910013 B
GADR 55
VOLUME 1

CONSOLIDATED DESIGN REPORT FOR THE MODEL FSV-1 SHIPPING CASK

CONFIGURATIONS A, B, C, D

GENERAL ATOMICS

ALL REFERENCES TO MODEL FSV-1 CASK IN THIS DOCUMENT MEAN FSV-1 CASK UNIT NO. 3.

910013 B
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ROLL 2243-NC

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SECTION 1.0

GENERAL INFORMATION

1.0 GENERAL INFORMATION

1.1. INTRODUCTION

Volume I of GADR 55 provides a description and an evaluation of Model FSV-1 in Configurations A, B, C and D and evaluations and diagrams that may apply to all configurations A, B, C, D, E, F and G.

Volume II of the GADR 55 provides a description and an evaluation of the Model FSV-1 packaging in Configurations E, F and G.

Table 1-1 provides a descriptive tabulation of the first four Model FSV-1 configurations. Figures 1-1 through 1-4 show the principal features of these Model FSV-1 configurations.

1.2. PACKAGE DESCRIPTION

Model FSV-1 in Configurations A, B, C and D are designed and evaluated for the transport of large quantities of solid, nonfissile, irradiated and contaminated hardware. These packages have a loaded weight of approximately 46,000 pounds and the maximum weight of the cavity contents is 3,720 pounds. The length of the package is 208 inches with a maximum outside diameter of 31 inches for a length of 11.375 inches and the outside diameter of the remainder of the package is 28 inches. These configurations have been grouped together since the impact limiter is NOT used in any of these shipping configurations.

1.2.1. Packaging

Model FSV-1 in Configurations A, B, C and D all use the same cask body as shown on National Lead Company drawings 70296F, Rev. 2; 70086F, Rev. 7; and General Atomics drawing 1501-003, Rev. C. Only Configuration A uses the inner container as shown on the above referenced drawings. Configuration B uses a burial liner without supplemental shielding as shown on Fig. 1-2. Configurations C and D have supplemental shielding in the form of a ring on the cover plate for the burial liner. These configurations are described on GA drawings GADR 55-2-10, issue D, and GADR 55-2-11, issue A and issue B. The cover plate and supplemental shield ring for configuration C are made of stainless steel as shown on GADR 55-2-11, issue B. In Configuration D these components are made of carbon steel as shown on GADR 55-2-11 issue A. Configurations C and D also have optional temporary shield tubes as shown on drawing GADR 55-2-14, Issue N/C.

1.2.2 Operational Features

Model FSV-1 has a smooth external surface that simplifies decontamination. Lifting attachments on the package consist of sockets rather than trunnions since sockets are less likely to be damaged in a manner that would impair any safety function of the package. Tie-down of the package to the rear support on the transport semitrailer is by means of four (4) socket head cap screws which are installed into threaded inserts located in the base of the cask body. This attachment arrangement prevents any damage that is likely to impair any safety function of the package.

1.2.3 Contents of Packaging

The contents of Configurations A, B, C and D may consist of solid, nonfissile, irradiated, and contaminated hardware. Examples of such reactor hardware may include, but are not limited to, control rods, fuel channels, poison curtains, shrouds, power range monitors, and miscellaneous structures. Configurations C and D use optional temporary shield tubes inside the burial liner for shipment of irradiated hardware requiring additional gamma shielding.

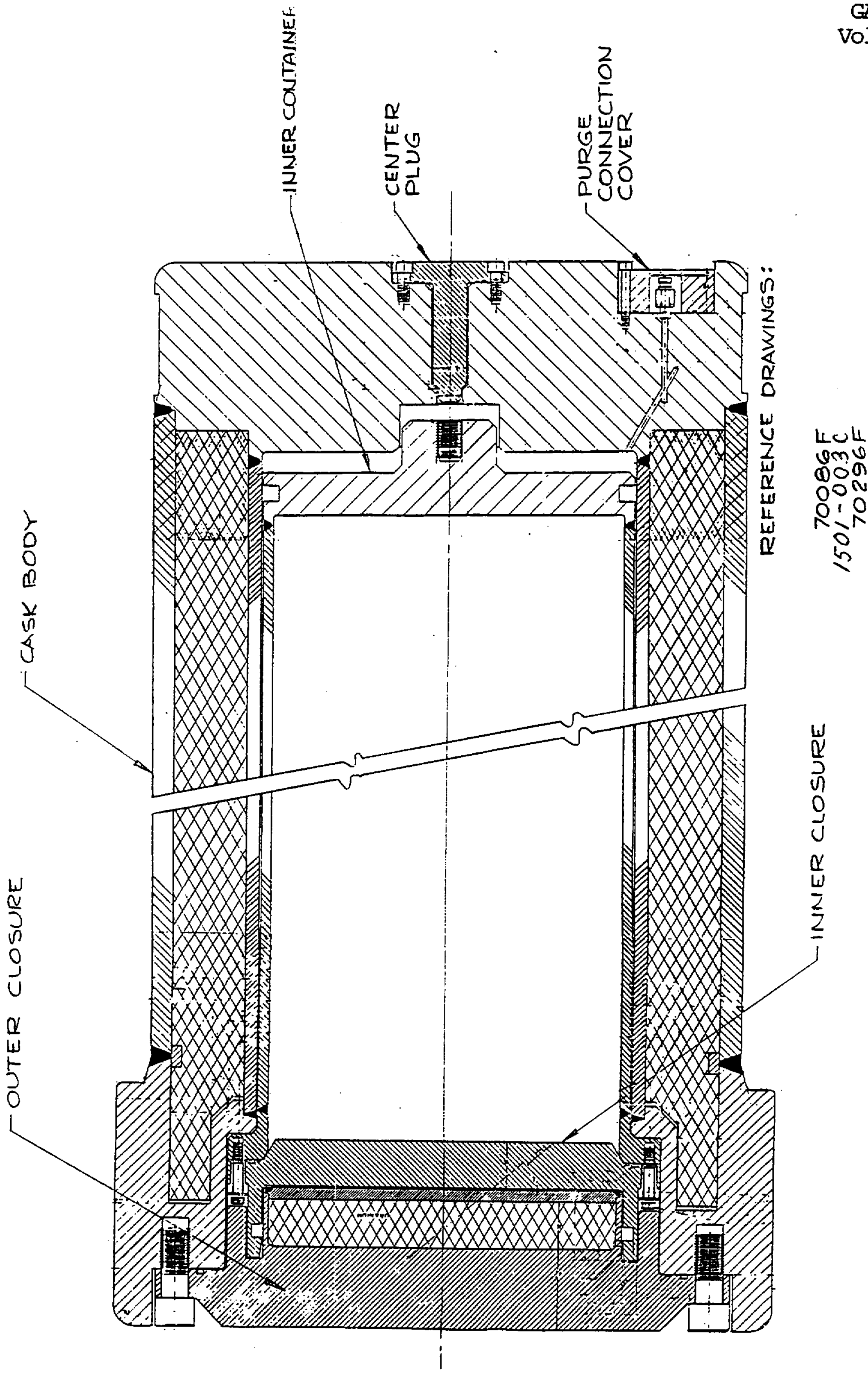
TABLE 1-1
MODEL FSV-1 CASK CONFIGURATIONS A THROUGH D

Configuration	Reference Drawings	Authorized Contents	Allowable Weight-Cask Cavity	Allowable Weight-Contents	Remarks
A	70086F, Rev. 7[a] 1501-003, Rev. C[c] 70296F, Rev. 2[a]	Solid nonfissile irradiated and contaminated hardware	3720 lb	1800 lb	Impact limiter not used. Requires inner container. Loaded wt 46,025 lb
B	70086F, Rev. 7 1501-003, Rev. C[c] 70296F, Rev. 2	Solid nonfissile, irradiated and contaminated hardware	3720 lb	3080 lb	Impact limiter not used. Inner container not required; used with burial liner and coverplate. Loaded weight 46,025 lb.
C	70086F, Rev. 7 1501-003, Rev. C[c] 70296F, Rev. 2 GADR 55-2-10, Issue D GADR 55-2-11, Issue B (GADR-55-2-14, Issue N/C optional)	Solid nonfissile, irradiated, contaminated hardware and optional temporary shield tube	3720 lb	2970 lb[b]	Impact limiter not used; inner container not required, used with burial liner. Supplemental shield ring and coverplate (both stainless steel) used for the burial liner. wt: 750 lb. Optional temporary shield tube may be used. Loaded weight 46,025 lb.
D	70086F, Rev. 7 1501-003, Rev. C[c] 70296F, Rev. 2 GADR 55-2-10, Issue D GADR 55-2-11, Issue A (GADR-55-2-14, Issue N/C optional)	Solid nonfissile, irradiated and contaminated hardware	3720 lb	2970 lb	Impact limiter not used; supplemental shield ring and coverplate (both carbon steel) used for burial liner. Optional shield tube may be used. wt: 750 lb Loaded weight 46,025 lb.

[a]National Lead Company drawing.

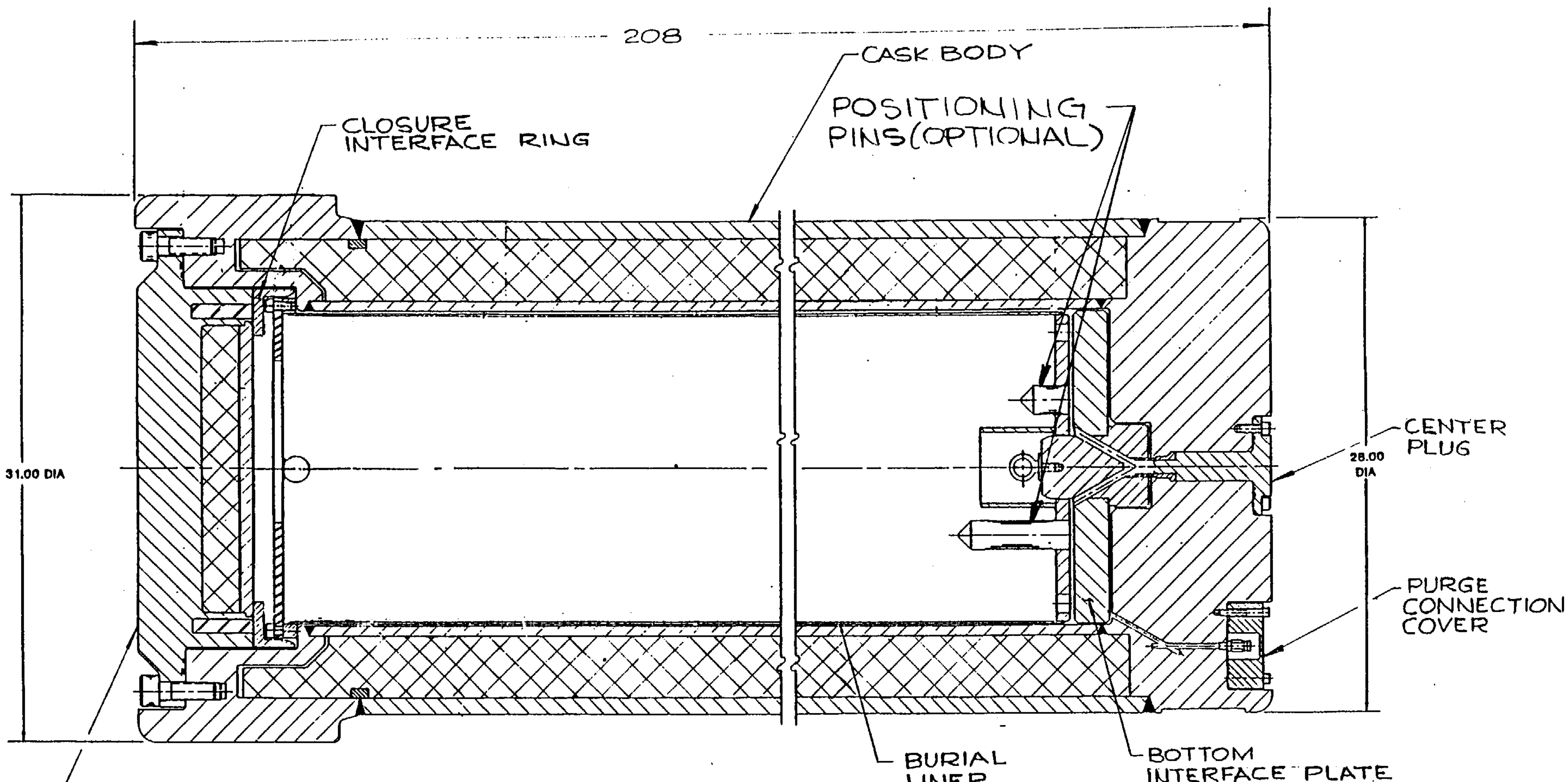
[b]Including optional shield tube.

[c]General Atomics drawing.



MODEL FSV-1 CASK
CONFIGURATION A

FIGURE 1-1

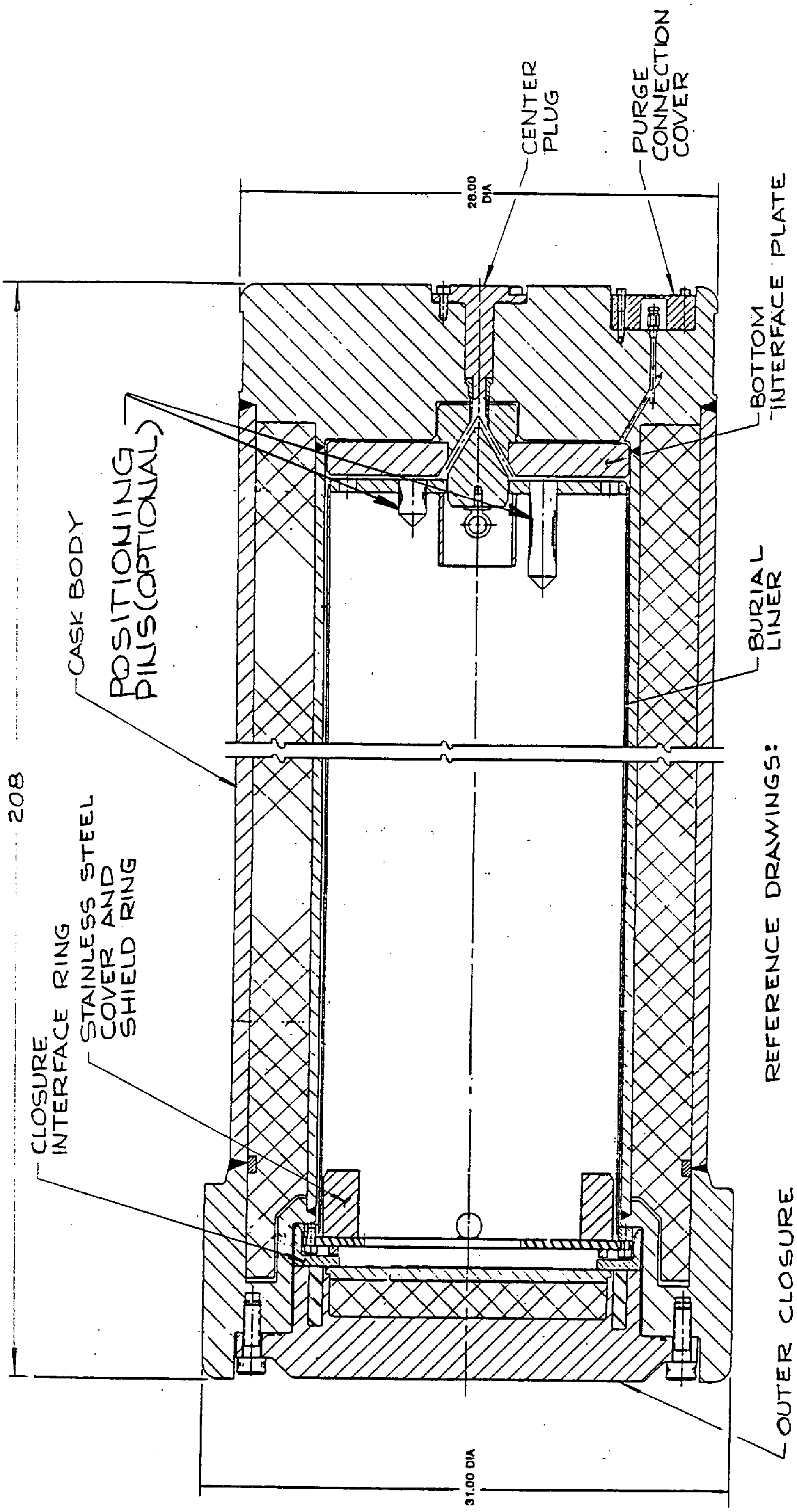


REFERENCE DRAWINGS:

70086F
1501-003C
70296F

FSV-I CONFIGURATION B
FOR IRRADIATED HARDWARE
WITH BURIAL LINER

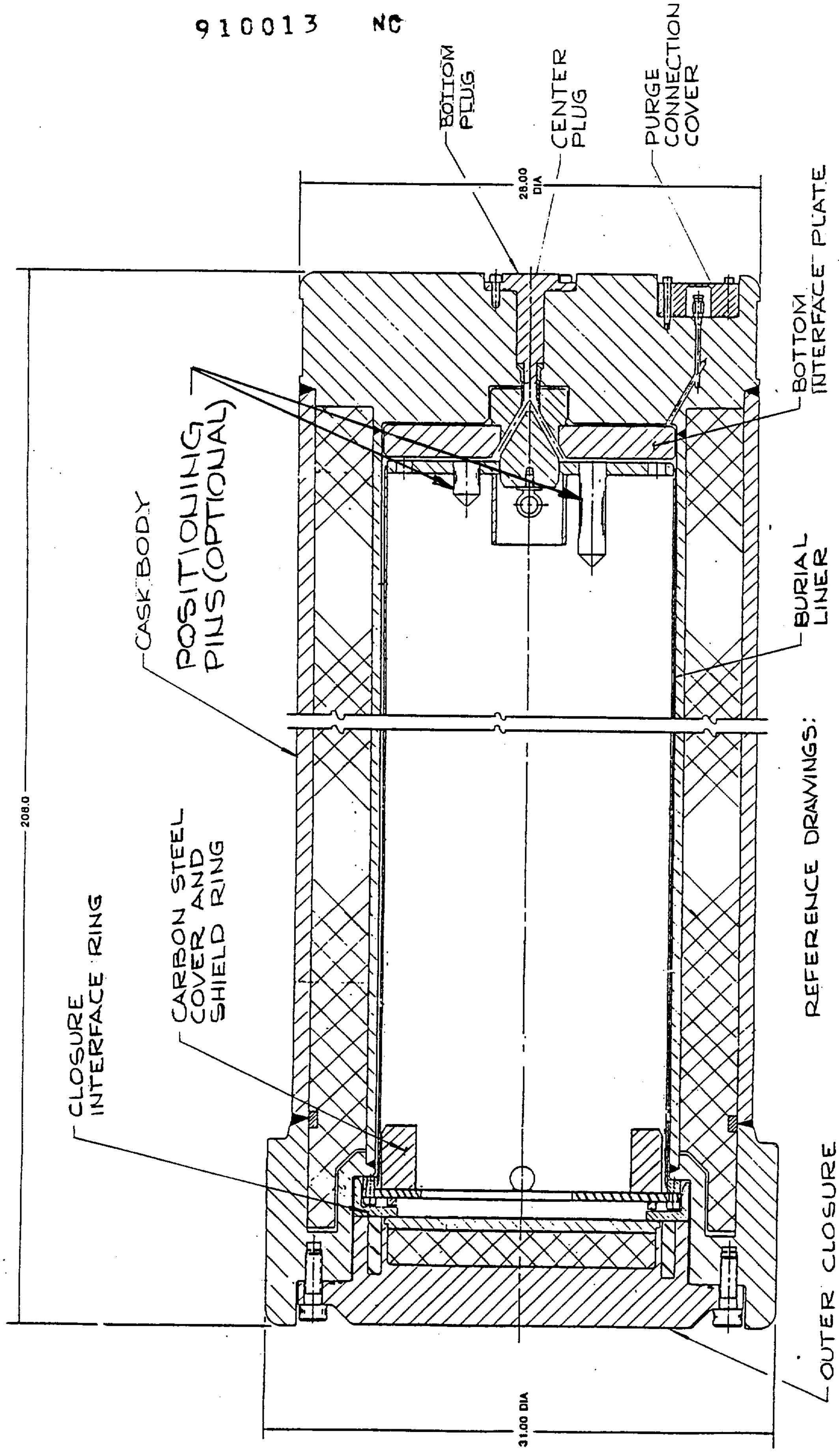
FIGURE 1-2



FSV-1 CONFIGURATION C
FOR IRRADIATED HARDWARE
WITH SHIELDED BURIAL
LINER COVER

70086F
1501-003C
70296F
GADR 55-2-10
GADR 55-2-11

FIGURE 1-3



REFERENCE DRAWINGS:

70086F
1501-003C
70296F
GADR 55-2-10
GADR 55-2-11

FSV-1 CONFIGURATION D
FOR IRRADIATED HARDWARE
WITH SHIELDED BURIAL LINER
COVER - CARBON STEEL

FIGURE 1-4

FIGURE WITHHELD UNDER 10 CFR 2.390

(Applicable for Configurations A,B,C and D)

FIGURE WITHHELD UNDER 10 CFR 2.390

(Applicable for Configurations A,B,C and D)

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

Configuration C
Supplemental Shield Ring and Cover Plate
(Stainless Steel)

FIGURE WITHHELD UNDER 10 CFR 2.390

Configuration D
Supplemental Shield Ring and Cover Plate
(Carbon Steel)

FIGURE WITHHELD UNDER 10 CFR 2.390

Configurations C and D
Shield Tube (Optional)

FIGURE WITHHELD UNDER 10 CFR 2.390

SECTION 2.0

STRUCTURAL EVALUATION

2.0 STRUCTURAL EVALUATION

2.1 STRUCTURAL DESIGN

2.1.1 Discussion

Principal structural components of Model FSV-1 in Configurations A, B, C, and D are the cask body with outer closure and either an inner container or an inner coverplate. Configurations A through D do not require use of the impact limiter.

2.1.2 Design Criteria

Model FSV-1 is designed to comply with the regulations in regard to the release of radioactive material and external radiation dose rate for the normal conditions of transport and the hypothetical accident conditions. Model FSV-1 was designed and evaluated in accordance with the applicable regulations that were in effect prior to April 1969.

2.2 WEIGHTS AND CENTERS OF GRAVITY

A summary of the weights of model FSV-1 Configurations A, B, C, and D is presented in Table 2-1. Model FSV-1 cask body Configurations A, B, C, D have been evaluated for the normal conditions of transport and the hypothetical accident conditions while containing a total weight of 3720 pounds. This total weight consists of 1920 pounds for the inner container and 1800 pounds for the radioactive contents.

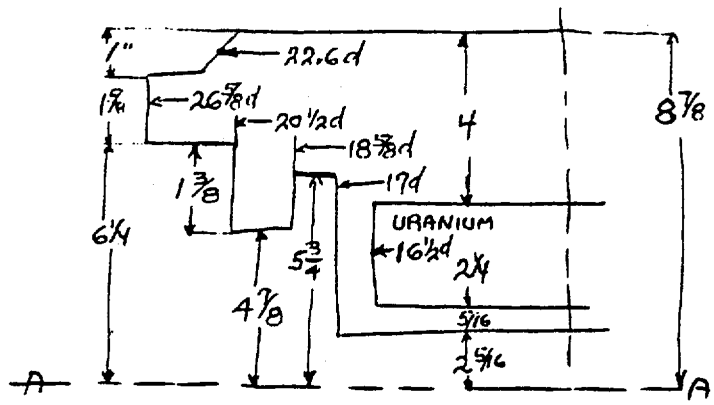
2.2.1 Weight Calculations - Model FSV-1 Configuration A

TABLE 2-1

	Configuration A	Configuration B	Configuration C	Configuration D
Cask Body	42,305	42,305	42,305	42,305
Inner Container	1,920	not used	not used	not used
Burial Liner/ Spacer	not used	640	750	750
Contents - Allowable	1,800	3,080	2,970	2,970
Total	46,025	46,025	46,025	46,025

The center of gravity of Model FSV-1 Configurations A, B, C, and D is located 105.5 inches from the bottom of the package.

2.2.1.1 Cask Closure

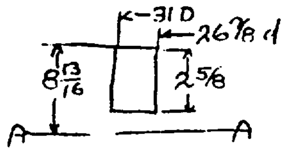


		V (in³)	y	Vy
22.6d	400 in² × 1	= 400 in³	× −8 3/8 =	−3350
26 7/8 d	560 × 1 5/8	= 910	× −7 1/16 =	−6430
20 1/2 d	330 × 1 3/8	= 455	× −5 9/16	−2530
17 d	227 × 3 7/16	= 780	× −4 1/32 =	−3140
		+ 2545 in³		−15,450. in⁴
−18 7/8 d	−273 × 7/8	= −239	× 5 5/16	+ 1330
−16 1/2 d	−214 × 2 1/4	= −482	× 3 3/4 =	+ 1809
		− 721		+ 3139
		+ 1824 in³		− 12,311 in⁴
		.29		.29
	(SS) wt =	530 lbs	M =	− 3.580 in.lbs.

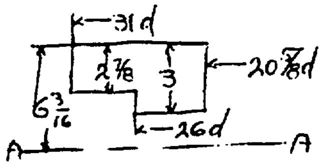
Uranium

16 1/2 d	+214 × 2 1/4	= +482	× −3 3/4 =	−1809
		.683		.683
		330 lbs	M =	−1235 in lbs
	TOTAL WT. HEAD =	860 LBS.	M =	−4815 in lbs.

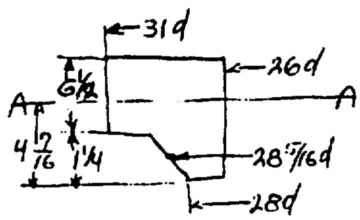
2.2.1.2 <u>Cask Body</u>



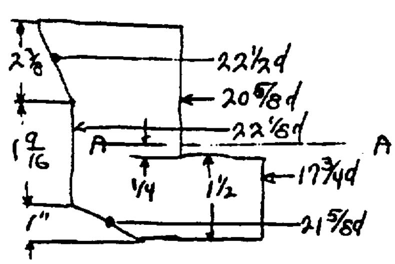
31d $+752\ in^2$
26 7/8 d -568
$184 \times 2\,5/8 = 483\ in^3 \times -7\tfrac{1}{2}'' = -3622$
$.29$ $.29$
wt = 140 lbs M = −1050 in lbs



31d $+752\ in^2 \times 2\,7/8 = 2160\ in^3 \times -4\,3/4'' = -10{,}250.$
26d $+530 \times 1/8 = 66 \times -3\,1/4 = -216.$
$+2226$ $-10{,}466$
$-20\,7/8\,d$ $-335 \times 3 = -1005 \times -4\,11/16 = +4850$
$+1221\ in^3$ $-5616.$
$.29$ $.29$
wt = 354. lbs M = −1628 in lbs

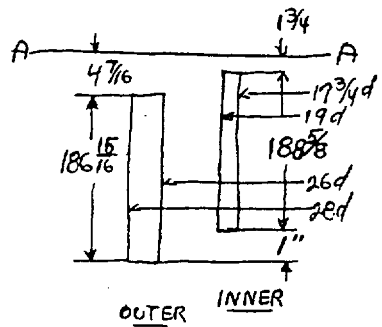


31d $752\ in^2 \times 6.5 = 4880 \times -1/16 = -305.$
28 5/16 d $630 \times 1\,1/4 = 787 \times +3\,13/16 = +3000.$
$+5667$ $+2695$
$-26d$ $-530 \times 7\,3/4 = -4100 \times +9/16 = -2300$
$+1567\ in^3$ $+395.$
$.29$ $.29$
wt = 455 lbs M = +114 in lbs



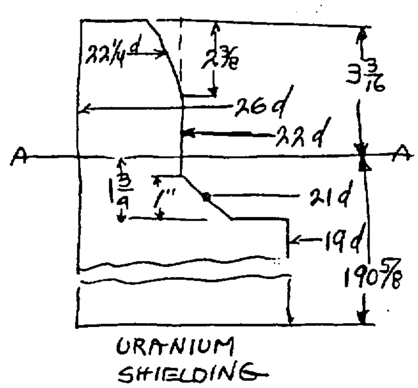
22 1/2 d $397\ in^2 \times 2\,3/8 = 942\ in^3 \times -2\,1/4 = -2120$
22 1/8 d $385 \times 1\,9/16 = 601 \times -9/32 = -169$
21 5/8 d $367 \times 1 = 367 \times +1\,1/4 = +458$
$+1910$ -1831
$-20\,5/8\,d$ $-335 \times 3\,7/16 = -1154 \times -1\,15/32 = +1670$
$-17\,3/4\,d$ $-247 \times 1\,1/2 = -370 \times +1 = -370$
-1524 $+1300$
$+386$ -531
$.29$ $.29$
wt = 112 lbs W = −154 in lbs

2.2.1.2 Cask Body (Continued)



28d $613 in^2$
−26d -530
$83 in^2 \times 186\frac{15}{16} = 15{,}500 in^3 \quad \times +97\frac{29}{32} = +1{,}511{,}000.$
$\times .29 \qquad\qquad \times .29$
(outer) wt 4500 lbs M = +439,000

19d $283.5 in^2$
−17 3/4 d -247
$36.5 in^2 \times 188\frac{5}{8} = 6870 in^3 \quad \times +96.06 = +660{,}000$
$\times .29 \qquad\qquad \times .29$
(inner) wt = 1990 lbs M = 191,200 "lb



26d $530 in^2 \times 193\frac{13}{16} = +102{,}750 in^3 \quad \times +93\frac{23}{32} = +9{,}630{,}000.$

−19d $-283.5 \times 188\frac{7}{8} = -53{,}500 \quad \times +96\frac{3}{16} = -5{,}150{,}000$

−21d $-346 \times 1 = -346. \quad \times +1\frac{1}{4} = -437$

−22d $-380 \times 1\frac{9}{16} = -594 \quad \times -\frac{1}{32} = +19$

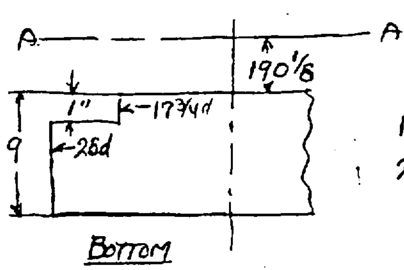
−22 1/4 d $-389 \times 2\frac{3}{8} = -925 \quad \times -2 = +1850$

$-55{,}365 \qquad -5{,}148{,}563$

$+47{,}385 \qquad +4{,}481{,}437$

$\times .683 \qquad \times .683$

URANIUM wt 32,400 lbs M = +3,060,000"



17 3/4 d $247 in^2 \times 1 = 247 in^3 \quad \times +190\frac{5}{8} = +47{,}100$

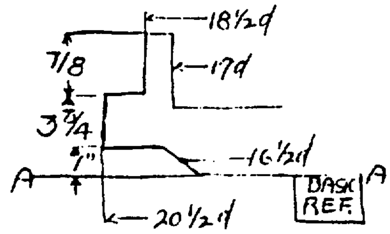
28 d $613 \times 8 = 4904 \quad \times +195\frac{1}{8} = +960{,}000$

$+5151 \qquad +1{,}007{,}100.$

$\times .29 \qquad \times .29$

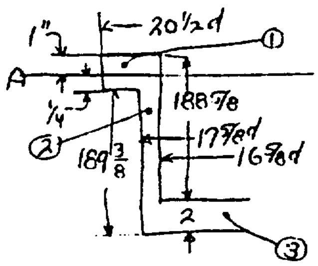
wt = 1494 lbs M = 292,060 in lb

2.2.1.3 Inner Container



HEAD

18½d 268 in² × 7/8 = 234 in³ × −5 3/16 = −1212
20½d 330 × 3 3/4 = 1238 × −2 7/8 = −3560
16½d 213 × 1 = 213 × −½ = −107
+1685 in³ −4879
−17d −227 × 3 7/8 = −766 × −3 15/16 = +3010
+919 −1869
.29 .29
wt = 266 lbs M = −542



CONTAINER

$wt_1 = \frac{330 - 217}{113} \times 1\frac{1}{4} \times .29 = 41.$ lbs $\times -\frac{7}{8} =$ $-16.$

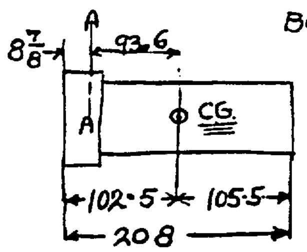
$wt_2 = \frac{244 - 217}{27} \times 187\frac{7}{8} \times .29 = 1470.$ $\times +93\frac{15}{16} =$ $+138,000.$

$wt_3 = 244 \times 2 \times .29 = 142.$ $\times 185\frac{7}{8} =$ $+26,800$

wt = 1653 lbs M = +164,784 in#

CONTENTS OF CONTAINER $300^{\#} \times 6 =$ 1800 lbs $\times 93\frac{27}{32} = M = +169,000$ in#

2.2.1.4 Weight Summation



		WT.	MOMENT
CASK	HEAD	860 LBS	-4815.
	BODY	140	-1050.
		354	-1628.
		455	+ 114.
		112	- 154.
		4500	+ 432,000.
		1990	+ 191,200
		32400	+ 3,060,000
		1494	+ 292,060
CASK-TOTAL EMPTY		42,305	+ 3,474,727
	CONTAINER	266	- 542
		1653	+ 164,784
	CONTENTS	1800	+ 169,000
CASK-TOTAL-LOADED		46,024 lbs x [93.6] =	+ 4,307,969 in lbs

2.2.2 Weight Calculation - Configuration B

2.2.2.1 Bottom Interface Plate

Plate:	$(17.625^2 - 3.76^2)\ \pi/4 \times 1.94 \times 0.285 =$	129
Pins:	$[(3.75^2 \times \pi/4 \times 3.75) + (2.25^2 \times \pi/4 \times 2.25)]\ 0.285 =$	14
	Total	143 lb

2.2.2.2 Burial Liner

Shell:	$(17.5^2 - 17.26^2)\ \pi/4 \times 187.5 \times 0.285 =$	350
Base:	$[(17.26^2 - 3.91^2)\ \pi/4 \times 0.75 + (1.625^2 \times \pi/4 \times 7.38)]\ 0.285 =$	52
Flange:	$(19.25^2 - 17.5^2)\ \pi/4 \times 0.75 \times 0.285 =$	11
Cover:	$[(19.25^2 \times \pi/4 \times 0.5) - (9.0 \times 2.0 \times 0.5) + (1.5^2 \times \pi/4 \times 15)]\ 0.285 =$	46
	Total	459 lb

2.2.2.3 Closure Interface Ring

$$[(19.5^2 - 15^2)\ \pi/4 \times 0.625 + (20.44^2 - 19.5^2) \times \pi/4 \times 2.38]\quad 0.285 = \quad 42\ \text{lb}$$

2.2.2.4 Total Allowable Content Weight - Configuration B

Model FSV-1 has been evaluated for a total weight of 46,024 lb of this, 3,719 lb were in the cavity of the cask body.

The bottom interface plate, the burial liner and the closure interface ring have a total weight of 644 lb, therefore, the allowable weight of the contents is:

3719 - 644 = 3075 lb (use 3080)

2.2.3 Weight Calculation - Configurations C and D

2.2.3.1 Shield and Impact Ring

$$\{[(17^2 - 13^2)\ \pi/4 \times 4] + [(16^2 - 15^2)\ \pi/4 \times 0.5]\}\ 0.285 = 111 \text{ lb}$$

2.2.3.2 Optional Temporary Shield Tubes

1-in. thick: $$\left\{\left[(6^2 - 4^2)\ \frac{\pi}{4} \times 144\right] + \left[(6^2)\ \frac{\pi}{4} \times 9\right]\right\} 0.285 = 717 \text{ lb}$$

2-in. thick: $$\left\{\left[(6^2 - 2^2)\ \frac{\pi}{4} \times 144\right] + \left[(6^2)\ \frac{\pi}{4} \times 9\right]\right\} 0.285 = 1104 \text{ lb}$$

2.2.3.3 Total Allowable Weight - Configurations C and D

The 3,719 lb allowable for the cavity of the cask body is also applicable to the Configurations C and D. The weight of the shield ring and impact ring is added to the 644 lb from Section 2.2.2.4. Now the allowable weight of the contents is:

3719 - (644 + 111) = 2964 lb (use 2970)

When an optional temporary shield tube is used, its weight will be considered part of the contents weight.

