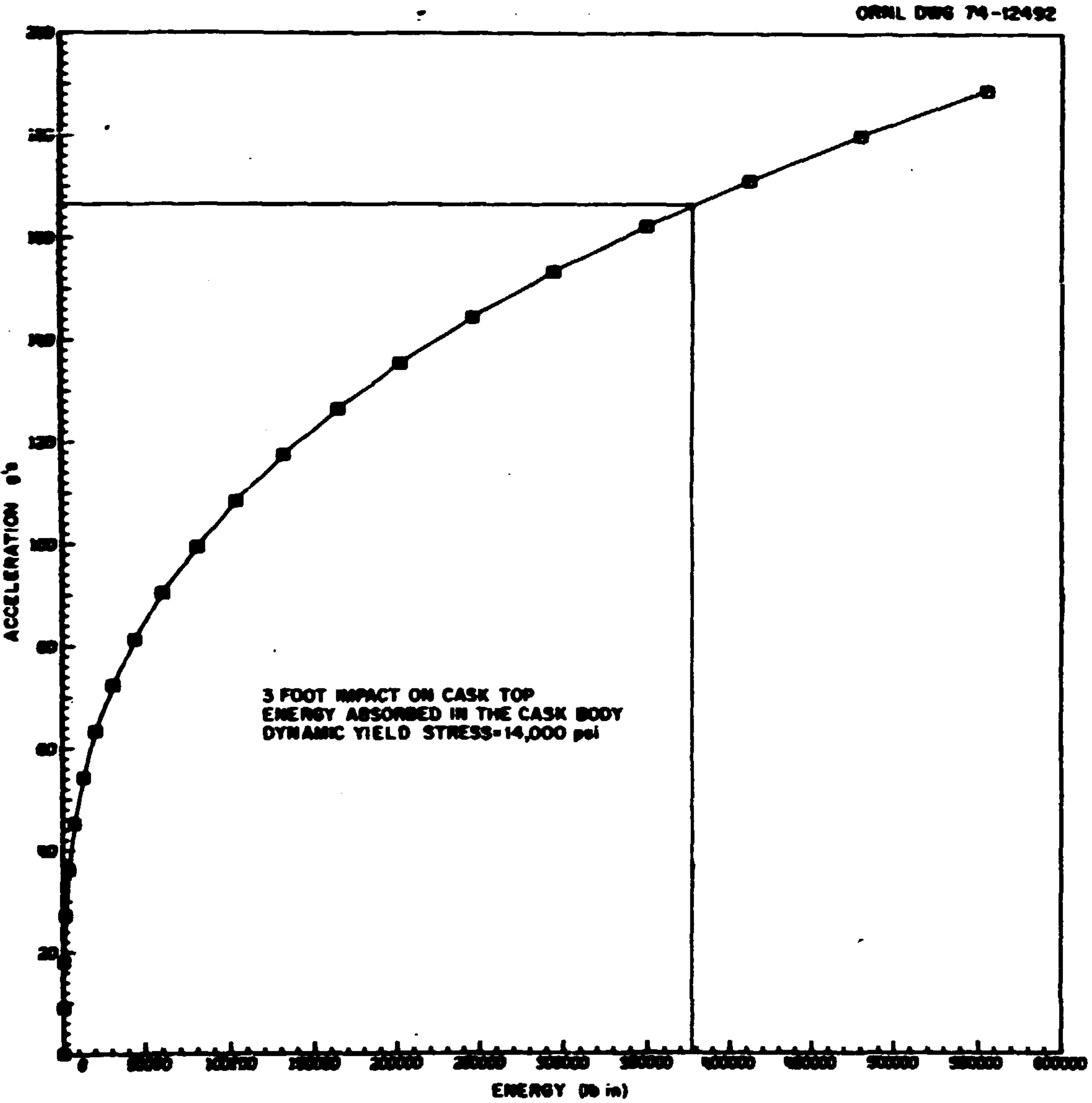


Fig. 1.20. Top impact — energy absorbed in the cask body; dynamic yield stress = 14,000 psi.

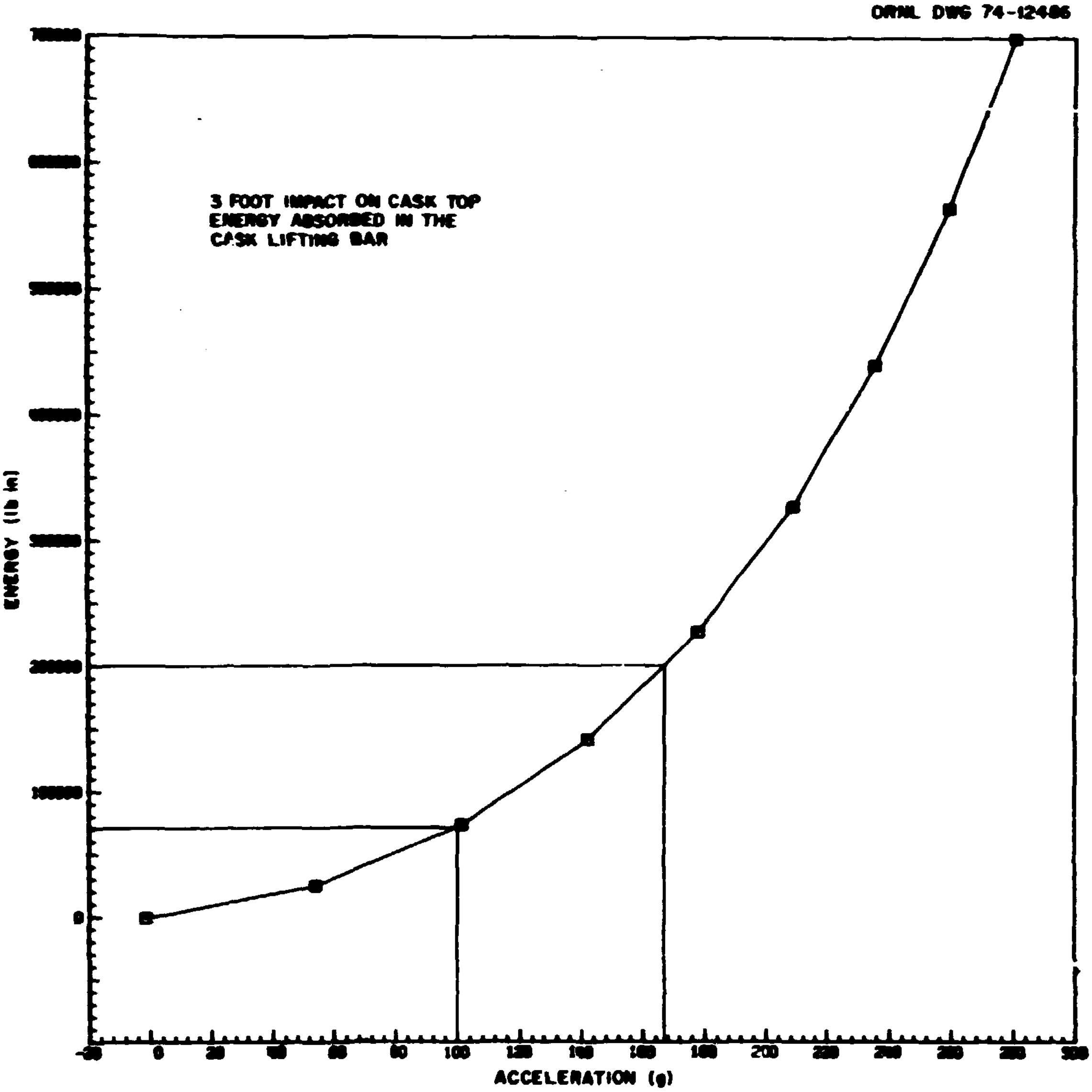


Fig. 1.21. Top impact — energy absorbed in the lift bar.

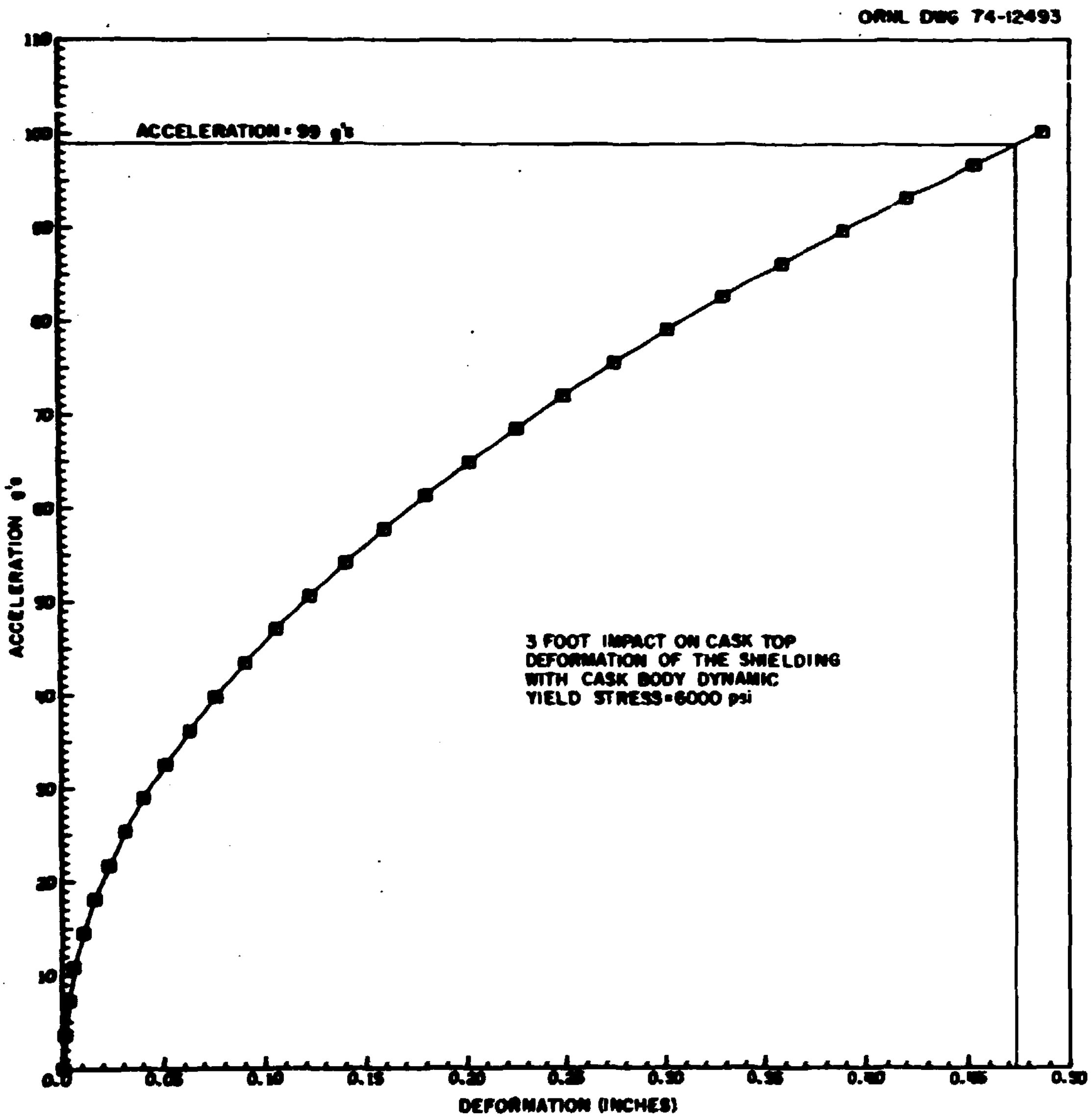


Fig. 1.22. Top impact — shielding deformation.

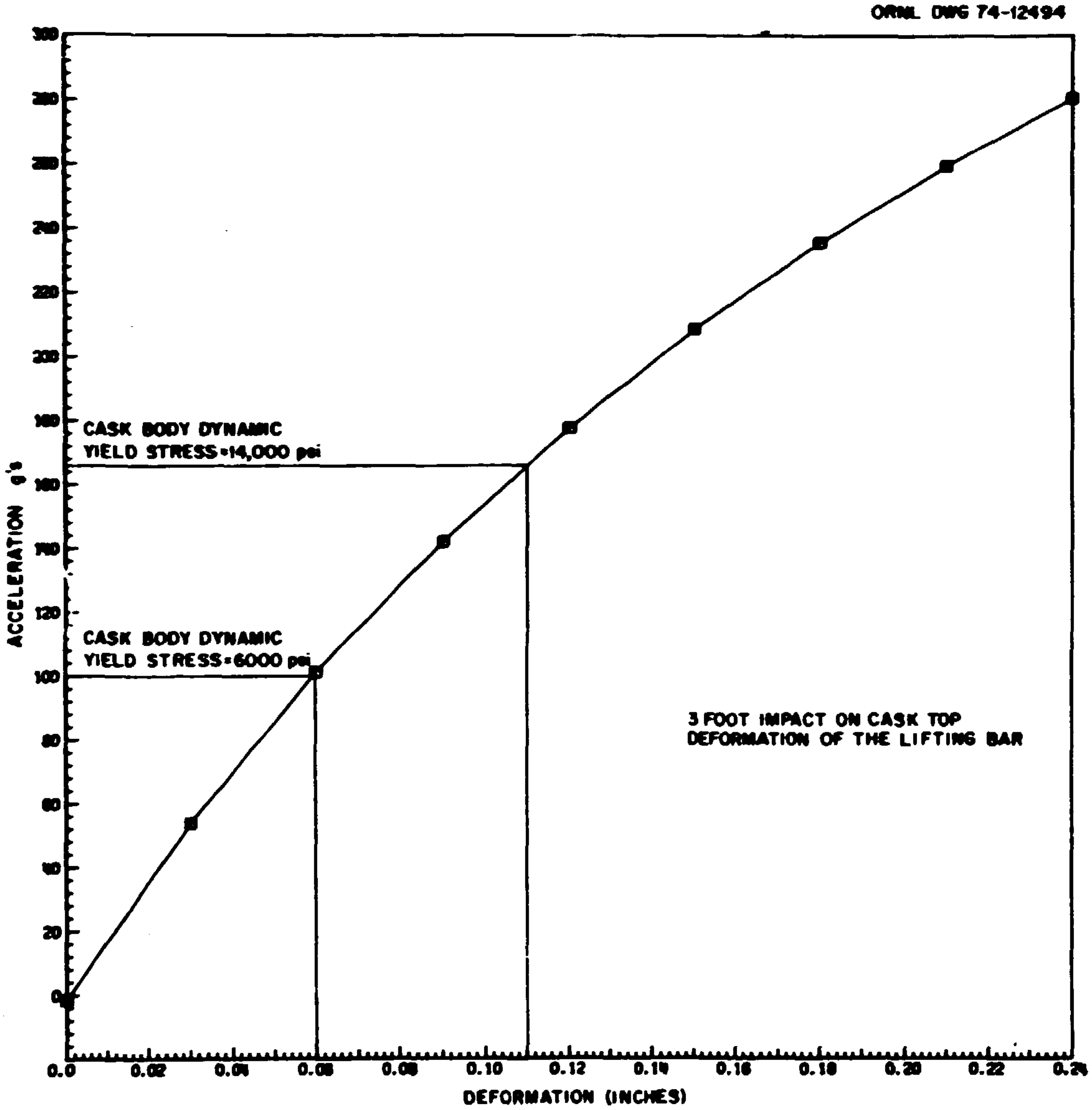


Fig. 1.23. Top impact — lift bar deformation.

maximum reduction in shielding would not result in radiation doses in excess of those allowed by the regulations. The bolts securing the sliding gate would be loaded in tension, and the rear plug would be loaded in shear by the gate. By comparison with Sect. 1.5.1.3, the gate will remain in place.

1.4.6.4 Impact on side. If the cask impacted on its side with its axis horizontal, oriented radially such that the point of impact is between the lifting bar and the tie-down bar, the four shell stiffener rings would contact the impact surface and absorb energy while plastically deforming. These rings have a height-to-thickness ratio of 3.33. The data by Davis,[22] previously discussed in Sect. 1.4.6.3, indicates that the deformation of these rings will be primarily compression and that buckling will not take place until a very large compressive stress is reached. From Fig. 1.18, this stress is estimated to be in excess of 200,000 psi.

An ORNL computer program, 1016 CASK, has been written to calculate the response of a cask equipped with stiffening ring energy absorbers. A program listing and the derivation of equations are presented in Appendix C. The program is based on the experimentally determined dynamic compressive material properties discussed in Sect. 1.1. Figure 1.24 is the calculated deformation response of the cask. It can be seen that the rings would deform about 0.47 in., and the acceleration would reach 147g's. These are less than were calculated in Sect. 1.4.6.3. It is concluded that the cask can withstand this impact.

1.4.7 Penetration

The regulations for normal conditions of transport also stipulate that the package be capable of withstanding the impact of the flat end of a vertical steel cylinder which weighs 13 lb, has a diameter of 1-1/4 in., and is dropped from a height of 4 ft, normally onto the exposed surface of the package that is expected to be the most vulnerable to puncture. This test would not reduce the effectiveness of the container and would result in no more than a very superficial dent in the steel surface of the container.

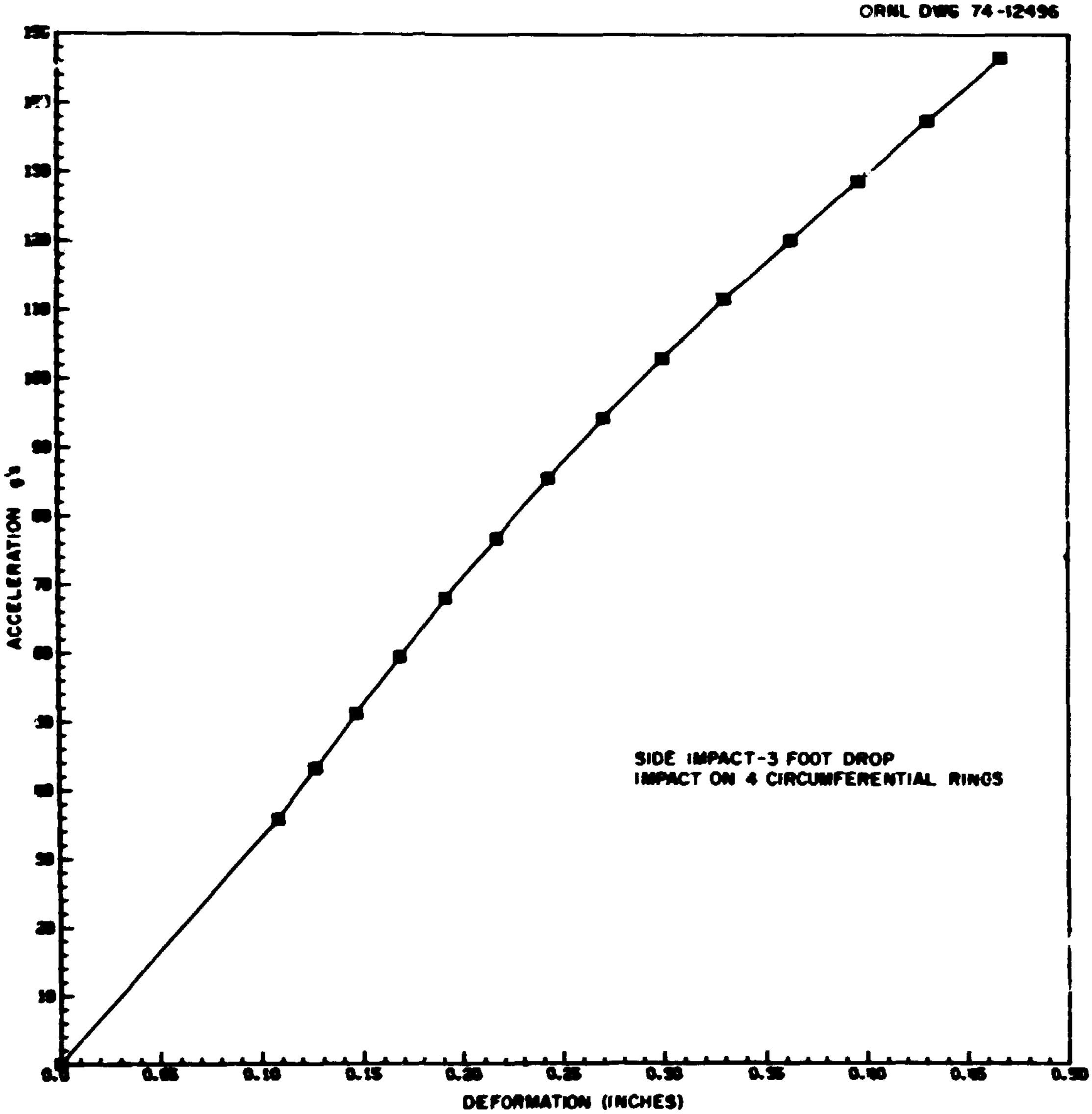


Fig. 1.24. Side impact — shielding deformation vs acceleration.

1.4.8 Compression

It is required that packages weighing less than 10,000 lb be capable of withstanding a compression load of five times the container weight or 2 lb/in.^{2} distributed uniformly across the top and bottom, whichever is greater. The container weighs 16,000 lb; hence it is exempt from the compression requirement.

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

The effects of the thermal exposure are evaluated in Sects. 1.8 and 2. The cask is constructed of low-carbon steel, stainless steel, and lead, which would not be affected by water immersion. The effect of water immersion on criticality is considered in Sect. 5.

1.5.1 Free drop

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

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

It cannot be determined by inspection which orientation results in maximum damage. Therefore, as in Sect. 1.4.6, impact orientations of (1) on the corner, (2) on the end, with the axis of the cask vertical, (3) on the top of the cask, directly on the lifting bar with the axis of the cask horizontal, and (4) with the axis of the cask horizontal, impacting between the lifting bar and the tie-down lugs, are considered.

1.5.1.1 Corner impact. The program 1001 CASK was used to evaluate the corner impact as discussed in Sect. 1.4.6.1. The calculated acceleration-deformation histories of the impact are shown in Fig. 1.25 for the lower limit for a dynamic yield stress of 6000 psi and in Fig. 1.26 for the upper limit for a dynamic yield stress of 14,000 psi. The deformation is maximum at the lower value for dynamic yield stress. The calculated maximum deformation is 5.3 in. (see Fig. 1.25). From Fig. 1.27 it can be seen that for maximum deformation the shielding in the corner is equivalent to the shielding in the cask walls. It is concluded that a corner drop will not result in radiation dose rates in excess of those allowed by the regulations.

This impact places the bolts securing the plugs and gate in tension. The vectorial fraction of the acceleration which loads the bolts is

$$A = A_{max} \cos \theta ,$$

where

A_{max} = peak acceleration for the upper limit of dynamic yield stress (see Fig. 1.26),

θ = angle between the cask and the impact surface = 16.6°,

$$A_{max} = 230(\cos 16.6°) = 220g's .$$

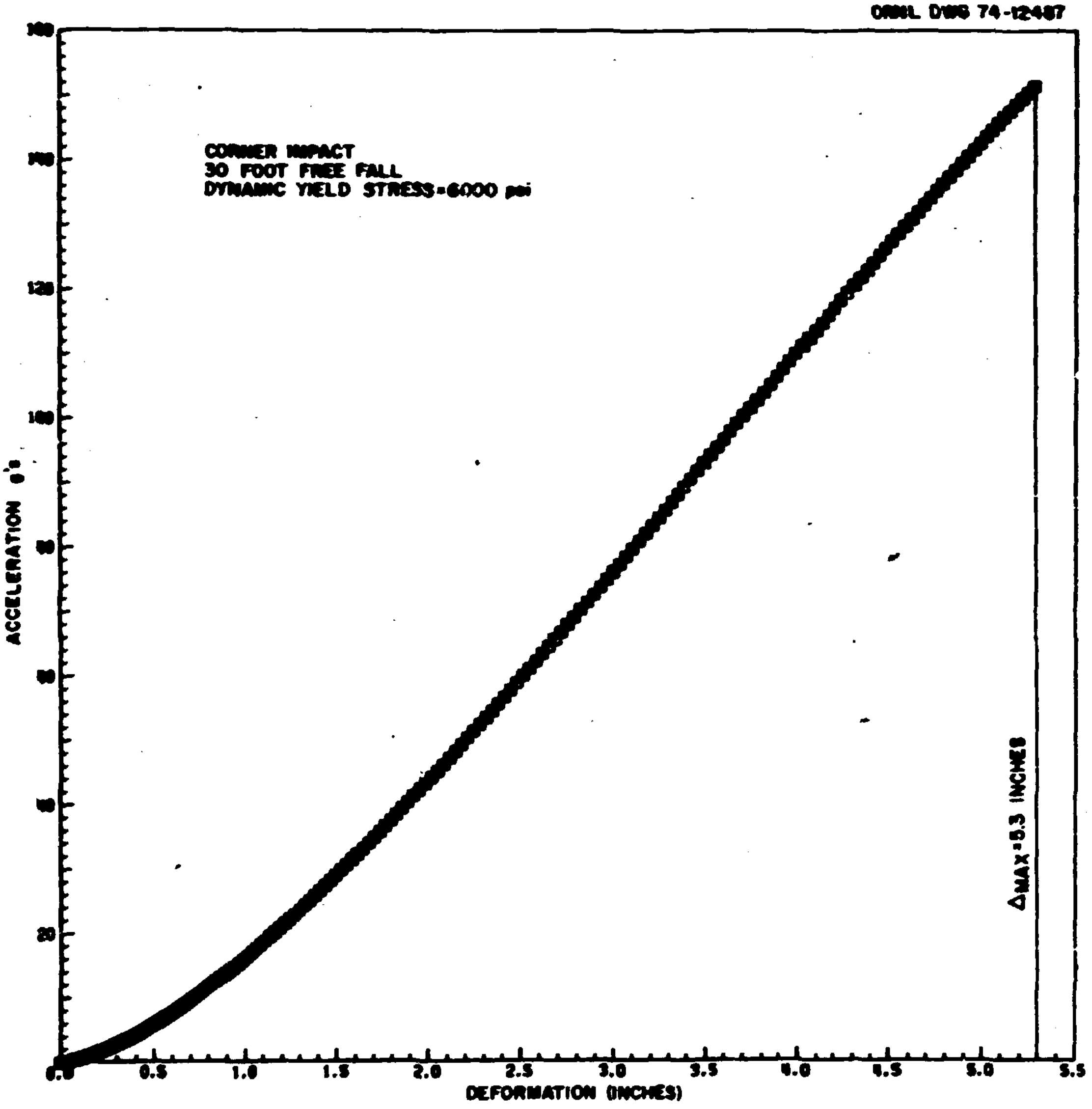


Fig. 1.25. Corner impact — dynamic yield stress = 6000 psi.

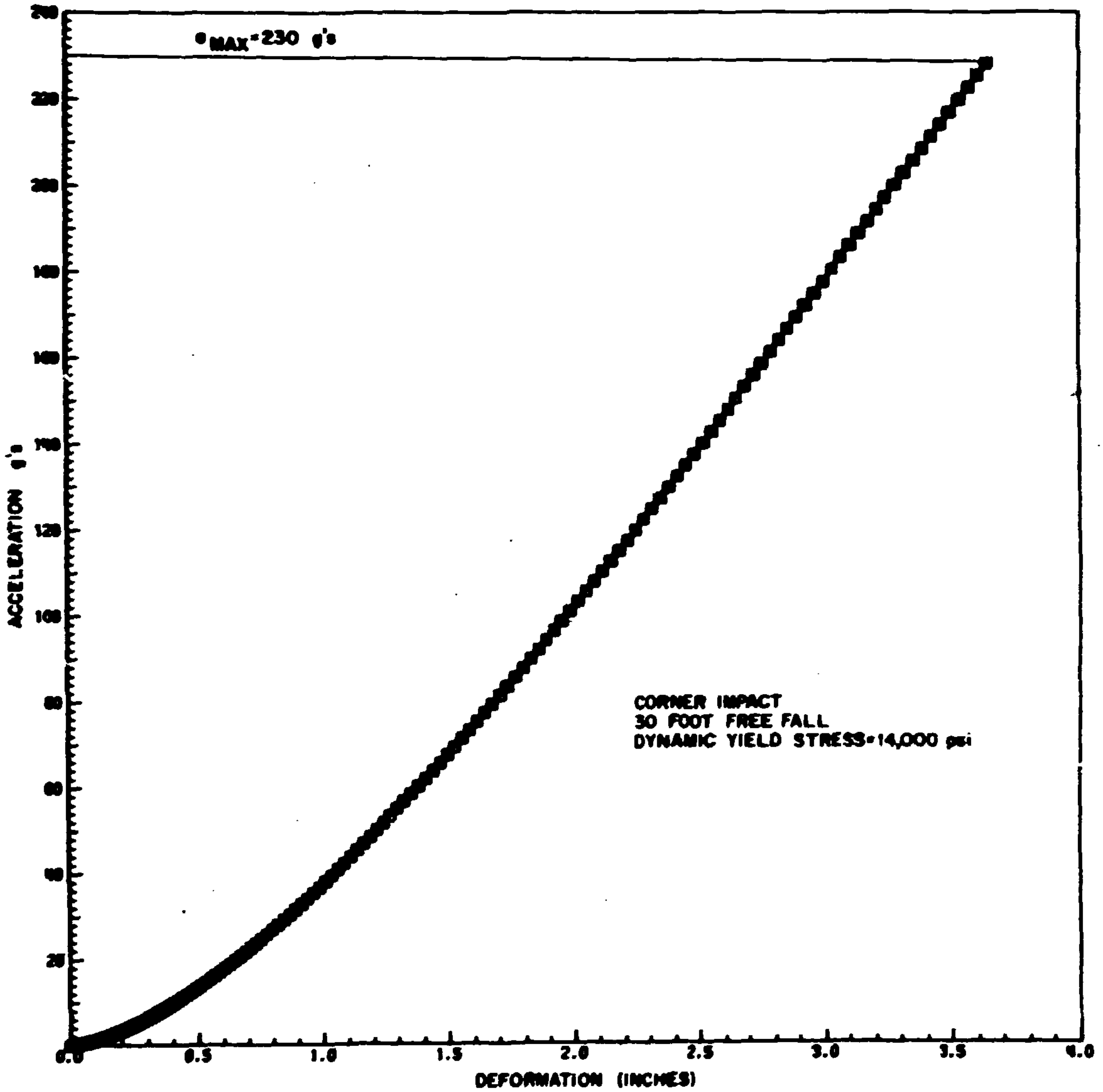


Fig. 1.26. Corner impact — dynamic yield stress = 14,000 psi.

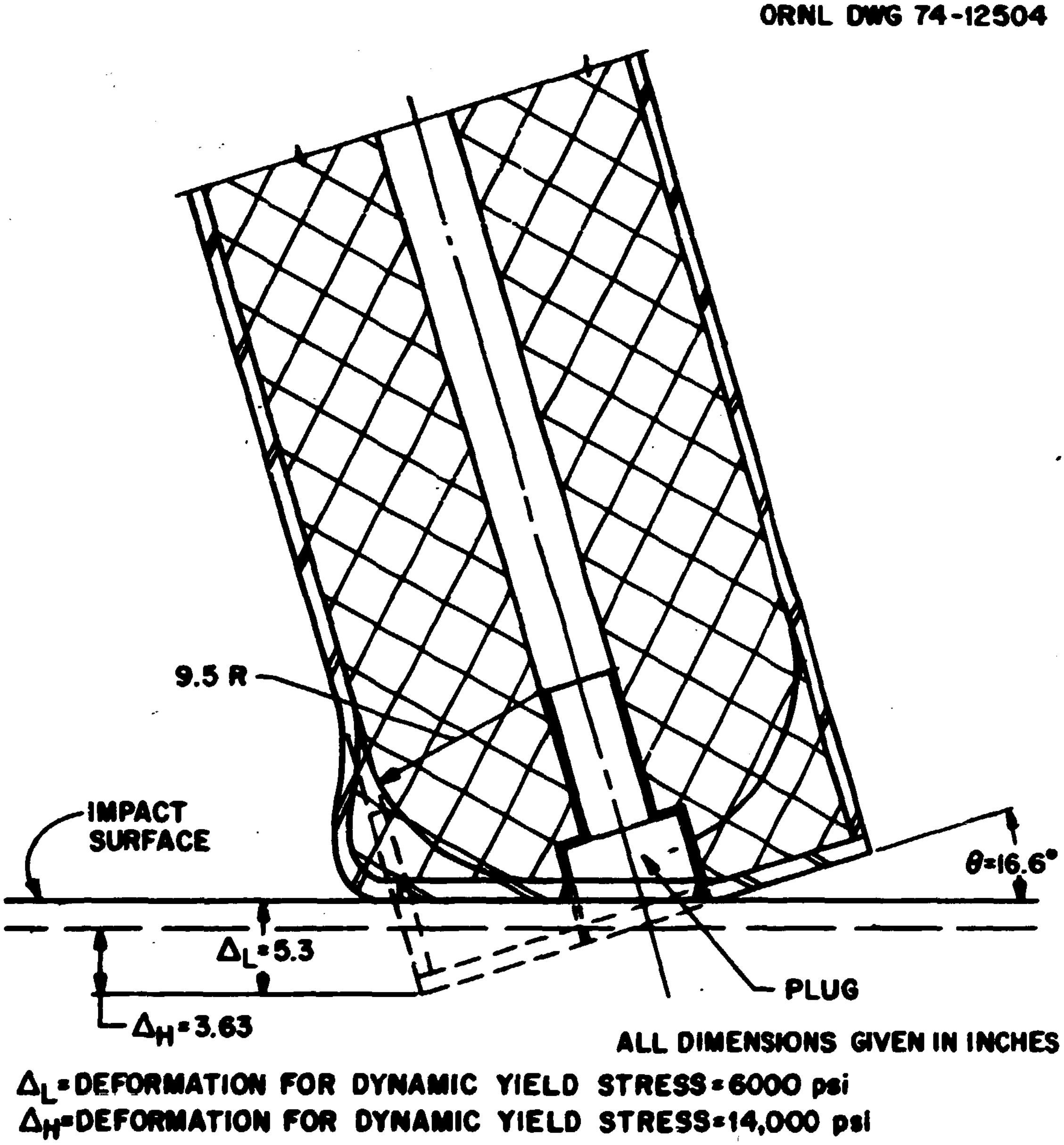


Fig. 1.27. Corner impact shielding loss.

The cask access plug, which weighs 110 lb, is secured by eight 1/2-13NC stainless steel cap screws. These screws must withstand the inertia forces applied by the plug and the contents. The tensile stress, σ, in these screws is

$$\sigma = \frac{\text{force}}{\text{area}} = \frac{a(W_p)}{gNa_s} = \frac{(220)(210)}{8(0.142)} = 40{,}700 \text{ psi} \ ,$$

where

W_p = weight of the cask plug and contents (lb),
N = number of cap screws,
g = gravitational constant,
A_s = stress area of one cap screw (in.^{2}) (see ref. 20).

For an impact on the sliding gate, the modified bolt would again be loaded as described in Sect. 1.4.6.1. The resulting stress, σ, would be

$$\sigma = \frac{\text{force}}{\text{area}} = \frac{A_{max}(W'p)}{gA_s} = \frac{220(40)g}{g(0.184)} = 48{,}900 \text{ psi} \ .$$

The notation and area are the same as in Sect. 1.4.6.1.

The stress is less than the ultimate stress for stainless steel bolts;[12] hence it is concluded that the plug will remain in place. The lower cover, which weighs 30 lb, is also secured by eight 3/8-10NC cap screws. Using the equation above, the stress is

$$\sigma = \frac{220(130)}{8(0.0775)} = 46{,}100 \text{ psi} \ ,$$

which is less than the ultimate strength for stainless steel bolts.[12]

The welds joining the shells to the flat heads may fail (fracture) and allow a path for shielding loss if the impact is followed by a fire. The effect of shielding loss is discussed in Sect. 4.

1.5.1.2 End impact. The calculatory techniques and the computer program CEIR,[21] discussed in Sect. 1.4.6.2, will be used to evaluate the effects of the accident end drop. Figure 1.28 is a machine plot of the calculated shielding deformation with respect to acceleration of the

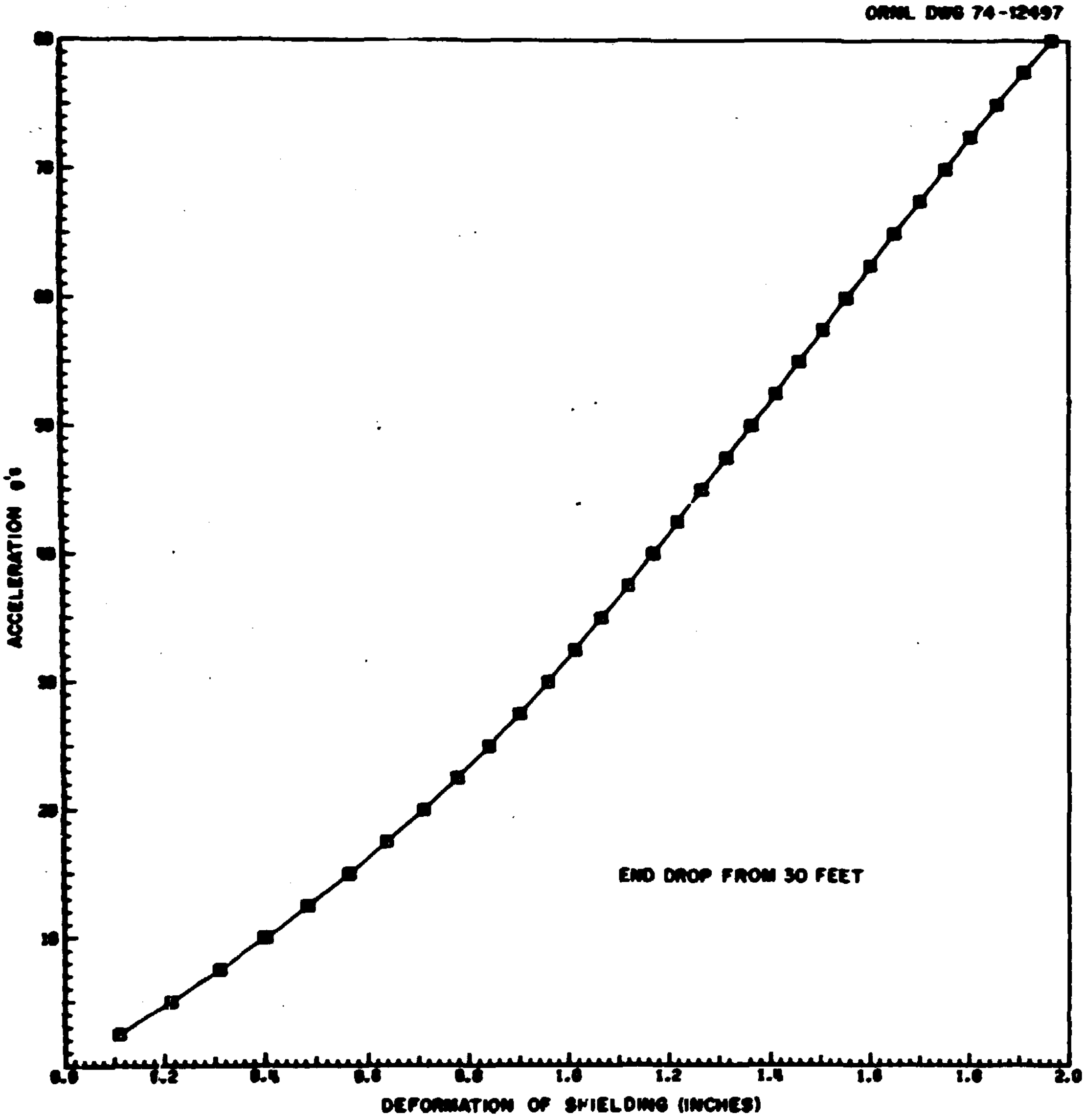


Fig. 1.28. End impact — shielding deformation vs acceleration.

cask. When the cask's total kinetic energy of 5.76×10^6 in.•lb is absorbed, the acceleration will be 80g's. It can be seen that the shielding will deform 1.94 in. This reduction in shielding is illustrated in Fig. 1.29.

