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SAFETY ANALYSIS REPORT
VITRIFIED HIGH LEVEL WASTE
TYPE B SHIPPING CASK

REVISION 0

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NOTE

This report is formatted according to the guidelines of Regulatory Guide 7.9, "Standard Format and Content of Part 71 Applications for Approval of Packaging for Radioactive Material," Proposed Revision 2.

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CHAPTER ONE
GENERAL INFORMATION

1.0 GENERAL INFORMATION

1.1 Introduction

This Safety Analysis Report describes the design, analyses, and principle features of the Vitrified High Level Waste (VHLW) Cask. In preparing this report a detailed evaluation of the design has been performed to ensure that all safety, licensing, and operational goals for the cask and its associated Department of Energy program can be met. The functions of this report are:

- To fully document that all functional and regulatory requirements of 10CFR71 can be met by the package.
- To document the design and analyses of the cask for review by the Nuclear Regulatory Commission.

The VHLW Cask is the reusable shipping package designed by GNSI under Department of Energy contract DE-AC04-89AL53-689 for transportation of Vitrified High Level Waste, and to meet the requirements for certification under 10CFR71 for a Type B(U) package. The VHLW cask has been designed as packaging for transport of canisters of Vitrified High Level Waste solidified at Department of Energy facilities.

1.2 Package Description

1.2.1 Packaging

The package configuration is shown in Figure 1-1. Cask assembly drawings are included in Appendix 1.3. The package consists of a ductile iron shielding insert, primary and secondary lids, a stainless steel overpack, and a toroidal-shaped impact limiter located at each end of the overpack. A single canister of vitrified high-level waste is transported inside the shielding insert cavity. The cavity is covered by the primary lid. The primary lid is held in place by the secondary lid which is welded to the cask body. The shielding insert, primary lid, and secondary lid are all contained within the cask overpack.

The cask overpack has two sections: a lower base plate and an upper cylinder which is open at the bottom. The two sections are bolted together using 16 cap screws. The joint between the two sections is sealed using a silicone O-ring.

A pair of trunnions are attached to the outside walls at each end of the cask. The trunnions are used for moving the cask, and for securing it during transport over the road.

1.2.1.1 Key Design Parameters

Table 1-1 shows the principle criteria used for the design of the VHLW cask.

1.2.1.2 Cask Shielding Insert

The VHLW Cask shielding insert is made from ductile iron conforming to ASTM A 874-89, "Ferritic Ductile Iron Castings Suitable for Low-Temperature Service." The overall height of the insert is nominally 133½"(3,390 mm), and the overall diameter nominally 41½" (1054 mm). A single VHLW canister is transported inside the insert in the integrally cast cylindrical cavity. The internal cavity has a minimum diameter of 25.29" (642 mm) in diameter, and has a minimum height of 119" (3,022 mm) with the primary lid in place. The ductile iron body has walls which are at least 7.25" (184 mm) thick, and a base which is at least 6.5" (165 mm) thick.

The VHLW Cask shielding insert is shown in Fig. 1-2, and the insert with both primary and secondary lids in place is shown in Fig. 1-3. Additional cask drawings are provided in Appendix 1.3 of this Chapter. The overall dimensions are summarized in Tab. 1-2 and materials are summarized in Tab. 1-3.

1.2.1.3 Cask Overpack

The VHLW contents of the package are transported inside the shielding insert, which in turn is inside the stainless steel overpack. The overpack forms the containment boundary for the package. Figure 1-4 shows the cask overpack, and Figure 1-5 the containment boundary. The cask is assembled by placing the loaded shielding insert on the overpack baseplate, and lowering the barrel region down over the insert until it mates with the base plate. The overpack is made from ASME SA-240 stainless steel. The overpack walls are 1½"thick, except below the impact limiters, where they are 1" thick. The overpack base plate is 2" thick. The external dimensions of the overpack are nominally 139 inches long and 46 inches in diameter, except for the base plate which is 60.5 inches in diameter.

1.2.1.4 Containment System

The containment system is formed by the cask overpack and seals. The containment vessel is defined as the inner surface of the overpack and the closure o-ring seals. Containment system testing based on the payload characteristics is analyzed in Section 4.

1.2.1.5 Covers and Seals

The cask overpack top, sides, overpack body base plate, and overpack base are all fabricated from ASME SA-240 stainless steel. The top is a 1"-thick plate, 45" in diameter, welded to the side walls. The side walls are composed primarily of a 1½"-thick plate rolled to a 43" inside diameter. This overpack is bolted to a 2"-thick overpack base plate by 16 socket head cap screws, 1"-8 UNC threaded by 3-1/2" long.

The overpack body base plate and the overpack base plate are sealed by a pair of silicone o-ring seals. The inner O-ring is 47.2" in diameter. The second O-ring is 50.9" in diameter and is used with the first to create a region used for leak testing. Figure 1-6 shows the seals and test port.

1.2.1.6 Trunnions and Lifting Equipment

Two pairs of trunnions (upper and lower) are located on the cask overpack. These will be stainless steel conforming to ASTM A-276. The trunnions are welded to pads, which are in turn welded to the overpack. The pads are used to preclude damage to the overpack in the event of a failure of a trunnion weld.

1.2.1.7 Impact Limiters

The impact limiters are designed to limit the deceleration loads on the cask to less than approximately 100 g's during hypothetical accident conditions, so that the stress levels in the cask are within allowable values. The design uses polyurethane foam with a density of 17 lb/ft^3 encased in a carbon steel skin approximately one-eighth inch thick.

Foam limiters have a history of successful use in the spent fuel shipping industry. Because of this, as well as the fact that the material is highly stable and does not degrade over time, the polyurethane foam was selected for use in the limiter. Data from Reference 1-1, which reports the results of tests run by Sandia National Laboratories for half-scale casks that utilized polyurethane foam limiters, was used in the VHLW analysis.

Figure 1-1 shows the configuration and dimensions of the cask and impact limiters that were used in the design analyses. Each limiter is torus-shaped. The nominal outside diameters of the top and bottom impact limiters are 90.25" (229.2 cm) and 96" (243.8 cm), respectively. The nominal inside diameters of the top and bottom impact limiters are 45.5" (115.6 cm) and 61" (154.9 cm), respectively. A section of both is recessed so that they fit snugly over the ends of the cask. They are held securely onto the ends of the cask by eight lugs on each impact limiter and eight lugs at each end of the cask which are fastened by 16 sets of nuts, washers, and bolts.

1.2.1.8 Shipping and Tiedown System

The cask will be mounted for shipping in a horizontal orientation. The cask is mounted on the trailer by engaging the upper trunnions with a lifting yoke, lifting the cask and resting the lower trunnions on trunnion mounts on the trailer, then pivoting cask into the horizontal orientation. The cask is tied down during transport by the cask trunnions. Figure 1-7 is an illustration of the cask and trailer combination.

1.2.1.9 Packaging Weight

A breakdown of weight between packaging and contents is shown in Table 1-4.

1.2.2 Operational Features

Refer to the drawings of the packaging in Appendix 1.3. There are no complex operational requirements associated with the package.

1.2.3 Contents of Packaging

The VHLW Cask is designed to transport single canisters of two high-level waste types, designated as:

- VHLW - West Valley (WV)
- VHLW - Savannah River (SR)

The VHLW - WV and VHLW - SR canisters are produced at the West Valley Demonstration Project (Ref. 1-2) and the Defense Waste Processing Facility at the Savannah River Plant (Ref. 1-3), respectively. Outside dimensions for these two canisters are shown in Figure 1- 8.

Canisters can also be produced at other sites. These canisters from the other sites may also be transported in the VHLW cask provided their contents fit within the parameters for the cask established in this SAR.

1.2.3.1 VHLW - WV

This waste form is borosilicate glass (Ref. 1-2, page 3). The room temperature density of the glass is 2.70 g/cm^3 (Ref. 1-2, page 4). The canister is fabricated from stainless steel and has the dimensions shown in Figure 1-7. The canister wall has a minimum thickness of 0.13" (0.34 cm) (Ref. 1-2, page 6). A 100% full canister contains 2246 kg of glass. The estimated maximum decay heat is 390 watts per canister (Ref. 1-2, page 9).

1.2.3.2 VHLW - SR

This waste form is also borosilicate glass (Ref. 1-3, page 9). The canister is fabricated from stainless steel and has the dimensions shown in Figure 1-7. The canister wall has a nominal thickness of 3/8 inches (0.95 cm) (Ref. 1-3, page 16). The reference design canister is filled with 3,700 lb of glass, which occupies 85% of the free canister volume. However, after operational experience is gained the canister may be filled with 4,200 lb of glass (Ref. 1-3, page 17).

The nominal loading (3,700 lbs of glass) generates a maximum of 690 watts assuming a source due to oxides from 5-year-old sludge and precipitate from 15-year-old supernate (Ref. 1-3, page 10). Ratioing this heat load to the maximum anticipated glass loading of 4,200 lbs yields a maximum decay heat load of (4,200 lbs / 3,700 lbs)(690 watts) = 783 watts.

1.2.3.4 Summary of Package Contents

The essential data for the cask contents is summarized in Tab. 1-5. This data is based upon the maximum radionuclide inventory of each waste form.

TABLE 1-1
DESIGN CRITERIA

Design Parameter	Criterion
Shielding	49 CFR 173
Weight	DOT Limit for Gross Vehicle Weight (GVW)
Thermal	10 CFR 71.73, 10 CFR 71.43 (g), Reg-Guide 7.8
Structural	10 CFR 71.51, 10 CFR 71.71, 10 CFR 71.73, RegGuides 7.6 and 7.8
Criticality	K_{eff} + 2 S.D. less than 0.95 (Standard practice)
Containment	10 CFR 71.51, ANSI N14.5

TABLE 1-2
NOMINAL DIMENSIONS

Parameter	Inches	Cm
Overall length without impact limiter	139	353.1
Overall length with impact limiter	188.6	479.0
Outside diameter, overpack base area	60.5	153.7
Outside diameter, overpack barrel (not incl. trunnions)	46	116.8
Cavity diameter	25.3	64.3
Cavity length	119	302.3
Shield insert wall thickness (min.)	7.25	18.4
Shield insert bottom thickness	6.5	16.5
Primary lid thickness	8	20.3
Secondary lid thickness	2	5.1
Overpack wall thickness	1½	2.5
Overpack base plate thickness	2	5.1

TABLE 1-3
MATERIALS

Component	Material
Overpack	Stainless Steel SA-240, Gr. 304L
Cask Shielding Insert	Ductile iron ASTM A-874
Primary Lid	Ductile iron ASTM A-874
Cover Plate	Ductile iron ASTM A-874
Trunnions	Stainless steel 304L, ASTM A-276
Bolts	ASTM A-192
Impact Limiters	Foam with carbon steel cover

TABLE 1-4
WEIGHT SUMMARY

Component	Weight (lbs)
Cask shielding insert and lids	29,800
Contents	5,500
Overpack	12,500
Impact limiters	6,800
Miscellaneous	400
TOTAL	55,000

TABLE 1-5
SUMMARY OF CASK CONTENTS

Maximum Cask Inventory	VHLW-WV	VHLW-SR
Fissionable nuclides, g U-233 U-235 Pu-239 Pu-241 Cm-244	 440. 210. 120. 3.5 1.7 (Ref. 1-2, p. 39)	 < 1E-3 82.3 236. 18.7 (Ref. 1-3, p. 18 based on 4,200 lb of glass)
Thermal power, W (Note: For conservatism the hypothetical accident analysis assumes 1000 W)	390 (Ref. 1-2, p. 9)	783 (Calculated in Section 1.2.3.3 based on 4,200 lb of glass)
Activity, Ci	130,000 (Calculated in Tab. 4-3)	265,000 (Calculated in Table 4-3)
Surface dose rate (canister limit for transportation), R/h	8,250 (Calculated in Sec. 5.4.2.2)	7,810 (Calculated in Section 5.4.2.1)
Canister wall thickness in cm	 0.13 0.34 (Ref. 1-2, p. 6)	 0.38 0.95 (Ref. 1-3, p. 16)
Glass density, g/cc	2.70 (At room temperature; Ref. 1-2, p. 4)	2.74 (Based on average of 3 samples at 25°C; Ref. 1-3, p. 57)
Empty canister mass lbs kg	(Ref. 1-2, p. 6) 516 234	(Ref. 1-3, p. 16) 1,100 499
Total Mass of Canister and Glass (Maximum Loading) lbs kg	(Ref. 1-2, p. 6) 5,468 2,480	(Ref. 1-3, p. 16-17) 5,300 2,404

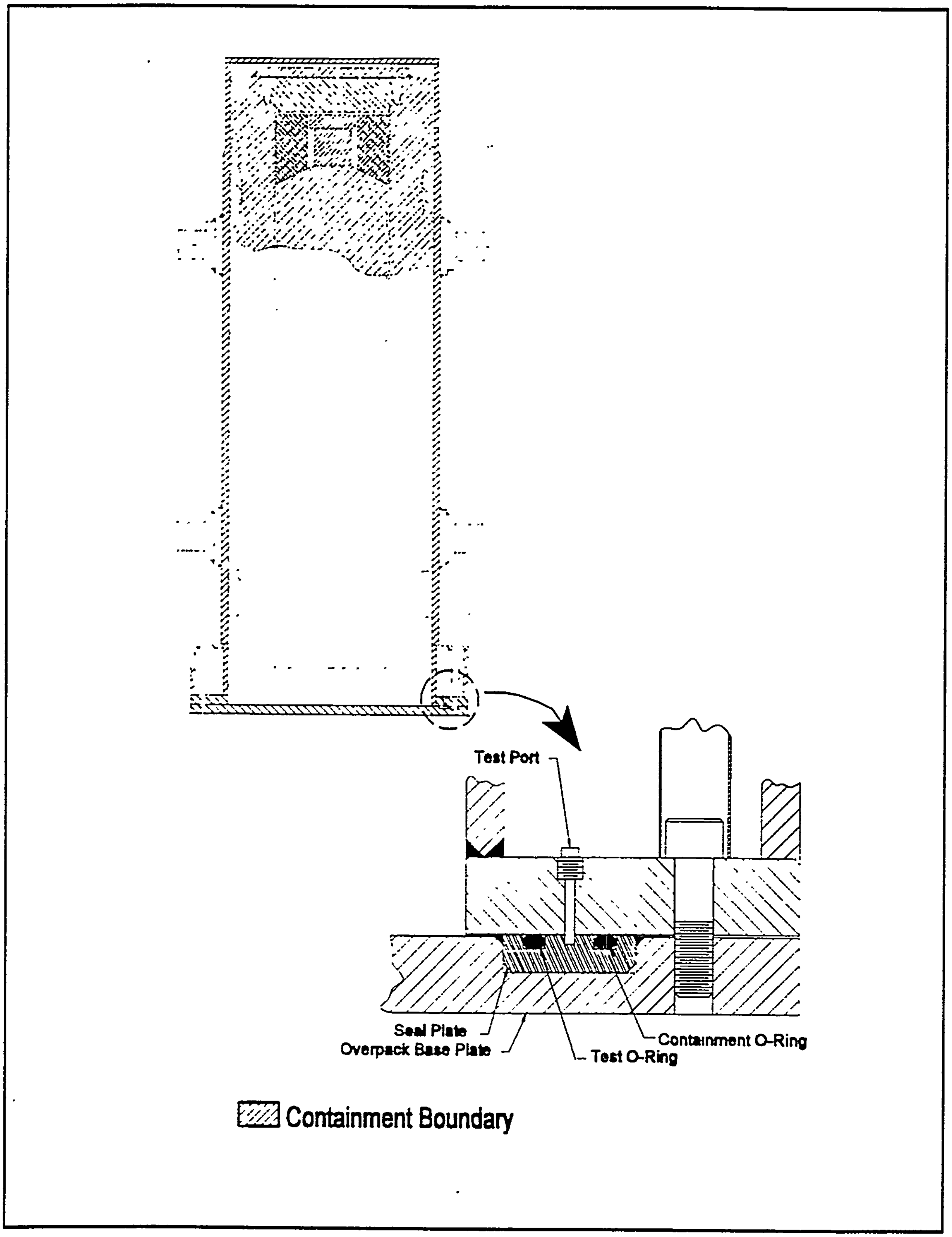


Figure 1-5
Containment Boundary

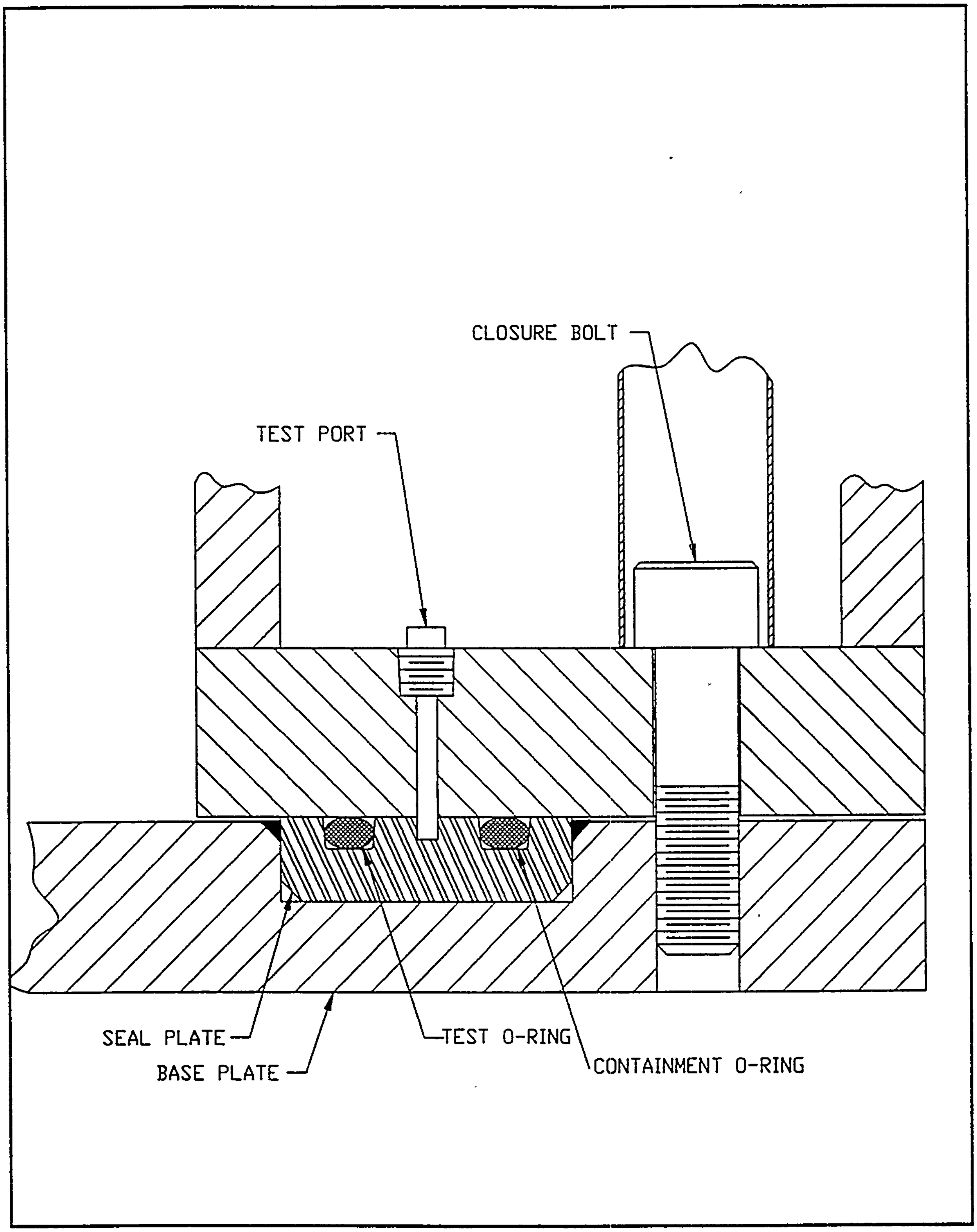


Figure 1-6
Containment Seal and Test Port

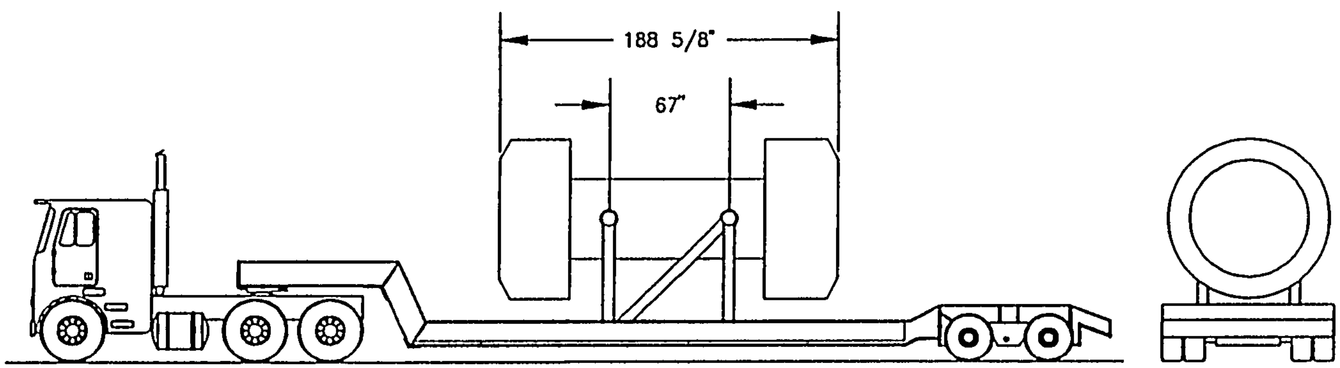


Figure 1-7
Shipping and Tiedown Arrangement

REFERENCES

1-1 G.W. Wellman, "Transportation System Impact Limiter Design Using Rigid Polyurethane Foam," June, 1985, Sandia Report, SAND84-2271.TTC-0532.

1-2 Eisenstatt, Larry R., *Description of the West Valley Demonstration Project Reference High-Level Waste Form and Canister*, National Technical Information Service, Springfield, Virginia, July 28, 1986, DOE/NE/44139-26.

1-3 Baxter, R. G., *Defense Waste Processing Facility Waste Form and Canister Description*, National Technical Information Service, Springfield, Virginia, December 1988, DP-1606, Revision 2.

CHAPTER TWO
STRUCTURAL EVALUATION

2.0 STRUCTURAL EVALUATION

This section identifies and describes the structural design of the VHLW Cask package, components, and safety systems for compliance with performance requirements of 10 CFR 71.

2.1 Structural Design

2.1.1 Discussion

The VHLW cask package has been designed to provide a shielded containment vessel that can withstand the loading due to the Normal Conditions of Transport, as well as those associated with the Hypothetical Accident Conditions in 10 CFR 71.73.

The VHLW cask package consists of four basic components which maintain the structural integrity of the package and safe containment of the waste:

(1) Austenitic stainless steel overpack (Pressure Boundary)
(2) Lid and seal system (Pressure Boundary)
(3) Impact limiters (protects the cask in case of accidental drops)
(4) Ductile iron shielding insert (provides shielding only)

2.1.2 Design Criteria

The requirements for evaluation of a cask for licensing are given in 10 CFR 71.4(a), as follows:

> *"The effects on a package of the tests specified in §71.71 (Normal Conditions of Transport) and the tests specified in §71.73 (Hypothetical Accident Conditions) must be evaluated by subjecting a sample package or scale model to test, or by other method of demonstration acceptable to the Commission, as appropriate for the particular feature being considered."*

In this Safety Analysis Report (SAR), compliance with the requirements of 10 CFR 71.41(a) is demonstrated by analysis. The cask is analyzed in this and following Chapters for meeting the requirements of the Normal Conditions of Transport and the Hypothetical Accident Conditions. The analyses include, in this Chapter, demonstrating that the VHLW cask package safely withstands loads from the accidental drops and other accidents specified in §71.73(c). Design of the VHLW Cask has included analyses of the package for appropriate loads and stresses and allowance for proper safety factors to ensure the package meets the standards for Type B packages.

Regulatory Guide 7.6 "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels," (Ref. 2-1) has been used in conjunction with Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks," (Ref. 2-2) to evaluate the package according to the requirements of §§71.71 and §§71.73. Table 2-1 summarizes the temperature and pressure loadings associated with the normal and hypothetical accident conditions for the VHLW cask package.

2.1.2.1 Allowable Stress Limits

Normal Conditions

Stress Limits for Components Other Than Bolts

The stress limits for components other than bolts are given in RegGuide 7.6 (Ref. 2-1). The primary membrane stresses (P_m) are limited to S_m, the design stress intensity, and the primary membrane plus bending stresses (P_m+P_b) are limited to 1.5 S_m. The sum of primary membrane, membrane plus bending and secondary stresses (Q) is limited to 3.0 S_m. Symbolically,

$$P_m \leq S_m$$
$$P_m + P_b \leq 1.5\ S_m$$
$$P_m + P_b + Q \leq 3.0\ S_m$$

The value of S_m is obtained from Table 2A of the ASME Code, Section II, Part D, (Ref. 2-3).