2.3 MECHANICAL PROPERTIES OF MATERIALS

2.3.1 Model FSV-1 Packaging (Configurations A, B, C, D)

2.3.1.1 "As-Cast" Unalloyed Depleted Uranium

Density

18.9 grams/cc or 0.683 lb/in^3

Mechanical Properties

Ultimate Tensile Strength	60,000 to 100,000 psi
Yield Strength	25,000 to 45,000 psi
Elongation	8% to 15%
Modulus of Elasticity	Approximately 24 (10)^6 psi
Hardness	Rockwell B 65 to 90

Thermal Expansion	6.5 (10)$^{-6}$ in/in°F

2.3.1.2 Stainless Steel Pipe, Type 304 per ASTM Spec. A-351, Grade CF-8

Physical Properties

Density	0.287 lb/in.^{3}
Specific Gravity	7.94 grams/cc
Melting Range	2550° to 2650°F
Modulus of Elasticity	28 x 10^6 psi
Specific Heat (32° to 212°F)	0.12 Btu/lb/°F

Thermal Conductivity

At 200°F	9.4 Btu/hr/ft^2/°F/ft
At 1000°F	12.5 BTU/hr/ft^2/°F/ft

Mean Coefficient of Thermal Expansion

32° to 212°F	9.6 in./in./°F x 10^6
32° to 600°F	9.9 in./in./°F x 10^6
32° to 1000°F	10.2 in./in./°F x 10^6

Mechanical Properties (at 72°F)

Ultimate Tensile Strength	70,000 psi
Yield Strength	30,000 psi
Elongation	35%
Hardness	R_B 88

2.3.1.3 <u>Stainless Steel Forgings, Type 304 per ASTM Spec. A-182, Grade F-304</u>

Physical Properties

Same as 2.3.1.2

Mechanical Properties

Ultimate Tensile Strength	70,000 psi
Yield Strength	30,000 psi
Elongation	40%
Hardness	R_B 88

2.3.1.4 <u>Uranium Welds</u>. All uranium welding will be accomplished using single V-butt joints and inert direct current tungsten arc welding. The inert gas used for shielding and trailing shields shall be welding grade argon. The filler and base metals shall be depleted uranium.

2.3.1.5 Stainless Steel Welds (Refs. 2-1 and 2-2). All stainless steel welds will be in accordance with the "Rules for Construciton of Nuclear Vessels" (Ref. 2-1). All of the welding procedures and welders will be qualified in accordance with "Welding Qualifications" (Ref. 2-2).

2.3.1.6 Seals (Refs. 2-3, 2-4, and 2-19).

1. All metal O-rings shall be self-energized for use in bolted flange assemblies. These O-rings will be made of silver plated Inconel X tubing. Service temperature is -320° to +1300°F. The following metal O-rings or equivalent have been selected for sealing Model FSV-1 (Configurations A through D).

   a) Cask Closure Seal - United Aircraft products, Inc. Cat. No. U-6420-22000-SEA; OD = 22.01; ID = 21.76; Tube Dia. = 0.125.

   b) Inner Container Closure Seal - United Aircraft Products, Inc. Cat. No. U-6420-17430-SEA; OD = 17.44; ID = 17.19; Tube Dia. = 0.125.

   c) Cask Center Plug Seal - United Aircraft Products Inc. Cat. No. U-6420-02813-SEA; OD = 2.81; ID = 2.56; Tube Dia. = 0.125.

   d) Cask Purge Connection Cover Seal - United Aircraft Products, Inc. Cat. No. U-6420-02630-SEA; OD = 2.62; ID = 2.38; Tube Dia. = 0.125.

All elastomer O-rings shall be molded per AMS Specification 3304 of silicone rubber or equivalent. Service temperature for this material is -100°

to +500°F. The material will resist temperatures up to 700°F for short periods. The following silicone rubber O-rings or equivalent have been selected for sealing Model FSV-1 (Configurations A through D).

a) Cask Closure Seal - Parco No. PRP-568-392; OD = 23.375; ID - 23.00; Dia = 0.187.

b) Inner Container Closure Seal - Parco No. PRP-568-386; OD = 17.375; ID = 17.00; Dia. = 0.187.

c) Cask Center Plug Seal - Parco No. PRP-568-236; OD = 3.500; ID = 3.25; Dia. = 0.125.

d) Cask Purge Connection Cover seal - Parco No. PRP-568-233; OD = 3.125; ID = 2.875; Dia. = 0.125.

2.3.1.7 Fasteners (Refs. 2-5, 2-6, and 2-7)

a. The bolts used in the assembly of the inner container are alloy steel per AMS 6322 with cadmium plating per QQ-P-416, Type 11, Class 3. These bolts are heat treated for 180KSI min, ultimate tensile strength with a hardness of R_C40-44. The 1/2-inch size used in fastening the inner container closure to the container body has a minimum axial tensile strength of 26,700 lb. (Ref. 2-5).

b. The bolts of the inner container closure are threaded into "screw-lock" inserts made of Type 18-8 stainless steel (per AMS-7245B) wire having an ultimate tensile strength of approximately 200,000 psi. These "screw-lock" inserts meet military specification for locking torque and vibration. The internal thread conforms to thread form standards issued by the Department of Commerce (Ref. 2-6).

c. The bolts used in the assembly of the cask closure to the shipping cask body shall be cadmium plated per QQ-P-416 alloy steel per FF-S-86C with the following physical properties for 1-1/4-7 UNC size (Ref. 2-7):

Tensile Strength, min.	160,000 psi
Yield Strength, min.	130,000 psi
Heat Treatment	R_C36-43

2.3.2 Configurations B, C and D

The following materials are used in addition to those used in the model FSV-1 Configuration A. Only Configuration D uses the stainless steel in the burial liner cover and the shield ring.

2.3.2.1 Carbon Steel (ASTM A36)

Physical Properties

Density	490 lb/ft^3
Modulus of Elasticity	30×10^6 psi
Specific Heat	0.11 Btu/lb°F

Thermal Conductivity

At 32°F	26.5 Btu/hr-ft°F
At 212°F	26.0 Btu/hr-ft°F
At 572°F	25.0 Btu/hr-ft°F

Coefficient of Thermal Expansion

70 - 250°F	6.77×10^{-6} in/in°F
70 - 550°F	7.34×10^{-6} in/in°F

Mechanical Properties

Ultimate Tensile Strength	58,000 - 80,000 psi
Yield Strength	36,000 psi
Elongation	23%

2.3.2.2 Stainless Steel Type 304 (ASTM A240)

Physical Properties:

Density	496 x lb/ft^3
Modulus of Elasticity	28 x 10^6 psi
Specific Heat	0.12 Btu/lb°F

Thermal Conductivity:

At 32°F	8.0 Btu/hr-ft°F
At 212°F	9.4 Btu/hr-ft°F
At 572°F	10.9 Btu/hr-ft°F

Coefficient of Thermal Expansion:

70 to 250°F	8.54 x 10^{-6} in/in°F
70 to 550°F	9.33 x 10^{-6} in/in°F

Mechanical Properties:

Ultimate Tensile Strength	75,000 psi
Yield Strength	30,000 psi
Elongation	40%

2.4 GENERAL STANDARDS FOR ALL PACKAGES

2.4.1 Chemical and Galvanic Reactions

Investigations have shown that uranium combines with stainless steel by solid state diffusion at temperatures above 1000°F. The iron-uranium eutectic melts at 1337°F so that if the two materials are in intimate contact at this temperature a molten alloy will be formed (Ref. 2-8).

Other investigations have shown that uranium in contact with stainless steel will penetrate the stainless steel by solid state diffusion in 24 hours at 1400°F. At 1355°F there was no attack on the stainless steel.

Recent tests of stainless steel - uranium - stainless steel assemblies wherein the surfaces of the stainless steel next to the uranium were spray coated with a 0.005-inch-thick coating of copper showed this coating to be an effective barrier to diffusion between the stainless steel and uranium at temperature up to 1750°F (Ref. 8). All surfaces of stainless steel in contact with the depleted uranium shielding will be coated with 0.005-inch-thick copper coating for the model FSV-1 packaging.

2.4.2 Positive Closure

Twenty four (24) high strength, socket head cap screws, torqued to 1000 foot-pounds are used to secure the outer closure to the cask body.

2.4.3 Lifting Devices

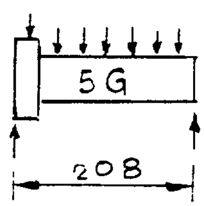
Model FSV-1 Configurations A through D are lifted by means of two sockets installed in machined recesses located in the enlarged diameter section of the closure end of the cask body. A dedicated lifting device with a ball located on each arm is used to lift the package. The sockets are removable and can be replaced if damaged in any way.

2.4.4 Tiedown Devices

During transport the Model FSV-1 cask is attached to the rear support on the semitrailer by four (4) high strength socket head cap screws which are installed in threaded holes located in the base of the cask. The upper end of the package rests in a saddle and is restrained by a tie-down strap.

2.5 STANDARDS FOR TYPE B PACKAGING

2.5.1 Load Resistance



5g - Uniformly Distributed

WT = 46024 lb

W = 5(46024) = 230,120 lb

$$\text{Max at center} = \frac{W\ell}{8} = \frac{230120}{8}(208) = 6{,}000{,}000 \text{ in. lb}$$

Assume only outer shell is stressed

OD = 28" ID = 26"

$$I = \frac{\pi}{4}(R^4 - r^4) = \frac{\pi}{4}(14^4 - 13^4) = \underline{7750} \text{ in.}^4$$

$$Z = \frac{7750}{14} = 554 \text{ in.}^3$$

$$S_b = \frac{M}{Z} = \frac{6{,}000{,}000}{554} = \underline{\underline{10{,}800 \text{ psi}}} \text{ ok, less than } 30{,}000 \text{ psi}$$

2.5.2 External Pressure

25 psig Roark XVI Case 3c (Stability)

17-5/8 OD - 16-5/8 ID - 1/2 wall - 190-5/8 long

$$p^1 = \frac{1}{4}\ \frac{E}{1-\nu^2}\ \frac{t^3}{r^3} = \frac{1}{4}\ \frac{30(10^6)}{(1-.09)}\ \frac{(1/2)^3}{(8.31)^3} = \underline{1793} \text{ psi} \qquad \text{o.k.}$$

2.6 NORMAL CONDITIONS OF TRANSPORT

2.6.1 Differential Thermal Expansions

2.6.1.1 Clearances. The cask and its container assemblies are stainless steel and uranium constructions. No lead is present and thus there are no problems associated with voids of this kind, which vary greatly in volume with changes in temperature and also shift in position within the cask. The uranium is monolithic and jacketed by the steel. The dimensional proportions of the cask shielding cylinder uranium require that there be minimal clearances for machining and assembly purposes. These clearances are a substantial part of the differential expansions which developed in several of the cases examined. The location of gaps and materials of construction are shown on Fig. 2-1.

2.6.1.2 Coefficients of Expansion. Coefficient of expansion used for depleted uranium is 6.5×10^{-6} in./in.°F. This value is obtained from records of the NL Company-Albany plant and refer specifically to as-cast 0.2% molybdenum uranium - unalloyed composition.

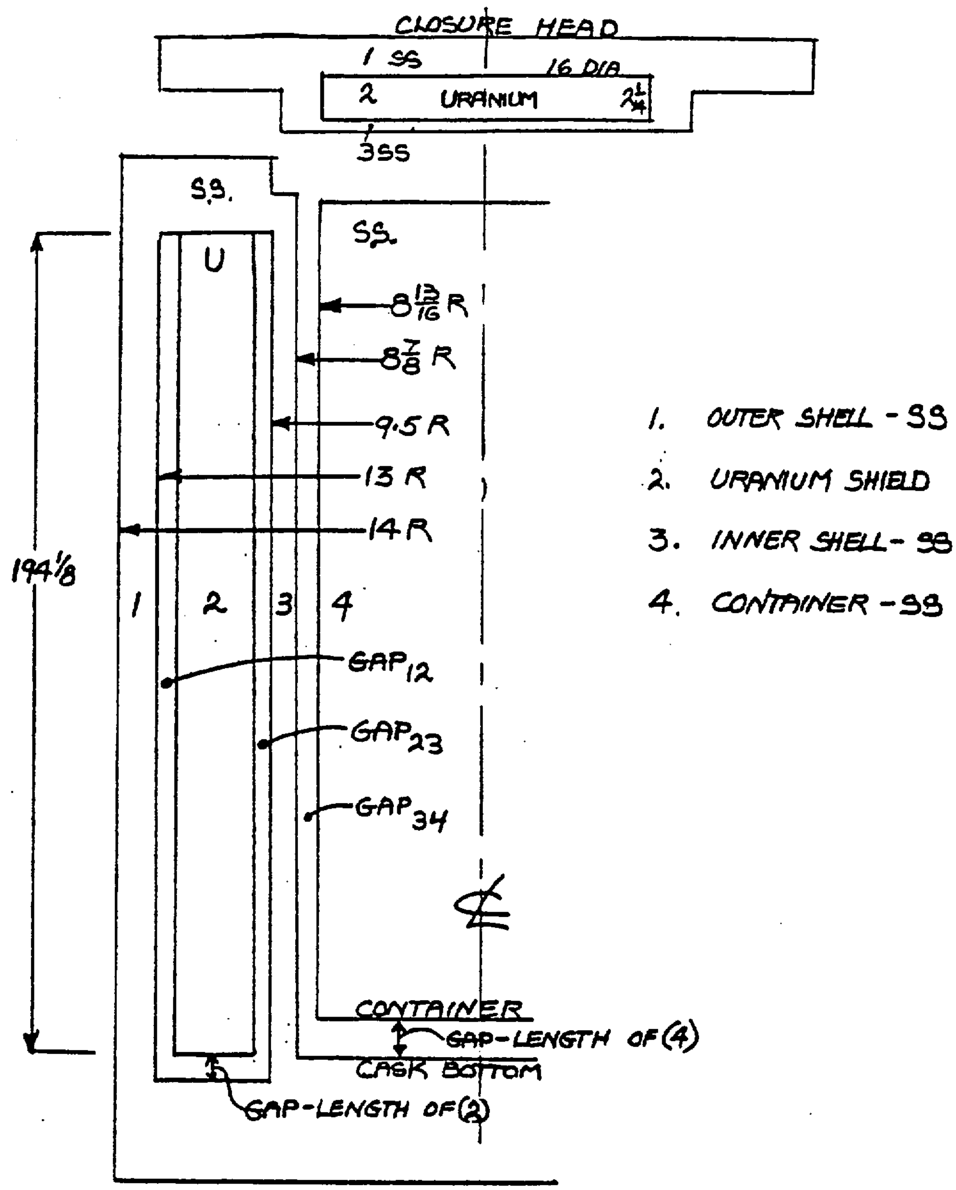


FIGURE 2-1 Location of Gaps and Materials for Model FSV-1 in Configurations A, B, C and D

Stainless Steel values are from Section III, Table N-426 of the Nuclear Code, as follows:

A = instantaneous values at given temperature
B = mean coefficient (from 70°F to indicated temperature)

A	B	Temp °F
9.11	9.11	70
9.73	9.47	300
10.43	9.82	600
10.90	10.05	800

2.6.1.3 Temperature Distribution. Temperature distribution through the cask under hypothetical accident conditions has been obtained from memorandum III, a part of the specification, dated 18 April 1968, and titled "Heat Transfer Calculations for PSC Fuel Shipping Cask". Heat generation rates were chosen in each case to give the maximum differential temperatures.

2.6.1.4 Cases Investigated. The following cases are investigated relative to axial and to radial differential expansions and contractions for the two uranium bodies contained within the stainless steel structure.

Case 1 - 30 minutes after start of fire (1101 Btu/hr fuel rate)
Case 2 - 10 hours after start of fire (2322 Btu/hr fuel rate)
Case 3 - start up - cask 70° - container and inner shell 240°
Case 4 - Immersion in water 70° - container and inner shell 240°
Case 5 - Low temp. - 40° whole cask - No container
Case 6 - Low temp. - 40° cask - Container and inner shell 240°

2.6.1.5 Analysis of Uranium Shielding in Cask Body

In the calculations + is a clearance or gap
- is an interference (based on original 0 gap)

The various negative (-) dr or dl values thus indicate the minimum initial clearances at 70°F required to prevent interference and stressed conditions. These requirements are reflected in the drawings.

The maximum values required for such clearances for the cask itself are:

Gap 12 = -0.0322 from case 2	Interferences - to be prevented by suitable mfg. clearances.
Gap 23 = -0.015 from case 2	
Gap 34 = -.0367 from case 3	
Length container = -0.309 from case 6	

Case 1

$T_1 = 1120°$ $T_3 = 430°$ $T\theta = 70°$ $T_4 = 370°$

Gap 12 Assume $T_2 = T_3$ for max. diff.

$dr = (13")(T_1 - T\theta)(10.05)10^{-6} - (13")(T_2 - T_0)(6.5)10^{-6}$

$= 0.137 - 0.0304 = +\ \underline{0.1066"}$ SS > U gap

Gap 23 Assume $T_2 = T_3$ for min. clearance

$dr = (9.5")(T_2 - T_0)(6.5)10^{-6} - (9.5")(T_3 - T_0)(9.6)10^{-6}$

$= 0.0222 - 0.328 = -\ \underline{0.0106\ U < SS}$ interference

Gap 34 Assume T_4 = 370° from 2322 Btu/hr fuel rate

dr=(8-7/8")(T_3 - T_0)(9.6)10^{-6} -(8-13/16")(T_4 -T_0)(9.5)10^{-6}

= 0.0306 - 0.0251 = + 0.0055 gap

Length of U. Assume T_2=T_3 for max. differential

dl=(194-1/8)(T_1-T_0)(10.05)10^{-6} -(194 1/8)(T_3-T_0)(6.5)10^{-6}

= 2.05 - 0.455 = 1.595" expansion SS > U gap

Container shows gap.

Case 2

T_1 = 220° T_3 = 340° T_0 = 70° T_4 = 370°

GAP 12 Assume T_2=T_3 for min. clearance

dr=(13")(T_1 - T_0)(9.4)10^{-6} -(13)(T_2 - T_0)(6.5)10^{-6}

= 0.0183 - 0.0228 = -0.0045 U > SS interference

Gap 23 Assume T_2=T_1 for min. clearance

dr=(9.5")(T_2 - T_0)(6.55)10^{-6} -(9.5)(T_3 - T_0)(9.47)10^{-6}

= 0.00925 - 0.0243 - 0.015 U < SS interference

Gap 34 Assume T_4 = 370°

dr=(8-7/8")(T_3 - T_0)(8.47)10^{-6} -(8-13/16)(T_4 -T_0)(9.47)10^{-6}

= 0.0227 - 0.025 - 0.0023 interference

Case 3 Cask at original dimen. T_4 = 241° T_0 = 70° T_3 = 70°

Gap 34 dr=0-(8-13/16)(T_4-T_0)(9.7)10^{-6}

= - 0.0367" container increase - interference

Length Container

$dl=(187-5/8)(T_4-T_0)\ (9.7)10^{-6}$

$=-0.309$ container increase interference

Case 4

$T_1 = 70^{\circ}$ T_2 assumed $= T_3 = 450^{\circ}$ $T_0 = 70^{\circ}$ $T_4 = 240^{\circ}$

Gap 12 $= 0 -(13)(T_2-T_0)\ (6.5)10^{-6}$

$= 0 - 0.0322 = -.0322$ SS < U interference

Gap 23 $= 0$

Gap 34 = negligible

Length Container - in time same as case 3

Case 5

$T_1=T_2=T_3 = 40^{\circ}$ $T_0 = +70$

Gap 12 $dr = (13)(T_1 - T_0)(9.11)10^{-6} -(13)(T_1-T_0)(6.5)10^{-6}$

$= -0.013 + 0.0093 = 0.0037$ SS < U interference

Gap 23 $dr = (9.5)(T_2 - T_0)(6.5)10^{-6} -(9.5)(T_3-T_0)(9.11)10^{-6}$

$= -0.0068 = 0.0095 = + 0.0027$ gap

Case 6

$T_1=T_2 = -40^{\circ}$ $T_3=T_4 = 240^{\circ}$ $T_0 = 70^{\circ}$

Gap 23 $dr = (9.5)(T_2 - T_0)(6.5)10^{-6} -(9.5)(T_3-T_0)(9.11)10^{-6}$

$= -0.0068 - 0.0147 = -0.0218$ interference

2.6.1.6 Analysis of Uranium Shielding in Cask Closure

Case 1

Assume same gradients as given for cask.

$T_1 = 1120° \quad T_2 = 340° \quad T_0 = 70°$

$\Delta t_s = 1050°$ for SS space expansion

$\Delta t_u = 430-70 = 360°$ for U expansion from original machined dimension

Length $dl = (16'') [\Delta t_s \; 10.05 - \Delta t_u \; 6.5] 10^{-6}$

$= 16 \; [1050(10.05) - 360 \; (6.5)] 10^{-6}$

$= 16 \; (11000 - 2340) 10^{-6} = 0.1384$ gap

Thickness - also negligible

$$dt = \frac{2\text{-}1/4}{16} (0.1384) = 0.0195 \text{ gap}$$

Case 2

$T_1 = 220° \quad T_3 = 340° \quad T_o = 70°$

$\Delta t_s = 150°$

$\Delta t_u = 340 - 70 = 270°$

Length $dl = 16 \; [\Delta t_s \; (9.47) - \Delta t_s \; (6.5)] 10^{-6}$

$= 16 \; [150 \; (9.47) - 270 \; (6.5)] \; 10^{-6}$

$= 16 \; (1420 - 1750) 10^{-6}$

$= 5280\ (10^{-6}) = -\ \underline{0.00528''}$

<u>Thickness</u> dw - $0.00528 \times \dfrac{2\text{-}1/4''}{16} = -$ <u>0.00075 interference</u>

<u>Case 3</u>

No diff. exp.

<u>Case 4</u>

No diff exp.

<u>Case 5</u>

Temp. drop = $-40 - (+70) = -110°$

<u>Length</u> dl = $16\ (-110)\ (9.11 - 6.5)10^{-6}$

$= -4600\ (10^{-6}) = 0.0046$ interference

<u>Case 6</u>

No diff exp.

<u>Summary all cases</u>. For disc. max. interference is only 0.00528 in. assuming metal to metal fit at 70°.

Manufacturing clearances would be greater than this for the uranium disc in the closure head.

2.6.2 <u>Vibration</u>

This cask is designed for transport by trailer only. Therefore, the only concern is that the fundamental frequency of vibration for the cask as a simply supported beam, loaded by its own weight, be appreciably higher than the repeatable impulse frequencies for the trailer itself.

The cask is considered to have a total moment of inertia (I) equal to the sum of the individual I values of the two shells and the uranium cylinder.

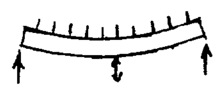
$$I_{outer\ shell} = \pi/4\ (14^4 - 13^4) = 7{,}750\ \text{in.}^4$$

$$I_{inner\ shell} = \pi/4\ (9.5^4 - 8.875^4) = 1{,}530$$

$$I_{uranium} = \pi/4\ (13^4 - 9.5^4) = \underline{16{,}041}$$

$$I_{total} = 25{,}321\ \text{in.}^4$$

Total weight of cask and contents = 46,500 lb



ℓ = 208 in.

$$\text{Frequency} = \frac{3.55}{\sqrt{\frac{5}{384}\frac{W\ell^3}{EI}}} = \frac{3.55}{\sqrt{\frac{5}{384}\frac{(46{,}500)(208)^3}{29 \times 10^6\ (25{,}321)}}}$$

$$= \underline{41.2} \quad \text{cycles per second (cps)}$$

Fundamental frequencies developed in trailers are generally in the range of 4 to 16 cps (see "Shock and Vibration Handbook, Vol. 3, Sect. 45).

2.6.3 Internal Pressure 50 psig Roark XIII - Case 1

See section 2.5.2 for inner container description

Hoop Stress

$$S_2 = \frac{PR}{t} = \frac{50(8.62)}{1/2} = 872 \text{ psi} \quad \text{ok, less than 30,000 psi}$$

Meridional Stress

$$S_1 = \frac{PR}{2t} = \frac{862}{2} = 481 \text{ psi}$$

Radial Displacement

$$= \frac{R}{E}(S_2 - \nu S_1)$$

$$= \frac{8.62}{30(10^6)}[862 - 0.3\ (431)Z] = \frac{6300}{30(10^6)} = 0.00021 \text{ inches} \quad \text{ok}$$

2.7 HYPOTHETICAL ACCIDENT CONDITIONS

2.7.1 Free Drop

The dynamics of the 30-foot free fall requires that a value be found for the maximum stress at impact in order to use structural analysis methods based on statics.

Literature on the subject of dynamic stresses is largely theoretical and seldom of engineering application value. The complexity can be reduced by limiting the problem to (1) compressive stresses on flat impact (2) at 44 ft/sec and (3) to steel, aluminum and uranium materials.

The most promising engineering formula is that for dynamic compression of rigid-plastic cylinders and is the one used herein. It is well authenticated by:

(1) Goldsmith: Impact - eq. 5.97 page 191

(2) Cristensen: Dynamic plasticity - eq 7.8 page 55

$$\rho v_1^2 = \varepsilon_1 \; (P_1 - P_y)$$

$$\rho = \frac{\text{lb/in}^3}{386} \qquad v_1^2 = [44 \text{ ft/sec x } 12]^2 = 278{,}784 \text{ (in/sec)}^2$$

where P_1 = initial, and maximum stress corresponding to moment of impact,

ε_1 = max. strain corresponding to P_1, and

P_y = static compressive yield point (log 0.002 in/in strain method)

Values of ρ and ρv_1^2

Aluminum	ρ = 0.097/386 = 0.000251	ρv_1^2 = 70
Steel (incl SS)	ρ = 0.290/386 = 0.0007512	= 209
Copper	ρ = 0.332/386 = 0.00086	= 240
Lead	ρ = 0.41/306 = 0.001062	= 296
Uranium	ρ = 0.683/386 = 0.001769	= 493

Typical Dynamic Properties

Material	Static Curve	P_y 0.002 offset	P_1	ε_1	P_1-P_y	$\varepsilon_1(R-P_y)$	$\frac{P_1-P_y}{P_y}$
Uranium Cast	NLC (Computed)	73,000	90,000	0.029	17,000	493.	0.233
302 SS	Goldsmith Fig. 250	41,350 F_{cy} = 35,000 (304SS)	53,800	0.01675	12,450	208	0.301

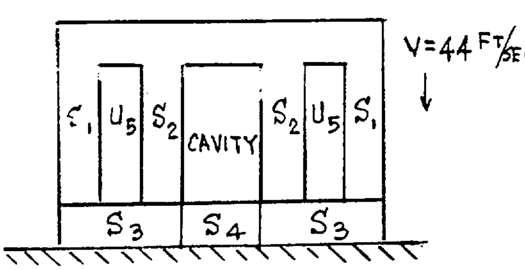
$$P_1 = 40{,}000 + \frac{825{,}000}{\varepsilon}$$

$$\varepsilon_1 = \frac{P_1 - 40{,}000}{825{,}000}$$

0.24 Carbon	Goldsmith Fig. 372	35,000	45,000	0.020	10,000	200	
Ni-Cr Stl	Goldsmith Fig. 118	220,000	228.000	0.024	8,000	192	0.036

2.7.1.1 End Drop. The dynamic analysis required for the cask and its parts, in the flat drop attitude, can be based on the concept of simple cylinders which behave as solid rods impacting squarely upon a rigid surface at the velocity of the specified free fall distance of 30 feet. This velocity is 44 ft/sec.

Values for stress, strain, K-E and G loadings can be derived for the individual masses and for the cask as a whole.



MODEL FOR ANALYSIS

S_1 = Outer S.S. shell

S_2 = Inner S.S. shell

U_5 = Uranium cylinder

These are considered separate cylinders

S_1 and S_2 weights include parts of the head weight

S_3 = SS plate - acting as striking plate under S_1, U_5 and S_2

S_4 = part of S.S. plate stressed by impact from container, etc

	Area	Weight
S_1	86.3 in^2	5,125 lb (incl. 635 lb head)
S_2	36.8 in^2	2,260 lb (incl. 270 lb head)
U_5	250.9 $in.^2$	32,400 lb
	374 $in.^2$	39,785 lb
S_3	378.5 $in.^2$	990 lb
S_4	248.5 $in.^2$	5,249 lb (1,919 container, 1,800 contents)
	Total	46,024 lb

Initial and maximum stresses developed by striking a rigid mass are calculated for uranium and steel, derived from

$$\rho v_1^2 = \varepsilon(P_1 - P_y) \text{ as previously shown}$$

P_1 uranium = 90,000 psi

P_1 stainless steel = 53,800 psi

For cylinders S_1, U_5 and S_2, the assumption of striking a rigid mass is conservative. Actually, they strike against an intermediate mass S_3, with some consequential reduction in stress.

S_3, on its under-surface, does strike a rigid mass, and counts S_1 U_5 and S_2 only as added load, considered as an equivalent weight of steel, added to the height of S_3 as a cylinder.

Stress differentials at the interfaces with S_3 are considered localized and quickly find equilibrium, producing a local increase in stress intensity in S_3 to match a reduced stress in U_5.

Total force developed at impacting face $F = P_1$ (area)

For S_1 $\quad F_1 = 86.3\ in^2 \times 53{,}800\ psi = 4{,}640{,}000\ lb$

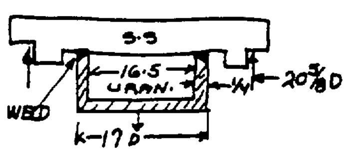
S_2 $\quad F_2 = 36.8\ in^2 \times 53{,}800\ psi = 1{,}975{,}000\ lb$

U_5 $\quad F_5 = 250.9\ in^2 \times 90{,}000\ psi = 22{,}581{,}000\ lb$

G's Developed $\qquad$ $G = F/wt$

S_1	4,640,000/5125 =	905 G
S_2	1,975,000/2260 =	875 G
U_5	22,581,000/32,400 =	697 G
S_3	29,196,000/39,785 =	735 G for bottom of cask and closure head.

Strength of Weld - Closure Head Flange



Weight $\quad$ Uranium block 330 lb

SS enclosure $\underline{\ 30}$

360 lb

Area of weld = area of shell

$= \pi/4\ (17^2 - 16.5^2) = 12.5\ in.^2$

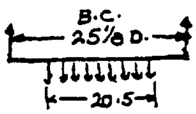
Force in weld = (360 lb) x (735 G) = 264,000 lb

Stress in weld = 264,000/12.5 = 21,100 psi

The full penetration weld has substantially the strength of the parent metal. Assume 80% of 30,000 psi yield strength for stainless steel = 24,000 psi.

$$= \frac{24{,}000}{21{,}100} - 1 = 13.7\%$$

Strength of Plate in Bending and Shear



Weight = 850 lb - SS plate and uranium

Load = (860) x (735 G) = 632,000 lb

r_o = 10.25"

a = 12.56"

Roark table X

Stress at center of head, Case 2: t = 4 in. max

$$\text{Max } S_r = S_t = \frac{-3W}{2\pi\ mt^2}\left[m + (m+1)\log_e a/r_o - (m-1)\frac{r_o^2}{4a^2}\right]$$

$$= \frac{-3(632{,}000)}{628(10/3)4^2}\left\{10/3 + 13/3\log_e \frac{12.56}{10.25} - 7/3\ \frac{10.25^2}{4 \times 12.56^2}\mu\right.$$

$$= 5650\ [10/3 + 13/3\ (0.230) - 3.9] = 5650\ (0.31)$$

= <u>1750 psi</u> ok 30,000 psi yield strength

Stress at edge, Case 7: t = 2-5/8 in.

$$\text{Max } S_r = \frac{3W}{2\pi t^2}\quad 1 - \frac{r_o^2}{2a^2} = \frac{3(632{,}000)}{628(2.625)^2}\quad 1 - \frac{10.25^2}{2(12.56)^2}$$

= 43,700 (1 - 0.334) = <u>29,200 psi</u> ok 30,000 psi yield strength

Shear at edge (20.625 diam) t = 2-5/8 in.

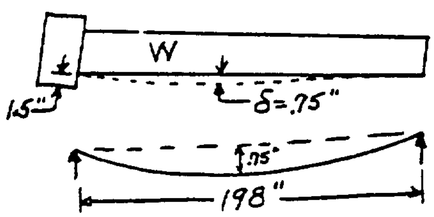
Area in shear $= 2\pi\ rt = \pi\ (20.625)\ 2.625$
$= 170.5\ in.^2$

$$S_s = \frac{632{,}000}{170.5} = \underline{3700}$$

$$F_{SU} = 0.60\ (70{,}000\ psi) = 42{,}000$$

$$M.S = \frac{42{,}000}{37{,}000} - 1 = 10.3$$

2.7.1.2 Side Drop



Deflection at mid-length is limited to 0.75 in. by contact with base

Find (W•g) to give $\delta = 0.75$ in.

$$\delta = \frac{5}{384}\ \frac{W\ell^3}{EI} = 0.75\ in.$$

$$\therefore\ (W \cdot g) = \frac{0.75\ (384)\ EI}{5\quad \ell^3} = \frac{57.6\ (29)\ 10^6 I}{(198)^3}$$

$$(W \cdot g) = 215\ I$$

Let W = 46,024 lb = total weight of loaded cask.

Let $I = \Sigma I$ for outer shell, inner shell, and 1-1/2 in. of welded uranium. The rest of the 3-1/2 in. total thickness of uranium contributes mass and not stiffness. This is very conservative, since the middle cylinder spans the region of max stress and deflection. All three cylinders have the same deflections.

$$I_1 \text{ outer shell} = \frac{\pi}{4}(14^4 - 13^4) = 7750 \text{ in.}^4 \qquad \Sigma I/r = \frac{17,980}{14} = 1284$$

$$I_2 \text{ inner shell} = \frac{\pi}{4}(9.5^4 - 8.875^4) = 1530 \text{ in.}^4 \qquad = \frac{17,980}{9.5} = 1895$$

$$I_3 \text{ uranium} = \frac{\pi}{4}(13^4 - 11.5^4) = 8700 \text{ in.}^4 = \frac{17,980}{13} = 1385$$

$$\Sigma I = 17,980 \text{ in.}^4$$

Now $(W \cdot g) = 215\ (\Sigma I)$

$$= 215\ (17,980) = 3,880,000 \text{ lb}$$

$$g = \frac{3,880,000}{46,024} = \underline{83.8\ g}$$

$$M = \frac{(W \cdot g)\ell}{8} = \frac{3,880,000}{8}(198) = 95,900,000 \text{ in. lb}$$

and

$$S_1 \text{ outer shell} = \frac{95,900,000}{1284} = \underline{74,700 \text{ psi}}$$

$$S_2 \text{ inner shell} = \frac{95,900,000}{1895} = \underline{50,600 \text{ psi}}$$

$$S_3 \text{ uranium} = \frac{95,900,000}{1385} = \underline{69,200 \text{ psi}}$$

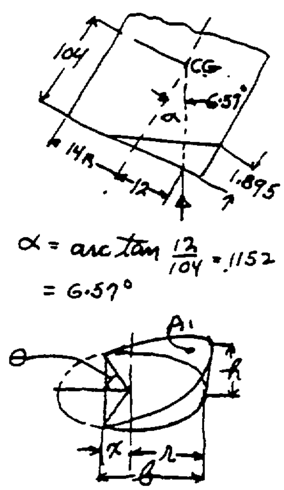
All these stresses are momentary peaks and local S_3 for uranium is less than that sustained in the test.