Tests reported by Shappert and Evans[19] demonstrate that the shielding will deform as illustrated. These same tests indicate the adequacy of the program CEIR for predicting lead deformation.

1.5.1.3 Impact on top. The analytical techniques and discussion in Sect. 1.4.6.3 for the 3-ft drop when the cask impacted on the lift bar are valid for the 30-ft free fall if the compressive stress in the lift bar does not reach the critical buckling stress. Figure 1.30, 1.31, and 1.32 are plots of absorbed energy with respect to acceleration for the lift bar and the cask body at the lower and upper limits of dynamic yield stress. By superposition, it was found that for the lower limit of dynamic yield stress the peak acceleration would be 212g's. For the upper limit of dynamic yield stress, the cask acceleration will reach 362g's. The deformation in the lift bar will be maximized when the upper limit of dynamic yield stress is used in the calculations. This deformation, δ (see Fig. 1.33), is 0.415 in. The bar has a height, h, of 6 in., and the strain $\varepsilon = \delta/h = 0.415/6 = 0.069$ in./in. The strain does not reach the critical buckling strain of 0.22 in./in.; hence the bar will fail in compression, and the program 1014 CASK is applicable. The deformation in the cask body will be a maximum when the yield stress is at the lower limit of 6000 psi.

From Fig. 1.34 the deformation is 2.34 in. The shielding redistribution is illustrated in Fig. 1.35. The effect of the shielding loss is discussed in Sect. 4.

1.5.1.4 Impact on side. The computer program discussed in Sect. 1.4.6.4 will be used to evaluate the effects of the accidental side impact. Figure 1.36 is the calculated deformation-acceleration response curve of the cask. It can be seen that the calculated deformation would be about 1.6 in. and the acceleration approximately 500g's. This is less deformation than calculated in Sect. 1.5.1.2 and only slightly more acceleration; it is concluded that the cask can withstand this drop.

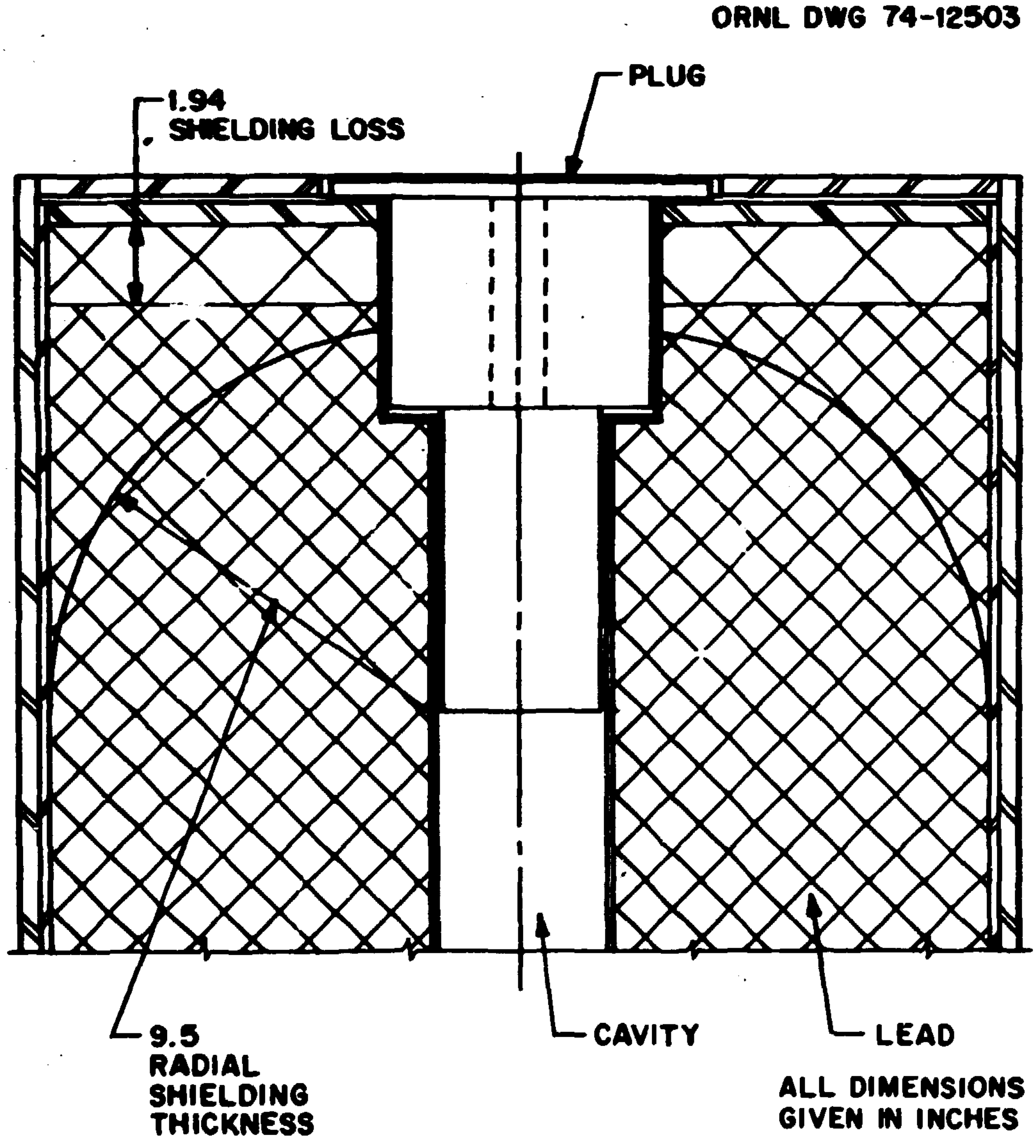


Fig. 1.29. End impact shielding loss.

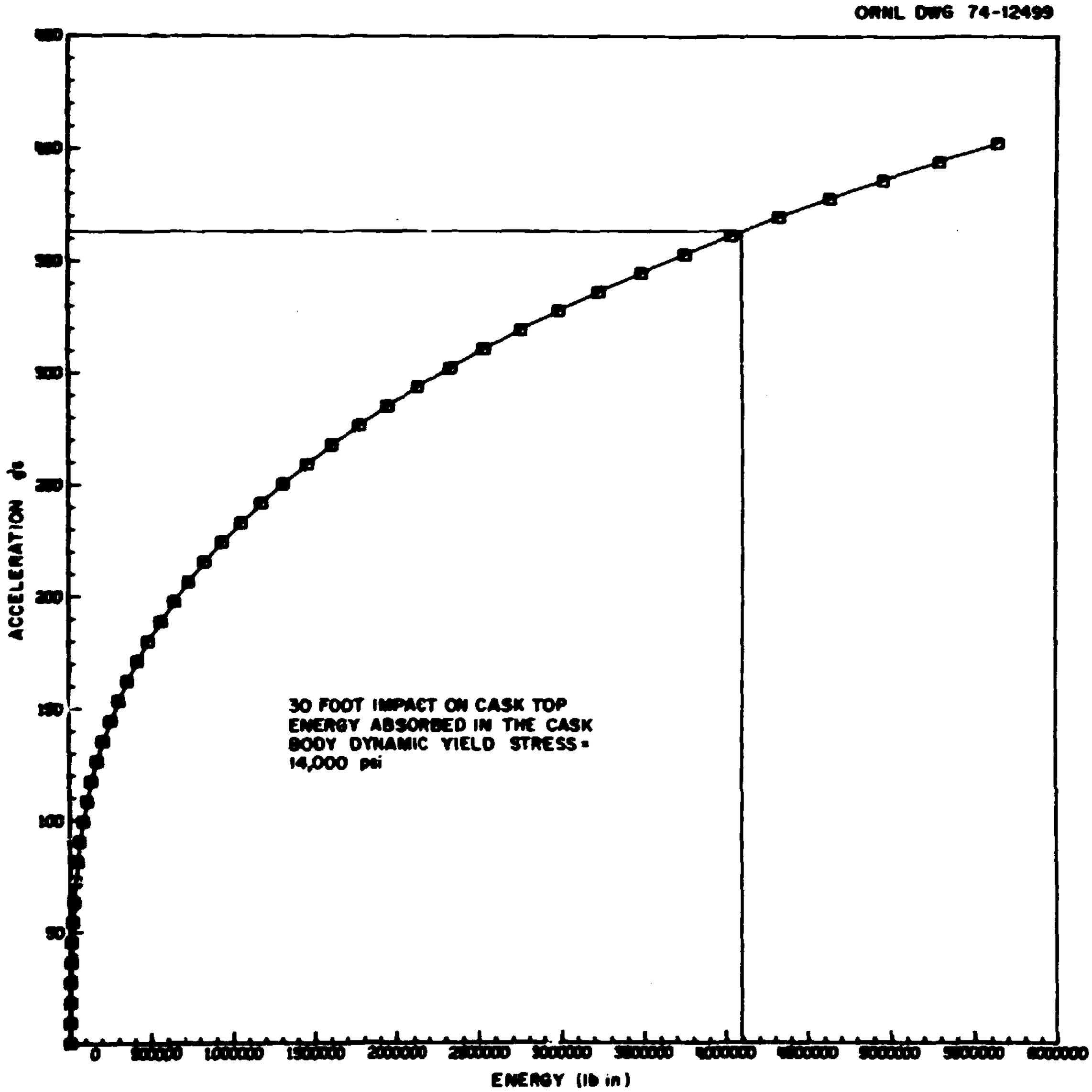


Fig. 1.30. Top impact — energy absorbed in the cask body; dynamic yield stress = 14,000 psi.

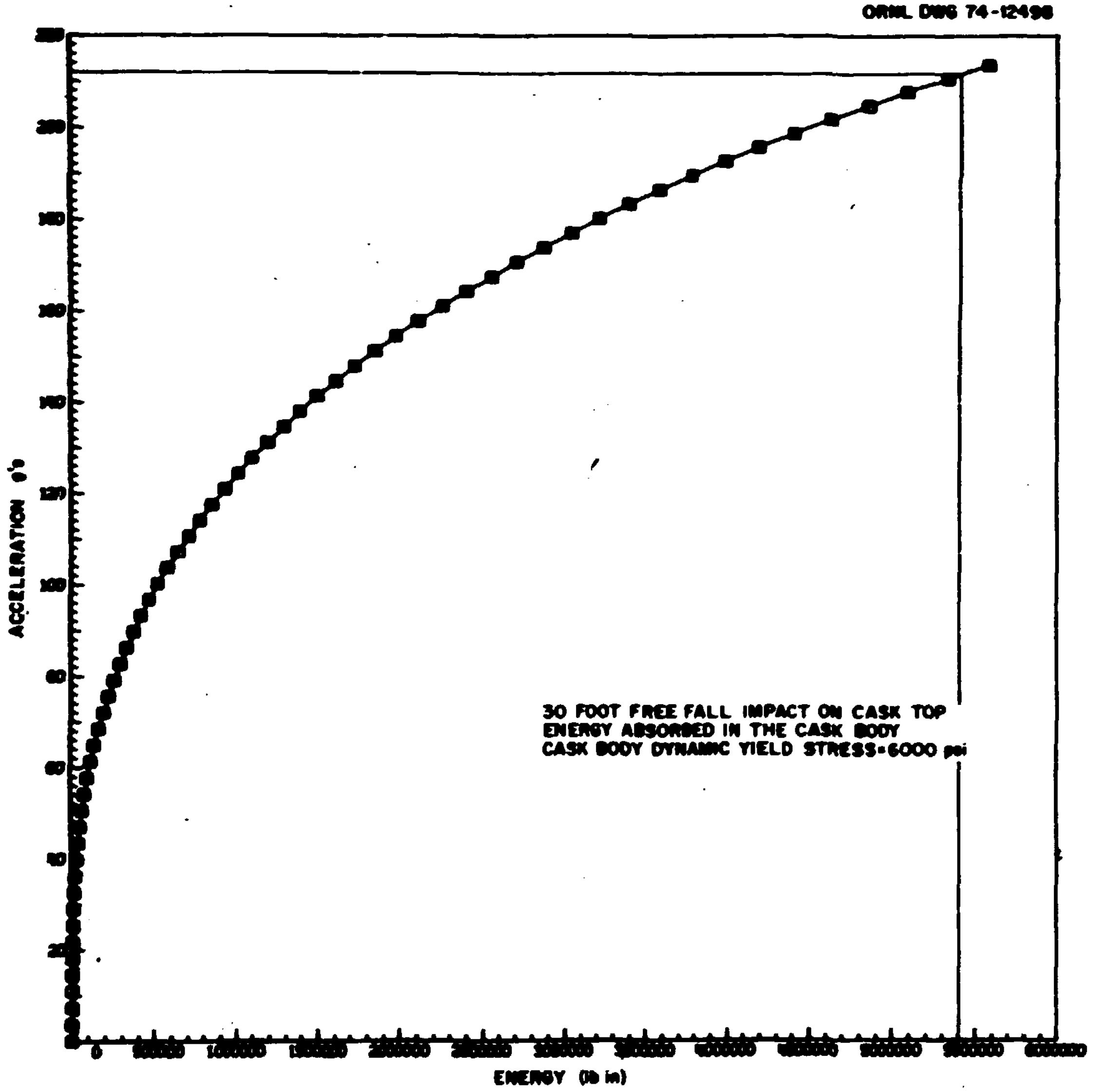


Fig. 1.31. Top impact — energy absorbed in the cask body; dynamic yield stress = 6000 psi.

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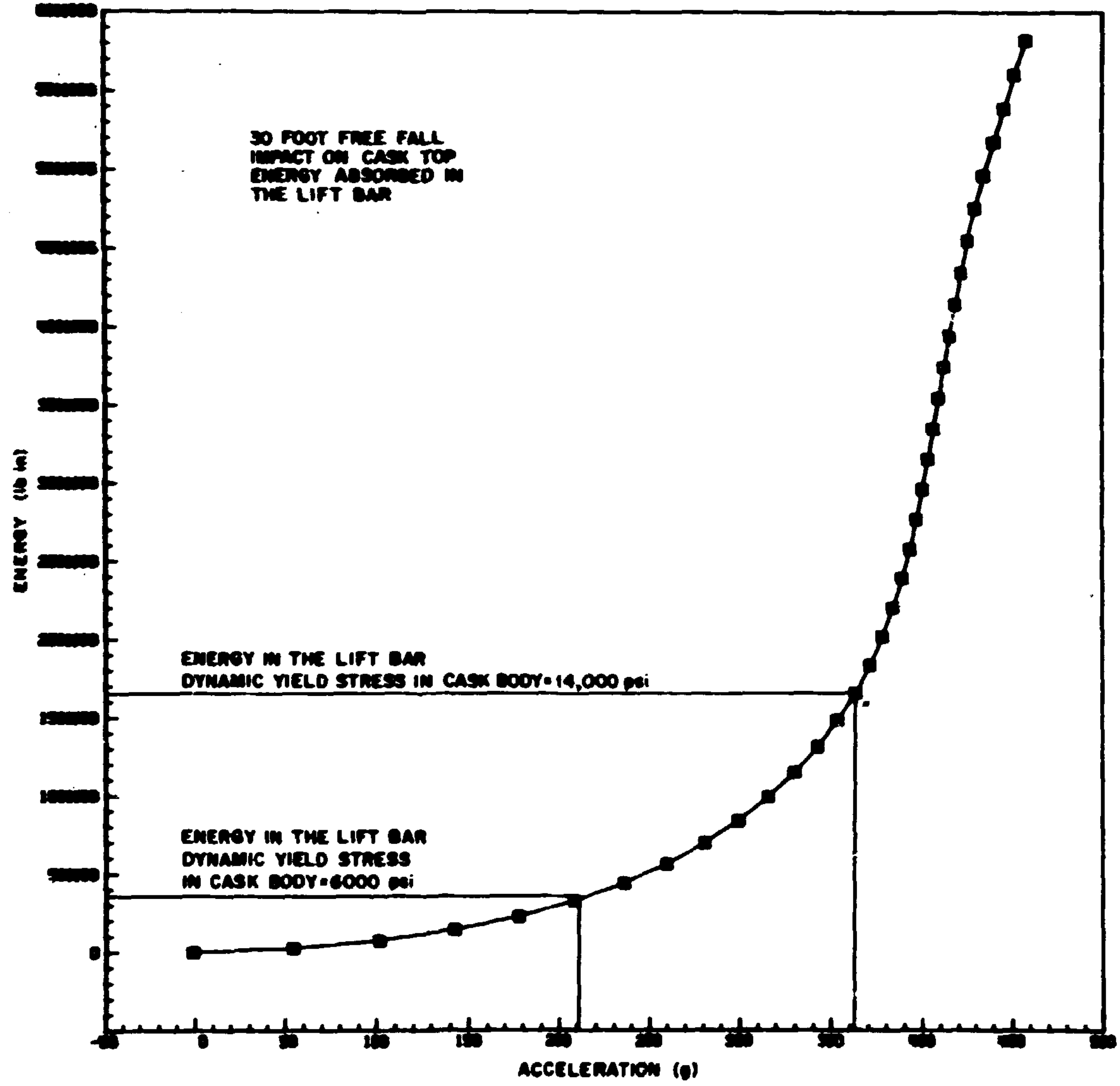

Fig. 1.32. Top impact — energy absorbed in the lift bar.

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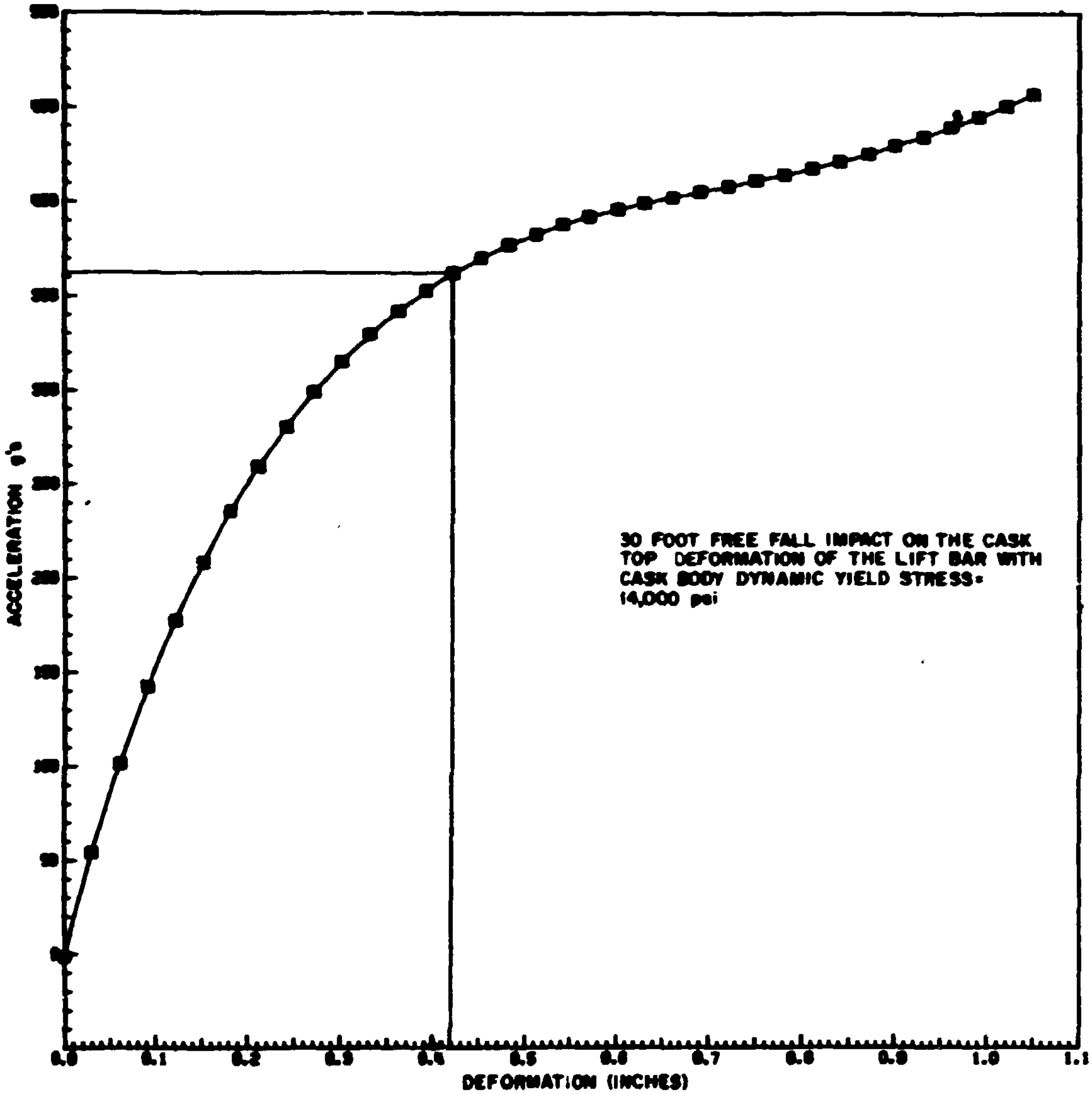

Fig. 1.33. Top impact — lift bar deformation.

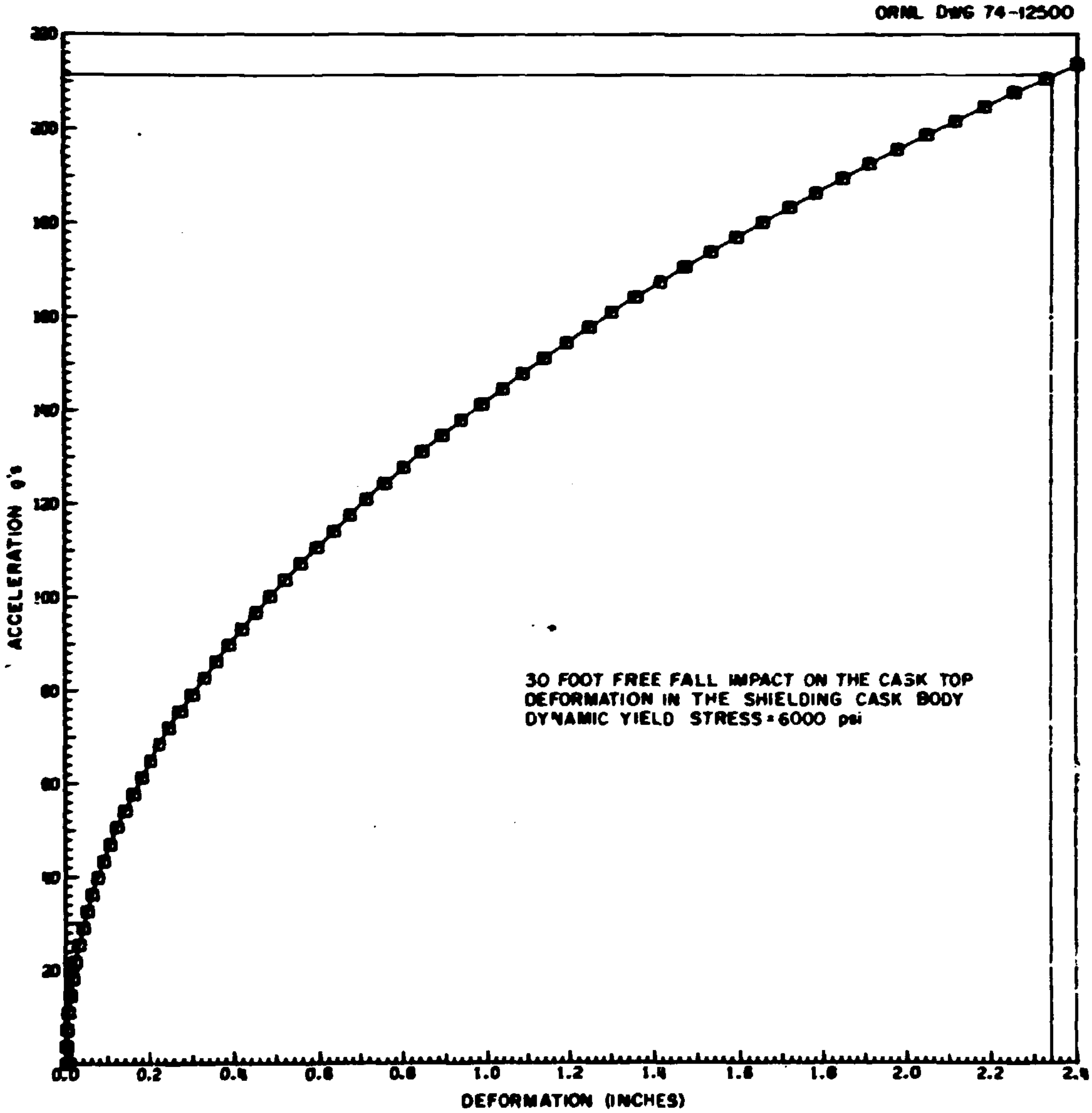

Fig. 1.34. Top impact — body deformation.

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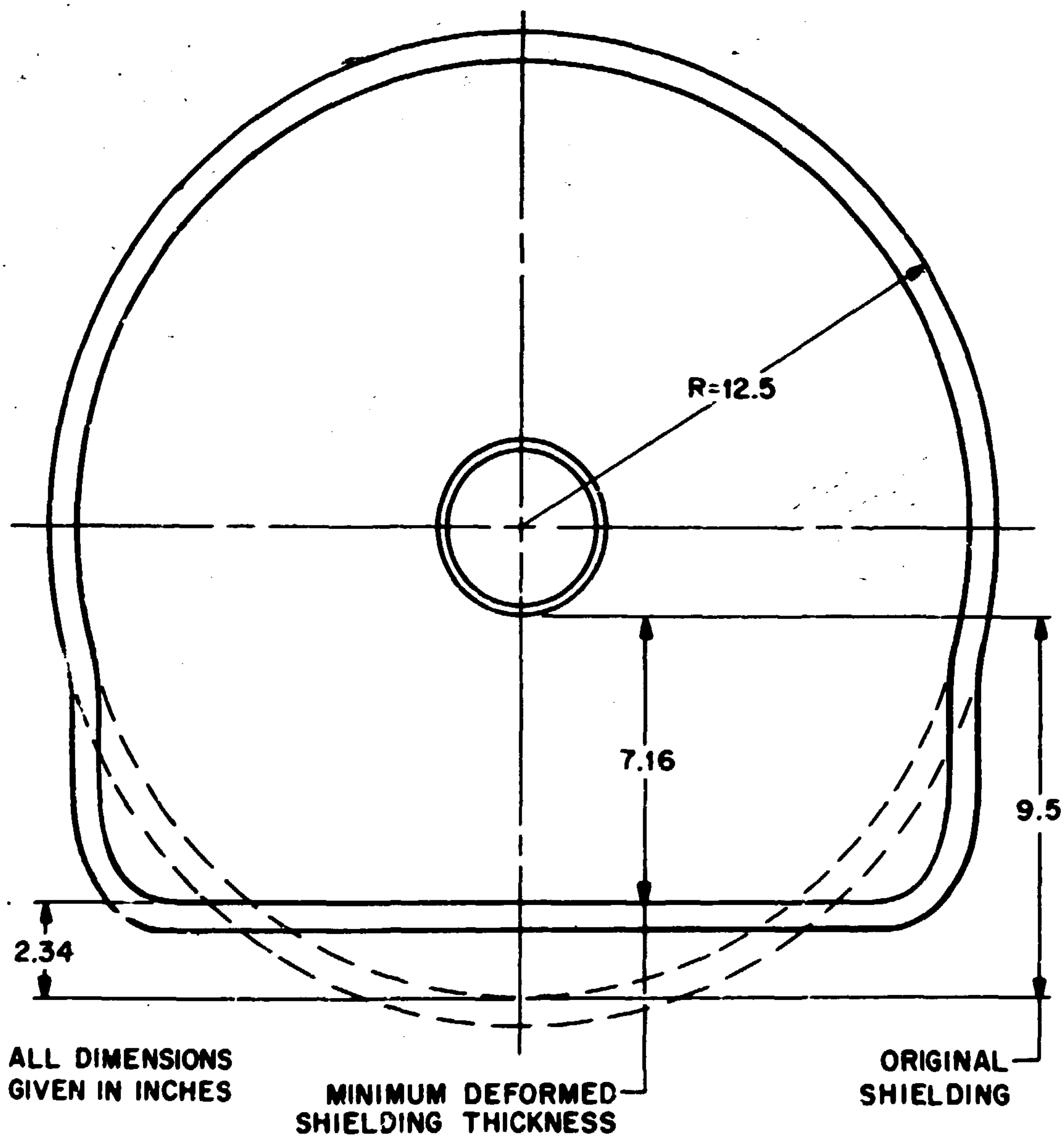

Fig. 1.35. Top impact — shielding loss.

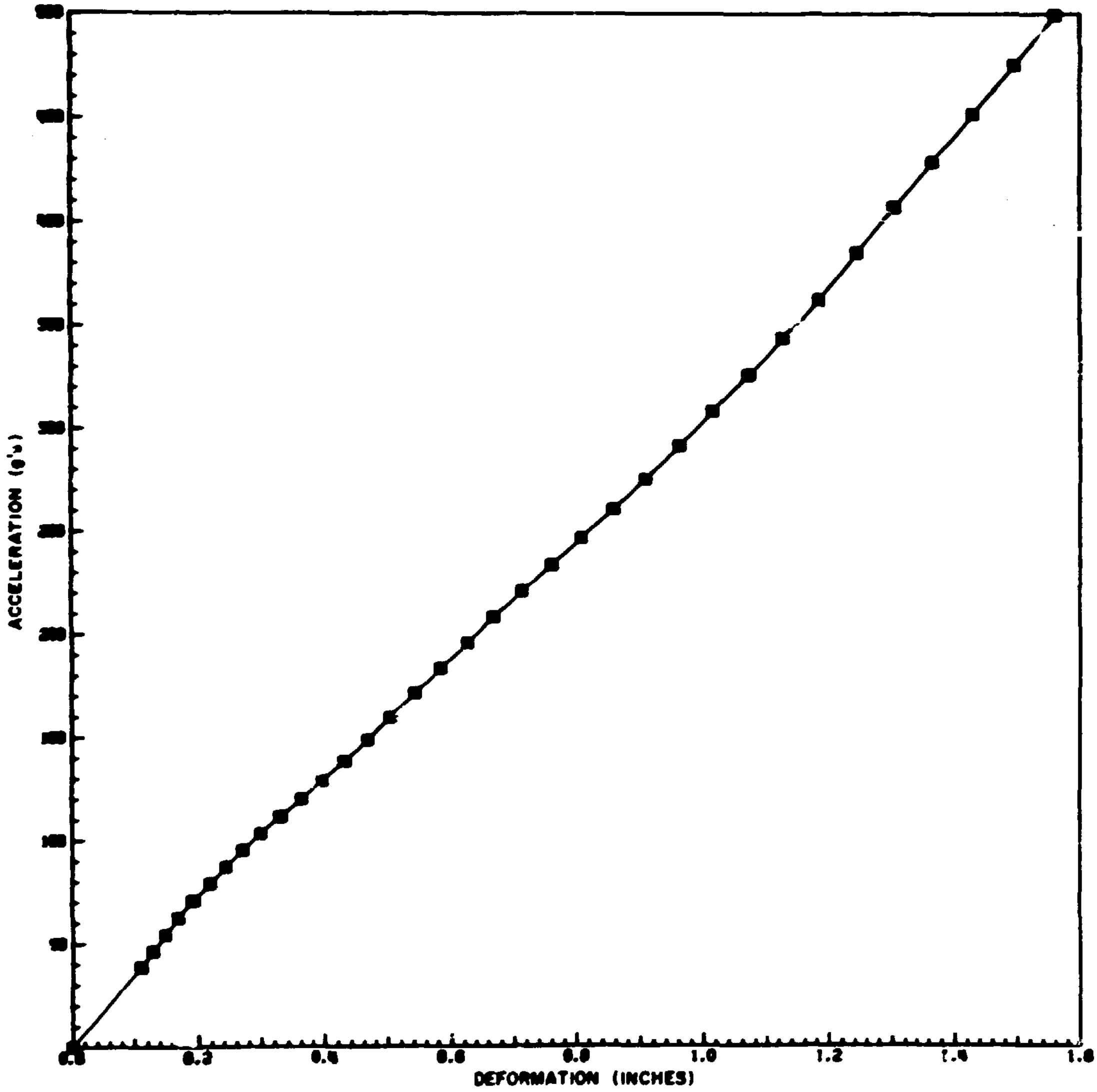

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Fig. 1.36. Side impact — shielding deformation vs acceleration.

1.5.2 Puncture

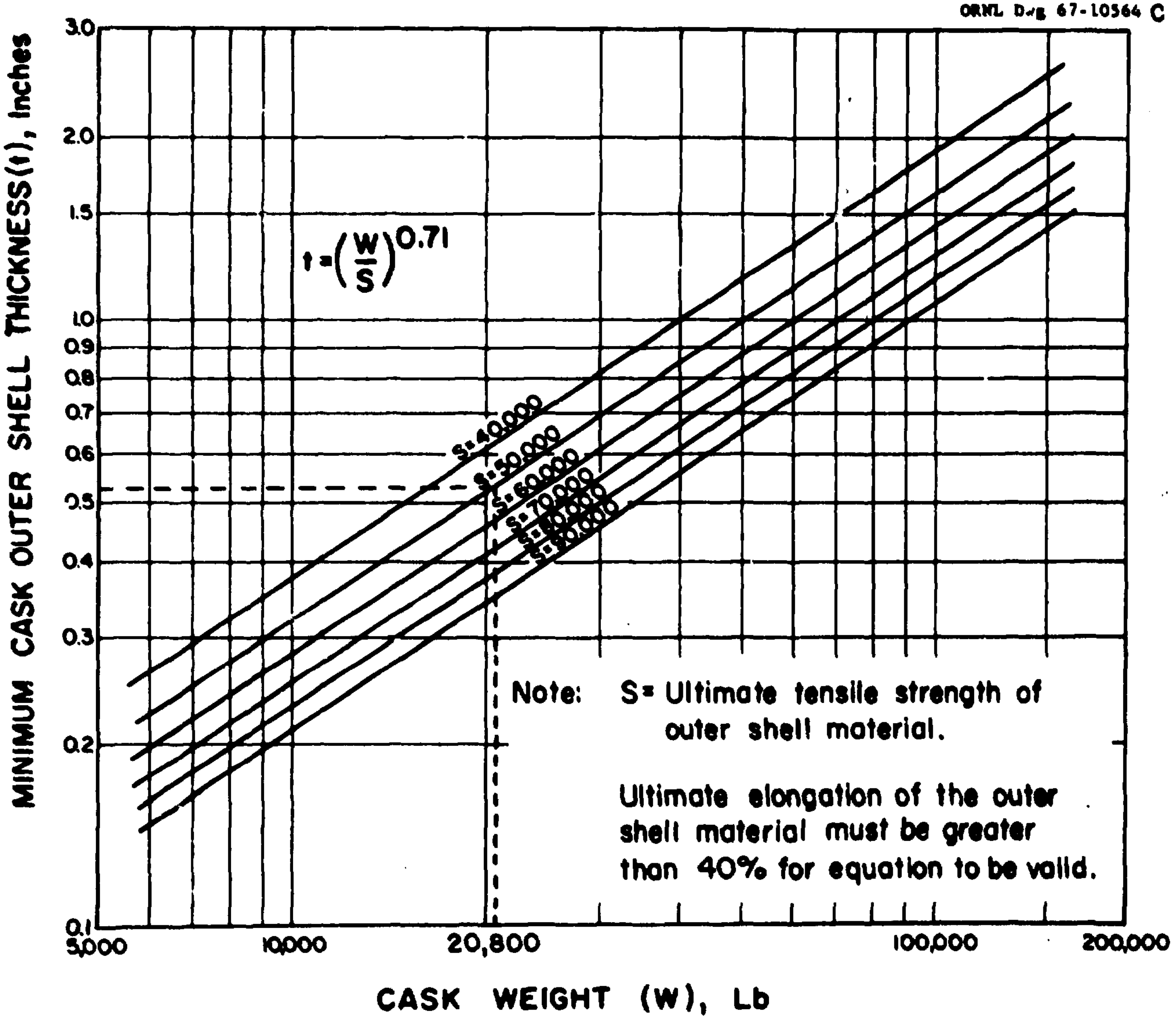
The second in the sequence of hypothetical accident conditions to which the cask must be subjected is a free drop through a distance of 40 in. to strike in a position to which maximum damage is expected, the top end of a vertical cylindrical mild-steel bar mounted on an essentially unyielding horizontal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

It is concluded that the shell will not puncture if the cask impacted as described above. If the cask contacted the bar in the vicinity of one of the closures, secondary containment would be lost. There would be a small local reduction in shielding.

Data published by Nelms[23] indicate a mild-steel clad, lead-shielded cask weighing 16,000 lb would require a shell thickness of 0.53 in. to resist puncture. The cask outer shell consists of a 1/2-in.-thick "steel" shell over a 1/4-in.-thick "mild-steel" shell (see Fig. 0.1). From this, it is concluded that the bar will not result in failure of the cladding. Figure 23 from the Nelms report[23] is reproduced as Fig. 1.37, with the solution for the cask's weight added.