Stress Limits for Bolts

The tensile stress in bolt cross-sections is limited to 2 S_m. S_m is obtained from Table 4 of the ASME Code, Section II, Part D, (Ref. 2-3). The maximum allowable stress intensity resulting from primary tension plus bending is 3 S_m.

Hypothetical Accident Conditions

Stress Limits for Components Other Than Bolts

The stress limits for components other than bolts are given in RegGuide 7.6 (Ref. 2-1). These are as follows:

P_m	$\leq$	lesser value of 2.4 S_m or 0.7 S_u	
$P_m + P_b$	$\leq$	lesser value of 3.6 S_m or S_u	
$\tau_{average}$	$\leq$	0.42 S_u	[Allowable is taken from ASME, Section III, Appendix F (Ref. 2-3).]

where:

S_u = ultimate strength

τ = shear stress

Stress Limits for Bolts

Stress limits for bolts under service level D conditions are obtained from article F-1335 of the ASME Code, Section III, Appendix F (Ref. 2-3). These limits are as follows:

Stress Category	Allowable
Average tensile stress	F_{tb} = lesser value of 0.7 S_u or S_y
Tensile plus bending stress	$F_{bb} = S_u$
Shear stress	F_{vb} = lesser value of 0.42 S_u or 0.6 Sy
Combined stress	$\frac{f_t^2}{F_{tb}^2} + \frac{f_v^2}{F_{vb}^2} \leq 1.0$

where:

f = applied stress

F = allowed stress (from ASME Code, Section III, Appendix F, Article F-1335, Ref. 2-3)

Table 2-2 summarizes the allowable stresses for the VHLW cask package under various loading conditions.

2.1.2.2 Buckling

Buckling, per Regulatory Guide 7.6 (Ref. 2-1), is an unacceptable failure mode for the containment vessel. The intent of this provision is to preclude large deformations which would compromise the validity of linear analysis assumptions and quasi-linear stress allowables as given in paragraph C.5 of NRC Regulatory Guide 7.6. The only component in the VHLW cask package, which may be considered as a potential candidate for buckling is the shell of the overpack. This is shell is, however, backed by the ductile cast iron cask, which does not permit it to have a long unsupported length. Therefore, the shell would not buckle under any loading condition.

2.1.2.3 Brittle Fracture

The primary material used in the package, on the containment boundary, is SA-240 Grade 304L stainless steel. This material has an austenitic micro-structure and does not experience a ductile to brittle transition in the temperature ranges of interest (down to -40°F). Hence it is considered safe from brittle fracture. Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1 m)," (Ref. 2-4) specifically excludes austenitic stainless steels from consideration for brittle fracture.

The bolts used to secure the lid to the cask body are not be considered as fracture critical components based on the discussion in NUREG/CR-1815 (Reference 2-5) which states the following:

> *"Bolts are generally not considered as fracture critical components because multiple load paths exist and because bolted systems are designed to be redundant. In other words, failure of one or more bolts normally do not lead to penetration or rupture of the container."*

2.1.2.4 Impact Limiter Foam Strain

The impact limiter is designed to absorb energy through inelastic deformation during the hypothetical accident conditions. Strain, rather than stress, is used as the limiting parameter to assure that the material does not bottom out. The maximum limiting strain was established as 80% since the stress and corresponding forces applied to the cask become large, and the "stiffness" of the impact system becomes large.

2.1.2.5 Tie-Downs and Lifting Devices

Cask and Lifting Devices

10 CFR 71.45 (a) requires that the cask lifting devices be capable of supporting three times the weight of the loaded package without generating any stress in the cask in excess of the yield strength. Analyses in this chapter will show that no stresses shall be generated in any material in excess of yield strength. Maximum stresses and safety factors are computed in Section 2.5.1.

Tie-Downs

10 CFR 71.45 (b) paragraph (1) requires that the tie-downs be designed such that no stresses exist in any material of the package in excess of yield strength for the specified 10-5-2g loading condition. Maximum package stresses and factors of safety are computed in Section 2.5.2.

2.1.2.6 Failure of the Tie-Down and Lifting Devices

Tie-down, cask lifting, and lid lifting devices are designed such that failure of the device under excessive loads will not impair the ability of the package to meet the other requirements specified in 10 CFR 71.45.

Sections 2.5.1 and 2.5.2 demonstrate that at the excessive load for which a device fails, each component of the package which is required for meeting the shielding and containment requirements before and after the normal and accident events, has had no stress generated in excess of its material yield strength. This leads one to conclude that if the remaining components have not yielded, they remain intact and undeformed and may be considered for meeting the shielding and containment requirements for normal and accident conditions.

Failure is predicted for an equivalent state of stress which produces a maximum shear stress of

$$\sigma_{Failure} = \frac{S_u}{\sqrt{3}} = 0.577 S_u$$

where:

S_u = material's ultimate tensile strength.

2.2 Weights and Centers of Gravity

The weight breakdown of the VHLW cask package is as follows:

• Stainless Steel Overpack	12,500	lbs
• Ductile Iron Cask	29,800	lbs
• Upper Impact Limiter	3,300	lbs
• Lower Impact Limiter	3,500	lbs
• Payload	5,500	lbs
• Miscellaneous	400	lbs
Total	55,000	lbs

The center of gravity of this package is located at the geometric center of the package.

2.3 Mechanical Properties of Materials

The package is fabricated from stainless steel, with low carbon content, and structural foam. Table 2-3 shows the temperature dependent mechanical properties of all the material used in the fabrication of the package. This table includes the materials used on the pressure boundary as well as ductile iron, which has been used in the package as a shielding material. Table 2-4 shows the allowable values of primary stress intensities for normal and hypothetical accident conditions. Since the highest temperature in the package during the normal conditions is 200°F, the allowable values are based on this temperature.

The energy absorbing impact limiters are constructed of self-extinguishing rigid polyurethane foam of 17 lbs/ft^3 nominal density. Table 2-5 lists the stress-strain properties of the polyurethane foam at various temperatures. Figures 2-1 & 2-2 show these properties in a graphical form. Foam samples will be taken during the actual foaming process and tested in accordance with Chem-Nuclear Specification 49023-611-3.

2.4 General Standards for All Packages

This section demonstrates that the general standards and loading conditions for all packages of 10 CFR 71.43 are met.

2.4.1 Minimum Package Size

The VHLW package meets the requirement specified in 10 CFR 71.43(a); which states as follows: "The smallest overall dimension of a package must not be less than 10 cm (four in.)." Refer to the drawings of the package in Appendix 1.3.

2.4.2 Tamperproof Feature

The VHLW cask package will be sealed with an approved tamper-indicating seal and suitable locks to prevent inadvertent and undetected opening. The tamper-indicating seal is shown on the drawings of the package in Appendix 1.3.

2.4.3 Positive Closure

The positive closure system has been previously described in Section 1.2.1.

2.4.4 Chemical and Galvanic Reactions

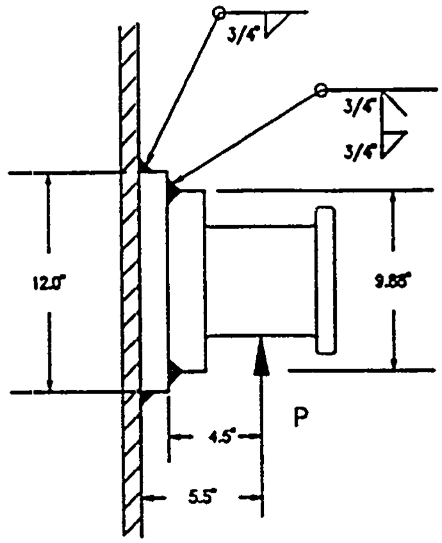
The material from which the packaging is fabricated (stainless steel, ductile iron, and polyurethane foam) will not cause significant chemical, galvanic, or other reaction in air, nitrogen, or water atmosphere. The contents of the package, borosilicate glass, are non-reactive and are sealed within a stainless steel canister, and therefore will not react with the packaging materials.

2.5 Lifting and Tie-Down Standards for All Packages

2.5.1 Lifting Devices

The cask is equipped with two pairs of trunnions. Both pairs are used to tie the cask down during transport; for conservatism, in this chapter it will be assumed that only one pair supports the cask during transport. The top pair of trunnions is used for lifting the cask, and the bottom pair for rotation of the cask from the horizontal to the vertical position. These trunnions are structurally evaluated using the criteria in 10 CFR 71.45.

The highest load on the trunnion occurs when the cask is being transported with the crane. In this case, the weight of the cask is applied to the two trunnions. Title 10 CFR 71.45 specifies that these trunnions must be able to support three times the weight of the cask without exceeding their yield strength.



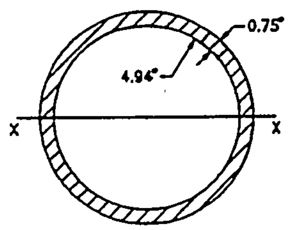
The critical component in the lifting arrangement are the welds between the trunnion-trunnion pad and between trunnion pad-overpack shell. The stresses in these welds are calculated in this section to show that these welds can sustain three times the weight of the entire package, without exceeding yield strength of the material.

Load per trunnion, $P = 3 \times 55{,}000 / 2$
$= 82{,}500$ lbs

Bending moment about the trunnion-trunnion pad weld centerline is:

$$M = 82{,}500 \times 4.5 = 371{,}250 \text{ in-lb}$$

The weld is specified as ¾" grove plus ¾" fillet weld around the circumference of the trunnion base (9.88 inch diameter). The section modulus of this weld is:



$$Z_{xx} = \pi r^2 t$$
$$= \pi \times (9.88/2)^2 \times 0.75 = 57.5 \text{ in}^3$$

Therefore, the weld stress due to bending load is:

$$\sigma = 371{,}250 / 57.5$$
$$= 6{,}457 \text{ psi} << S_y = 25{,}000 \text{ psi}$$

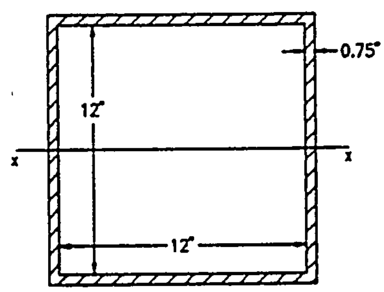
$$\text{F.S.} = 25{,}000 / 6{,}457 = 3.87$$

Bending moment about the trunnion pad-overpack shell centerline is:

$$M = 82{,}500 \times 5.5 = 453{,}750 \text{ in-lb}$$

The weld is specified as ¾" fillet weld all-around a 12" × 12" plate.

Moment of inertia of the weld about, xx, is:



$$I_{xx} = 2/3 \, t \, d^3$$
$$= 2/3 \times 0.75 \times 0.707 \times 12^3$$
$$= 610.8 \text{ in}^4$$

Section modulus,

$z_{xx} = 610.8 / 6 = 101.8 \text{ in}^3$

Therefore, the weld stress due to bending load is:

$$\tau = 453{,}750 / 101.8$$
$$= 4{,}457 \text{ psi} << 0.6 S_y = 15{,}000 \text{ psi}$$

$$\text{F.S.} = 15{,}000 / 4{,}457 = 3.37$$

It should be noted that the trunnion pads are welded to a 1" thick shell by ¾" fillet welds. Therefore, under the excessive load the welds will fail before the shell is over-stressed. Thus the requirement that the failure of lifting device under excessive load shall not impair the ability of the package to the other requirements specified in 10 CFR 71.45, is satisfied by the VHLW cask package.

2.5.2 Tie-Down Devices

The tie-down system for transporting the VHLW cask package is designed to load conditions defined in 10 CFR 71, Paragraph 71.45 (b). This load condition is defined as follows:

> *"... the system must be capable of withstanding, without generating stress in any material of the package in excess of its yield strength, a static force applied to the center of gravity of the package having a vertical component of two times the weight of the package and its contents, a horizontal component along the direction in which the vehicle travels of 10 times the weight of the package with its contents and a horizontal component in the transverse direction of five times the weight of the package with its contents."*

The VHLW cask package is transported in a horizontal orientation on a trailer, which is fitted with a specially-designed cradle. It is assumed that only one of the two pairs of trunnions are engaged to the shipping cradle, making them the part of the tie-down system. Therefore, the trunnions and their attachment must be able to sustain the above mentioned loading without exceeding the yield strength of the material.

The trunnions are evaluated in this section for 10 g longitudinal loading, which envelopes the loading in the other two directions. The stresses in the trunnion attachment are computed by ratioing the stresses calculated in section 2.5.1 (lifting loading), where the evaluation was performed for a 3 g longitudinal loading. The factor of safety on the trunnion-trunnion pad weld is $3 \times 3.87 = 11.61$ and that on the trunnion pad-overpack shell weld is $3 \times 3.37 = 10.1$. Since the factor of safety is larger than 10 on both welds, the stresses will remain within the yield strength of the material for a 10 g of longitudinal acceleration, satisfying the requirements of 10 CFR 71.45.

2.6 Normal Conditions of Transport

The package has been designed, constructed and the contents limited such that the performance requirements specified in 10 CFR 71.43 and 71.51 will be met when the package is subjected to the normal conditions of transport specified in 10 CFR 71.71. The ability of the package to satisfactorily withstand the normal condition of transport has been assessed as described in the following paragraphs:

2.6.1 Heat

Evaluation of VHLW cask package for heat loading has been performed using analytical techniques described in Section 3.4.

2.6.1.1 Summary of Pressure and Temperatures

Pressures and temperatures in the VHLW cask package during the normal conditions are evaluated in Section 3.4. These temperatures and pressures, as summarized below, are used to perform the calculations reported in the following sections.

Average Temperature of the Overpack	170.2 °F
Maximum Temperature Difference Across the Wall	0.3 °F
Maximum Internal Pressure	28.6 psia

2.6.1.2 Differential Thermal Expansion

Under normal conditions of transportation of the cask, the temperature distribution in the cask body is fairly uniform. Differential thermal expansion between various components of the cask are very small. The stresses due to differential thermal expansion are accounted for automatically in the finite element model of the VHLW cask package described in Section 2.10.3.2. Although these stresses are classified as secondary stresses according to the ASME B&PV code, they have been treated as primary stresses in the evaluation of the VHLW cask package.

2.6.1.3 Stress Calculation

Stresses due to combined effects of pressure and thermal loading are calculated and presented in Section 2.10.3.2. A finite element model, similar to the one used for the normal hypothetical drop analysis, was used to compute the stresses.

2.6.1.4 Comparison with Allowable Stresses

The stresses due to normal conditions, pressure, and thermal loading combined with 1-foot drop loading have been shown to be within the allowable stresses of normal conditions loading (See

Tables 2-8 and 2-9). Therefore, the stresses due to pressure and thermal loading alone will also be within the allowable values.

2.6.2 Cold

10 CFR 71.71 (c)(2) requires that the package should demonstrate the capability to withstand a cold environment of -40°F ambient temperature. The concern at this temperature is the brittle fracture of the cask components. The material of construction of the VHLW package is ASME SA-240 Gr 304L Stainless Steel. This material has an austenitic micro-structure and does not experience a ductile to brittle transition in the temperature ranges of interest (down to -40°F). Hence it is considered safe from brittle fracture. Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1 m)," (Ref. 2-4) specifically excludes austenitic stainless steels from consideration for brittle fracture. Hence a brittle fracture of the package to the specified minimum temperature of -40°F is not expected. The package will maintain its containment capability in this environment.

2.6.3 Reduced External Pressure

10 CFR 71.71 (c)(3) requires that the package should be able to withstand a reduced external pressure of 3.5 psia. Since the internal pressure in the VHLW overpack is 28.6 psia, the package should be able to withstand a 28.6 - 3.5 = 25.1 psi internal pressure. The maximum stress intensity for 26 psi internal pressure is 11,532 psi (see Table 2.10.3-1). For 25.1 psi internal pressure, the maximum stress intensity will be $11{,}532 \times 25.1/26 = 11{,}133$ psi, which is well within the allowable stress of 25,050 psi.

2.6.4 Increased External Pressure

10 CFR 71.71 (c)(4) requires that the package should be able to withstand an increased external pressure of 20 psia. The results presented in Table 2.10.3-1 for an internal pressure of 21 psi show that a maximum stress of 9,292 psi is expected under this loading. For 20 psi internal pressure, the maximum stress will be $9{,}292 \times 20/21 = 8{,}850$ psi which is well within the allowable stress of 25,050 psi.

2.6.5 Vibration

The package is similar to many other proven cask with many years of operational use in a transport environment. This experience demonstrates that vibrations normally incident to transport will have no effect upon the package.

2.6.6 Water Spray

Not applicable, since the package exterior is constructed of steel.

2.6.7 Free Drop

The regulatory requirement of free drop, 10 CFR 71.71(c)(7), specifies the drop height based on the package gross weight. For a package weighing 55,000 lbs, this height is 1-foot. Therefore, the VHLW cask package has been analyzed for a free drop of one foot.

The package must survive a one-foot free fall onto a flat, unyielding surface without reducing its effectiveness in withstanding subsequent accident conditions. Using the techniques described in Appendix 2.10.1, and accounting for the temperature variation during the normal operation (-20 °F to 100 °F), the maximum decelerations experienced by the package for a one-foot drop have been calculated to be:

Drop Orientation	Deceleration (g's)
End (Top Down)	15.8
End (Bottom Down)	24.3
Side	13.6
Corner (Top Down)	9.6
Corner (Bottom Down)	8.9

Results from the CASKDROP program (Ref. 2-6,2-7, and 2-8) are summarized in Table 2-6 for all the orientations. The stresses resulting from these loads (Table 2-7) have been obtained from the stresses under the corresponding hypothetical accident condition loading, ratioed in proportion of peak decelerations. These stresses are combined with maximum normal temperature and pressure stresses as indicated in Table 2-1. The maximum membrane and membrane plus bending stress intensities, arising from different free-drop scenarios and combined with the pressure and temperature loading, are summarized in Tables 2-8 and 2-9. These tables also compare the stress intensities with the allowable values and present the corresponding factors of safety.

2.6.7.1 End Drop

The maximum membrane stress intensity, due to a free-drop on the package top, is 3,370 psi and the maximum membrane plus bending stress intensity is 11,284 psi. The maximum membrane stress intensity, due to a free-drop on the package bottom, is 3,386 psi and the maximum membrane plus bending stress intensity is 11,819 psi.

2.6.7.2 Side Drop

The maximum membrane stress intensity, due to a free-drop on the side, is 2,637 psi and the maximum membrane plus bending stress intensity is 8,272 psi.

2.6.7.3 Corner-Over-C.G. Drop

The maximum membrane stress intensity, due to a free-drop on the package top, is 2,130 psi and the maximum membrane plus bending stress intensity is 7,649 psi. The maximum membrane stress intensity, due to a free-drop on the package bottom, is 2,999 psi and the maximum membrane plus bending stress intensity is 6,654 psi.

2.6.8 Corner Drop

This requirement is not applicable since the VHLW package is fabricated of steel and weighs more than 110 lbs.

2.6.9 Compression

Not applicable since the package weighs more than 10,000 lbs and is not a wooden package.

2.6.10 Penetration

Impact energies resulting from a 13 pound rod dropping from a height of 40 inches will have no significant effect on the VHLW cask package overpack. The impact limiters fully protect both ends of the package leaving only the central portion exposed. The overpack wall is made of one inch thick stainless steel shell and backed with over 7 3/4 inches of ductile iron, which is sufficient to absorb the impact energy. No valves, valve covers or fragile protrusions exist.

Conclusions

As a result of the above assessment, it is concluded that under normal conditions of transport, the package complies with the following conditions:

1. There will be no release of radioactive material from the containment vessel.
2. The effectiveness of the packaging will not be substantially reduced.
3. There will be no mixture of gases or vapors in the package which could, through any credible increase in pressure or an explosion, significantly reduce the effectiveness of the package.

2.7 Hypothetical Accident Conditions

The package has been designed and its contents are limited in such a way that the performance requirements specified in Section 71.51 of 10 CFR 71 will be met if the package is subjected to the hypothetical accident conditions specified in 10 CFR 71.73.

To demonstrate the structural integrity of the VHLW overpack when subjected to hypothetical accident conditions, a series of analyses were performed. These analyses include the following specified conditions: 1) End Drop (top and bottom ends), 2) Side Drop, and 3) C. G. Over Corner (top and bottom ends). For the thirty-foot drop analyses, loads were derived by computing energy absorption of the foam impact limiters as described in detail in Section 2.10.1. A summary of all analyses performed is shown in Table 2-10 and are described in additional detail in Section 2.10.2.

The stresses arising from the hypothetical accident conditions loading are combined with maximum temperature and pressure stresses as indicated in Table 2-1. The maximum membrane and membrane plus bending stress intensities, arising from different hypothetical accident scenarios combined with the pressure and temperature loading, are summarized in Tables 2-12 and 2-13. These tables also compare the stress intensities with the allowable values and present the corresponding factors of safety.

2.7.1 <u>Free Drop</u>

Section 71.73 of 10 CFR 71 requires that the package survive a thirty-foot drop onto a flat unyielding surface. Analytical methods (finite element modeling and hand calculations) were used to demonstrate the VHLW overpack's capability to withstand the effects of these accident conditions. The analytical techniques are described in Section 2.10.2.

As described in Section 1.2, the package features cylindrical energy absorbing impact limiters surrounding each end of the cask body. These impact limiters are designed to minimize damage to the cask body from thirty-foot drops at any orientation onto an unyielding surface. The analyses described in this section demonstrate that these impact limiters function as designed in that they prevent the cask body from being subjected to stresses in excess of the allowable levels or from experiencing any permanent damage. This behavior assures that the package will retain containment integrity even under the most severe conditions expected.

Using the methods described in Section 2.10, three thirty-foot drop orientations are considered: 1) End, 2) Side, and 3) Corner Over C.G.

2.7.1.1 Thirty-Foot End Drop

Due to variations in the top and bottom configurations of the VHLW overpack, separate analyses were run for the two end drop impact conditions.

2.7.1.1.1 Bottom End Impact

The analysis for the thirty-foot bottom end drop condition consisted of an equivalent static analysis of the cask subjected to the peak dynamic acceleration. This acceleration is calculated using the energy methods described in Section 2.10.1 and shown in Table 2.10.2-1. The peak acceleration for the end drop condition was determined to be 59.8g's and is imposed on the finite element model as a region of pressure corresponding to the location of the limiter. Peak stresses from the finite element model are shown to be approximately 31,230 psi near the bottom of the cask.

2.7.1.1.2 Top End Impact

The analysis for the thirty-foot top end drop accident condition is much the same as that for the bottom end analysis with the appropriate consideration of the different geometry. The peak acceleration for this case was 40.5g's which resulted in a maximum stress of 28,933 psi.

2.7.1.2 Thirty-Foot Side Drop

The analysis for the thirty-foot side drop condition consisted of a finite element model of the cask (as described in Section 2.10.2.3). Behavior of the impact limiters during the side drop accident condition is determined using the energy methods as described in Section 2.10.1. Results of the limiter analysis indicate that the cask will be subjected to a maximum deceleration of 93.5g's during the impact and that the maximum limiter deflection will be approximately 14.2 inches. Calculations show that if the cask were to fall oriented such that the trunnions were facing downward there would still be adequate clearance to prevent the trunnions from contacting the impact surface.

The highest stress intensity in the overpack is approximately 56,867 psi. This stress intensity is local in nature but for conservatism, has been classified as membrane plus bending.

2.7.1.3 Corner Drop

Two analyses were run considering the effects of dropping the cask in an orientation such that the center of gravity of the assembly was over the point of impact. This orientation is an extreme case in that the entire energy from the falling assembly must be absorbed by the limiter which contacts the cask in a relatively small area. This results in the high limiter contact loads. For the cases considered, top and bottom end drops, the calculated cask deceleration loads were 41.3g's and 48.8g's respectively.

2.7.1.3.1 Bottom End Corner Drop

The bottom end corner drop analysis, using the calculated maximum deceleration of 48.8g's, results in stresses well below the allowable limits. The largest membrane plus bending stress intensity is 32,907 psi.

2.7.1.3.2 Top End Corner Drop

The top end corner drop analysis, using the calculated maximum deceleration of 41.3g's, results in stresses well below the allowable limits. The maximum membrane plus bending stress intensity of 28,624 psi occurs in the baseplate of the package.

2.7.1.4 Bolt Evaluation

The bolt loads on the VHLW cask package due to various drop conditions are obtained from the finite element models used for that condition. These loads are presented in Table 2-14 for all the drop scenarios analyzed in this report. The table also presents the factors of safety on the axial and shear loads, as well as the interaction of axial and shear load factors, defined in section 2.1.2.1. The bolts are torqued to produce approximately 27,000 lbs of preload. It is shown that under all the drop conditions the bolt loads never exceed this value. Therefore, the bolted joint will provide adequate sealing during these events.