The side drop test is considered satisfactory, with no permanent beam deformations - only local crushing deformations.

2.7.1.3 Corner Drop

Bottom Corner

In corner drop calculations the assumption is made that the ungula developed at the impact position represents the total compressive effects at a local point, rather than the actual nonlinear distribution of strain throughout the whole impacting mass, both elastic and plastic. It allows calculation of maximum stress values, etc., without regard for actual distribution of stress and strain at noncritical values.



The calculated ungula is a greater volume than will actually result from impact, for this reason.

$$V_{(ungula)} = \frac{h}{b} r^3 \left[\sin\theta - \frac{\sin^3\theta}{3} - \theta\cos\theta\right]$$

$$\frac{h}{b} = 0.1152 \qquad r^3 = 14^3 = 2744$$

$$\therefore \quad = (0.1152)2744[\ ] = 317[\ ]$$

Assume center of impact 2 in. from edge, at R = 12 in.

Total weight impacting on SS bottom plate = <u>46024 lb</u>

KE = (46024)(360 in.) = <u>16,600,000 in. lb</u>

Mean flow stress for SS. (Approximately)

$$P = 53{,}800 \text{ psi}$$

$$\frac{KE}{P} = \frac{16{,}600{,}000}{53{,}800} = \underline{308 \text{ in.}^3}$$

This is the calculated ungula volume

$$\therefore \text{ Vol} = 317\ [\ \ ] = 308 \qquad [\ \ ] = \frac{308}{317} = 0.972$$

Let $\theta = 100°$, then $\left[0.9848^3 - \frac{0.9848^3}{3} - (1.745)(-0.1736)\right] = 0.970$

and $\theta = 1.745$ radians

$$x = r\cos\theta = 14(0.1736) = \underline{2.43\text{ in.}}$$

$$b = r + x = 14 + 2.43 = \underline{16.43\text{ in.}}$$

$$h = b\ (0.1153) = 1.895\text{ in.}$$

Contact area A_1 = approx. $\frac{\pi r^2}{2} + 2rx = \frac{615.75}{2} + 28\ (2.43)$

$$A_1 = 307.9 + 68 = \underline{375.9\text{ in.}^2}$$

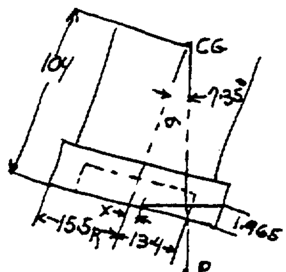
$$F_{max} = A_1P_1 = (375.9)(53{,}800) = \underline{20{,}200{,}000\text{ lb}}$$

$$F/wt = \frac{20{,}200{,}000}{46{,}024} = \underline{438\text{ G}}\text{ vertically,}$$

<u>Component along axis</u>

$$(438\text{ G})(\cos 6.57°) = 438\ (0.99343) = \underline{435\text{ G}}$$

Top Corner (Method similar to bottom impact analysis)



$\alpha = \arctan \frac{13.4}{104} = 7.35°$

Assume center of impact at edge of closure, R = 13.4 in.

$$\frac{KE}{P_1} = 308 \text{ in.}^3 = \text{Volume of ungula}$$

$$V = 308 \text{ in.}^3 = \frac{h}{b} r^3 \left[\sin\theta - \frac{\sin^3\theta}{3} - \theta \cos\theta\right]$$

$$\frac{h}{b} = \frac{13.4}{104} = 0.129 \qquad r^3 = (15.5.)^3 = 3724$$

$$[\ ] = \frac{308}{0.129(3724)} = 0.641$$

Let $\theta = 89°$, then $[\ ] = 0.99985 - 0.333 - (1.5533 \times 0.0174) = 0.639$

$x = r \cos\theta = 15.5 \times 0.0174 = \underline{0.27 \text{ in.}}$

$b = 15.5 - 0.27 = \underline{15.23}$

$h = 0.129\ b = \underline{1.965}$

Contact area = approximately $\frac{\pi r^2}{2} - 2rx = \frac{754.8}{2} - 31(0.27)$

$A_1 = 377.4 - 8.4 = 369$ $\underline{\text{in.}^2}$

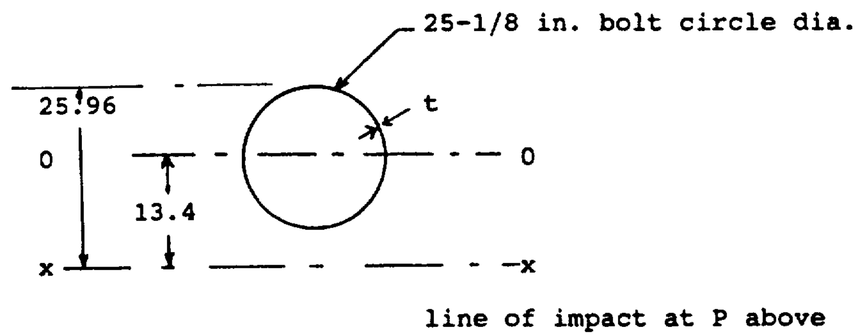
$F_{max} = A_1P_1 = (369)\ 53{,}800 = \underline{19{,}850{,}000}$ lb

$= F/wT = 19{,}850{,}000/46{,}024 = \underline{430\ G}$ vertically

<u>Component along axis</u>

$(430G)(\cos 7.35°) = 430\ (0.99178) = \underline{426.5G}$

<u>BOLT LOADS</u>



Let A = Tensile area of 24 bolts (1-1/4 - 7) = 24 x 0.9684 in.^{2}

= $\underline{23.24\ \text{in.}^2}$ assume this area as a thin ring with a bolt circle diameter

= 25-1/8 in.

Then $t = \dfrac{A}{2\pi r} = \dfrac{23.24}{\pi \times 25.125} = \underline{0.294}$

$$I_{oo} = \frac{\pi}{4}(R^4 - r^4) = \frac{\pi}{4}(12.71^4 - 12.42^4) = 1808\ \text{in.}^4$$

$$I_{xx} = I_{oo} + A(13.4)^2 = 1808 + 4173 = 5980\ \text{in.}^4$$

<u>Weights</u> 860 closure

1919 container

<u>1800 contents</u>

4579 lb Total

Moment about axis xx

M = (4579 lb)(426.5 G) x 13.4 in. =

<u>26,169,443</u> in. lb

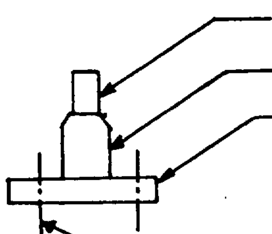
$$S_t = \frac{My}{I_{xx}} = \frac{26,169,433 \times 25.96}{5980} = \underline{113,605 \text{ psi}}$$

Bolts are heat-treated to 130,000 psi yield strength

$$\text{M.S.} = \frac{130,000}{113,605} - 1 = 14.4\%$$

Note that the actual <u>dynamic</u> strength is somewhat greater, therefore, the bolts will not yield under dynamic loading and the cask design provides the required integrity.

<u>Bottom Plug</u>



1-1/8 dia x 3 in. $\pi/4(1.125)^2 \times 3 = 3.0 \text{ in.}^3$

1-5/8 dia x 5 in. $\pi/4(1.625)^2 \times 5 = 10.4 \text{ in.}^3$

5-1/2 dia x 1 in. $\pi/4(5.5)^2 \times 1 = \underline{23.8} \text{ in.}^3$

$37.2 \text{ in.}^3 \times .284 =$ <u>10.57 lbs</u>

4 socket head cap screws
1/2-13 thds.

Component of acceleration along axis of cask in corner drop is 435 G.

Impact force on drain equation is

F = (W•g) = (10.57) 435 = <u>4600 lb</u>

Each socket head cap screw has a tensile yield strength of 2700 lb.

$$M.S. = \frac{4x27000}{4600} - 1 = 23.5$$

2.7.2 Puncture

This cask has uranium as shielding between the inner and outer shells. Therefore, piercing of the outer shell with potential loss of shielding in the fire case cannot occur.

Instead, a shallow indent appears on the stainless steel outer shell where the edge of the 6-in. diameter pin partly cuts into it. This is clearly shown in report KY-546 by Clifford (Ref. 2.9). Actually, the pin is more damaged than the cask.

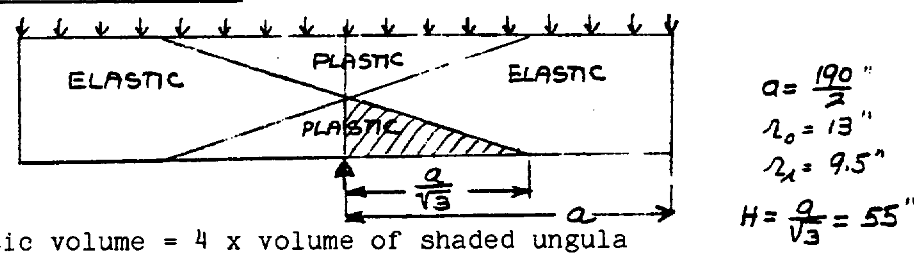
Energy is, however, absorbed in the three concentric shells of the cask in bending, with the possible formation of a plastic hinge.

The approximate distribution of moments among the shells can be made, assuming elastic deflections and an extreme fiber stress of 30,000 psi for both uranium and stainless steel inner and outer shells, with the same deflections, of course. Relative values follow;

34.2%	25,300 in. lb	1 in. SS outer shell
59.%	43,500 in. lb	3-1/2 in. uranium
6.8%	5,030 in. lb	5/8-in. inner shell
100%	73,830 in. lb	

Reference 2-10, pages 1302 thru 1307, gives the plastic region diagram in a beam when the midsection is just completely plastic.

For the uranium cylinder



The plastic volume = 4 x volume of shaded ungula

$$= 4 \quad \left(\frac{2}{3}\right)(r_o^2 - r_i^2)\ H = 4\left(\frac{2}{3}\right)(13^2 - 9.5^2)\ 55$$

$$= 11{,}520 \text{ in.}^3$$

Each plastic cubic inch has been elongated 0.2% to reach a terminal stress of 30,000 psi (yield point for uranium).

The energy absorbed is

$$U = \frac{30{,}000}{2}\ (11{,}520)\ (0.002) = \underline{345{,}600 \text{ in. lb}}$$

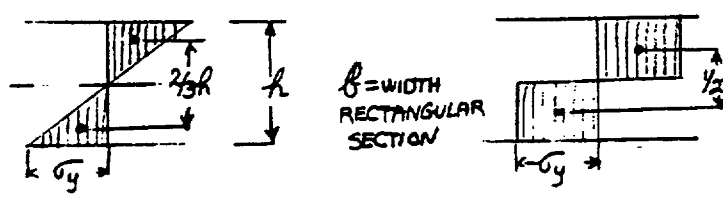
The total energy of the 40-in. fall is

$$U_{tot} = (46{,}500 \text{ lb})\ 40 \text{ in.} = 1{,}860{,}000 \text{ in. lb}$$

The difference must be absorbed in bending of the "plastic hinge."

$$U_B = 1,860,000 - 345,600 = \underline{1,514,400 \text{ in. lb}}$$

Determination of plastic section modulus



Elastic

$$M_E = \frac{\sigma_y}{2} \times \frac{h}{2} \left(\frac{2}{3} h\right) b$$

$$= \sigma_y \frac{bh^2}{6}$$

Plastic

$$M_p = \sigma_y \times \frac{h}{2} \left(\frac{h}{2} b\right)$$

$$= \sigma_y \frac{bh^2}{4}$$

$$\therefore M_p = \frac{3}{2} M_E$$

For the circular section of the uranium cylinder

$$I = \frac{\pi}{4} (r_o^4 - r_i^4) \qquad Z_E = \frac{\pi}{4} \frac{(r_o^4 - r_i^4)}{r_o}$$

and

$$Z_p = \frac{3}{2} \frac{\pi}{4} \frac{(r_o^4 - r_i^4)}{r_o}$$

$$= \frac{3\pi}{8} \frac{(13^4 - 9.5^4)}{13} = 1860$$

The plastic moment at the midplane is

$$M_p = \sigma_p Z_p$$

$$= (30{,}000)(1860) = 55{,}800{,}000 \text{ in. lb}$$

But

$$U_B = M\theta$$

or

$$1{,}574{,}400 = 55{,}800{,}000\ (\theta)$$

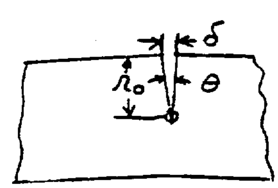
$$\theta = \frac{1{,}514{,}400}{55{,}800{,}000} = 0.0271 \text{ radians} = \underline{1.56°}$$

Estimated Actual Angle of Bend and Elongation

We are now justified in assuming that the actual conditions, showing loadings on all three shells, would reduce their common angle of bend to

$$(0.59\ (1.56°) = 0.925°\ \theta$$

For the outer fibers of the outer shell this gives



$$r_o = 14 \qquad \delta = r_o\theta = (14)(0.925)\ (0.01745) = 0.226 \text{ in.}$$

Consider this to be the measured elongation over a 2-in. gage length tension test piece.

$$\frac{0.226}{2} = 11.3\% \text{ elongation}$$

Stainless steel has 40% elongation   o.k.   No Rupture

Uranium elongation 13/14 in. (11.3) = 10.5% elong. at R = 13 in.

10.5/14 in. (11.3) = 8.5% elong. at R = 10.5 in.

9.5/14 in. (11.3) = 7.7% elong. at R = 9.5

2.7.3 Evaluation of FSV-1 Configuration C

2.7.3.1 Discussion. The following sections provide the structural analyses used to verify that the burial liner cover with the 2 in. x 4 in. shield ring will remain in place during the hypothetical accident conditions. For these analyses the burial liner is part of configuration C and the unit is subjected to a 30-ft drop onto an essentially unyielding surface.

2.7.3.2 Evaluation Criteria. The allowable stress criteria set forth in NRC Regulatory Guide 7.6, "Design Criteria for Structural Analysis of Shipping Cask Containment Vessels" (Ref. 2-11) are specified for linear analysis only. Nonlinear analysis is acceptable and the acceptance criteria will be reviewed on a case-by-case basis by NRC staff.

Due to the anticipated nonlinear response of the structure during the hypothetical drop from 30 ft, a nonlinear, large deformation, large strain, finite element computer program was used to perform the analysis. The drop condition was evaluated by the criteria set forth in Appendix F, Section III of the ASME Boiler and Pressure Vessel Code for Level D Service. These limits have been established for extremely unlikely loadings for which the public safety is to be assured; and are comparable to the hypothetical accident condition for cask design. The loading is assumed to be applied once and therefore, no consideration is required for fatigue.

When using inelastic component analysis, section F-1324.6 specifies a limit on the primary membrane stress (P_m) as defined in Subsection NB 3221 using a value for stress intensity of (S_m) equal to the greater of 0.7 S_u or S_y + 1/3 (S_u - S_y). S is the ultimate stress and S_y is the yield stress for the material. No correction factor α is allowed for evaluation of primary bending stresses. Therefore, the limit on primary local membrane plus primary bending: (P_l + P_b) is the same as for primary membrane (P_m).

A further degree of conservatism was added to the criteria by using the lower limit of S_y + 1/3 (S_u - S_y) to check the primary membrane stresses and the larger 0.7 S_u limit when checking primary membrane plus primary bending stresses.

The above criteria are conservative for dynamic impact since they are based on load controlled events for which margin is evaluated against a parameter such as internal pressure or applied load. The cask drop condition is an energy controlled event where the structure must absorb the kinetic energy of impact. Limits on stress restrict the allowable strain energy absorbed by the cask material to a small fraction of the energy which it is capable of absorbing.

2.7.3.3 Computer Program. The response of the burial liner cover and shield ring will be significantly nonlinear. This nonlinear response results from both material nonlinearity and nonlinearity caused by significant geometrical distortion from the initial configuration. Suitable programs for this type of analysis must incorporate these nonlinearities and be effectively coded if reasonable solutions are to be achieved.

HONDOII (Ref. 2-12) is the computer program used for the structural analysis which meets the above requirements. HONDOII has a wide selection of nonlinear material subroutines formulated to accommodate both large displacements and finite strains. It also has slide line capabilities which allow rigorous treatment of contact, sliding and release conditions between two or more bodies. Spatially, the program employs a four-node isoparametric quadralateral element. In time, the program performs the integration using a central difference time integrator. Since the time integration scheme is only conditionally stable with respect to time step size, the program continuously monitors the step size and adjusts it to keep the calculation stable. Initial conditions on velocity are allowed, and can correctly simulate the hypothetical drop condition.

The HONDOII Type 6 material model was used in the analysis. This model is formulated for finite strain elastic-plastic behavior with strain hardening. The strain hardening behavior may be isotropic, kinematic, or a combination of the two. Isotropic hardening was used since significant stress reversal is not anticipated and large strain formulations using kinematic hardening have recently been shown to give erroneous results under certain stress conditions (Ref. 2-13). The material model uses Cauchy or true stress and Signorine strain measure for finite deformations. Therefore, the program requires the input of the true stress vs. true strain. All comparisons of the computed stresses to the allowable stresses was done using true stresses to be mathematically and physically consistent.

2.7.3.4 Material Model Properties.

Type 304 Stainless Steel

The true stress vs. true strain curve used in the analysis was constructed from data taken from the ASME Code (Ref. 2-1) and the Aerospace Structural Metals Handbook (Ref. 2-14). The tabulated minimum yield strength and ultimate strength at a representative temperature of 150°F were taken from the ASME Code Tables I.2.2 and I.3.2, respectively. The Aerospace Structural Metals Handbook was used to interpolate an engineering strain value at the maximum load in order to determine the true stress and true strain at the ultimate stress.

The following equations from EPRI report NP-1921 (Ref. 2-16) were used to convert engineering stress and strain values to true stress and true strain.

$$\sigma_{true} = \sigma_{engineering} (1 + \varepsilon_{engineering})$$

$$\varepsilon_{true} = \ln (1 + \varepsilon_{engineering})$$

These relations are valid up to the maximum load in the uniaxial tension test.

The constructed stress vs. strain curve for stainless steel is shown in Fig. 2-2. Also shown on the figure is a typical true stress vs. true strain curve for type 304 stainless steel at room temperature taken from Ref. 2-15. The hardening slope of the two curves is essentially the same, however, the ASME code value for the ultimate stress and strain are significantly below typical values. This implies that for a given applied load the strains from a calculation using minimum properties will be larger than if nominal values had been used and a larger percentage of the allowable stress will be calculated. Thus, conservatism has been introduced by using the code values. The hardening modules (E_h) for the material is developed form the ASME code values.

Carbon Steel ASTM A36

The true stress vs. true strain curve for carbon steel (ASTM A36) was constructed in much the same way as those for stainless steel. The strain at

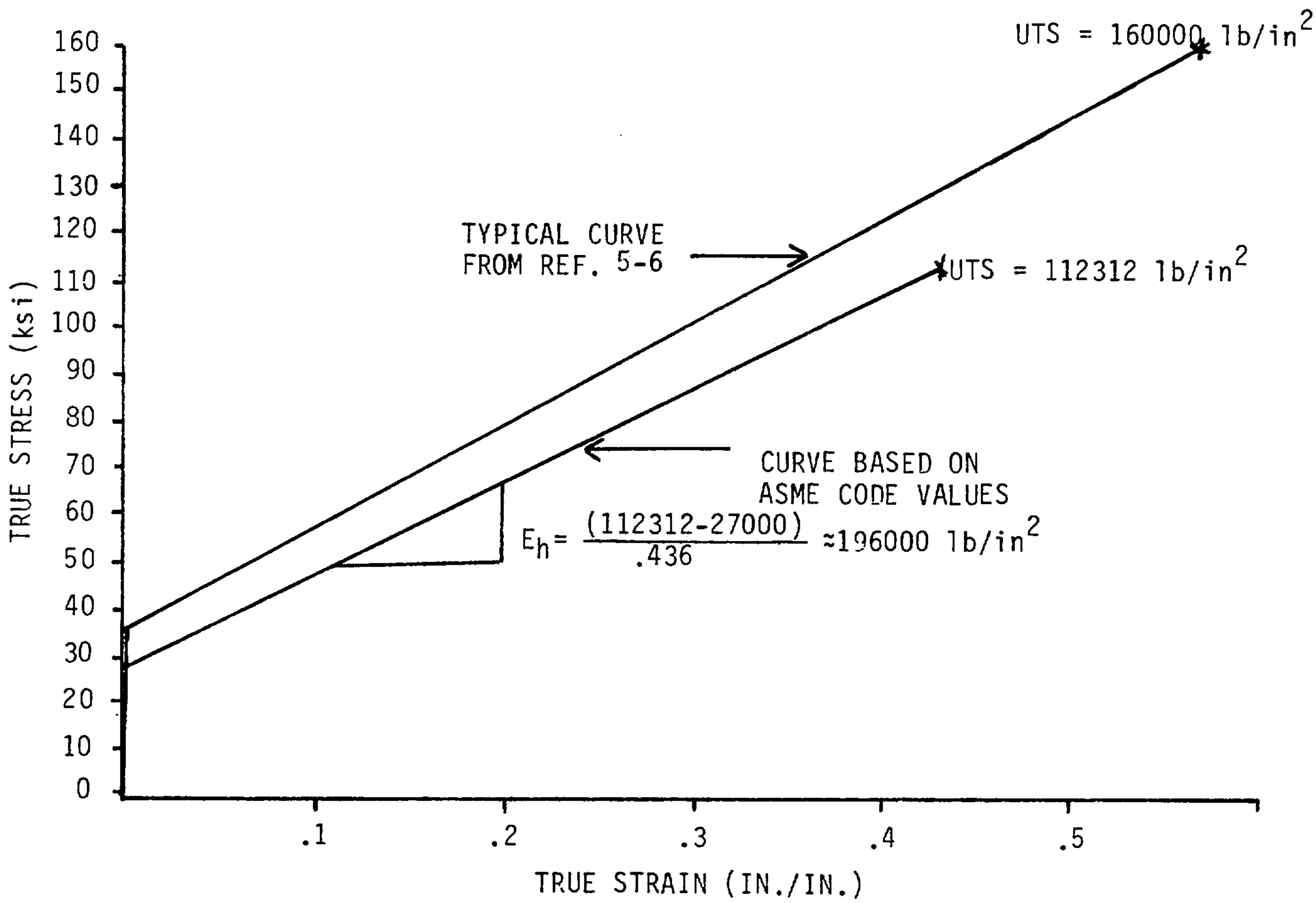


FIGURE 2-2 TRUE STRESS VS. TRUE STRAIN
FOR 304 STAINLESS STEEL

maximum load was estimated to be 17.5% based on representative data for carbon steels. The true stress vs. true strain curve (Fig. 2-3) was constructed for the carbon steel flange and burial liner.

The burial liner does not have to survive the drop condition. It is included in the analysis only to apply an appropriate boundary condition to the burial liner cover plate during the 30-ft drop event.

The following table summarizes the material data used in the analysis and the reference source for each property.

Property	Value at 150°F	Reference
Carbon Steel ASTM A36		
Young's Modulus	27.8×10^2 lb/in.^{2}	ASME Code Table I-6.0
Poisson's Ratio	0.29	Mark's Handbook page 5-6
Mass Density	0.000732 lb-sec^2/in.^{4}	Mark's Handbook page 6-10
Yield Strength	34320 lb/in.^{2}	Figure 2-3
Hardening Modulus	224720 lb/in.^{2}	Figure 2-3
Stainless Steel 304		
Young's Modulus	27.9×10^6 lb/in.^{2}	ASME Code Table I-6.0
Poisson's Ratio	0.305	Mark's Handbook page 5-6
Mass Density	0.000749 lb-sec^2/in.^{4}	Mark's Handbook page 6-10
Yield Strength	27,000 lb/in.^{2}	Figure 2-2
Hardening Modulus	196,000 lb/in.^{2}	Figure 2-2

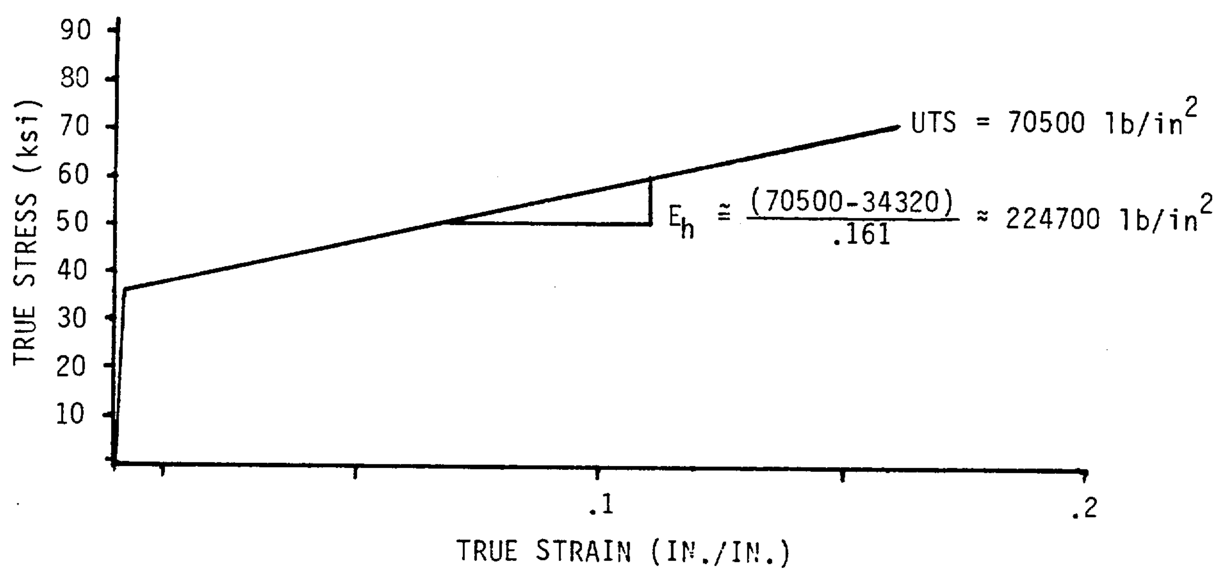


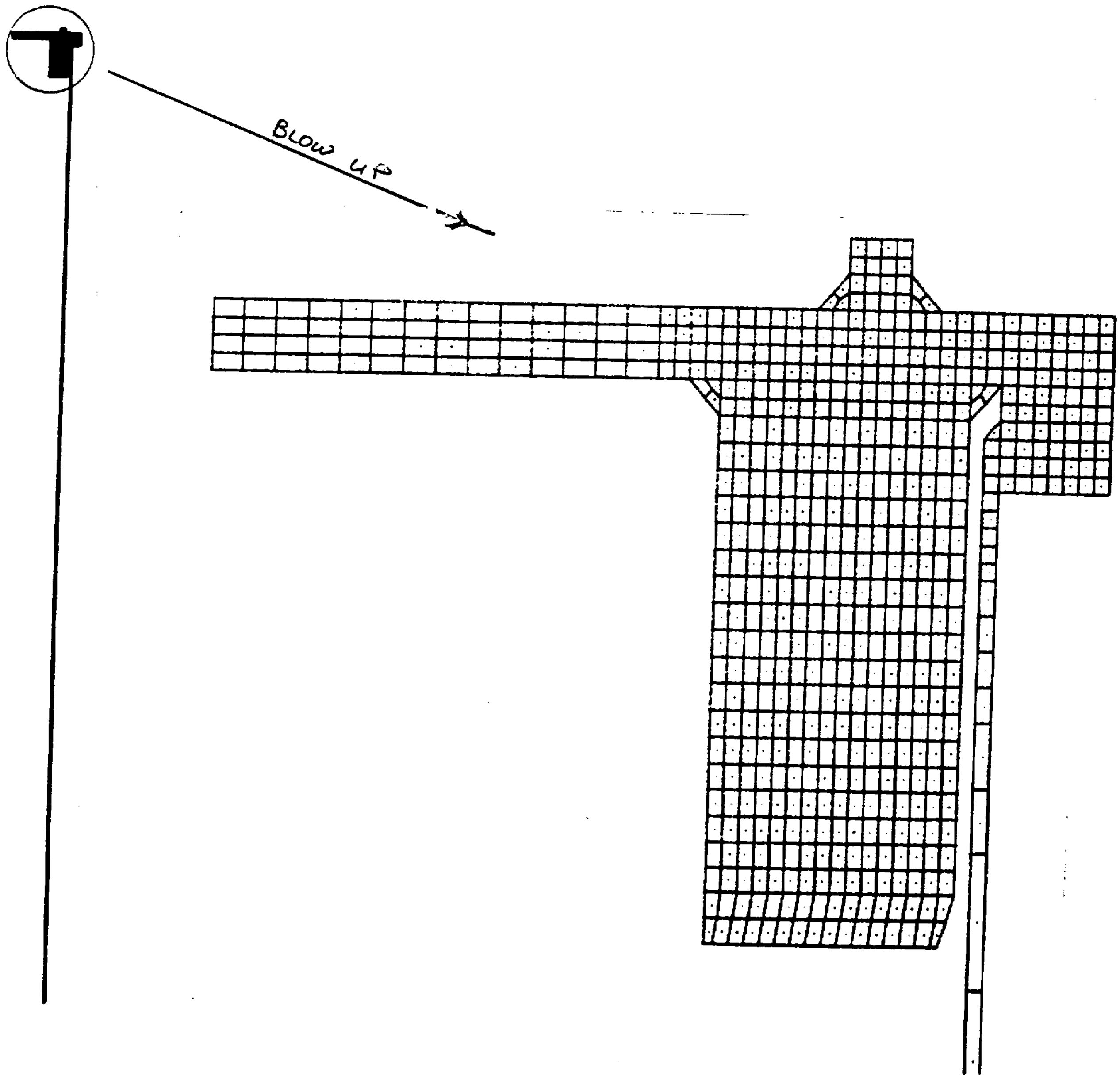
FIGURE 2-3 TRUE STRESS VS. TRUE STRAIN CURVE FOR ASTM A-36 CARBON STEEL

2.7.3.5 Finite Element Model. The finite element model of the burial liner cover and shield ring assembly is shown in Fig. 2-4. Figure 2-4a shows the overall model and Fig. 2-4b shows a detail of the cover shield ring area. The 1/2-in. x 1/2-in. impact ring is attached to the 1/2-in. thick cover plate by 1/4-in. fillet welds. The 2 x 4 in. shield ring is attached to the cover plate by 1/4-in. goove welds with 1/4-in. fillet reinforcements. Slide lines are specified along the gaps between the rings and the cover plate. A slide line is specified between the bottom of the cover plate and the top of the burial liner flange. The bolts are not included in the analysis. A final slide line was used to represent the contact between the bottom of the liner flange and the support from the cask body. The sliding interfaces are shown in Fig. 2-5.

The support point of the cask was assumed to stop instantaneously at the time the stress wave reached the support flange, allowing the burial liner to be conservatively analyzed independently from the overall cask. A portion of the burial liner cylinder was included in the model to prevent reflections from the cut-off point from interfering with the solution in the cover plate and shield ring area. The impact is essentially over in the flange area in about 0.25 milliseconds. The stress wave will travel about 140 in. in this period of time. Ninety inches of burial liner was included in the model allowing greater than 0.85 milliseconds before the solution at the flange is perturbed.

In order to account for the slot in the cover plate, an equivalent axisymmetric model was constructed. The area of the slot was converted into an equivalent circular hole of equal area. The weight of the lifting bar was uniformly distributed over the central plate from a radius of 2.4 in. to 6 in. This approximation gives a reasonable representation of the behavior of the plate. It will be shown in the results section that there is considerable margin when the plate stresses are compared to the allowable stresses.

HONDO II MODEL



OVERALL MODEL

FIGURE 2-4a

BLOW UP AT COVER AND FLANGE

FIGURE 2-4b

FIGURE 2-4 FINITE ELEMENT MODEL

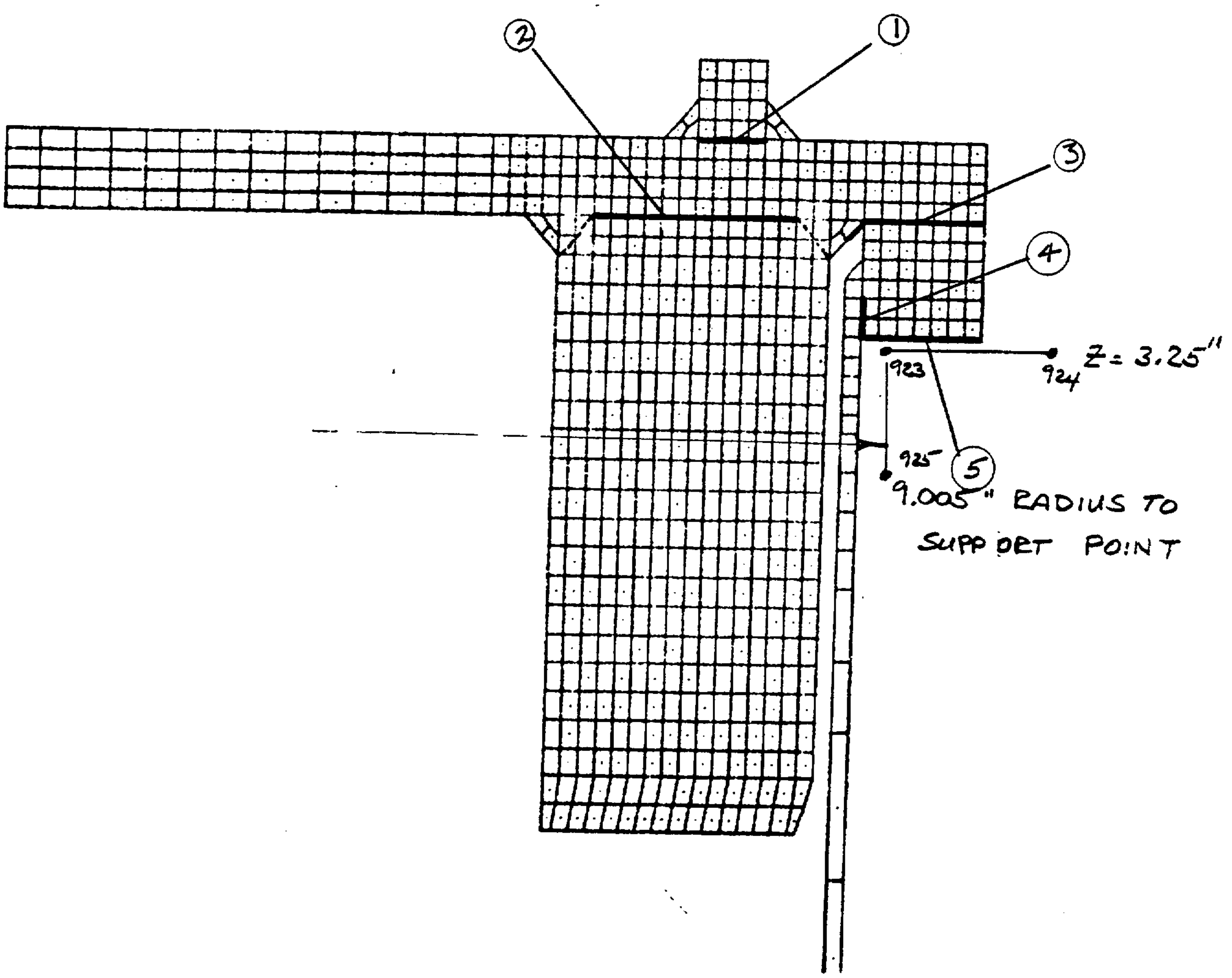


FIGURE 2-5 SLIDING INTERFACES

2.7.3.6 Results of Analysis. The deformed shape of the cover plate and shield ring assembly is shown in Fig. 2-6 at 0.84 milliseconds. At this time, all of the nodes in the cover plate and shield ring have positive velicity and are rebounding. The top cover is separating from the burial liner flange and a gap is opening between the flange and the cover. The deformed shape plot allows a means of determining the critical areas in the model, i.e., those areas where the elements are highly distorted. These critical areas were confirmed by looking at time history plots of the effective stresses throughout the model. The critical areas which are examined in detail are shown in Fig. 2-7. This figure also shows the element numbers associated with each area. Figures 2-8 through 2-22 show the time history plots for the effective values of primary membrane stress and the primary membrane plus primary bending stress at the critical sections shown in Fig. 2-7.