1.6 Special Form

The ORNL Operations Division certifies that a material conforms to the special form requirements of Appendix D of 10 CFR Part 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. A typical example of special form capsules is illustrated in Fig. 1.38. The cross section may be circular or rectangular.



$t = \left(\frac{W}{S}\right)^{0.71}$

Note: S = Ultimate tensile strength of outer shell material.

Ultimate elongation of the outer shell material must be greater than 40% for equation to be valid.

Fig. 1.37. Cask puncture.

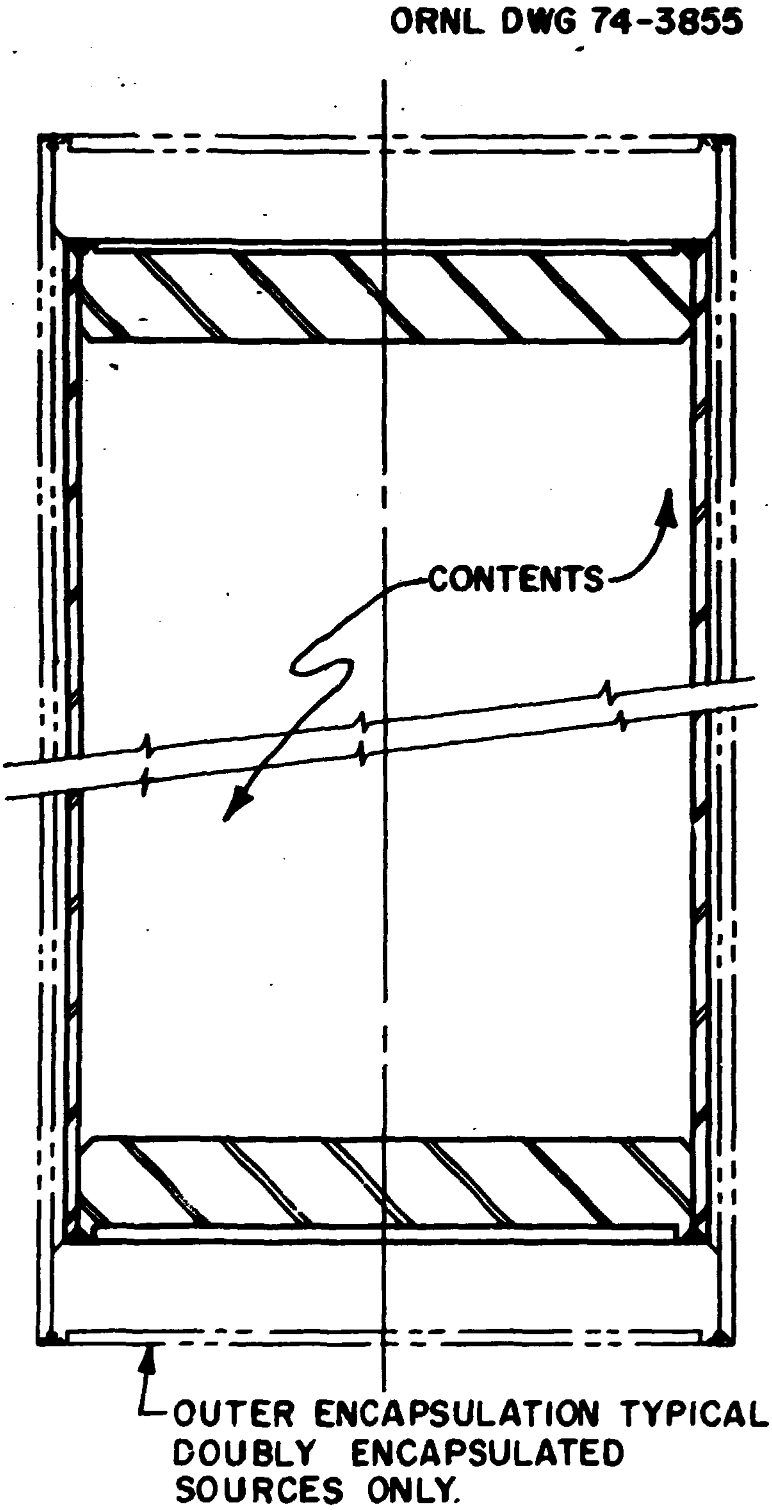


Fig. 1.38. Typical special form encapsulation.

1.7 Inner Container Design

Typical inner 2R containers used at ORNL are shown in Figs. 1.39, 1.40, 1.41, and 1.42. Materials and bolting are limited to austenetic stainless steels purchased in accordance with ASME or ASTM specifications. Design temperature is taken as 500°F, which is the maximum calculated temperature for the inner container under normal conditions (see Sect. 2). Assuming assembly at 70°F and 14.7 psia air pressure, a temperature of 500°F will produce a pressure of

$$P_2 = P_1T_2/T_1 = [(14.7)(500 + 460)]/(70 + 460) = 26.6 \text{ psia}$$

in the container. Assuming the least external pressure experienced to be 0.5 atmospheric pressure (see Sect. 1.4.3), the greatest gauge pressure experienced is 26.6 - 7.35 = 19.28 psig. Hence, design pressure is established conservatively as 20 psig. Design stress is 10,300 psi, which is the minimum listed in the tables for 500°F.[24]

For use with this cask, the containers will have the minimum head and wall thicknesses given in Table 1.2. These dimensions are based on the requirements of Specification 2R[4] and of Sect. VIII of the ASME Boiler and Pressure Vessel Code,[24] whichever is greater. The applicable equations for sizing shells and heads are, for the shell, Eq. (1), paragraph UG 27, which is

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

Table 1.2. Dimension schedule for Specification 2R containers

d	t_s	t_f	t_h	t_a	Bolts	
					No.	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

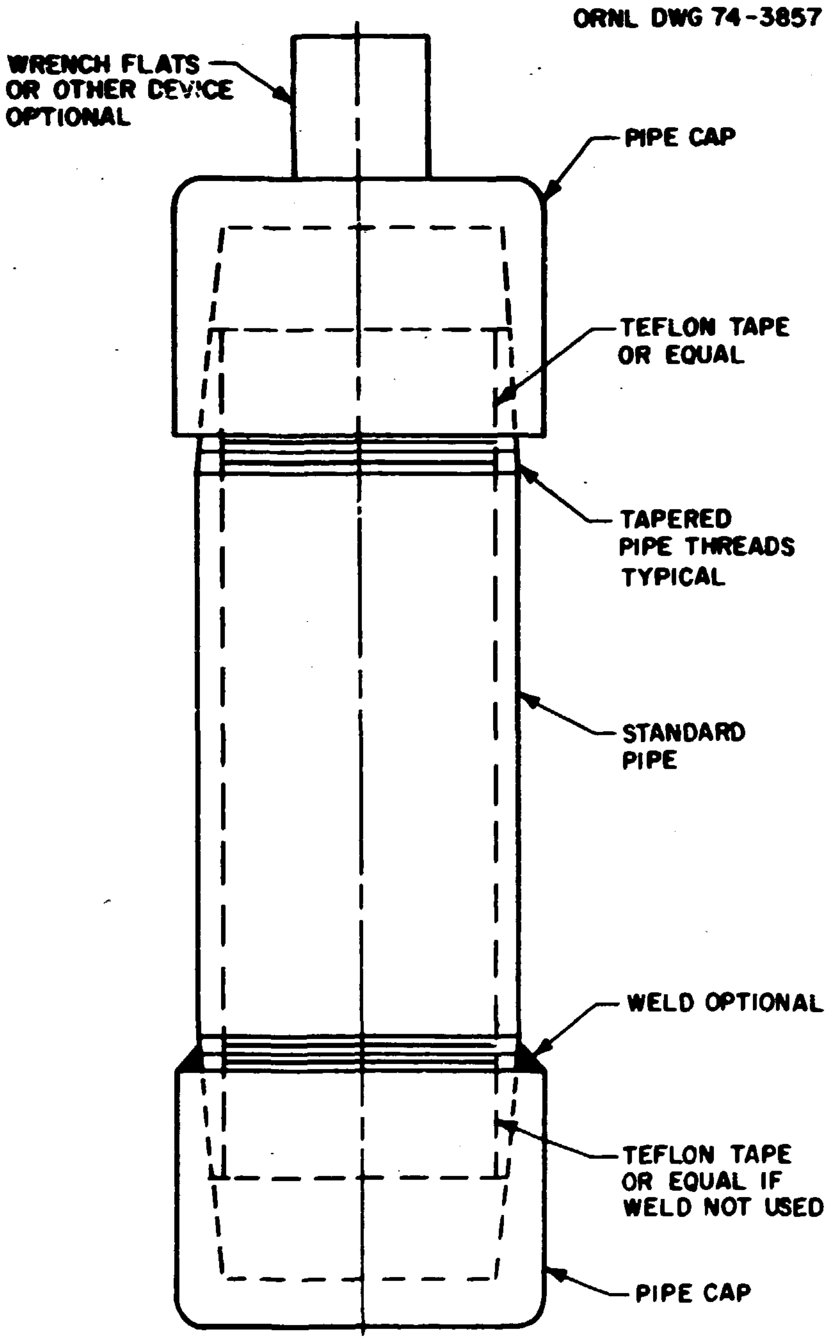


Fig. 1.39. Pipe element 2R container.

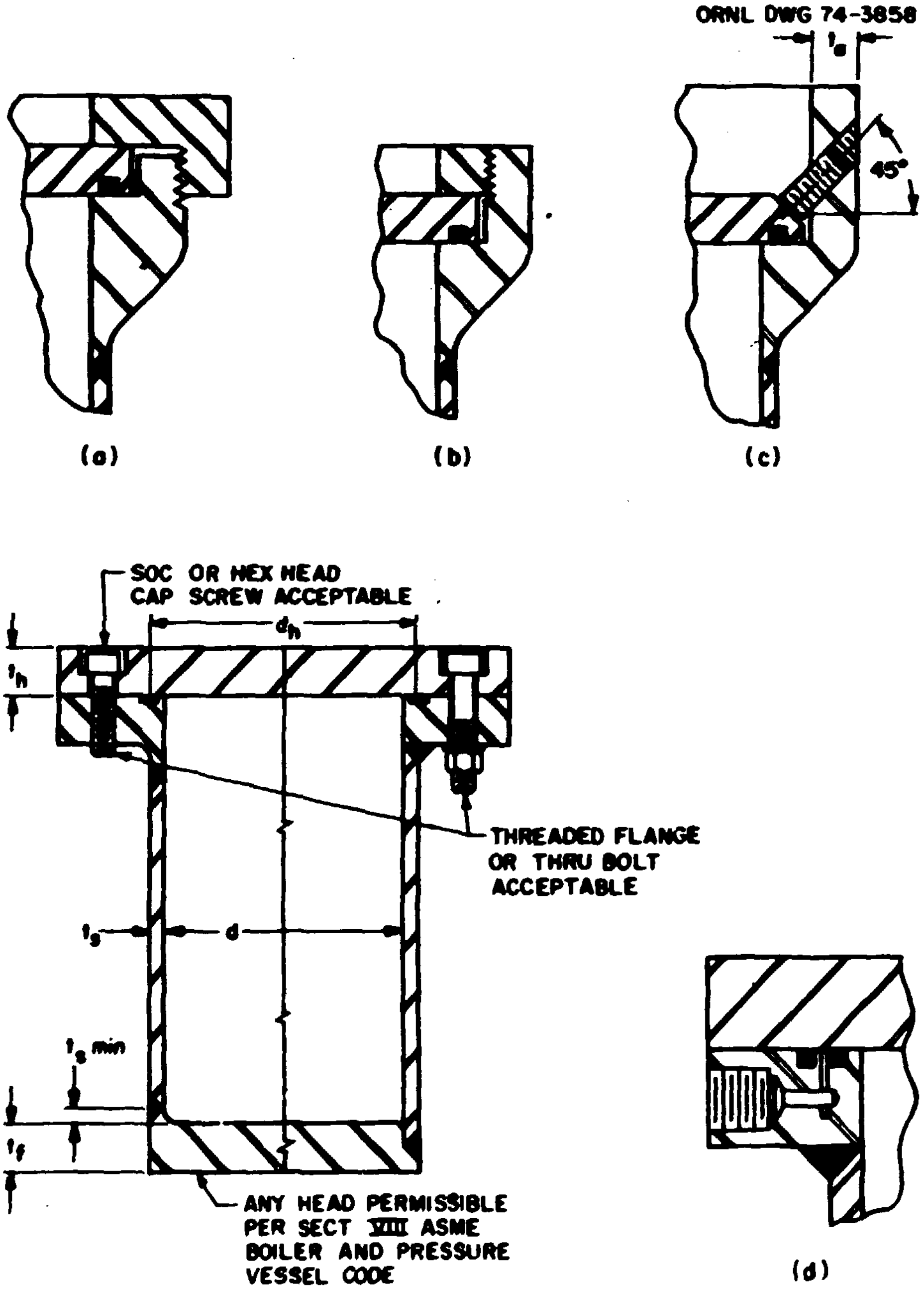


Fig. 1.40. Typical 2R container.

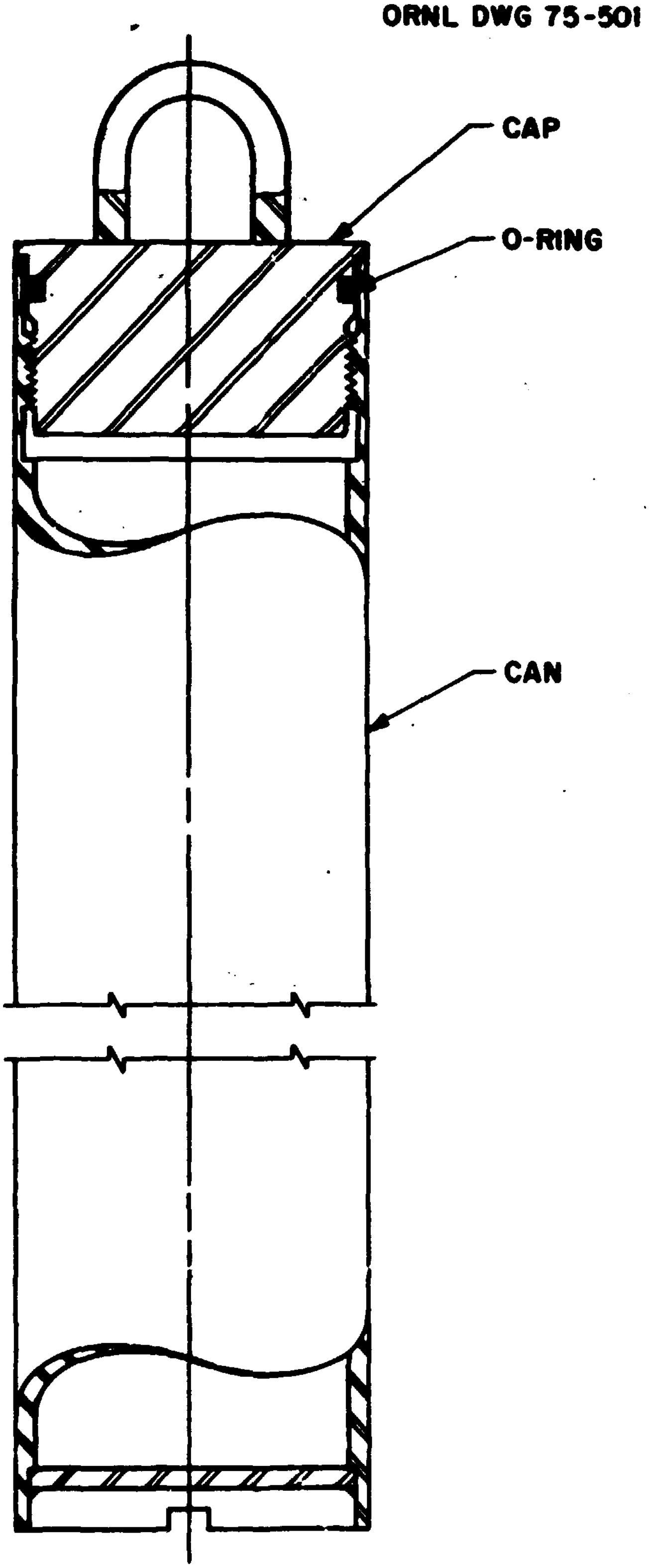


Fig. 1.41. Typical 2R container.

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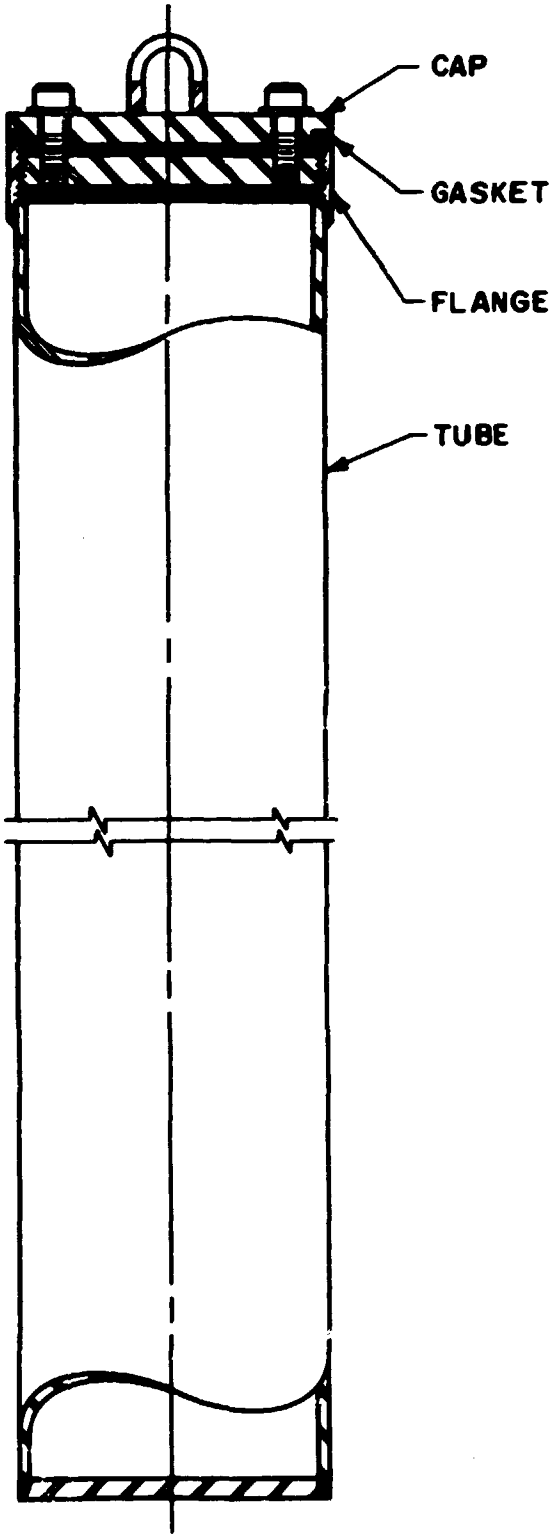

Fig. 1.42. Typical 2R container.

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

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

Reinforcement (increased thickness) is required when the container is equipped with a leak check tap (Fig. 1.40) in the head. From paragraph UG 39,

$$A = 0.5\ dt ,$$

$$d_h = d + 0.375 \text{ (see Fig. 1.39).}$$

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 gauge 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 (see Table 1.2) will occur for the greatest value of d^2/n which corresponds to $d = 4$ in., $n = 8$ bolts. This stress is

$$\sigma = [(20)\pi(4)^2]/[(4)(8)(0.0317)] = 933 \text{ psi} .$$

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 that required by Specification 2R to facilitate fabrication. Silicone rubber, Teflon, or metallic gaskets made from metals having a melting point in excess of 800°F are used in 2R containers shipped in this cask.

Fabrication is in accordance with ORNL Quality Assurance Procedures. Applicable approved ORNL welding procedures are used for welding. All welds are appropriately inspected in accordance with approved ORNL weld inspection procedures.

1.8 Thermal and Thermal Expansion Stresses

The cask is subjected to internal and external sources of heat. The thermal stresses and the stresses which result from differential expansion of dissimilar materials are evaluated and discussed below.

1.8.1 Normal conditions

During normal transport the cask is subjected to solar heat loads and the decay heat from the contents. In Sect. 2 the temperature distribution from six distinct cases with respect to heat load and environment are reported. Study of these distributions reveals that the most damaging gradients result from the case with the cask loaded with 1000 W (the maximum permissible heat load) and subjected to 130°F ambient with solar heat load. There are no temperature differences large enough to result in damaging thermal stresses.

The cask is constructed of materials which have coefficients of thermal expansion which differ considerably. The lead shielding has a coefficient of 16.3×10^{-6} in./in.·°F as compared with 6.5×10^{-6} in./in.·°F for steel and 9.2×10^{-6} in./in.·°F for stainless steel (see Sect. 1.1). As the cask's temperature increases, the lead expands more than the steel outer shell or stainless steel cavity shell. The outer shell is placed in longitudinal and radial tension. The inner cavity is placed in longitudinal tension, and the lead is loaded in both radial and longitudinal compression.

The program FEATS,[25] a finite-element program, was utilized to evaluate the thermal expansion stresses. The simplified model shown in Fig. 1.43 was assumed for this calculation. It was also assumed that the shielding cavity was completely full of lead and that there were no thermal expansion stresses in the cask when the entire cask was at a temperature of 70°F. The temperature distribution from Table 2.2 for

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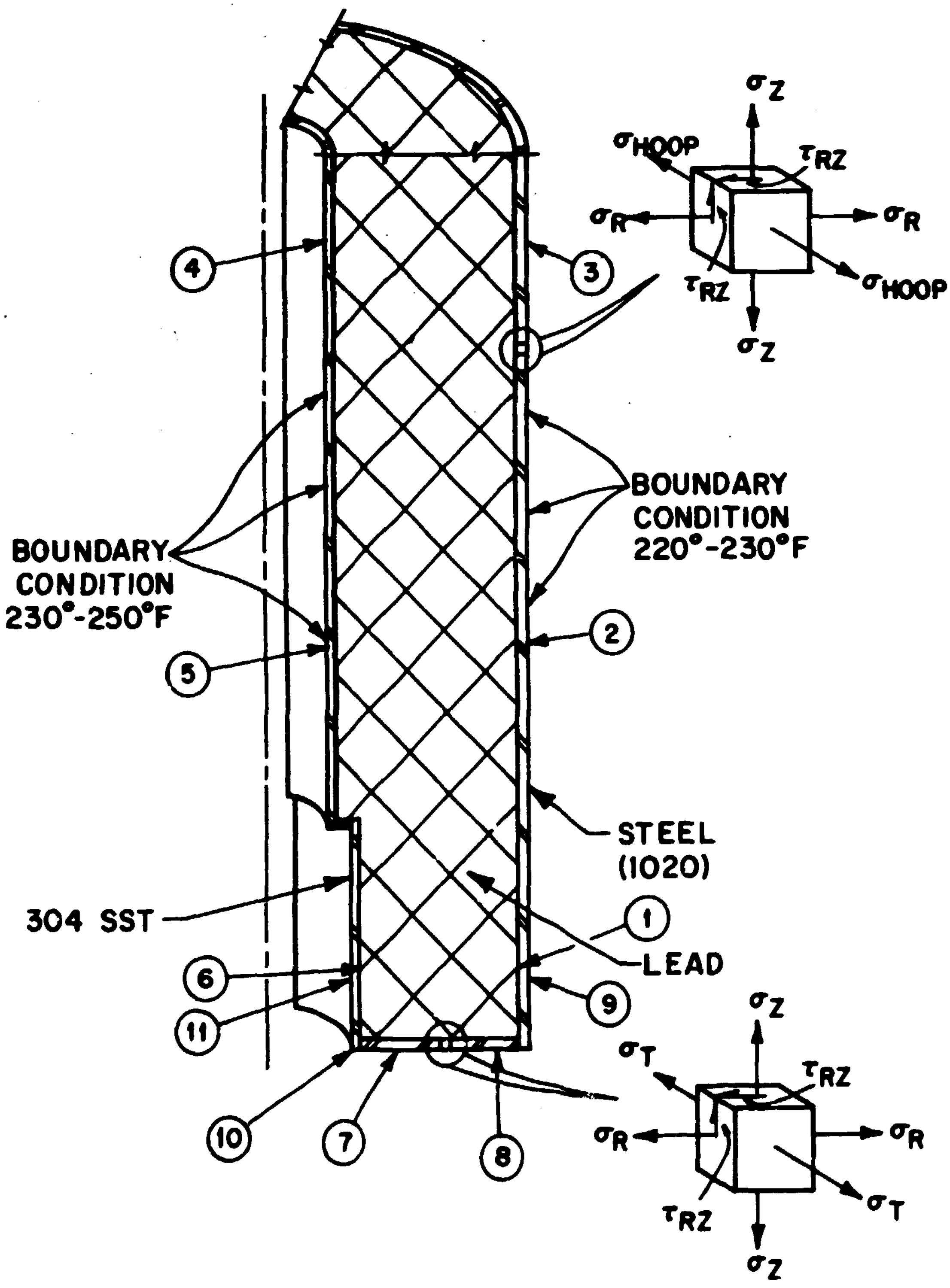

Fig. 1.43. FEATS thermal expansion stress model (axisymmetric).

a decay heat load of 1000 W and solar heat load at 130°F ambience was input to FEATS. Stresses at the points of interest identified on Fig. 1.43 are presented in Table 1.3.

Table 1.3. Point stresses from FEATS thermal stress analysis for normal conditions of transport

		RZ Mohr's circle			
Point no.	FEATS element no.	Max. stress (psi)	Min. stress (psi)	Principal stress angle (deg)	Hoop stress
1	112	195	-2,140	74.0	-3,000
2	242	1,800	-10	-2.2	2,300
3	542	1,500	-26	0	2,600
4	523	-96	-6,750	90.0	-3,200
5	223	-540	-5,000	86.0	3,200
6	99	-60	-3,700	-88.0	8,500
7	16	2,300	740	6.8	5,500
8	23	600	-880	44.0	2,200
9	68	11,900	2,700	17.0	3,700
10	15	-61	-13,700	89.0	-12,200
11	57	1,350	-5,600	56.5	-21,400

The above stresses are below the endurance limits for the materials of construction, and it is concluded that there will be no failure or loss of effectiveness due to thermal expansion stresses. If higher expansion stresses than those computed did exist for a nonhomogeneous or concentrated heat source, they would not be of serious consequence, since expansion stresses beyond yield are self-limiting and would not result in any failure.

1.8.2 Accident conditions

During the thermal (fire) portion of the specified accident sequence, the cask temperatures increase as illustrated in Figs. 2.2 and

2.3. There are no thermal gradients (temperature differences) large enough to result in significant thermal stresses.

During the fire, a portion of the lead will melt. The maximum quantity of melted lead, illustrated in Fig. 2.3, occurs a few minutes after the fire is extinguished. It is not known whether the shell will be ruptured as a result of the free-fall accidents. If the shell did not rupture, the cladding would be required to expand to accommodate the increase in lead volume due to melting and thermal expansion. If the shell did rupture, lower stresses would result. The calculations below demonstrate that the cask shell can expand and accommodate the increased volume without catastrophic failure. The assumptions made for normal transport are also made here. The temperatures, dimensions, etc., used in the calculations are presented in Table 1.4. Dimension symbols are illustrated in Fig. 1.44. Temperatures are taken from Fig. 2.2 and thermal coefficients of expansion from Table 1.1.

Table 1.4. Accident thermal expansion parameters

Dimension symbol	Cold dimension (in.)	Final temperature (°F)	ΔT (°F)	α (in./in.·°F)	Final dimension (in.)
r_o	11.75	980	9.0	6.5×10^{-6}	11.82
r_i	2.25	470	400	9.2×10^{-6}	2.39
r_p	3.50	520	450	9.2×10^{-6}	3.51
r_1	10.24				
r_2	9.74				
r_3	10.07				
ℓ_1	36.88	470	400	9.2×10^{-6}	37.02
ℓ_2	5.12	520	450	9.2×10^{-6}	4.9
ℓ_3	41.0	980	910	6.5×10^{-6}	41.24
ℓ_4	1.88				

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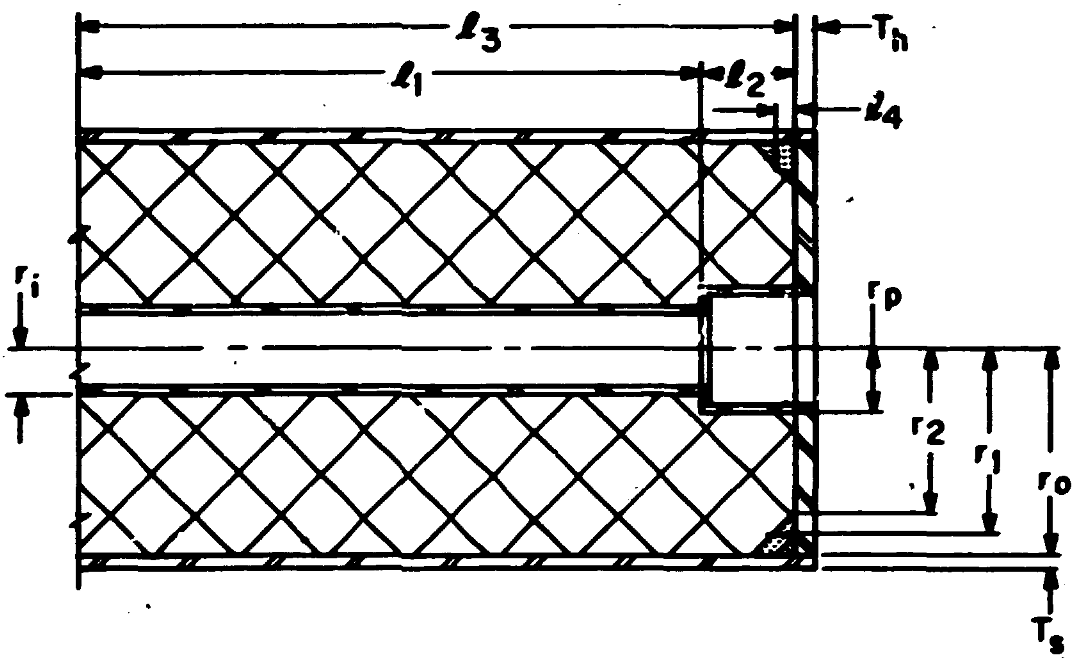

Fig. 1.44. Model for accident condition thermal expansion calculations.

The initial lead and shell volume (dimensions are cold dimensions, Table 1.4) is

$$V_i = \pi[\ell_1(r_o^2 - r_i^2) + \ell_2(r_o^2 - r_p^2)]$$

$$= \pi\{36.88[(11.75)^2 - (2.38)^2] + 4.88[(11.75)^2 - (3.5)^2]\}$$

$$= 17{,}270 \text{ in.}^3 \ .$$

The final shell volume (dimensions are final dimensions, Table 1.4) is

$$V_f = \pi[\ell_1(r_o^2 - r_i^2) + \ell_2(r_o^2 - r_p^2)]$$

$$= \pi\{(37.02[(11.82)^2 - (2.39)^2] + 4.90[(11.82)^2 - (3.51)^2]\}$$

$$= 17{,}500 \text{ in.}^3 \ .$$

The volume of melted lead (see Fig. 2.3, dimensions are cold dimensions, Table 1.4) is

$$V_m = \pi\left[\ell_3(r_o^2 - r_1^2) + \frac{r_3(r_1 - r_2)\ell_4}{2}\right]$$

$$= \pi\{41.0[(11.75)^2 - (10.24)^2] + \frac{(10.07)(10.24 - 9.74(1.88)}{2}\}$$

$$= 4290 \text{ in.}^3 \ .$$

The final lead volume is $V_2 = V_i + V_i\alpha_T + V_m\alpha_m$, where α_T and α_m are volumetric expansion coefficients for lead (see Fig. 1.2):

$$V_2 = 17{,}270(1 + 0.0305) + 4290(0.0325) = 17{,}940 \text{ in.}^3 \ .$$

The increase in volume which the shell must accommodate is

$$\Delta V = V_L - V_f = 17{,}940 - 17{,}550 = 390 \text{ in.}^3 \ .$$

The cask shell is a complex structure, braced in both the radial and longitudinal directions. It is further complicated by being of laminated construction. It is felt most of the shell expansion will be in the form of circumferential strain. It is conservative to assume that all the strain is in the circumferential direction for the purpose of showing that the shell can expand to accommodate the increase in volume. The equation for this increase is

$$\Delta V = \ell_3\pi\{[r_o(1 + \varepsilon)]^2 - r_o^2\} .$$

Solving for ε, the circumferential strain is

$$\varepsilon^2 + 2\varepsilon - \frac{\Delta V}{\ell_3\pi\ {}^2} = 0 .$$

By the quadratic formula,

$$\varepsilon = \frac{-2 + [(2)^2 + (4)(1)\ (\Delta/\ell\pi r_o^2)]^{1/2}}{2}$$

$$= \frac{-2 + [2^2 + 4(390)/41.24\pi(11.82)^2]^{1/2}}{2} = 0.011 \text{ in./in.}$$

This strain is small when compared with the ultimate strain (elongation) of steel (see Table 1.1), and it is concluded that the shell will not rupture.

1.9 Accident Pressure Stresses

The maximum calculated cask cavity pressure during the accident is 15 psig (see Sect. 2.4.4). The tensile stress, σ, in the plug bolts from this is

$$\sigma = \frac{F}{A_T} = \frac{P\pi r^2}{NA} ,$$

where

F = force,

A_T = total bolt area (in.^{2}),

P = pressure (psi),

r = plug radius (in.),

N = number of bolts,

A = stress area of one bolt (from ref. 20) (in.^{2}).

For the lower cover, secured by eight 1/2-13NC bolts, the stress is

$$\sigma = \frac{15\pi(6.75)^2}{8(0.141)} = 1900 \text{ psi} .$$

For the lower cover, secured by eight 3/8-16 NC bolts, the stress is

$$\sigma = \frac{15(\pi)(4.25)^2}{8(0.0775)} = 1370 \text{ psi} .$$

At these stresses, the bolts would continue to secure the plugs to the cask and maintain shielding.

2. THERMAL EVALUATION

The package must remain effective after exposure to severe thermal environments. Applicable normal and accident environments are specified in the regulations[1-3] and discussed below. Analytical evaluations and tests have been utilized to demonstrate the ability of the package to remain effective after exposure to the specified environments.

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 regulations[3] 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,[17] modified to evaluate phase change of materials, was used to determine the temperature distribution. Analyses were made with the cask maximum permissible heat loads of 350 W for common-carrier transport and 1000 W for exclusive-use vehicle. The temperature distribution for a 100°F ambient condition with 1000 W internal heat load was input as starting temperatures for the accident (fire) calculation.

2.2 Thermal Properties of Materials

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

2.3 Thermal Evaluation for Normal Conditions of Transport

2.3.1 Thermal model

The model used for the heat transfer computations is shown in Fig. 2.1. The contents are modeled as a uniform body, nominally with physical properties of stainless steel, with the decay heat evenly distributed throughout. The assumed model results in slightly higher inner container surface temperatures than actual, since no contact with the cask cavity was assumed. The area of contact will be small in practice, and the above assumption is reasonable. It is recognized that the calculated contents temperature will be lower than the actual contents temperature. A separate calculation (see Sect. 2.3.6) was made to determine the centerline temperature for what is considered a more severe loading than actual.

Table 2.1. Material properties used in thermal analysis

Material	Temperature (°F)	Thermal conductivity (Btu/hr·ft·°F)	Density (lb/in.^{3})	Heat capacity (Btu/lb·°F)	Latent heat (Btu/lb)
Lead[a,b]	32.0	20.3	0.4109	0.031	11.3 at 621.3°F
	212.0	19.3			
	392.0	18.2			
	572.0	17.2			
304 SST[c,d]	32.0	8.5	0.2824	0.120	
	260.0	9.8			
	440.3	10.6			
	620.3	11.4			
	752.0			0.135	
	800.3	12.2			
	980.3	13.0			
	1160.0	13.8			
Mild steel[e]	32.0		0.2840	0.105	
	77.0	41.1			
	167.0			0.120	
	392.0			0.135	
	752.0			0.150	
	1112.0			0.170	
	1292.0			0.200	
	1405.0			0.200	
	1414.0			0.164	
	1423.0			0.168	
	1472.0	16.92			
	1742.0			0.160	
Air[f]	32.0	0.0140	4.69×10^{-5}	0.240	
	100.0	0.0154	4.11×10^{-5}	0.240	
	200.0	0.0174	3.47×10^{-5}	0.241	
	300.0	0.0193	3.51×10^{-5}	0.243	
	400.0	0.0212	2.66×10^{-5}	0.245	
	500.0	0.0231	2.38×10^{-5}	0.247	
	600.0	0.0250	2.16×10^{-5}	0.250	
	700.0	0.0268	1.97×10^{-5}	0.253	
	800.0	0.0286	1.82×10^{-5}	0.256	
	900.0	0.0303	1.68×10^{-5}	0.259	
	1000.0	0.0319	1.57×10^{-5}	0.262	
	1500.0	0.0400	1.17×10^{-5}	0.276	

[a] Thermal conductivity, density, and specific heat of lead were obtained from J. P. Holman, *Heat Transfer*, McGraw-Hill, New York, 1972.

[b] The latent heat of lead was obtained from W. M. Rohsenow et al., *Handbook of Heat Transfer*, McGraw-Hill, New York, 1973.

[c] The thermal conductivity values for stainless steel were obtained from Y. S. Touloukian, *Thermal Conductivity*, 1970.

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

[e] The properties of mild steel (SAE 1020 carbon steel) were obtained from *A Compilation of Thermal Property Data for Computer Heat-Conduction Calculations*, UCRL-50589.

[f] The properties of air were obtained from F. Kreith, *Principles of Heat Transfer*, International Textbook Company, Scranton, Pa., 1965.