Bolt Torque

The bolt torque is established using the following well known torque equation (see Reference 2-9)

$$T = K D F$$

where,

T = Applied torque
K = Nut Factor = 0.2
D = Nominal bolt diameter = 1.0 inch
F = Bolt preload = 27,000 lbs

Thus,

$$T = 0.2 \times 1.0 \times 27{,}000 = 5{,}400 \text{ in-lb} = 450 \text{ ft-lb}$$

Consequently, a torque of 500±50 ft-lb has been specified in the design. The lower value of the tolerance will provide 450 ft-lb torque, as established above.

Thread Engagement

The required thread engagement of the bolts with the lid is evaluated using the formulas from Reference 2-9. Because the lid material is weaker than the bolt material, failure will occur at the root of the lid threads. The equation of shear area and the minimum length of engagement required to develop full strength of the threads are:

$$A_{TS} = \pi\, n\, L_e\, D_{min} \left[\frac{1}{2n} + 0.57735\ (D_{min} - E_{nmax})\right]$$

and,

$$L_e = \frac{2 A_s S_{st}}{S_{nt} \pi n D_{min} \left[\frac{1}{2n} + 0.57735\ (D_{min} - E_{nmax}\right]}$$

where:

D_{min} = Min. O.D. of the bolt = 1.0 inch
E_{nmax} = Max. P.D. of cask threads = 0.9188 inch
S_{ut} = Tensile strength of the bolt material = 100,000 psi
n = No. of threads per inch = 8
A_s = Stress area of the bolt threads = 0.606 in^2
S_{nt} = Tensile strength of the cask material = 70,000 psi
A_{TS} = Shear area at root of the cask treads, in^2
L_e = Length of thread engagement required to develop full strength, inch

Thus,

$$L_e = \frac{2 \times 0.606 \times 100{,}000}{70{,}000 \times \pi \times 8 \times 1 \times [\frac{1}{2 \times 8} + 0.57735 \ (1 - 0.9188)]}$$

$$= 0.6298 \text{ inch}$$

The actual thread engagement provided is 1½ inch, which is much larger than the required thread engagement.

2.7.2 Puncture

10 CFR 71.73 c (2) requires package free fall 40 inches onto a 6 inch diameter mild steel bar without significant damage. The most critical regions are the wall and the ends of the cask.

2.7.2.1 Wall

Steel casks dropped onto their wall were studied by Nelms (Structural Analysis of Shipping Casks, Vol. 3 Effects of Jacket Physical Properties and Curvature on Puncture Resistance, June 1968). (Ref. 2-10)

The equation developed empirically by Nelms is:

$$t_{req} = (W/S_u)^{0.71}$$

where:

t_{req} = outer shell thickness required (inch)
W = weight of the cask (lbs)
S_u = tensile strength of the outer shell (psi)

For the VHLW cask overpack,

$$t = 1.5 \text{ inch}$$
$$W = 55{,}000 \text{ lbs}$$
$$S_u = 70{,}000 \text{ psi}$$

Therefore:

$$t_{req} = (55{,}000/70{,}000)^{0.71} = 0.8426 \text{ in.}$$

The outer shell thickness of this cask is 1.5 inch which is sufficient to satisfy the Nelms expression.

In addition to the empirical Nelms equation the stresses resulting from the drop are estimated as follows:

The maximum load a 6 inch diameter mild steel bar can exert on the package is:

$$A = \text{area of steel bar}$$
$$F_{max} = 45{,}000 \times \pi \times 6^2/4 = 1.26 \times 10^6 \text{ lbs}$$

The deceleration, $a = 1.26 \times 10^6 / 55{,}000 = 22.9$ g's

The maximum bending moment in the cask, assuming the cask acts as a beam, is:

$$M = w\,\ell^2 / 8$$
$$w = \text{uniform load} = 55{,}000 / 139 = 395.7 \text{ lb/in}$$
$$= 9{,}061.5 \text{ lb/in for } 22.9 \text{ g's}$$
$$M = 9{,}061.5 \times 139^2 / 8$$
$$= 2.19 \times 10^7 \text{ in-lb}$$

The section modulus of the outer shell of the cask is:

$$Z = \pi/4 \times (R_o^4 - R_i^4) / R_o$$
$$R_o = \text{outer radius} = 22.5 \text{ inch}$$
$$R_i = \text{inner radius} = 21.5 \text{ inch}$$
$$Z = \pi \times (22.5^4 - 21.5^4) / (4 \times 22.5) = 1{,}487.5$$
$$\sigma_{bend} = 2.19 \times 10^7 / 1{,}487.5 = 14{,}723 \text{ psi} << 25{,}000 \text{ psi (Yield Strength)}$$

2.7.2.2 Ends

The thicknesses of the baseplate is 2", which are much larger than required thickness of 0.8426 inch to satisfy the Nelm's equation.

2.7.3 Thermal

2.7.3.1 Summary of Pressures and Temperatures

The maximum temperatures and pressures resulting from the hypothetical accident conditions presented in section 3.5.4 and Table 3.1 are summarized as follows:

(1) Maximum overpack pressure = 40.4 psia
(2) Temperatures:

- Barrel Outside Surface 1,280° F
- Barrel Inside Surface 1,270° F
- Seal Area 275° F

2.7.3.2 Differential Thermal Expansion

Differential thermal expansion between various components of the VHLW cask package and the temperature gradient produce significant stresses. Section 2.10.3.2 conservatively evaluates the stresses due to the fire accident.

2.7.3.3 Stress Calculations

The ANSYS (Reference 2-11) finite element model of the VHLW overpack, as described in Section 2.10.3, was also used to evaluate stresses in the cask due to the fire accident. Appropriate temperature and pressures were applied at corresponding finite element faces to represent the largest loading the overpack will experience under such conditions. Table 2.10.3-1 summarizes the pressure stresses, in the overpack. The combined (thermal and pressure) stress intensity plot is shown in Figure 2.10.3-3. A maximum stress intensity of 28,347 psi (see Figure 2.10.3-3) results in the flange at the bolt locations. This is caused mainly by the bolt preload as well as due to the differential thermal expansion between the stainless steel overpack and carbon steel bolts. The allowable stress for this loading is $3S_m = 3 \times 16{,}700 = 50{,}100$ psi. Therefore, a factor of safety of 50,100/28,347 = 1.77 exists in the design against the hypothetical fire accident conditions.

2.7.4 Water Immersion - Fissile Material

The requirement of 10 CFR 71.73 (c) (4) is not applicable, since VHLW package does not carry fissile material.

2.7.5 Water Immersion - All Packages

10 CFR 71.73 (c) (5) requires an immersion in water with a pressure of 21 psig for eight hours. Review of the stresses summarized in Table 2.10.3-1 for a 21 psig pressure indicates the stresses are low, and this test will have no significant effect on the package.

2.7.6 Summary of Damage

The structural integrity of the VHLW package has been demonstrated, by analytical models, to be maintained during the hypothetical accident conditions. The condition of the package after the hypothetical accident is:

(1) Impact limiters are crushed during the 30 foot drop condition. Cask stresses are less than those prescribed by NRC Regulatory Guide 7.6.

(2) Small local deformations to the overpack shell may result from the 40 inch puncture condition. There will be no loss of shielding and the containment vessel will not be deformed.

Table 2-12 summarizes the maximum Primary Stresses during the hypothetical accident conditions.

2.8 Special Form - Not Applicable

2.9 Fuel Rods - Not Applicable

TABLE 2-1
SUMMARY OF NORMAL AND ACCIDENT CONDITION LOADING[1]

Normal or Accident Condition	Ambient Temp. (°F)	Actual Pressure (psia)		Equivalent Pressure (psig)		Comments
		Internal	External	Internal	External	
NORMAL CONDITION						
Hot Environment	100	28.6[2]	14.7	13.9	0	Analyzed for int. press. of 26 psi
Cold Environment	-40	28.6	14.7	13.9	0	Analyzed for int. press. of 26 psi
Increased External Pressure (20 psia)	-20	0	20	0	20	Analyzed for ext. press. of 21 psi
Minimum External Pressure (3.5 psia)	100	28.6	3.5	25.1	0	Analyzed for int. press. of 26 psi
Free Drop (1 ft.)	100	28.6	14.7	13.9	0	This condition results in the largest Primary and Secondary S.I. for normal condition.
ACCIDENT CONDITION						
Free Drop (30 ft.)	100	28.6	14.7	13.9	0	This condition results in the largest Primary and Secondary S.I. for accident condition.
Puncture (40 in.)	100	28.6	14.7	13.9	0	Analyzed for int. press. of 26 psi
Fire	1475	40.4	14.7	25.7	0	This condition results in the largest Secondary S.I. for accident condition.
Immersion	100	0	21	0	21	Analyzed for ext. press. of 21 psi

NOTE: (1) These loading combinations are derived from the NRC Regulatory Guide 7.8, July, 1987.
(2) Determined in Section 3.4.

TABLE 2-2
ALLOWABLE STRESS INTENSITIES FOR VARIOUS STRESS CATEGORIES

Stress Category	Allowable Stresses, Other than Bolting		Allowable Stresses, Bolting	
	Normal Conditions	Accident Conditions	Normal Conditions	Accident Conditions
Primary Membrane	S_m	Lesser of: 2.4 S_m 0.7 S_u	Lesser of: 2.0 S_m 1.0 S_y	S_y
Primary Membrane + Primary Bending	1.5 S_m	Lesser of: 3.6 S_m 1.0 S_u	Lesser of: 3.0 S_m 1.0 S_y	S_u
Range of Primary + Secondary	3 S_m	NA	NA	NA
Bearing	S_y	S_y Containment Boundary S_u Elsewhere	S_y	S_y
Pure Shear	0.6 S_m	0.42 S_u	1.2 S_m	Lesser of: 0.6 S_y 0.42 S_u

NOTES: (1) Based on Regulatory Guide 7.6 requirements.
(2) Based on ASME B&PV, Section III Div.1 requirements.

TABLE 2-3
MATERIAL PROPERTIES OF THE MATERIALS USED IN VHLW PACKAGE

Material Specification	Grade or Type	Temperature (°F)	Yield Stress, S_y (psi)	Ultimate Strength, S_u (psi)	Membrane Stress Allowable, S_m (psi)	Young's Modulus, E (psi)	Coeff. of Thermal Expansion, α (in/in)
SA-240[1]	Type 304L	-20	25,000	70,000	16,700	28.7×10^6	-
		100	25,000	70,000	16,700	28.1×10^6	8.55×10^{-6}
		200	21,400	66,200	16,700	27.6×10^6	8.79×10^{-6}
		300	19,200	60,900	16,700	27.0×10^6	9.00×10^{-6}
SA-516[1]	Grade 60	-20	38,000	70,000	23,300	29.9×10^6	-
		100	38,000	70,000	23,300	29.3×10^6	6.50×10^{-6}
		200	34,600	70,000	23,100	28.8×10^6	6.67×10^{-6}
		300	33,700	70,000	22,500	28.3×10^6	6.87×10^{-6}
SA-193[1]	Gr. B7	-20	75,000	-	35,000	30.0×10^6	-
		100	75,000	100,000	35,000	29.5×10^6	5.73×10^{-6}
		200	69,900	-	32,600	29.0×10^6	6.09×10^{-6}
		300	67,200	-	31,400	28.5×10^6	6.43×10^{-6}
ASTM A-874[2][3]	-	70	29,000	32,900	8,225	25.0×10^6	-
		200	27,900	31,700	7,925	-	6.46×10^{-6}
		400	24,300	30,700	7,675	-	6.72×10^{-6}
		500	22,700	25,900	6,475	-	6.85×10^{-6}

NOTES: (1) From ASME B&PV Code, Section II, 1992 Edition.
(2) Ductile Iron is not considered as a structural element. Its properties have been obtained from the German data, reported in the CASTOR V/21 Cask SAR.

TABLE 2-4
PRIMARY STRESS INTENSITY ALLOWABLES FOR VHLW CASK PACKAGE

Material	Component	S_m (psi)	S_y (psi)	S_u (psi)	Normal Conditions (psi)		Accident Conditions (psi)	
					Membrane	Membrane + Bending	Membrane	Membrane + Bending
SA-240 Grade 304L	Overpack	16,700	21,400	66,200	16,700	25,050	40,000	60,120
SA-516 Grade 70	Attachments	23,100	34,600	70,000	23,100	34,650	49,000	70,000
A-874	Cask	7,925	27,900	31,700	7,925	11,888	19,020	28,530
SA-193 Grade B7	Bolts	32,600	69,900	100,000	65,200	69,900	69,900	100,000

NOTES:
(1) See Table 2-2 for the basis of stress allowables.
(2) The stress intensity allowables are calculated on 200°F.

Table 2-5
STRESS-STRAIN PROPERTIES OF GENERAL PLASTICS' 17 LB/FT^3 FOAM

Temperature	Strain (%)									
	10	20	30	40	50	60	65	70	75	80
Stress Parallel to Rise Direction										
-20°F	1,175	1,213	1,298	1,475	1,829	2,626	3,384	4,483	6,600	11,395
75°F	878	911	985	1,127	1,400	2,021	2,642	3,500	5,356	8,906
100°F	756	795	866	996	1,249	1,824	2,396	3,382	5,210	9,432
Stress Perpendicular to Rise Direction										
-20°F	1,172	1,234	1,312	1,477	1,814	2,589	3,291	4,258	6,523	12,490
75°F	879	924	993	1,115	1,394	2,008	2,614	3,559	5,216	8,669
100°F	738	789	859	982	1,222	1,778	2,316	3,222	4,889	8,826

GENERAL NOTES:

(1) Source: General Plastics Last-A-Foam FR 3700 Technical Manual.

(2) The compressive stress at any temperature can be expressed as:

$$\sigma = A\ (\text{density})^B$$

A and B as a function of strain are presented by General Plastics in table forms for various temperatures.

TABLE 2-6
RESULT OF THE CASKDROP ANALYSIS
FOR 1-FOOT DROP OF THE VHLW CASK

Drop Orientation	I.L. at -20°F		I.L. at 75°F		I.L. at 100°F	
	Decelerat ion g's	Crush Inch	Deceleration g's	Crush inch	Deceleration g's	Crush inch
End (Top Down)	15.8	2.0	13.7	2.2	12.8	2.4
End (Bottom Down)	24.3	1.3	20.9	1.5	19.5	1.6
Side	13.6	2.44	11	2.82	10.1	3.02
Corner (Top Down)	9.6	5.34	7.2	8.97	7.2	9.79
Corner (Bottom Down)	8.9	5.48	8.4	4.76	6.9	7.54

TABLE 2-7
STRESS INTENSITY IN THE VHLW OVERPACK UNDER 1-FOOT DROP LOADING

Component	Stress Category	Stress Intensity, psi				
		1′ End Drop Top Down	1′ End Drop Bottom Down	1′ Side Drop	1′ Corner Drop Top Down	1′ Corner Drop Bottom Down
Endplate	Membrane	337	35	897	1,186	705
	Membrane + Bending	1,511	766	5,122	4,629	5,025
Barrel	Membrane	1,216	1,937	1,350	1,419	720
	Membrane + Bending	5,081	3,882	6,381	2,826	6,618
Outer Cover	Membrane	173	1,536	2,637	621	2,323
	Membrane + Bending	1,260	3,252	8,272	1,144	5,995
Annular Ring	Membrane	92	1,000	1,712	1,708	2,999
	Membrane + Bending	1,087	2,743	5,908	1,843	5,081
Baseplate	Membrane	3,370	3,386	984	2,130	1,485
	Membrane + Bending	11,284	11,819	4,014	7,649	6,654

GENERAL NOTES: (1) The stress intensities in this table are obtained by factoring the stress intensities for 30′ drop, reported in Table 2-11 by deceleration ratios corresponding to the drop orientation.

TABLE 2-8
MAXIMUM MEMBRANE STRESS INTENSITIES AND FACTORS OF SAFETY UNDER NORMAL LOADING CONDITIONS

Loading Condition	Stress Intensity in the Overpack Component, psi				
	Endplate	Barrel	Outer Cover	Annular Ring	Baseplate
1′ End Drop (Top Down)	337	1,216	173	92	3,370
1′ End Drop (Bottom Down)	35	1,937	1,536	1,000	3,386
1′ Side Drop	897	1,350	2,637	1,712	984
1′ Corner Drop (Top Down)	1,186	1,419	621	1,708	2,130
1′ Corner Drop (Bottom Down)	705	720	2,323	2,999	1,485
1′ Drop (Maximum)	1,186	1,937	2,637	2,999	3,386
Max. Internal Pressure (26 psi)	7,309	1,013	791	218	2,435
Max. External Pressure (21 psi)	5,920	828	808	149	1,266
1′ Drop (max.) + Max. Internal Pressure	8,495	2,950	3,428	3,217	5,821
1′ Drop (max.) + Max. External Pressure	7,106	2,765	3,445	3,148	4,652
Maximum Stress Intensity	8,495	2,950	3,445	3,217	5,821
Allowable Stress Intensity	16,700	16,700	16,700	16,700	16,700
Factor of Safety	1.97	5.66	4.85	5.19	2.87

TABLE 2-9
MAXIMUM MEMBRANE + BENDING STRESS INTENSITIES AND FACTORS OF SAFETY UNDER NORMAL LOADING CONDITIONS

Loading Condition	Stress Intensity in the Overpack Component, psi				
	Endplate	Barrel	Outer Cover	Annular Ring	Baseplate
1′ End Drop (Top Down)	1,511	5,081	1,260	1,087	11,284
1′ End Drop (Bottom Down)	766	3,882	3,252	2,743	11,819
1′ Side Drop	5,122	6,381	8,272	5,908	4,014
1′ Corner Drop (Top Down)	4,629	2,826	1,144	1,843	7,649
1′ Corner Drop (Bottom Down)	5,025	6,618	5,995	5,081	6,654
1′ Drop (Maximum)	5,122	6,618	8,272	5,908	11,819
Max. Internal Pressure (26 psi)	11,532	5,136	2,015	416	4,550
Max. External Pressure (21 psi)	9,292	4,136	1,242	351	2,518
1′ Drop (max.) + Max. Internal Pressure	16,654	11,754	10,287	6,324	16,369
1′ Drop (max.) + Max. External Pressure	14,414	10,754	9,514	6,259	14,337
Maximum Stress Intensity	16,654	11,754	10,287	6,324	16,369
Allowable Stress Intensity	25,050	25,050	25,050	25,050	25,050
Factor of Safety	1.5	2.13	2.44	3.96	1.53

TABLE 2-10
RESULT OF THE CASKDROP ANALYSIS
FOR 30-FOOT DROP OF THE VHLW CASK

Drop Orientation	I.L. at -20°F		I.L. at 75°F		I.L. at 100°F	
	Deceleration g's	Crush Inch	Deceleration g's	Crush inch	Deceleration g's	Crush inch
End (Top Down)	38.4	13.9	39.3	16.6	40.5	17.8
End (Bottom Down)	59.8	8.0	50.2	9.9	48.6	10.9
Side	69.5	12.2	84.1	13.6	93.5	14.2
Corner (Top Down)	37.7	24.5	37.7	27.4	41.3	28.5
Corner (Bottom Down)	47.6	19.8	46.7	22.2	48.8	23.1

TABLE 2-11
STRESS INTENSITY IN THE VHLW OVERPACK UNDER 30-FOOT DROP LOADING

Component	Stress Category	Stress Intensity, psi				
		30′ End Drop Top Down	30′ End Drop Bottom Down	30′ Side Drop	30′ Corner Drop Top Down	30′ Corner Drop Bottom Down
Endplate	Membrane	865	86	6,170	5,101	3,034
	Membrane + Bending	3,872	1,885	35,217	19,914	21,618
Barrel	Membrane	3,118	4,767	9,284	6,104	3,098
	Membrane + Bending	13,025	9,553	43,872	12,156	28,470
Outer Cover	Membrane	443	3,781	18,130	2,673	9,993
	Membrane + Bending	3,231	8,003	56,867	4,922	25,789
Annular Ring	Membrane	235	2,460	11,770	7,348	12,900
	Membrane + Bending	2,786	6,751	40,681	7,928	21,859
Baseplate	Membrane	8,638	8,332	6,764	9,165	6,388
	Membrane + Bending	28,925	29,086	27,593	32,907	28,624

TABLE 2-12
MAXIMUM MEMBRANE STRESS INTENSITIES AND FACTORS OF SAFETY UNDER HYPOTHETICAL ACCIDENT LOADING CONDITIONS

Loading Condition	Stress Intensity in the Overpack Component, psi				
	Endplate	Barrel	Outer Cover	Annular Ring	Baseplate
30′ End Drop (Top Down)	865	3,118	443	235	8,638
30′ End Drop (Bottom Down)	86	4,767	3,781	2,460	8,332
30′ Side Drop	6,170	9,284	18,130	11,770	6,764
30′ Corner Drop (Top Down)	5,101	6,104	2,673	7,348	9,165
30′ Corner Drop (Bottom Down)	3,034	3,098	9,993	12,900	6,388
30′ Drop (Maximum)	6,170	9,284	18,130	12,900	9,165
Max. Internal Pressure (26 psi)	7,309	1,013	791	218	2,435
Max. External Pressure (21 psi)	5,920	828	808	149	1,266
30′ Drop (max.) + Max. Internal Pressure	13,479	10,297	18,921	13,118	11,600
30′ Drop (max.) + Max. External Pressure	12,090	10,112	18,938	13,049	10,431
Maximum Stress Intensity	13,479	10,297	18,938	13,118	11,600
Allowable Stress Intensity	40,000	40,000	40,000	40,000	40,000
Factor of Safety	2.97	3.88	2.11	3.05	3.45

TABLE 2-13
MAXIMUM MEMBRANE + BENDING STRESS INTENSITIES AND FACTORS OF SAFETY UNDER HYPOTHETICAL ACCIDENT LOADING CONDITIONS

Loading Condition	Stress Intensity in the Overpack Component, psi				
	Endplate	Barrel	Outer Cover	Annular Ring	Baseplate
30′ End Drop (Top Down)	3,872	13,025	3,231	2,786	28,925
30′ End Drop (Bottom Down)	1,885	9,553	8,003	6,751	29,086
30′ Side Drop	35,217	43,872	56,867	40,681	27,593
30′ Corner Drop (Top Down)	19,914	12,146	4,922	7,928	32,907
30′ Corner Drop (Bottom Down)	21,618	28,470	25,789	21,859	28,624
30′ Drop (Maximum)	35,217	43,872	56,867	40,681	32,907
Max. Internal Pressure (26 psi)	11,532	5,136	2,015	416	4,550
Max. External Pressure (21 psi)	9,292	4,136	1,242	351	2,518
30′ Drop (max.) + Max. Internal Pressure	46,749	49,008	58,882	41,097	37,457
30′ Drop (max.) + Max. External Pressure	44,509	48,008	58,109	41,032	35,425
Maximum Stress Intensity	46,749	49,008	58,882	41,097	37,457
Allowable Stress Intensity	60,120	60,120	60,120	60,120	60,120
Factor of Safety	1.29	1.23	1.02(1)	1.46	1.61

NOTES: (1) The stress in this component is local in nature, which subsides quickly with distance (see Figure 2.10.2-18 for the contour plot). This stress intensity is conservatively classified as membrane + bending.

Table 2-14
BOLT LOADS DURING HYPOTHETICAL FREE DROP CONDITIONS

Condition	FEM Axial Load, lbs	Preload lbs	Max. Axial Load, lbs	Axial Stress psi	F.S. on Axial Stress(1)	Shear Stress psi	F.S. on Shear Stress(2)	Combined Ratio(3)
End (Top Down)	15,121	27,000	27,000	44,554	1.65	0		0.406
End (Bottom Down)	12,416	27,000	27,000	44,554	1.65	0		0.406
Side	15,350	27,000	27,000	44,554	1.65	20,201	2.079	0.638
Corner (Top Down)	10,770	27,000	27,000	44,554	1.65	5,036	8.340	0.421
Corner (Bottom Down)	13,515	27,000	27,000	44,554	1.65	28,069	1.496	0.853

NOTES: (1) Factor of safety on axial stress is equal to the axial stress allowable (69,900 psi) divided by the applied axial stress.
(2) Factor of safety on shear stress is equal to the shear stress allowable (42,000 psi) divided by the applied shear stress.
(3) For combined stress definition see section 2.1.2.1.