The primary membrane stresses at the critical regions were determined by averaging the stresses through the thickness of the plate. The primary membrane plus primary bending stresses were extrapolated to the edge of the plate. This averaging was done on a stress component basis and then combined into an effective value using the equation:

$$\sigma_{eff} = \sqrt{\frac{(\sigma_r - \sigma_z)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_r - \sigma_\theta)^2 + 6(\pi_{rz})^2}{2}}$$

Table 2-2 shows the primary membrane and the primary membrane plus primary bending stresses for the critical sections and the percentage of the allowable stress.

As may be seen from Table 2-2, the calculated stresses are significantly below the allowable stresses established for the critical sections. The cover plate and attached shield ring have been shown to satisfy criteria which

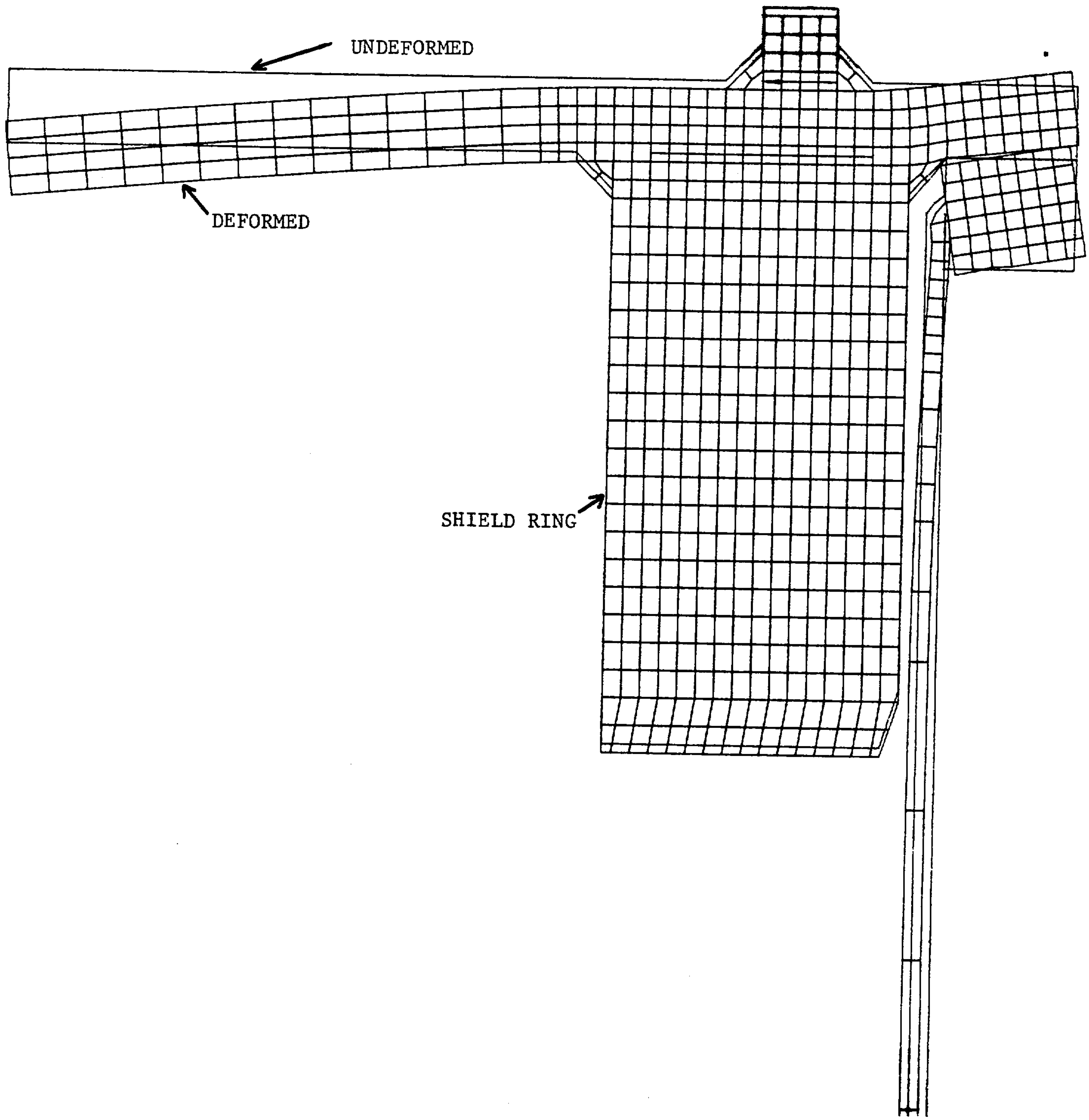


FIGURE 2-6 DEFORMED SHAPE AT .84 MILLISECONDS

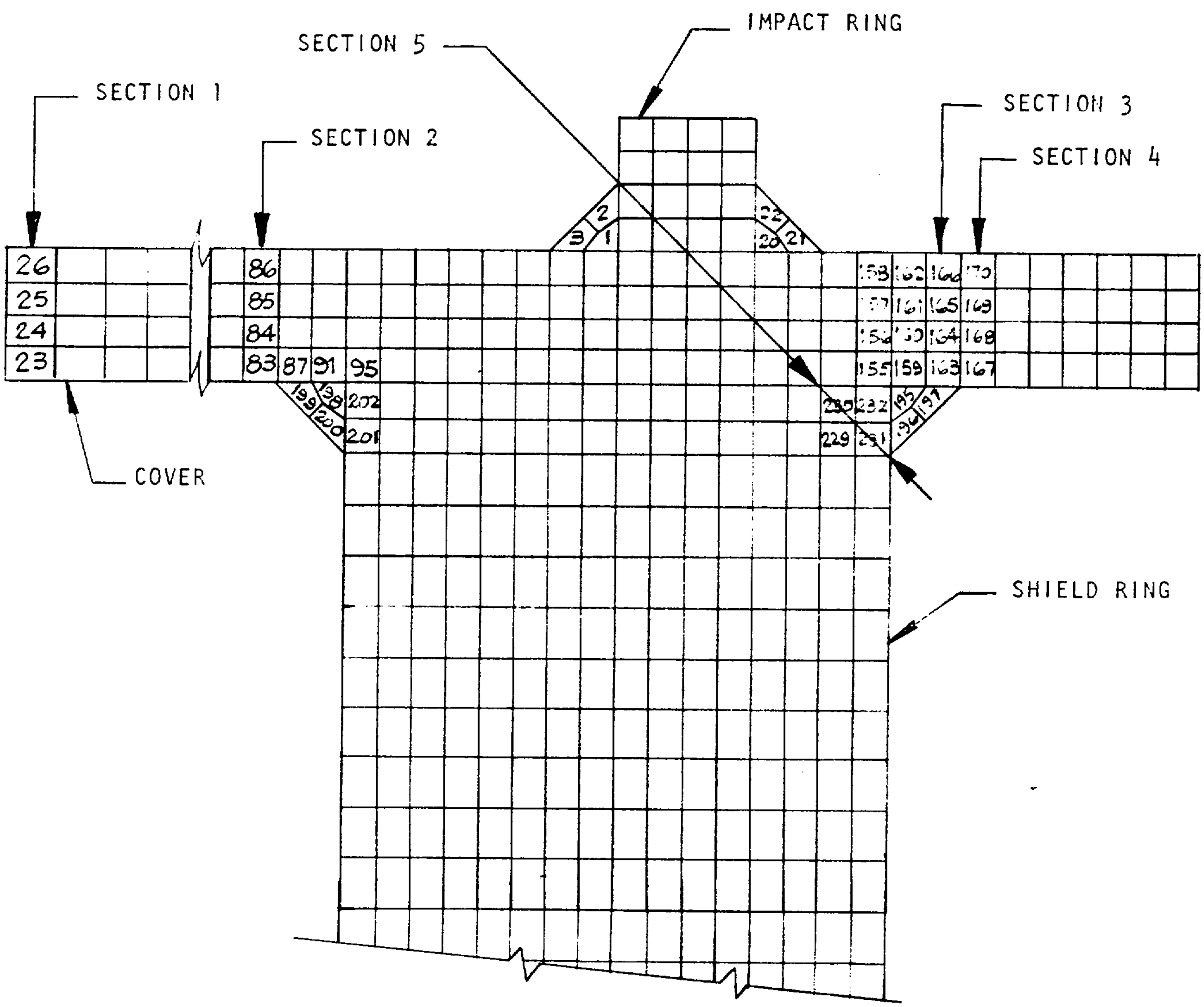


FIGURE 2-7 LOCATION OF SECTIONS USED
FOR PRIMARY STRESS EVALUATION

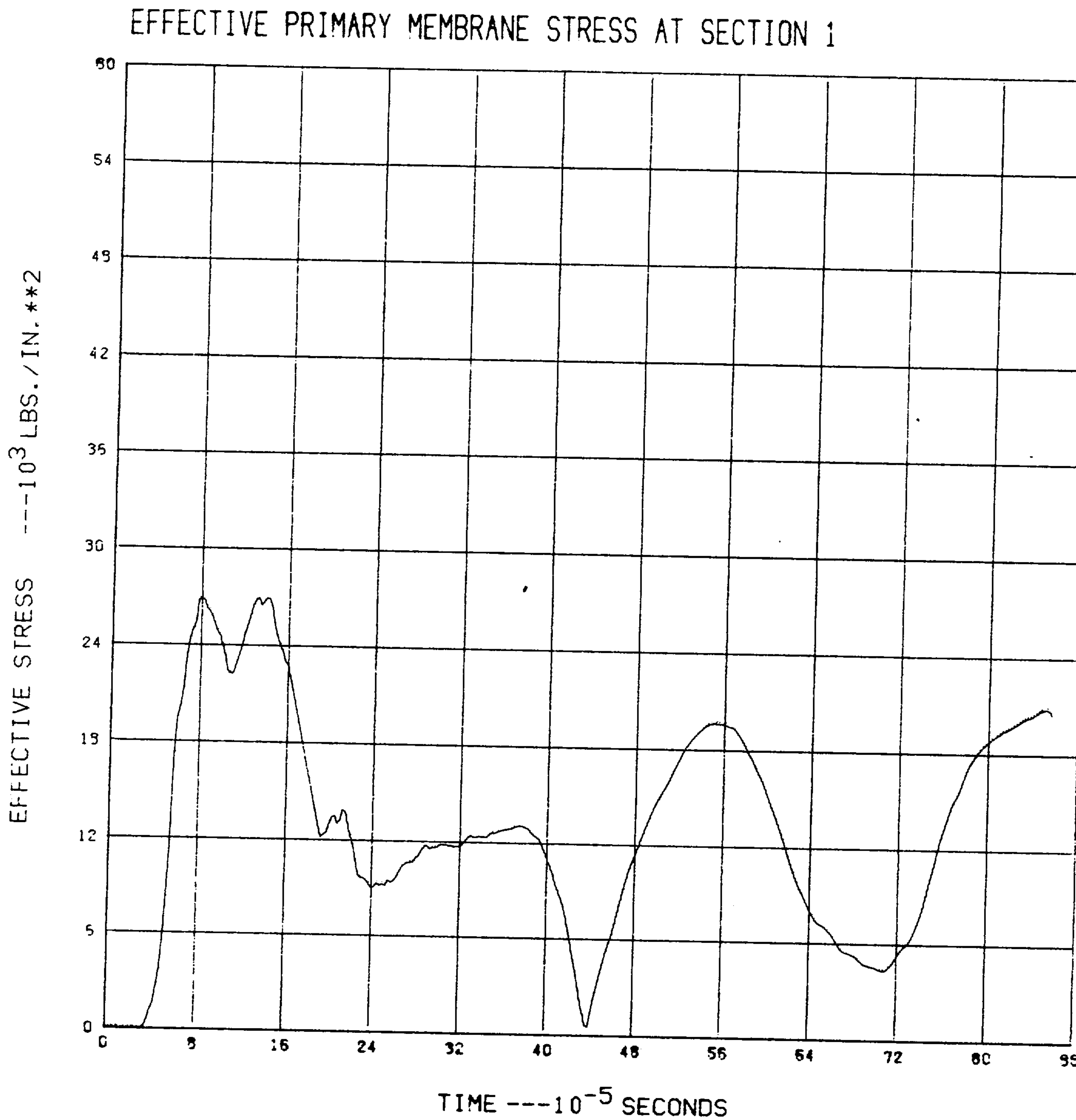


FIGURE 2-8 SECTION 1

PRIMARY MEMBRANE STRESS

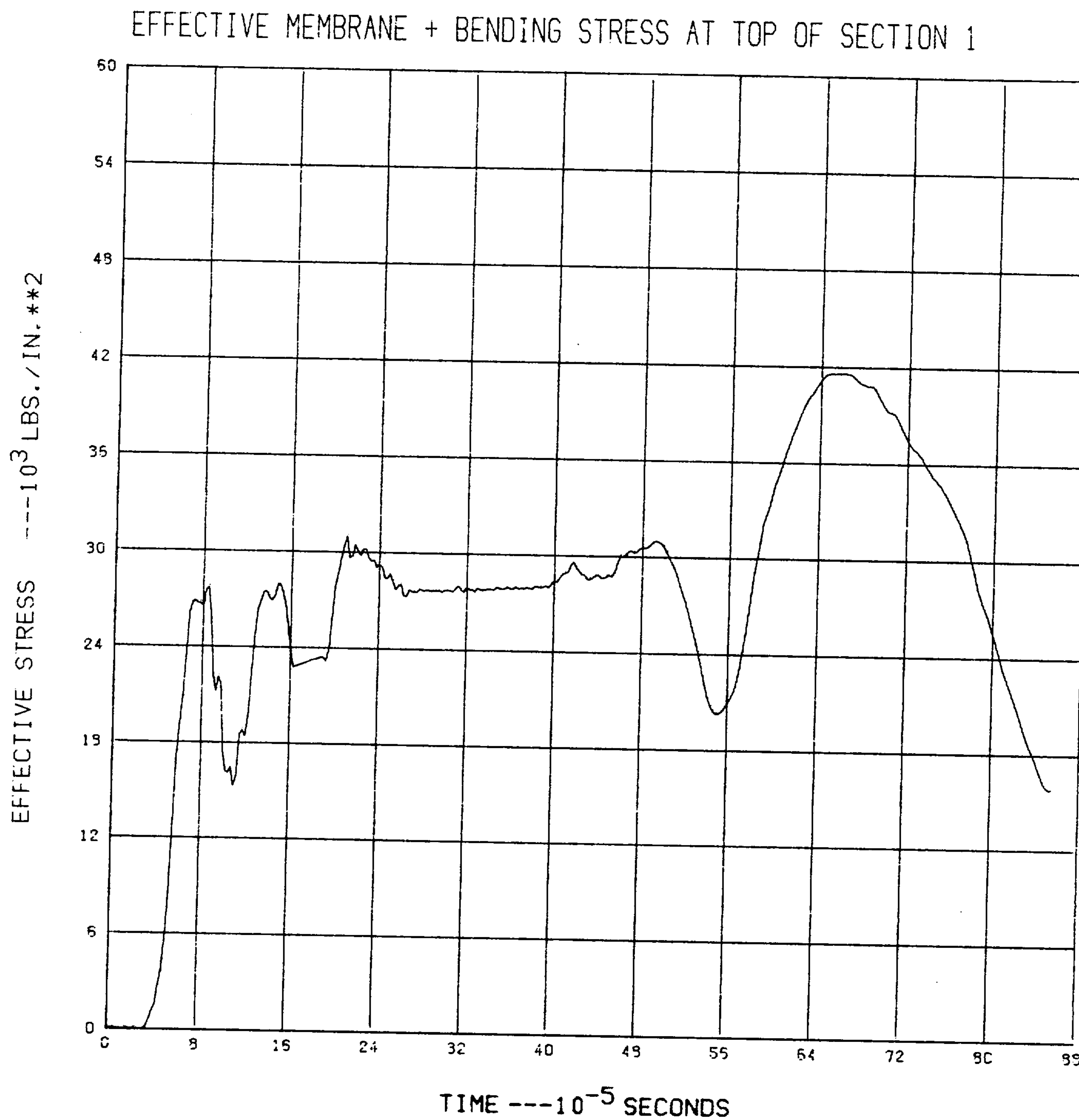


FIGURE 2-9 SECTION 1

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT TOP OF PLATE

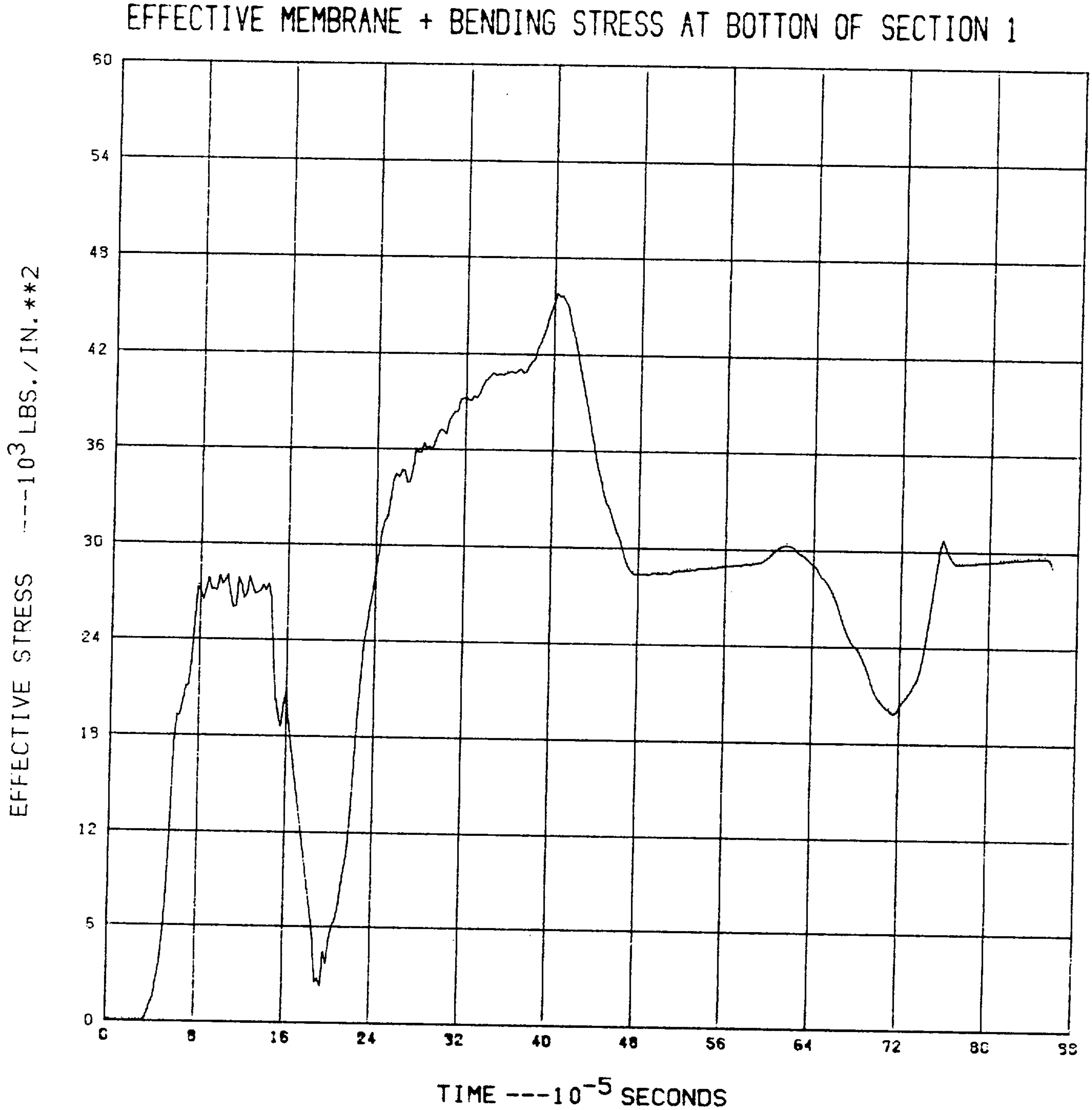


FIGURE 2-10 SECTION 1

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT BOTTOM OF PLATE

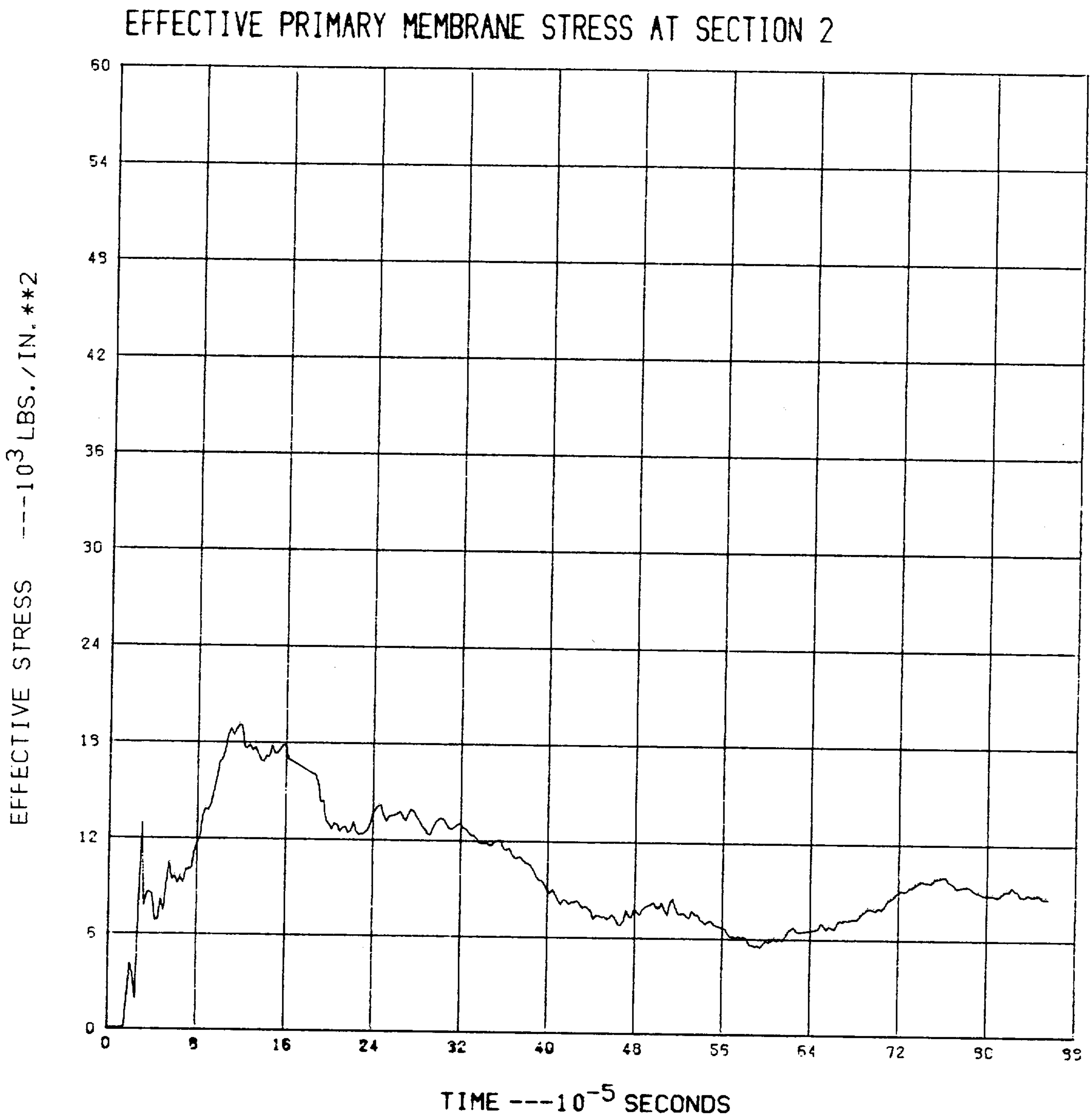


FIGURE 2-11 SECTION 2
PRIMARY MEMBRANE STRESS

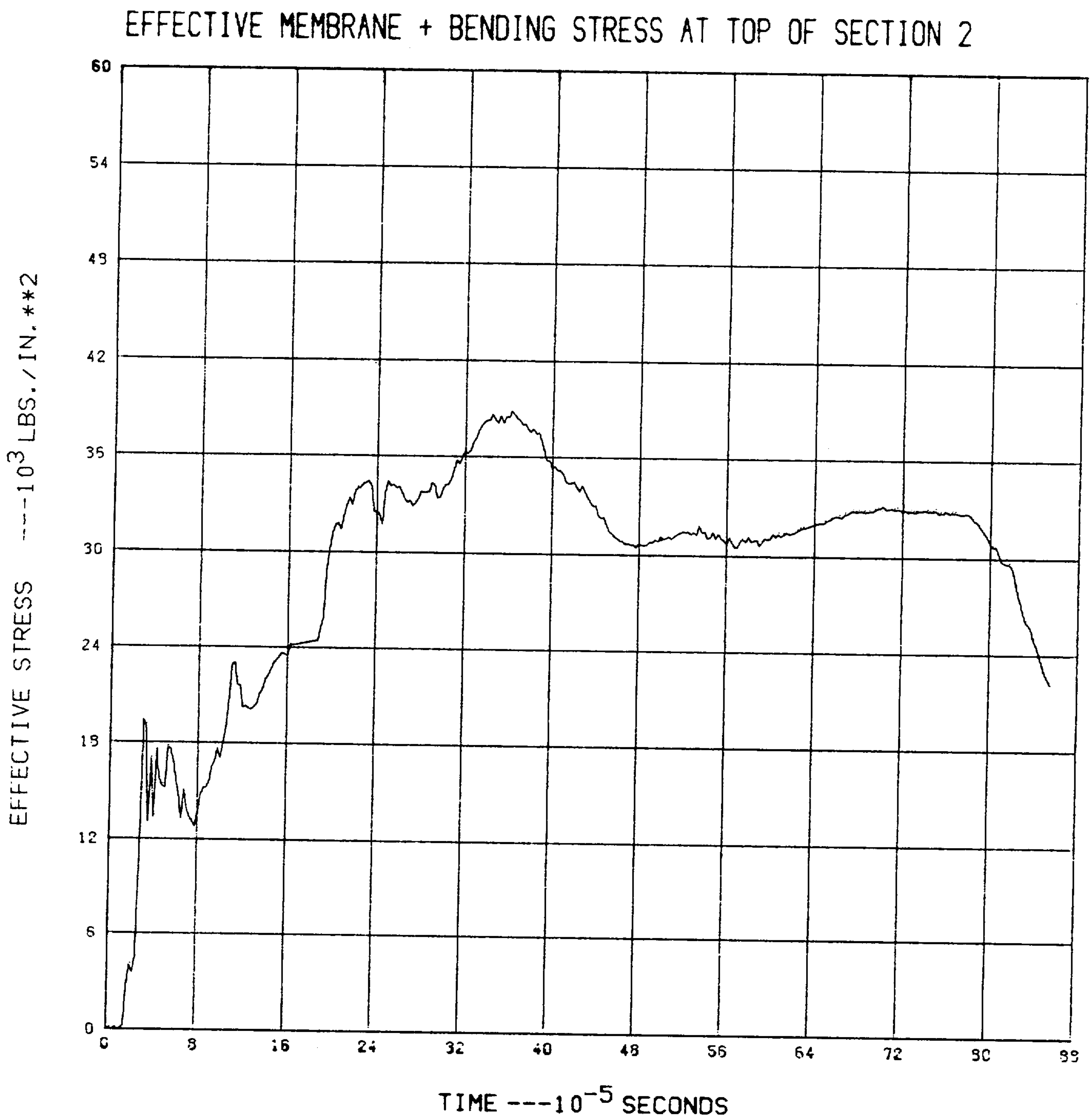


FIGURE 2-12 SECTION 2

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT TOP OF PLATE

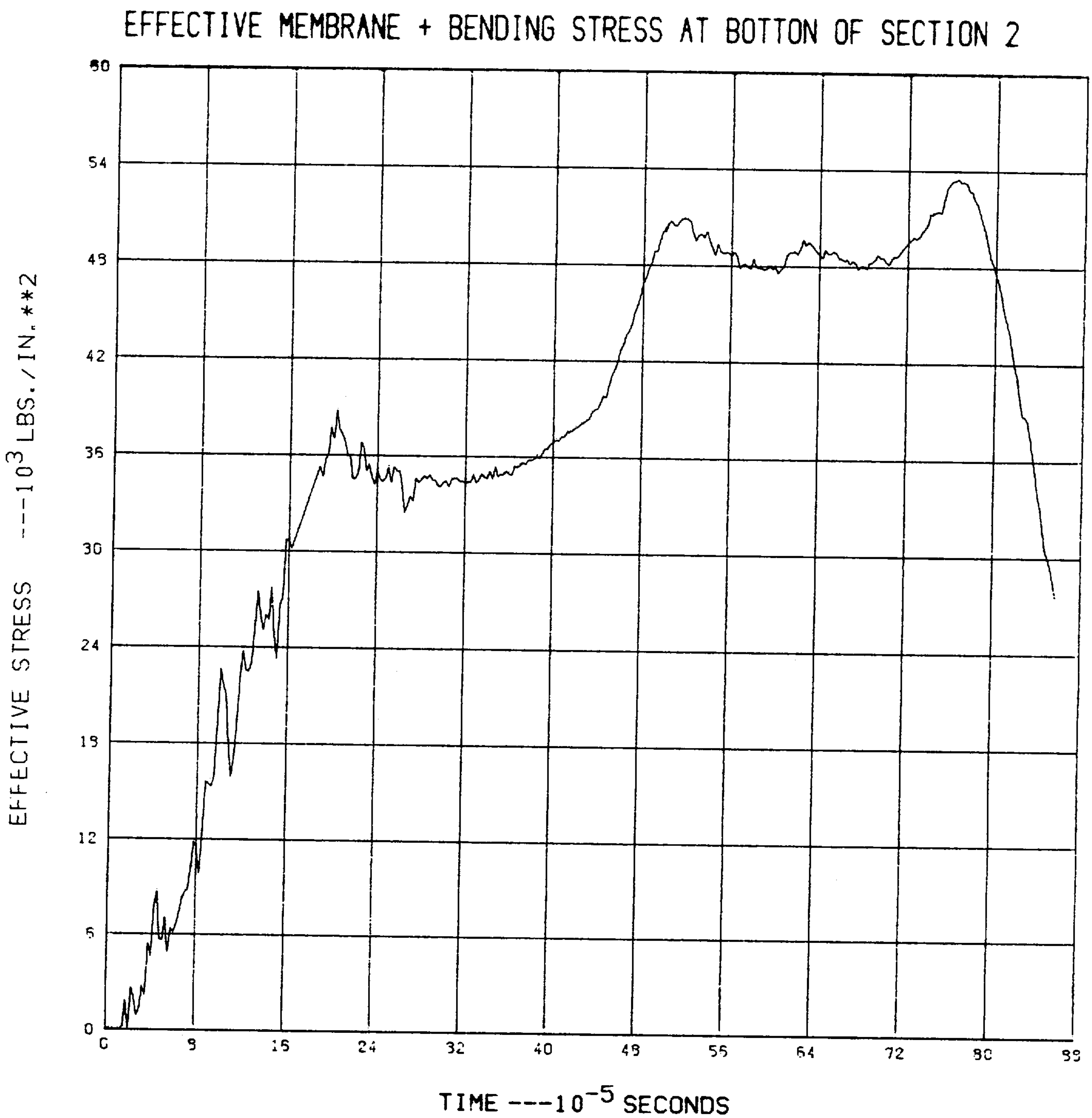


FIGURE 2-13 SECTION 2

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT BOTTOM OF PLATE

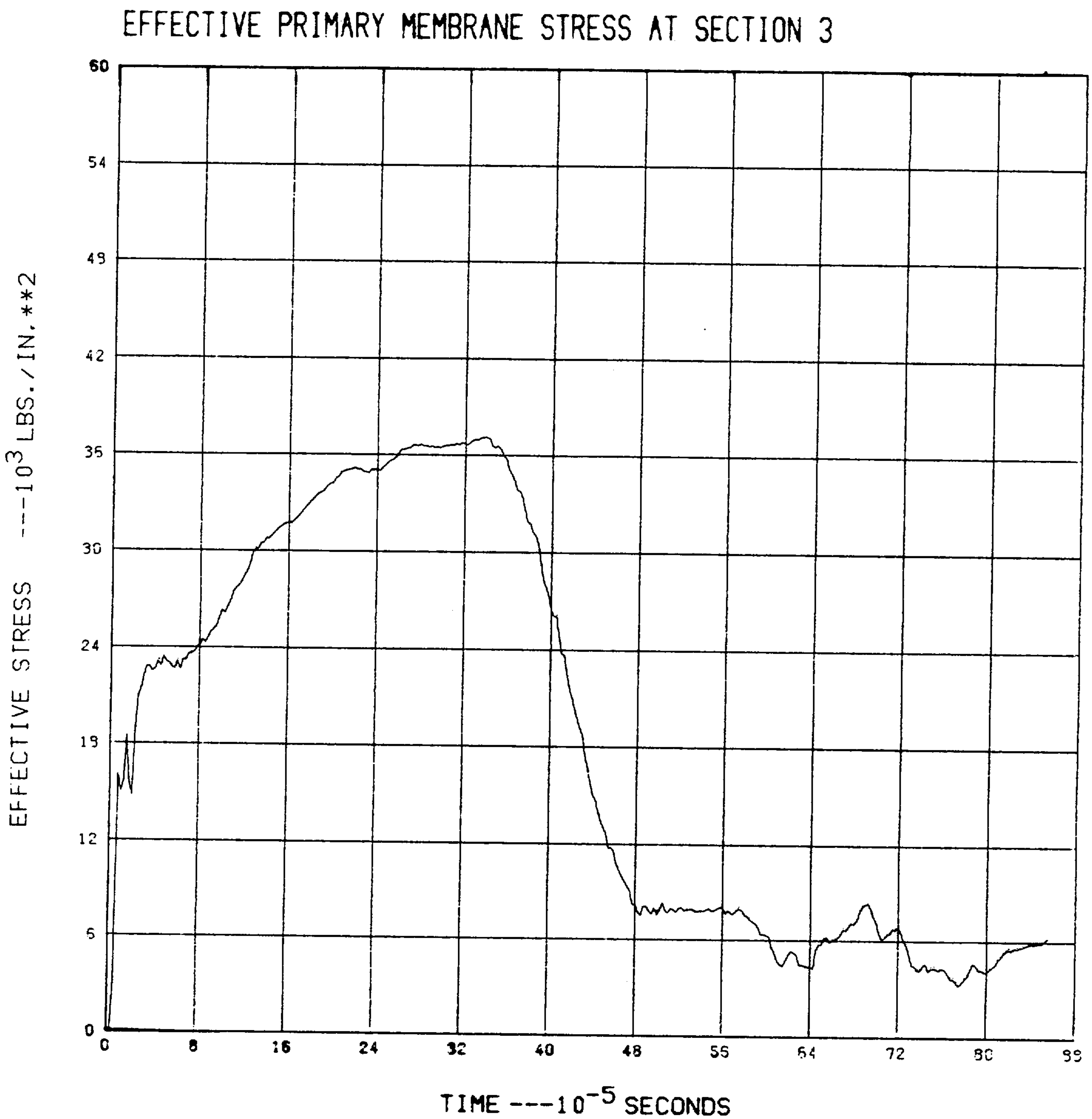


FIGURE 2-14 SECTION 3
PRIMARY MEMBRANE STRESS

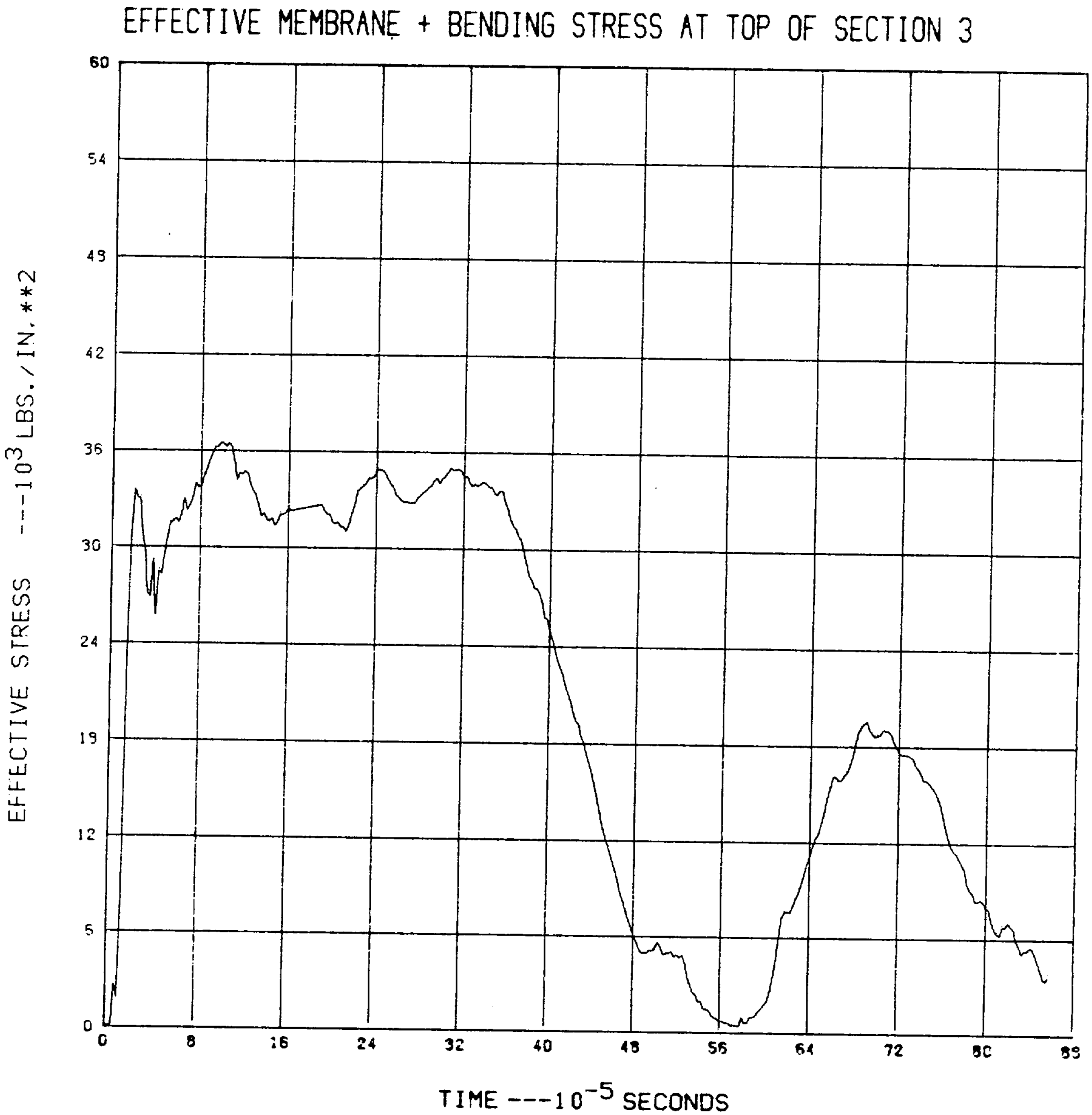


FIGURE 2-15 SECTION 3

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT TOP OF PLATE

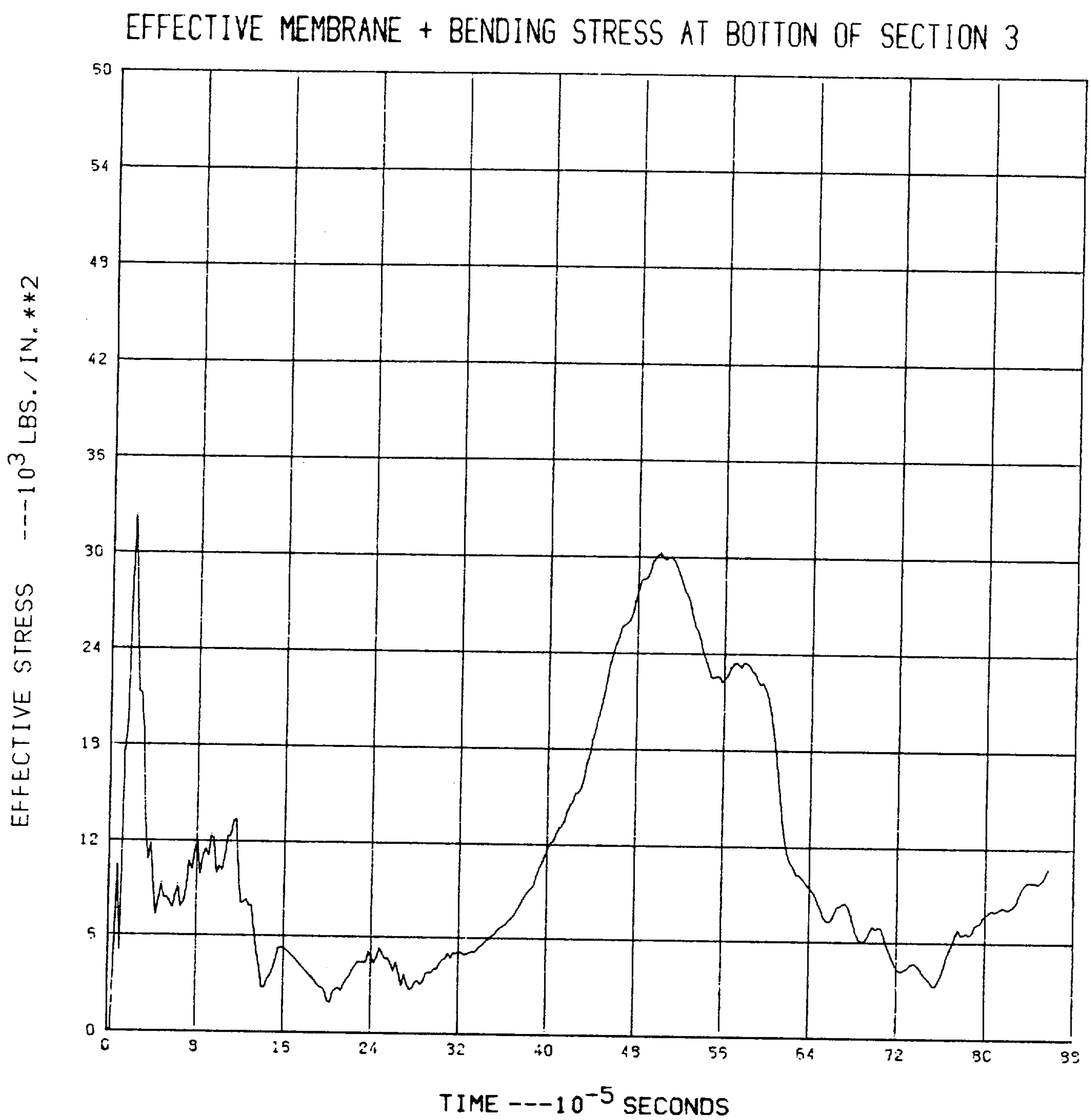


FIGURE 2-16 SECTION 3

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT BOTTOM OF PLATE

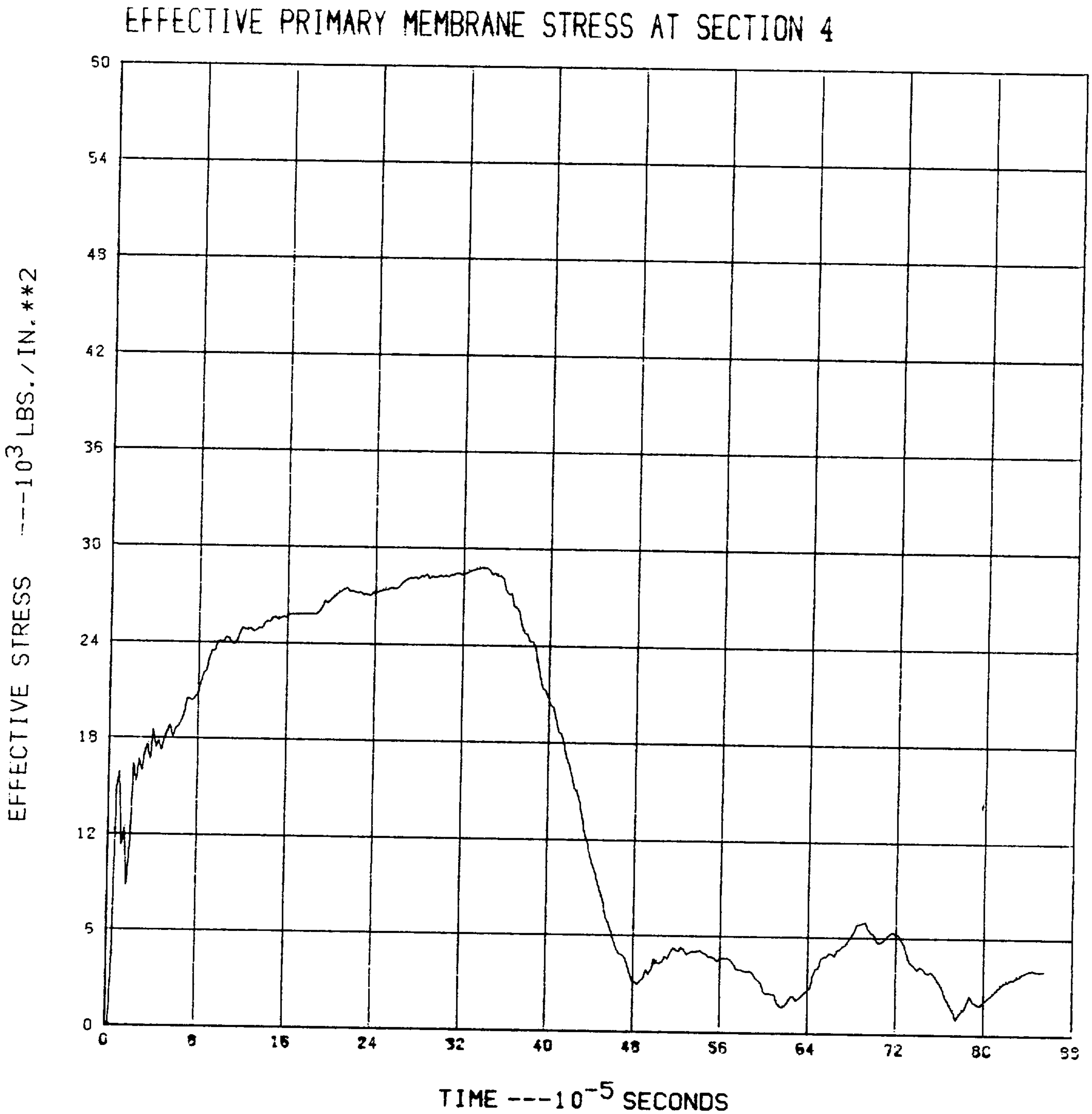


FIGURE 2-17 SECTION 4
PRIMARY MEMBRANE STRESS

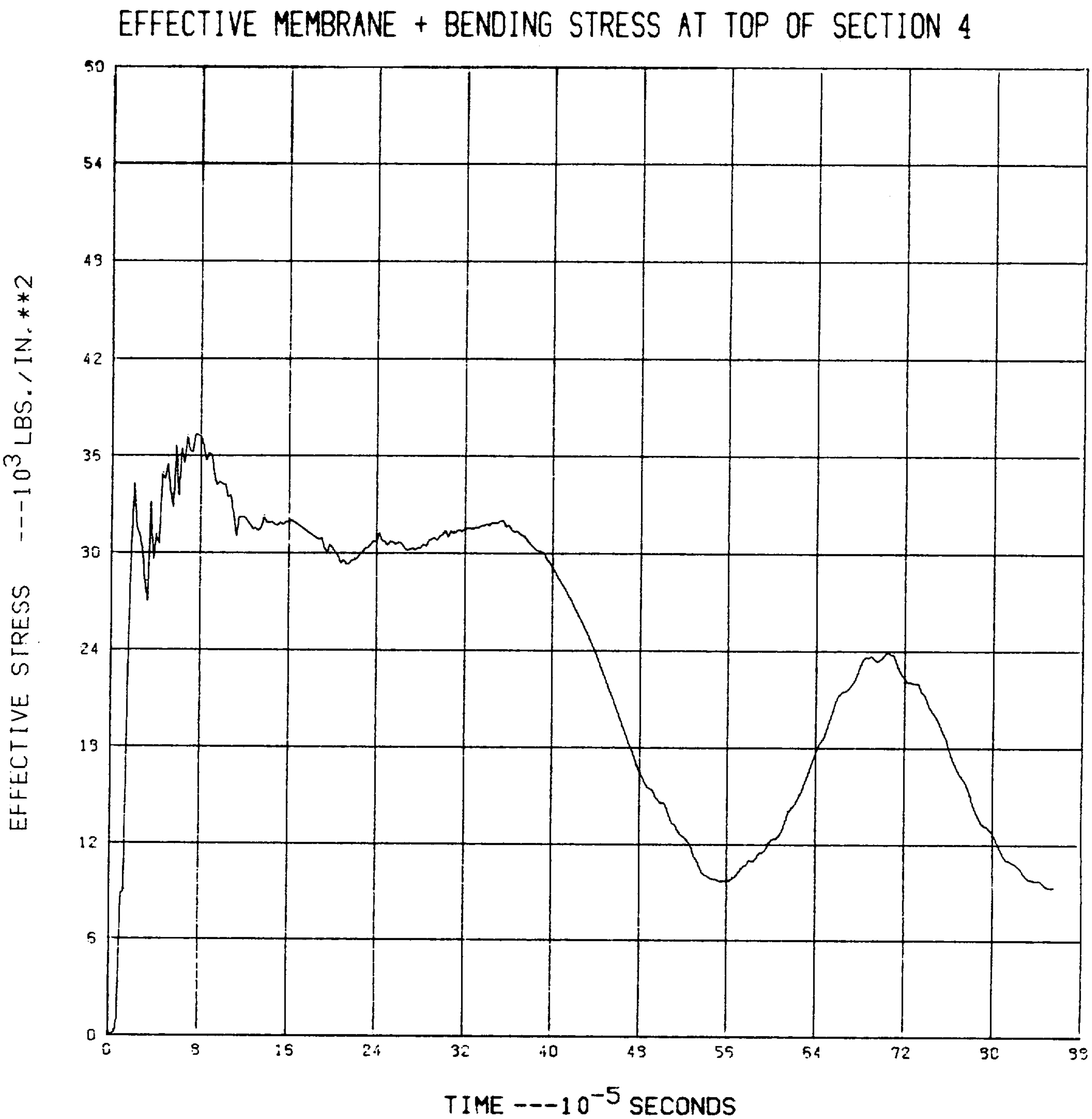


FIGURE 2-18 SECTION 4

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT TOP OF PLATE

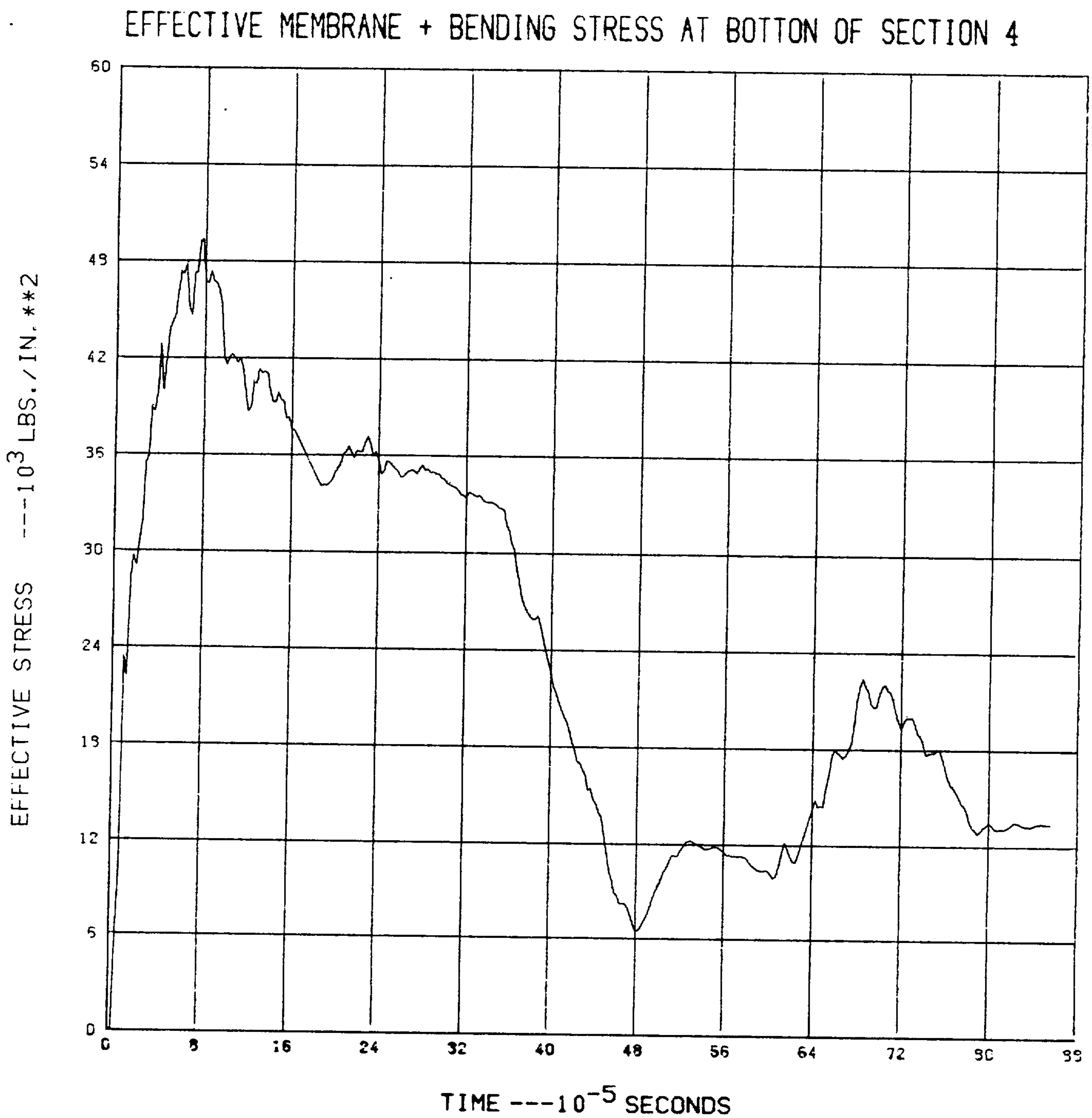


FIGURE 2-19 SECTION 4

PRIMARY MEMBRANE PLUS PRIMARY BENDING STRESS
AT BOTTOM OF PLATE

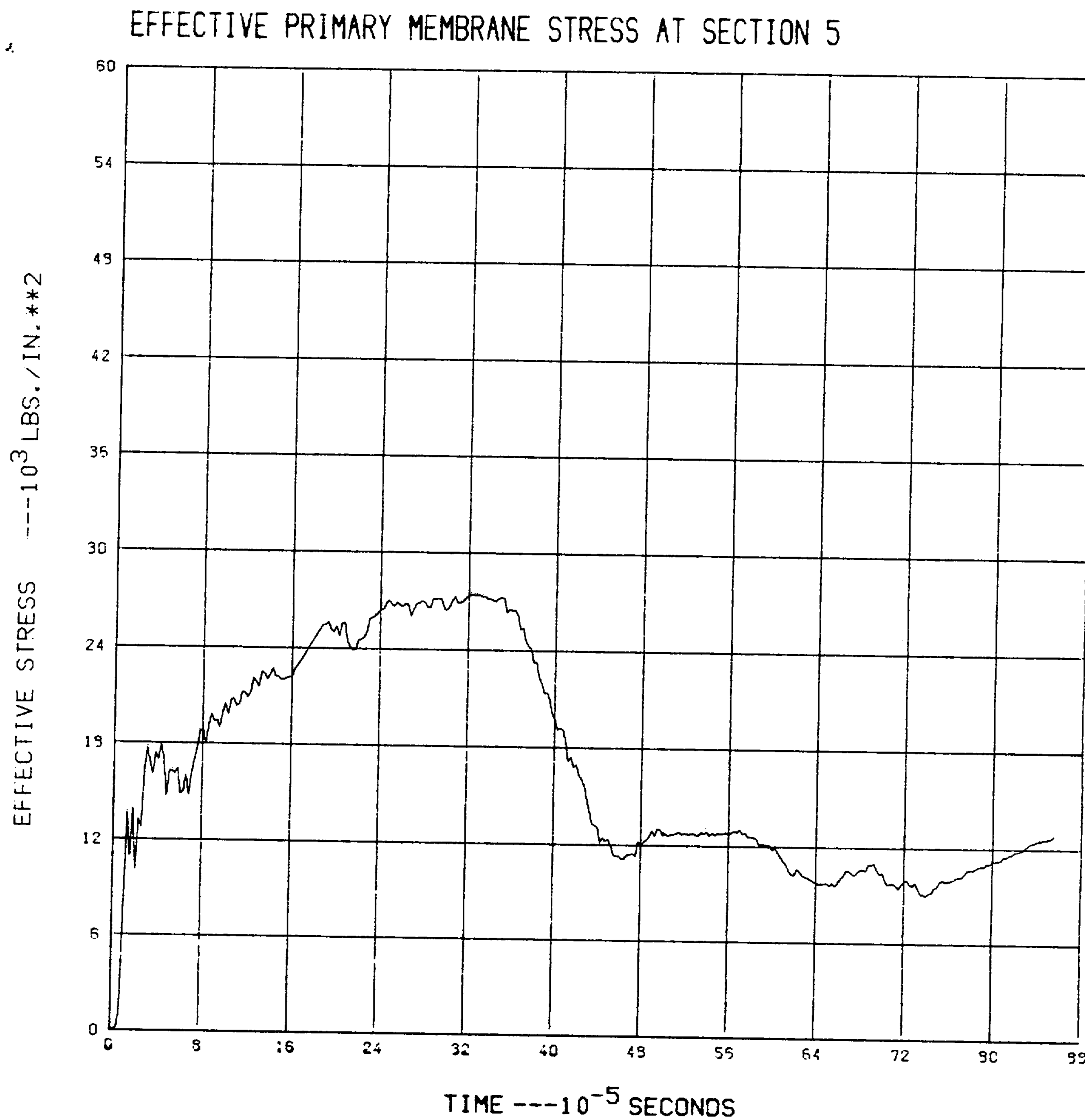


FIGURE 2-20 SECTION 5
PRIMARY MEMBRANE STRESS

EFFECTIVE MEMBRANE + BENDING STRESS AT TOP OF SECTION 5

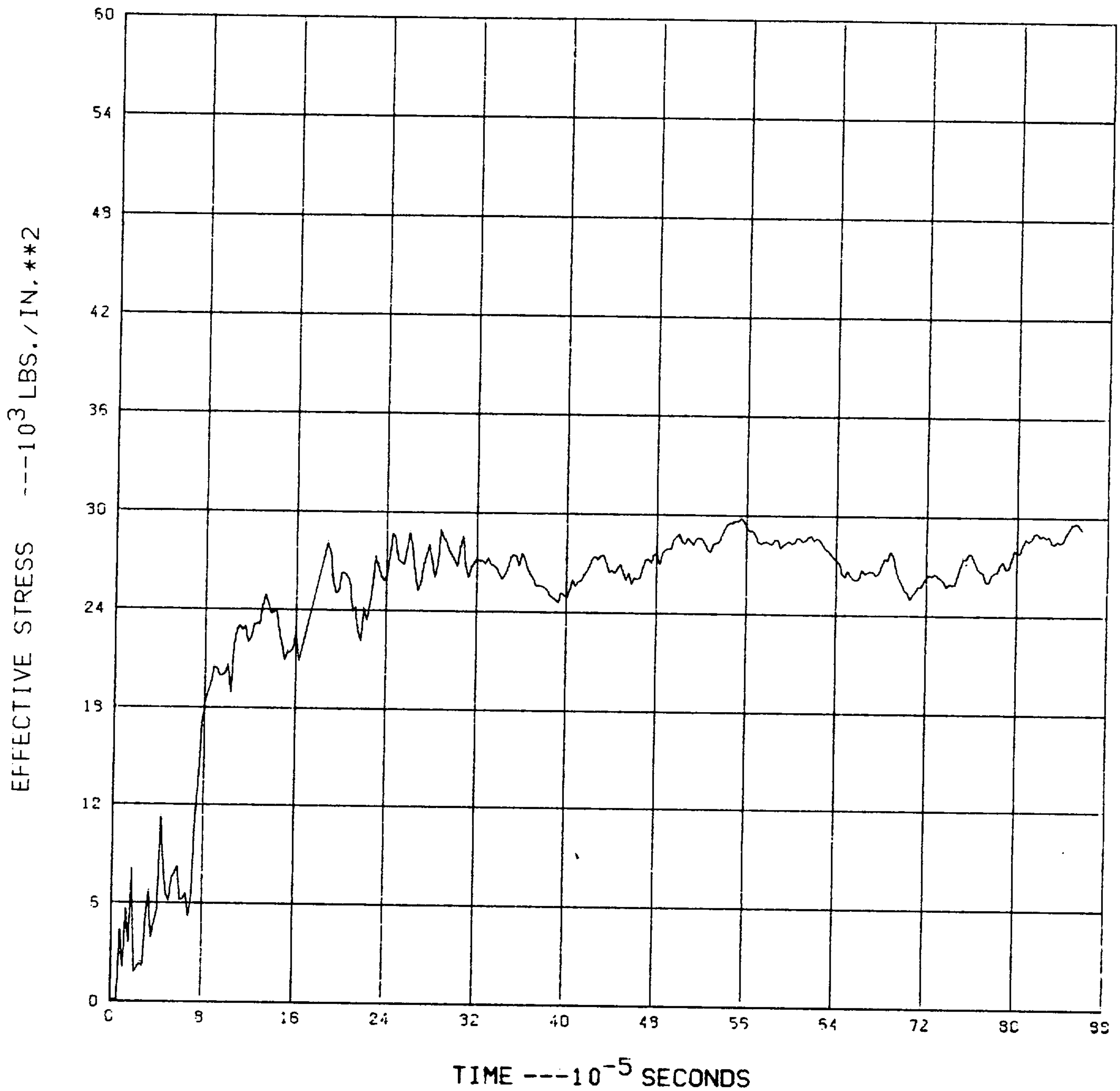


FIGURE 2-21 SECTION 5

PRIMARY MEMBRANE PLUS PRIMARY BENDING
AT INSIDE EDGE OF WELD

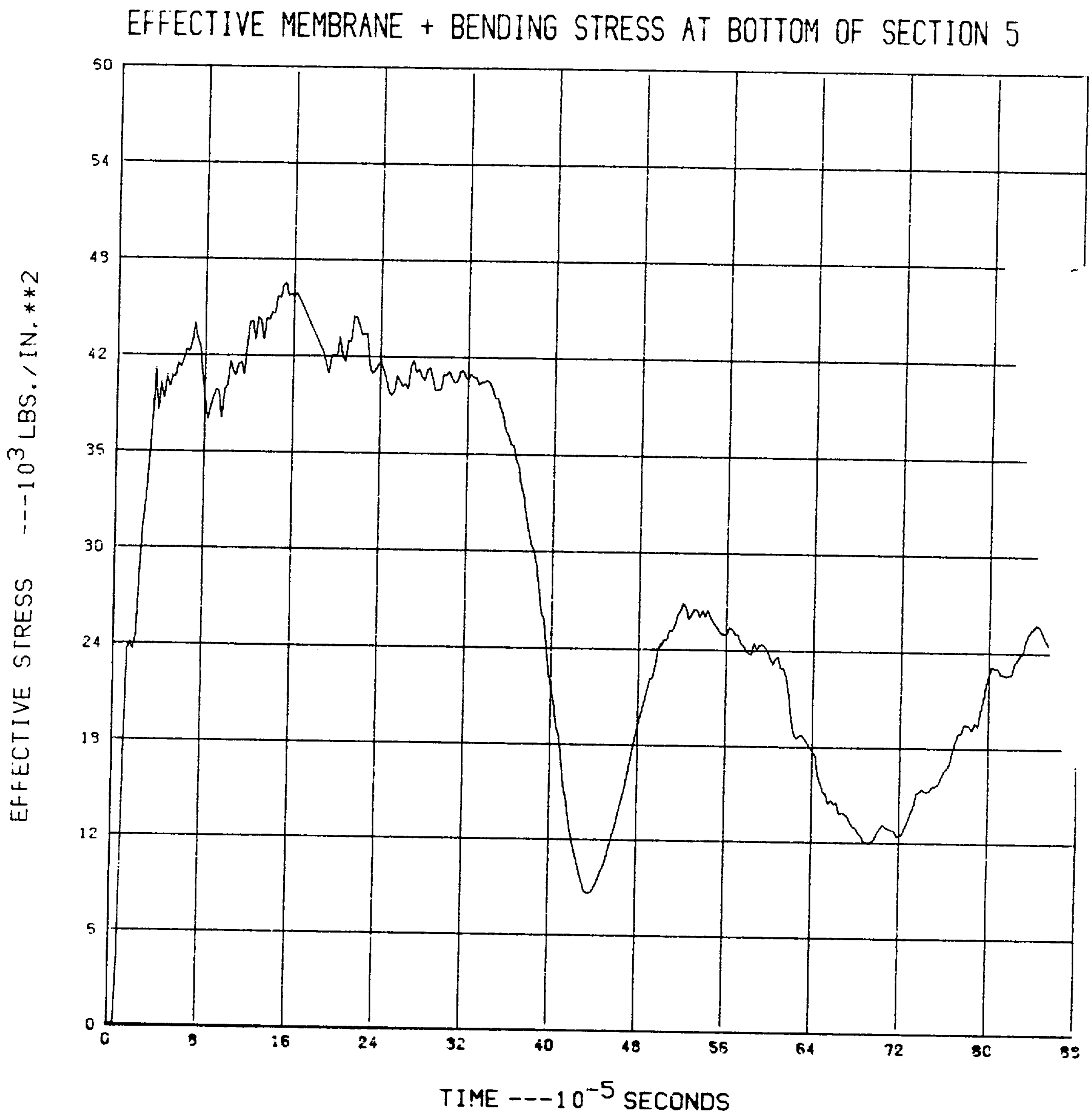


FIGURE 2-22 SECTION 5

PRIMARY MEMBRANE PLUS PRIMARY BENDING
AT OUTSIDE EDGE OF WELD

TABLE 2-2
PRIMARY STRESSES

Location	Effective Stress (psi)	Time of Max Stress (ms)	% of Allowable
Section 1 Center of Plate			
General Membrane*	26,975	0.14	49
Membrane + Bending Top+	41,615	0.65	53
Membrane + Bending Bottom	45,806	0.403	58
Section 2 Inner Edge of Ring			
General Membrane	19,079	0.118	34
Membrane + Bending at Top	38,851	0.363	49