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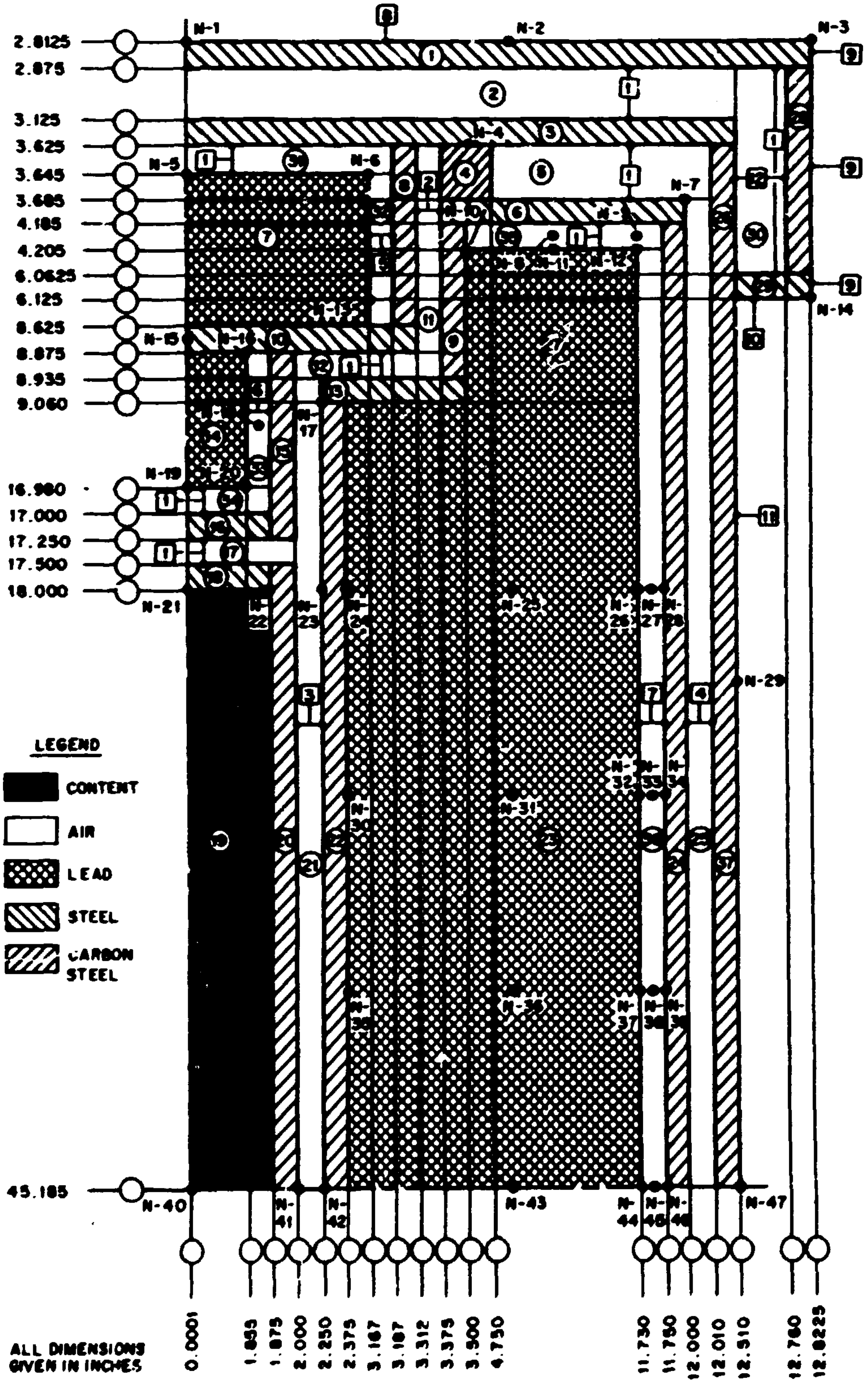

Fig. 2.1. Heating map.

In calculating the steady-state temperatures for the 130°F environment in direct sunlight, it was assumed that a solar heat flux of 144 Btu/hr·ft^2 was incident upon the entire outer surface of the cask and that the fraction of the incident solar flux absorbed by the cask is equal to the absorptivity (0.6) of the outer surface of the cask. The value of 144 Btu/hr·ft^2 was obtained by numerical integration of Fig. 5.3 from the *Cask Designer's Guide* by Shappert.[9] A second steady-state analysis was made assuming the ambient temperature was 100°F and the solar heat load was reduced to zero.

2.3.2 Maximum temperatures

Temperatures at points of interest throughout the cask are given in Table 2.2. Data are presented for the normal conditions of transport.

The maximum accessible surface temperature for the 100°F ambient temperature case demonstrates that the package complies with DOT regulations. The maximum surface temperature with a heat load of 1000 W, the limit for a sole-use vehicle, is 150°F as compared with the allowable of 180°F. The maximum surface temperature for a 350-W heat load is 122°F, which is the allowable limit for common-carrier transport.

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 (see Sect. 1.4.2).

2.3.4 Maximum internal pressure

There will be an increase in pressure in the central cavity, in the contents, and in the gap region above the contents caused by an increase in temperature in the regions. If ideal-gas behavior and constant gas volume is 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_2, is

$$P_2 = (14.7)T_2/530 ,$$

Table 2.2. Cask temperatures

Location[a]	Heat load (350 W)			Heat load (1000 W)		
	Atmospheric conditions					
	-40°F shade	100°F shade	130°F direct sunlight	-40°F shade	100°F shade	130°F direct sunlight
N-1	28	110	190	-6	120	200
N-2	28	110	190	-7	120	200
N-3	25	110	190	1	130	210
N-4	18	120	200	22	150	220
N-5	-15	120	200	31	150	230
N-6	-15	120	200	31	150	230
N-7	-17	120	200	23	150	220
N-8	-16	220	200	27	150	230
N-9	-17	120	200	25	150	220
N-10	-16	120	200	27	150	230
N-11	-16	120	200	28	150	230
N-12	-16	120	200	28	150	230
N-13	-15	120	200	31	150	230
N-14	-20	120	200	15	140	220
N-15	-14	120	210	35	160	230
N-16	-14	120	210	35	160	230
N-17	-15	120	200	31	150	230
N-18	-11	130	260	43	160	240
N-19	8	130	211	50	170	250
N-20	-8	130	210	50	170	250
N-21	160	250	310	370	420	460
N-22	160	250	310	360	420	460
N-23	12	130	210	39	160	240
N-24	13	120	210	39	160	240
N-25	14	120	210	35	160	230
N-26	15	120	210	33	160	230
N-27	16	120	200	29	150	230
N-28	16	120	200	25	150	230
N-29	9.2	120	200	24	150	230
N-30	11	128	210	46	176	250
N-31	12	126	210	40	160	240
N-32	-12	120	208	38	160	240
N-33	-13	120	210	33	155	230
N-34	-15	120	210	29	150	230
N-35		130	210	50	170	250
N-36	-10	130	210	43	165	240
N-37	-11	130	210	41	165	240
N-38	-12	120	210	36	160	235
N-39	-14	120	210	31	155	235
N-40	200	270	330	415	470	510
N-41	180	270	330	410	460	500
N-42	-7	130	210	50	175	250
N-43	-1.7	130	210	44	165	245
N-44	-10	130	210	42	165	240
N-45	-12	120	210	35	160	240
N-46	-14	120	210	32	155	235
N-47	-15	120	200	27	150	230

---

[a] See Fig. 2.1 for locations.

where T_2 is the elevated gas temperature. See Fig. 2.1 for region locations, identified by a number within a circle.

Air pressure in the upper cavity of the plug (regions 31 and 32) is

$$P_2 = 14.7\left(\frac{690}{530}\right) = 19.11 \text{ psia} = 4.4 \text{ psig} .$$

Air pressure between the outer shells (regions 5 and 25) is

$$P_2 = 14.7\left(\frac{680}{530}\right) = 18.94 \text{ psia} = 4.2 \text{ psig} .$$

Air pressure in the main shielding cavity (regions 35 and 36) is

$$P_2 = 14.7\left(\frac{690}{530}\right) = 19.2 \text{ psia} = 4.5 \text{ psig} .$$

Air pressure in the cask cavity (regions 11, 12, and 21) is

$$P_2 = 14.7\left(\frac{700}{530}\right) = 19.4 \text{ psia} = 4.7 \text{ psig} .$$

Air pressure in the lower cavity of the plug (regions 33 and 34) is

$$P_2 = 14.7\left(\frac{700}{530}\right) = 19.4 \text{ psia} = 4.7 \text{ psig} .$$

Air pressure in the 2R container (region 19) is

$$P_2 = 14.7\left(\frac{945}{530}\right) = 26.21 \text{ psia} = 11.5 \text{ psig} .$$

All of the above pressures result from temperatures in the 130°F ambience direct sunlight, with a decay heat load of 1000 W.

2.3.5 <u>Minimum internal pressure</u>

There will be a decrease in pressure in the central cavity, in the contents, and in the gap region above the contents caused by a decrease in temperature in the regions. If ideal-gas behavior and constant gas volume is 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_2, is

$$P_2 = (14.7)T_2/530 ,$$

where T_2 is the gas temperature.

Air pressure in the upper cavity of the plug (regions 31 and 32) is

$$P_2 = 14.7\left(\frac{445}{530}\right) = 12.3 \text{ psia} .$$

Air pressure between the outer shells (regions 5 and 25) is

$$P_2 = 14.7\left(\frac{440}{530}\right) = 12.3 \text{ psia}$$

Air pressure in the main shielding cavity (regions 35 and 36) is

$$P_2 = 14.7\left(\frac{445}{530}\right) = 12.4 \text{ psia} .$$

Air pressure in the cask cavity (regions 11, 12, and 21) is

$$P_2 = 14.7\left(\frac{450}{530}\right) = 12.5 \text{ psia} .$$

Air pressure in the lower cavity of the plug (regions 33 and 34) is

$$P_2 = 14.7\left(\frac{450}{530}\right) = 12.5 \text{ psia} .$$

Air pressure in the 2R container (region 19) is

$$P_2 = 14.7\left(\frac{640}{530}\right) = 17.75 \text{ psia} .$$

All of the above pressures result from temperatures in the -40°F ambience, with a decay heat load of 350 W.

2.3.6 Maximum contents temperature

The simplifying assumption that the contents of the cask consist of a homogeneous solid as opposed to an array of cylindrical rods results in a lower calculated centerline temperature for the contents.

Cox[26] presents a correlation for calculating a corrected centerline temperature for an array of cylindrical rods:

$$T_1 = \left. \frac{Q_1 K}{\sigma A_1} + T_2^4 \right.^{0.25} ,$$

where

T_1 is the centerline temperature (°R),

Q_1/A_1 is the heat flux from one rod ($\mathrm{Btu/hr \cdot ft^2}$),

σ is the Stefan-Boltzmen constant (0.1714×10^{-8} $\mathrm{Btu/hr \cdot ft^2 \cdot {}^\circ F^4}$),

T_2 is the mean temperature of the 2R container (°R),

K is a dimensionless constant from Fig. 19 of Cox's report.

Based on an array of 37 1/4-in. rods,

$$A_1 = \pi DL = \pi(0.25)(54.375)/144 ,$$

$$A_1 = 0.2966 \ \mathrm{ft}^2 ,$$

$$Q = \frac{1000 \ \mathrm{W}}{37 \ \mathrm{rods}} \times \frac{3.413 \ \mathrm{Btu/hr}}{\mathrm{W}} = 92.24 \ \mathrm{Btu/hr \cdot rod} ,$$

$$T_2 = 446^\circ\mathrm{F} = 906^\circ\mathrm{R} ,$$

$$K = 11,$$

$$T_1 = \left(\frac{92.24(11)}{(0.1714 \times 10^{-8})(0.2966)} + 906^4 \right)^{1/4}$$

$$= 1280^\circ\mathrm{R} = 820^\circ\mathrm{F} .$$

This is below the maximum allowable cladding temperature, and the fuel will not melt.

2.4 Hypothetical Thermal Accident Evaluation

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

2.4.1 Thermal accident analysis

The effects of the hypothetical thermal accident were analyzed using the same geometric model in a HEATING-3 (ref. 17) computer calculation that was used for the normal conditions analysis. The boundary condition parameters were adjusted to include the 1475°F radiant environment for the 30-min thermal exposure. The surface convection parameters were adjusted during the postexposure time period to account for the elevated surface temperature. The insulating effect of the intumescent paint was neglected in the thermal accident. This was done because the insulating effect is variable with the time of exposure, and the conductivity as a function of time is unknown. Note that the corners, which are more vulnerable to lead melting, are protected by three layers of paint. It is concluded that the model represents a conservative case, and the actual temperatures would be lower than calculated and less lead than calculated would melt. The damage resulting from the free fall would not significantly affect the heat transfer. Therefore, the undamaged model will be assumed. The fire shield would be deformed but would remain effective as a radiation shield.

2.4.2 Thermal model

The computer model described in Sect. 2.4.1 was used to determine the temperature distribution within the container during the 30-min thermal exposure and postexposure cooldown period. The air gaps between the outer shell and the lead were eliminated and contact was assumed. The steady-state temperature distribution resulting from 100°F ambience and a decay heat load of 1000 W was used to start the calculation. 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. 2.2 (see Table 2.2 and Fig. 2.3 for explanation of these point locations).

2.4.4 Maximum pressures

The cavity pressure increase cannot be precisely calculated, since the seal has been predicted to fail. Since such a seal could fail over some significantly broad range of temperatures, the maximum temperature at failure is assumed to be the maximum cavity temperature, and the pressure increase is calculated as in Sect. 2.3.4:

$$P_1 = \frac{P_1T_2}{T_1} = \frac{(14.7)(1070)}{530} = 29.7 \text{ psia} = 15.0 \text{ psig} .$$

The pressure in the inner container is

$$P_2 = \frac{P_1T_2}{T_1} = \frac{(14.7)(1060)}{530} = 29.4 \text{ psia} = 14.7 \text{ psig} .$$

2.4.5 Damage assessment

The calculated temperature will not result in loss of primary containment (see Sect. 3). The secondary seals will fail as a result of high temperatures and release secondary coolant (air), which is not contaminated. A portion of the lead shielding will melt as illustrated in Fig. 2.3. The consequences of the potential shielding loss is discussed in Sect. 4. The deflection of the shell resulting from expansion of the lead is discussed in Sect. 1.8.

It is concluded that the fire will not result in loss of containment, in radiation levels in excess of those allowed by the regulations, or in catastrophic failure of the cask shell.

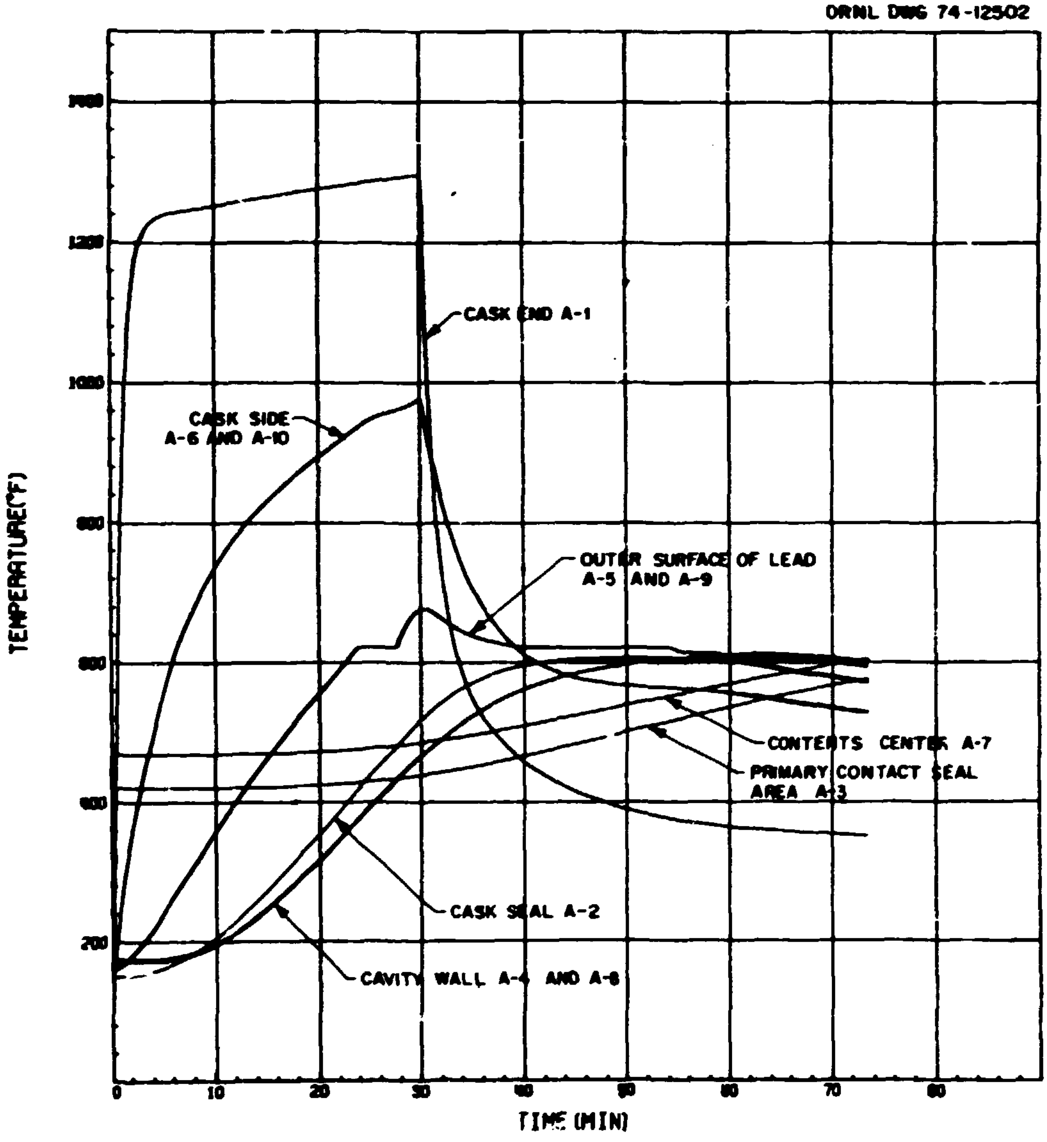

Fig. 2.2. Cask temperature.

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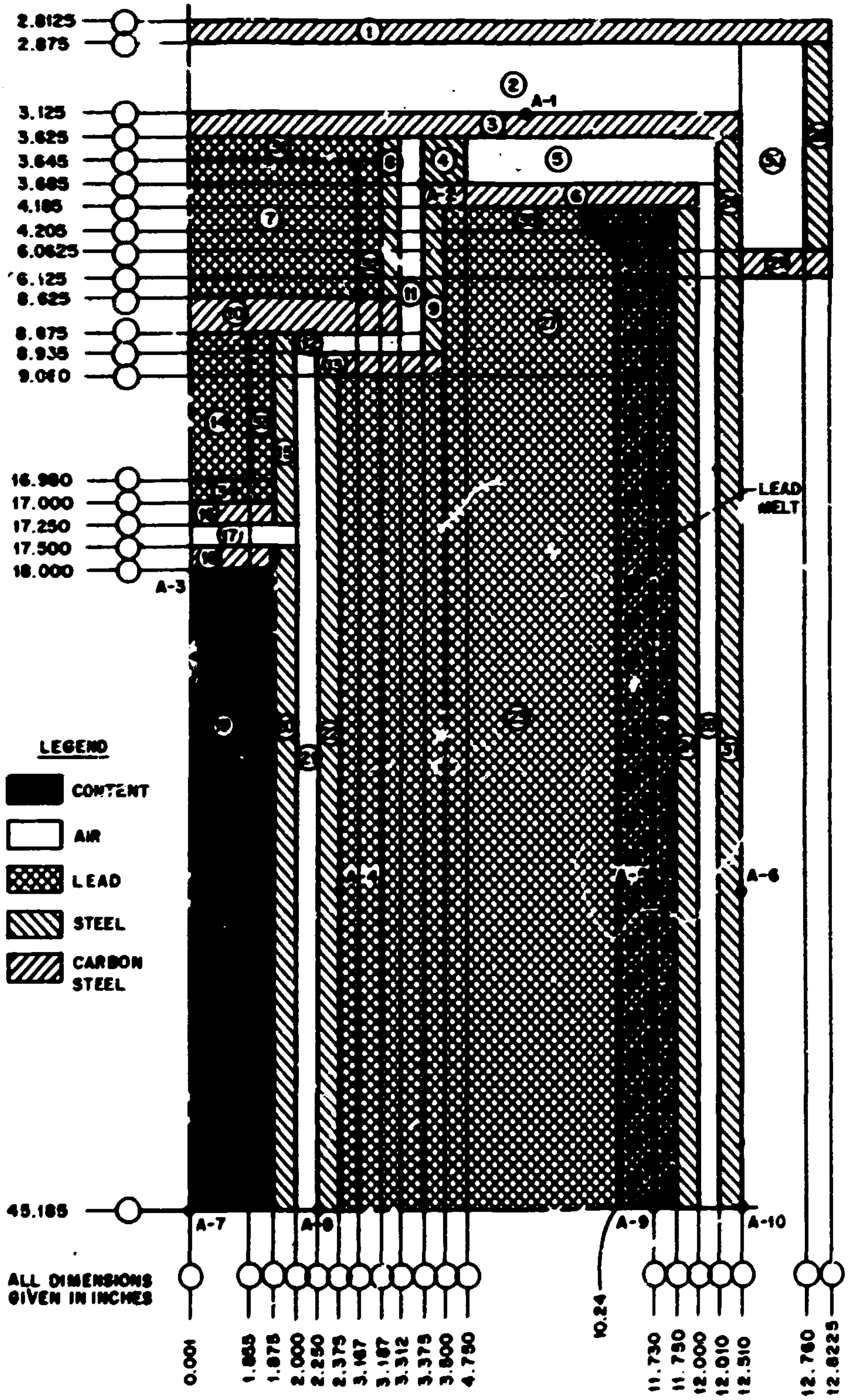

Fig. 2.3. Lead melting.

3. CONTAINMENT

It is required[1-3] that packages maintain containment of the radioactive contents during normal and specified accident conditions. The containment boundaries and capabilities of the package are outlined below.

3.1 Containment Boundaries

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

3.1.1 Primary containment

The cladding of fuel elements or the experiment shells that served as containment boundaries in the reactor during irradiation serve as primary containment for shipment; however, if it is known or suspected that this containment boundary may be breached, the item is enclosed in a Specification 2R container.

All other materials shipped which do not conform to "special form" are contained in a Specification 2R container or equivalent (see Sect. 1.7), which forms primary containment. Typical examples of ORNL 2R containers are illustrated in Figs. 1.38, 1.39, 1.40, and 1.41. These containers are designed to be "leak-tight" to the extent that water will not leak from the container at the anticipated pressure and temperature. The container shown in Fig. 1.39(d) is designed for leak checking and will be leak-tight to the extent that leaks are not detectable by time-pressure-drop techniques. All powders and other dispersibles will be shipped in 2R containers which are leak checked. Solids such as metal specimens, etc., may be shipped in containers which are not designed for leak checking.

For "special form" shipments, the welded encapsulation forms primary containment. See Fig. 1.37 for an example of "special form" encapsulations and Sect. 1.6 for a 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 a mass spectrometer or leak-detection techniques with an elevated-temperature-solution immersion bubble. Occasionally, irradiated metal specimens which conform to the requirements for "special form" are shipped in the cask. These specimens do not have total transferable surface contamination in excess of allowable release limits, hence do not require a primary containment vessel.

3.1.2 Secondary containment

The cask inner cavity and gasketed plugs form secondary containment for all shipments. Secondary containment is pressure tested in accordance with the procedures in Appendix F.

3.2 Requirements for Normal Conditions of Transport

The 2R containers are designed (see Sect. 1.7) for pressures and temperatures in excess of those encountered in normal transport; hence there will be no release of radioactive material and no loss or contamination of coolant. 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). The pressure rises encountered will be less than those experienced in the special form thermal test. There will be essentially no contamination of primary coolant (air) and no loss of coolant. Normal conditions of transport will not cause loss of secondary containment. The pressure rise in the cask cavity will not result in a pressure in excess of allowable (see Sect. 1.4). The temperatures encountered are within the operating limits for materials forming secondary containment.

3.3 Containment Requirements during the Hypothetical Accident

Containment of the radioactive materials will be maintained during and after the specified 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 by the regulations demonstrate this. The "special form" thermal test results in temperatures in excess of those applicable to the contents during the specified thermal exposure (see

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

Likewise, the design pressure and temperature (see Sect. 1.7) for the 2R containers are not exceeded during the accident.

The temperature of the primary seal will not reach 600°F (see Fig. 2.2). It will remain above 500°F for a few hours (estimated to be less than 5 hr by extrapolation of Fig. 2.2). Note that the cask is cooled according to the regulations after the centerline temperature has begun to fall.

Data published by Parker Seal Company[18] and reproduced in Fig. 3.1 show that silicone rubber gaskets have a life of 12 hr above 500°F. The calculated seal temperatures are below the failure temperature of the specified metal gaskets. It is concluded that primary containment will not be lost due to the fire. The impact will not overstress the 2R container. Hence there will be no detectable loss of contents from the 2R container. The tests outlined in Sect. 3.4 were conducted to establish the ability of 2R containers to maintain containment after impact from a 30-ft drop.

Secondary containment will be lost as a result of the accident. The free-fall accidents would result in failure of mechanical seals and possibly rupture of secondary containment welds. Likewise, the fire would result in thermal decomposition of the closure gaskets.

3.4 Containment Testing

On August 21, 1974, two Specification 2R containers as illustrated in Figs. 3.2 and 3.3 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 to enhance 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

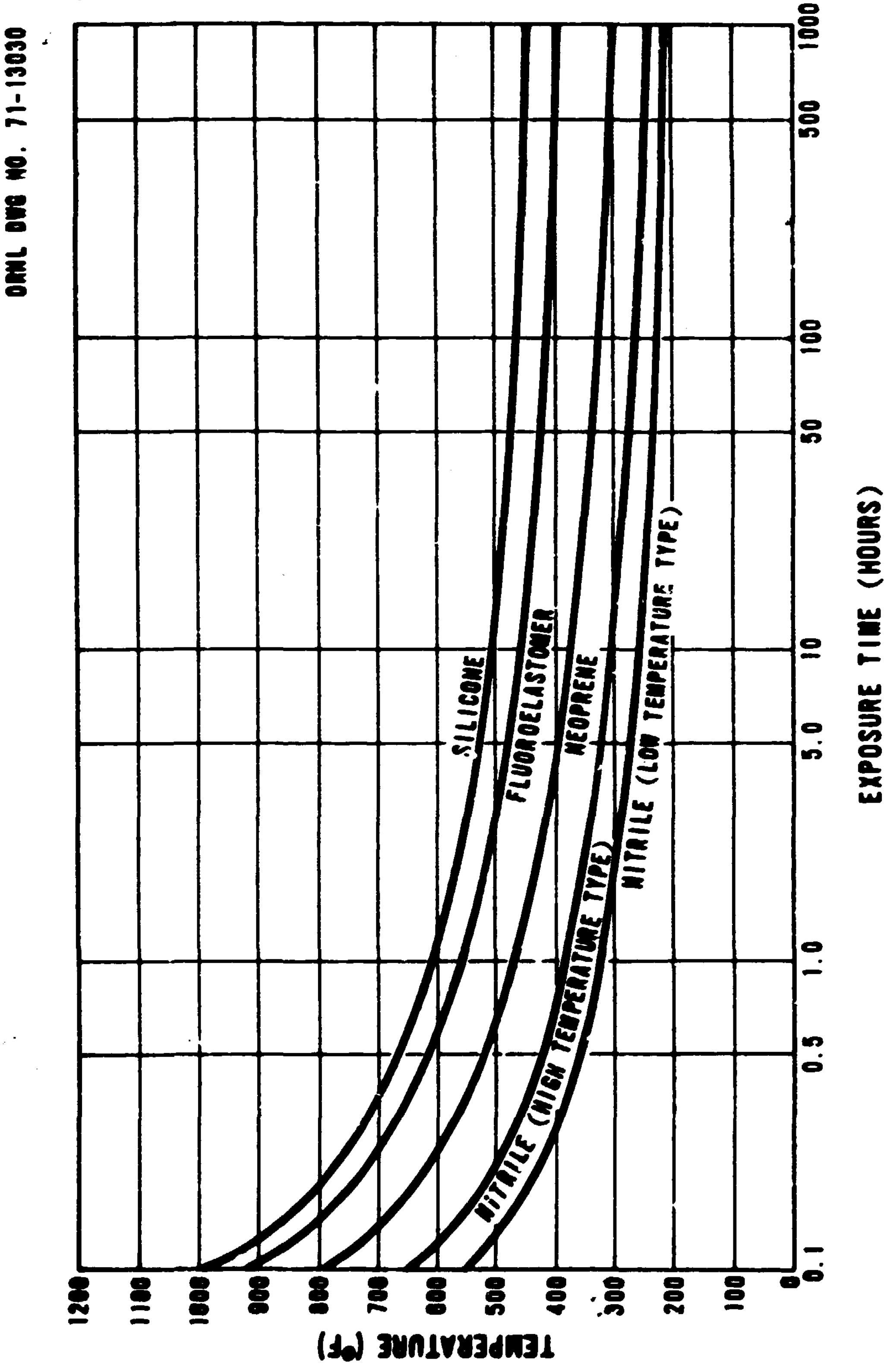

Fig. 3.1. Seal compound temperature resistance.

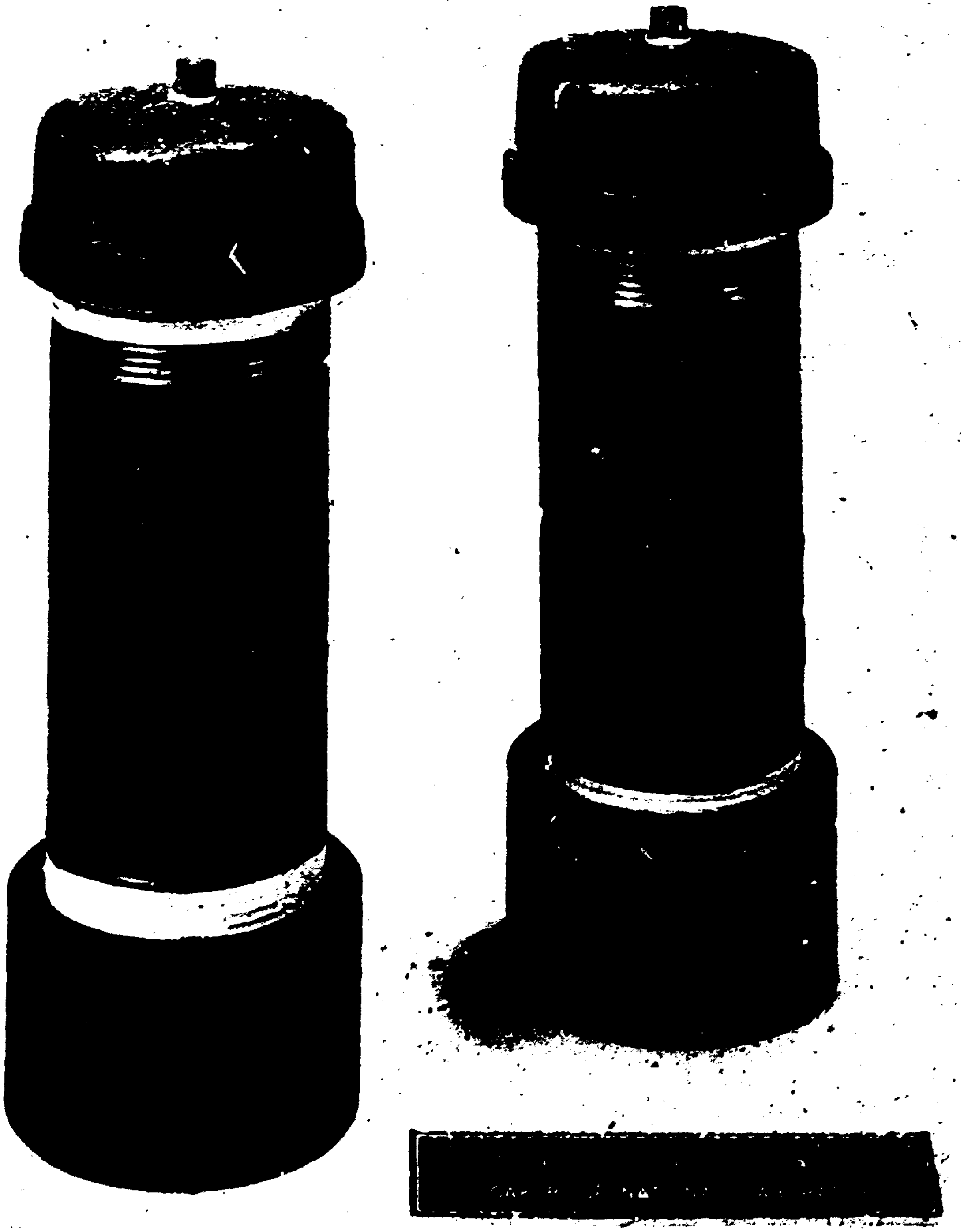

Photo 2468-74

Fig. 3.2. The 2R test model.

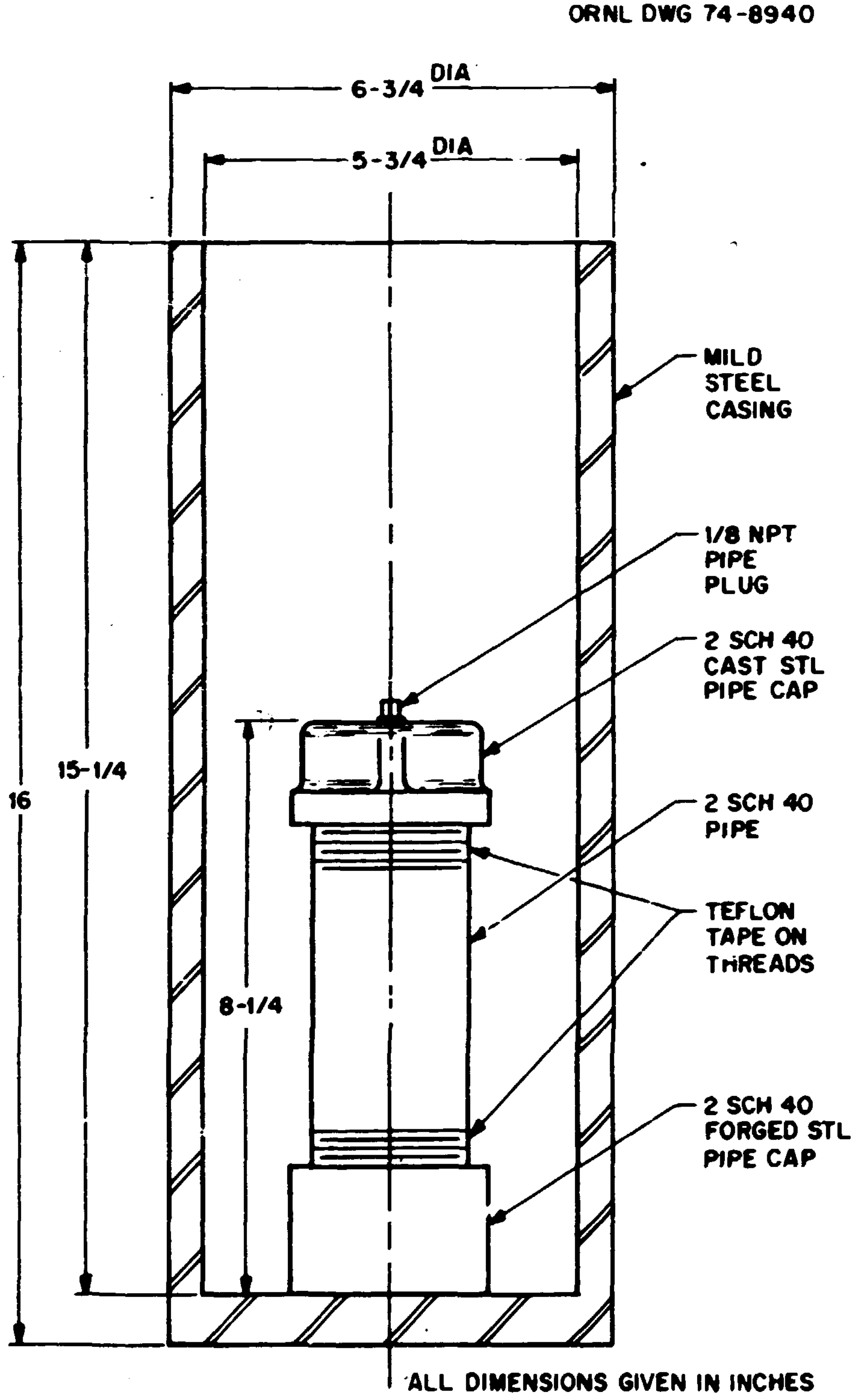

Fig. 3.3. The 2R test model.

shortage of forged caps. In all the tests below, the forged cap is nearest the point of impact. The cask 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 (see Fig. 3.3) and dropped from a height of 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, which 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 a height of 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 it was 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 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.

Two inner 2R containers similar to those (see Figs. 1.40 and [illegible]1) used with the cask were drop tested by the ORNL Chemical Technol. Division to establish their containment capability. These tests demonstrated that the containers were adequate to maintain containment of the contents after the 30-ft free fall. A copy of the original test report is reproduced in Appendix D.

4. SHIELDING

The regulations[2,3] specify maximum permissible radiation dose rates for both normal and accident conditions. For normal conditions, the dose rate at the surface of a package may not exceed 200 millirems/hr. Also, the transport index may not exceed 10, which limits the rate at 3 ft from the package surface of 10 millirems/hr. It is also required that after the specified accident the dose rate at 3 ft may not exceed 1000 millirems/hr.

4.1 Normal Conditions

Shielding is formed by a minimum of 9.5 in. of lead and 0.75 in. of steel and stainless steel. After loading, but prior to removal from the loading area, the cask is surveyed as outlined in the operating procedures (see Appendix F) for conformance to dose rate requirements. Thus, a calculation of dose rates for normal conditions is not necessary.

4.2 Accident Conditions

The free-fall accident would locally reduce the shielding as discussed in Sect. 1.5. The specified thermal accident (Sect. 2.4) could result in loss of shielding if the shell ruptured and the lead which had melted were lost. Since rupture of the shell is credible due to the unknown quality of the welds, it is assumed for the purpose of accident condition shielding evaluation that all lead which melts is lost. These shielding reductions are summarized in Figs. 1.27, 1.29, 1.35, and 2.3. The largest shielding reduction results from the side impact. The calculations below demonstrate that the dose rate will not be increased beyond the limit allowed by the regulations. The shielding model, shown in Fig. 4.1, is assumed for dose rate calculations. The effective lead shielding thickness, d, following the side impact is 7.16 in.