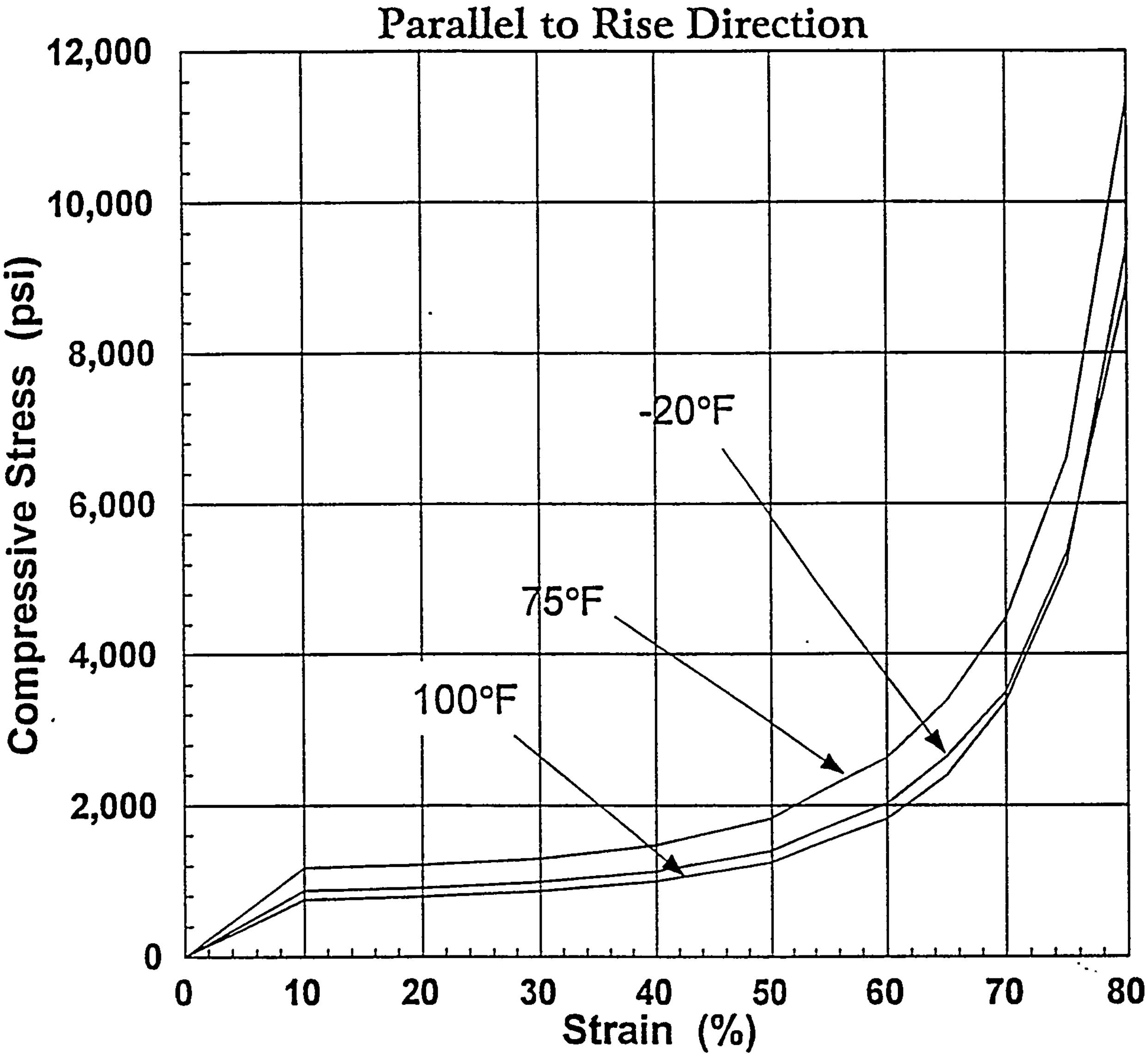


Figure 2-1
Polyurethane Foam Stress-Strain Property
Parallel to Rise Direction

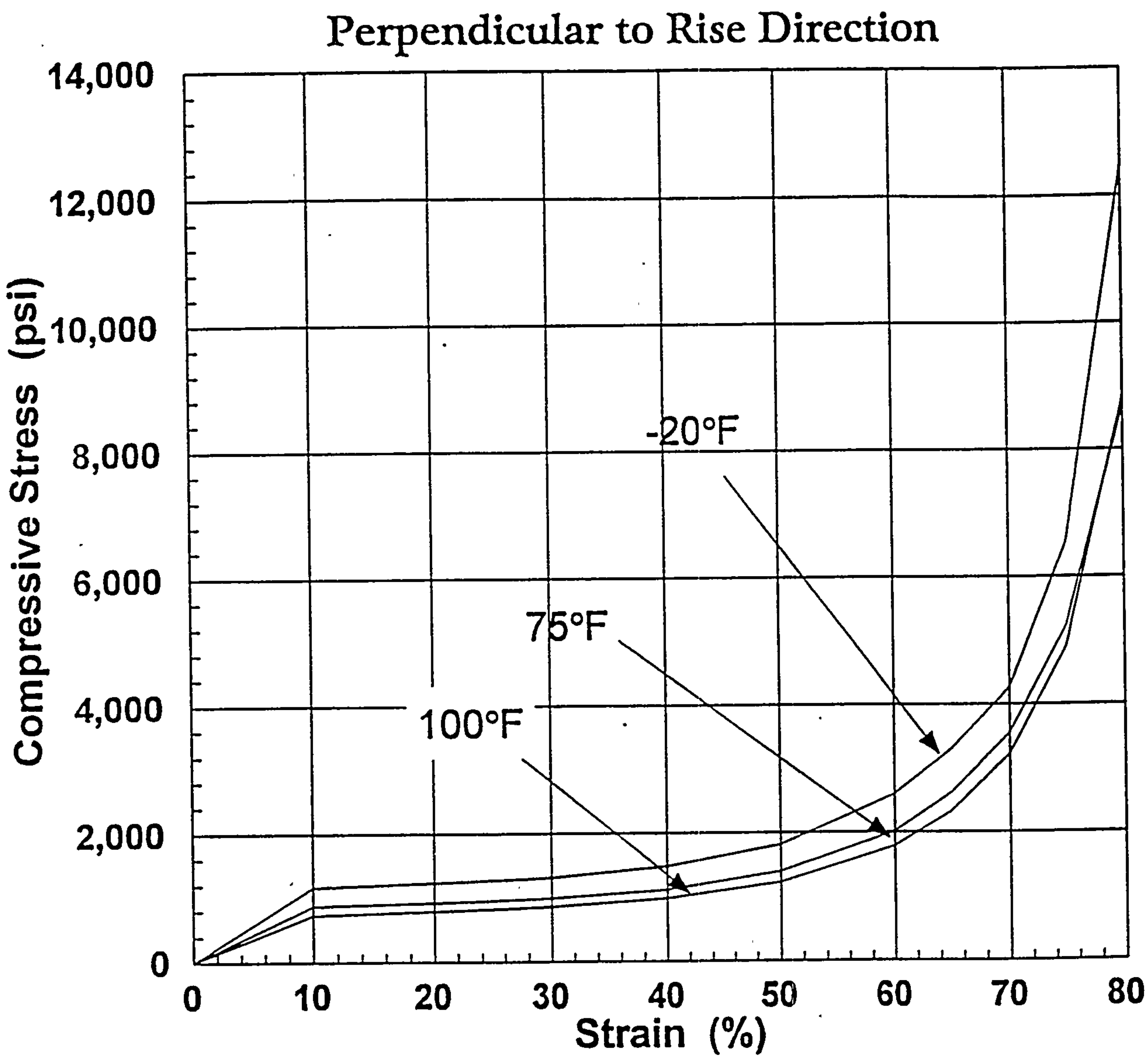


Figure 2-2
Polyurethane Foam Stress-Strain Property
Perpendicular to Rise Direction

2.10 Appendix

2.10.1 Analytical Methods

2.10.1.1 General Discussion on Foam Impact Limiter

A short discussion of the analytical methods used to evaluate the cask during the drop conditions is provided in this section. The most significant assumption is the use of a quasi-static model wherein the energy absorbing impact limiter is analyzed separately from the cask. The cask is initially assumed rigid in order to determine the maximum loads imposed on it. These maximum loads are applied statically to the cask to permit evaluation of the stresses in the cask. This uncoupled assumption is a realistic approach since most of the impact energy is absorbed by the impact limiter. The impact limiter's design criteria is specifically selected to justify this uncoupled analysis.

The rigid foam impact limiters are designed to absorb all the energy of the drop. No energy is absorbed by the unyielding surface or by deformation of the cask. The analytical methods used to predict the impact limiter's behavior in the end, side, and corner drops are similar. The impact limiter's behavior is determined from the following energy equation:

$$E = W \times (h + \delta) = \int F\, dx$$

where:

W	=	package weight
h	=	drop height
δ	=	maximum impact limiter deformation
F	=	total force developed by the impact limiter at deformation dx
dx	=	incremental displacement of the foam

This equation is solved in all three drop orientations. The only difference among the three orientations is the calculation of the total force for the different crushed foam geometries.

Chem-Nuclear Systems has developed a computer program CASKDROP (References 2-6, 2-7, & 2-8) to solve this equation for all three drop orientations. This program accounts for the non-linear stress-strain relationship of the foam. The actual stress-strain values (see Figures 2-1 and 2-2) for the foam properties used are input to the program.

The foam stress-strain relation given in Figures 2-1 and 2-2 show the primary variation of <u>stress</u> as a function of <u>strain</u> for 17 lb/ft^3 density polyurethane foam used in the VHLW cask impact limiters. This simplified constitutive relation, <u>alone</u> has proven to be sufficiently accurate to be used for the design and certification of several recent Type B packages, among them the T-3 [USA/9132/B(M)F], CNS 1-13C II [USA/9152/B()], and CNS 10-160B [USA/9204/B(U)]. Variations with thickness, or other geometric aspects, such as the influence of "backing", enter the stress (and load) prediction problem as factors dictating the state of strain at a particular point within the impact limiter. Given that particular strain at a point within the limiter, the state of crush stress is strictly governed by the relation shown in Figures 2-1 and 2-2.

Of note, the literature documents the variation of crush stress with two "second-order" variables, namely; temperature and strain-rate, see References 2-12, 2-13, 2-14, & 2-15. Temperature effects are accounted for in the analyses by using the stress-strain data at three different temperatures; extreme cold conditions (-20°F), normal operating conditions (75°F) and the extreme hot conditions (100°F).

Strain-rate stiffening effects are traditionally ignored in package design. In general, the effect of strain rate stiffening is to significantly increase the energy absorption margin of safety while simultaneously slightly increasing deceleration loads causing a slight reduction in load margins of safety. This due to the fact that "energy absorbed" relates the total area under the long, nearly constant stress plateau from 5% to 60% strain; whereas, "peak loads" relates to the strain hardening regime beyond 60% strain, where strain-rate effects disappear. The net effect of neglecting strain-rate effects can thus be shown to be "conservative".

2.10.1.2 Cask Drop Computer Model

The following discussion presents the techniques used in the CASKDROP program to evaluate the three drop orientations. The primary variations are (1) the geometrical evaluations used to evaluate the crushed foam portions, and (2) the means of evaluating the crushing effectiveness of the various geometrical regions. The CASKDROP program divides the crushed foam portions into grids of up to 100 rectanguloid solids and iterates on 2% increments of material strain up to a predetermined limit (80 percent -- see Section 2.1.2.4). The effectiveness relates to whether the foam volume is backed by the cask body or is unbacked.

A constant multiplier is utilized for crushing effectiveness, wherein 1.0 equates to full backing and 0.0 is unbacked. The foam properties (see Figures 2-1 and 2-2) are input into the program at 1% increments of strain.

2.10.1.2.1 End Drop Model

The CASKDROP code calculates the total force, at a given displacement of the impact limiter, with an equation of the following general form:

$$F = K_1 A_1 \sigma_1 + K_2 A_2 \sigma_2$$

where:

A_1, A_2	=	Areas of regions 1 and 2, respectively. (See Fig. 2.10.1-1 for region definition)
σ_1, σ_2	=	Stresses in Regions 1 and 2, respectively.
K_1, K_2	=	Constants for regions 1 and 2, respectively. (1.0 for backed, 0.0 for unbacked)

The first term corresponds to the foam that is directly below the cask (backed), and the second term is the foam around the sides of the cask (unbacked), as shown in Figure 2.10.1-1.

The program increments the impact limiter deformation until the impact energy is totally absorbed. The maximum force and g load are determined from the impact limiter force at the last displacement increment after all the energy has been absorbed. This load is applied to the cask as an inertia load, as described in Section 2.10.2-1.

2.10.1.2.2 Side Drop Model

The procedure for calculating the force in the side drop is slightly different than the end drop. The strain and stress vary with X as shown in Figure 2.10.1-2. The total force is the integration of the stress times the contributing area at a point.

The geometrical parameters are shown in Figure 2.10.1-2. In addition, the user can control the effectiveness of the regions shown in Figure 2.10.1-3. Control of these regions allows the user to bound the behavior of the impact limiter. Control of the backed and unbacked regions, variation of foam stiffness properties, and other parameters with the CASKDROP code allows the user to conservatively bound the behavior of the impact limiter.

The side drop calculation results in forces, or pressures, on contributing areas as a function of X as shown in Figure 2.10.1-2.

Once the maximum load developed by the impact limiter on the cask has been determined, the load is applied statically to the cask, and resisted by the deceleration inertia of the cask and contents. It should be noted that bounding assumptions are used to conservatively bound the uncertainties of the impact limiter's behavior.

2.10.1.2.3 Corner Drop

The corner drop method is very similar to the side drop, except the strains, stresses and forces on the cask are calculated on a two dimensional grid shown in Figure 2.10.1-4.

At each iteration, or displacement of the impact limiter, the program calculates strain, stress and force at each grid point. The displacement is incremented until all the energy of the drop is absorbed. The forces and pressures on the grid area corresponding to the last iteration are printed by the program.

The corner drop portion of the code also allows the user to selectively control the effectiveness of different regions of the impact limiter. The regions for the VHLW cask at an impact angle where the cask corner is over the center of gravity are shown in Figure 2.10.1-5.

The vertical loading on the cask is according to the following equation, which assumes the impact limiter and the cask are uncoupled and rigid.

$$F_T = M_c\, a_c + M_p\, a_p + M_{UIL}\, a_{UIL}$$

where,

F_T	=	Total lower impact limiter load on the cask
M_c	=	Mass of the cask
M_p	=	Mass of the payload
M_{UIL}	=	Mass of the upper impact limiter
a_c	=	Acceleration of cask
a_p	=	Acceleration of payload
a_{UIL}	=	Acceleration of upper impact limiter

For a static analysis $a_c = a_p = a_{UIL}$, therefore:

$$F_T = (M_c + M_p + M_{UIL})\, a_c$$

The acceleration of the cask a_c, is determined with the following equation:

$$a_c = \frac{F_T}{M_c + M_p + M_{UIL}}$$

It should be noted that the mass of the lower impact limiter is conservatively neglected. The F_T value calculated by the CASKDROP code does include the inertia loads of the lower impact limiter. Therefore, the acceleration in this equation is conservatively calculated.

The angle of impact is selected so that the center of pressure of the inertia loads is directly over the center of pressure of the impact limiter loads at the maximum load. This results in no net moment applied to the cask and no energy transformed into rotational energy of the cask. The entire drop energy is absorbed by the lower impact limiter.

The impact limiter has two types of regions, backed and unbacked. Backed regions project vertically up to the cask body, and unbacked regions do not. Figure 2.10.1-5 illustrates backed and unbacked regions of the impact limiter.