Membrane + Bending at Bottom	53,501	0.765	68
Section 3 Plate at Flange			
General Membrane	37,112	0.340	67
Membrane + Bending at Top	36,496	0.098	46
Membrane + Bending at Bottom	32,235	0.020	41
Section 4 Plate at Flange			
General Membrane	28,822	0.338	52
Membrane + Bending at Top	37,303	0.075	47
Membrane + Bending at Bottom	49,310	0.078	63
Section 5 Outer Weld			
General Membrane	27,435	0.323	49
Membrane + Bending at Top	29,884	0.555	38
Membrane + Bending at Bottom	46,525	0.153	59

*Membrane Allowable = $S_y + 1/3\ (S_{ut} - S_y) = 55{,}437$ psi
(See page 5-2 for criteria and 5-3 for application)

+Membrane + Bending Allowable 0.7 S_{ut} = 78,618 psi ensure that the shield ring will remain in place and be functional following the 30-ft hypothetical accidental drop.

2.7.3.7. Flat Top End Drop

In the flat top end drop, the typical burial liner contents (control rods) will bear upon the shield ring. An impact ring 1/2 in. x 1/2 in. in cross section is provided on the outside of the burial liner cover to transmit all of the load from the burial liner and contents to the interface ring attached to the cask closure. As analyzed in Section 2.7.1.3, the cask closure is designed to absorb loads from a mass well in excess of the four control rods and burial liner.

2.7.4 Evaluation of the Optional Temporary Shield Tubes

2.7.4.1 Discussion. The following sections provide structural analyses which demonstrate that the optional temporary shield tubes withstand the hypothetical accident conditions and maintain shielding effectiveness. The evaluation for hypothetical drop conditions in Section 2.7.1 shows that the maximum longitudinal and transverse cask decelerations during the corner drops is less than those for the end and side drops. Thus, only these two drop orientations are selected for evaluation.

As shown in drawing GADR 55-2-14 in Chapter 1, the optional temporary shield tubes are austenitic stainless steel. The sidewalls of the shield tubes are 6 in. diameter pipe, with either a 1-in. or 2-in. wall thickness. The bottom is 4 in. thick, and the lid is 5 in. thick. The lid is fastened with 1/2-13 UNC bolts and 3/8-in. locating pins which are also stainless steel.

2.7.4.2. Evaluation Criteria. Although the temporary shielding is not a containment boundary component, for conservatism the design criteria from USNRC Regulatory Guide 7.6, "Design Criteria for Structural Analysis of

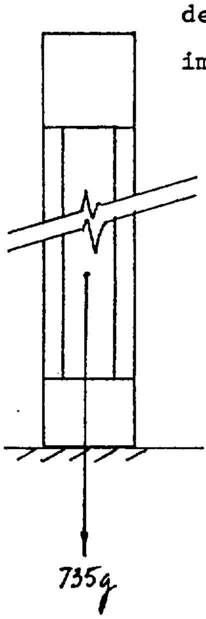
Shipping Cask Containment Vessels," will be used. Applying these criteria, the allowable stress intensities become:

Primary membrane	2.4 Sm = 40 ksi.
Membrane plus bending	3.6 Sm = 60 ksi.

for S_m = 16.7 ksi. Based on Table I-1-2 of the ASME Code (Ref. 2-17), 16.7 is the minimum value of S_m for the austenitic stainless steels to be used for the optional shield tubes. This value of S_m is allowable for temperatures less than 300°F, and is consistent with the thermal results presented in Section 3.4.

Because the shielding is austenitic stainless steel, brittle fracture is not a concern.

2.7.4.3. <u>End Drop</u>. The temporary shielding will be analyzed for a 735 g deceleration during the end drop, the same deceleration calculated for the impacting end of the cask in Section 2.7.1.1.