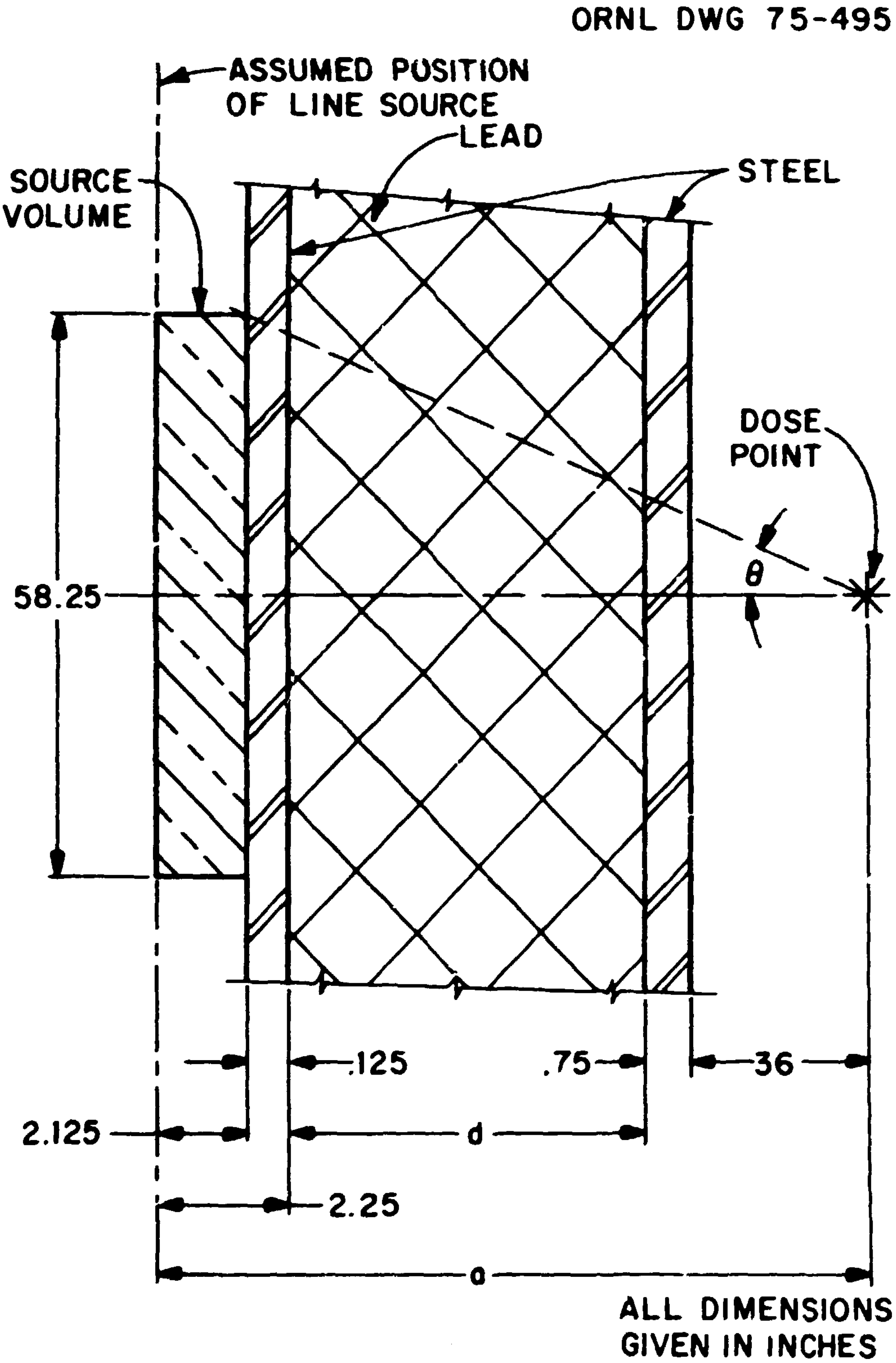

Fig. 4.1. Accident shielding model.

It can be conservatively assumed that all of the source photon energy is converted to heat. If it is further conservatively assumed that the source decays by the liberation of one 1-MeV photon per disintegration, then the photon source which will produce 1000 W of heat is given by

$$1000 \text{ W} \times \frac{1 \text{ MeV/sec}}{1.60206 \times 10^{-13}} \times \frac{1 \text{ photon}}{1 \text{ MeV}} = 6.24 \times 10^{15} \text{ photons/sec} .$$

It should be noted that no neutron sources will be transported.

A simple shielding model assuming a line source and slab shields, shown in Fig. 4.1, allows one to calculate the flux, ϕ, at the dose point using the expression[27]

$$\phi = \frac{S_L}{2\pi a} [AF(\theta, b_1) + (1 - A)F(\theta, b_2)] ,$$

where

S_L = photon source per unit length,

a = distance from line source to dose point,

A = coefficient in two-term exponential expression for buildup factor, B, where $B = Ae^{-\mu\alpha t} + (1 - A)e^{-\mu\beta t}$, and α and β are the exponential coefficients, experimentally determined,

μ = linear attenuation coefficient of the shield material,

t = thickness of the shield material,

$F(\theta, b)$ = a geometric function given by $\int_0^\theta e^{-b \sec \theta'} d\theta'$,

θ = angle shown in Fig. 4.1,

$b_1 = \mu_1' t$,

$\mu_1' = \mu(1 + \alpha)$,

$b_2 = \mu_2' t$,

$\mu_2' = \mu(1 + \beta)$.

Buildup in the steel will be neglected since the steel thicknesses are very small.

For 1-MeV photons in lead,[28]

$\mu = 0.776\ \text{cm}^{-1}$,

$A = 2.45$,

$\alpha = -0.045$,

$\beta = 0.178$.

and the F functions are available in graphical form.[27]

The calculation of the dose rate at a point 3 ft from the point of side impact is shown below:

$$S_L = \frac{6.24 \times 10^{15}\ \text{photons/sec}}{58.25\ \text{in.} \times 2.54\ \text{cm/in.}} = 4.22 \times 10^{13}\ \text{photons/cm·sec} ,$$

$$a = 2.25 + 7.16 + 0.75 + 36.0 = 46.16\ \text{in.} = 117.25\ \text{cm} ,$$

$$t = 7.16\ \text{in.} = 18.19\ \text{cm} ,$$

$$\theta = \tan^{-1} \frac{(58.25/2)}{a} = 33° ,$$

$$\mu_1' = \mu(1 + \alpha) = 0.776(1 - 0.045) = 0.74 ,$$

$$b_1 = \mu_1' t = 0.74(18.19) - 13.48 ,$$

$$\mu_2' = \mu(1 + \beta) = 0.776(1 + 0.178) = 0.91 ,$$

$$b_2 = \mu_2' t = 0.91(18.19) = 16.55 ,$$

$$F(32°,\ 13.48) \approx 4.2 \times 10^{-7} ,$$

$$F(32°,\ 16.55) \approx 1.6 \times 10^{-8} ,$$

$$\phi = \frac{4.22 \times 10^{13}}{2\pi(117.25)} [2.45(4.2 \times 10^{-7}) - 1.45(1.6 \times 10^{-8})]$$

$$= 5.76 \times 10^{4} \text{ photons/cm}^2\cdot\text{sec} .$$

In order to convert this flux to a dose rate, a conversion factor for 1-MeV photons is[27]

$$(2 \times 10^{-3} \text{ mR/hr})/(\text{photons/cm}^2\cdot\text{sec}) .$$

A dose rate of gamma radiation of 1 R/hr is approximately equivalent to a dose rate of 1 rem/hr, since the relative biological effectiveness for gamma radiation is unity. Thus the dose rate at 3 ft, D, is

$$D = (5.76 \times 10^{4})(2 \times 10^{-3}) = 115 \text{ millirems/hr} .$$

This is much less than the allowed postaccident dose rate of 1000 millirems/hr. Thus the cask is expected to provide adequate radiation shielding following any of the accidents specified by regulations.

5. CRITICALITY

The regulations require that a Fissile Class I package be so designed and constructed and its contents so limited that any number of such undamaged packages would be subcritical in any arrangement, and 250 such packages would be subcritical in any arrangement if each package were subjected to the sequence of the hypothetical accident conditions, and immersion in water must be considered.

The cask has been approved by the ORNL Criticality Committee (NSR 342, Revision 1, and additional information in Appendix E) for a maximum loading of 1250 g of fissile isotopes (combinations of ^{235}U, ^{233}U, and plutonium) with the stipulation that, if the mass loading exceeds 800 g of fissile isotopes, the material will be so arranged that the fissile loading will not exceed 250 g per linear foot under normal and accident conditions. This requirement restricts the contents to a safe mass per foot for infinitely long water-reflected cylinders and ensures safety during loading and unloading underwater. The overall mass limit of 1250 g of fissile isotopes and the 4-in. diameter render the cask safe against redistribution of the contents in an accident. Also, as shown in the structural analysis, the contents of the cask will remain inside the cavity in the hypothetical accident conditions, the cask will not be effectively changed in dimensions, and it can be concluded that any number of such casks in any arrangement would remain subcritical.

6. QUALITY ASSURANCE

The regulations[1,2] require packaging to be designed, fabricated, and operated in compliance with an established formal quality assurance program. This compliance is discussed below.

6.1 Fabrication, Inspection, and Acceptance Tests

The fabrication work on these casks was performed prior to the requirements for a formal quality assurance program. The casks were fabricated by National Welding and Manufacturing Company of Newton, Connecticut, based on design by the Equipment Design Group of CANEL, a division of Pratt and Whitney Aircraft Corporation. The cask will be modified to improve its structural integrity and to enable it to comply with the thermal accident requirements of the regulations. The modifications have been designed by the Equipment Design Section of the ORNL General Engineering Division. The modifications will be made in ORNL Shops in accordance with normal shop fabrication procedures. Material was specified on the original drawings as "HR STL," any 300-series stainless steel, and lead. There are no inspection reports or material certifications in existence except as outlined below. Since fabrication, the containers have been in continuous use without failure, incident, or apparent loss of effectiveness.

Upon completion of the modifications, ORNL Inspection Engineering will inspect the containers. The modification will be done in accordance with ORNL quality assurance procedures. The inspection report will become part of the cask permanent quality assurance file.

The Specification 2R inner containers are designed as outlined in Sect. 1.7 and are fabricated in accordance with ORNL or equivalent quality assurance procedures. Welds are made by qualified welders and appropriately inspected. Material is purchased in accordance with ASTM or ASME specifications. The completed vessels are inspected for conformance to fabrication drawings and pressure tested (see Sect. 1.7). Reusable inner containers are inspected prior to each use.

Special form materials are fabricated to conform to the requirements of the regulations. Each encapsulation is leak checked by appropriate methods. Fuel element and experiment cladding is fabricated in accordance with established procedures; leak checking of such cladding is routinely done.

6.2 Operating Procedures and Routine Inspection

Operating and routine inspection procedures and standard checklists to ensure that all shipments are safe and comply with the regulations[1-3] have been prepared and are followed by the ORNL Operations Division. A copy of the procedures and the checklists are presented in Appendix F. When the cask is loaned to others, the checklists are forwarded to that organization.

6.3 Periodic Maintenance and Inspection

Annual inspections are performed by Hot Cell Operations and Inspection Engineering personnel, and an inspection is performed at the time of each shipment by operating personnel according to the procedures in Appendix F. Upon return to ORNL, the casks are again visually inspected to ensure that they are in good repair. Maintenance is required only when an inspection indicates damage.

REFERENCES

1. *Code of Federal Regulations*, Title 10, Part 71, "Transport of Licensed Materials."

2. *United States Atomic Energy Commission Manual*, vol. 0000, General Administration, Part 0500, Health and Safety, Chapter 0529, "Safety Standards for the Packaging of Radioactive or Fissile Materials," June 14, 1973.

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8. J. H. Evans, *Structural Analysis of Shipping Casks, Vol. 8, Experimental Study of the Stress-Strain Properties of Lead under Specified Impact Conditions*, ORNL/TM-1312 (August 1970).

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25. J. A. Swanson, *FEATS: A Computer Program for the Finite Element Thermal Stress Analysis of Plane or Axisymmetric Solids,* WANL-TME-1888, Westinghouse Electric Corporation, Astronuclear Laboratory, Pittsburgh, Pennsylvania (December 1968).

26. R. L. Cox, *A Computer Program for Calculating Temperatures Attained by LMFBR Fuels from Decay Heat Emission,* ORNL/TM-3773 (June 1973).

27. T. Rockwell, *Reactor Shielding Manual,* Van Nostrand, New York, 1956.

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Appendix A

AS-BUILT DRAWINGS

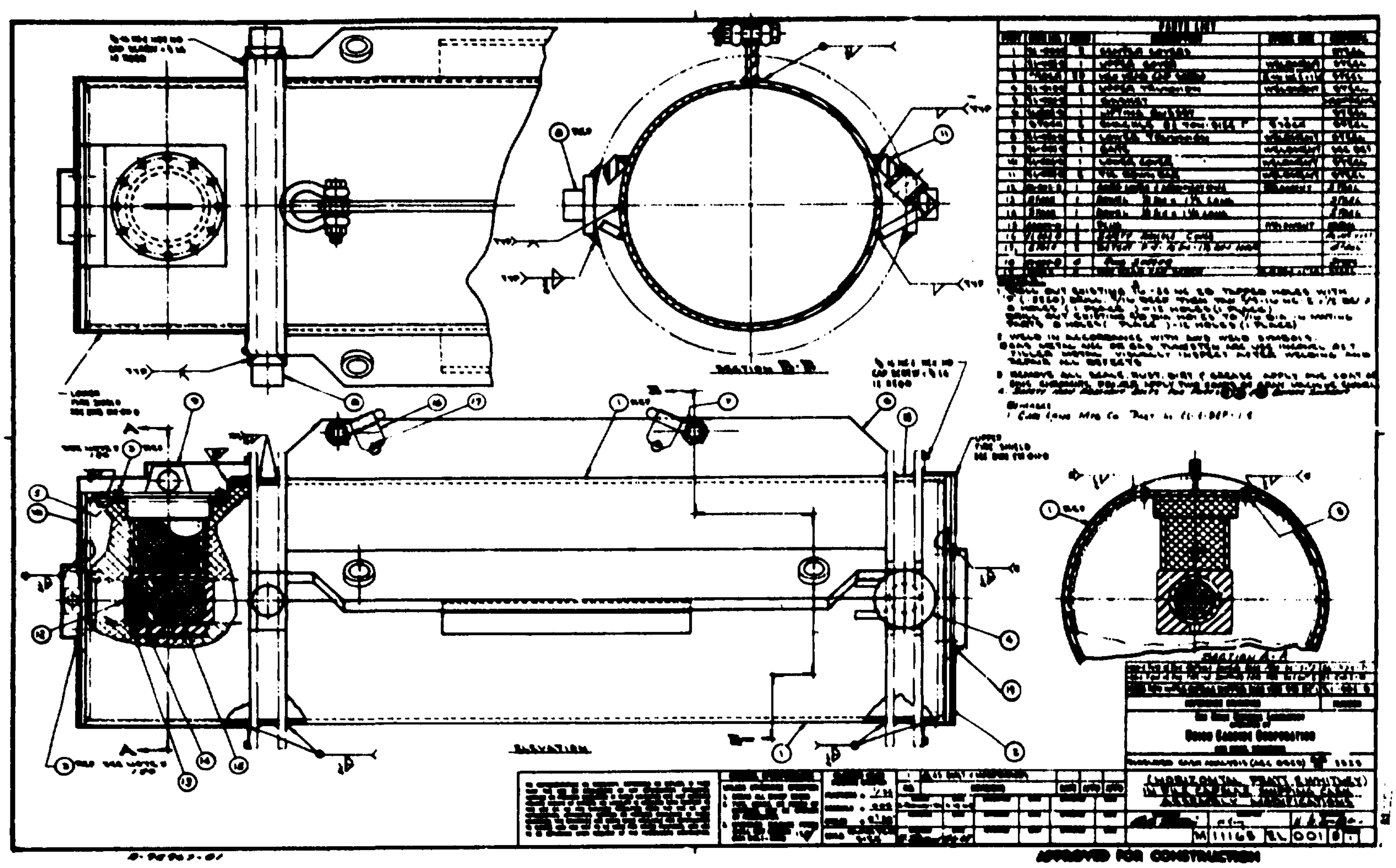

Fig. A.1. Horizontal Pratt & Whitney in-pile capsule shipping cask assembly, modifications.

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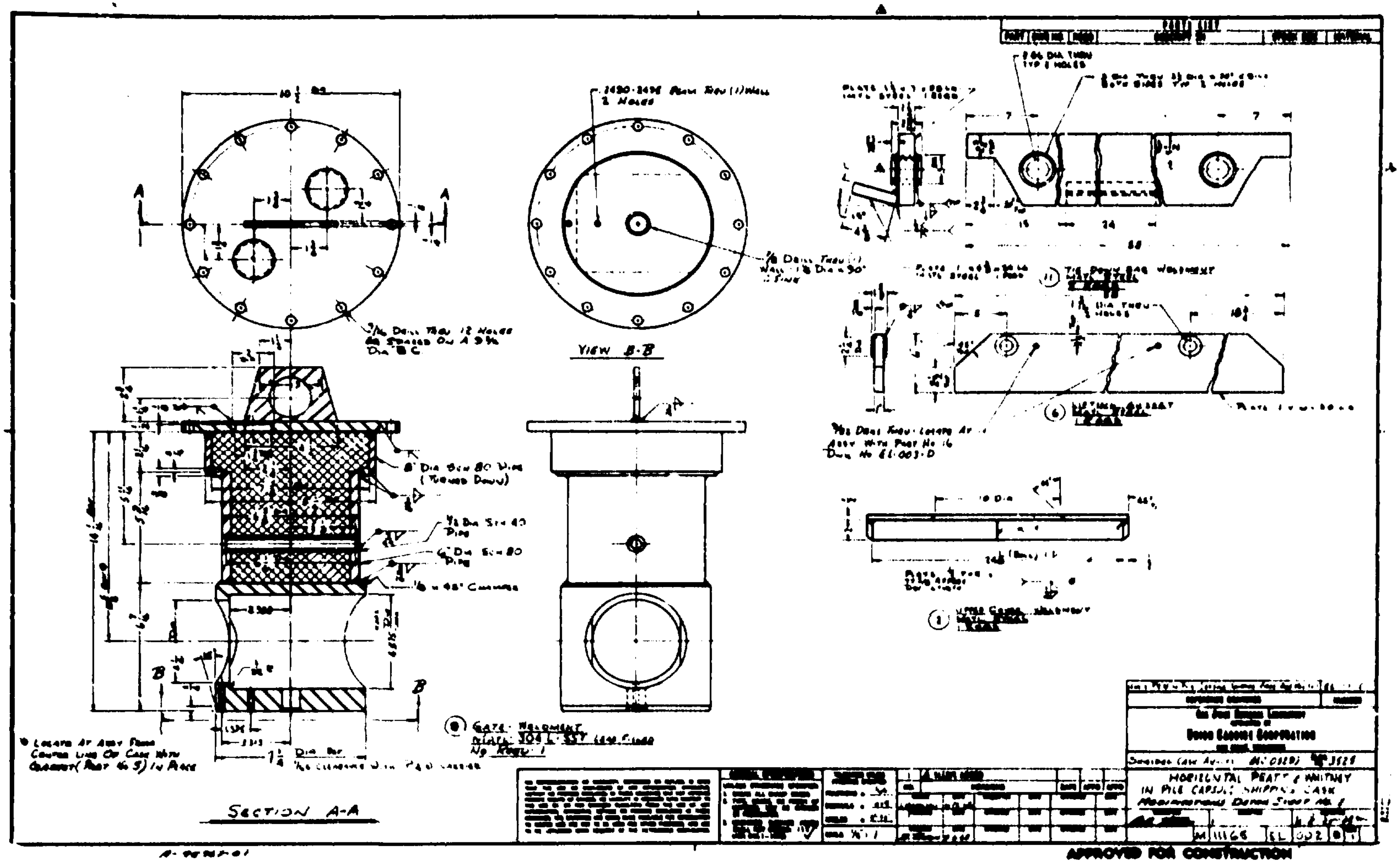

Fig. A.2. Horizontal Pratt & Whitney in-pile capsule shipping cask, modifications detail.

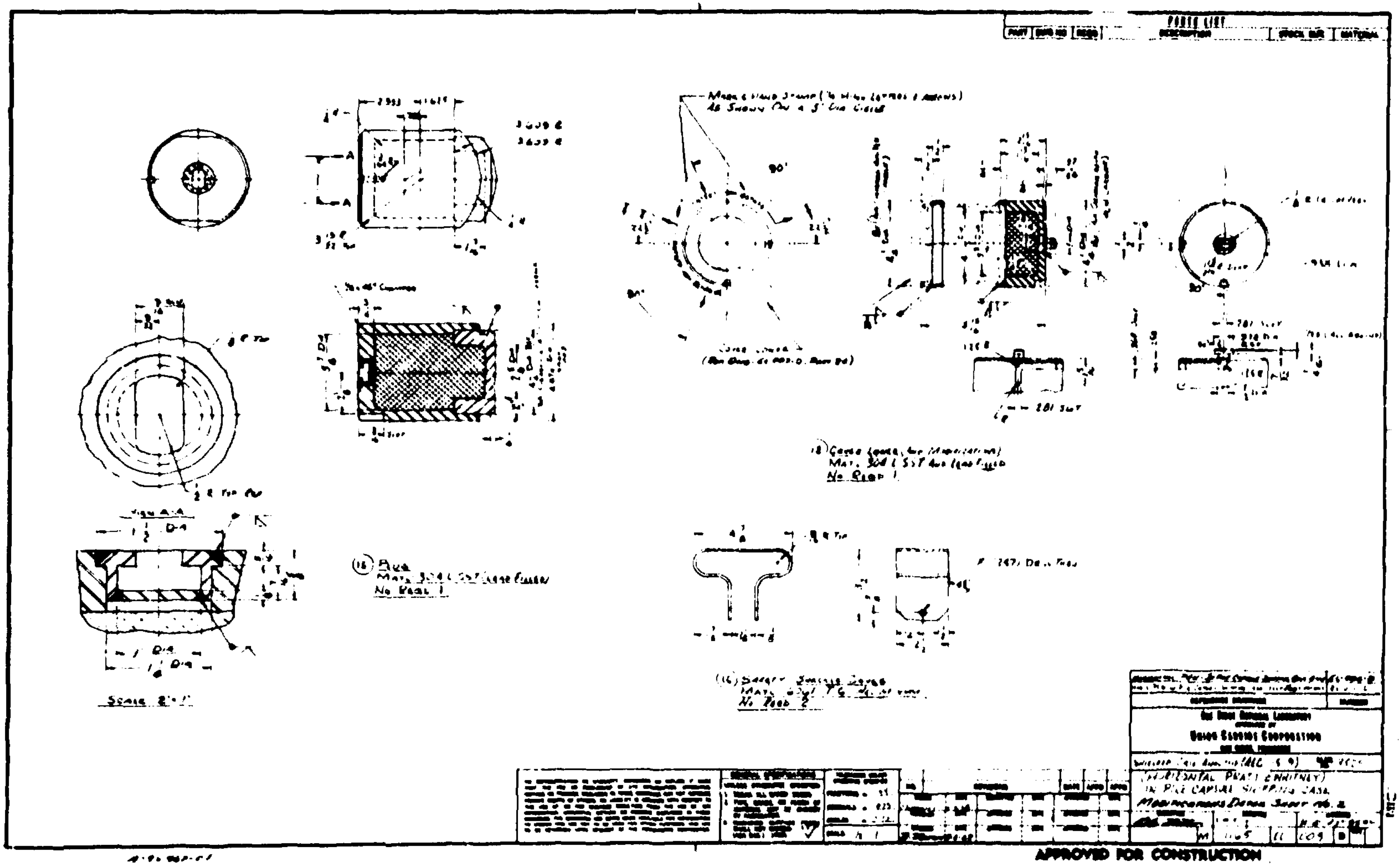

Fig. A.3. Horizontal Pratt & Whitney in-pile capsule shipping cask, modifications detail.

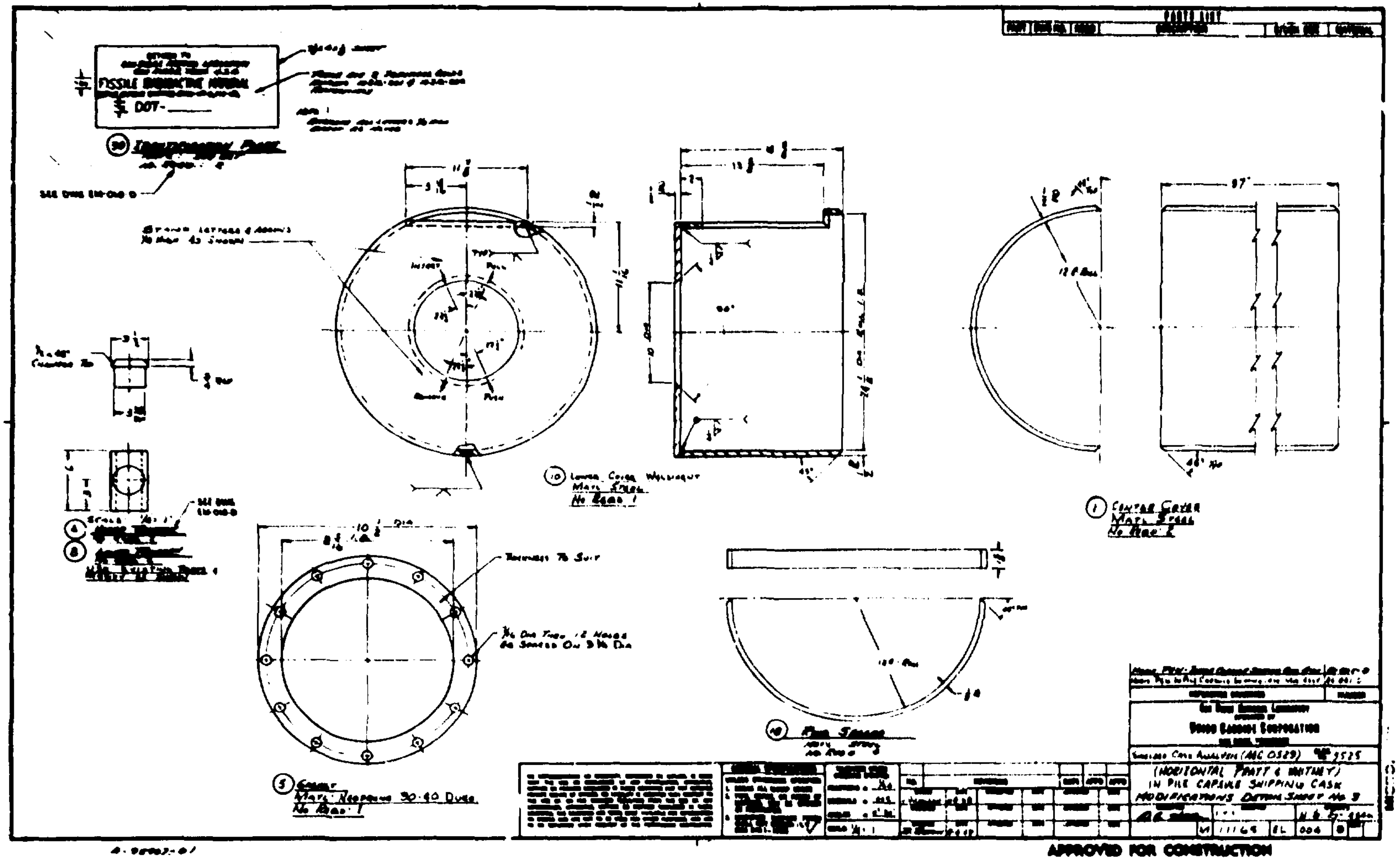

Fig. A.4. Horizontal Pratt & Whitney in-pile capsule shipping cask, modifications detail.

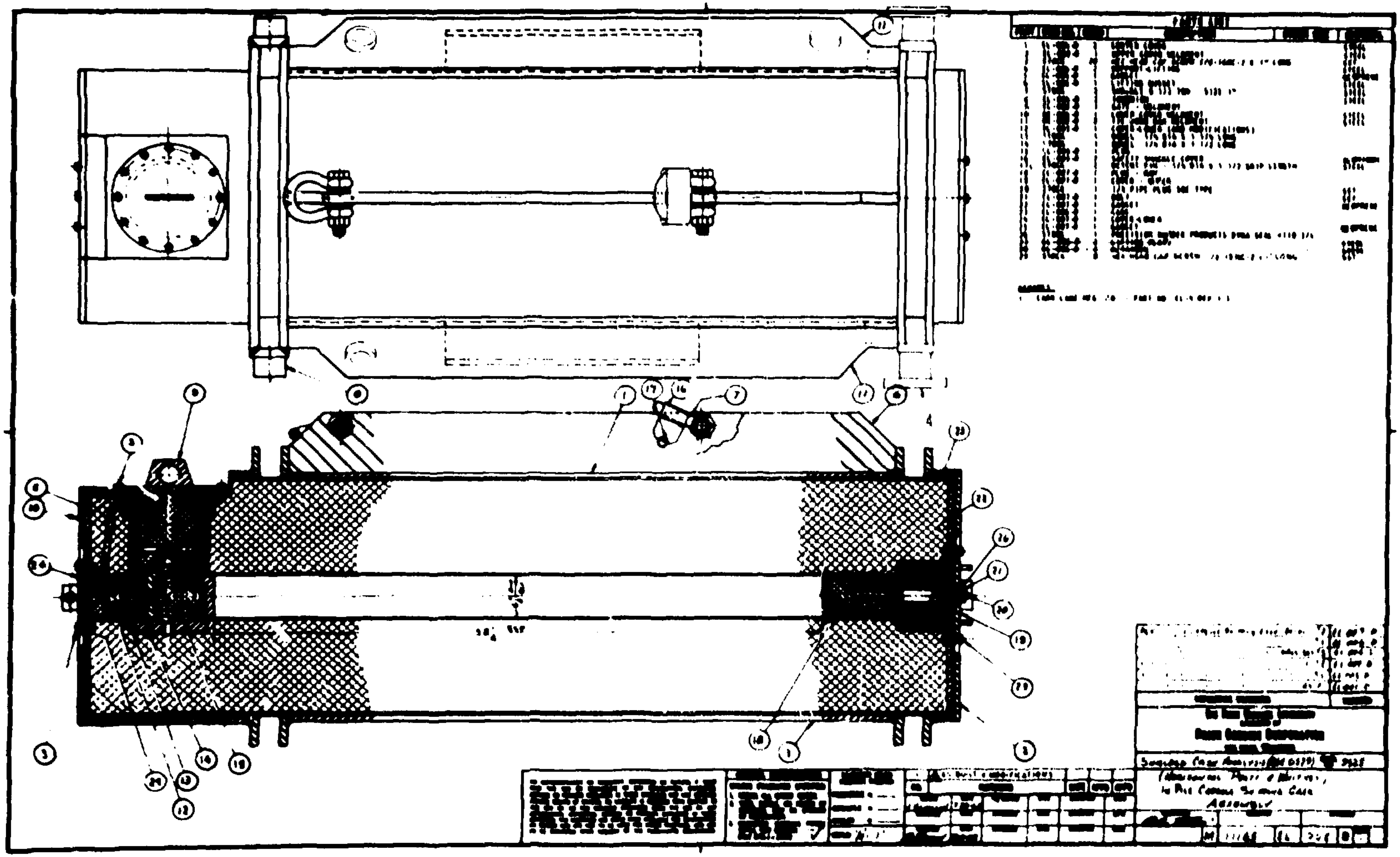

Fig. A.5. Horizontal Pratt & Whitney in-pile capsule shipping cask assembly.

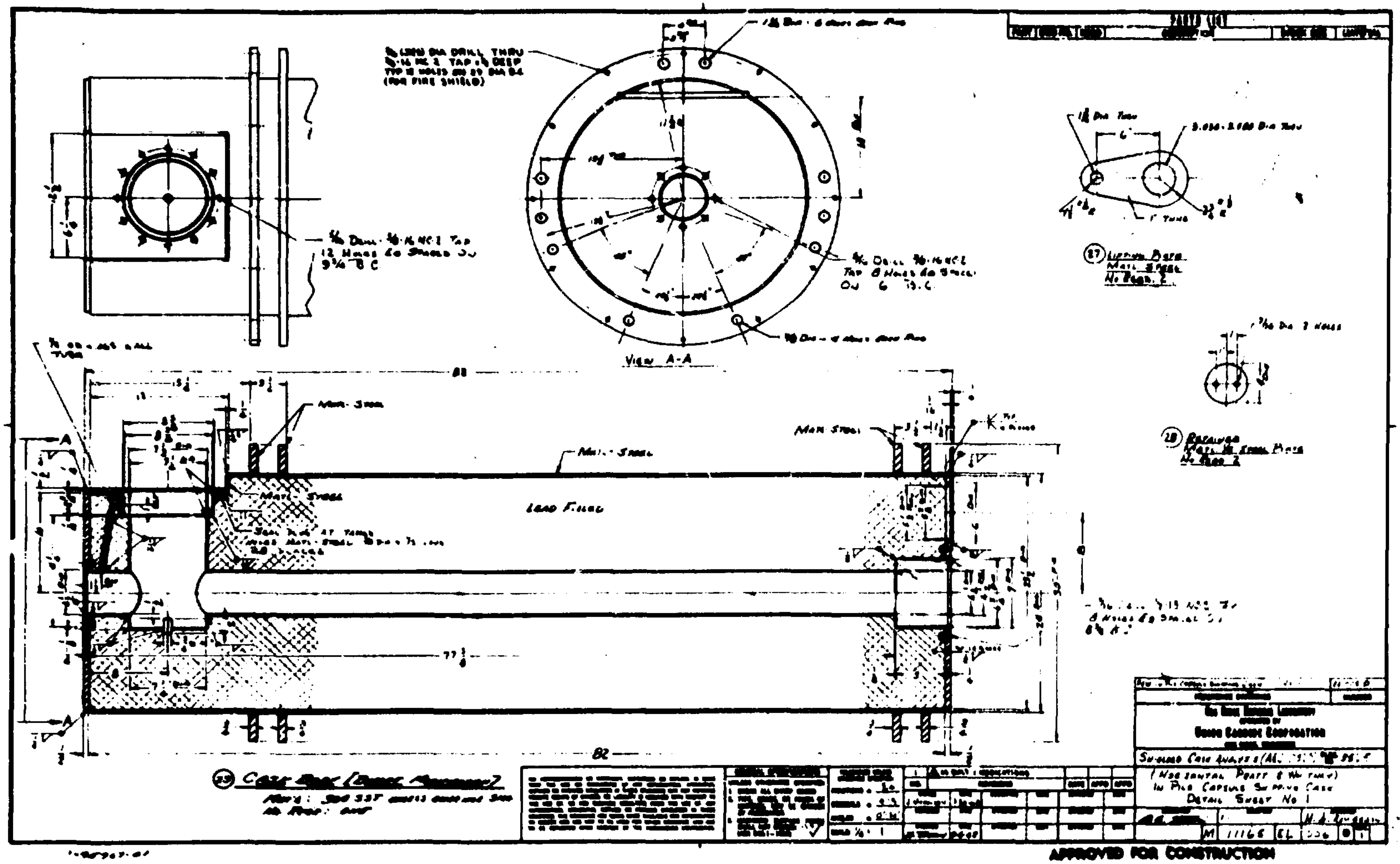

Fig. A.6. Horizontal Pratt & Whitney in-pile capsule shipping cask, detail.

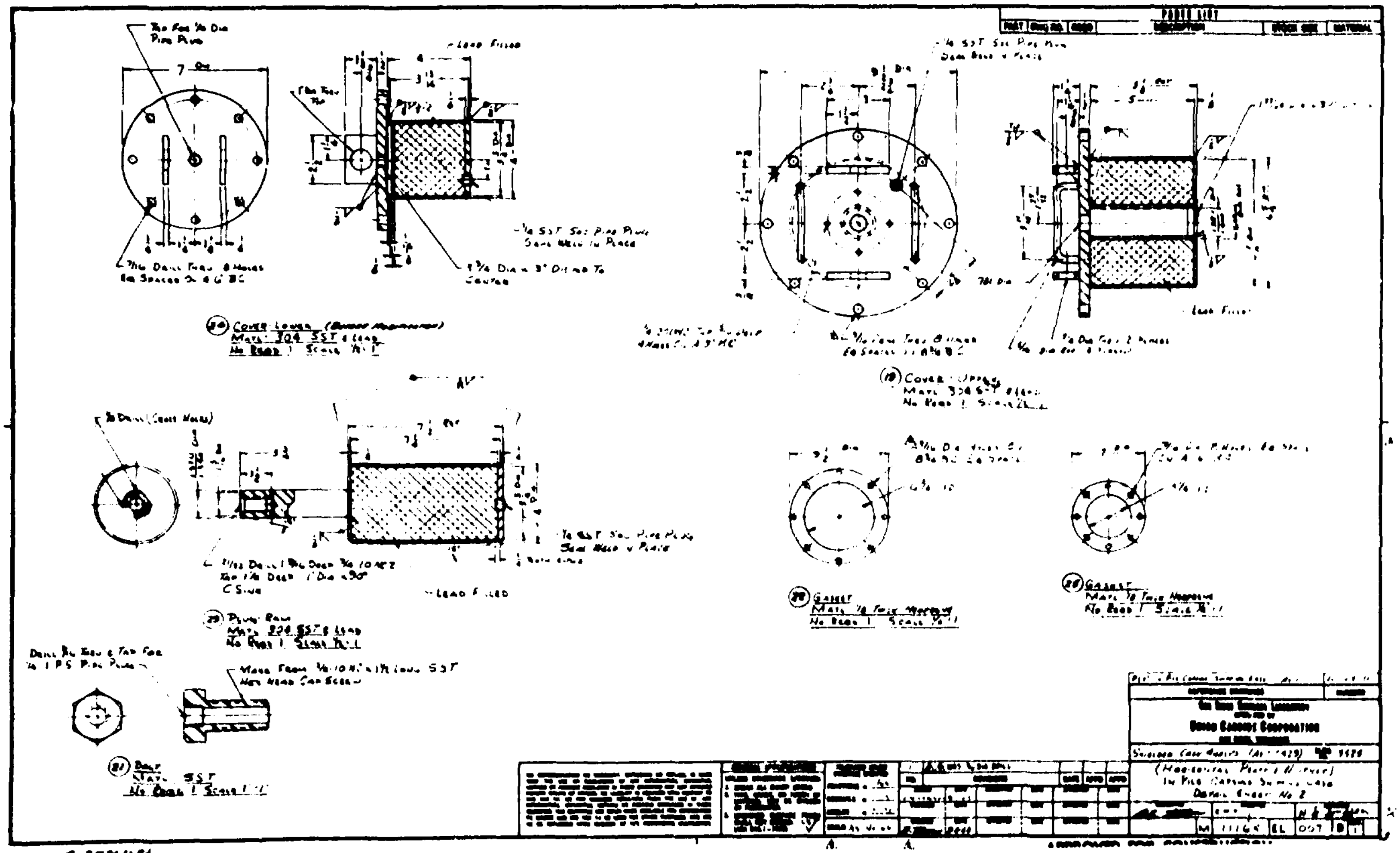

Fig. A.7. Horizontal Pratt & Whitney in-pile capsule shipping cask, detail.