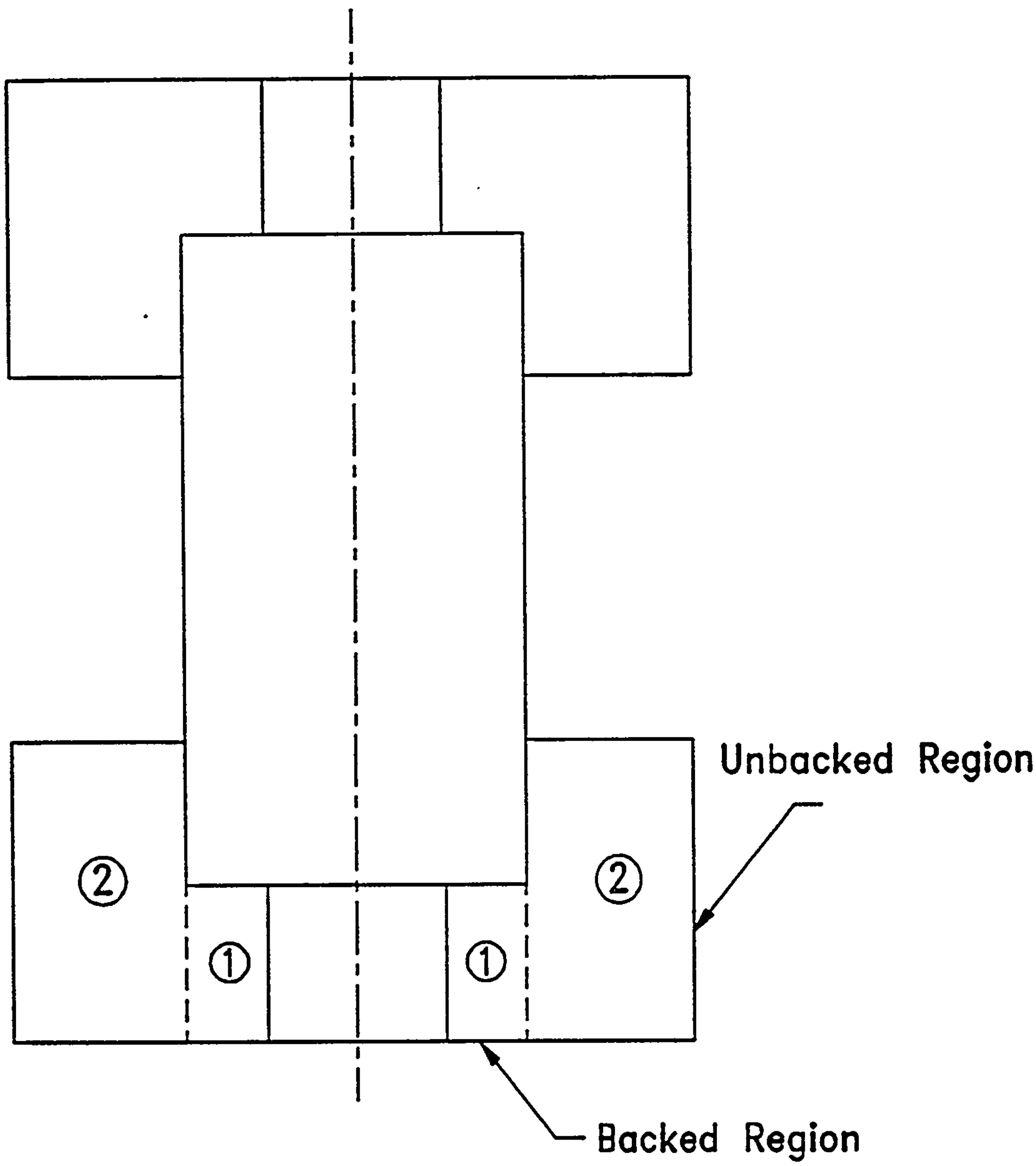


FIGURE 2.10.1-1
End Drop - Region Definition

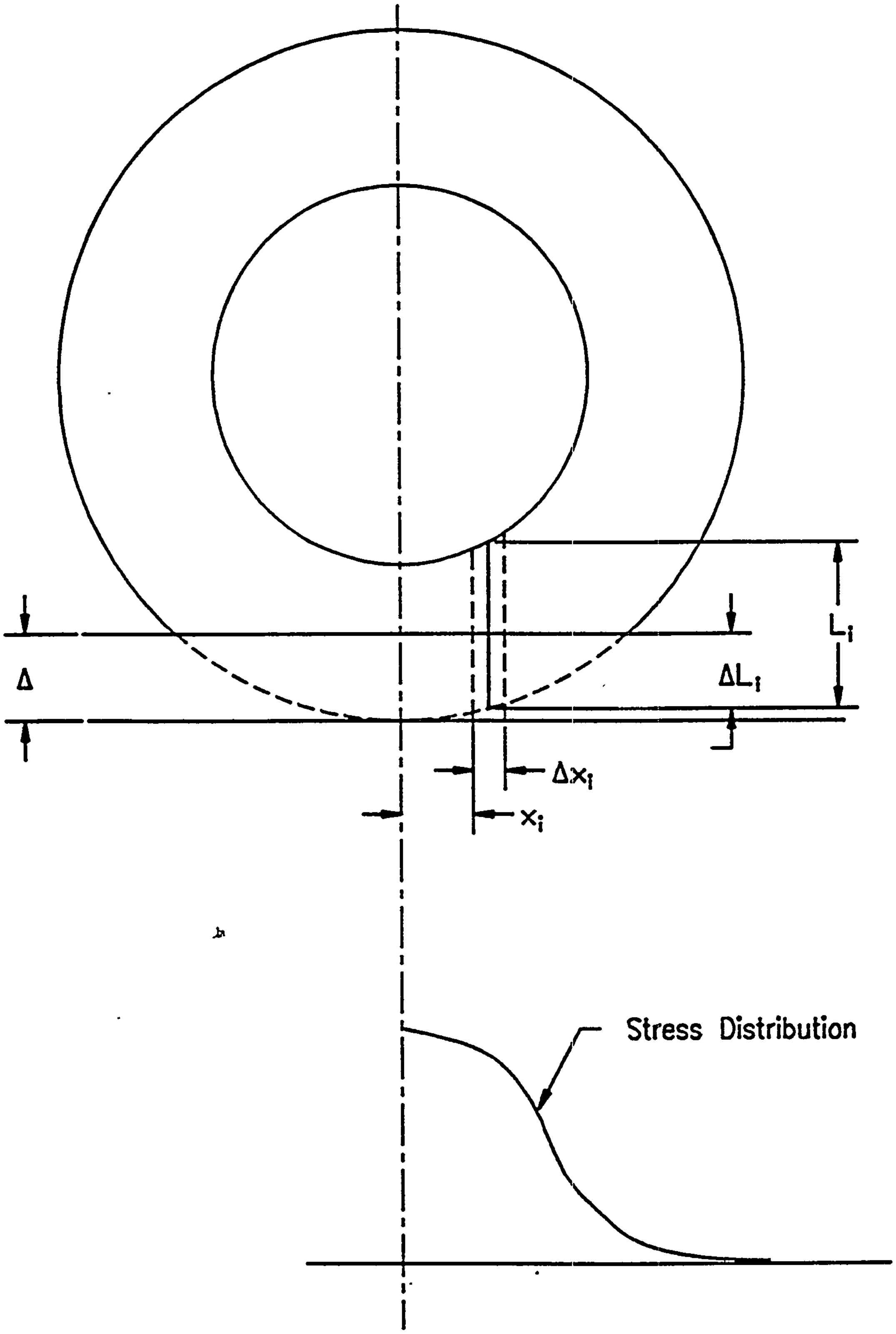


FIGURE 2.10.1-2
Side Drop Variable Definition

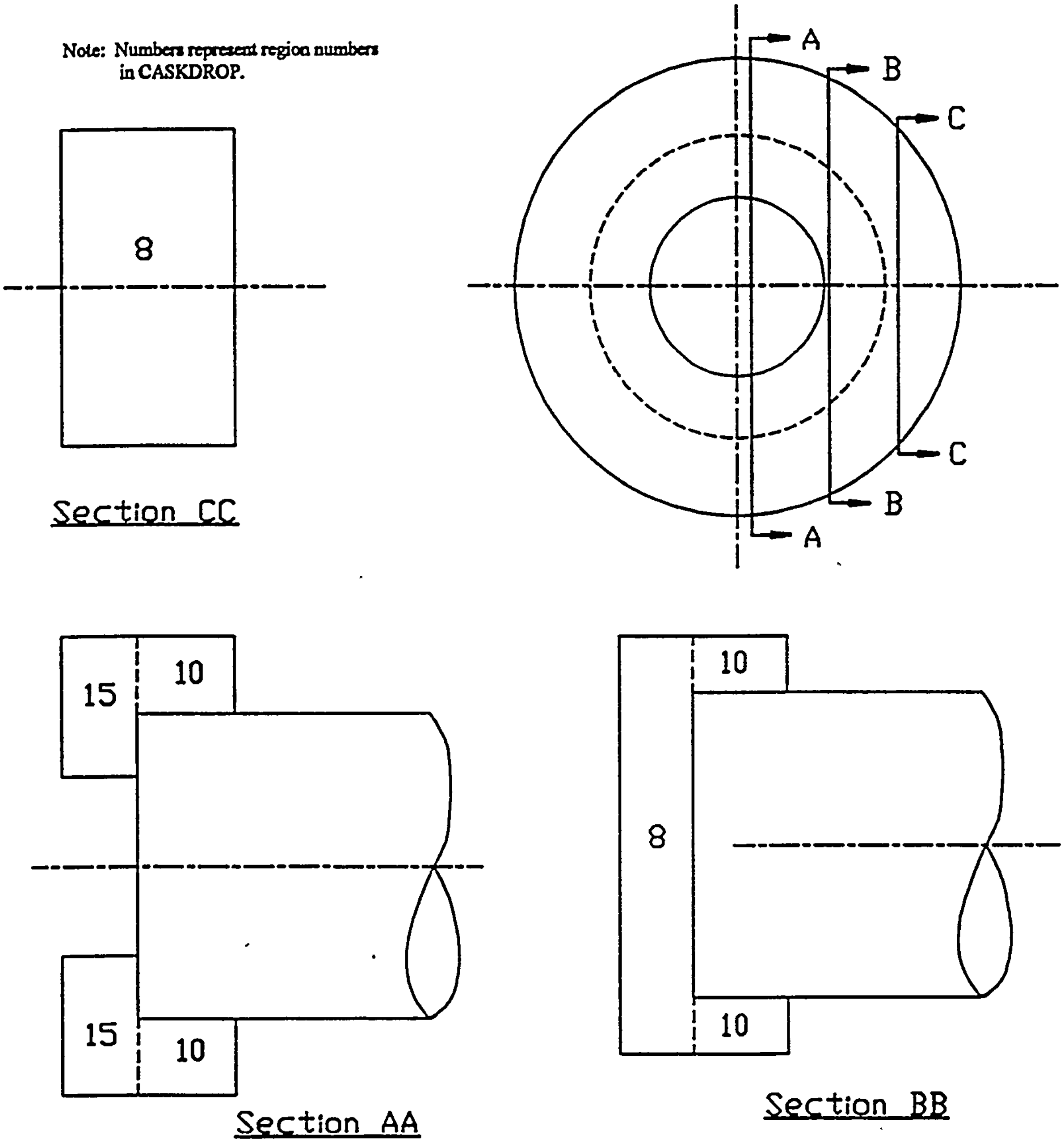


FIGURE 2.10.1-3
Side Drop - Region Definition

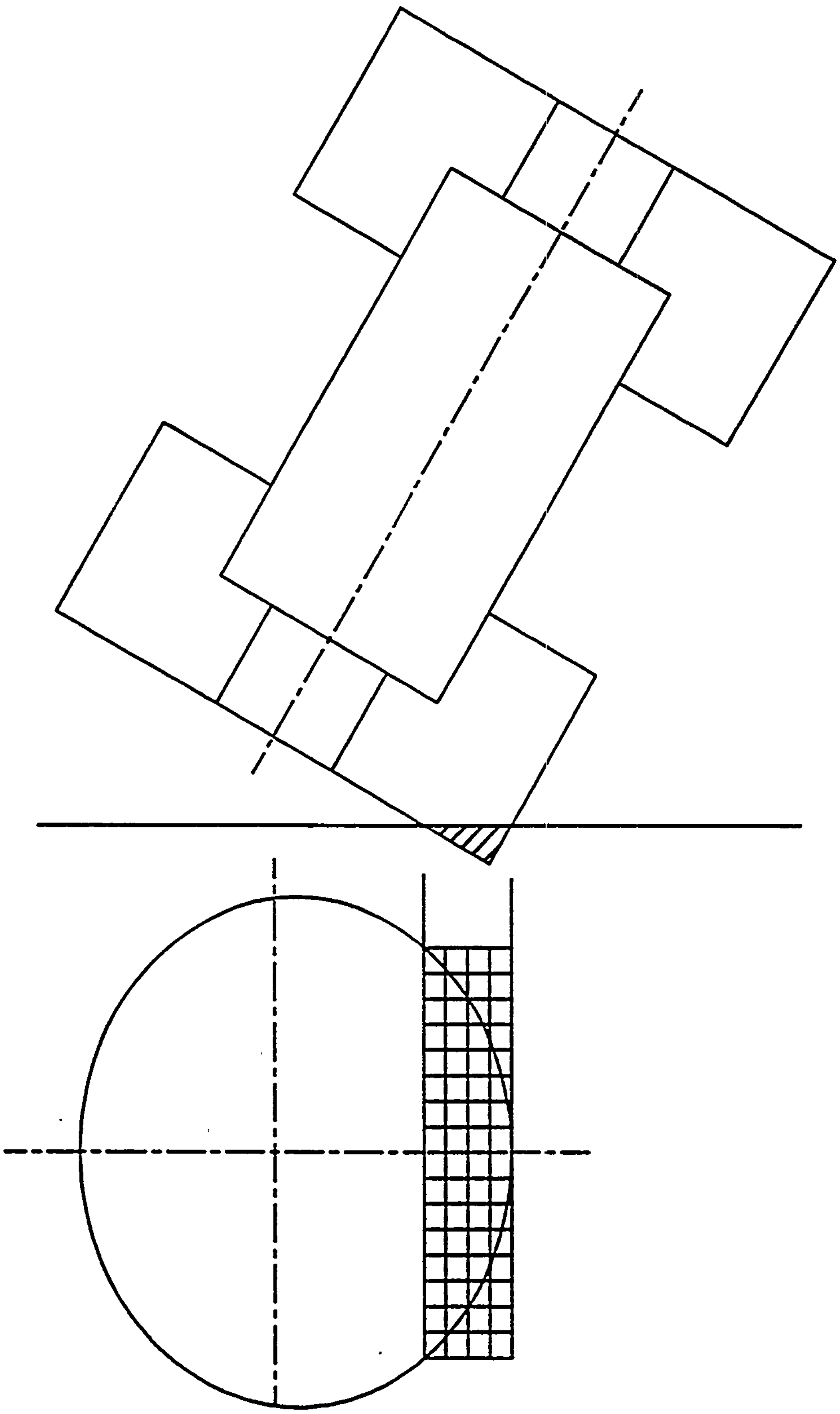


FIGURE 2.10.1-4
Corner Drop - Grid Formation

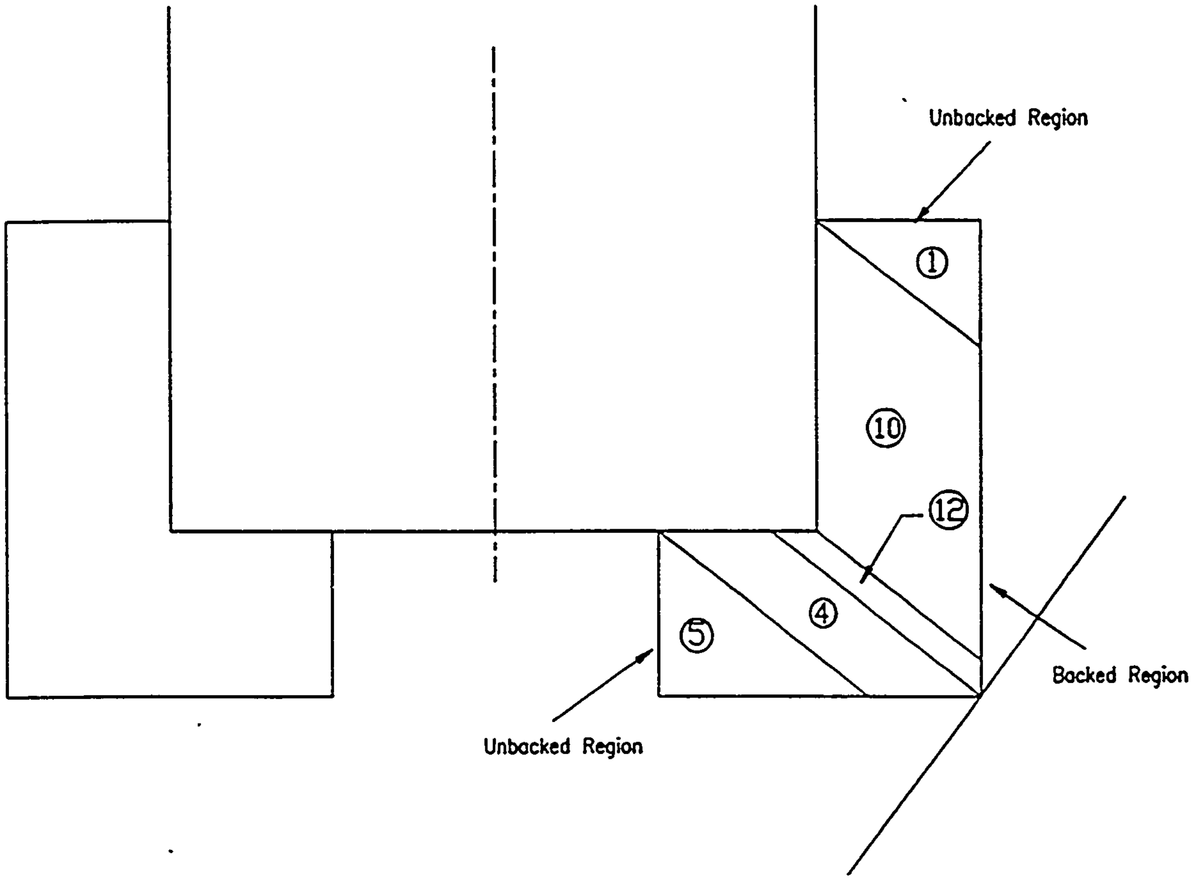


FIGURE 2.10.1-5
Corner Drop - Region Definition

2.10.2 Detailed Descriptions of Analysis

The VHLW overpack was analyzed, for all accident conditions, using the ANSYS (Ref. 2-11) general purpose finite element program. The finite element model is comprised of eight-node brick elements (STIF45) with a limited number of shell elements (STIF63) used to model the gusset plates in the bottom end torus area. A three-dimensional model is necessary due to the lack of symmetry in the geometry since gusset plates are utilized at 22.5° intervals (16 gussets around the circumference). The hold-down bolts are spaced at 22.5° intervals. The cask body is modeled using STIF45 elements. Note that there is a 0.75 inch radial gap between the inside surface of the overpack and the outer surface of the VHLW cask body. For the purposes of this analysis it is assumed that the cask is centered radially for the end drop analyses and the corner-over-C.G. analyses.

The bolts on the bottom end of the cask overpack were preloaded with 27,000 lbs each. The preload in the finite element model was initiated with the initial strain for the beam elements. The magnitude of initial strain was evaluated by a trial run. In the trial run an initial strain of 0.001 was applied to all beam elements with no other loading in the model. The axial forces in the beam elements were obtained from the analysis. Then the initial strain was linearly adjusted such that the axial force on each beam element was 27,000 lbs.

The cask was assumed to be in contact with the overpack on the impact side for the side drop calculations. Radial coupling was used to simulate contact. By coupling the corresponding nodes on the outside surface of the cask body to the nodes on the overpack inside diameter in the radial direction, the surfaces are allowed to slide (no friction) but cannot "overlap". Detailed plots showing coupled nodal pairs are included in the following sections.

It can be seen from the finite element models that the mesh is much finer along the bottom centerline. This was done to better represent the local contact and to provide more accuracy near the points of load application which are expected to be the more highly stressed locations.

The body of the VHLW cask is also represented in the finite element model. The cask is assumed to remain essentially intact during all hypothetical accident conditions. This assumption is critical to the way the loads are distributed onto the overpack. The cask body is quite rigid and will experience little deformation, thus the load from the side drop, for instance, will be essentially borne by the ends of the overpack with the cask spanning the distance between the impact limiters. The effect of the overpack stiffness is, of course, included by specifying radial coupling between the overpack and cask surface. It is shown that the stresses in the body of the shipping cask are quite low and are well below the allowable stress for the cask material.

The ANSYS finite element models are shown in Figure 2.10.2-1 and -2. Detailed specifications of the loading and restraints are described in the following sections. In all cases, the limiter and content loading were imposed on the finite element by assumed pressure distributions. In addition to the pressures, a minimal number of translational restraints were imposed on the models to prevent rigid body movement. The reaction forces at these restraints were then

checked, after the analysis run, to ensure that no substantial forces were required to restrain the model. This, in effect, verified that the pressures calculated were accurate.
A summary of the imposed loading conditions, magnitude, location and source is shown in Table 2.10.2-1.

2.10.2.1 End Drop

The end drop accident conditions are summarized in Table 2.10.2-1. Due to variations in the geometry and loading, a separate analysis was required for each end, top and bottom.

Bottom End Drop

The bottom end drop loading is shown in Figure 2.10.2-3. Uniform pressure is applied over the annular area as shown in this figure. The value of the pressure is calculated as follows.

$$P = \frac{W \times a}{A}$$

where:

W	=	Loaded weight of cask + top limiter = 51,000 lbs
a	=	Maximum deceleration, g's = 59.8 g's
A	=	Bottom annular area

$$= \frac{\pi}{4}(60.5^2 - 20^2) \qquad = 2{,}561 \text{ in}^2$$

Thus,

$$P = \frac{51{,}000 \times 59.8}{2{,}561} \qquad = 1{,}191 \text{ psi}$$

The pressure loading is shown in the ANSYS plot presented in Figure 2.10.2-4. The acceleration of 59.8g's was applied using a global acceleration command. Figure 2.10.2-5 shows the finite element model used for this analysis. The left view shows both overpack and cask while the right view shows only the overpack elements. Note that only 45° of the total cask is necessary to simulate the full 360° as the geometry is repeated periodically. Symmetry boundary conditions are utilized at the cut edges.

The cask was restrained axially at one node to prevent numerical instability. A trial run was made to determine the imbalance between the acceleration and applied pressure. The pressure was adjusted slightly based upon the reaction force so calculated and the analysis rerun. The final run was made and the reaction force was checked to assure that the unbalanced load was negligible.

The stress results are shown in Figures 2.10.2-6 through -9. The stresses in the overpack are shown in Figures 2.10.2-6 and -7. As can be seen from these figures the stresses in most parts of the cask are less than 4,000 psi. The highest stresses occur at the location where the gusset plates inside to annulus provide a stiffening effect on the bottom plate. The maximum stress intensity is 31,230 psi.

The stresses in the cask are shown in Figure 2.10.2-8 and -9. The cask body is essentially in compression everywhere. The highest stress occurs at the outside edge of the bottom end of the cask. The stress is 10,245 psi.

Top End Drop

The analysis of the thirty-foot drop onto the top end of the overpack is carried out using the same methods as described in the previous section. The only major difference in the two analyses is the deceleration which is 40.5g's for the top end impact. The pressure applied to the overpack lid can be calculated as follows:

$$P = \frac{W \times a}{A}$$

where:

W	=	Loaded weight of cask + top limiter = 51,000 lbs
a	=	Maximum deceleration, g's = 40.5 g's
A	=	Bottom annular area

$$= \frac{\pi}{4}(45^2 - 20^2) \qquad = 1,276 \text{ in}^2$$

Thus,

$$P = \frac{51,000 \times 40.5}{2,561} \qquad = 1,619 \text{ psi}$$

The loading for this case is shown in Figure 2.10.2-10. The finite element model is identical to that used for the bottom end drop with the following exceptions. First, the pressure is applied to the top of the overpack. Secondly, the cask lid is coupled axially to the overpack lid in all areas which would be in contact during the impact. The acceleration is, of course, applied in an opposite sense to simulate the top end impact. The cask is assumed to be centered in the overpack with a .75 inch radial clearance. The pressure boundary conditions are shown in Figure 2.10.2-11.

The results of this analysis are presented in Figures 2.10.2-12 through -14. As can be seen from Figure 2.10.2-12, the highest calculated stress is at the point of the bolt preloads. This value is 28,933 psi. The area which would be expected to be most critical is the unbacked span (see

Figure 2.10.2-10) of the overpack which is subjected to pressure loading from the impact limiter. The stresses in this area are quite low, approximately 10,000 psi (see Figure 2.10.2-13).

The stresses in the cask body are shown on Figure 2.10.2-14. The highest stress is 6,703 psi. This stress may be classified as a bearing stress and as such is limited to 31,700 psi for the cask body material. The membrane and membrane plus bending stresses are very low in the cask body (see Figure 2.10.2-14).

2.10.2.2 Side Drop

Analysis of the thirty-foot side drop accident condition utilized the three-dimensional finite element model shown in Figure 2.10.2-15. Due to the symmetry of the geometry and the loading only 180° of the cask needed to be modeled. The effects of the other half of the model are included by using the appropriate translational restraints at the plane of symmetry. The loads imposed on the model consist of pressures on the element faces that are contacted by the limiters. Due to the nonlinear characteristics of the impact limiters and the cylindrical shape of the cask body, the circumferential load will vary. This load as well as the distribution pattern is shown in Figure 2.10.2-16. The pressure is constant up to 45° and then linearly tapers to zero at 90°. The value of the pressure is calculated such that the pressure loading provides static equilibrium for the maximum deceleration. Thus, the maximum deceleration of 93.5g's is exactly balanced by the applied pressure. The pressure values used for this analysis are P_T = maximum pressure on top end = 3,281 psi, P_B = maximum pressure on bottom end = 2,847 psi.

Due to the weight distribution of the cask and the difference in area of the outside of the limiter between the top and bottom ends, the pressures are different at each end. The correct pressure value was determined by trial and error. A trial pressure was applied to both ends initially and the cask was restrained by holding both ends (displacement constraints). The analysis was run and the reaction forces were calculated at the vertical restraints. The pressure was then adjusted such that the reaction loads at each end were zero. The reanalysis resulted in a balance of the deceleration loading and the applied pressure to simulate the crush of the limiter.

The cask is connected to the overpack by nodal coupling. Figure 2.10.2-17 shows the nodes that are coupled in the radial direction. Both top and bottom ends used this same coupling pattern. All nodes along the 0° line are coupled. Nodes up to 57° are coupled radially in the area which is covered by the impact limiter (15 inches along the length).

The results of this analysis are shown in Figures 2.10.2-18 through -21. As can be seen in Figures 2.10.2-18 and -19, the overpack stresses are quite low everywhere except in the annular ring on the bottom end. The unsupported annular plate develops a stress intensity of 56,867 psi at the highest stressed location. Figure 2.10.2-19 provides a different viewpoint which clearly shows the highly stressed areas. The presence of the gusset plate in the annular ring is obvious from the stress distribution. The only stresses of significance in the top end occur at approximately 90° around the circumference from the symmetry plane. The radial coupling between the cask body and overpack is terminated at 57°, thus, there is some local deformation of the overpack. This stress (approximately 35,000 psi) is well below the limit on membrane plus bending (60,120 psi). It is also noted that the local deformation will be limited by the presence of the cask surface. Thus, these stresses may be considered to have the characteristics of a secondary stress in that the deformation of structure is self-limiting.

Figures 2.10.2-20 and -21 show the stresses in the cask body. As can be seen, the stresses are below 10,000 psi everywhere except at the top and bottom edges of the cask. These very local areas are subjected to locally high compression.

2.10.2.3 C.G. Over Corner Drop

C.G. Over Corner - Bottom Down

The analyses of the drop condition which places the center of gravity of the package directly over the corner of the package is evaluated using the same finite element model as the side drop case. The angle of impact is calculated from the geometry as 24.8°. The acceleration vector is input such that it passes through the center of gravity of the combined cask-overpack mass and through the hypothetical point of impact of the overpack onto the unyielding surface if the impact limiter were not present to prevent this contact. This angle is illustrated in Figure 2.10.2-22.

The deceleration load is equilibrated by pressure on the overpack which corresponds to the impact limiter response to crushing. The pressure distribution is shown in Figure 2.10.2-22. Note that there will be a horizontal as well as vertical component of the pressure because of the angle of impact. The pressures were determined as follows.

The vertical component of pressure on both the bottom and sides of the overpack is combined and the sum of these must be exactly equal to the weight of the package multiplied by the peak deceleration (48.8g's). The horizontal component of pressure summed over the bottom end of the overpack must be equal to the horizontal component of pressure acting on the side wall of the annular ring. The pressure distributions were assumed to vary linearly on both the bottom face and linearly around the circumference on the annular ring. This can be seen from the pressure distribution plots in Figure 2.10.2-22. This was accomplished by trial and error using the ANSYS program to calculate the pressure values. This technique produced a pressure distribution which has zero net force in the horizontal direction and a net force of the 48.8 times the weight vertically. This does not, however, produce a net zero moment about the center of gravity. An angular acceleration about the center of gravity was required to provide moment equilibrium

The static analysis was performed with symmetry boundary conditions (described previously) at the cut face (180°). Node points were restrained at two points horizontally and one point vertically to prevent rigid body motion. The reaction loads at these points were determined to be negligible when the final analysis run was made.

The cask body was coupled to the overpack in the same manner as described in section 2.10.2.3 for the side drop and the bottom end of the cask was coupled to the bottom of the overpack in areas of contact. The top ends of both the cask and overpack were not coupled or otherwise connected.

The stress results from this analysis are shown in Figures 2.10.2-23 through -25. It may be seen that the stresses in the overpack are highest in the annular ring. The maximum stress is 28,624 psi in all plates except the gusset. The gusset plate stress intensity has a maximum stress intensity value of 30,548 psi.

The highest stress intensity in the cask body is 26,131 psi. This is a very local stress caused by bearing at the corner of the cask. This value is also well below the allowable stress of 31,700 psi (Table 2-3) for ductile iron.

C.G. Over Corner - Top Down

Loading for the top impact limiter C.G. over corner analysis is similar to the loading for bottom impact case with the exception that axial loadings and limiter loads are imposed at the top end rather than the bottom. The angle of impact is calculated from the geometry as 17.1°. The pressure distribution on the cask overpack is shown in Figure 2.10.2-26.

The vertical component of pressure on both the bottom and sides of the overpack is combined and equated to the weight of the package multiplied by the peak deceleration of 41.3g's. The horizontal component of pressures was verified to be zero.

The results of this analysis are presented in Figures 2.10.2-27 through 2.10.2-29.

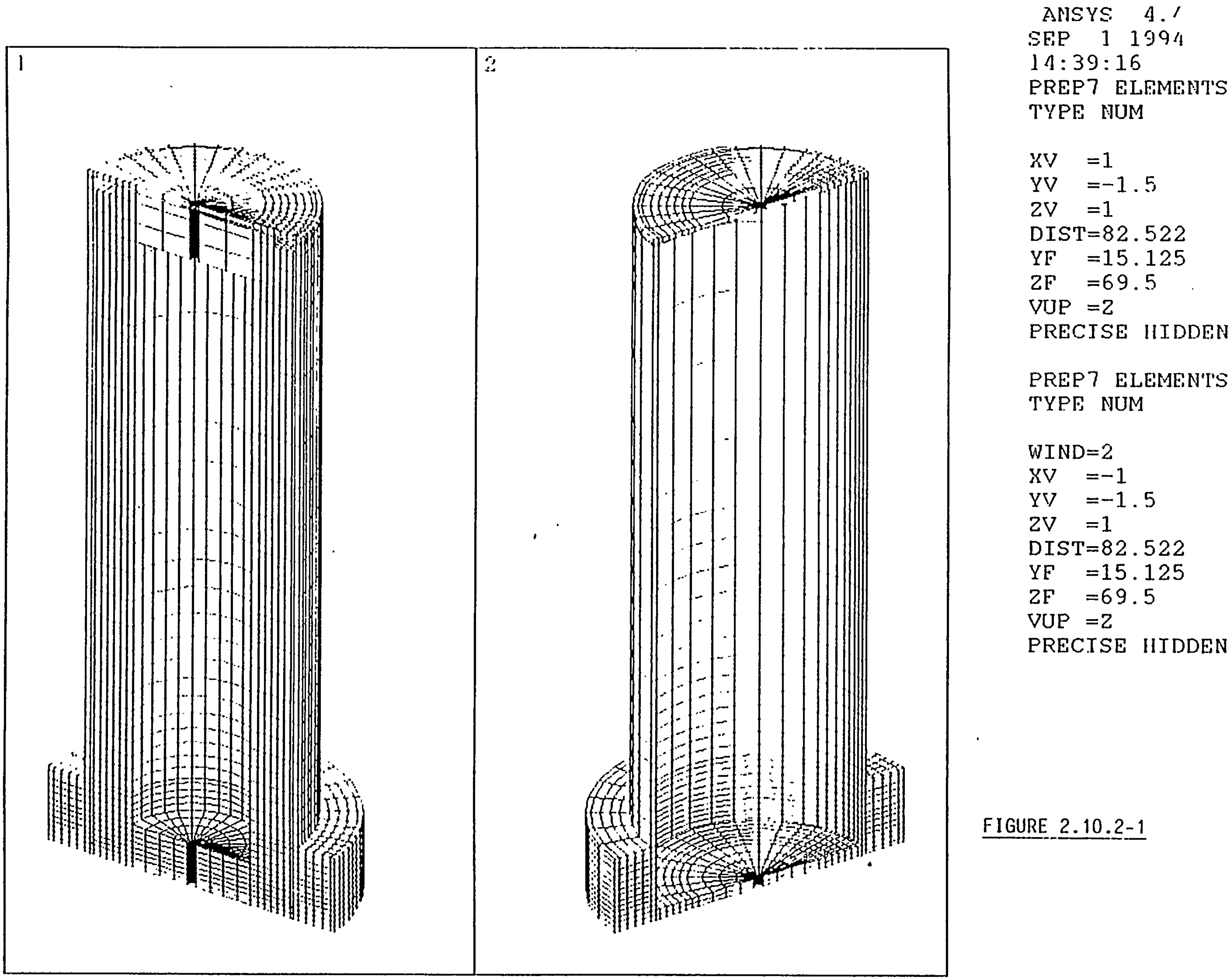
The stresses in the overpack are highest at the top end (as expected) and are located in the unbacked area of the top plate. This area spans the distance from the edge of the overpack to the secondary lid on the cask. This may be seen in Figure 2.10.2-3. Note that for this analysis, the cask was assumed to be in contact with the inside surface of the overpack.