<u>Sidewalls</u>

$$\sigma = \frac{WG}{A}$$

where W = canister weight

G = 735 g's

A = cross sectional area of shielding sidewalls

For the 1-in.-thick shielding:

$$A = \frac{\pi}{4} [(6 \text{ in.})^2 - (4 \text{ in.})^2] = 15.7 \text{ in.}^2$$

$$W_{sidewall} = A \text{ (144 in.)} \left(0.285 \frac{\text{lb}}{\text{in.}^3}\right) = 644 \text{ lb}$$

$$A_{end} = \frac{\pi}{4}\,(6\text{ in.})^2 = 28.3\text{ in.}^2$$

$$W_{end} = A_{end}\,(5\text{ in.})\left(0.285\,\frac{\text{lb}}{\text{in.}^3}\right) = 40\text{ lb}$$

Therefore:

$$\sigma = \frac{(644 + 40)\text{ lb }(735\text{ g})}{15.7\text{ in.}^2} = 32.0\text{ ksi} < 40\text{ ksi, F.S.} = 1.25$$

For the 2-in.-thick shielding:

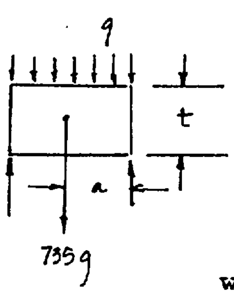
$$A = \frac{\pi}{4}\,[(6\text{ in.})^2 - (2\text{ in.})^2] = 25.1\text{ in.}^2$$

$$W_{sidewall} = A\,(144\text{ in.})\left(0.285\,\frac{\text{lb}}{\text{in.}^3}\right) = 1{,}030\text{ lb}$$

Therefore:

$$\sigma = \frac{(1030 + 40)\text{ lb }(735\text{ g})}{25.1\text{ in.}^2} = 31.3\text{ ksi} < 40\text{ ksi, F.S.} = 1.28$$

<u>Ends</u>



For the maximum plate stress, assume simply supported:

$$\sigma_b = \frac{6M}{t^2}$$

where $M = q\,\dfrac{a^2\,(3 + \nu)}{16}$ (Ref. 2-18, p. 363)

$t_1 = 5$ in., $t_2 = 4$ in.

$\nu = 0.3 =$ Poisson's ratio

$q = g\,\dfrac{(W_{end})}{(A_{end})}$

$a = 3$ in.

For the 5-in.-thick lid:

$$q = \frac{(735\ g)\ (40\ lb)}{28.3\ in.^2} = 1039\ \frac{lb}{in.^2}$$

$$M = \frac{\left(1039\ \frac{lb}{in.^2}\right)(3\ in.)^2\ (3.3)}{16} = 1{,}929\ \frac{in.\ -\ lb}{in.}$$

$$\sigma_b = \frac{6\ (1929\ lb)}{(5\ in.)^2} = 0.5\ ksi \ll 60\ ksi,\ F.S. = 120$$

For the 4-in.-thick bottom plate:

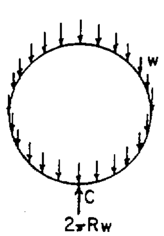
$$q = \frac{(735\ g)\ (32\ lb)}{28.3\ in.^2} = 831\ \frac{lb}{in.^2}$$

$$M = \frac{\left(831\ \frac{lb}{in.^2}\right)(3\ in.)^2\ (3.3)}{16} = 1542\ \frac{in.\ -\ lb}{in.}$$

$$\sigma_b = \frac{6\ (1542\ lb)}{(4\ in.)^2} = 0.6\ ksi \ll 60\ ksi,\ F.S. = 100$$

2.7.4.4 Side Drop. During the side drop, the sidewall of the optional temporary shield tube is uniformly supported and decelerates at 84 g's, the maximum cask deceleration during the side drop calculated in Section 2.7.1.2.

From Ref. 2-18, p. 231:



$$M_{max} = \frac{3}{2}\ WR^2 \text{ at pt. C} \qquad (1)$$

$$T = T_A U + V_A Z + LT_T \qquad (2)$$

$$V = T_A Z + V_A U + LT_V \qquad (3)$$

where W = weight per unit inch circumference

R = radius = 3 in.

$$T_A = \frac{WR}{2}$$

$$V_A = 0$$

$$LT_A = -WRXZ$$

$$LT_V = -WRXU$$

X = angular distance to C = π radiaus

$U = \cos X = -1$

$Z = \sin x = 0$

For the 1-in.-thick shielding, assuming a 1-in. depth:

$$w = \frac{\text{weight}}{\text{circumference}} \times G = \frac{(15.7 \text{ in.}^2)(1 \text{ in.})\left(0.285 \frac{\text{lb}}{\text{in.}^3}\right)(84 \text{ g})}{\pi \text{ (6 in.)}} = 20 \frac{\text{lb}}{\text{in.}}$$

$$T_A = \frac{\left(20 \frac{\text{lb}}{\text{in.}}\right)(3 \text{ in.})}{2} = 30 \text{ lb}$$

$$LT_T = 0$$

$$LT_V = -\left(20 \frac{\text{lb}}{\text{in.}}\right)(3 \text{ in.})(\pi)(-1) = 188.5 \text{ lb}$$

Substituting into equations (1) through (3):

$$M_{max} = \frac{3}{2}\left(20 \frac{\text{lb}}{\text{in.}}\right)(3 \text{ in.})^2 = 270 \text{ in.-lb per 1-in. depth}$$

$$T = (30 \text{ lb})(-1) + 0 + 0 = -30 \text{ lb}$$

$$V = 0 + 0 + 188.5 \text{ lb} = 188.5 \text{ lb}$$

Then:

$$\sigma_m = \frac{T}{A} + \frac{V}{A} = \frac{30 \text{ lb} + 188.5 \text{ lb}}{1 \text{ in.}^2} = 0.2 \text{ ksi} << 40 \text{ ksi, F.S.} = 200$$

$$\sigma_m + \sigma_b = 0.2 + \frac{6M}{t^2} = \frac{6 \text{ (270 in.-lb)}}{(1 \text{ in.})^2} = 1.8 \text{ ksi} < 60 \text{ ksi, F.S.} = 33$$

where A is the cross-sectional area of the tube at pt. C, the point of impact, assuming a 1-in. depth.

For the 2-in.-thick shielding, assuming a 1-in. depth:

$$w = \frac{\text{weight}}{\text{circumference}} \times G = \frac{(25.1\ \text{in.}^2)(1\ \text{in.})\left(0.285\ \frac{\text{lb}}{\text{in.}^3}\right)(84\ g)}{\pi\ (6\ \text{in.})} = 32\ \frac{\text{lb}}{\text{in.}}$$

$$T_A = \frac{\left(32\ \frac{\text{lb}}{\text{in.}}\right)(3\ \text{in.})}{2} = 48\ \text{lb}$$

$$LT_T = 0$$

$$LT_V = -\left(32\ \frac{\text{lb}}{\text{in.}}\right)(3\ \text{in.})(\pi)(-1) = 302\ \text{lb}$$

Substituting into equations (1) through (3):

$$M_{max} = \frac{3}{2}\left[32\ \frac{\text{lb}}{\text{in.}}\right](3\ \text{in.})^2 = 432\ \text{in.-lb per 1-in. depth}$$

$$T = 48\ \text{lb}\ (-1) + 0 + 0 = -48\ \text{lb}$$

$$V = 0 + 0 + 302\ \text{lb} = 302\ \text{lb}$$

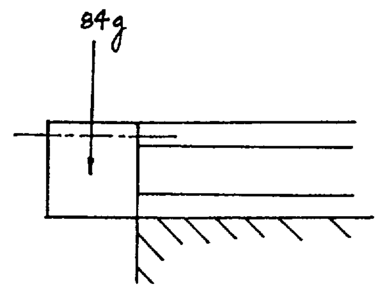
Then:

$$\sigma_m = \frac{T}{A} + \frac{V}{A} = \frac{48 + 302}{2\ \text{in.}^2} = 0.2\ \text{ksi} \ll 40\ \text{ksi, F.S.} = 200$$

$$\sigma_m + \sigma_b = 0.2 + \frac{6M}{t^2} = \frac{6\left(432\ \text{in.} - \frac{\text{lb}}{\text{in.}}\right)}{(2\ \text{in.})^2} = 0.8\ \text{ksi} \ll 60\ \text{ksi, F.S.} = 75$$

Bolts and Locating Pins

Since the temporary shielding is supported uniformly on all sides, there will be no stress on the bolts or locating pins during a side drop. However, for conservatism, the lid will be assumed to be supported during a side drop as follows.



Since the locating pins have a tighter fit than the bolts, they will react shear.

$$\tau_{pin} = \frac{W_{lid}G}{2A_\sigma} \text{ (shear)}$$

where G = 84 g's

A_σ = stress area of a 3/8-in. pin = 0.1104 in.^{2}

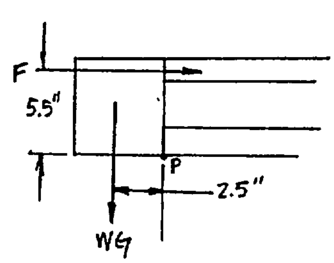
3 = number of pins

W_{lid} = 40 lb

$$\tau_{pin} = \frac{(40 \text{ lb})\ (84)}{2\ (0.1104 \text{ in.}^2)} = 15.2 \text{ ksi}$$

$$\sigma = 2\tau = 30.4 \text{ ksi} < 40 \text{ ksi, F.S.} = 1.3$$

The bolts will react the moment which tends to rotate the lid. Conservatively assuming that only one of the three bolts reacts this moment:



$$\Sigma M_p = 0 = (40\ \text{lb})(84\ \text{g})(2.5\ \text{in.}) - F(5.5\ \text{in.})$$

$$F = 1.53\ \text{kips}$$

$$\sigma_{bolt} = \frac{F}{A}$$

where A = stress area at a 1/2-13 UNC bolt = 0.1419 in.^2

$$= \frac{1.53\ \text{kips}}{0.1419\ \text{in.}^2} = 10.8\ \text{ksi} < 40\ \text{ksi, F.S.} = 3.7$$

Welds

Again, since the optional temporary shield tube is supported uniformly on all sides, there will be no stress on the welds. However, for conservatism, the welds will be assumed to support the end during side deceleration as follows:

$$\tau = \frac{W_{end}}{A_w}$$

where $G = 84$ g's

$$A_w = \frac{\pi}{4}\left[(6\ \text{in.})^2 - (5.5\ \text{in.})^2\right] = 4.5\ \text{in.}^2$$

$$W_{end} = 32\ \text{lb}$$

Therefore:

$$\tau = \frac{(32\ \text{lb})\ (84\ \text{g})}{4.5\ \text{in.}^2} = 0.6\ \text{ksi}$$

$$\sigma = 2\tau = 1.2\ \text{ksi} < 40\ \text{ksi, F.S.} = 33.$$

2.7.4.6 Summary of Results. The results of the structural evaluation for the optional temporary shield tubes are summarized in Table 2-3. As shown in the table, all of the stresses calculated are below the allowables of Regulatory Guide 7.6.

TABLE 2-3
SUMMARY OF STRUCTURAL RESULTS
FOR THE OPTIONAL TEMPORARY SHIELD TUBES[a]
(All stresses in ksi)

	1-in.-Thick	2-in.-Thick	Allowable
	End Drop		
Sidewall	32.0	31.3	40
Lid	0.5	0.5	60
Bottom plate	0.6	0.6	60
Bolts	0	0	40
Welds	0	0	40
	Side Drop		
Sidewall	1.8	0.8	60
Ends	0	0	40
Locating pins	30.4[b]	30.4[b]	40
Bolts	10.8[b]	10.8[b]	40
Welds	0.6	0.6	40

[a]End and side drops bound corner drop results.

[b]Since the shield tubes are supported uniformly on all sides, these stresses are actually zero during a side drop. However, for conservatism, they have been assumed to carry the side drop deceleration.

2.8 APPENDIX

2.8.1 Low Temperature Uranium Bar Drop Tests

2.8.1.1 Discussion. In an effort to obtain a preliminary indication of the ductility properties of uranium at subzero temperatures, a series of drop test was scheduled and conducted at National Lead Company's Albany branch. Samples of unalloyed depleted uranium were tested along with various samples of low alloys to serve as a basis for comparison.

Various diameters of as cast depleted uranium round bar were used; however, each round bar was cut to length such that the length to diameter ratio was 8 to 1 - this being approximately the same as the L/D ratio of the depleted uranium in Model FSV-1 Configurations A, B, C and D.

Most drops were conducted from a height of 29 feet, 3 inches onto essentially unyielding surfaces of either steel or concrete. Two samples, also from a height of 29 feet 3 inches, were dropped on a sharp edged fulcrum. Temperature at the top of drop of all samples ranged between -55°F to -60°F.

Results of these preliminary drop test indicated that the unalloyed depleted uranium exhibited good ductility properties at low temperatures. Furthermore, it wasn't until the third 29 feet 3 inches drop of a test specimen that ductility failure occurred. A 1-3/16" diam by 9-1/2 inch long unalloyed depleted uranium round bar was dropped on a concrete impact surface with no visible failure resulting. The same test specimen was then dropped from the same height of 29 feet 3 inches and at the same temperature of -60°F on a steel plate. This time a slight bend in the bar was noted. On the third test, the specimen was dropped on the sharp edge of a steel angle. Along with a greater bend in the bar, it was noted that a small crack developed opposite the side of impact.

2.8.1.2 Results

Test No.	Specimen Drop No.	Material (As-Cast)	Diameter (in.)	Attitude at Impact	Impacting Surface	Test Results
1	1	U-2% Mo	1-1/4	Horizontal	Concrete	No failure
2	1	Unalloyed	1-3/16	Horizontal	Concrete	No failure
3	1	Unalloyed	1-3/16	Horizontal	Concrete	No failure
4	1	U-1% Mo, 1% Nb	0.6	Horizontal	Concrete	No failure
5	1	U-1% Mo, 1% W	0.6	45° Corner Drop	Concrete	No failure
6	1	U-1% Nb, 1% W	0.6	45° Corner Drop	Concrete	No failure
7	1	U-1% Ta, 1% W	0.6	Horizontal	Concrete	No failure
8	1	Unalloyed	0.6	Horizontal	Concrete	No failure
9	1	Unalloyed	0.6	Horizontal	Concrete	No failure
10	2	Unalloyed	1-3/16	Horizontal	Stl Plate	Slight Bend
11	2	Unalloyed	1-3/16	Horizontal	Stl Plate	Slight Bend
12	2	U-2% Mo	1-1/4	Horizontal	Stl Plate	No failure
13	2	U-1% Mo, 1% W	0.6	Horizontal	Stl Plate	No failure
14	2	Unalloyed	0.6	Horizontal	Stl Plate	Slight Bend
15	3	Unalloyed	1-3/16	Horizontal	90° Corner	Bent & Cracked
16	3	Unalloyed	1-3/16	Slight Angle Corner Drop	90° Corner	Bent

Test Conditions

Height of drop	29'3"
Temperature of specimens	-55°F to -60°F
Material Condition	As cast
Material Configuration	Round bars, L/D = 8:1

2.8.2 Low Temperature 1/8 Scale Uranium Shell Impact Tests

2.8.2.1 Purpose of Tests. Experimental knowledge is required of the effects of impact loads as used in casks with uranium shielding and having relatively large L/D ratios. The experimental test specimen was subjected to several puncture tests to determine the amount of deformation and to observe the surface condition of the uranium in the impacted areas.

2.8.2.2 Material Used. An as cast 0.2% - 0.3% molybdenum-uranium cylindrical shell, 1/8 the size of the actual shielding in the shipping cask, was used for this series of tests.

Comparative dimensions and weights:

	1/8 Scale Cylindrical Shell	Full Size Uranium Shielding
Outside diameter	3-1/4"	26"
Inside diameter	2-3/8"	19"
Length	24-3/8"	194"
Weight	64 lb	32,800 lb

2.8.2.3 Test Procedures. Tests were conducted using the indoor drop test facilities of NLC, Wilmington branch.

An iron-constantan thermocouple was attached to the outer surface of the uranium cylindrical shell. The thermocouple extension leads were connected to a calibrated pyrometer indicator.

The test specimen was then submerged in a solution of acetone and dry-ice until it reached a temperature of approximately -60°F. With the thermocouple still attached, the uranium was connected to a quick release mechanism which, in turn, was attached to an overhead crane. The entire assembly was moved over the impact area which consisted of a 3/4 inch wide carbon steel fulcrum 4 inch deep and 12 inch long welded to a 12 inch x 12 inch x 3/4 inch carbon steel base plate. This weldment was resting on a steel anvil pad supported by a concrete foundation. With the use of a scaled line and plumb bob, the test specimen was raised to a height of 40 inches over the fulcrum. Its long axis was positioned level and perpendicular to the long axis of the fulcrum so that the center of gravity of the shell would impact against the fulcrum.

When the pyrometer indicator measured a surface temperature of -40°F the solenoid on the release mechanism was actuated, pulled a release pin and allowed the test specimen to free fall on the fulcrum.

This same test was conducted at 60 inches, 80 inches, 100 inches and 120 inches. Measurements were taken after each test of the outside diameter, inside diameter, length and angle of bend.

2.8.2.4 Results. Results of all free fall fulcrum tests proved negative. The test specimen experienced no dimensional changes or deformations.

The 120 inches drop test had a rebound after impact of 31-1/4 inches above the fulcrum--the test specimen remained level during the rebound. Although no damage occurred to the uranium, the 3/4 inch fulcrum received an indentation approximately 1/4 inch deep.

2.8.3 Uranium Weld Joint Study

2.8.3.1 Discussion. Successful completion of side puncture tests on a uranium casting scale model has prompted a review of impact condition analyses and has also allowed consideration of a type of joint for the uranium sections which permits a greatly reduced depth of welding.

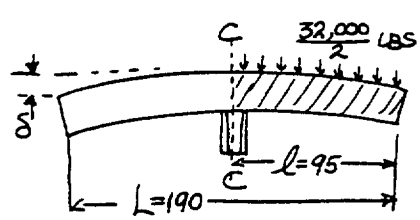
The previous calculations for side wall puncture assumed the onset of plastic hinge deformation at 30,000 psi, and required that 83% of the kinetic energy of the 40 in. drop had to be absorbed by this mechanism. The new drop tests proved that more than double this height of drop did not produce any measurable permanent set. Obviously, justification of this performance requires that the calculated instantaneous peak bending stresses be allowed to reach for higher values and still be elastic.

The effects of this new performance are now investigated in regard to accident conditions, and include the behavior of the redesigned joints under such loadings.

According to the tests, separately reported, a drop height of 120 in., with a rebound of 31-1/4 in., can be credited, conservatively, with kinetic energy proportional only to a drop of 120 - 31-1/4 = 88-3/4 in. This means that energy 2.22 times the specified 40 in. drop was successful absorbed elastically.

2.8.3.2 Puncture Side Wall - 88-3/4 in. Drop Analysis. The stainless steel outer shell, as the member directly exposed to penetration by the steel piston, is not critical. The piston merely cuts partly into the wall, due to the back-up effects of the uranium cylinder.

The uranium cylinder (as tested) is taken as a model, but calculations are now made on a full size cylinder analyzed as a separate body in an elastic drop up to 88-3/4 in.



Consider 1G Load on Cantilever

$D = 26$ in., $d = 19$ in.

$\ell = 95$ in., $L = 190$ in.

Vol. = (531-284) in.^{2} (190 in.) = 46,930 in.^{3} total

Wt = 46,930 (0.683) = 32,000 lb total

$I = 0.0491\ (26^4 - 19^4) = 16{,}041$ in.^{4}

$Z = 16{,}041/13 = 1235$ in.

$$M_c = \frac{w\ell}{2} = \frac{32{,}000}{2}\ \frac{95}{2} = 760{,}000 \text{ in. lb}$$

$$\delta = \frac{w\ell^3}{8EI} = \frac{16{,}000\ (95)^3}{8(29)\ 10^6\ (16{,}041)} = 0.0369 \text{ in.}$$

$$S_b = \frac{M_c}{Z} = \frac{760{,}000}{1235} = 615 \text{ psi}$$

From Marks Handbook, sixth edition, page 5-44:

$$U_{cantilever} = \frac{n^2}{m}\left(\frac{K}{c}\right)^2 \frac{S^2V}{2E} \text{ for uniform load}$$

$$n = 2 \quad m = 8 \quad K = \text{rad. gyr.} = \frac{\sqrt{D^2 + d^2}}{4} \text{ for tube section}$$

$c = D/2$

Therefore,

$$U_{cant.} = \frac{(2)^2}{8}\ \frac{4}{16}\ \frac{(D^2 + d^2)}{D^2}\ \frac{S^2V}{2E} = \frac{D^2 + d^2}{16D^2}\ \frac{S^2V}{E} \text{ for 1/2 beam lgth.}$$

$$U_B = \frac{D^2 + d^2}{8D^2} \frac{S^2V}{E} \quad \text{for full length beam as above}$$

$$= \frac{26^2 + 19^2}{8 \times 26^2} \frac{S^2(46{,}930)}{29\ (10^6)} = \frac{674 + 361}{8\ (676)} S^2 \frac{1615}{10^6} = \frac{310}{10^6} S^2$$

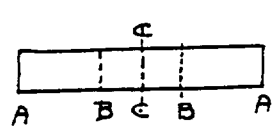
Now S = 615 psi for 1G load

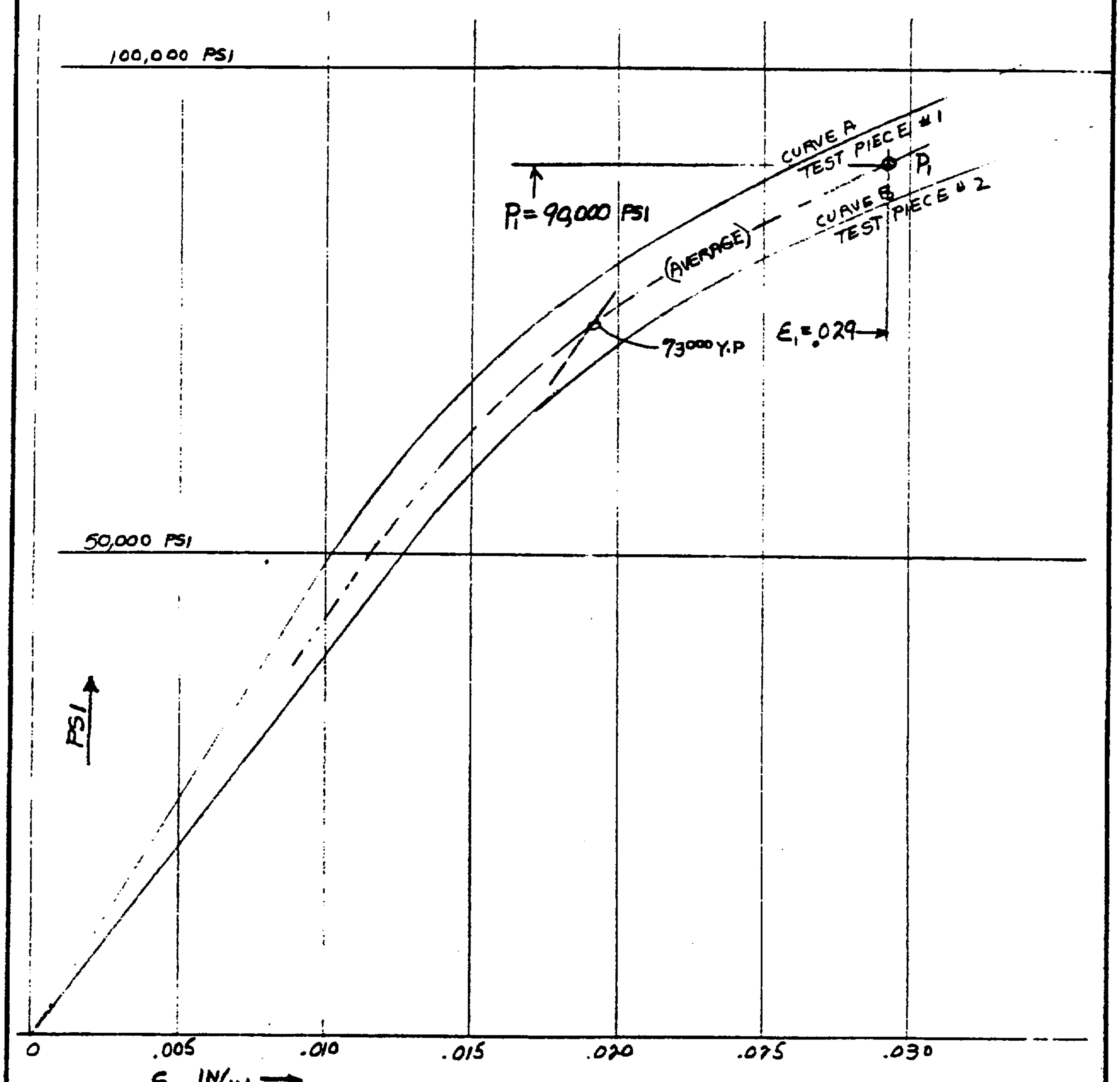
$$U_B = \frac{310\ (615)^2}{10^6} = 117 \text{ in. lb} \quad \text{Note: } U_B \ \alpha\ S^2 \ \alpha\ (G's)^2$$

Line	G's	S psi	δ in.	$(G's)^2$	U_B in. lb	Height Drop
1	1	615.	0.00369	1	117	
2	50	30,750	0.1845	2500	292,500	
3	104.5	64,300	0.386	10,920	1,280,000	40
4	156.	96,000	0.575	24,280	2,840,000	88-75

The stress of 96,000 psi is reached "instantaneously" and only at the top mid point of the beam. This peak is quite consistent with nominal properties of unalloyed cast uranium. Static compression, stress-strain curves for cast, unalloyed depleted uraniium are shown in Fig. 2-23.

The specification is limited to the values of Line 3. The joints are actually at positions B and the moment and stress is reduced to 4/9.





STATIC COMPRESSION STRESS-STRAIN CURVES
UNALLOYED DEPLETED URANIUM
"AS CAST" FOR SHIELDING - N.L.C. FEB. 1970
BACKUS

FIGURE 2-23

$$\frac{M_B}{M_C} = \frac{(2/3\ Wt)(2/3\ell)}{(Wt)(\ell)} = 4/9 \quad \therefore \quad S_B = \frac{4}{9} S_C = \frac{4}{9}(64{,}300)$$

$$= \underline{28{,}600 \text{ psi}}$$

2.8.3.3 <u>Results</u>. Since the "solid" cylinder of the tests (equivalent to full depth penetration weld) has withstood at its midsection <u>96,000 psi</u>, it would be theoretically possible to reduce the depth of an outside weld for position B so that Z for the weld area is only

$$Z_{B2} = \frac{28{,}600}{96{,}000}\ 1235 = \underline{368}$$

to find the i.d. which corresponds to this Z value, let

$$Z_{B2} = 368 = \frac{0.098}{26}(26^4 - d^4) = 0.00378\ [457{,}000 - d^4]$$

$$d^4 = \frac{1725 - 368}{0.00378} = 359{,}000$$

$$d = 24.5 \text{ in.} \quad \therefore \quad t = \frac{26 - 24.5}{2} = \underline{3/4\text{-in. weld req'd min.}}$$

To be quite conservative, it is desirable to <u>double this depth</u> of weld, using <u>2</u> layers of 3/4-in. penetration welds (in offset relationship), providing continuous beam strength in an outer annulus 1-1/2 in. thick out of a total of 3-1/2-in. wall. The inner 2 in. would be machined with interlocking steps (four of 1/2-in. each) providing concentric shear rings and an effective shielding pattern as shown on Fig. 2-24.

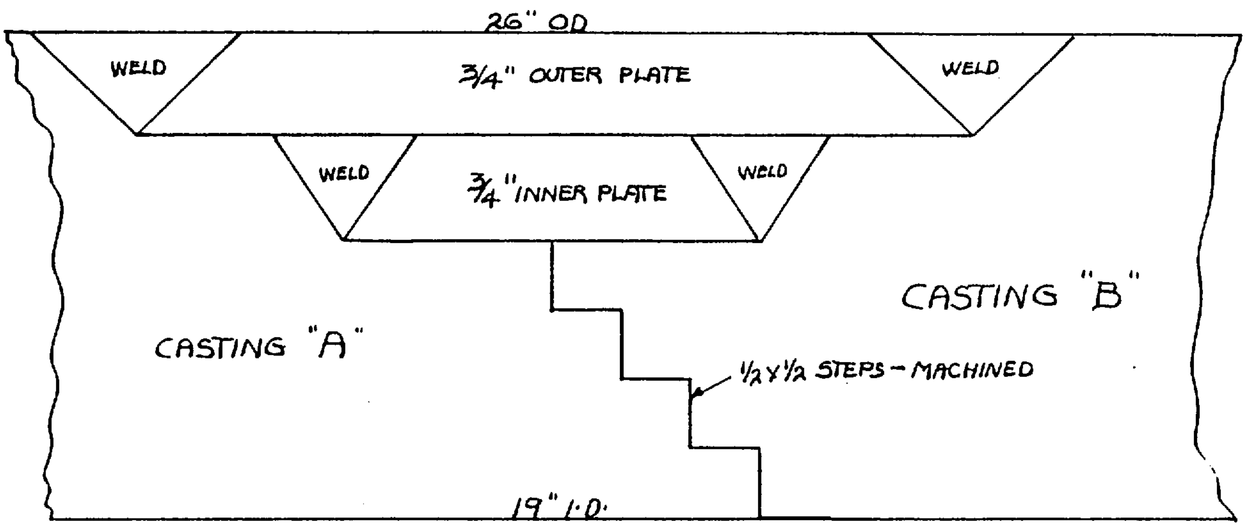


FIGURE 2-24 Depleted Uranium Joint Detail

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SECTION 3.0

THERMAL EVALUATION

3.0 THERMAL EVALUATION

Although Model FSV-1 in Configurations A, B, C and D is not currently used for the transport of high temperature gas-cooled (HTGR) spent fuel elements, the following thermal evaluation is included to document the thermal performance of the package. The contents of Model FSV-1 in Configurations A, B, C and D will not exceed the 4.1 kW of decay heat from six (6) spent fuel elements.

3.1 DISCUSSION

Model FSV-1 in Configurations A, B, C, and D is designed and evaluated for the normal conditions of transport and the hypothetical accident condition.

3.2 SUMMARY OF THERMAL PROPERTIES OF THE MATERIALS

Table 3-1 lists the thermal properties of the materials which constitute the cask as they were used in the analysis. References for these properties may be found in Section 3.2 of Vol. II.

3.3 TECHNICAL SPECIFICATIONS OF COMPONENTS

3.3.1 Spent Fuel Heat Generation

The fuel blocks being shipped in this cask have been irradiated, and the fissionable fuel has been partially consumed. Due to residual isotope activity, there is a continuing "after-heat" which decays with time, depending on the isotope half-life. This activity is absorbed by the fuel and cask components and is realized in the form of heat. This heat generation is predictable and has been used in the calculations.

It is assumed that the spent fuel is loaded into the shipping cask no sooner than 100 days after the reactor is shut down. Thus the maximum heat generation that the cask need be designed for is obtained from fuel loaded 100 days after the reactor shutdown.

TABLE 3-1
THERMAL PROPERTIES OF MATERIALS

Helium

$K = 1.29 \times 10^{-3} * T°R^{0.674}$ Btu/hr-ft-°F

$C_p = 1.242$ Btu/lb-°F

Air

$K = 0.0146 + 1.695 \times 10^{-5} * T°F$ Btu/hr-ft-°F

$C_p = 0.25$ Btu/lb-°F

Stainless Steel (Type 304)

$K = 29.1 - 0.0059 * T$ °F

$C_p = 55$ Btu/ft^3-°F

$\epsilon = 0.8$

$\alpha = 9.5 \times 10^{-6}$ in./in.-°F

Depleted Uranium

$K = 14.8$ Btu/hr-ft°F

$C_p = 38$ Btu/ft^3-°F

$\epsilon = 0.5$

$\alpha = 9.6 \times 10^{-6}$ in./in.-°F

Spent Fuel Block

$K = 10.0$ Btu/hr-ft-°F

$C_p = 32$ Btu/ft^3 - hr

$\epsilon = 0.8$

The fuel element after-heat was calculated at GA in analysis prior to this one. The calculated heat generation recommended for thermal analysis purposes is 2322 Btu/hr per fuel block at 100 days and 1101 Btu/hr at 200 days. Of these quantities, 88% is realized within the fuel block and the remaining 12% is generated within the first inch of the surrounding shielding.

The decay heat generation is summarized in Table 3-2.

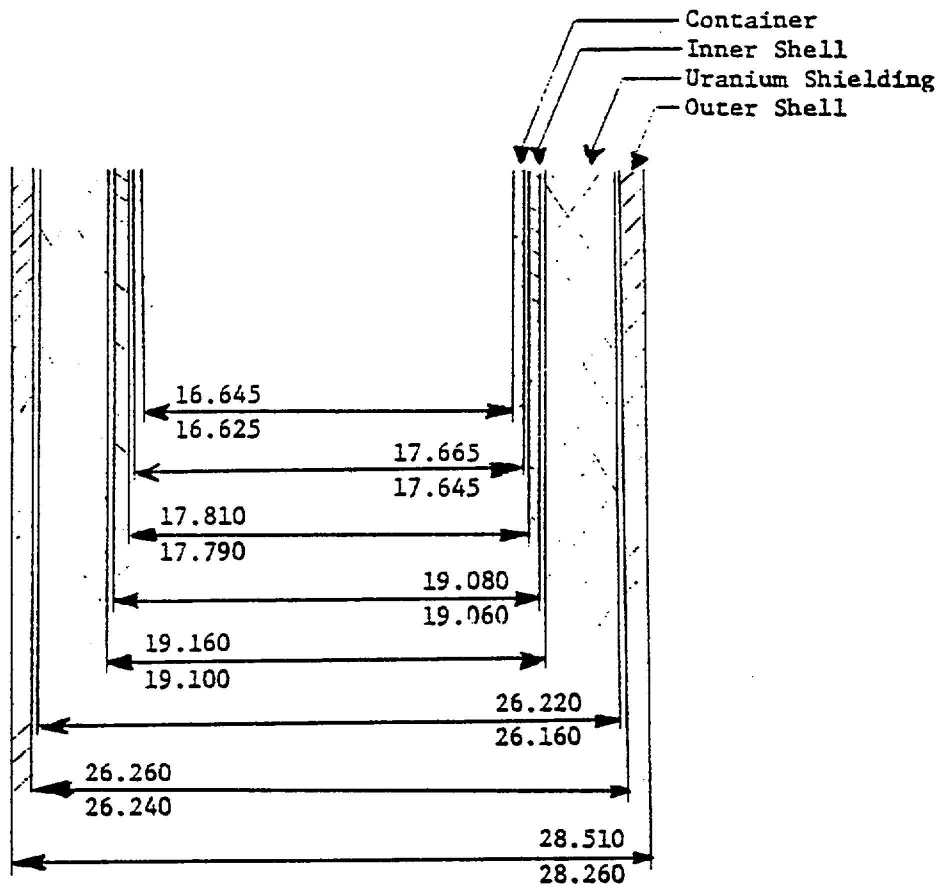
3.3.2 Cask Dimension

Manufacturing tolerances allow a rather significant variation in the raidal gaps. Although it is very unlikely that the parts would ever be manufactured and assembled such that one cask had either all maximum or minimum gaps, the analyses were made using both extreme cases to illustrate the maximum possible range of temperatures that may be encountered. These gaps are illustrated on Fig. 1. The fire accident (Case 3) was calculated using only the minimum gaps in order to illustrate the worst condition for the inner part of the cask.

The significant radial dimensions shown on Fig. 3-1 were used with appropriate coefficients of thermal expansion. Thus, the correct gaps were recalculated as the cask changed in temperature. The net effect of this is to decrease the gap sizes under normal conditions when the inner shells are hotter than the outer shells. In the fire accident, however, the hotter outer shells will expand away from the inner shells, increasing the resistance of the gap and retarding the heat flow into the inner part of the assembly.

TABLE 3-2
CALCULATED AFTER-HEAT GENERATION
OF FUEL BLOCK (INC. Pa 233)
Btu/hr

Day Time days	Betas	Gammas	Total
100	1353.	969.	2322.
150	967.	540.	1507.
200	767.	334.	1101.