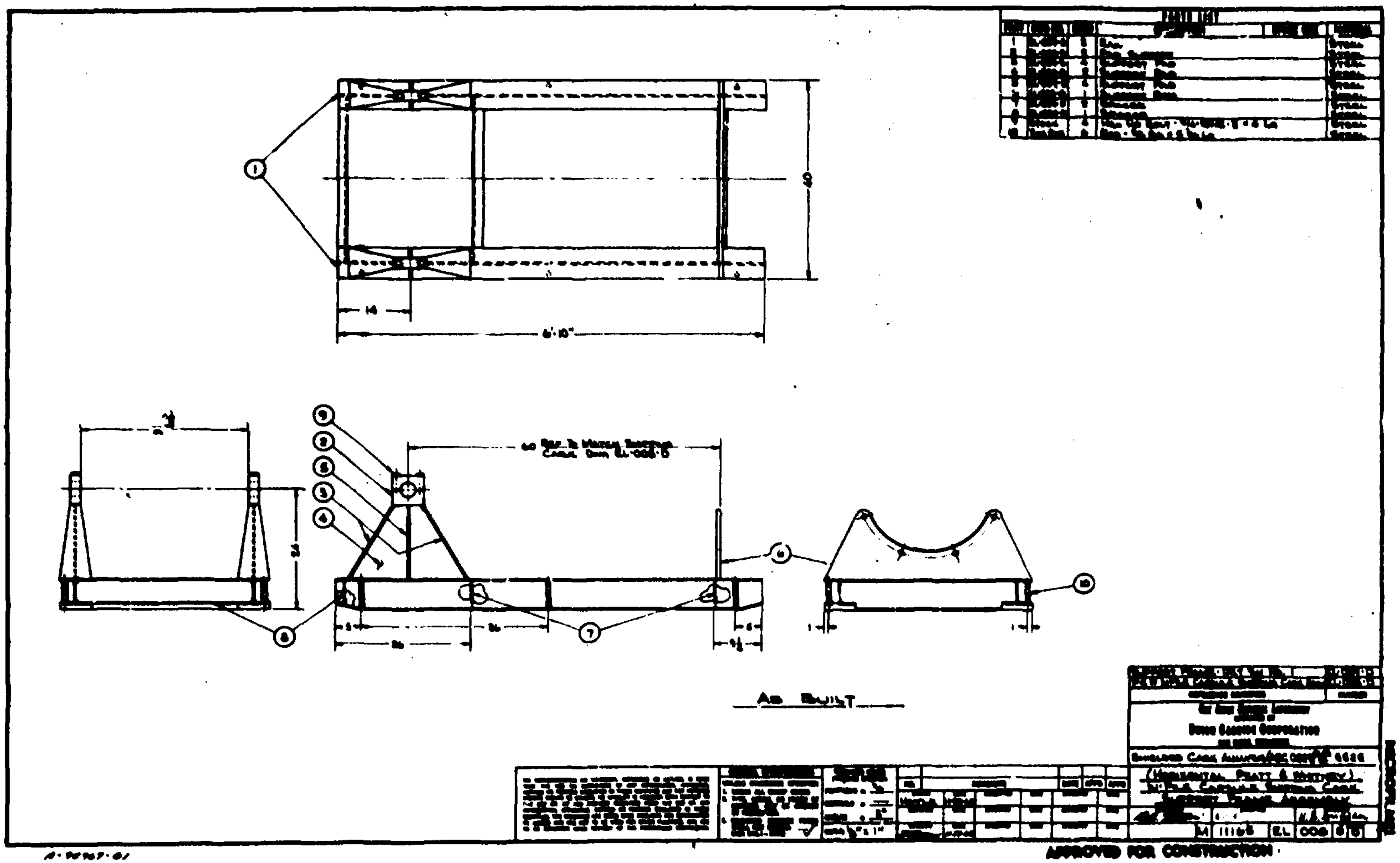

Fig. A.8. Horizontal Pratt & Whitney in-pile capsule shipping cask, support frame assembly.

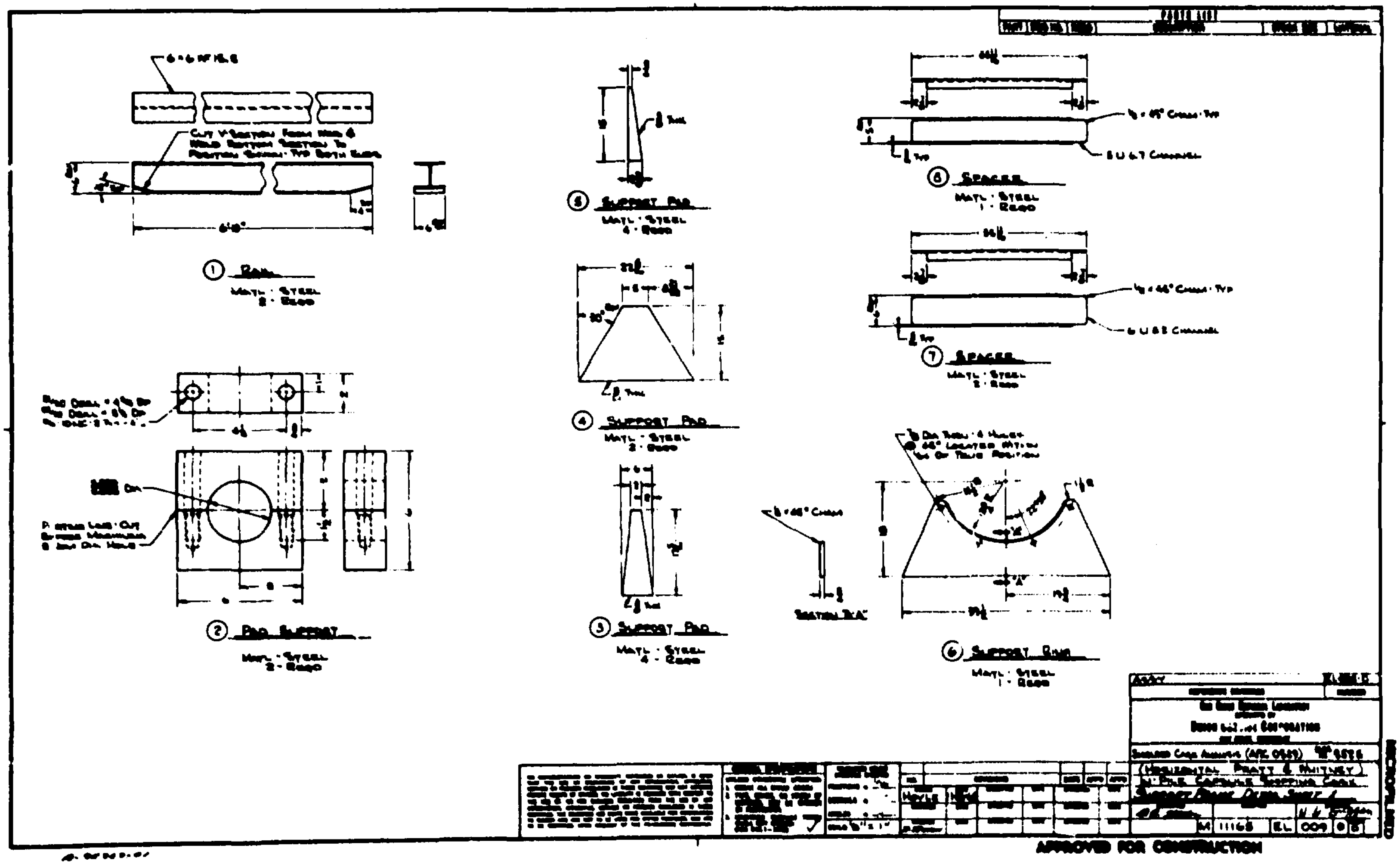

Fig. A.9. Horizontal Pratt & Whitney in-pile capsule shipping cask, support frame detail.

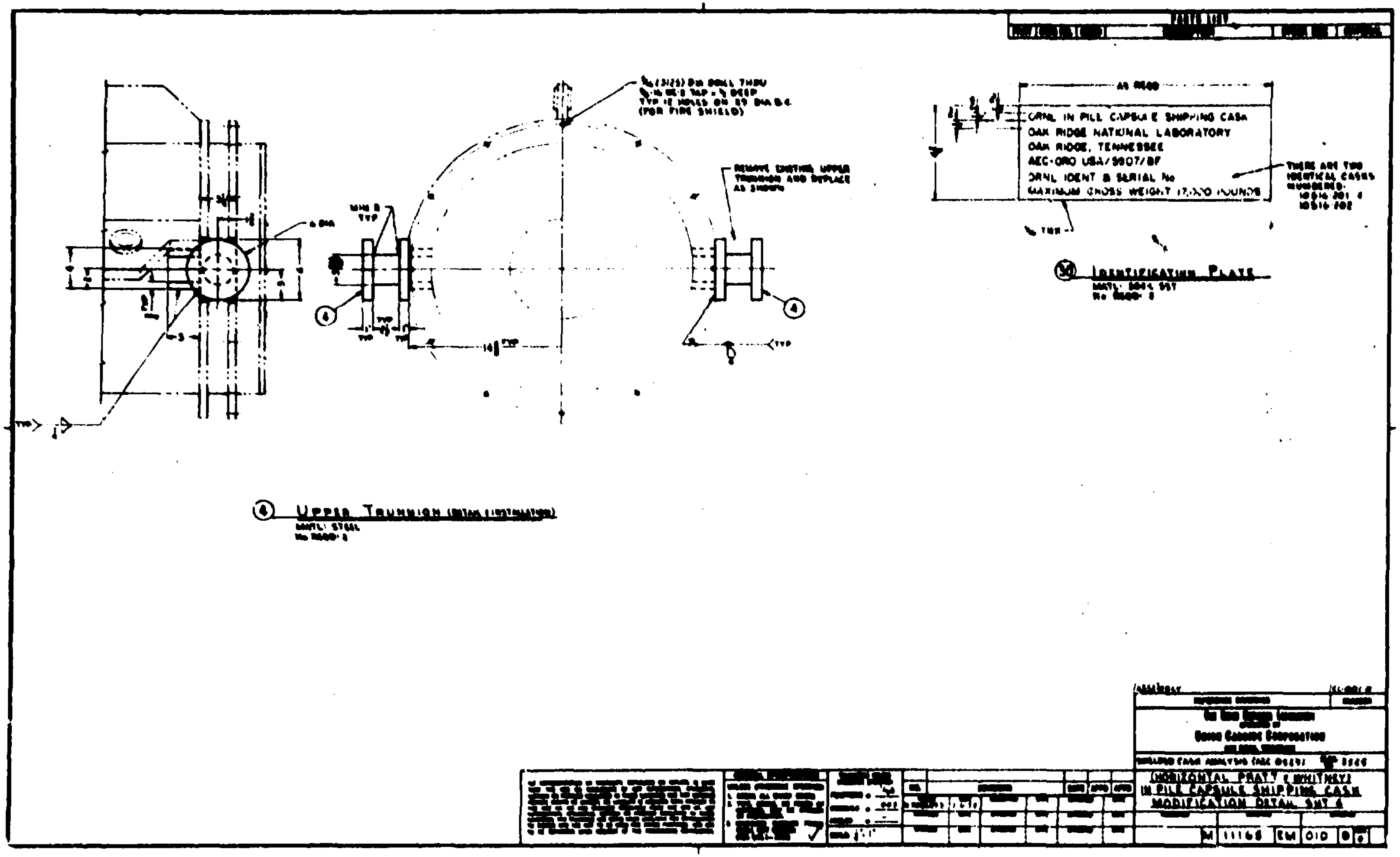

Fig. A.10. Horizontal Pratt & Whitney in-pile capsule shipping cask, modification detail.

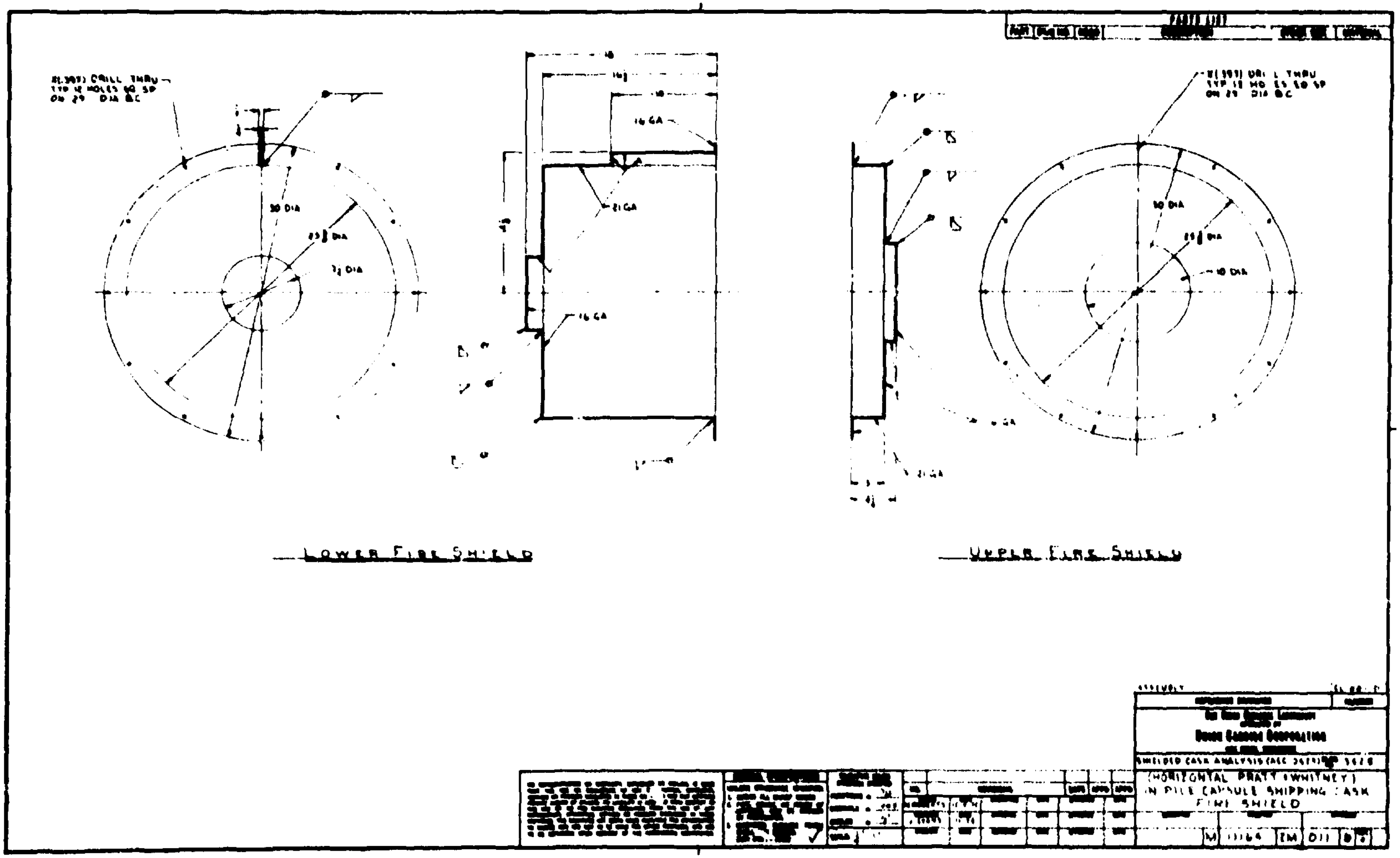

Fig. A.11. Horizontal Pratt & Whitney in-pile capsule shipping cask, fire shield.

Appendix B

APPROVAL DOCUMENTS

INTRA-LABORATORY CORRESPONDENCE
OAK RIDGE NATIONAL LABORATORY

June 10, 1975

TO: J. H. Evans, E. M. King

From: Transportation Committee

SUBJECT: Approval of SARP - ORNL In-Pile Capsule Shipping Cask

The ORNL Transportation Committee has reviewed the subject SARP in light of the requirements (internal review) of paragraph B of AEC Immediate Action Directive 5201-3. Particular attention was given to the areas of structural integrity, thermal resistance, radiation shielding, nuclear criticality safety, and quality assurance. This review did not necessarily consider editorial, typographical, or computational correctness, these matters being the responsibility of the authors and their sponsors.

It has been determined that the container meets the requirements of ERDAM 0529 and the SARP is approved for submission to the ERDA requesting a certificate of compliance and approval of the cask for use in offsite shipments of fissile and radioactive materials.

ORNL Transportation Committee

EMK:JNR:bb

cc: Transportation Committee

Form AEC-618
(12-73)
10 CFR 71
AECM 5201

U.S. ATOMIC ENERGY COMMISSION

CERTIFICATE OF COMPLIANCE

For Radioactive Materials Packages

1a. Certificate Number	1b. Revision No.	1c. Package Identification No.	1d. Page No.	1e. Total No. Pages
5907	1	USA/5907/BLF (DOE-OR)	1	2

2. PREAMBLE

2a. This certificate is issued to satisfy Sections 173.393b, 173.394, 173.395, and 173.396 of the Department of Transportation Hazardous Materials Regulations (49 CFR 170-189 and 14 CFR 103) and Sections 146-19-10a and 146-19-100 of the Department of Transportation Dangerous Cargoes Regulations (46 CFR 146-149), as amended.

2b. The packaging and contents described in item 5 below, meets the safety standards set forth in Subpart C of Title 10, Code of Federal Regulations, Part 71, "Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions."

2c. This certificate does not relieve the consignor from compliance with any requirement of the regulations of the U.S. Department of Transportation or other applicable regulatory agencies, including the government of any country through or into which the package will be transported.

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

(1) Prepared by (Name and address):

Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, Tennessee 37830

(2) Title and identification of report or application:

Safety Analysis for the ORNL In-Pile Capsule Shipping Cask

Report No: ORNL/ENG/TM-10

(3) Date: November 1977

4. CONDITIONS

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

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

(a) Packaging:

(1) Model No.: ORNL In-Pile Capsule Shipping Cask.

(2) Description:

Packaging for irradiated experimental capsules and spent fuel elements. Containment consists of the cladding or jackets of fuel elements or capsules or an inner container meeting DOT Specification 2R or special form. The inner cavity is 4 3/4 in. I.D. x 58 in. long. The cask is 24 in. O.D. x 83 in. long. Shielding consists of 9 1/2 in. of lead between a 1/8 in. thick stainless steel inner liner and a 0.75 in. total thickness, carbon steel outer shell. Access to the cavity is through:

(i) A sliding gate having 12 - 3/8" dia. closure bolts.
(ii) A lower plug having 8 - 3/8" dia. closure bolts.
(iii) An upper plug having 8 - 1/2" dia. closure bolts.

Each opening is gasketed with a neoprene gasket. The cask gross weight is 17,000 lb. The skid weighs 1,000 lb.

6a. Date of Issuance October 13, 1977

6b. Expiration Date

FOR THE U.S. ATOMIC ENERGY COMMISSION

7a. Address of Issuing Office:

Department of Energy
Post Office Box E
Oak Ridge, Tennessee 37830

7b. Signature, Name, and Title of Approving Official:

William H. Travis, Director
Safety & Environmental Control Division

(3) Drawings:

The cask was constructed in accordance with Pratt & Whitney Drawing CLR-10572-12 and modified in accordance with Oak Ridge National Laboratory Drawings M-11165-EL-001-D through -011-D.

(b) Contents:

(1) Type and Form of Material

Solid, large quantity of radioactive materials, fissile and non-fissile, encased in metal cladding, meeting special form or packaged in DOT Specification 2R inner container and whose decay heat load does not exceed 350 watts when shipped by common carrier. When shipped by exclusive use vehicle, the decay heat load will not exceed 1,000 watts.

(2) Maximum quantity of material per package

Fissile material is limited to 1250g per shipment; however, if the total quantity of fissile material exceeds 800g, the distribution of fissile material is further limited to 250g per linear foot.

(c) Fissile Class I

Appendix C

COMPUTER LISTING AND DERIVATION OF EQUATIONS

1. 1001 CASK
2. 1005 CASK
3. 1014 CASK
4. 1016 CASK

Program 1001 CASK
Derivation of Equations

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

The expression

$$dU - S\ dV\ ,$$

where

S = specific energy,

V = displaced volume of material,

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

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

$$dV - (1/2)XY\ dZ\ ,$$

where, by trigonometry,

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

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

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

It follows that

$$dU = SXY\ dZ/2\ ,$$

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

ORNL DWG 74-9726

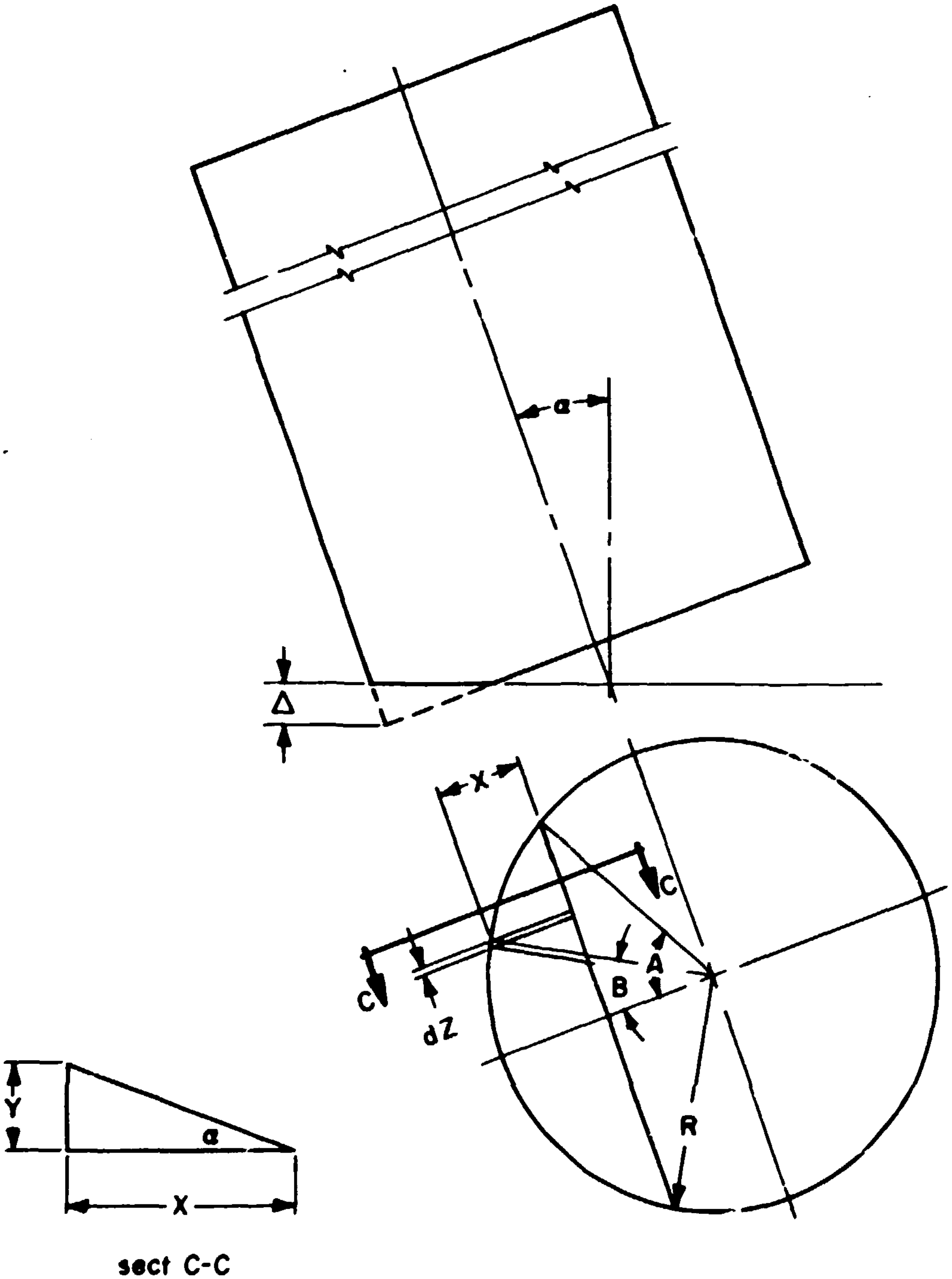

Fig. C.1. Computational diagram.

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. A is started small, incremented, and the energy required compared with the potential energy of the cask. In this manner a calculated impact history is produced. The program also computes other variables, using the expressions below:

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

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

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

or

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

where

V_o = initial velocity (fps),
M = cask mass ($\mathrm{lb \cdot sec^2/ft}$),
W = weight (lb),
h = drop height (ft),
g = gravitational constant ($\mathrm{lb_m \cdot ft/lb_f \cdot sec^2}$).

The time is computed from the relationship

$$a = dV/dT ,$$

or

$$dt = dv/a ,$$

and summary techniques.

```
**FTN,L,E,G.
C             PROGRAM NUMBER  1001-CASK
C  MADE OF A HOMOGENEOUS MATERIAL / AN IDEAL STRESS-STRAIN RELATIONSHIP
C  IMPACTING AN UNYIELDING SURFACE. THE CASK IMPACTS ON ITS CORNER
C  THIS PROGRAM COMPUTES THE RESPONSE OF A CASK HAVING RIGHT CYLINDRICAL
C  GEOMETRY.
C   BY JOHN EVANS P.E., GENERAL ENGINEERING DIVISION, OAK RIDGE NATIONAL LAB.
C
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              O=ANGLE AT WHICH CASK IMPACTS
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
      DIMENSION V(1000),AR(1000),F(1000),U(1000),T(1000),AN(1000),
     1 X(1000),AG(1000)
      PI=3.141596254
      S=0.0
      ANA = 0.0
C  INPUT MATERIAL CONSTANT
C  INPUT CASK GEOMETRY
      W=16000.
      C=84.
      R=12.5
 1010 FORMAT(1H ,30X,'O. R. N. L. IN PILE SHIPPING CASK')
      O=ATAN(2.*R/C)
      SM=0.0
      DO 90 M=1,5
      SM=1.+SM
      S=4000.+(2000.*SM)
C  INPUT TEST CONDITION
      H=36.0
      DO 20 NN=1,2
      IF(NN .NE. 1) H=360.
C  INPUT ANGLE INCREMENTS
   30 BB=.01
      AA=.01
      WRITE (51,1002)
      WRITE (51,1002)
      WRITE (51,1010)
      WRITE (51,1002)
      WRITE (51,1002)
C  ZERO SUBSCRIPTED VARIABLES
      DO 14 I=1,1000
      AN(I)=0.0
      AG(I)=0.0
      V(I)=0.0
```

```
      X(I)=0.0
      T(I)=0.0
      P(I)=0.0
      U(I)=0.0
      AR(I)=0.0
   14 CONTINUE
C  ZERO NONSUBSCRIPTED VARIABLES
      TA=0.0
      AE=0.0
      A=0.0
      AR=0.0
      TX=0.0
      U=0.0
      XX=0.0
      XA=0.0
      UT=W*H
      VV=SQRT((64.*H)/12.)
      DO 1 I=1,1000
      AR=0.0
C  INCREMENT ANGLE A
    9 A=A+AA
      CA=COS(A)
      B=0.0
      AE=0.0
      SUMU=0.0
   10 DO 2 J=1,1000
C  INCREMENT ANGLE B
      B=B+BE
      CB=COS(B)
C  CALCULATE VOLUME DISPLACED
   11 CC=(CB-CA)
      BY=TAN(O)*R*CC
      BX=R*CC
   12 DZ=R*CB*BB
      DU=BY*BX*DZ*S
C  CALCULATE ENERGY ABSORBED
      SUMU=SUMU+DU
C  CALCULATE AREA
   13 DA=2.*BX*DZ/COS(O)
      AE=AE+DA
      IF(B.GE.A) GO TO 3
    2 CONTINUE
    3 U(I)=SUMU
      IF(U(I).GE.UT) GO TO 4
      AR(I)=AE
C  CALCULATE FORCE
      F(I)=AR(I)*S
C  CALCULATE VELOCITY
    5 VA  =SQRT((64./(12.*W))*(UT-U(I)))
C CALCULATE ACCELERATION
      AG(I)=F(I)/W
C CALCULATE DEFORMATION
      XA  =(TAN(O)*COS(C)*R*(1.-CA))
      X(I)=XA
C CALCULATE TIME
      TX=(XA-XX)/((VV+VA)*6.)
    7 TA=TA+TX
```

```
      T(I)=TA*1000.
      XX=XA
    6 V(I)=VA
    8 VV=VA
      AN(I)=A*57.3
      IF(U(I).GE.UT) GO TO 4
    1 CONTINUE
    4 CONTINUE
C    OUTPUT-WRITE LOOP
      K=I-1
      WRITE (51,1002)
      WRITE(51,1004)
 1004 FORMAT (1H, 9X,37HCASK GEOMETRY AND MATERIAL PROPERTIES)
      WRITE (51,1002)
      WRITE(51,1005)
 1005 FORMAT (1H, 4X,6HRADIUS,8X,6HLENGTH,10X,6HWEIGHT,6X,
     1         15HSPECIFIC ENERGY)
      WRITE(51,1006)
 1006 FORMAT (1H, 4X,6HINCHES,8X,6HINCHES,10X,6HPOUNDS,8X
     1         13HLB-IN/CU. IN.)
      WRITE(51,1002)
 1002 FORMAT(1H0)
      WRITE(51,1007) R,C,W,S
 1007 FORMAT (F11.3,F14.3,F16.1,F18.1)
      WRITE(51,1002)
      WRITE(51,1000)
 1000 FORMAT (1H.,4X,11HDEFORMATION,4X,8HVELOCITY,7X,4HTIME,13X,5HFORCE,
     1         10X,6HENERGY,5X,12HACCELERATION)
      WRITE(51,1001)
 1001 FORMAT (1H, 6X,6HINCHES,7X,8HFT./SEC.,4X,12HMILLISECONDS,8X,
     1         6HPOUNDS,10X,6HLB-IN.,10X,3HX G)
      WRITE(51,1002)
      DO 15 I=1,K
      WRITE(51,1003) X(I),V(I),T(I),F(I),U(I),AG(I)
 1003 FORMAT(1H ,F14.4,F13.2,F16.5,F15.2,F16.2,F12.2)
   15 CONTINUE
      CALL QWIKPL(X,AG,K,'LINEAR','J.H.EVANS$')
   20 CONTINUE
   90 CONTINUE
      STOP
      END
```

Program 1005 CASK
Derivation of Equations

When a cylindrical cask fabricated from a homogeneous material impacts on its side, the deformation can be approximated as shown in Fig. C.2. The volume, V, of material displaced, shown shaded in Fig. C.2, 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 ideally plastic material, that is, one that 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

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

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. The deflection, X, is

$$X = R(1 - \cos\theta)\ .$$

The area, A, at the surface is

$$A = 2LR\sin\theta\ .$$

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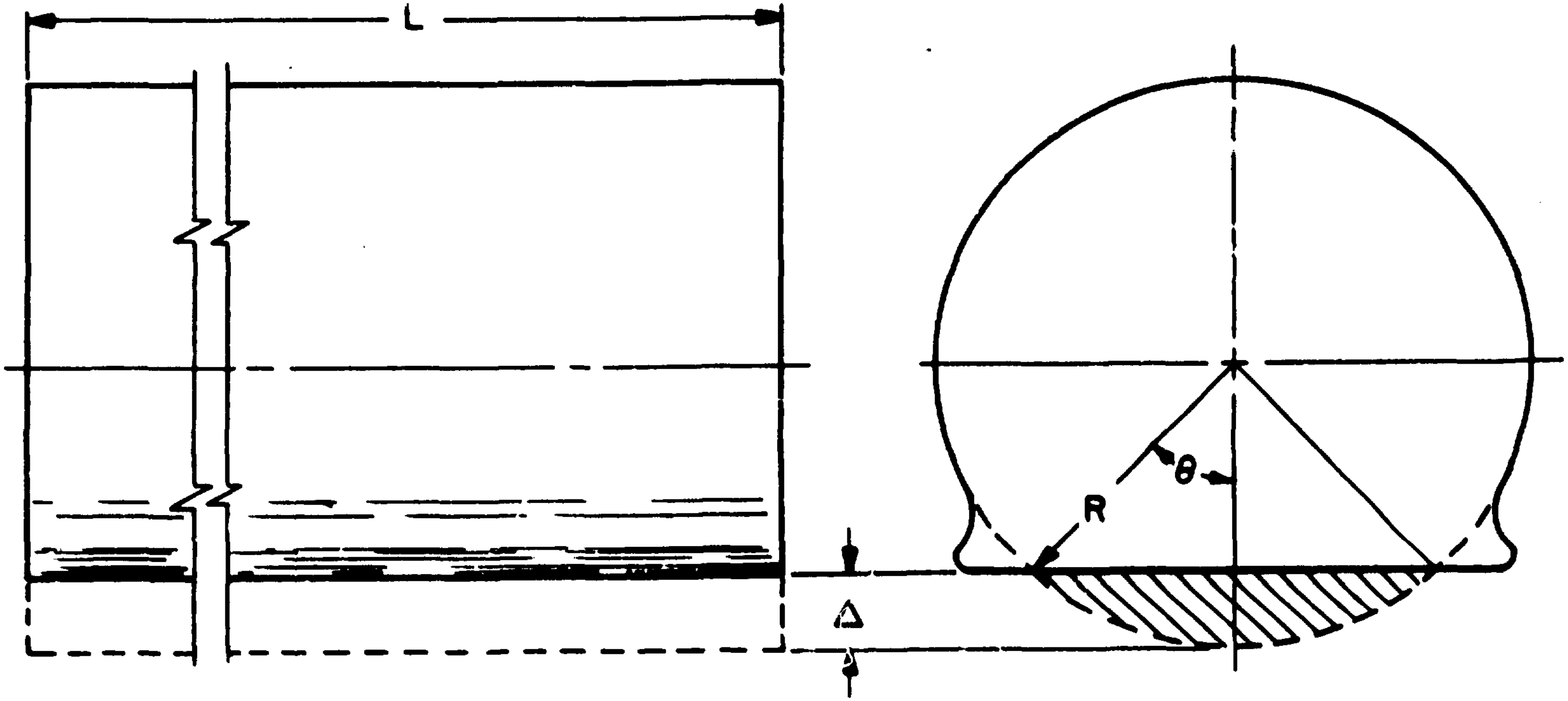

Fig. C.2. Cask model.