The highest stresses (membrane + bending) are found to be 19,914 psi for this case. (Note: The bolt preload causes a very local stress which exceeds this value (see Figure 2.10.2-28). However, this is a local anomaly caused by the bolt preload acting at a single node point. The true stress will be much less and, clearly, this effect is not significant to the analysis provided herein.)

Figure 2.10.2-29 shows that the cask body has very low stresses everywhere except at the edge which is in contact with limiter at impact. The maximum value, 25,976 psi, may be considered to be a local bearing stress and is well below the bearing allowable stress of 31,700 psi.

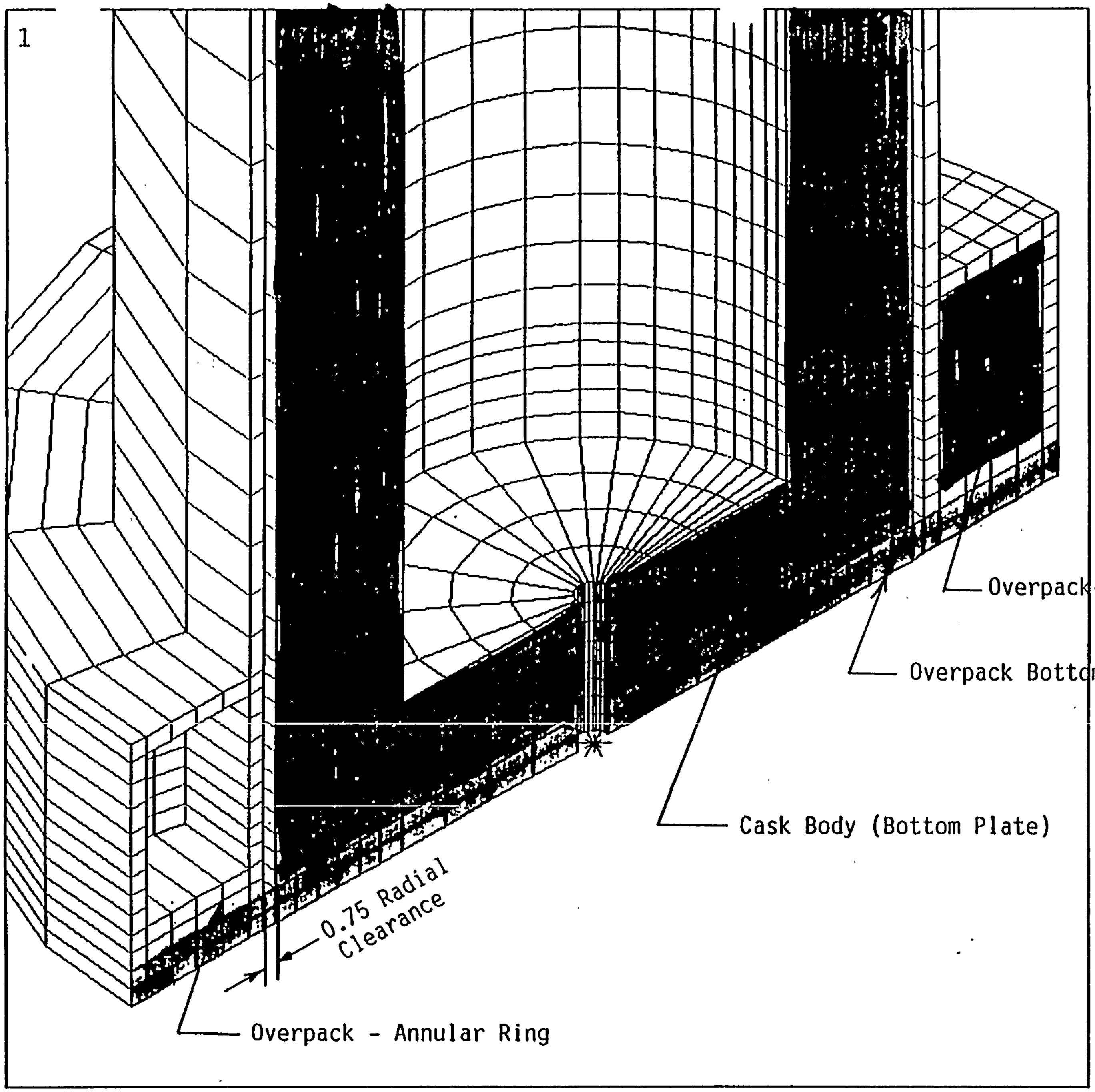
Table 2.10.2-1
SUMMARY OF 30-FOOT ACCIDENT LOAD CONDITIONS

Case Sections	Magnitude	Orientation	Location	Source
End Drop (Bottom Down)	59.8 g's	90	At Annular Limiter Contact	Limiter Analysis 2.10.1
End Drop (Top Down)	40.5 g's	-90	At Annular Limiter Contact	Limiter Analysis 2.10.1
Side Drop	93.5 g's	0	Along Limiter I.D. Contact 45°	Limiter Analysis 2.10.1
C.G. over Corner (Bottom Down)	48.8 g's	65.2	Bottom End + Side Loads	Limiter Analysis 2.10.1
C.G. over Corner (Top Down)	41.3 g's	72.9	Top End + Side Loads	Limiter Analysis 2.10.1