	Max	Min
Container Wall	0.520	0.500
Gap	0.0825	0.0625
Inner Shell Wall	0.645	0.625
Gap	0.050	0.010
Shielding Thickness	3.560	3.500
Gap	0.050	0.010
Outer Shell Wall	1.135	1.000

Fig. 3-1 Model FSV-1 shipping cask diameters and tolerances at major shells (all dimensions in inches)

3.4 THERMAL EVALUATION OF THE MODEL FSV-1 PACKAGE

3.4.1 Summary of Results

Steady-state and transient thermal analyses were conducted on thermal models of each end of the cask, the models far enough down the length of the cask to eliminate any end effects. Since no unexpected results were obtained from the analysis of the relatively simple lower end, only the temperatures of the upper end are summarized in Table 3-3.

It is noteworthy that the surface of the cask is below 212°F, although high enough to cause discomfort to personnel in contact with it. The solar heating is a significant contributor to the total cask heat.

The FSV-1 cask in Configurations A, B, C and D may be wrapped in a reinforced plastic material such as Herculite to keep the exterior of the cask clean and to prevent "weeping." Although two or three layers of this material (0.02 in. thick) coupled with a potential air-gap between layers increases the overall thermal resistance slightly, the results listed in Table 3-3 are conservatively high temperatures for this condition. The temperatures in Table 3-3 are based on 4.1 kilowatts of heat generation in the cask. When the cask is wrapped with reinforced plastic, the allowable heat generation is 0.5 kilowatts.

TABLE 3-3
SUMMARY OF RESULTS

No.	Location Gap Tolerances	Temperatures (°F) 130° Ambient 100 Day Heat Max Gaps	130° Ambient 100 Day Heat Min Gaps	130° Ambient 200 Day Heat Max Gaps	-40° Ambient 100 Day Heat Max Gaps	-40° Ambient 100 Day Heat Min Gap	Fire Acc. Maximum Temps. Min Gap
1	Cask Seal	141	137	133	-14	-15	1220
2	Container Seal	155	146	137	3	0	655
3	Fuel Surface - Max	278	266	200	153	143	284
4	Fuel Centerline - Max	284	272	203	160	149	291
5	Container Wall - Max	174	159	147	28	14	502
6	Inner Shell - Max	161	149	141	13	2	715
7	Shielding - Center	152	146	137	3	0	829
8	Outer Shell - Max	146	144	134	-4	-3	1397

The cask surface temperature can be assumed to be the same as the outer shell temperature.

Figures 3-5 and 3-8 are the calculated temperature matrices from the computer output. Locations 1 - 8 are identified on Fig. 3-5.

3.4.2 Thermal Model

Basic temperatures were calculated by a numerical finite-difference method. A digital computer code, RAT*, was used to perform the actual calculations.

The cask system was modeled in a form suitable for input to this code. The regions modeled are shown on Figs. 3-2 and 3-3.

RAT is a digital computer code that is applicable to calculating transient temperatures in a two-dimensional network of points. It may also be used to obtain steady-state solutions by extending a transient calculation to the point where time dependence of results becomes negligible.

The network is specified by establishing a grid system, locating individuial materials within that grid system, and identifying the applicable thermal parameters that define those materials. The grid system must be a regular one specified by two sets of grid lines parallel to the coordinate axes in one of the following three systems: orthogonal (X-Y), cylindrical (R-Z), or circular (R-θ):

The materials are located by subdividing the grid system into blocks, or regions of adjacent points. Each block is defined by its four bounding

*RAT is an acronym for "radial-axial temperatures."

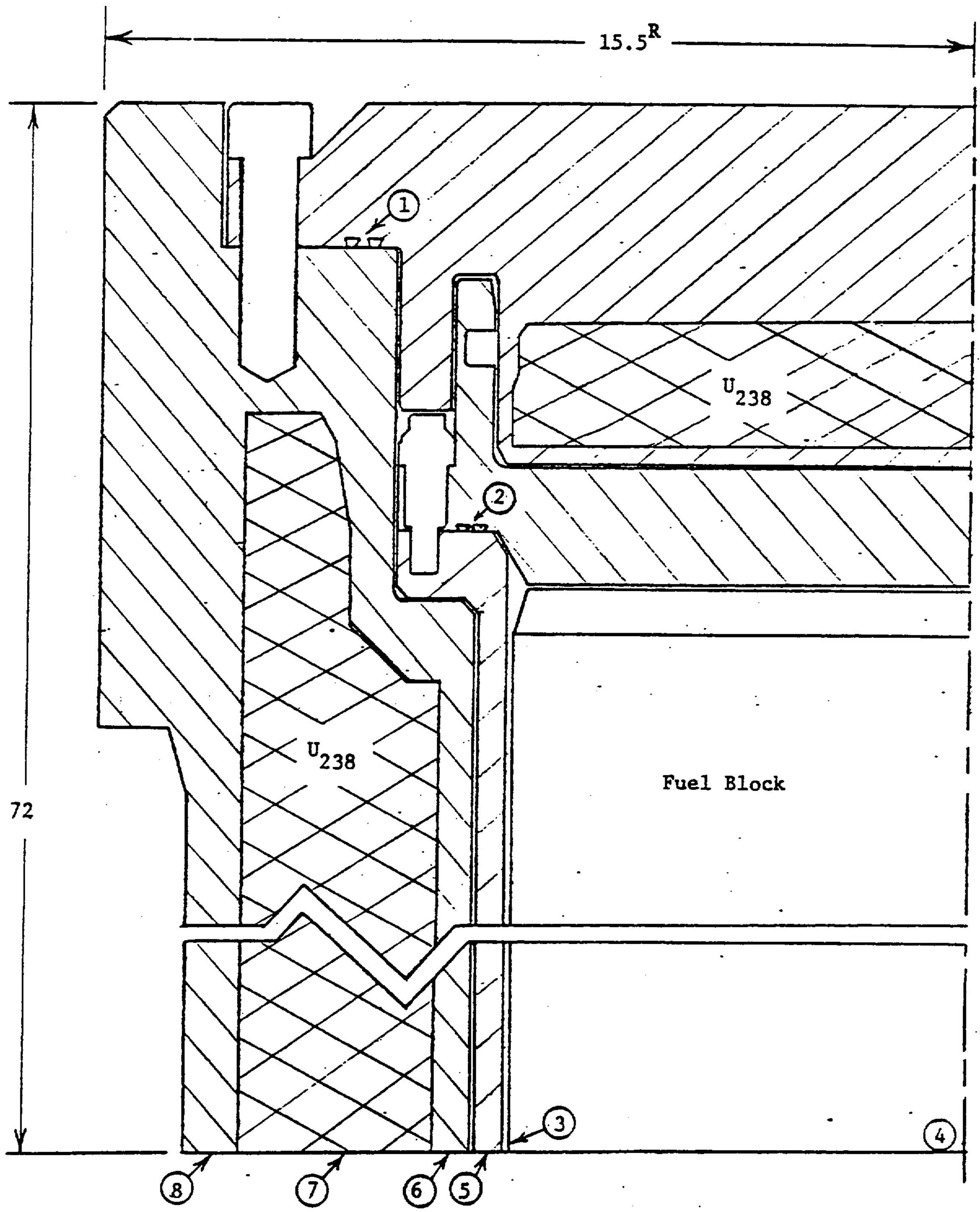


Fig. 3-2. Temperature locations noted in Table 3-1 and Fig. 3-5 Cask Model Upper-End.

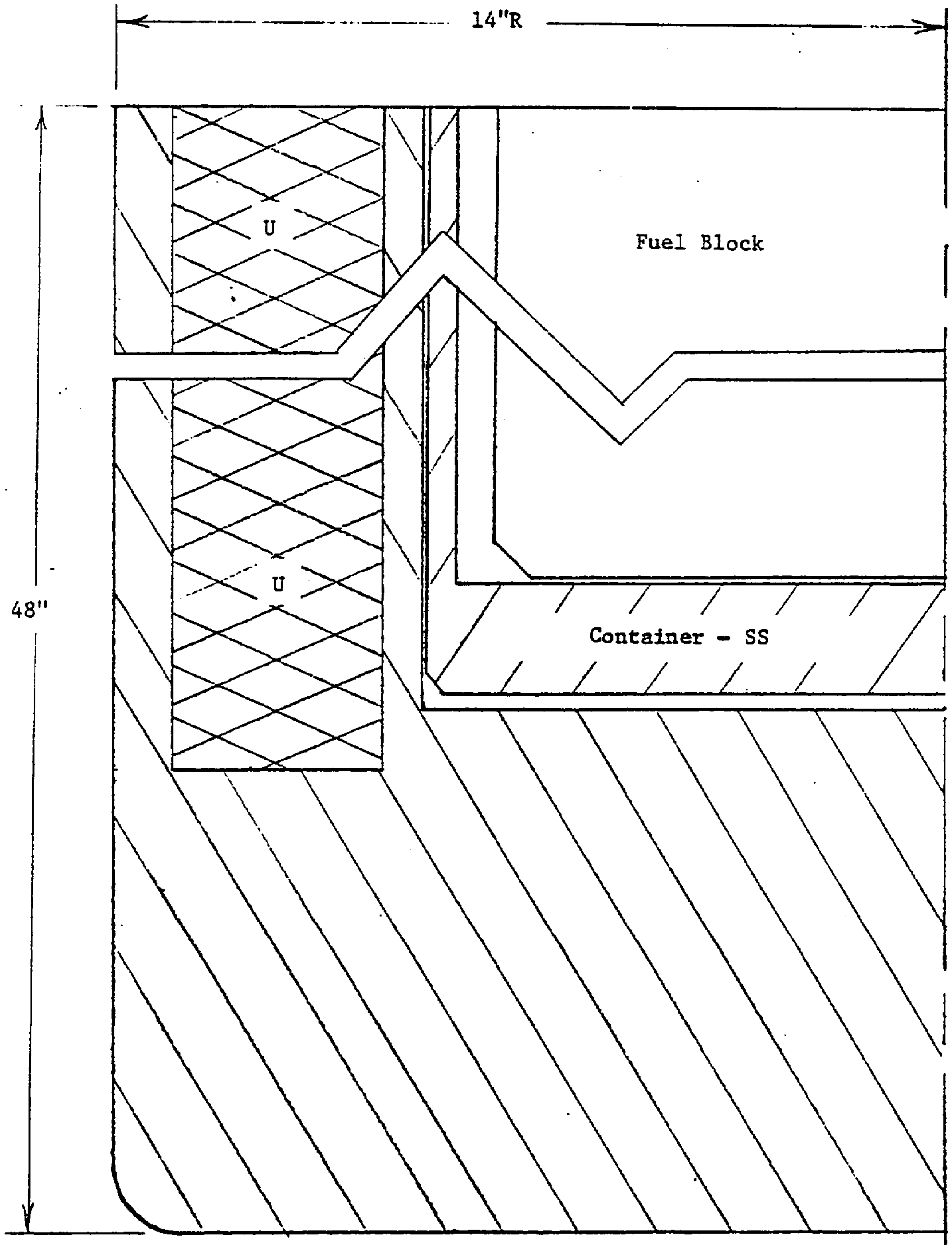


Fig. 3-3. Cask model - lower end.

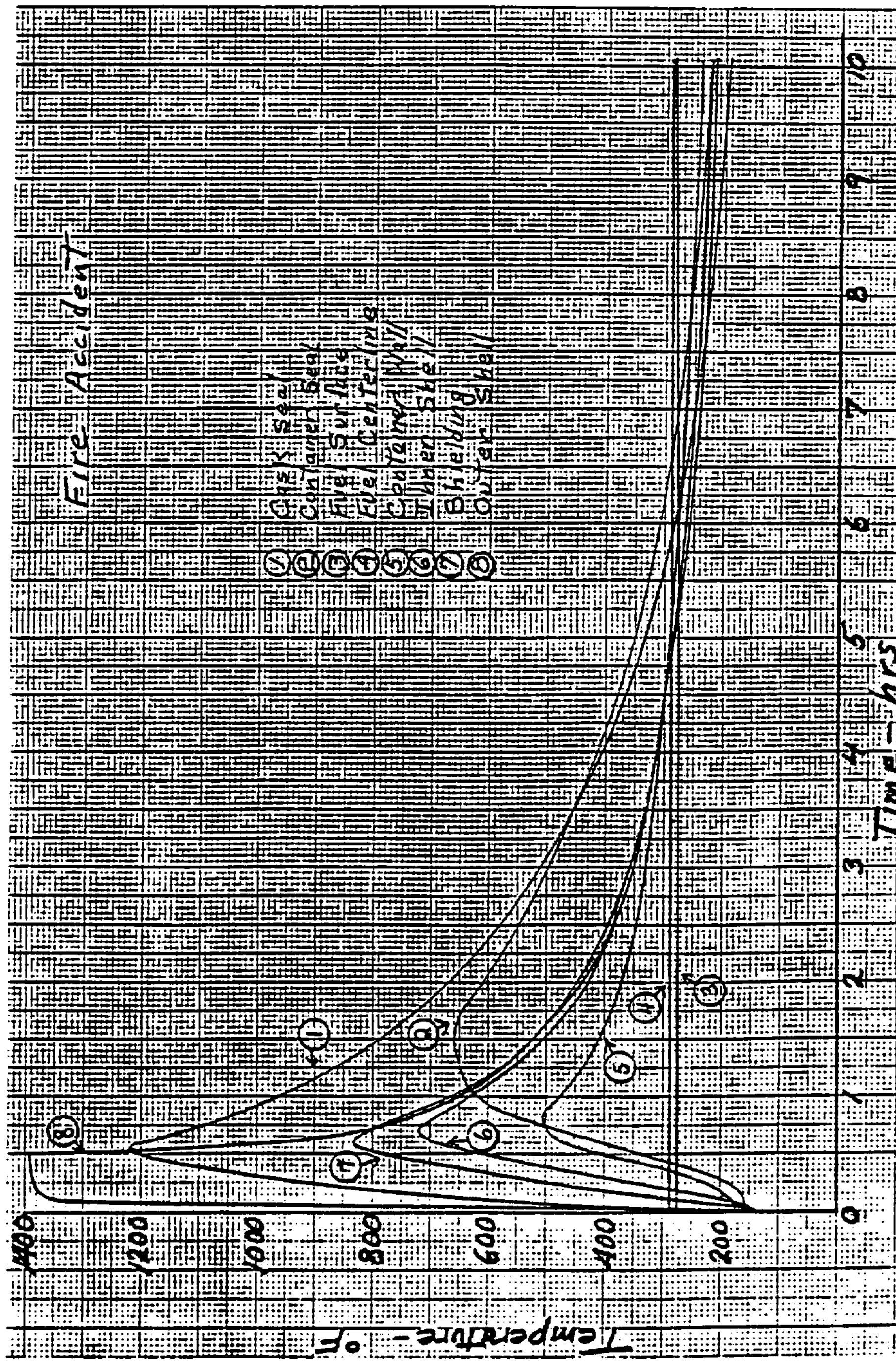


Fig. 3-4. Fire accident.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
2	0	139	139	139	139	139	138	138	138	138	138	138	138	138	138	139	138	138	139	138	138	137	137	137	137
3	0	140	140	139	139	139	139	139	139	139	139	139	139	139	138	139	138	138	138	138	138	138	137	137	137
4	0	140	140	140	140	139	139	139	139	139	139	139	139	139	139	139	138	138	138	138	138	138	138	137	137
5	0	141	141	140	140	140	140	140	140	140	139	139	139	139	139	139	139	138	139	138	138	138	138	138	138
6	0	141	141	141	141	141	141	141	141	141	141	141	141	141	140	140	138	138	138	138	138	138	138	138	138
7	0	143	142	142	142	142	142	142	142	142	141	141	142	142	140	140	139	139	139	139	138	138	138	138	138
8	0	143	143	143	143	143	143	143	143	143	142	142	142	142	140	140	139	139	139	139	139	138	138	138	139
9	0	145	145	144	144	144	144	144	144	144	143	143	143	143	141	141	139	139	139	139	139	139	138	138	138
10	0	146	146	145	145	145	145	145	145	145	144	144	144	144	141	141	140	140	140	140	139	139	138	138	138
11	0	147	146	146	146	146	146	146	146	146	145	145	145	145	144	143	140	140	140	140	140	139	138	138	138
12	0	148	148	147	147	147	147	147	147	147	146	146	146	146	146	146	142	142	142	140	140	140	139	139	139
13	0	149	149	148	148	148	147	147	147	147	147	147	147	147	147	147	143	143	143	140	140	140	139	139	139
14	0	150	150	149	149	148	148	148	148	148	148	148	148	147	147	147	144	144	143	141	141	140	139	139	139
15	0	151	151	150	150	149	149	149	149	148	148	148	148	148	148	148	144	144	141	141	141	141	140	139	139
16	0	152	152	151	151	150	150	150	149	149	149	148	148	148	148	149	145	145	142	142	141	141	140	140	140
17	0	231	230	229	227	226	205	175	156	150	149	149	149	149	149	149	146	146	142	142	142	141	140	140	140
18	0	232	231	230	228	227	209	180	158	150	150	149	147	147	147	147	146	146	142	142	142	142	140	140	140
19	0	234	233	231	230	229	213	187	170	158	151	149	147	147	147	147	146	146	143	143	142	142	141	140	140
20	0	235	234	233	231	230	215	189	172	159	153	150	147	147	147	147	147	146	143	143	143	142	141	141	141
21	0	236	235	234	232	231	216	190	173	160	153	150	147	147	147	147	147	144	143	143	143	143	141	141	141
22	0	238	238	236	234	233	218	192	174	161	155	151	148	148	148	147	144	144	144	144	143	143	141	141	141
23	0	242	241	240	238	237	222	195	177	164	157	153	149	149	149	145	145	145	144	144	144	144	141	141	141
24	0	247	246	245	243	242	226	198	180	166	159	155	150	150	150	146	146	145	145	145	145	145	142	142	142
25	0	252	252	250	248	247	231	202	183	169	161	157	152	152	152	147	146	146	146	146	146	145	142	142	142
26	0	258	257	255	253	252	235	206	186	171	164	158	153	153	153	148	147	147	147	147	146	146	142	142	142
27	0	262	261	260	258	257	239	209	188	173	165	160	154	154	154	148	148	148	147	147	147	147	142	142	142
28	0	265	264	263	261	260	242	211	190	174	166	161	155	155	155	149	148	148	148	148	147	147	142	142	142
29	0	270	269	267	265	264	246	214	192	176	168	162	156	156	156	149	149	149	148	148	148	147	143	142	142
30	0	275	274	272	270	266	249	216	194	178	169	163	157	157	157	150	149	149	149	149	148	148	143	143	143
31	0	278	277	275	273	271	252	218	196	179	170	164	158	158	157	150	150	150	149	149	149	148	143	143	143
32	0	280	279	277	275	273	254	220	197	180	171	164	158	158	158	151	150	150	150	149	149	148	143	143	143
33	0	281	280	278	276	275	255	221	197	180	171	165	158	158	158	151	150	150	150	150	149	149	143	143	143
34	0	282	281	279	276	275	255	221	197	180	171	165	159	158	158	151	150	150	150	150	149	149	143	143	143
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3-5. Model FSV-1 shipping cask thermal analysis.
130°F day, 100 day heat
Maximum gaps - Reference Case

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
2	0	138	138	138	138	138	138	138	138	138	137	137	137	137	137	137	137	137	137	137	137	137	136	136	136
3	0	139	139	138	138	138	138	138	138	138	138	138	138	138	138	137	137	137	137	137	137	137	137	137	137
4	0	139	139	139	139	139	138	138	138	138	138	138	138	138	138	138	138	137	137	137	137	137	137	137	137
5	0	140	140	139	139	139	139	139	139	139	139	138	138	138	138	138	138	137	137	137	137	137	137	137	137
6	0	140	140	140	140	140	140	140	140	140	140	140	140	140	139	139	138	138	138	138	137	137	137	137	137
7	0	141	141	141	141	141	141	141	141	141	140	140	140	140	139	139	138	138	138	138	138	137	137	137	137
8	0	142	142	142	142	142	141	141	141	141	141	141	141	141	139	139	138	138	138	138	138	138	137	137	137
9	0	143	143	143	143	143	143	143	143	143	142	142	142	142	140	140	138	138	138	138	138	138	138	138	138
10	0	144	144	144	144	144	144	144	144	144	143	143	143	143	140	140	139	139	139	139	138	138	138	138	138
11	0	145	145	145	144	144	144	144	144	144	144	144	144	144	143	141	139	139	139	139	139	138	138	138	138
12	0	146	146	146	145	145	145	145	145	145	144	144	144	144	144	144	140	140	140	139	139	139	138	138	138
13	0	147	147	147	146	146	146	146	146	146	145	145	145	145	145	145	141	141	141	139	139	139	138	138	138
14	0	148	148	148	147	147	146	146	146	146	146	146	146	146	146	145	142	142	142	140	140	139	139	139	139
15	0	149	149	148	148	148	147	147	147	146	146	146	146	146	146	146	143	143	140	140	140	140	139	139	139
16	0	150	150	149	149	149	148	148	146	146	146	146	146	146	146	146	143	143	141	141	140	140	140	139	139
17	0	226	225	224	222	221	201	172	153	147	147	147	147	147	146	146	144	144	141	141	141	141	140	140	140
18	0	227	227	225	224	222	205	176	155	148	148	146	145	145	145	145	144	144	141	141	141	141	140	140	140
19	0	229	228	227	225	224	209	183	166	155	148	147	145	145	145	145	144	144	142	141	141	141	140	140	140
20	0	230	230	228	226	225	211	185	168	156	149	147	145	145	145	145	144	144	142	142	142	141	141	140	140
21	0	231	231	229	228	227	212	186	169	156	150	147	145	145	145	145	145	142	142	142	142	141	141	141	141
22	0	233	233	231	229	229	213	187	170	157	150	148	145	145	145	145	143	143	142	142	142	142	141	141	141
23	0	237	236	234	233	232	216	190	172	159	152	148	145	145	145	144	144	143	143	143	143	142	142	142	142
24	0	241	241	239	237	236	220	192	174	160	153	149	146	146	146	144	144	144	144	144	143	143	142	142	142
25	0	247	246	244	242	241	225	196	176	162	154	150	147	147	146	145	145	145	144	144	144	144	143	142	142
26	0	251	250	249	247	246	229	198	178	163	155	151	147	147	147	146	145	145	145	145	144	144	143	143	143
27	0	255	254	253	251	250	232	201	180	164	156	152	148	148	147	146	145	145	145	145	145	144	143	143	143
28	0	258	257	256	254	252	234	202	181	165	157	152	148	148	148	146	146	145	145	145	145	144	143	143	143
29	0	262	261	259	257	256	237	204	182	166	157	153	148	148	148	146	146	146	145	145	145	144	143	143	143
30	0	266	265	263	261	260	241	207	184	167	158	153	149	149	149	147	146	146	146	146	145	145	143	143	143
31	0	269	268	266	264	263	243	208	185	168	159	154	149	149	149	147	147	146	146	146	146	145	144	143	143
32	0	271	270	268	266	264	244	209	186	168	159	154	149	149	149	147	147	146	146	146	146	145	144	143	143
33	0	272	271	269	267	265	245	210	186	169	159	154	149	149	149	147	147	147	146	146	146	145	144	144	143
34	0	272	271	269	267	266	246	210	186	169	159	154	150	149	149	147	147	147	146	146	146	145	144	144	144
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3-6. Model FSV-1 shipping cask thermal analysis.
130°F day,
100 day heat
Minimum gaps - Reference Case

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39
2	0	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-15	-15	-15
3	0	[illegible]	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14
4	0	[illegible]	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-14	-14
5	0	[illegible]	-13	-13	-13	-12	-12	-12	-12	-12	[illegible]	-12	-12	-12	-12	-12	-13	-13	-13	-13	-13	-13	-13	-13	-13
6	0	[illegible]	-12	-12	-12	-12	-12	-12	-12	-12	-10	-10	-10	-10	-11	-11	-12	-12	-12	-12	-12	-13	-13	-13	-13
7	0	-12	-12	-12	-11	-11	-11	-10	-10	-10	-10	-10	-10	-10	-11	-11	-12	-12	-12	-12	-12	-12	-12	-12	-12
8	0	-12	-12	-12	-11	-10	-10	-10	-9	-9	-9	-9	-9	-9	-10	-10	-11	-11	-11	-12	-12	-12	-12	-12	-12
9	0	[illegible]	-6	-6	-7	-7	-6	-6	-5	-5	-5	-5	-5	-5	-9	-10	-11	-11	-11	-11	-11	-11	-12	-12	-12
10	0	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-9	-9	-9	-10	-10	-10	-10	-11	-11	-11	-11
11	0	[illegible]	-0	-0	-0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-3	-5	-8	-9	-9	-9	-9	-10	-11	-11	-11
12	0	5	5	4	3	2	1	1	1	0	0	0	0	0	0	1	-6	-6	-7	-8	-9	-9	-11	-11	-11
13	0	[illegible]	8	7	5	4	4	3	3	3	3	2	2	2	2	2	-4	-5	-5	-8	-8	-8	-10	-10	-10
14	0	[illegible]	8	7	6	5	4	4	4	4	3	3	3	3	3	2	-3	-3	-3	-7	-7	-7	-10	-10	-10
15	0	[illegible]	8	8	7	6	6	6	6	4	4	4	4	3	3	3	-2	-2	-6	-6	-6	-6	-9	-9	-9
16	0	10	9	9	7	7	7	7	4	4	4	4	4	4	4	4	-1	-1	-5	-5	-5	-6	-9	-9	-9
17	0	[illegible]	103	101	99	97	49	6	6	6	5	5	5	4	4	4	-0	-0	-4	-5	-5	-5	-8	-8	-9
18	0	[illegible]	104	102	100	98	56	6	6	6	6	3	1	1	1	0	0	-0	-4	-4	-4	-5	-8	-8	-8
19	0	107	106	104	102	100	79	44	25	13	7	4	1	1	1	0	0	0	-4	-4	-4	-4	-8	-8	-8
20	0	[illegible]	107	106	103	102	83	51	30	16	8	4	1	1	1	0	0	0	-3	-4	-4	-4	-8	-8	-8
21	0	[illegible]	108	107	105	104	85	53	32	17	9	5	1	1	1	1	0	-3	-3	-3	-3	-4	-7	-7	-7
22	0	111	111	109	107	106	88	55	34	18	10	6	1	1	1	1	-2	-3	-3	-3	-3	-3	-7	-7	-7
23	0	115	114	113	111	110	91	58	38	20	12	7	2	2	2	-1	-2	-2	-2	-2	-2	-3	-6	-6	-6
24	0	[illegible]	120	118	116	115	96	62	40	23	15	9	4	4	4	-1	-1	-1	-1	-1	-2	-2	-5	-5	-5
25	0	[illegible]	126	124	122	121	101	66	43	26	17	11	6	6	5	-0	-0	-0	-0	-0	-1	-1	-5	-5	-5
26	0	132	131	130	128	127	106	70	46	29	19	13	7	7	7	0	0	0	-0	-0	-0	-0	-5	-5	-5
27	0	137	136	135	133	132	111	74	49	31	21	14	8	8	8	1	1	0	0	0	0	-0	-5	-5	-5
28	0	141	140	138	136	135	114	76	50	32	22	15	9	9	9	1	1	1	1	0	0	0	-5	-5	-5
29	0	[illegible]	145	143	141	140	118	79	53	34	24	17	10	10	10	2	2	1	1	1	1	0	-5	-5	-5
30	0	151	150	149	146	145	123	83	56	36	25	18	11	11	11	3	2	2	2	2	1	1	-4	-4	-5
31	0	155	154	152	150	149	126	85	57	37	27	19	12	12	12	3	3	3	2	2	2	1	-4	-4	-4
32	0	158	157	155	153	151	[illegible]	87	59	38	27	20	12	12	12	4	3	3	3	2	2	2	-4	-4	-4
33	0	159	158	156	154	153	129	88	59	39	28	20	13	13	13	4	3	3	3	3	2	2	-4	-4	-4
34	0	[illegible]	159	157	155	154	130	88	60	39	28	20	13	13	13	4	3	3	3	3	2	2	-4	-4	-4
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3-7. Model FSV-1 shipping cask thermal analysis.
-40°F Day
100 Day Heat
Maximum Gap

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39	-39
2	0	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-16	-16	-16	-16
3	0	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15
4	0	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-15	-15	-15	-15	-15	-15
5	0	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14
6	0	[illegible]	[illegible]	[illegible]	-13	-13	[illegible]	-13	-13	-13	-12	-12	-12	-12	-13	-13	-13	-14	-14	-14	-14	-14	-14	-14	-14
7	0	[illegible]	[illegible]	[illegible]	-13	-12	-12	-12	-12	-12	-11	-11	-11	-11	-12	-12	-13	-13	-13	-13	-13	-13	-13	-14	-14
8	0	-14	-13	-13	-12	-12	-11	-11	-11	-11	-10	-10	-10	-10	-12	-12	-13	-13	-13	-13	-13	-13	-13	-13	-13
9	0	-10	-10	[illegible]	-9	-9	-8	-8	-7	-7	-7	-7	-7	-7	-11	-11	-12	-12	-12	-12	-12	-12	-13	-13	-13
10	0	-5	-5	[illegible]	-6	-6	-5	-5	-5	-5	-5	-5	-5	-5	-11	-11	-11	-11	-11	-11	-12	-12	-12	-12	-12
11	0	[illegible]	-2	-2	-3	-3	-3	-4	-4	-4	-4	-4	-4	-4	-5	-7	-10	-10	-10	-10	-11	-11	-12	-12	-12
12	0	[illegible]	2	1	[illegible]	-0	-0	-1	-1	-1	-2	-2	-2	-1	-1	-1	-8	-8	-8	-10	-10	-11	-11	-11	-11
13	0	5	4	3	2	1	1	0	0	0	0	-0	-0	-0	-0	-0	-7	-7	-7	-10	-10	-10	-11	-11	-11
14	0	[illegible]	5	4	3	2	1	1	1	1	0	-0	-0	0	0	-0	-6	-6	-6	-9	-9	-9	-10	-10	-10
15	0	6	5	4	3	3	3	2	2	0	0	0	0	0	0	0	-5	-5	-8	-8	-8	-9	-9	-10	-10
16	0	[illegible]	6	5	4	4	[illegible]	4	1	1	1	1	1	1	0	0	-4	-4	-7	-7	-8	-8	-9	-9	-9
17	0	96	97	95	93	91	44	2	2	2	1	1	1	1	1	0	-3	-3	-7	-7	-7	-7	-8	-8	-8
18	0	99	[illegible]	[illegible]	94	92	51	2	2	2	2	0	-2	-2	-2	-2	-3	-3	-6	-7	-7	-7	-8	-8	-8
19	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	73	39	21	9	3	0	-2	-2	-2	-2	-2	-3	-6	-6	-6	-7	-8	-8	-8
20	0	102	101	99	97	96	77	45	25	11	3	0	-2	-2	-2	-2	-2	-2	-6	-6	-6	-6	-7	-7	-7
21	0	[illegible]	102	100	[illegible]	97	75	48	27	12	4	0	-2	-2	-2	-2	-2	-5	-5	-5	-6	-6	-7	-7	-7
22	0	105	104	103	101	100	81	49	28	13	4	1	-2	-2	-2	-2	-5	-5	-5	-5	-5	-6	-6	-7	-7
23	0	108	[illegible]	[illegible]	104	105	[illegible]	52	30	14	5	2	-1	-1	-2	-3	-4	-4	-4	-4	-4	-5	-6	-6	-6
24	0	[illegible]	113	[illegible]	109	[illegible]	[illegible]	55	32	16	7	2	-1	-1	-1	-2	-3	-3	-3	-3	-3	-4	-5	-5	-5
25	0	119	[illegible]	117	115	114	[illegible]	58	35	17	8	4	-0	-0	-0	-2	-2	-2	-2	-3	-3	-3	-4	-4	-4
26	0	124	124	122	120	119	[illegible]	61	37	19	9	4	0	0	-0	-1	-2	-2	-2	-2	-2	-3	-4	-4	-4
27	0	[illegible]	126	[illegible]	125	[illegible]	102	64	39	20	10	5	0	0	0	-1	-1	-1	-2	-2	-2	-3	-4	-4	-4
28	0	132	131	130	128	[illegible]	105	66	40	21	11	6	1	0	0	-1	-1	-1	-1	-2	-2	-2	-4	-4	-4
29	0	137	136	134	132	131	[illegible]	69	42	22	12	6	1	1	1	-0	-1	-1	-1	-1	-2	-2	-4	-4	-4
30	0	142	141	139	137	136	112	71	44	24	13	7	1	1	1	-0	-0	-0	-1	-1	-1	-2	-3	-4	-4
31	0	145	144	142	140	139	115	73	45	24	13	8	2	2	2	0	-0	-0	-0	-1	-1	-2	-3	-3	-3
32	0	147	146	[illegible]	142	141	117	75	[illegible]	25	14	8	2	2	2	0	-0	-0	-0	-0	-1	-1	-3	-3	-3
33	0	149	148	[illegible]	144	[illegible]	[illegible]	75	46	25	14	8	2	2	2	0	-0	-0	-0	-0	-1	-1	-3	-3	-3
34	0	149	148	[illegible]	144	[illegible]	119	76	47	26	14	8	2	2	2	0	0	-0	-0	-0	-0	-1	-3	-3	-3
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3-8. Model FSV-1 shipping cask thermal analysis.
-40°F day
100 day heat
Minimum Gaps

grid lines and the material that it contains. The material is given in terms of a material numbering system. Parameters that define each material are the applicable thermal properties and the volumetric heat generation rate.

Blocks of materials may be separated by narrow gaps that contain stagnant gases. The gases are located in terms of a gas numbering system and are defined by their individual thermal conductivities. Heat transfer across these gaps is by one-dimensional conduction and radiation.

Boundary conditions at external boundaries are specified either by sink temperature and unit surface conductance or by the thermal parameters of a flowing coolant. These parameters are the coolant properties and flow conditions.

The thermal parameters for the materials, gases, and coolants may be given in functional form. Many of the calculation variables are available for use in these functions.

3.4.3 Analysis

Ambient Conditions

a. The maximum temperature day is defined as having an air temperature of 130°F with full sun. Further, it was assumed that the cask and trailer are in still air with no convective cooling other than free convection. Using a correlation for free convection around a horizontal cylinder, the following function was used to calculate heat transfer coefficient (Ref. 1).

$$h = 0.221\ (S_t - T_a)^{0.25}$$

where S_t = cask surface temperature, and
T_a = ambient temperature.

Thermal radiation from the cask to its surrounding was also calculated. It was assumed that the emissivity of the cask was 0.6 and that the absorbtivity of the ambient surroundings was 1.0. Thus, using standard correlations:

$$Fe = \varepsilon_1 = 0.6$$

Solar heating was imposed on the thermal model in the form of surface heat generation. Since the model is a two-dimensional, radial-axial one, there can be no circumferential variation. Thus, the heat generation was imposed around the entire circumference of the cask. The net effect is for a higher than actual total heat input with conservatively high internal temperatures.

The net solar heating is 96 Btu/hr-ft^2. Past experience with shipping cask analysis has shown that the thermal response of a cask is very slow and that is is not necessary to calculate with a time dependent solar heating function. Thus, steady-state temperaures were calculated.

b. Minimum Temperature Day

The minimum temperature day was defined as an ambient condition of -40°F with no solar heating. The same free convection heat transfer coefficient as was used for the 130°F day was incorporated, as was the ability of the cask to radiate heat to its surroundings. If it were to be assumed that the truck was moving and that a relatively high air velocity existed on the cask surface, the cask surface-to-air Δt would be nil and the cask internal temperatures would drop accordingly.

c. Fire Accident

The fire accident is defined as a surrounding ambient condition of 1475°F. An overall surface heat transfer coefficient (h) simulating a strong convection condition was assumed. Reasonable values of h_c for hot, blowing gasses are in the range of 100 to 300 Btu/hr-ft^2-°F. The equivalent surface coefficient for thermal radiation (h_r) is approximately 30 Btu/hr-ft^2-°F at a median cask surface temperature. This assumes, again, that the emissivity of the fire is 1.0. In total, an h of 300 was concluded to be a maximum reasonable value for the fire accident.