It follows that the force, F, is

$$F = SA ,$$

and the acceleration, a, is

$$a = F/M - Fg/W .$$

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

$$dt - dv/a .$$

```
**FTN,L,M,E,G,A.
C                    PROGRAM NUMBER 1005-CASK
C
C
C    THIS PROGRAM ANALYZES THE IMPACT OF A CASK HAVING RIGHT
C    CYLINDRICAL GEOMETRY, IMPACTING WITH ITS AXIS HORIZONTAL , CODED BY
C    JOHN EVANS P.E.,  GEN.ENGR. DIV. ORNL, JUNE 1973.
C
C
C
C
C                             GLOSSARY OF NOTATION
C
C                    X=DEFLECTION(INCHES)
C                    U=ENERGY(LB-INCHES)
C                    P=FORCE(POUNDS)
C                    AG=ACCELERATION(G'S)
C                    V=VELOCITY(FT/SEC)
C                    W=WEIGHT OF THE CASK(POUNDS)
C                    H=DROP HEIGHT(INCHES)
C                    C=CASK LENGTH(INCHES)
C                    R=CASK RADIUS(INCHES)
C                    O=ANGLE SUBTENDED BY THE DEFORMED AREA(RADIANS)
C                    UT=TOTAL POTENTIAL ENERGY OF THE CASK (LB-INCHES)
C                    T=SHELL THICKNESS (IN.)
C                    TH=HEAD THICKNESS,PLUG END (IN.)
C                    TAH=HEAD THICKNESS,BOTTOM END (IN.)
C                    W=CASK WEIGHT (POUNDS)
C                    SL=SPECIFIC ENERGY OF SHIELDING MATERIAL  (IN-LB/CU.IN)
C                    SC=SPECIFIC ENERGY OF CLADDING IN COMPRESSION (IN-LB/CU IN)
C                    OO=INCREMENT OF ANGLE O
C                    TM=TIME (SEC.)
C                    G=ACCELERATION (FT/SEC/SEC)
C                    VL=VOLUME OF SHIELDING DISPLACED (CU.IN.)
C                    UH=ENERGY DISSIPATED IN DEFORMING THE HEADS  (IN.LB.)
C                    UL=ENERGY DISSIPATED IN DISPLACING SHIELDING (IN.LB.)
C                    ZZ=ENERGY DISSIPATED IN DEFORMING COOLING FINS(IN-LB)
C
      DIMENSION U(1000),X(1000),P(1000),G(1000),AG(1000),TM(1000)
     1,AP(1000),V(1000)
      ZZ=0.
C  INPUT CASK GEOMETRY
      TH=0.0
      TAH=0.0
      T=.75
      W=16000.
      R=12.5
      CL=58.
      DO 99 NN=1,2
C  INPUT TEST CONDITION
      H=36.
      IF(NN.NE.2) GO TO 98
      H=360.
   98 CONTINUE
C    CALCULATE CASK POTENTIAL ENERGY
      UT=W*H - ZZ
C    INPUT INCREMENT OF ANGLE,O
```

```
      OO=.01
C  INPUT MATL. PROPERTIES
      DO 90 M=1,2
      SL=4000.
      SC=100000.
      IF(M.EQ.1) GO TO 91
      SL=10000.
      SC=240000.
   91 CONTINUE
C    ZERO SUBSCRIPTED VARIABLES
      DO 1  I=1,1000                                                    1
      X(I)=0.0                                                          1
      U(I)=0.0                                                          1
      TH(I)=0.0
      G(I)=0.0
      P(I)=0.
      AG(I)=0.0                                                         1
      AP(I)=0.0                                                         1
      V(I)=0.0                                                          2
    1 CONTINUE                                                          1
C    ZERO NONSUBSCRIPTED VARIABLES
      UL=0.0
      UH=0.0
      DT=0.0
      TS=0.0
      PU=0.0
      VV=0.0                                                            3
      UU=0.0                                                            3
      PP=0.0
      XX=0.0                                                            3
      O=0.0
      V(1)=SQRT((64.*H/12.))
      VV=V(1)
      DO 2 I=1,1000
      IF(I.EQ.1) GO TO 21
      O=O+OO                                                           10
      SO=SIN(O)
      SOO=SIN(2.*O)/2.
      CO=COS(O)
C  CALCULATE VOLUME OF SHIELDING DISPLACED
C  EQUATION 1
      VL=(R*R*CL*(O-SOO))                                             EQ.
C  CALCULATE ENERGY DISSIPATED IN DISPLACING SHIELDING
C  EQUATION 2
      UL=SL*VL                                                        EQ.
C  EQUATION 6
      QO=O-SOO                                                        EQ.
C  EQUATION 12
      VH=(TH+TAH)*R*R*QO
C  EQUATION 13
      UH=SC*VH                                                       EQ.
      ARL=2.*R*SO*CL
      FORL=ARL*SL
      ARH=2.*R*SO*(TH + TAH)
      FORH=ARH*SC
      U(I)=UH + UL
C    COMPUTE DEFORMATION
```

```
      X(I)=R*(1.-CO)                                                     10
C     COMPUTE APPLIED FORCE
      P(I)=FORL + FORH
C     COMPUTE ACCELERATION
      G(I)=(P(I)*32.2)/W
      AG(I)=P(I)/W
      IF(U(I).GT.UT) GO TO  7
C     COMPUTE VELOCITY
    8 V(I)= SQRT((UT-U(I))*(64./(W*12.)))                                11
    7 CONTINUE
C     COMPUTE LAPSED TIME
      DT=0.
      IF(G(I)  .NE. 0.) DT=(VV-V(I))/G(I)
      TS=TS+DT                                                           11
      TM(I)=TS*1000.
C     COMPUTE PERCENTAGE ENERGY STORED
      PU=U(I)/UT
   21 CONTINUE
    5 XX=X(I)                                                            15
      UU=U(I)                                                            15
      VV=V(I)                                                            15
      PP = P(I)
      IF(U(I).GE.UT) GO TO 4                                             16
    2 CONTINUE                                                           16
    4 CONTINUE                                                           16
      J=I - 1
C     OUTPUT-WRITE LOOP
      WRITE(51,1009)
      WRITE(51,1009)
      WRITE(51,1002)
      WRITE(51,1008)
 1008 FORMAT(1H ,25X,'O. R. N. L. IN PILE SHIPPING CASK')
      WRITE(51,1002)
      WRITE(51,1009)
      WRITE(51,1009)
      WRITE(51,1002)
      WRITE(51,1004)
      WRITE(51,1002)
      WRITE(51,1005)
      WRITE(51,1006)
      WRITE(51,1002)                                                 11A 18
 1002 FORMAT(1H0)                                                    11B 19
 1004 FORMAT(1H ,30X,13HCASK GEOMETRY)
 1005 FORMAT (1H ,4X,6HRADIUS,9X,6HLENGTH,8X,10HSHELL THK.,5X,
     1        9HHEAD THK.,5X,9HHEAD THK.,7X,6HWEIGHT,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)
      WRITE(51,1007) R,CL,T,TH,TAH,W,SL
 1007 FORMAT(1H ,F10.3,4F15.3,F15.1,F12.0)
      WRITE(51,1002)                                                 11A 18
      WRITE(51,1009)
      WRITE(51,1009)
      WRITE(51,1002)
      WRITE(51,1000)
 1000 FORMAT (1H ,4X,11HDEFORMATION,4X,8HVELOCITY,7X,4HTIME,13X,5HFORCE,      1
     1        10X,6HENERGY,5X,12HACCELERATION)
```

```
      WRITE(51,1001)                                                       1
 1001 FORMAT (1H ,6X,6HINCHES,7X,8HFT./SEC.,4X,12HMILLISECONDS,8X,
     1         6HPOUNDS,10X,6HLB-IN.,10X,3HX G)                            1
      WRITE(51,1002)                                                  11A 18
 1009 FORMAT(1H, X,49H*************************************************,
     1        55H*******************************************************,
     2        14H**************)
      DO 11 I=1,J
      WRITE(51,1003) X(I),V(I),TM(I),P(I),U(I),AG(I)
 1003 FORMAT(1H ,F12.4,F13.2,F15.4,F18.2,F16.2,F12.2)
   11 CONTINUE                                                             10
      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
   99 CONTINUE
      STOP
      END
```

Program 1014 CASK
Derivation of Equations

The model shown in Fig. C.3 illustrates the general case of a cask equipped with an energy absorber which deforms in pure compression. If the force-deformation curve for the absorber is taken as shown in Fig. C.4, 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 an amount δ_n. It follows that

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

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

$$N\delta = X_n \ .$$

The deformation X_n may be written

$$X_n = \varepsilon_n L - N\delta \ .$$

Solving for ε_n, we have

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

There exists an expression

$$\sigma_i = f(\varepsilon_i) \ ,$$

where

σ = stress,

ε = strain,

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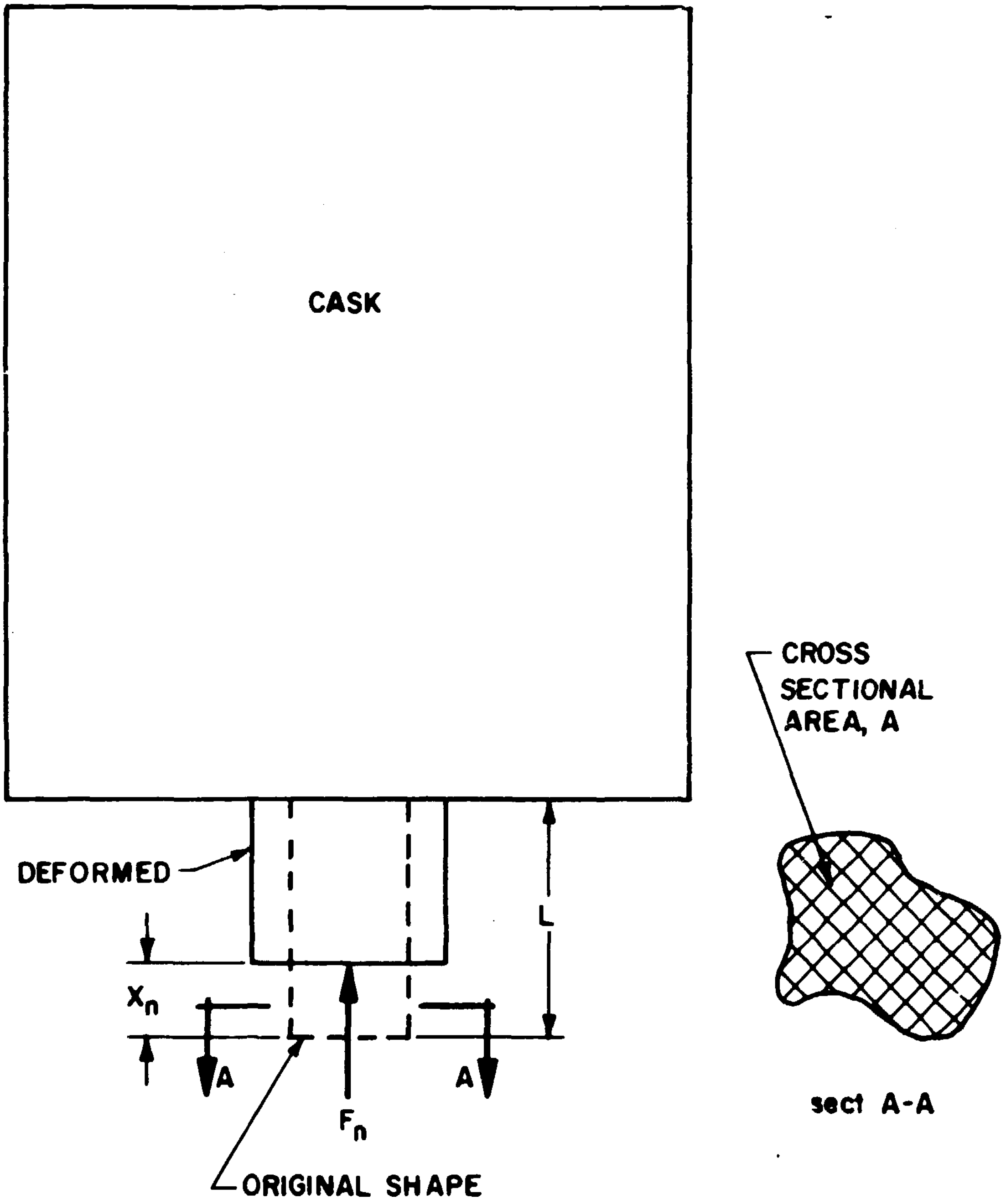

Fig. C.3. Cask model.

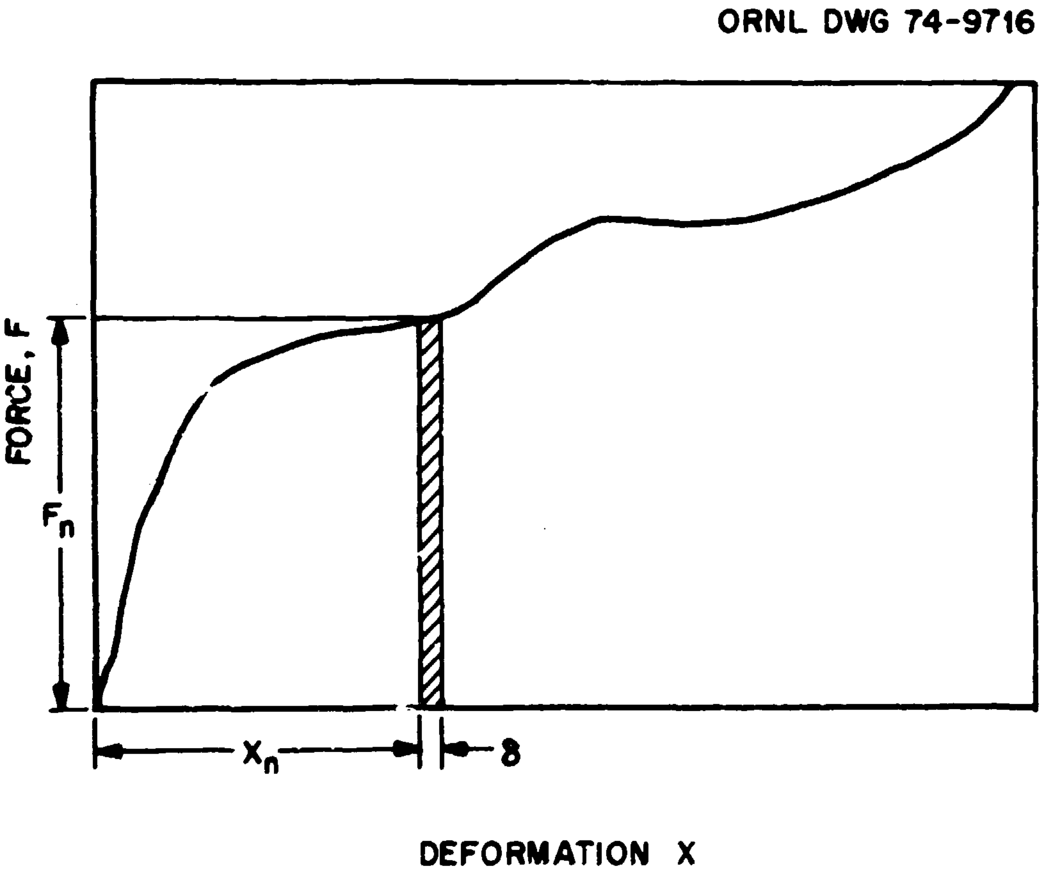

Fig. C.4. Force deflection curve.

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,

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

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 toroidal absorbers (see Fig. C.5c) and for rectangular absorbers (see Fig. C.5b and 5c) having a constant thickness. In the case of the toroidal absorber, the radius and thickness depth must be inserted in statement numbers 70, 71, and 72. For a rectangular absorber, the thickness, depth, and length must be inserted in statement numbers 71, 72, and 73. For absorbers of other geometry, the area must be computed by hand as 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 input is SST for 300 annealed series stainless steel and STL for mild steel. If a finer or coarser mesh is desired, the value of DE in statement 60 may be decreased or increased. The 1000 format should be altered to identify the cask.

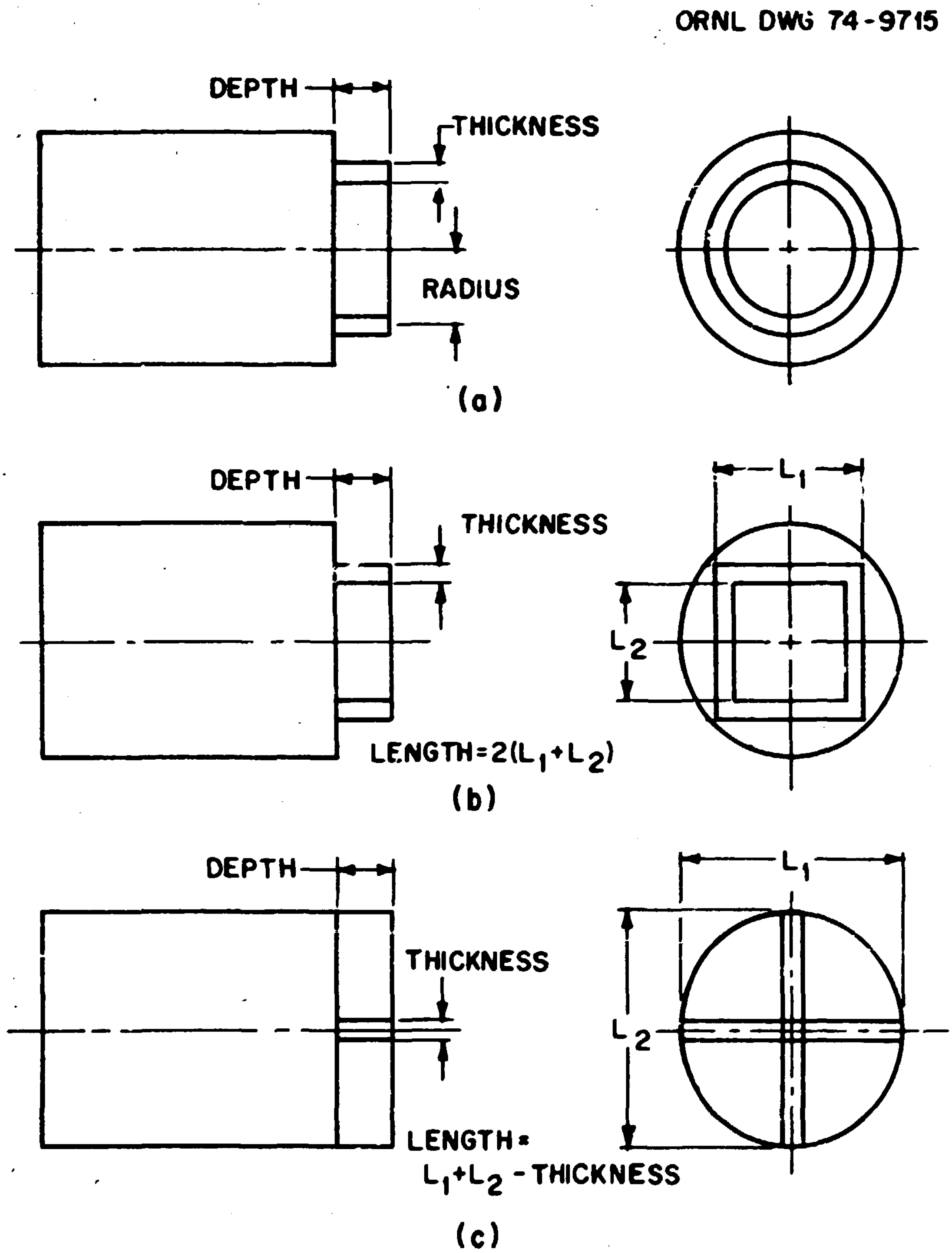

Fig. C.5. Typical absorbers.

```
@FTN,L,M,E,G,A.
C                        PROGRAM 1014 CASK
C THIS PROGRAM COMPUTES THE RESPONSE OF A RIGID CASK EQUIPPED WITH AN ENERGY,
C ABSORBER WHICH DEFORMS IN PURE COMPRESSION CODED BY JOHN EVANS PE ,OAK RIDGE
C NATIONAL LABORATORY, JUNE 1974
C                       GLOSSARY OF NOTATION
C
C               EE=AMOUNT STRAIN IS INCREMENTED-IN./IN.
C               S=STRESS PSI
C               DEF=ABSORBER DEFORMATION IN.
C               DU=DIFFERENTIAL ENERGY  IN.LB.
C               FORC=FORCE LB.
C               ENER=ENERGY DISSIPATED IN DEFORMING THE ABSORBER IN.LB.
C               ACC=ACCELERATION X G
C               STL=STEEL MILD OR LOW CARBON
C               SST=STAINLESS STEEL 300 SERIES
C               ALUM=ALUMINUM TYPE 6061-T6
C               DE=STRAIN IN./IN.
C               DS=STRAIN IN./IN.
C               AMATL=ABSORBER MATERIAL
C               WT=CASK WEIGHT LB.
C               RAD=ABSORBER RADIUS IN.
C               THK=ABSORBER THICKNESS IN.
C               TLEN=ABSORBER LENGTH IN.
C               DEPH=ABSORBER DEPTH IN.
C               AREA=ABSORBER AREA SQ.IN.
C               DL=CHANGE IN ABSORBER LENGTH IN.
C               A,B,C,D,E,E,G,H,O,P,Q,R=CONSTANTS IN THE STRESS EQUATION
C               HT=DROP HEIGHT IN.
                UT=CASKS TOTAL POTENTIAL ENERGY IN.LB.
C
      DIMENSION  DE(200),S(200),DEF(200),DU(200),FORC(200),ENER(200),
     2 ACC(200)
 1001 FORMAT (1H0)
 1002 FORMAT(1H ,1X,49H*************************************************,
     1       55H*******************************************************,
     2       14H**************)
 1003 FORMAT(1H ,23X,24HENERGY ABSORBER GEOMETRY)
 1004 FORMAT(1H ,12X,6HRADIUS,3X,9HTHICKNESS,3X,5HDEPTH,4X,6HLENGTH,5X,
     1    4HAREA)
 1005 FORMAT(1H ,F18.3,4F10.3)
 1006 FORMAT (1H ,16X,33HCASK GEOMETRY AND TEST CONDITIONS)
 1007 FORMAT(1H ,12X,11HCASK WEIGHT,3X,11HDROP HEIGHT,3X,9HPOTENTIAL,
     1       X, 6HENERGY)
 1008 FORMAT(1H ,F21.1,F14.1,F17.1)
 1009 FORMAT (1H , 1X,12HACC3LERATION,2X,11HDEFORMATION,6X 5HFORCE,6X,
     1    6HSTRESS,6X,6HSTRAIN,8X,6HENERGY)
 1010 FORMAT (1H , 5X,3HX G,10X,6HINCHES, 9X,4HLBS.,7X,4HPSI., 9X,
     1    5HIN/IN,9X,5HLB-IN)
 1011 FORMAT (1H ,F10.1,F13.3,F16.1,F12.1,F11.3,F12.1)
      DO 7, I=1,200
      DE(I)=0.0
      S(I)=0.0
      DEF(I)=0.0
      DU(I)=0.0
      FORC(I)=0.0
      ENER(I)=0.0
```

```
    7 ACC(I)=0.0
      SST=1.0
      STL=2.0
      ALUM=3.0
   60 EE=.005
      DS=0.0
C  INPUT ABSORBER MATERIAL
   88 AMATL=STL
C  INPUT RADIUS
   70 RAD=0.0
C  INPUT ABSORBER LENGTH
   73 TLEN=54.5
C  INPUT CASF WEIGHT
   80 WT=16000.
C  INPUT THICKNESS
   71 THK=1.0
C  INPUT ABSORBER DEPTH
   72 DEPH=6.0
C  INPUT ABSORBER AREA
   74 AREA=0.0
C   INPUT CASK IDENTIFICATION
 1000 FORMAT(1H ,8X,'O. R. N. L. INPILE CAPSULE SHIPPING CASK')
C  INCREMENT DEFORMATION
      DL=EE*DEPH
      PHI=3.14159265
      IF(RAD .GT. 0.) AREA=2.*RAD*PHI*THK
      IF(TLEN .GT. 0.) AREA=TLEN*THK
C  INPUT DROP HEIGHT
      IF(AMATL.NE.2.0) GO TO 6
    MILD STEEL COEFFICIENTS
      A=-4.36337724E+02
      B=3.52674012E+06
      C=-5.84344912E+07
      D=8.44752080E+08
      E=-1.00790838E+10
      F=8.32241264E+10
      G=-4.42875864E+11
      H=1.50685484E+12
      O=-3.25535392E+12
      P=[illegible].31754272E+12
      Q=-3.20487884E+12
      R=1.01910658E+12
      AA=0.5
      AB=345000.
      AC=73000.
    6 CONTINUE
      IF(AMATL.NE.1.0) GO TO 5
C   STAINLESS STEEL COEFICIENTS
      A=-6.60046824E+02
      B=3.27884020E+06
      C=-1.74360076E+08
      D=5.78280072E+09
      E=-9.29116096E+10
      F=8.46509048E+11
      G=-4.79173280E+12
      H=1.75760146E+13
      O=-4.20115552E+13
```

```
      P=6.33579656E+13
      Q=-5.48432768E+13
      R=2.07901540E+13
      AA=0.35
      AB=642000.
      AC=50300.
    5 CONTINUE
      IF(AMATL.NE.3.0) GO TO 12
      A=-2.37529992E+02
      B=8.77222216E+05
      C=-2.10395908E+07
      D=7.92526976E+08
      E=-1.19710816E+10
      F=9.28522728E+10
      G=-4.24976496E+11
      H=4.21919694E+12
      O=-2.22403424E+12
      P=2.51118460E+12
      Q=-1.60332062E+12
      R=4.43286884E+11
      AA=0.5
      AB=209100.
      AC=27900.
   12 CONTINUE
      HTA=48.
      IF(WT.GE.10000.) HTA=36.0
      IF(WT.GE.20000.) HTA=24.0
      IF(WT.GE.30000.) HTA=12.0
      HTB=360.
      DO 20 N=1,2
      HT=HTA
      IF(N .EQ. 2) HT=HTB
      UT=WT*HT
      SUMU=0.0
      DS=0.
      DO 1 I=1,200
      DE(I)=DS
      DEP(I)=DE(I)*DEPH
      IF(DS.GT.AA) GO TO 21
C     STRESS EQUATION
      S(I)=A+(B*DS)+(C*DS*DS)+(D*(DS**3.))+(E*(DS**4.))+(F*(DS**5.))+
     1 (G*(DS**6.))+(H*(DS**7.))+(O*(DS**8.))+(P*(DS**9.))+
     2 (Q*(DS**10.))+(R*(DS**11.))
   21 CONTINUE
      IF(DS.LE.AA) GO TO 22
      STRS=(AB*DS)+AC
   22 CONTINUE
C     COMPUTE FORCE
      FORC(I)=S(I)*AREA
C     COMPUTE ACCELERATION
      ACC(I)=FORC(I)/WT
C     COMPUTE ENERGY
      DU(I)=FORC(I)*DL
      SUMU=SUMU+DU(I)
      ENER(I)=SUMU
      DS=DS+EE
      IF(ENER(I).GE.UT) 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,THK,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 (6,1001)
      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 (6,1001)
      WRITE (6,1001)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1001)
      WRITE (6,1001)
      CALL QWIKPL(DEF,ACC,J,'LINEAR','J.H.EVANS$')
      CALL QWIKPL(DEF,ENER,J,'LINEAR','J.H.EVANS$')
      CALL QWIKPL(ACC,ENER,J,'LINEAR','J.H.EVANS$')
   20 CONTINUE
      STOP
      END
```

Program 1016 CASK
Derivation of Equations

When a cask equipped with stiffening rings as shown in Fig. C.6 impacts an unyielding surface, some fraction of the cask's kinetic energy will be dissipated by deforming the rings. For any arbitrary time during the deformation, material will have been displaced from the portion of the ring below the line representing the impact surface in Fig. C.6. For the cases where the ration $(R_o - R_i)/t_f$ is small, the ring will fail in pure compression. A typical element at the angular location θ dx wide and t_f deep will be deformed an amount Y. The force F on the element at any point in the deformation is

$$F' = \sigma \, dA \ ,$$

where

dA = differential area.

By trigonometry,

$$X = R_o \sin \theta \ ,$$

$$\theta = \sin^{-1} (X/R_o) \ ,$$

$$L_A = R_o \cos \theta - R_i \cos \alpha \ ,$$

$$Y = R_o(\cos \theta - \cos \phi) \ ,$$

$$dA = (R_o \theta \cos \theta) \ C_L \ ,$$

where

$$C_L = \sum T_f \ .$$

The strain in any element is

$$\varepsilon = Y/L_A \ .$$

ORNL DWG 74-12483

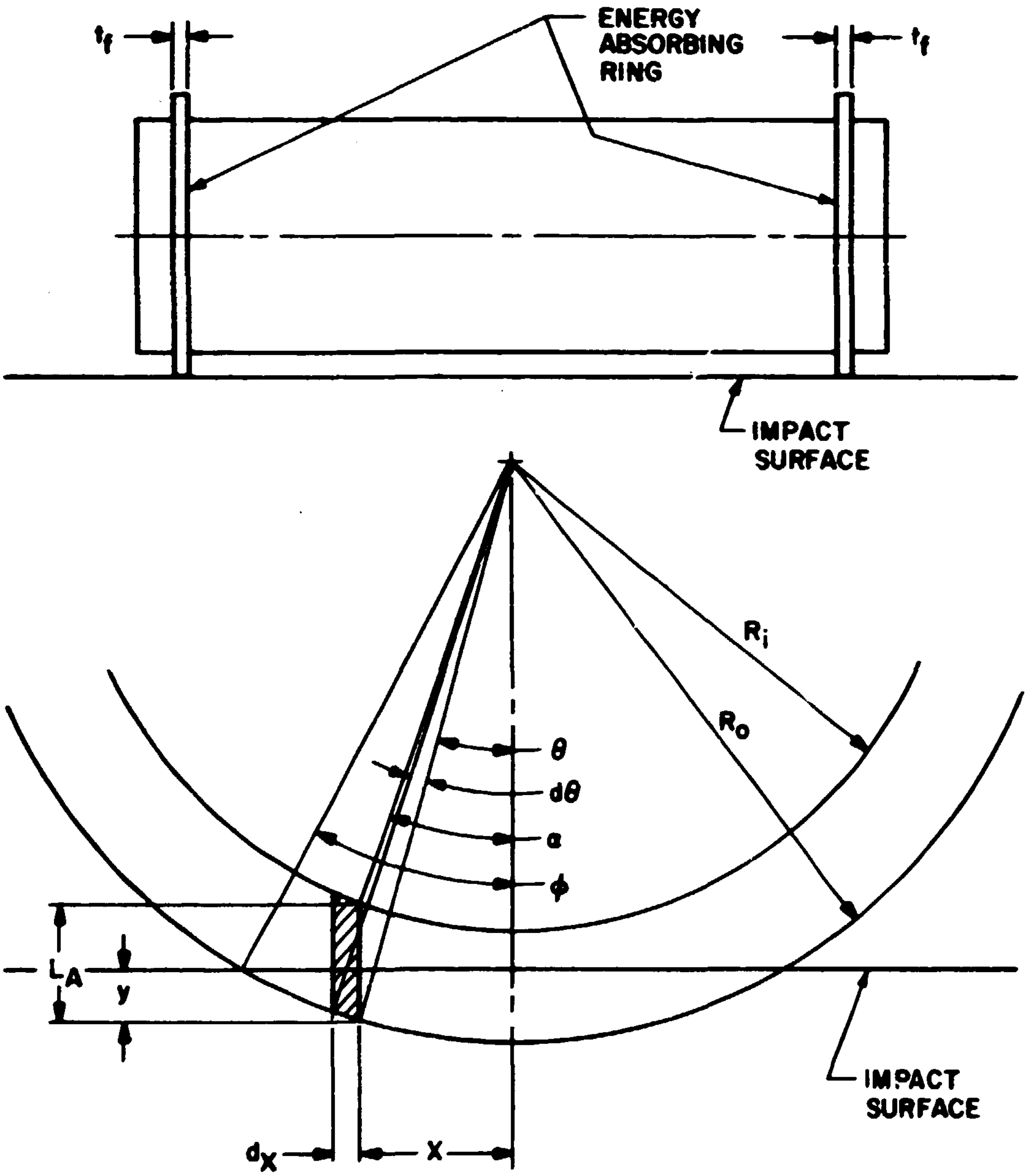

Fig. C.6. Cask model.

There exists an expression

$$\sigma = f(\varepsilon) = A_o + A_1\varepsilon + A_2\varepsilon^2 + \ldots + A_n\varepsilon^n .$$

From the above trigonometric relations the strain can be determined at any given location for a particular deformation described by ϕ. The force can then be calculated from

$$F' = f(\varepsilon)\ dA = C_L R_o\ d\theta \sum_{\theta=o}^{\theta=\phi} \cos\theta(A_o + A_1\varepsilon_\theta + A_2\varepsilon_\theta^2 + \ldots + A_n\varepsilon_\theta^n) .$$

The total force F is

$$F = \sum F' = 2C_L R_o\ d\theta \sum_{\theta=o}^{\theta=\phi} \cos\theta(A_o + A_1\varepsilon_\theta + A_2\varepsilon_\theta^2 + \ldots + A_n\varepsilon_\theta^n) ,$$

with $d\theta$ constant. The energy, U', absorbed by an element is

$$U' = \int F'\ dy = \int \sigma\ dA\ L_a\ d\varepsilon$$

$$= C_L R_o\ d\theta \cos\theta\ L_a\left(A_o\varepsilon_\theta + \frac{A_1\varepsilon_\theta^2}{2} + \frac{A_2\varepsilon_\theta^3}{3} + \frac{A_n\varepsilon\theta^{n+1}}{n+1}\right).$$

These expressions are utilized with the computer to effect a trial and error solution of the impact. A value is assigned to ϕ, and energy absorbed is computed. In this computation, θ is incremented a constant amount $d\theta$ until $\theta = \phi$. The total calculated absorbed energy is compared with the cask's potential energy. The value of ϕ is increased until the calculated energy equals the cask's potential energy. Force is calculated by a similar summing operation. Acceleration, maximum deformation, etc., are calculated using basic engineering mechanics principles.

```
**FTN,L,M,E,G,A.
C                          PROGRAM 1016 CASK
C THIS PROGRAM COMPUTES THE RESPONSE OF A RIGID CASK EQUIPPED WITH AN ENERGY,
C ABSORBER WHICH DEFORMS IN PURE COMPRESSION. THE ENERGY ABSORBER IS
C IN THE FORM OF CIRCULAR PINS OR SHELL STIFFENING RINGS, HAVING A LENGTH
C TO THICKNESS RATIO SUFFICIENT TO PREVENT BUCKLING. THE AXIS OF THE CASK IS
C HORIZONTAL. CODED BY JOHN EVANS, P. E. OAK RIDGE NATIONAL LABROTORY
C NOVEMBER 1974
C
C                        GLOSSARY OF NOTATION
C
C               EE=AMOUNT STRAIN IS INCREMENTED-IN./IN.
C               DEF=ABSORBER DEFORMATION IN.
C               DU=DIFFERENTIAL ENERGY  IN.LB.
C               FORCE=FORCE LB.
C               ENER=ENERGY DISSIPATED IN DEFORMING THE ABSORBER IN.LB.
C               ACC=ACCELERATION X G
C               STL=STEEL MILD OR LOW CARBON
C               SST=STAINLESS STEEL 300 SERIES
C               ALUM=ALUMINUM TYPE 6061-T6
C               AA=UPPER STRAIN LIMIT FOR THE NONLINEAR STRESS-STRAIN
C                   EQUATION IN./IN.
C               X=HORIZONTAL DISTANCE FROM POINT OF FIRST IMPACT TO POINT
C                   OF CALCULATION IN.
C               ALPHA=ANGLE DESCRIBED BY X AND RI
C               AL=LENGTH OF THE ELEMENTAL VOLUME IN.
C               CL=TOTAL THICKNESS OF THE ABSORBERS IN.
C               DE=STRAIN IN./IN.
C               DS=STRAIN IN./IN.
C               AMATL=ABSORBER MATERIAL
C               WT=CASK WEIGHT LB.
C               A,B,C,D,E,E,G,H,O,P,Q,R=CONSTANTS IN THE STRESS EQUATION
C               AB,AC=CONSTANTS IN THE STRAIGHT LINE STRESS EQUATION
C               HT=DROP HEIGHT IN.
C               UT=CASKS TOTAL POTENTIAL ENERGY IN.LB.
C               ANGL=ANGLE AT POINT OF CALCULATION ON THE ABSORBER
C               RO=OUTSIDE RADIUS OF THE ABSORBER IN.
C               RI= INSIDE RADIUS OF THE ABSORBER IN.
C               CL=OVERALL CASK LENGTH INCLUDING THE ABSORBER IN.
C               DA=AMOUNT ANGL (ANGLE) IS INCREMENTED
C               THETA=ANGLE AT POINT OF CALCULATION, MEASURED FROM
C                  RADIUS THROUGH POINT OF FIRST IMPACT
C               STRS=STRESS PSI
C               SSI=INTEGRAL OF THE STRESS EQUATION
C               DAREA=DIFFERENTIAL AREA SQ:IN.
C               OU=DIFFERENTIAL ENERGY IN.LB.
C               DFOR=DIFFERENTIAL FORCE LB.
C
C
C
      DIMENSION  DEF(500),FORCE(500),ACC(500),ENER(500),ANGL(500)
 1001 FORMAT (1H0)
 1002 FORMAT(1H ,1X,'*******************************************************
     1   ********************************************************')
 1003 FORMAT(1H ,23X,24HENERGY ABSORBER GEOMETRY)
 1   ; FORMAT(1H, 11X,14HOUTSIDE RADIUS, 6X,13HINSIDE RADIUS,6X,
     1        14HABSORBER DEPTH)
 1005 FORMAT(3F20.3)
```

```
 1006 FORMAT (1H ,16X,33HCASK GEOMETRY AND TEST CONDITIONS)
 1007 FORMAT(1H ,12X,11HCASK WEIGHT,3X,11HDROP HEIGHT,3X,9HPOTENTIAL,
     1       X, 6HENERGY)
   08 FORMAT(1H ,F21.1,F14.1,F17.1)
   09 FORMAT (1H , 1X,12HACCELERATION,2X,11HDEFORMATION,6X,5HFORCE,6X,
     1    5HANGLE,8X,6HENERGY)
 1010 FORMAT (1H , 5X,3HX G,10X,6HINCHES, 9X,4HLBS.,7X,7HDEGREES,
     1            9X,5HLB-IN)
 1011 FORMAT (1H ,F10.1,F13.3,F16.1,F12.1,F12.1)
      SST=1.0
      STL=2.0
      ALUM=3.0
   60 EE=.005
      DS=0.0
      DO 56 I=1,500
      DEF(I)=0.0
      FORCE(I)=0.0
      ACC(I)=0.0
      ENER(I)=0.0
   56 ANGL(I)=0.0
C*******************************************************************************
C  INPUT ABSORBER AND CASK GEOMETRY
C  INPUT OUTSIDE RADIUS OF THE ABSORBER
      RO=15.
C  INPUT INSIDE RADIUS OF THE ABSORBER
      RI=12.
C  INPUT TOTAL LENGTH OF THE ABSORBER
      CL=3.
C  INPUT CASK WEIGHT
      WT=16000.
   INPUT ABSORBER MATERIAL
      AMATL=STL
C  INPUT CASK NAME
 1000 FORMAT(1H ,8X,'O. R. N. L. IN-PILE SHIPPING CASK')
C*******************************************************************************
C  ANGLE INCREMENT
      DA=.01
C  INPUT DROP HEIGHT
      HTA=48.
      IF(WT.GE.10000.) HTA=36.0
      IF(WT.GE.20000.) HTA=24.0
      IF(WT.GE.30000.) HTA=12.0
      HTB=360.
    MILD STEEL COEFFICIENTS
      IF(AMATL.NE.2.0) GO TO 6
      A=-4.36337724E+02
      B=3.52674012E+06
      C=-5.84344912E+07
      D=8.44752080E+08
      E=-1.00790838E+10
      F=8.32241264E+10
      G=-4.42875864E+11
      H=1.50685484E+12
      O=-3.25535392E+12
      P=4.31754272E+12
      Q=-3.20487884E+12
      R=1.01910658E+12
```

```
      AA=0.5
      AB=345000.
      AC=73000.
    6 CONTINUE
      IF(AMATL.NE.1.0) GO TO 5
 STAINLESS STEEL COEFICIENTS
      A=-6.60046824E+02
      B=3.27884020E+06
      C=-1.74360076E+08
      D=5.78280072E+09
      E=-9.29116096E+10
      F=8.46509048E+11
      G=-4.79173280E+12
      H=1.75760146E+13
      O=-4.20115552E+13
      P=6.33579656E+13
      Q=-5.48432768E+13
      R=2.07901540E+13
      AA=0.35
      AB=642000.
      AC=50300.
    5 CONTINUE
      IF(AMATL.NE.3.0) GO TO 12
      A=-2.37529992E+02
      B=8.77222216E+05
      C=-2.10395908E+07
      D=7.92526976E+08
      E=-1.19710816E+10
      F=9.28522728E+10
      G=-4.24976496E+11
      H=1.21919694E+12
      O=-2.22403424E+12
      P=2.51118460E+12
      Q=-1.60332062E+12
      R=4.43286884E+11
      AA=0.5
      AB=209100.
      AC=27900.
   12 CONTINUE
      DO 20 N=1,2
      HT=HTA
      IF(N .EQ. 2) HT=HTB
      UT=WT*HT
      SUMU=0.0
      DS=0.
      DO 50 I=1,500
      IF(I.EQ.1) GO TO 50
      PHI=DA*FLOAT(I)+.1
      DEF(I)=RO*(1.-COS(PHI))
      ANGL(I)=PHI*57.3
      SUMF=0.0
      SUMU=0.0
      DO 51 JJ=1,500
      THETA=DA*FLOAT(JJ)
      IF(THETA.GE.PHI) GO TO 54
      DAREA=RO*DA*COS(THETA)*CL
      X=RO*SIN(THETA)
```

```
      ALPHA=ARSIN(X/RI)
      AL=(RO*COS(THETA))-(RI*COS(ALPHA))
      Y=RO*(COS(THETA)-COS(PHI))
      IF(Y.LE.0.0)  GO TO 53
      DS=Y/AL
STRESS EQUATION
      IF(DS.GT.AA)  GO TO 21
      STRS=A+(B*DS)+(C*DS*DS)+(D*(DS**3.))+(E*(DS**4.))+(F*(DS**5.))+
     1 (G*(DS**6.))+(H*(DS**7.))+(O*(DS**8.))+(P*(DS**9.))+
     2 (Q*(DS**10.))+(R*(DS**11.))
      SSI=A*DS+((B*DS*DS)/2.)+((C*(DS**3.))/3.)+((D*(DS**4.))/4.)+
     1 ((E*(DS**5.))/5.)+((F*(DS**6.))/6.)+((G*(DS**7.))/7.)+
     2 ((H*(DS**8.))/8.)+((O*(DS**9.))/9.)+((P*(DS**10.))/10.)+
     3 ((Q*(DS**11.))/11.)+((R*(DS**12.))/12.)
   21 CONTINUE
      IF(DS.LE.AA)  GO TO 22
      STRS=(AB*DS)+AC
      SSI=((AB*DS*DS)/2.0)+(AC*DS)
   22 CONTINUE
      DFOR=STRS*DAREA
      DU=SSI*DAREA*AL
      SUMF=SUMF+DFOR
      SUMU=SUMU+DU
   53 CONTINUE
   52 CONTINUE
   51 CONTINUE
   54 CONTINUE
      FORCE(I)=SUMF*2.
      ACC(I)=FORCE(I)/WT
      ENER(I)=SUMU*2.
      IF(DEF(I).GE.AL)  GO TO 55
      IF(ENER(I).GE.UT)  GO TO 55
   50 CONTINUE
   55 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) RO,RI,AL
      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 (6,1001)
      DO 10 I=1,200
      WRITE(6, 1011),ACC(I),DEP(I),FORCE(I),ANGL(I),ENER(I)
      IF(I.GE.J) GO TO 11
   10 CONTINUE
   11 CONTINUE
      WRITE (6,1001)
      WRITE (6,1001)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1002)
      WRITE (6,1001)
      WRITE (6,1001)
      CALL QWIKPL(DEP,ACC,J,'LINEAR','J.H.EVANS$')
      CALL QWIKPL(DEP,ENER,J,'LINEAR','J.H.EVANS$')
      CALL QWIKPL(ACC,ENER,J,'LINEAR','J.H.EVANS$')
   20 CONTINUE
  100 CONTINUE
      STOP
      END
```

Appendix D

2R CONTAINER TESTING REPORT

2R Container Testing

Below is an excerpt from the SARP for ORNL shipping cask D-38 by L. B. Shappert and B. B. Klima, outlining tests performed on the 2R container used in D-38. The figure numbers have been changed to be compatible with this report. Two D-38 2R inner containers were tested to establish the adequacy of this type of container as the primary containment vessel for radioactive materials. Specification 2R containers are described in Sect. 1.7. The containers and their drop sleeves are shown in Fig. D.1. The container was dropped inside the sleeve to simulate the condition of the container inside the cask. These drop sleeves consisted of a length of sched-40 stainless steel pipe with a 0.280-in.-thick plate welded over one end.