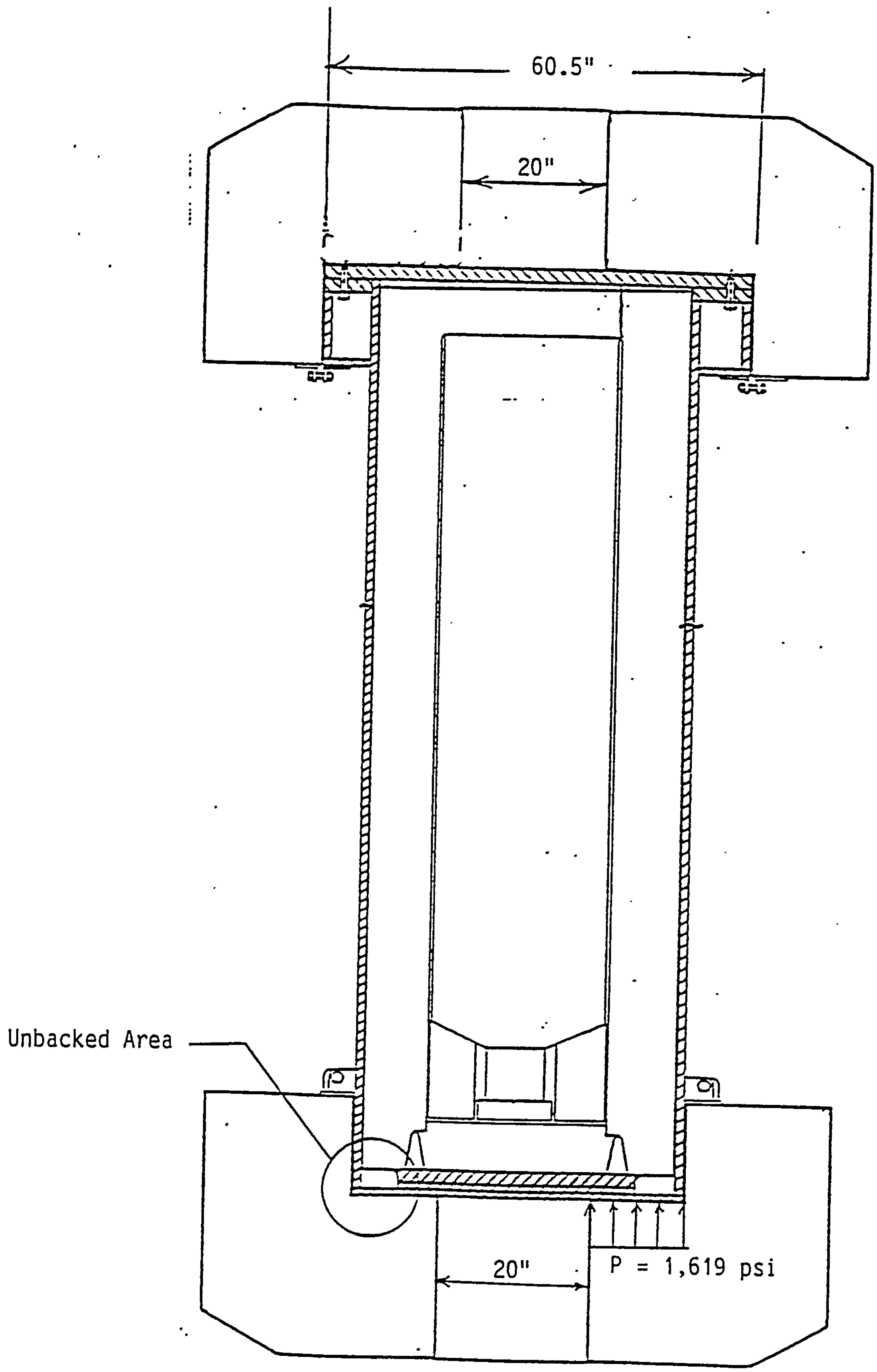
VHLW Cask - Finite Element Model

FIGURE 2.10.2-1



VHLW Transport Cask Assembly - Finite Element Model - Bottom End

FIGURE 2.10.2-2



END DROP

FIGURE 2.10.2-10

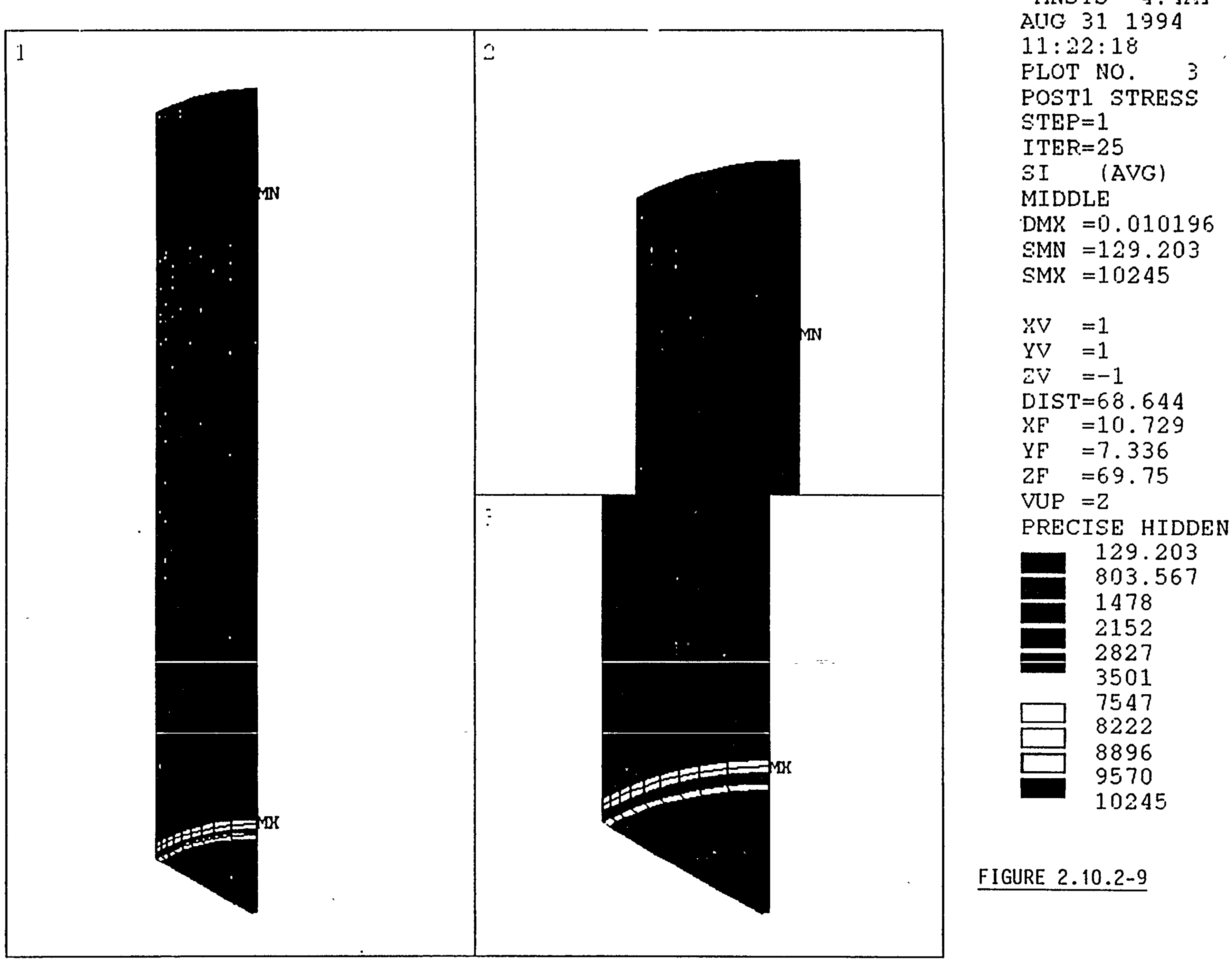


FIGURE 2.10.2-9

VHLW Cask - End Drop (Bottom Down) - Static Analysis

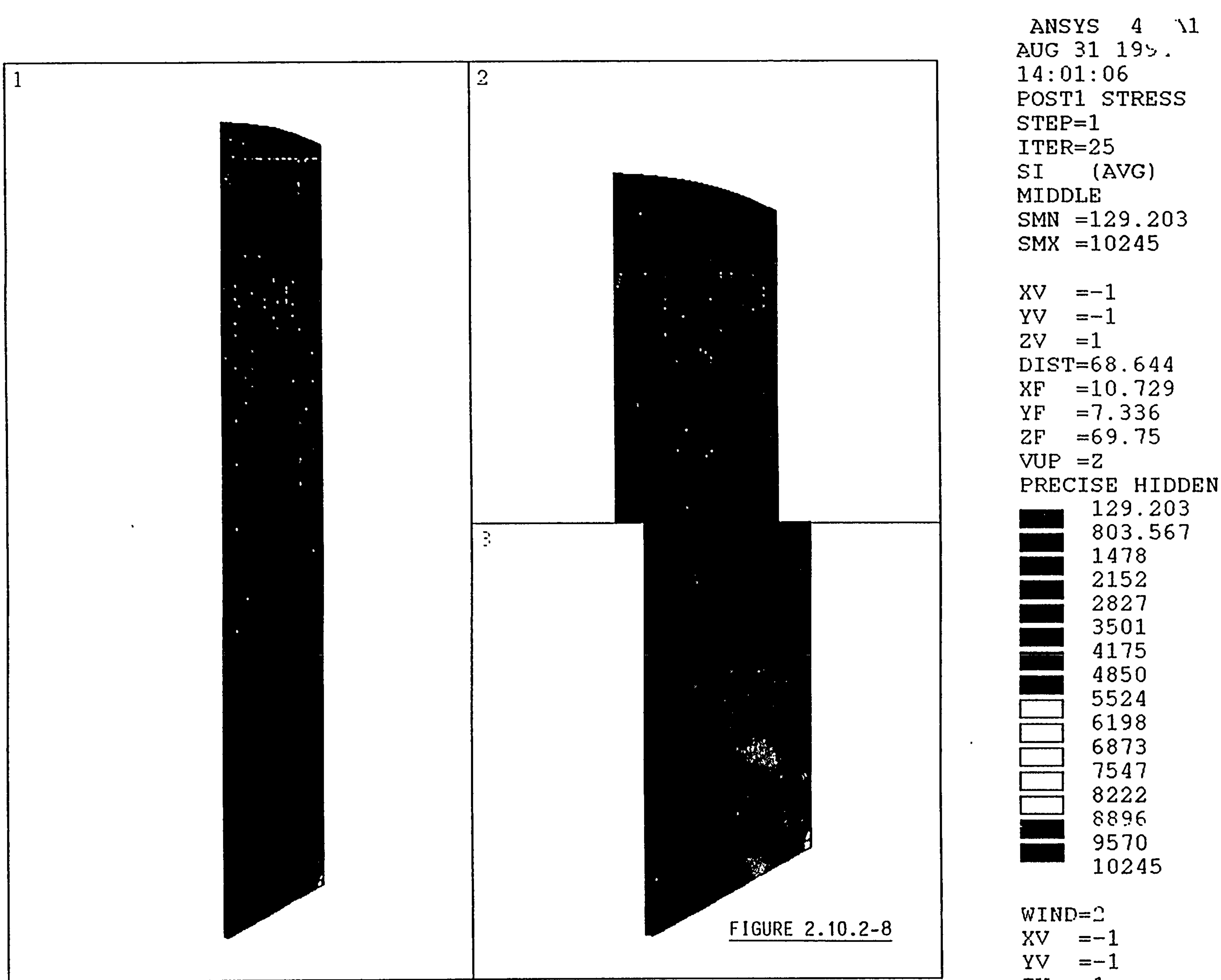


FIGURE 2.10.2-8

VHLW Cask - End Drop (Bottom Down) - Static Analysis

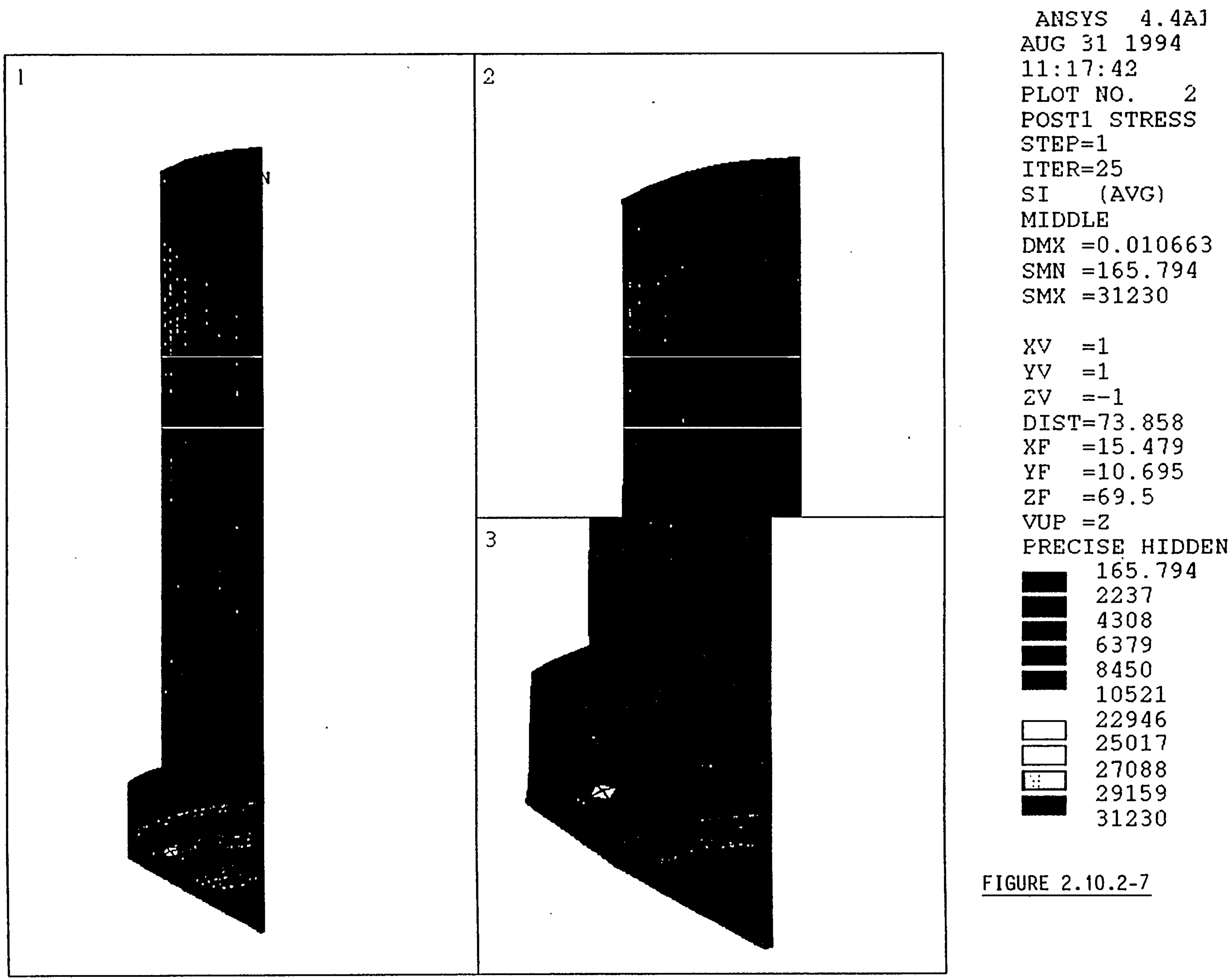


FIGURE 2.10.2-7

VHLW Cask - End Drop (Bottom Down) - Static Analysis

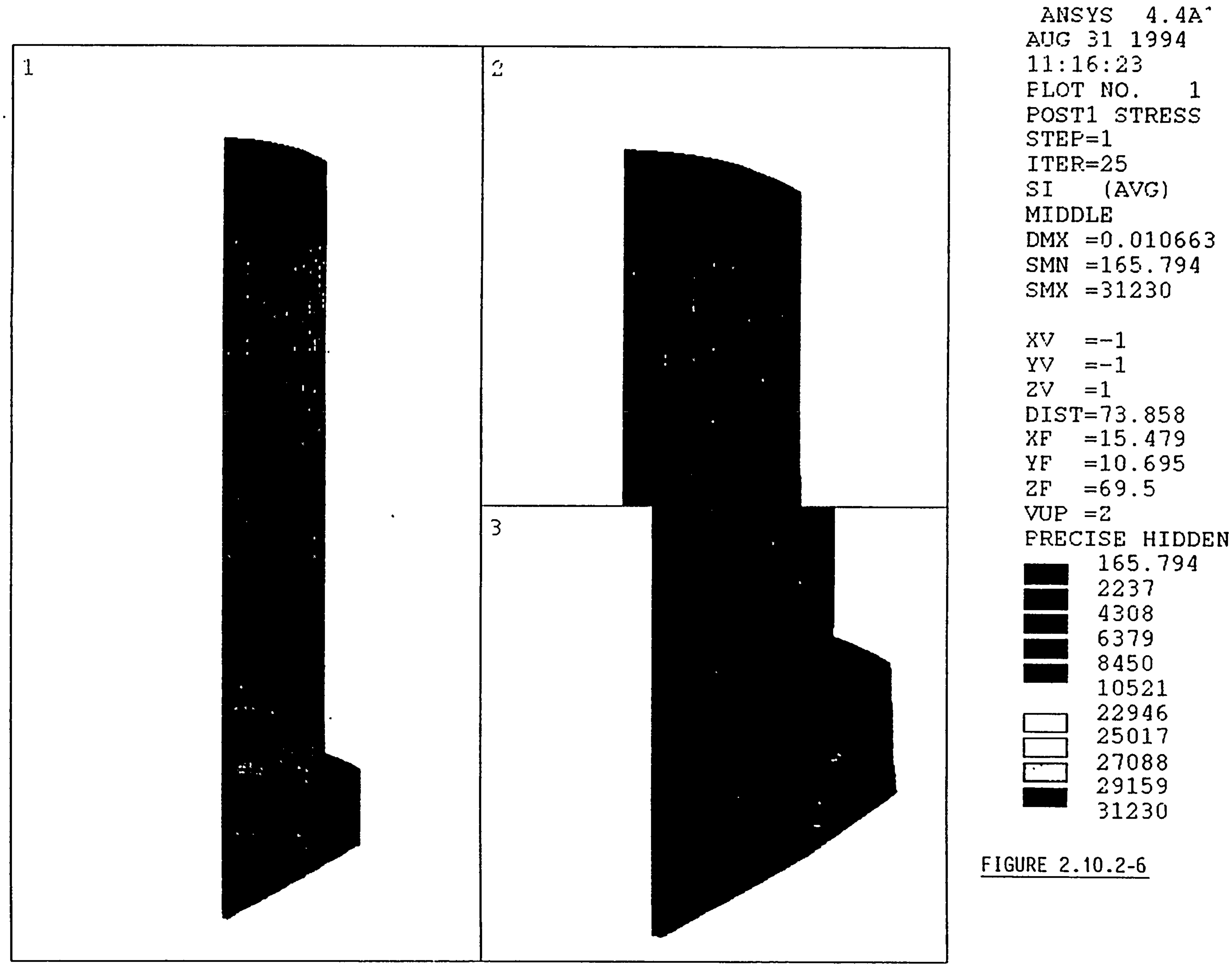


FIGURE 2.10.2-6

VHLW Cask - End Drop (Bottom Down) - Static Analysis

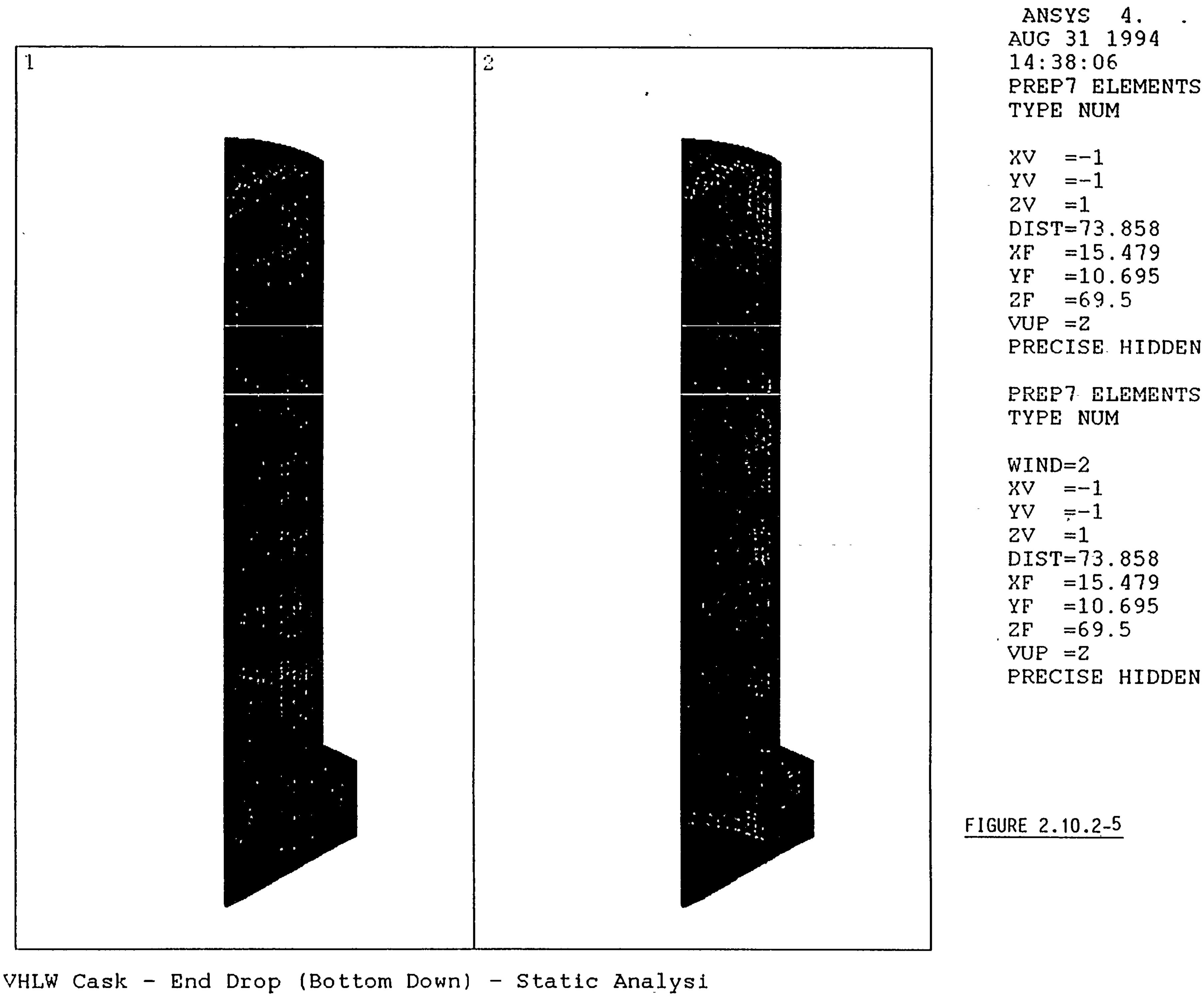
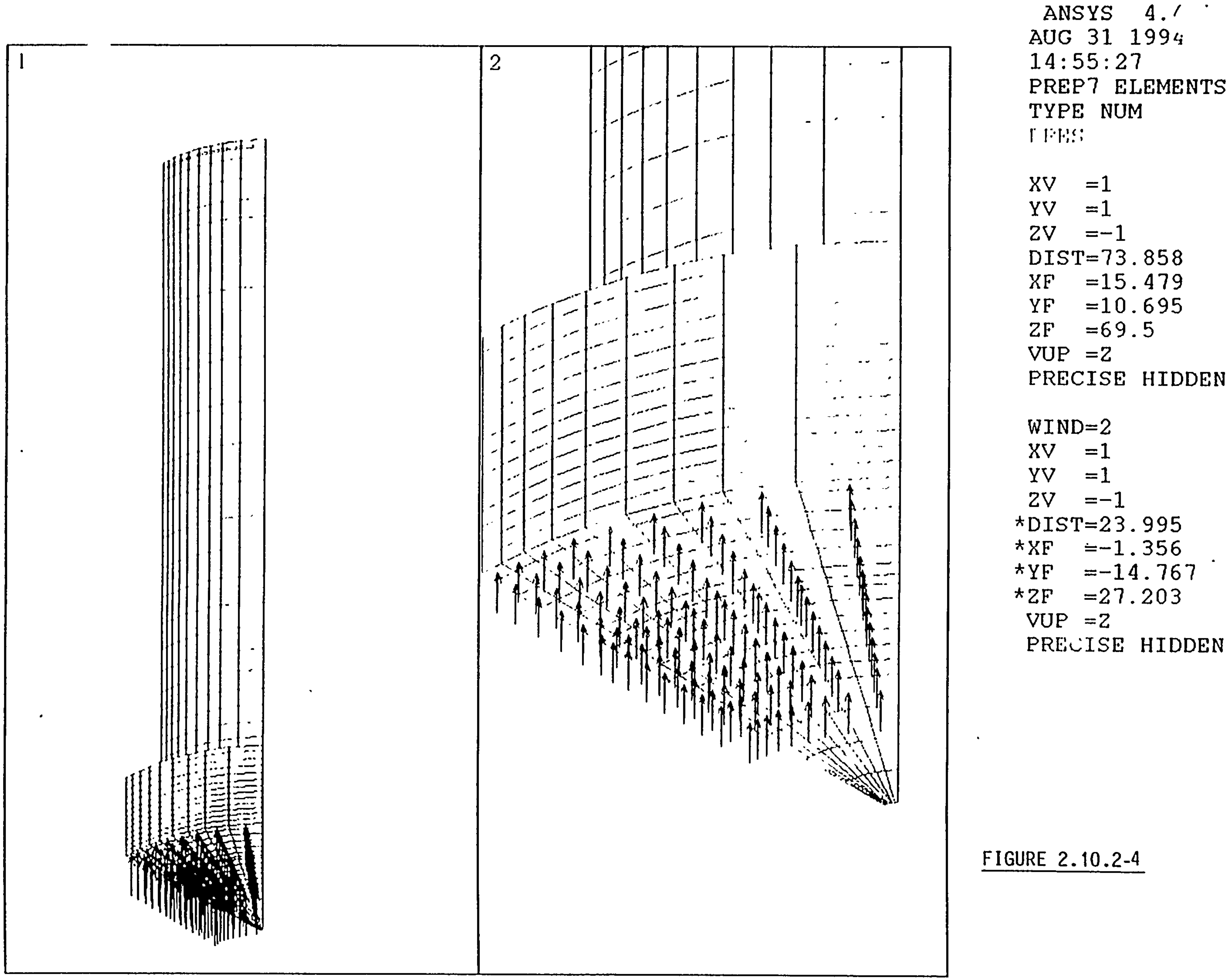
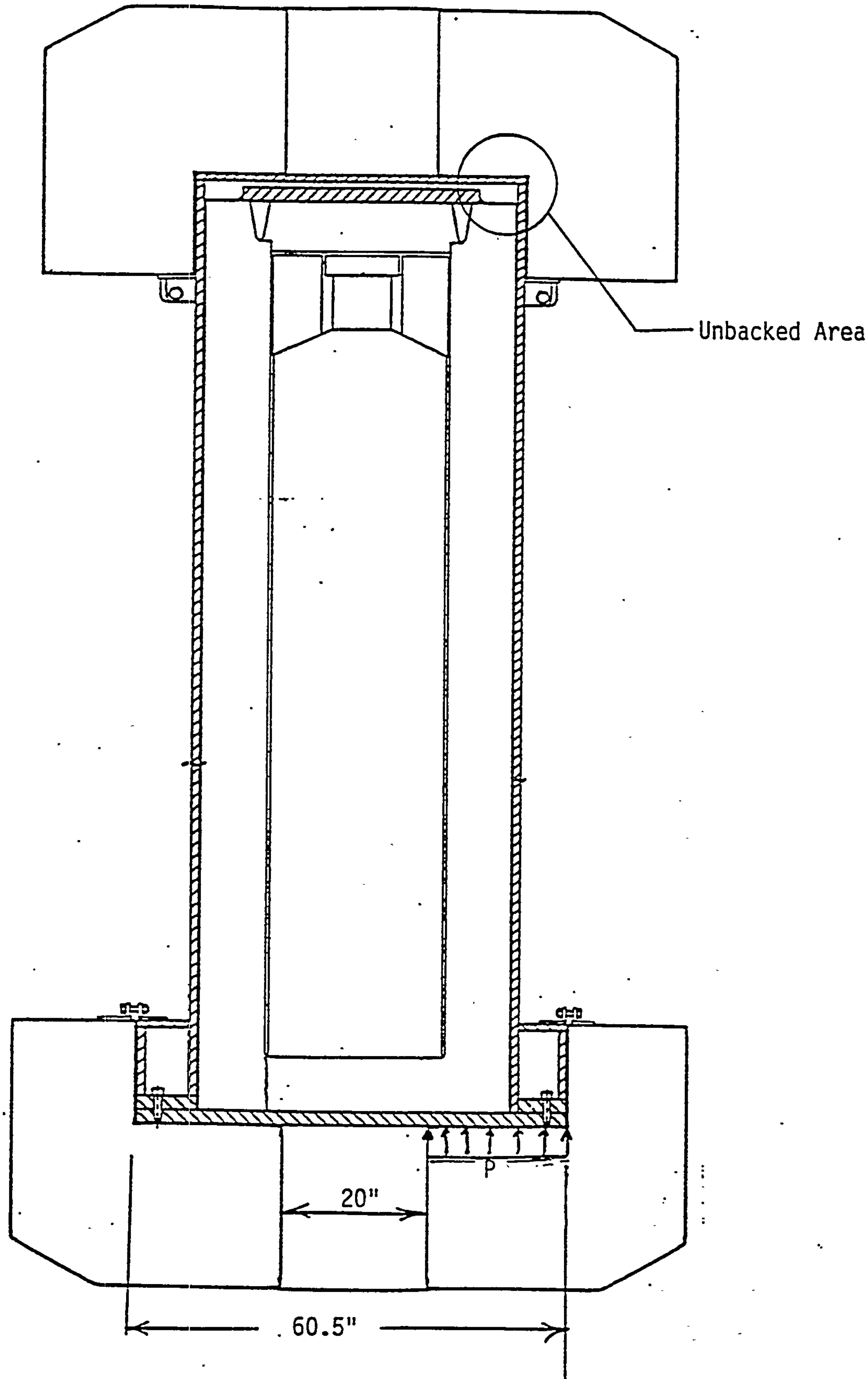


FIGURE 2.10.2-5



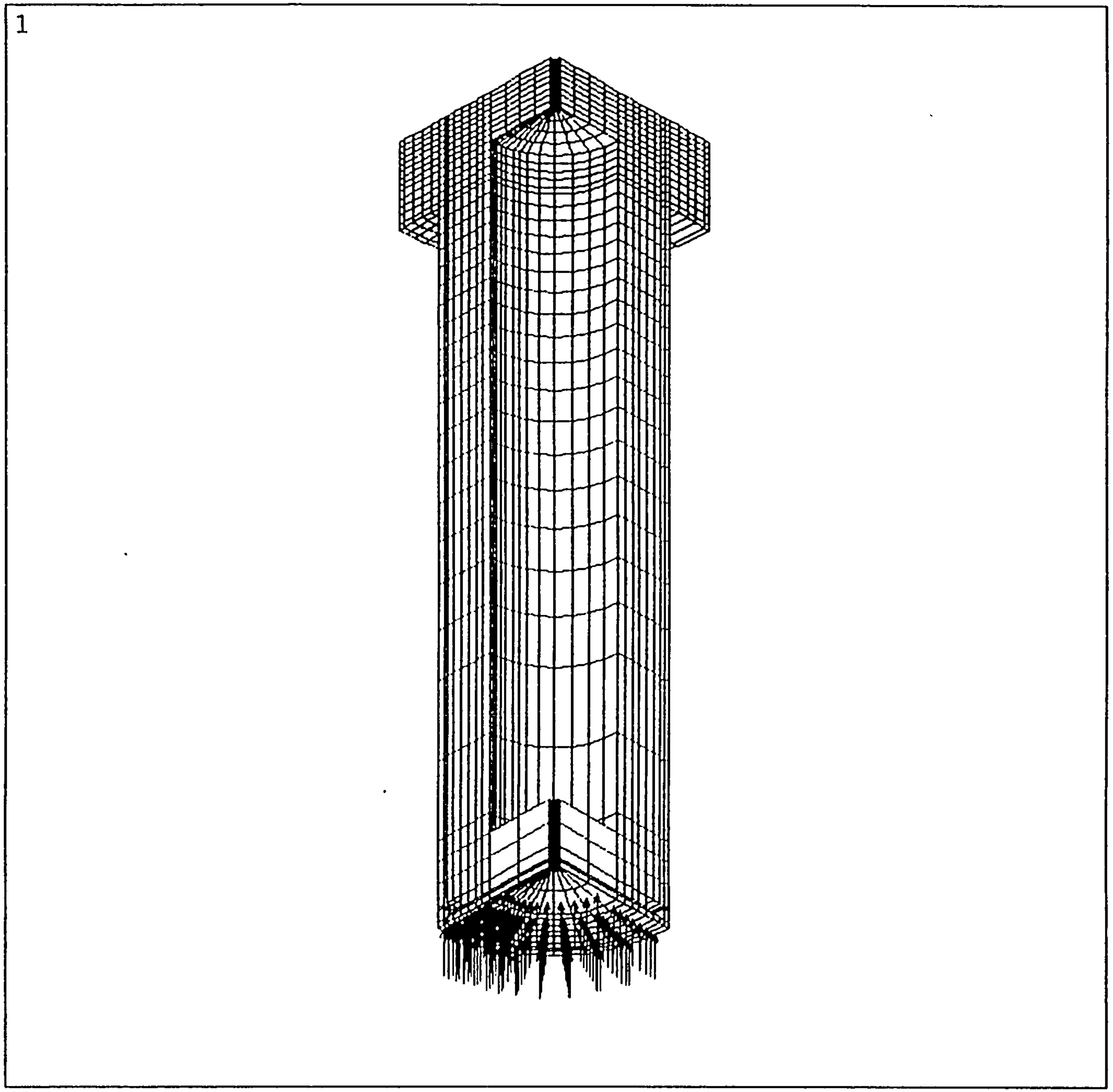
VHLW Cask - End Drop (Bottom Down) - Static Analysi

FIGURE 2.10.2-4



END DROP

FIGURE 2.10.2-3



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ZF =69.5
VUP =-Z
PRECISE HIDDEN