3.5 APPENDIX

3.5.1 RAT - Program Abstracts

RAT is a digital computer program for calculating transient and steady-state temperature distributions in two dimensions. The configurations of the bodies must be described by block boundaries and grid lines in either a rectangular, a cylindrical, or a polar coordinate system. Material properties may differ among blocks. Coolant streams are accommodated at external boundaries only.

Finite-difference heat transport equations, which may be nonlinear, are formulated for each cell defined by the grid lines and the heat paths between adjacent cells. The system of these equations is solved by an alternating direction method that has been found to be stable and efficient for most practical problems.

Some useful features of RAT are:

a. Director FORTRAN IV input of material and coolant properties in functional form.

b. Simple geometrical input.

c. Thermal radiation across internal gaps.

d. Anisotropic (bi-directional) material properties are permitted.

One small subroutine is written in machine language. Therefore, special attention is required in converting the code for use on different machines.

RAT calculates transient steady-state temperatures in two-dimensional problems by the finite difference method. The system to be analyzed may be bounded by flowing coolants and may contain internal gaps. There may be radiation across these gaps. Material and coolant thermal parameters may be functions of many different calculation variables, such as time and local temperature.

Restrictions: (1) The grid lines systems must be orthogonal in the rectangular, cylindrical, or polar coordinate system. (2) All radiation is treated one-dimensionally. (3) The size of a problem is governed by the following maximum values:

Radial Points	Axial Points	Radial Block Boundaries	Axial Block Boundaries	Blocks	Materials
35	35	23	23	110	15

Size:	Date:	Author:	Custodian:
47K	10/64	M. Troost	J. F. Petersen

Method: Overall effective values, which may include convection and radiation effects, are determined for the conductance points. The transient heat balance equations are then solved for the temperatures at the points using the method of Ref. 2.

Remarks: There are four versions of RAT. These versions differ from one another only in their dimensions. The program described here is the standard version. The other three versions have dimensions which give the following maximum values governing problem size:

Version	Radial Points	Axial Points	Radial Block Boundaries	Axial Block Boundaries	Blocks	Materials
A	25	50	16	28	110	15
B	27	40	25	32	110	15
C*	11	136	6	36	110	15

*This version has limited storage for material and coolant property functions.

3.5.2 Example Application of the RAT Code

The computer program RAT was developed at GA and is relatively unknown outside of the company. In order to illustrate the validity of this program as a thermal analysis tool, a text book transient problem was used as a standard of comparison. The text and problem are noted in Ref. 3. A summary of the results obtained by duplicating the problem with RAT is given on Fig. 3-9 along with the text results. It is noted that the computed results correlate closely with the text data.

The thermal model for the study is shown on Fig. 3-10 with the dimensional input data and samples of the computed results at selected times on the subsequent figures.

References

1. Aerospace Applied Thermodynamics Manual, SAE.

2. Peaceman, D. W., and Rachford, H. H., "The Numerical Solution of Parabolic and Elliptic Differential Equations," I. Soc. Indust. Appl. Math. 3 (1), 28 (1955).

3. Schneider, P. J., Conduction Heat Transfer, Addison-Wesley Company, Inc., Reading Mass., p. 236.

GA Documentation

1. Petersen, J. F., "Conversion of RAT, TAC, and RAT3D to FORTRAN V," ARD:12:69, March 10, 1969.

2. Ludwig, D. L., "A User's Manual for the RAT Heat Transfer Code," Gulf General Atomic Informal Report GAMD-8360, November 9, 1967.

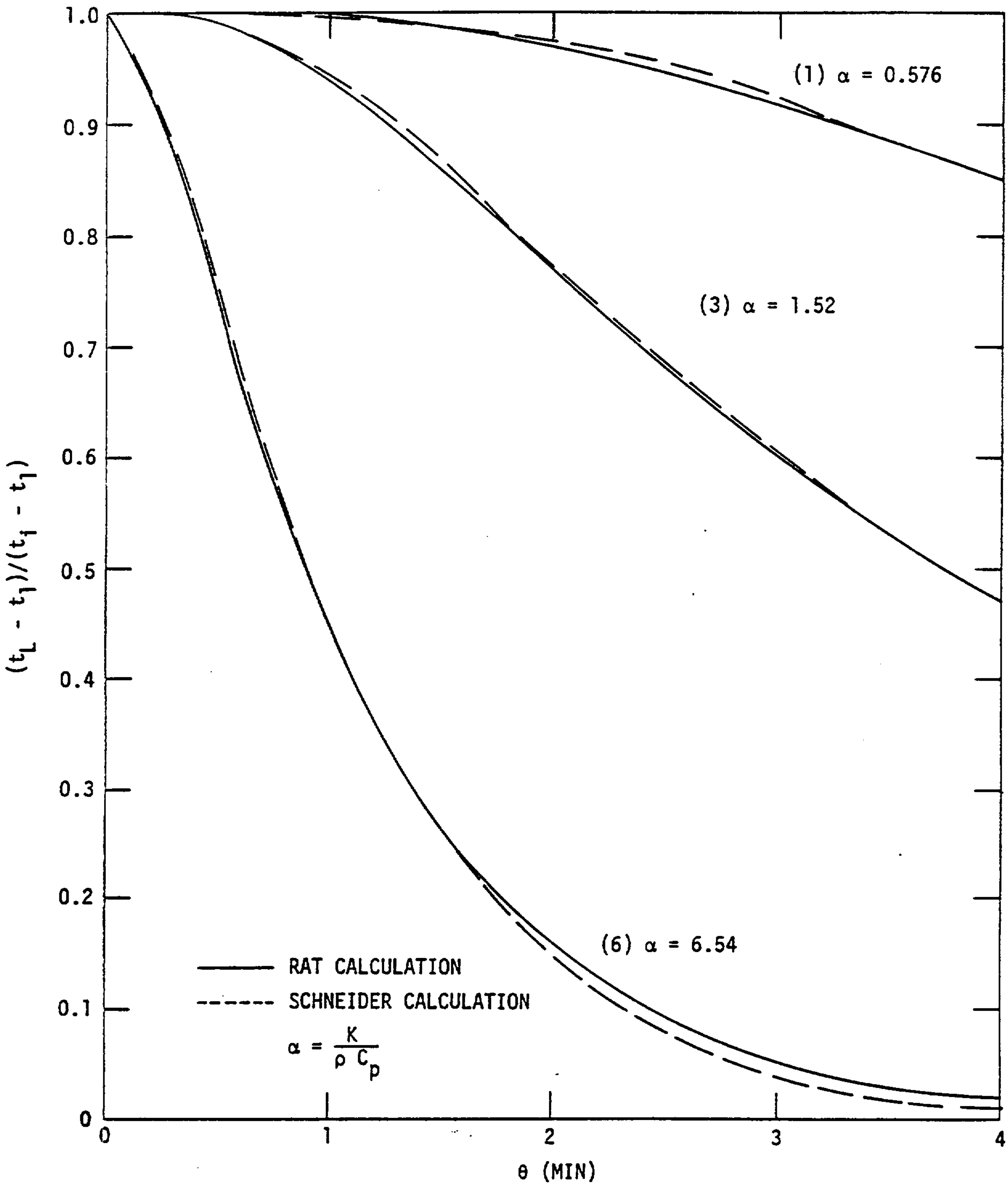
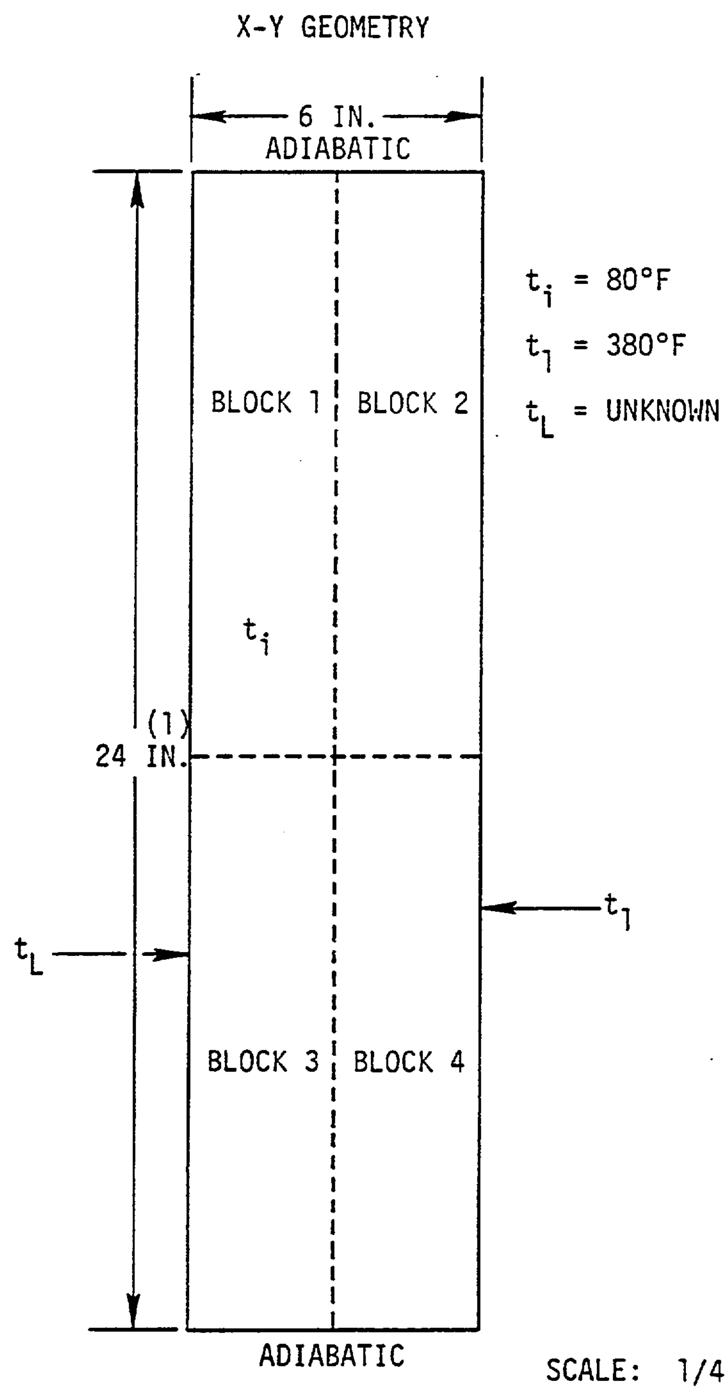


FIGURE 3-9 Results-RAT and text comparison



(1) NOTE: THIS DIMENSION IS NOT RELEVANT TO THE PROBLEM

FIGURE 3-10 **Thermal model - RAT test case transient 0 to 4 min**

```
          RAT RESULTS                                                    30 SEP 69  PAGE     6

   RAT  -    A TWO-DIMENSIONAL TRANSIENT HEAT TRANSPORT CODE, R-A, X-Y OR R-TH GEOMETRY, GENERAL ATOMIC
CASE 1 FOR NICKEL - DIFFUSIVITY = 0.576
     CHECK TEMP. RISE AT INSULATED REAR FACE OF A PLANE WALL 6 IN.
     THICK VERSUS TIME

PRINT OF THE INPUT
```

PROPERTIES OF THE BLOCKS

BLOCK NUMBER	LOW RADIAL BOUNDARY	HIGH RADIAL BOUNDARY	LOW AXIAL BOUNDARY	HIGH AXIAL BOUNDARY	SOLID MATERIAL NUMBER	RADIAL GAP THICKNESS	RADIAL GAP MATERIAL	AXIAL GAP THICKNESS	AXIAL GAP MATERIAL
1	.000 IN.	3.000 IN.	.000 IN.	12.000 IN.	1	-.0000 IN.	-0	-.0000 IN.	-0
2	3.000 IN.	6.000 IN.	.000 IN.	12.000 IN.	1	-.0000 IN.	-0	-.0000 IN.	-0
3	.000 IN.	3.000 IN.	12.000 IN.	24.000 IN.	1	-.0000 IN.	-0	-.0000 IN.	-0
4	3.000 IN.	6.000 IN.	12.000 IN.	24.000 IN.	1	-.0000 IN.	-0	-.0000 IN.	-0

Note: It is a program requirement that there be at least two blocks in each direction

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	80	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0000 HR. OR .0017 MIN. OR .10000 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

		1	2	3	4	5	6	7	8		9	10	11	12	13	14	15
1		0	0	0	0	0	0	0	0								
2		80	80	80	80	80	80	81	380								
3		80	80	80	80	80	80	81	380								
4		80	80	80	80	80	80	81	380								
5		80	80	80	80	80	80	81	380								
6		80	80	80	80	80	80	81	380								
7	t_L	80	80	80	80	80	80	81	380	t_1							
8		80	80	80	80	80	80	81	380								
9		80	80	80	80	80	80	81	380								
10		80	80	80	80	80	80	81	380								
11		80	80	80	80	80	80	81	380								
12		80	80	80	80	80	80	81	380								
13		80	80	80	80	80	80	81	380								
14		0	0	0	0	0	0	0	0								

(1) CASE FOR NICKEL
$\alpha = 0.576$

HAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	81	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0200 HR. OR 1.2000 MIN. OR 71.99999 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	81	81	85	96	128	196	310	380							
3	81	81	85	96	128	196	310	380							
4	81	81	85	96	128	196	310	380							
5	81	81	85	96	128	196	310	380							
6	81	81	85	96	128	196	310	380							
7	81	81	85	96	128	196	310	380							
8	81	81	85	96	128	196	310	380							
9	81	81	85	96	128	196	310	380							
10	81	81	85	96	128	196	310	380							
11	81	81	85	96	128	196	310	380							
12	81	81	85	96	128	196	310	380							
13	81	81	85	96	128	196	310	380							
14	0	0	0	0	0	0	0	0							

CASE FOR NICKEL
$\alpha = 0.576$

KAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	91	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0367 HR. OR 2.2000 MIN. OR 131.99998 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	91	91	101	125	170	239	330	380							
3	91	91	101	125	170	239	330	380							
4	91	91	101	125	170	239	330	380							
5	91	91	101	125	170	239	330	380							
6	91	91	101	125	170	239	330	380							
7	91	91	101	125	170	239	330	380							
8	91	91	101	125	170	239	330	380							
9	91	91	101	125	170	239	330	380							
10	91	91	101	125	170	239	330	380							
11	91	91	101	125	170	239	330	380							
12	91	91	101	125	170	239	330	380							
13	91	91	101	125	170	239	330	380							
14	0	0	0	0	0	0	0	0							

CASE FOR NICKEL
$\alpha = 0.576$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	108	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0533 HR. OR 3.2000 MIN. OR 191.99998 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	108	108	122	151	198	262	339	380							
3	108	108	122	151	198	262	339	380							
4	108	108	122	151	198	262	339	380							
5	108	108	122	151	198	262	339	380							
6	108	108	122	151	198	262	339	380							
7	108	108	122	151	198	262	339	380							
8	108	108	122	151	198	262	339	380							
9	108	108	122	151	198	262	339	380							
10	108	108	122	151	198	262	339	380							
11	108	108	122	151	198	262	339	380							
12	108	108	122	151	198	262	339	380							
13	108	108	122	151	198	262	339	380							
14	0	0	0	0	0	0	0	0							

CASE FOR NICKEL
$\alpha = 0.576$

FAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	124	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0667 HR. OR 4.0000 MIN. OR 239.99997 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	124	124	139	169	215	274	343	380							
3	124	124	139	169	215	274	343	380							
4	124	124	139	169	215	274	343	380							
5	124	124	139	169	215	274	343	380							
6	124	124	139	169	215	274	343	380							
7	124	124	139	169	215	274	343	380							
8	124	124	139	169	215	274	343	380							
9	124	124	139	169	215	274	343	380							
10	124	124	139	169	215	274	343	380							
11	124	124	139	169	215	274	343	380							
12	124	124	139	169	215	274	343	380							
13	124	124	139	169	215	274	343	380							
14	0	0	0	0	0	0	0	0							

CASE FOR NICKEL
$\alpha = 0.576$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	80	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .000 HR. OR .0017 MIN. OR .10000 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	80	80	80	80	80	80	83	380							
3	80	80	80	80	80	80	83	380							
4	80	80	80	80	80	80	83	380							
5	80	80	80	80	80	80	83	380							
6	80	80	80	80	80	80	83	380							
7	t_L 80	80	80	80	80	80	83	380 t_1							
8	80	80	80	80	80	80	83	380							
9	80	80	80	80	80	80	83	380							
10	80	80	80	80	80	80	83	380							
11	80	80	80	80	80	80	83	380							
12	80	80	80	80	80	80	83	380							
13	80	80	80	80	80	80	83	380							
14	0	0	0	0	0	0	0	0							

(2) CASE FOR TIN
$\alpha = 1.52$

HAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	107	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0200 HR. OR 1.2000 MIN. OR 71.99999 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	107	107	121	150	197	261	338	380							
3	107	107	121	150	197	261	338	380							
4	107	107	121	150	197	261	338	380							
5	107	107	121	150	197	261	338	380							
6	107	107	121	150	197	261	338	380							
7	107	107	121	150	197	261	338	380							
8	107	107	121	150	197	261	338	380							
9	107	107	121	150	197	261	338	380							
10	107	107	121	150	197	261	338	380							
11	107	107	121	150	197	261	338	380							
12	107	107	121	150	197	261	338	380							
13	107	107	121	150	197	261	338	380							
14	0	0	0	0	0	0	0	0							

CASE FOR TIN
$\alpha = 1.52$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	160	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0367 HR. OR 2.2000 MIN. OR 131.99998 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	160	160	175	203	243	293	350	380							
3	160	160	175	203	243	293	350	380							
4	160	160	175	203	243	293	350	380							
5	160	160	175	203	243	293	350	380							
6	160	160	175	203	243	293	350	380							
7	160	160	175	203	243	293	350	380							
8	160	160	175	203	243	293	350	380							
9	160	160	175	203	243	293	350	380							
10	160	160	175	203	243	293	350	380							
11	160	160	175	203	243	293	350	380							
12	160	160	175	203	243	293	350	380							
13	160	160	175	203	243	293	350	380							
14	0	0	0	0	0	0	0	0							

CASE FOR TIN
$\alpha = 1.52$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	208	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0533 HR. OR 3.2000 MIN. OR 191.99998 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	208	208	219	242	274	313	357	380							
3	208	208	219	242	274	313	357	380							
4	208	208	219	242	274	313	357	380							
5	208	208	219	242	274	313	357	380							
6	208	208	219	242	274	313	357	380							
7	208	208	219	242	274	313	357	380							
8	208	208	219	242	274	313	357	380							
9	208	208	219	242	274	313	357	380							
10	208	208	219	242	274	313	357	380							
11	208	208	219	242	274	313	357	380							
12	208	208	219	242	274	313	357	380							
13	208	208	219	242	274	313	357	380							
14	0	0	0	0	0	0	0	0							

CASE FOR TIN
$\alpha = 1.52$

HAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	239	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0667 HR. OR 4.0000 MIN. OR 239.99997 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	239	239	248	267	293	325	361	380							
3	239	239	248	267	293	325	361	380							
4	239	239	248	267	293	325	361	380							
5	239	239	248	267	293	325	361	380							
6	239	239	248	267	293	325	361	380							
7	239	239	248	267	293	325	361	380							
8	239	239	248	267	293	325	361	380							
9	239	239	248	267	293	325	361	380							
10	239	239	248	267	293	325	361	380							
11	239	239	248	267	293	325	361	380							
12	239	239	248	267	293	325	361	380							
13	239	239	248	267	293	325	361	380							
14	0	0	0	0	0	0	0	0							

CASE FOR TIN
$\alpha = 1.52$

RAT RESULTS

INITIAL TEMPERATURE DISTRIB

THE CURRENT TIME IS -.0000 HR. OR .0000 MIN. OR .00000 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEI

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	80	80	80	80	80	80	80	380							
3	80	80	80	80	80	80	80	380							
4	80	80	80	80	80	80	80	380							
5	80	80	80	80	80	80	80	380							
6	80	80	80	80	80	80	80	380							
7	80	80	80	80	80	80	80	380 t_1							
8	t_L 80	80	80	80	80	80	80	380							
9	80	80	80	80	80	80	80	380							
10	80	80	80	80	80	80	80	380							
11	80	80	80	80	80	80	80	380							
12	80	80	80	80	80	80	80	380							
13	80	80	80	80	80	80	80	380							
14	0	0	0	0	0	0	0	0							

(3) CASE FOR SILVER
$\alpha = 6.54$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	155	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0083 HR. OR .5000 MIN. OR 30.00000 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	155	155	170	198	238	288	345	380							
3	155	155	170	198	238	288	345	380							
4	155	155	170	198	238	288	345	380							
5	155	155	170	198	238	288	345	380							
6	155	155	170	198	238	288	345	380							
7	155	155	170	198	238	288	345	380							
8	155	155	170	198	238	288	345	380							
9	155	155	170	198	238	288	345	380							
10	155	155	170	198	238	288	345	380							
11	155	155	170	198	238	288	345	380							
12	155	155	170	198	238	288	345	380							
13	155	155	170	198	238	288	345	380							
14	0	0	0	0	0	0	0	0							

CASE FOR SILVER
$\alpha = 6.54$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	342	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0367 HR. OR 2.2000 MIN. OR 131.99998 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	342	342	344	349	356	365	374	380							
3	342	342	344	349	356	365	374	380							
4	342	342	344	349	356	365	374	380							
5	342	342	344	349	356	365	374	380							
6	342	342	344	349	356	365	374	380							
7	342	342	344	349	356	365	374	380							
8	342	342	344	349	356	365	374	380							
9	342	342	344	349	356	365	374	380							
10	342	342	344	349	356	365	374	380							
11	342	342	344	349	356	365	374	380							
12	342	342	344	349	356	365	374	380							
13	342	342	344	349	356	365	374	380							
14	0	0	0	0	0	0	0	0							

CASE FOR SILVER
$\alpha = 6.54$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	367	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0533 HR. OR 3.2000 MIN. OR 191.99998 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	367	367	367	369	372	375	378	380							
3	367	367	367	369	372	375	378	380							
4	367	367	367	369	372	375	378	380							
5	367	367	367	369	372	375	378	380							
6	367	367	367	369	372	375	378	380							
7	367	367	367	369	372	375	378	380							
8	367	367	367	369	372	375	378	380							
9	367	367	367	369	372	375	378	380							
10	367	367	367	369	372	375	378	380							
11	367	367	367	369	372	375	378	380							
12	367	367	367	369	372	375	378	380							
13	367	367	367	369	372	375	378	380							
14	0	0	0	0	0	0	0	0							

CASE FOR SILVER
$\alpha = 6.54$

RAT RESULTS

RESULTS

COOLANT TEMPERATURES

	INLET	OUTLET	FLOW (LB/HR)
INNER RADIAL	-459	374	0
OUTER RADIAL	0	0	0
UPPER AXIAL	0	0	0
LOWER AXIAL	0	0	0

THE CURRENT TIME IS .0667 HR. OR 4.0000 MIN. OR 239.99997 SEC.

TEMPERATURE GRID
THE RADIAL DIRECTION IS HORIZONTAL
THE AXIAL DIRECTION IS VERTICAL
THE TEMPERATURES ARE IN DEGREES FAHRENHEIT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	0	0	0	0	0	0	0							
2	374	374	375	375	376	378	379	380							
3	374	374	375	375	376	378	379	380							
4	374	374	375	375	376	378	379	380							
5	374	374	375	375	376	378	379	380							
6	374	374	375	375	376	378	379	380							
7	374	374	375	375	376	378	379	380							
8	374	374	375	375	376	378	379	380							
9	374	374	375	375	376	378	379	380							
10	374	374	375	375	376	378	379	380							
11	374	374	375	375	376	378	379	380							
12	374	374	375	375	376	378	379	380							
13	374	374	375	375	376	378	379	380							
14	0	0	0	0	0	0	0	0							

CASE FOR SILVER
$\alpha = 6.54$

GADR 55
Volume I

CONDUCTION HEAT TRANSFER

by

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10–5 Infinite plate. Consider the heating or cooling of a large plate of uniform thickness $L = 2\delta_1$. The temperature distribution through the plate, $t(x,\theta)$, is initially ($\theta = 0$) some arbitrary function of x as $t(x,0) = t_i(x)$, whereupon both face surfaces $x = 0$ and L are suddenly changed to and maintained at a uniform temperature t_1 for all $\theta > 0$.

The solution for the temperature history $t(x,\theta)$ must satisfy the characteristic partial-differential equation of Fourier, (1–8), as

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \theta}, \tag{10–6}$$

and the initial and boundary conditions

$$\begin{aligned} T &= T_i(x) \quad \text{at } \theta = 0; \quad 0 \le x \le L,\\ T &= 0 \quad \text{at } x = 0; \quad \theta > 0,\\ T &= 0 \quad \text{at } x = L; \quad \theta > 0, \end{aligned}$$

where, for convenience, we let $T = t - t_1$ so that $T_i(x) = t_i(x) - t_1$. Integrating (10–6) by the separation of variables method (Article 5–8) leads to product solutions of the form

$$T_\lambda = e^{-\lambda^2\alpha\theta}(C_1 \cos \lambda x + C_2 \sin \lambda x),$$

if the separation constant is chosen as $-\lambda^2$. In these solutions $C_1 = 0$ if T is to vanish at $x = 0$ for all $\theta > 0$. If T is also to vanish at $x = L$ for all $\theta > 0$, then $\sin \lambda L = 0$, so that $\lambda = n\pi/L$. This requires that the eigenvalues be integral as $n = 1, 2, 3, \cdots$. The solution, which now takes the form

$$T = \sum_{n=1}^{\infty} C_n e^{-(n\pi/L)^2\alpha\theta} \sin \frac{n\pi}{L} x,$$

is to finally satisfy the initial condition that

$$T_i(x) = \sum_{n=1}^{\infty} C_n \sin \frac{n\pi}{L} x.$$

This result is recognized as a Fourier sine-series expansion of the arbitrary function $T_i(x)$, for which the constant amplitudes C_n are given by

$$C_n = \frac{2}{L}\int_0^L T_i(x) \sin \frac{n\pi}{L} x dx.$$

The complete solution is therefore

$$T = \frac{2}{L}\sum_{n=1}^{\infty} e^{-(n\pi/2)^2\Theta} \sin \frac{n\pi}{L} x \int_0^L T_i(x) \sin \frac{n\pi}{L} x dx, \tag{10–7}$$

where Θ is the Fourier modulus in (10–2) with $\delta_1 = L/2$. The solution (10–7) is also that for an insulated rod of length L with end temperatures maintained at t_1, the rod heating or cooling from an initial temperature state $t_i(x)$.

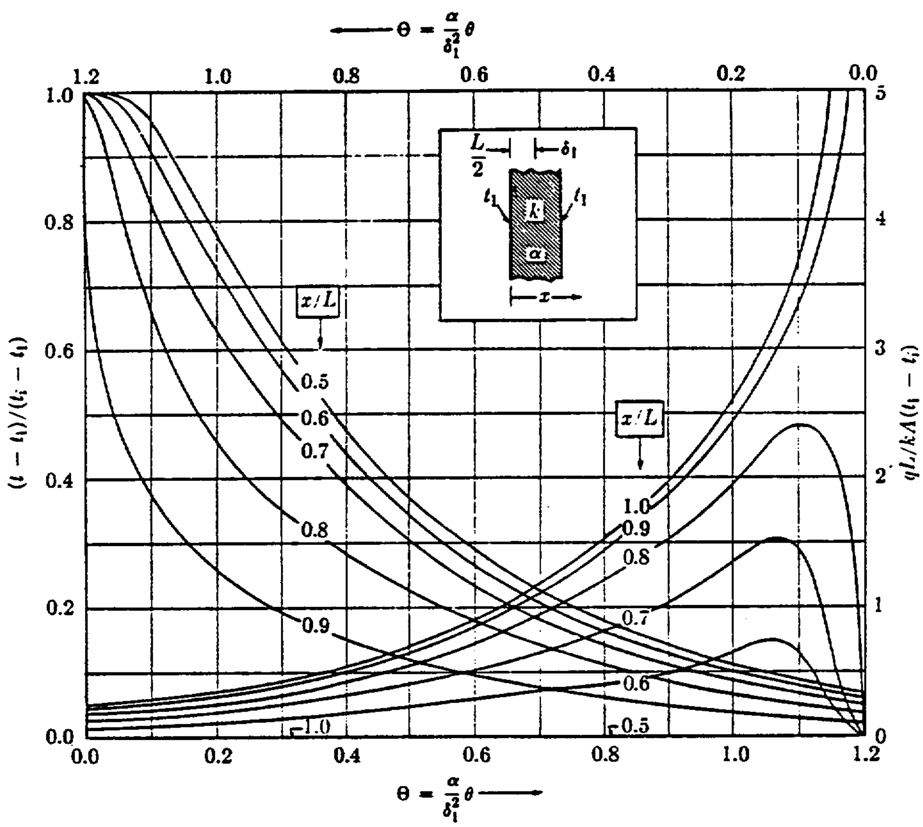

Fig. 10–2. Temperature history and instantaneous heat rate as a function of the Fourier modulus Θ for an infinite plate with negligible surface resistance.

Consider the special case represented by a uniform initial temperature $t_i(x) = t_i$. This is a practical case where $T_i(x) = t_i - t_1$, and for which (10–7) reappears in the particular form

$$\frac{t - t_1}{t_i - t_1} = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} e^{-(n\pi/2)^2\Theta} \sin \frac{n\pi}{L} x; \quad n = 1, 3, 5, \cdots. \tag{10–8}$$

Then the instantaneous rate at which heat is conducted across any plane of area A in the wall is $q = -kA\partial t/\partial x$, or

$$q(x,\theta) = 4\left(\frac{kA}{L}\right)(t_1 - t_i) \sum_{n=1}^{\infty} e^{-(n\pi/2)^2\Theta} \cos\frac{n\pi}{L} x; \quad n = 1, 3, 5, \cdots. \tag{10–9}$$

Notice that the heat flow is initially infinite at the two surfaces. The temperature history (10–8) and instantaneous heat rate (10–9) are shown in Fig. 10–2 for various stations in the plate.

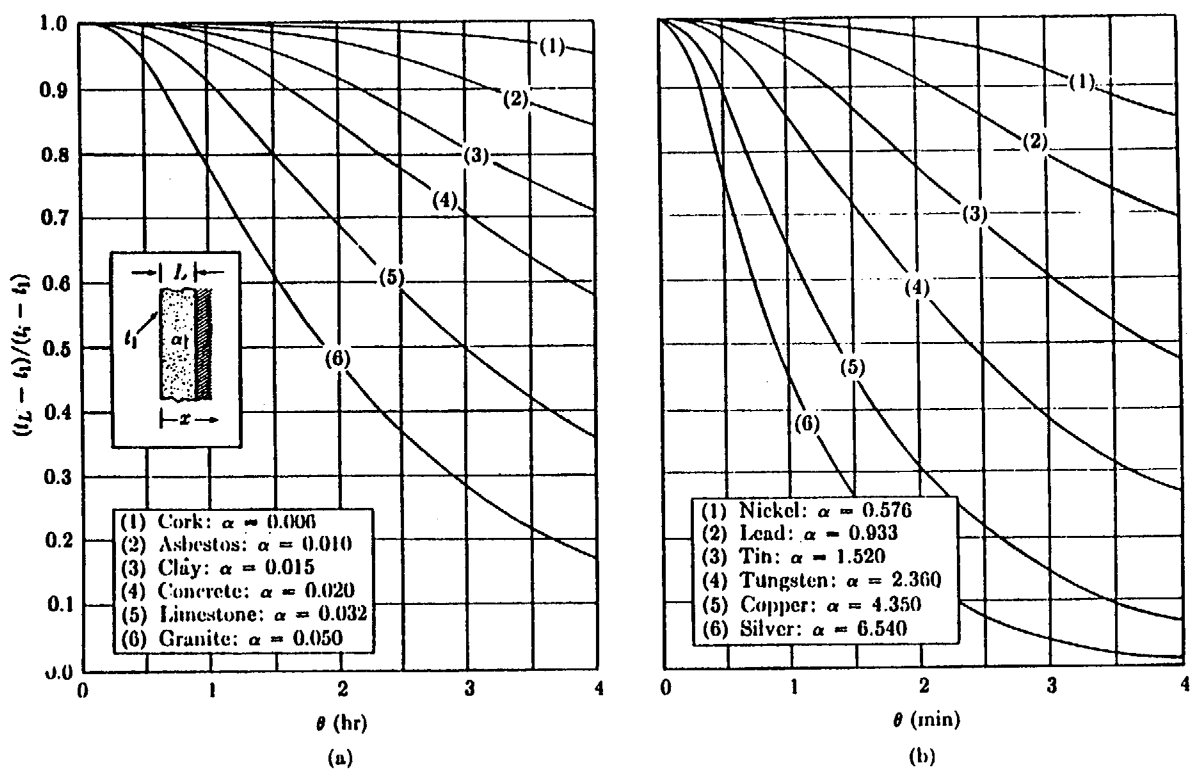

Fig. 10-3. Temperature rise at the insulated rear face of a plane wall 6″ thick, for various building materials (a) and pure metals (b).

Integration of (10–9) with respect to θ from $\theta = 0$ to θ gives for the cumulative heat rate in the plate

$$Q(x,\theta) = \frac{4}{\pi^2}\left(\frac{kAL}{\alpha}\right)(t_1 - t_i)\sum_{n=1}^{\infty}\frac{1}{n^2}[1 - e^{-(n\pi/2)^2\Theta}]\cos\frac{n\pi}{L}x;$$

$$n = 1, 3, 5, \cdots. \quad (10\text{–}10)$$

The series (10–8) has been accurately computed by Olson and Schultz (1) for the mid-plane temperature history at $x = L/2$ as given by

$$\frac{t(L/2,\theta) - t_1}{t_i - t_1} = \frac{4}{\pi} = [e^{-(1/4)\pi^2\Theta} - \tfrac{1}{3}e^{-(9/4)\pi^2\Theta} + \tfrac{1}{5}e^{-(25/4)\pi^2\Theta} - \cdots] = P(\Theta). \quad (10\text{–}11)$$

Values of $P(\Theta)$ for the plate are listed in Table A–8 of the Appendix, and later on we shall show how this particular series can be combined with an analogous series for the cylinder and semi-infinite solid to obtain solutions for a variety of other cases of practical interest.

EXAMPLE 10–2. As an example in the use of the plate series $P(\Theta)$, suppose that a large mass of combustible material is piled up against the 6″-thick wall of a large room. If a flash fire suddenly raises and maintains the temperature of the outside wall surface at t_1, how long will it take for the inside surface to reach the ignition temperature of the combustible material?

Solution. If the dimensions of the room are large compared with the wall thickness, then its walls can be approximated by an infinite plate 6″ thick and at a uniform temperature t_i preceding its exposure to fire at the face surface $x = 0$. Suppose further that the combustible material is of low thermal conductivity; the face surface at $x = L$ is then considered to be adiabatic.

A solution to the problem of the infinite plate with one insulated face is also encompassed in (10–8), for if we consider a plate of double thickness $2L$ with each face at t_1, then its mid-plane (around which the temperature is symmetrical) can be taken as the adiabatic face of the original plate. The temperature history at this adiabatic face is given by (10–11).

Values of $P(\Theta)$ with $L = 1$ are taken from Table A–8 and plotted in Fig. 10–3 for walls of various building materials in (a), and for large pure-metal walls in (b). Note that the units of time in (a) and (b) are hours and minutes respectively.

From these results we see that the walls of higher diffusivity have shorter allowable heating times, the duration being comparatively short for the metal walls. For example, if the ignition temperature of the stored material is 140°F, and the fire raises the outside surface temperature of the walls (initially at 80°F) to 380°F, then it would take a 6″ clay wall over three hours to reach $(t_L - t_1)/(t_i - t_1) = (140 - 380)/(80 - 380) = 0.8$, as compared with just three minutes for a 6″ lead wall.