The testing of the containers consisted of two 30-ft drops. The first drop was made such that the bottom of the container impacted flat on the surface. The second drop was made with the bottom of the container at an angle of 20° from the horizontal such that the center of gravity of the container was directly above the impacting corner. Both containers weighed 19 lb empty and were loaded with 25 lb of solids to bring the total weight of the dropped unit to 44 lb. Prior to the drop tests, both containers were tested and were leak-tight at 25 psig.

Figure D.2 shows the inner container and drop sleeve after the first test. This container impacted at an angle of 0° with the impact surface and sustained almost no visible damage. Figures D.3 and D.4 show the inner container and drop sleeve used in the second drop. This container impacted at an angle of 20° with the impact surface. A flattening of the drop sleeve is evident, but no damage was sustained by the inner container. The metal of the inner container was polished a little below the weld area.

The containers were tested after the drop and were leak-tight at 25 psig. The inner container met the requirements of the drop test.

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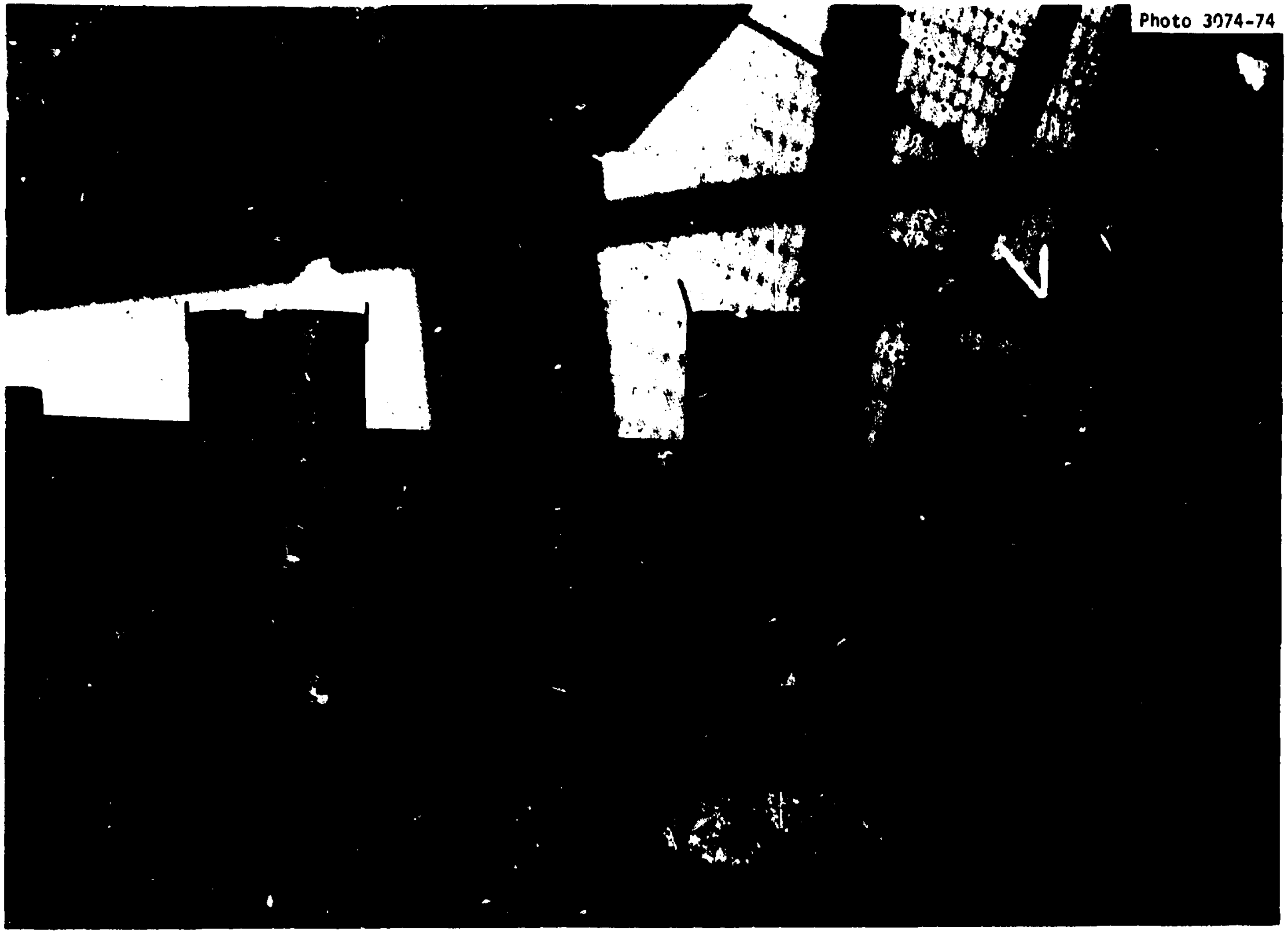


Photo 3074-74

Fig. D.1. Model before testing.

Fig. D.2. Model after first test.

Photo 3073-74

Fig. D.3. Model after second test.

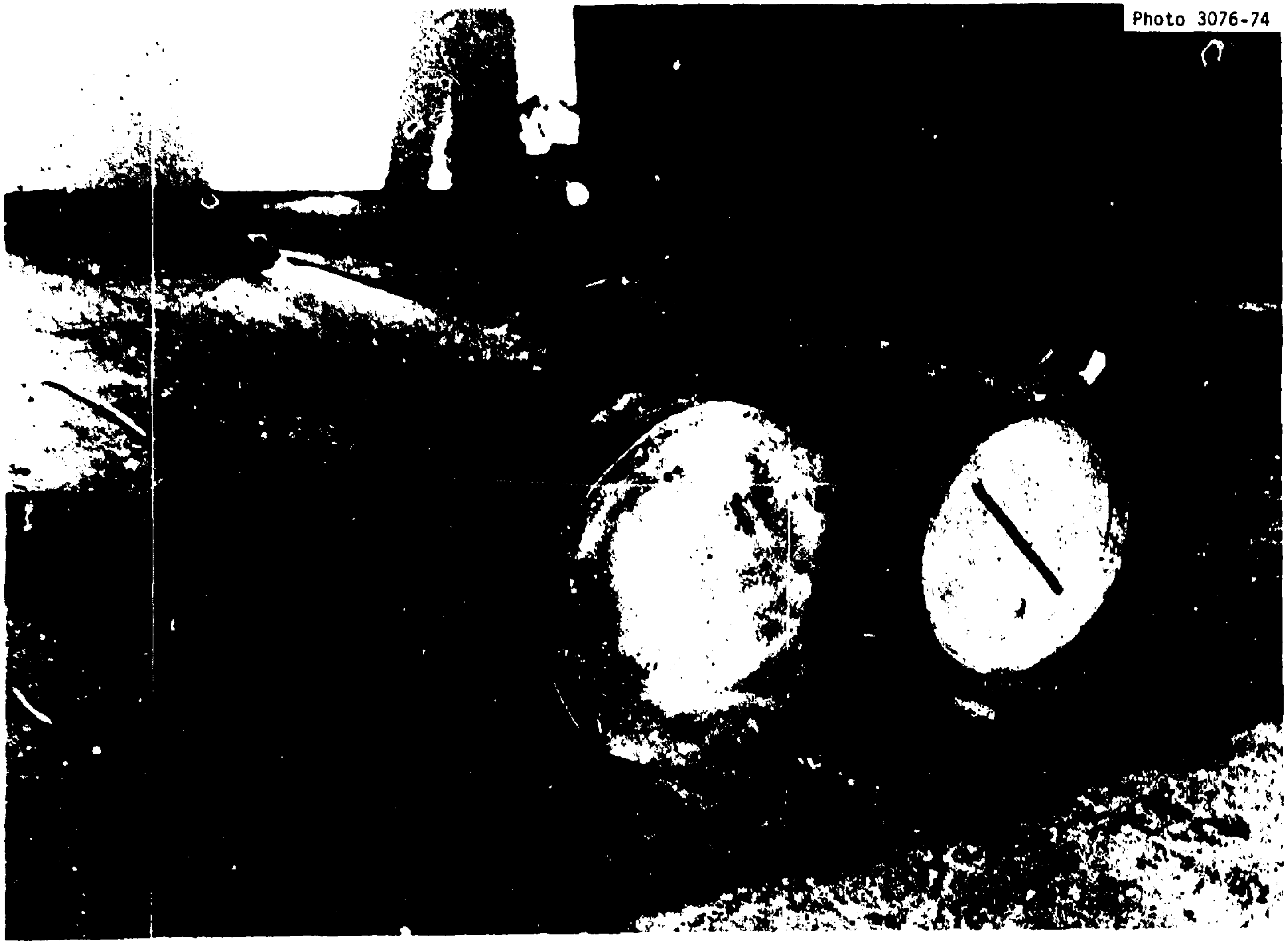


Fig. D.4. Model after second test.

Appendix E

NUCLEAR SAFETY REVIEW FORMS

REQUEST FOR NUCLEAR SAFETY REVIEW

NSR 342

Revision 1

EXPIRATION DATE
July, 197

This request covers operations with fissile material in a control area and or fissile material transfers that originate within the control area. The control area supervisor shall complete the blocks below and describe the process and or operations to be performed, emphasizing the provisions for nuclear criticality safety on the reverse side of this page. This request shall be approved by the Radiation Control Officers of the originating Division and the Division(s) to which fissile material will be transferred.

TITLE, CONTROL AREA, AND SUMMARY OF BASIC CONTROL PARAMETERS

(To be completed by the Control Area Supervisor)

TITLE (FOR REFERENCE PURPOSES): In-Pile Capsule Shipping Cask
DATE OF REQUEST: 6-10-74
DATE REVIEW REQUIRED: July 1,197
CONTROL AREA: Hot Cell Operations
CODE NO.: 25
BUILDING ROOM:
DIVISION: Operations

TYPE AND FORM OF MATERIAL	Nonfueled and fueled (^{233}U, ^{235}U, Th, Pu) experiments; solids o
ISOTOPIC ENRICHMENT (WT. %)	Normal to fully enriched.
QUANTITY OF FISSILE ISOTOPES — PER ISOLATED BATCH OR UNIT	1250 g
QUANTITY OF FISSILE ISOTOPES — TOTAL IN cask.	1250 g. Also, if total is > 800 g, linear density not to exceed 250g/ft.
QUANTITY OF FISSILE ISOTOPES — TOTAL TO BE PROCESSED	
Concentration or Density of Fissile Material	
Spacing of Fissile Units	
Proximity and Type of Neutron Reflectors or Adjacent Fissile Material	10 in. of lead shielding around cavity.
Limit on Moderation	
Limit on Neutron Absorbers	
Limit on Volume or Dimensions of Containers	Cavity dimensions 4½ in. diam by 58 in. long.

THIS REQUEST (MODIFIES, REPLACES) NSR'S NO. 342

RECOMMENDATIONS

(To be completed by the Criticality Committee)

This endorsement is based on our present understanding of the operation (whether acquired verbally or in writing) and is subject to review and cancellation.

The Committee recommends approval of this cask under the condition that if the mass loading exceeds 800 grams that the material will be so arranged that the fissile loading will not exceed 250 grams per linear foot under normal and accident conditions. This requirement restricts the contents to a safe mass per foot for infinitely long water reflected cylinders and ensures safety during loading and unloading under water. The over-all mass limit of 1.25 kg of fissile isotopes and the 4½ in. diameter render the cask safe against redistribution of the contents in an accident.

R.G.Affel for R. G. Affel
CHAIRMAN, CRITICALITY COMMITTEE

6/17/74
DATE

PROVISIONS FOR NUCLEAR CRITICALITY SAFETY

(To be completed by the Control Area Supervisor)

Provisions for nuclear criticality safety shall be described below in accordance with Appendices II and III of the AEC Manual Chapter 0530. This shall include brief descriptions of the process and/or all operations to be performed, plans and procedures for the operations for nuclear criticality safety, and the basic control parameters. Please attach 11 copies of referenced drawings and documents.

We request approval of this cask as a general-purpose-use cask for fissile Class I shipment of used reactor fuel elements and irradiated experiments (fueled and nonfueled). For example, for shipment of such items from other sites (such as EBR-II in Idaho) to the ORNL hot cells for metallurgical examination; and, after examination, for shipment of the same items to Savannah River or Idaho for fuel recovery. Fueled experiments have contained coated particle fuels of U, Pu, Th; clad oxide rods of U, Pu, Th; molten salt (MSRE) fuels.

This carrier may be loaded and unloaded under water.

The loading of the cask will not exceed 1250 g of fissile material (combinations of ^{233}U, ^{235}U, and plutonium)

In addition, if the loading exceeds 800 g, the material will be so arranged that the fissile loading will not exceed 250g/per linear ft under normal and hypothetical accident conditions.

Shipment will be by rail freight, motor vehicle, cargo aircraft, or ocean vessel.

This request is for use with a submission for approval by the AEC under the requirements of AECM-0529 for offsite shipments.

ORNL
CRITICALITY COMMITTEE

NSR 342
Revision 1

EXPIRATION DATE
July, 1977

RADIATION CONTROL OFFICER A.G. Stalla	DIVISION Operations	CONTROL AREA SUPERVISOR E. M. King	BUILDING
RADIATION CONTROL OFFICER	DIVISION	RADIATION CONTROL OFFICER	DIVISION

INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

April 18, 1975

To: R. G. Affel

From: J. W. Wachter

Subject: Nuclear Safety of In-Pile Shipping Cask (NSR 342)

The Director's Review Committee on Transportation has noted in its review of the In-Pile Capsule cask that the nuclear safety approval imposes a restriction on the linear density of fissile isotope in the cavity of the cask. Although the value of "safe mass per foot" used the nuclear safety analysis was derived from data in TID-7016, it does not appear explicitly. I have therefore used my notes on this review to prepare the following explanation for inclusion in your files as back-up for the SARP.

The restriction to 250 grams of fissile isotope per foot was arrived at by utilizing the relationship between fissile material solution density and the diameter of the safe infinitely long water-reflected cylinder. In the attached figure, the safe cylinder diameters of TID-7016 (Figures 3, 7, and 11) have been used to calculate the mass of fissile isotope in each centimeter length of the cylinder as a function of solution concentration. This "safe" linear density passes through a minimum for each isotope, and the lower bound of these is established by the Pu-239 isotope as 8.1 g/cm, or 0.25 kg/ft.

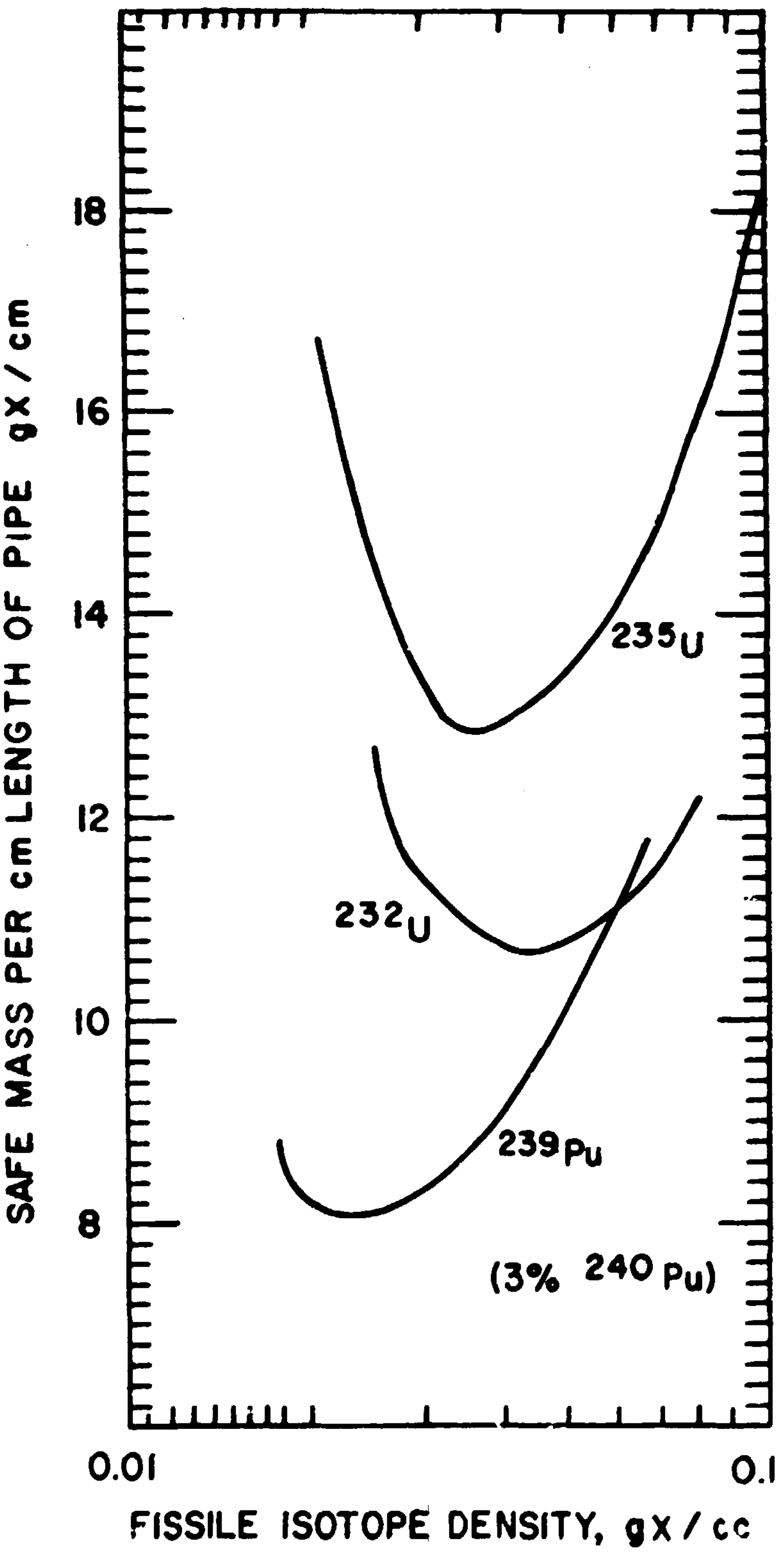
J. W. Wachter
Engineering Coordination and
Analysis Section
Chemical Technology Division

JWW:sd

Attachment

cc: J. H. Evans
E. M. King
J. P. Nichols
JWW File

ORNL DWG 77-15607



INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

June 10, 1974

To: Criticality Committee

Subject: NSR 342, In-Pile Capsule Shipping Cask

This is a resubmission of NSR 342. The usage of this cask has not changed. However, some wording was changed in relation to two items:

1. Some wording was changed to emphasize that the cask is a general-purpose-use cask.
2. Description of the loading (1,250 g total) was changed so that the 250g/linear ft applies only when the total exceeds 800 g fissile isotopes (^{233}U, ^{235}U, Pu).

E. M. King

E. M. King

EMK:jr

cc: J. A. Cox

Appendix F

OPERATING PROCEDURES AND CHECKLISTS

3026D Memo No. 17
3525 Memo No. 20

INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

August 19, 1971

To: 3026D and 3525 Cell Memo Books

Subject: Casks Used for Off-site Shipment of Radioactive Materials

Shielding casks used for off-site shipment of radioactive material must be DOT approved. The casks must be maintained in a good state of repair. Inspection check lists have been made for use prior to each shipment. Also, a more detailed inspection is scheduled on a periodic (approximately annual) basis and a check list has been made for this. Many of the radioactive materials coming to ORNL are shipped by others (such as Idaho Nuclear, Army) in our casks; loading procedures for Hot Cell Operations casks have been developed for their use. These inspection check lists and loading procedures follow and are a part of this memo:

1. Loop Transport Cask Inspection Sheet
2. Loop Transport Cask Annual Inspection Sheet
3. Loop Transport Cask Underwater Loading Procedure
4. Loop Transport Cask Horizontal Loading Procedure
5. In-Pile Capsule Shipping Cask Inspection Sheet
6. In-Pile Capsule Shipping Cask Annual Inspection Sheet
7. In-Pile Capsule Shipping Cask Underwater Loading Procedure
8. In-Pile Capsule Shipping Cask Horizontal Loading Procedure

Operating Supervisor

E. M. King
Department Superintendent

Division Superintendent

IN-PILE CAPSULE SHIPPING CASK
Inspection Sheet

Cask No. ______

Date ______

Prior to each shipment, the following items shall be checked to ensure that all parts are in good condition, firmly attached, and cask is properly sealed.

Indicate Satisfactory with (✓)

BEFORE LOADING

1. Lower Cover End
   - a. Sealing surface on cask and lower cover (item 24) in good condition (visual check) ______
   - b. Gasket (item 25) in good condition ______
   - c. Fire shield in good condition ______
   - d. Tamper seal holes in at least two cap screws of fire shield ______
2. Gate Section (item 9)
   - a. Sealing surface on cask and gate (item 9) in good condition ______
   - b. Gasket (item 5) in good condition ______
3. Upper Cover End
   - a. Sealing surface on cask and plug (item 19) in good condition ______
   - b. Gasket (item 22) in good condition ______
   - c. Fire shield in good condition ______
   - d. Tamper seal holes in at least two cap screws of fire shield ______
   - e. Ram plug gasket (item 26) in good condition ______

AFTER LOADING

4. Gate (item 9) firmly seated and screws tight ______
5. Lower cover (item 24) seated and cap screws tight ______
6. Upper cover (item 19) seated and screws tight ______
7. Plug ram (item 18) in position and holding bolt (item 21) tight ______
8. Pressure test: with 3 to 5 psi air on cavity of cask, soap bubble check all gasketed flanges for leaks:
   - a. No leaks at lower cover (item 24) ______
   - b. No leaks at gate (item 9) ______
   - c. No leaks at upper cover (item 19 and 21) ______
   - d. Pressure bled off and pipe plug and pipe cap of pressure test connection (item A) in place and tightened. ______
9. Upper and lower cover fire shields bolted securely in place (12 cap screws in each end) ______
10. Carrier bolted securely to skid ______
11. Carrier has properly authorized radiation tag showing carrier meets shipping tolerance ______

Inspected by ______________________ (operator)   Approved by: ______________________ (supervisor)

IN-PILE CAPSULE SHIPPING CASK

Annual Inspection Sheet

Cask No. __________

Date: __________

The following annual inspection shall be performed to ensure the cask meets and maintains the requirements as specified by the DOT approval. Annual inspection is to be performed by Hot Cell Operations and Inspection Engineering personnel.

1. Prepare carrier for inspection. Carrier should be checked by Health Physics so components handled are at acceptable radiation and contamination limits.

	Condition	
	Good	Bad
2. Lower Cover End		
a. Cap screws (item 3) and cap-screw holes	____	____
b. Gasket (item 25)	____	____
c. Gasket sealing surface on carrier	____	____
d. Lower cover (item 24) sealing surface	____	____
e. Gate lock plug (item 15) slides freely into position into cavity	____	____
f. Lower cover (item 24) slides freely into position and seats firmly against carrier	____	____
g. Lower cover fire shield, cap screws, and cap screw holes	____	____
3. Gate section (item 9)		
a. Gasket (item 5)	____	____
b. Cap screws (item 3) and cap screw holes	____	____
c. Gate (item 9) lifts and closes freely	____	____
4. Upper Cover End		
a. Gasket (item 22)	____	____
b. Cap screws (item 25) and cap screw holes	____	____
c. Upper cover seating surface	____	____
d. Gasket seating surface on carrier	____	____
e. Upper cover slides freely and seats firmly in carrier	____	____
f. Ram plug gasket (item 26)	____	____
g. Ram plug bolt (item 21)	____	____
h. Ram plug (item 18) slides freely through cavity of carrier	____	____
i. Lower cover fire shield, cap screws, and cap screw holes	____	____
5. Visually inspect all welds for cracks and other damage	____	____

	Condition	
	Good	Bad
6. Reassemble components of carrier, when they meet acceptable standards. Apply 3 to 5 psi pressure test on cask cavity. Soap-bubble check for leaks at all gasketed areas. Make any necessary repairs in a manner to assure that carrier can be successfully leak tested consistently.	_____	_____
7. All needed repairs and final inspection completed. Cask deemed to be in good condition and cirtified for use by		

____________________________ ________
Hot Cell Operator Date

____________________________ ________
(Inspection Engineering Dept.) Date

____________________________ ________
(Hot Cell Operations Supv.) Date

ORNL Contact:
E. M. King or A. A. Walls
FTS 615-483-1672
Comm Tel. 615-483-8611
Ext. 3-1672

OAK RIDGE NATIONAL LABORATORY

IN-PILE CAPSULE SHIPPING CASK

INSTRUCTIONS FOR UNDER-WATER LOADING

DOT Special Permit SP-5907
Weight: 16,000 lb.

Assembly Dwg. No. M-11165-EL-005D
Cavity 4 1/4 in. diam x 58 in. long

Normally, the cask is loaded in a pool vertically with the upper cover at the top and lower cover and gate at the bottom. References are made to Schematic M-11165-EL-010A. (We normally leave the cask attached to the skid for loading and unloading; however, if handling under your conditions is easier, the cask may be removed from the skid.)

1. Remove fire shield on each end of cask (12 screws on each end).
2. Remove cap screws (item 3) from the lower cover (item 24).
3. Pull lower cover out approximately 3/4 in. (It is limited by a mechanical stop).
4. Rotate lower cover 90° counterclockwise. The arrow on the plug will be aligned with "Insert or Remove" arrow on cask.
5. Pull cover (item 24) and gasket (item 25) straight out. (This allows the cask to drain when it is removed from the pool.)
6. Tilt the cask to the vertical position and move it to the pool.
7. Remove the cap screws (item 29) that hold the upper cover (item 19) before lowering the cask into the pool.
8. Lower the cask into the pool and remove upper cover (item 19) and plug ram (item 18). Keep track of the gasket (item 22).
9. Lift liner out by the bail; remove lid from liner.
10. Load irradiated materials into the liner.
11. Replace lid on liner.
12. Load liner with the irradiated materials into the cask.
13. Replace the gasket, plug ram, and upper cover; raise the cask until the cap screws can be installed.
14. Install the cap screws to hold upper cover in place.
15. Raise the cask out of the pool and allow it to drain.
16. Move the cask to the shipping area and tilt it to a horizontal position.
17. Insert lower cover with arrow aligned with "Insert or Remove" mark on cask until "dog" on lower cover engages in hole of Gate Lock Plug (item 15).
18. Rotate lower cover 90° clockwise (until arrow on plug is aligned with "Ship" position mark on cask.)
19. Push lower cover in until it seats. Replace cap screws.
20. Perform a Radiation Survey to determine the acceptability for shipping and decontaminate as needed.
21. Replace fire shields on each end (12 screws on each end).

2. Install tamper wires through holes in cap screws of fire shield on each end of the cask.

E. M. King or A. A. Walls
FTS 615-483-1672
Comm Tel. 615-483-8611
Ext. 3-1672

OAK RIDGE NATIONAL LABORATORY

IN-PILE CAPSULE SHIPPING CASK

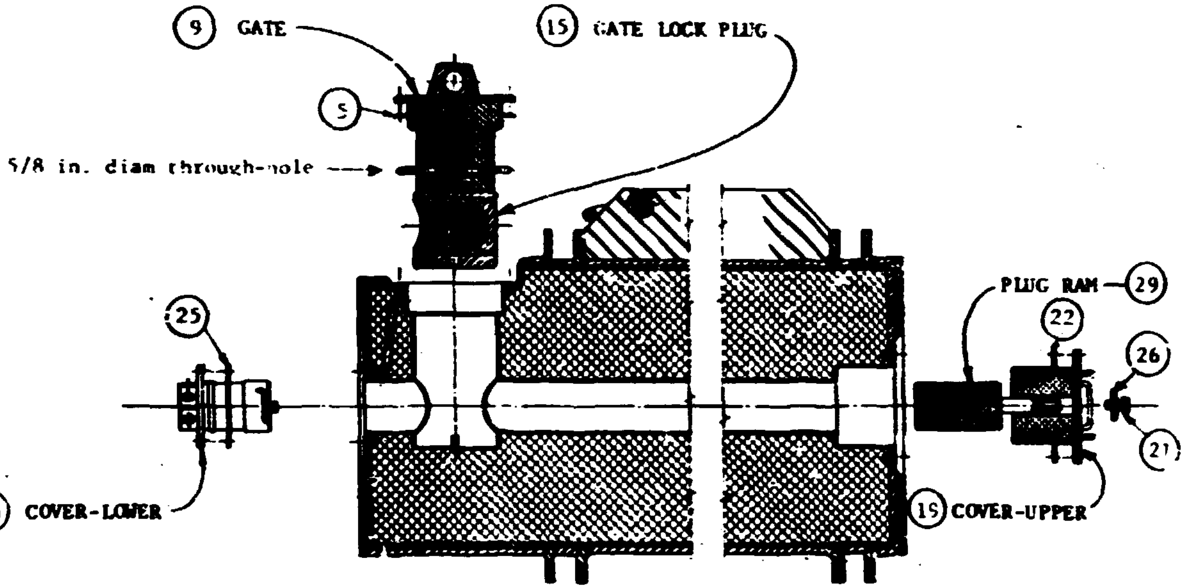
INSTRUCTIONS FOR HORIZONTAL LOADING

DOT Special Permit SP-5907
Weight 16,000 lb.

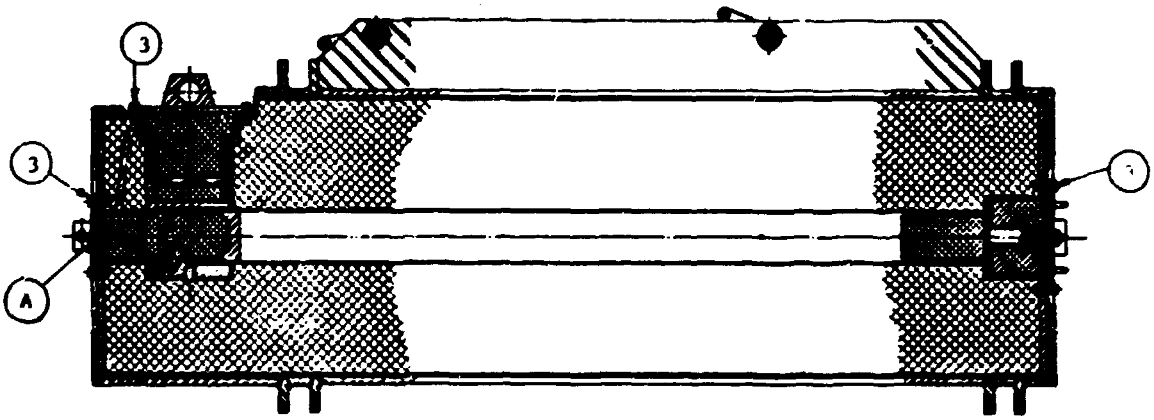
Assembly Dwg. No. M-11165-EL-005-D
Cavity 4 1/4 in. diam by 58 in. long

These instructions are for horizontal loading of the shielded cask at facilities equipped for horizontal port loading. The skid may be removed or left attached depending upon which is easier at your facility.

1. Remove fire shield on each end of cask (12 screws on each end).
2. Remove the cap screws (item 3) from the lower cover (item 24).
3. Pull lower cover (item 24) out approx. 3/4 in. (It is limited to a mechanical stop. This operation also pulls gate lock plug (item 15) from cavity of the cask.)
4. Rotate lower cover 90° counterclockwise. The arrow on plug will be aligned with "Insert or Remove" arrow on cask.
5. Pull cover (item 24) straight out with gasket (item 25).
6. Remove cap screws (item 3) from gate (item 9).
7. Make sure gate lock plug (item 15) has not shifted toward cavity of cask; it was automatically retracted in Step 2 from cask cavity and should remain in that position when lifting gate. Lift gate and gate lock plug (item 15) until 5/8 in. diam through hole is visible. Insert 1/2 in. diam rod to hold gate open.
8. Move cask into position at loading port.
9. Open loading port into cell.
10. If empty liner is in the cask, remove bolt (item 21) and gasket (item 26) with holds upper cover to plug ram (item 18). (If liner is attached to cask rather than inside cask, Steps 10 to 12, may be omitted, and the liner placed in the cell in a separate operation.)
11. Using special push rod, attach to plug ram and push empty liner into cell.
12. Retract plug ram and replace gasket and cap screw (item 21).
13. Remove lid from liner.
14. Load material to be shipped into liner, and replace lid on liner.
15. Remotely push liner into cask; ensure liner clears gate.
16. Remove rod from through-hole in gate, lower gate and gate lock plug into position and secure with cap screws.
17. Close cell loading port and move cask away from loading port.
18. Insert lower cover and gasket into carrier with arrow aligned with "Insert or Remove" mark on cask until "dog" on lower cover engages in hole of gate lock plug (item 15).
19. Rotate the lower cover 90° clockwise (until arrow on plug is aligned with "Ship" position on cask).
20. Push lower cover in until flange seats and replace cap screws.
1. Perform a radiation survey to determine the acceptability for shipping, decontaminate as needed.
22. Replace fire shield on each end of cask (12 screws on each end).
23. Install tamper wires through holes in cap screws of fire shield on each end of the cask.



CASK CROSS SECTION
PLUGS REMOVED



CASK CROSS SECTION
PLUGS INSTALLED

Dwg. No. [illegible]-11195-E -010-A

3026D Memo No. 21
3525 Memo No. 26

INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

April 22, 1974

To: Hot Cell Memo Book

Subject: Preparation of Radioactive Materials Packaging Information for Offsite Shipments

Form "Oak Ridge National Laboratory Radioactive Materials Packaging Information" must be prepared for all offsite shipments containing greater than one millicurie alpha or three curies beta-gamma solid, liquid, or gas. The person requesting the shipment must furnish and certify the information requested under General Information, Radioactive Contents, and Shipping Container. We must furnish and certify the information requested under Internal Container and External Container, except for the tamper seal. Health Physics will provide the Radiation Survey.

The filled-in (to this point) form is to be transmitted to the Isotopes Sales Dept. in the Isotopes Division -- along with the loaded container. The Isotopes Division is responsible for providing the tamper seal arranging tie-down inspection, and final approval of the shipment.

A copy of the form is attached.

R. L. Lines
Operating Supervisor

C. G. Stalls
Operating Supervisor

E. M. King
Department Supt.

Division Supt.

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–

2. DOT Specification No. 3. Nuclear Safety Review No.

4. Container determined proper for contents by Date

INTERNAL CONTAINER

1. Internal Containment: ☐ Glass Bottle ☐ Plastic Bottle ☐ "[illegible]" ☐ Conoseal ☐ Welded Capsule (specify capsule material) ____________

☐ Other (explain) ____________

2. Contamination level on internal container: Estimated ____________ Smeared ____________

Radiation level from internal container: Measured ____________ Calculated ____________

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, [illegible] ____________ 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) ____________

ipment Approved By | Date