FIGURE 2.10.2-11

VHLW Cask - End Drop - Top Down - Static Analysis

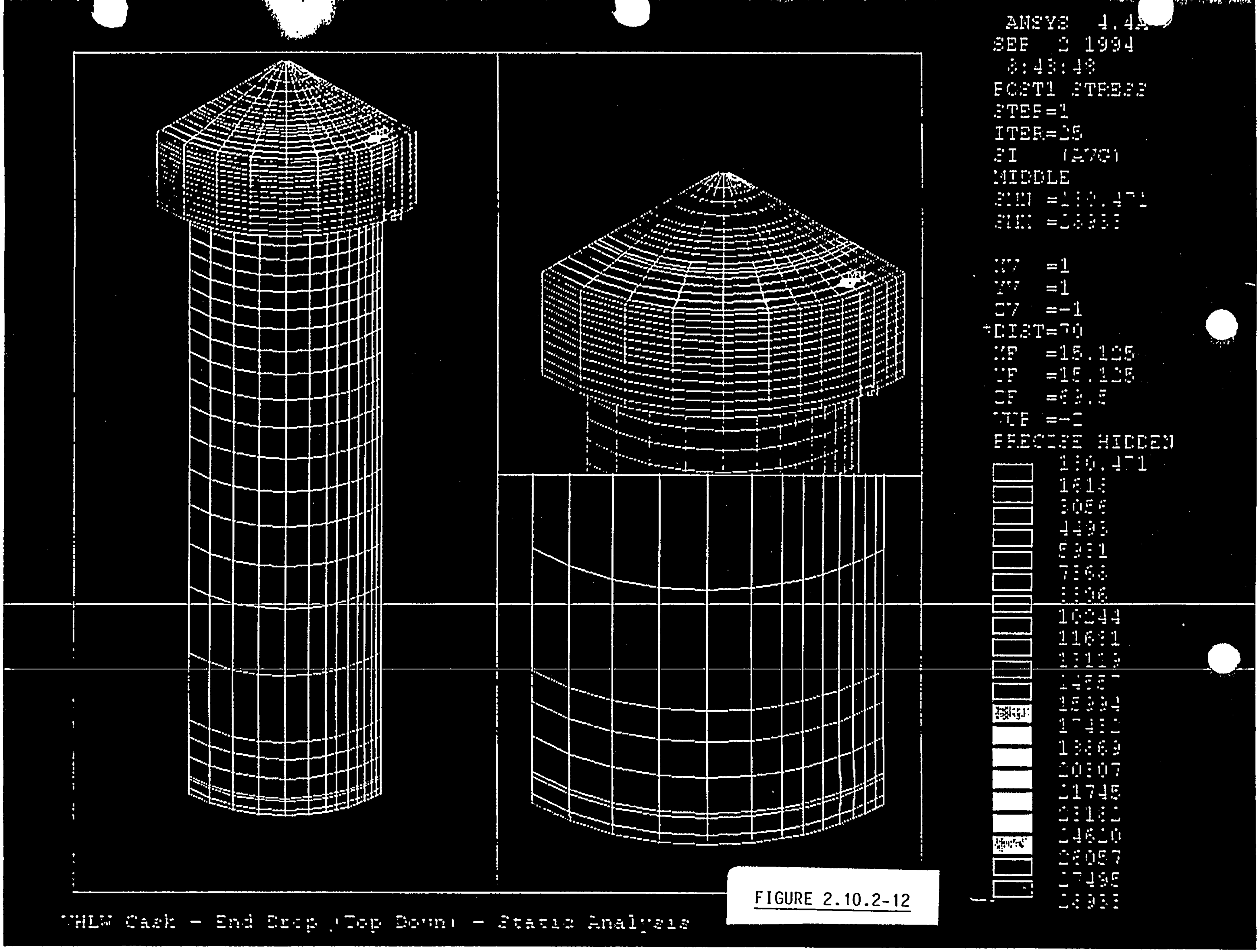


FIGURE 2.10.2-12

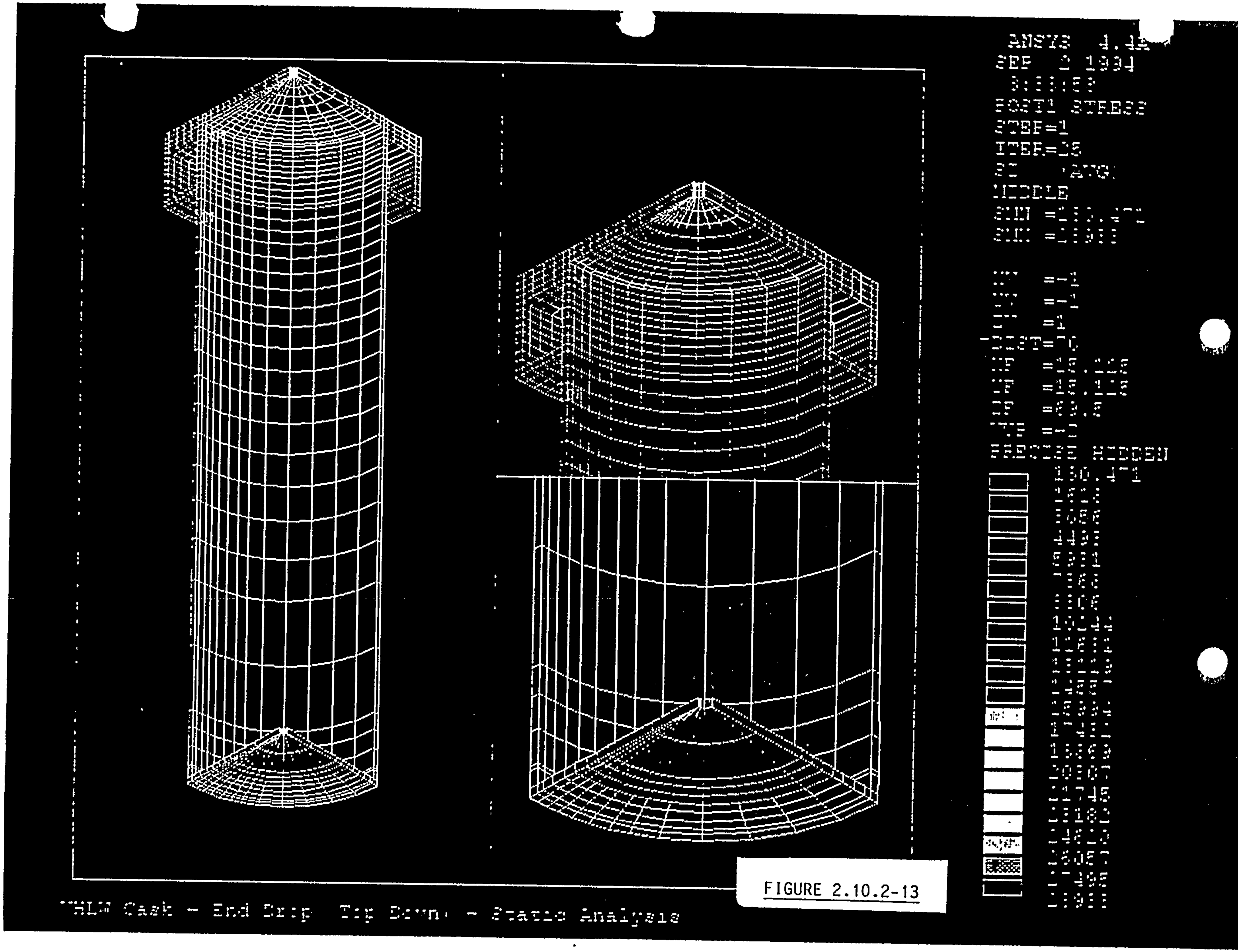


FIGURE 2.10.2-13

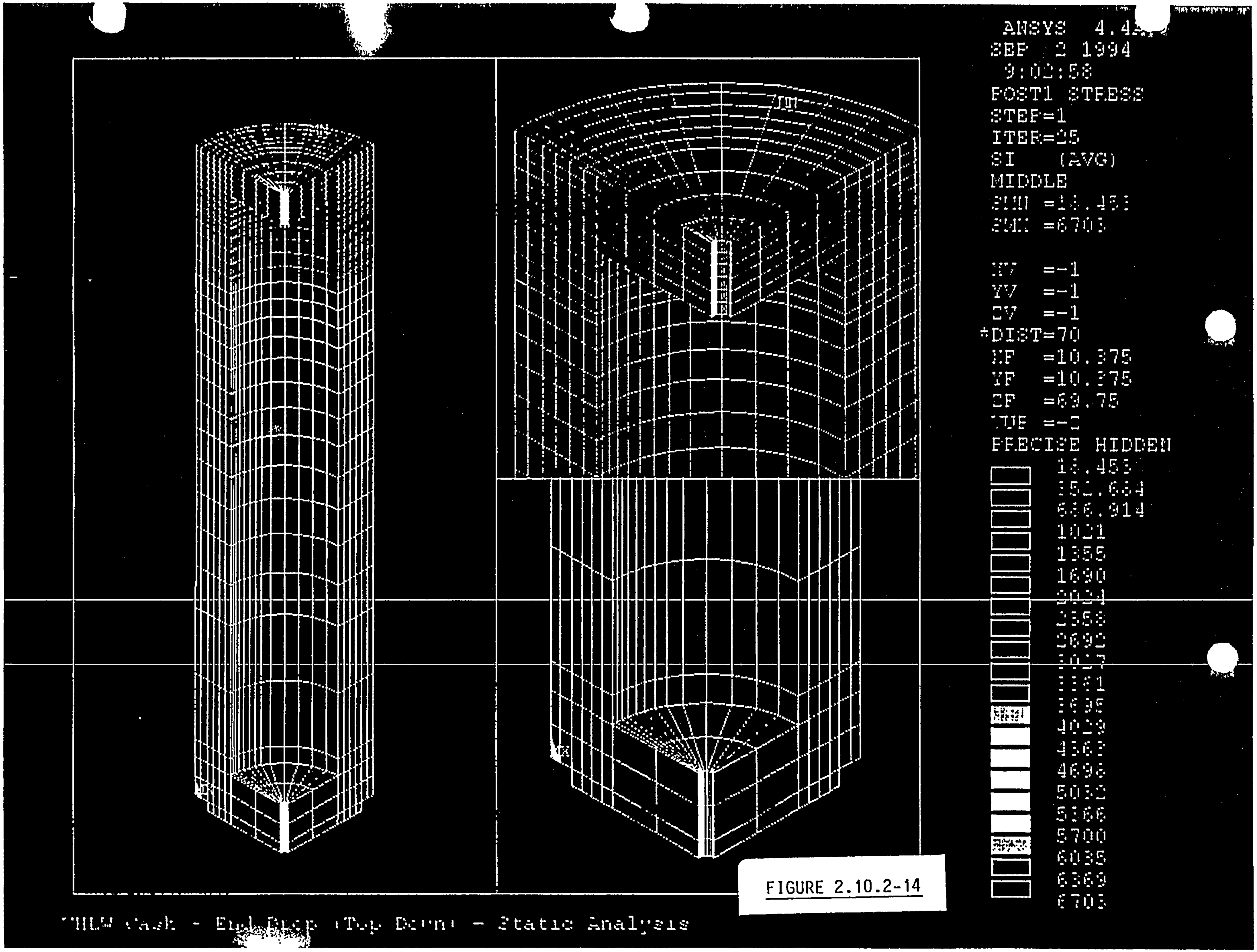
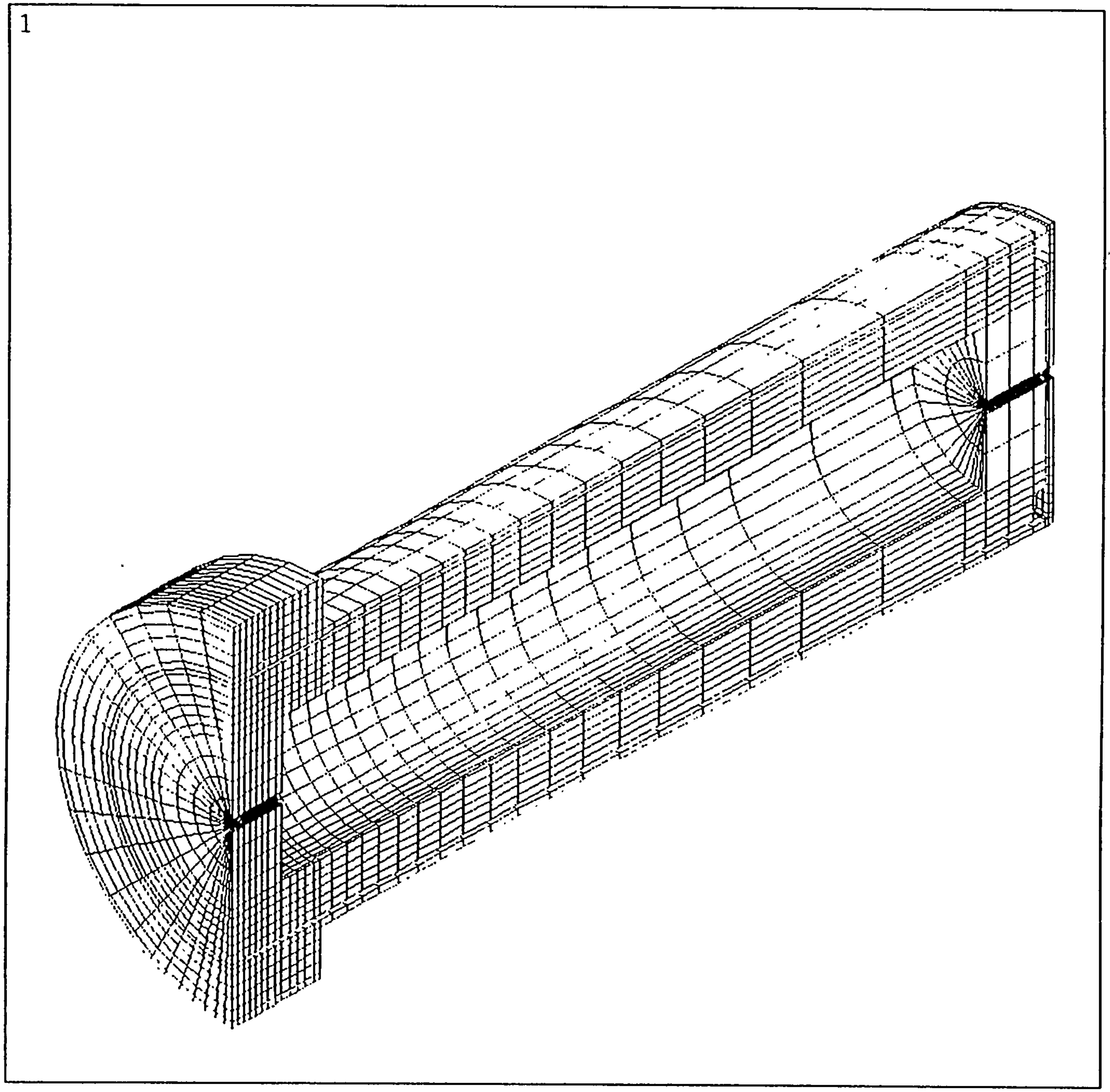


FIGURE 2.10.2-14



VHLW Cask - Side Drop - Static Analysis

FIGURE 2.10.2-15

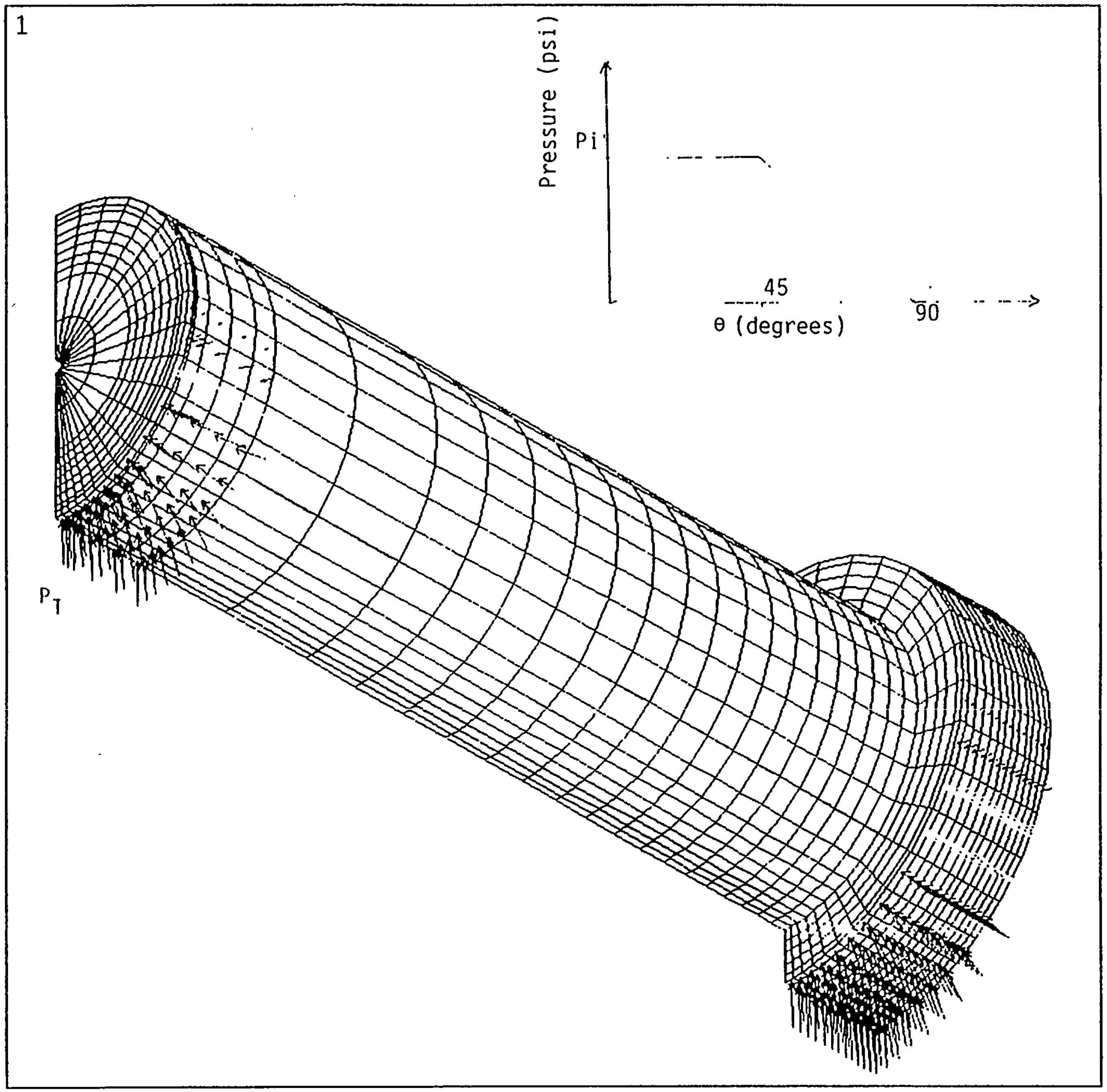


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FIGURE 2.10.2-16

VHLW Cask - Side Drop - Static Analysis

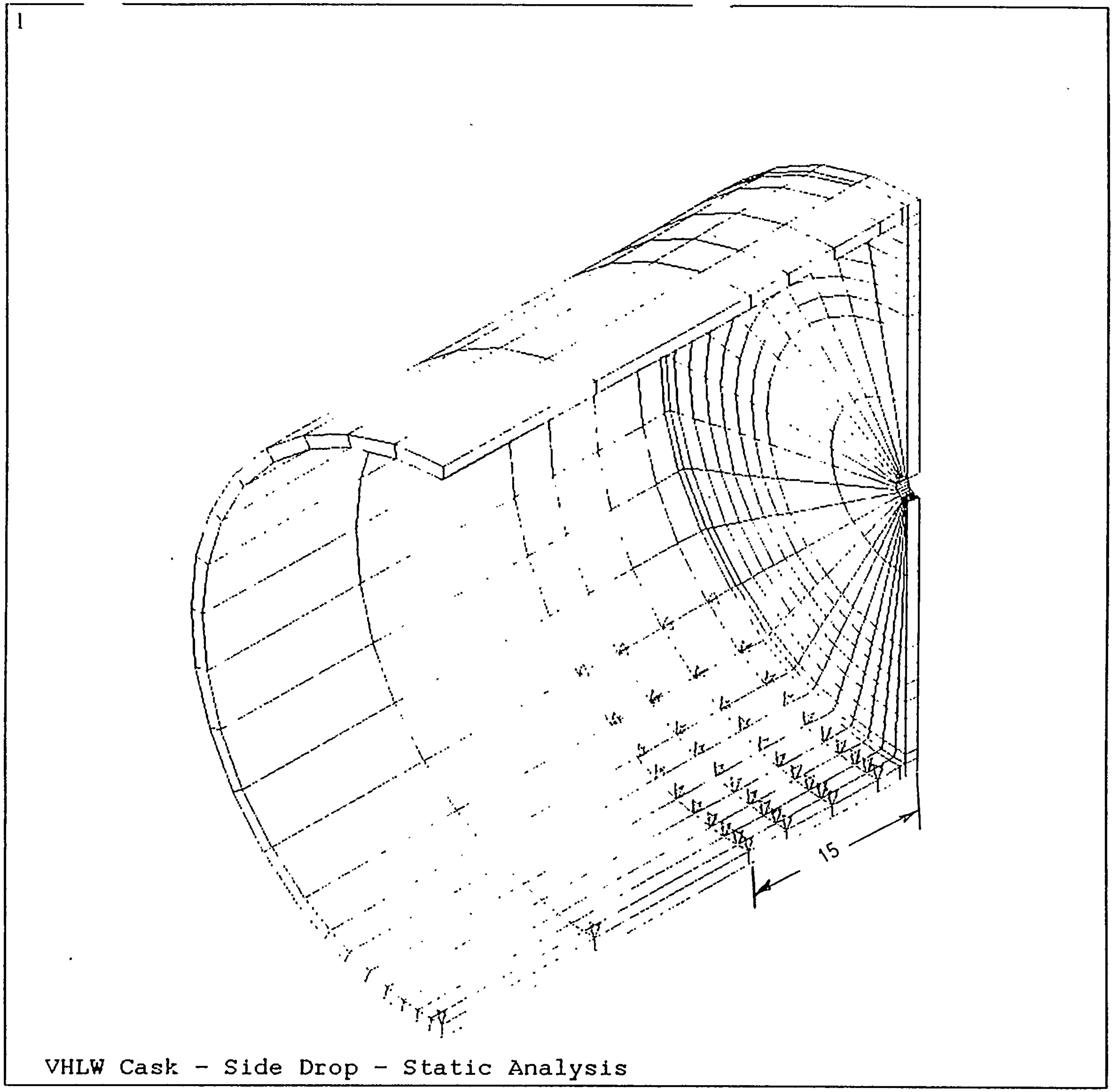

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FIGURE 2.10.2-17

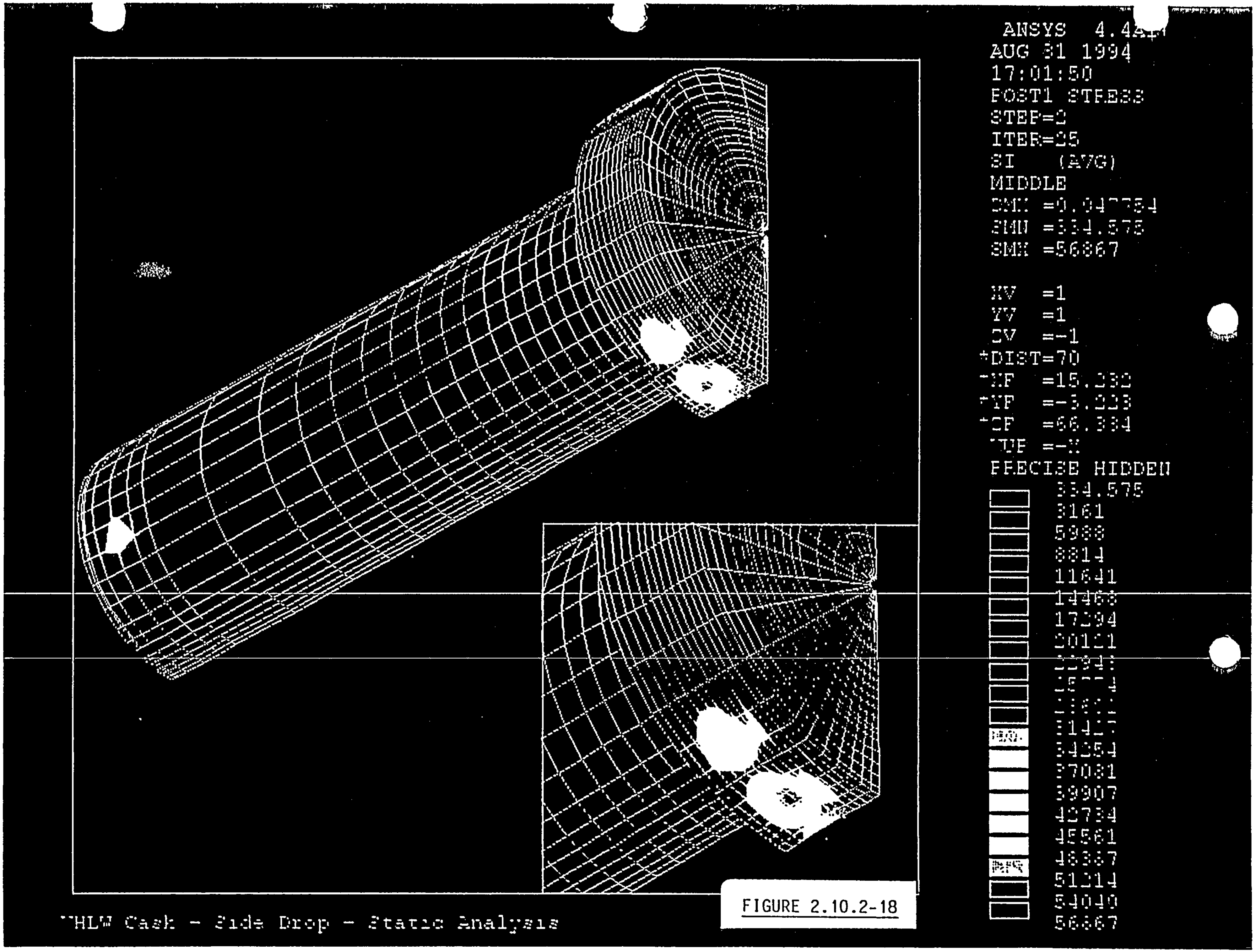


FIGURE 2.10.2-18

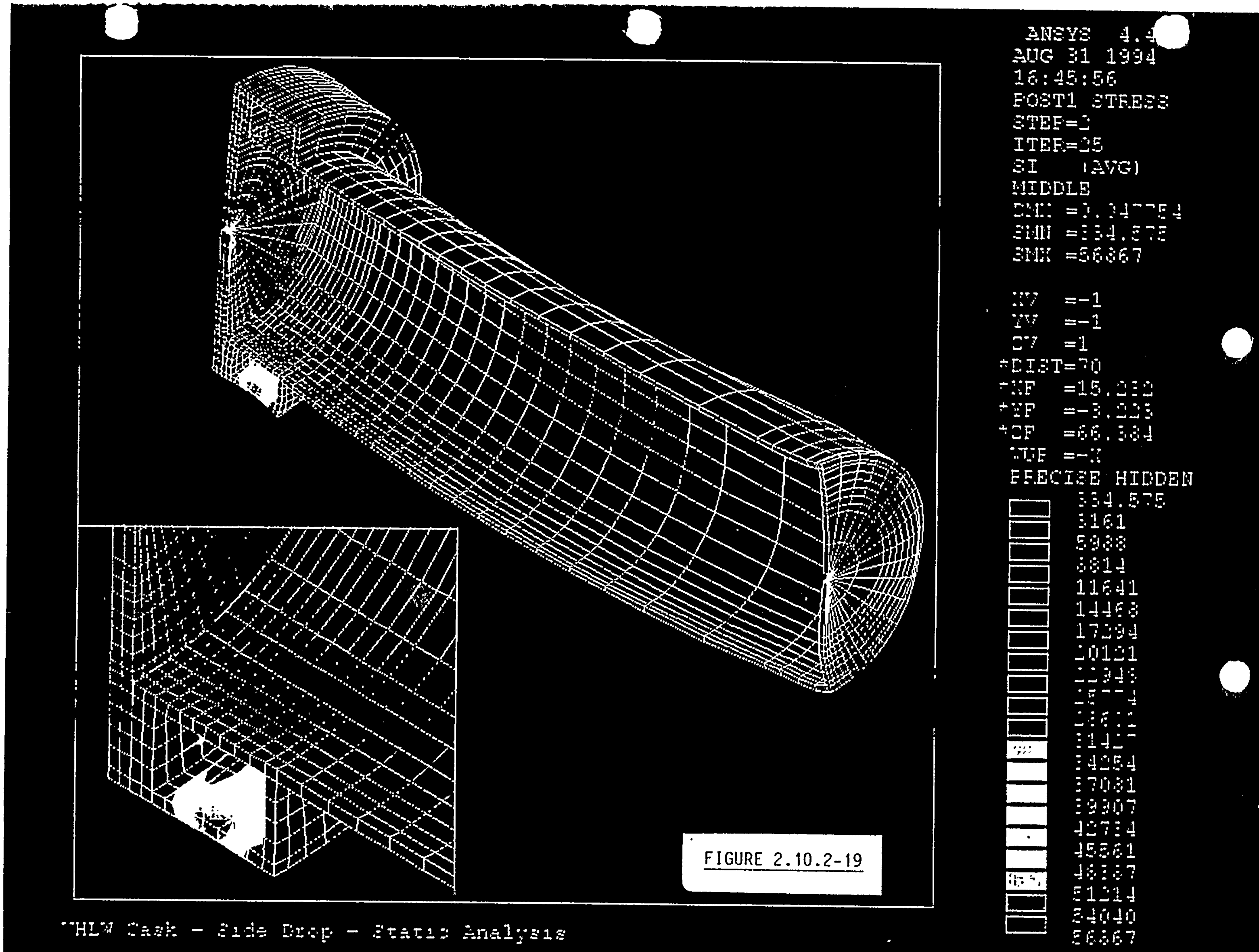


FIGURE 2.10.2-19

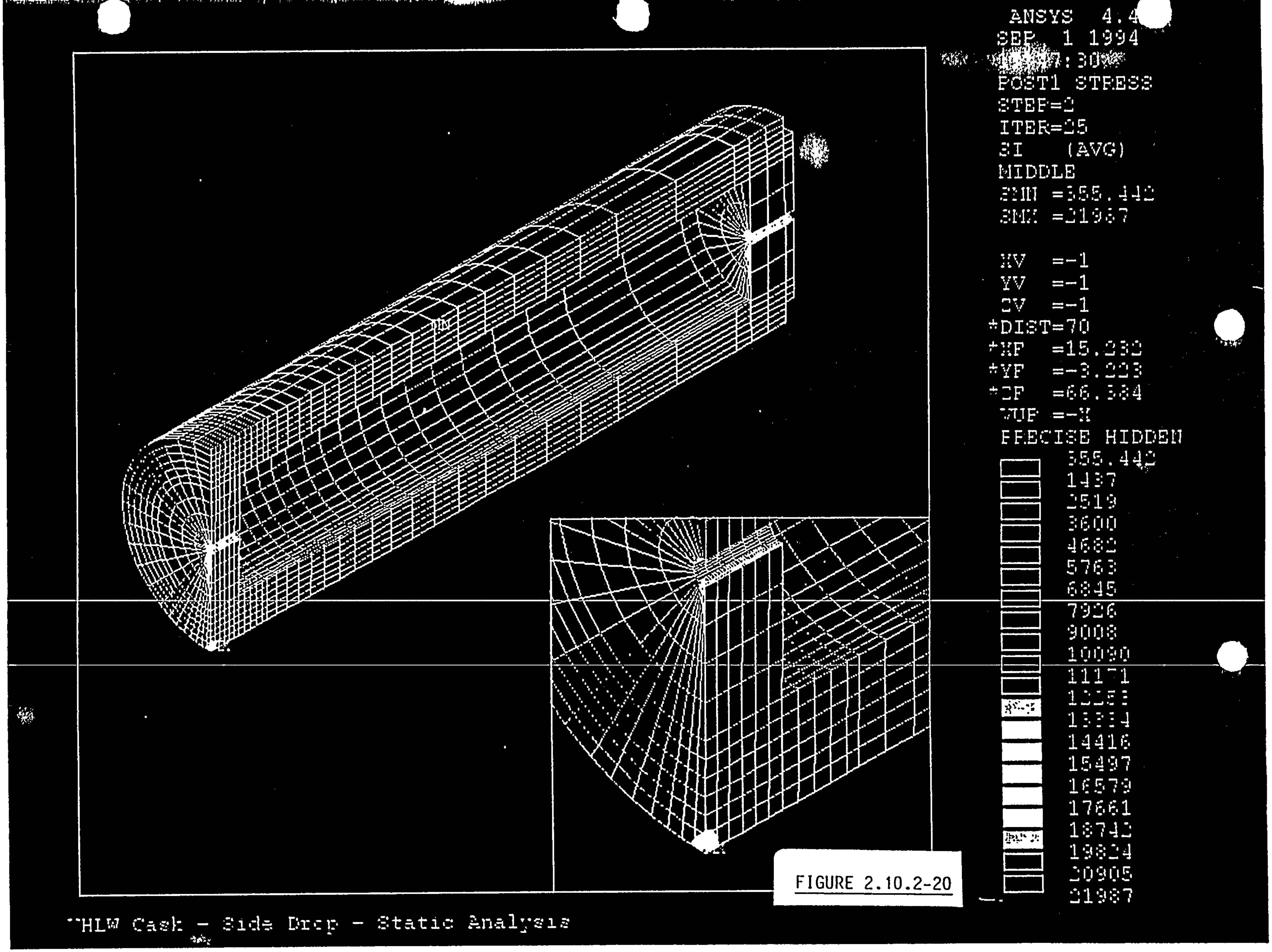


FIGURE 2.10.2-20

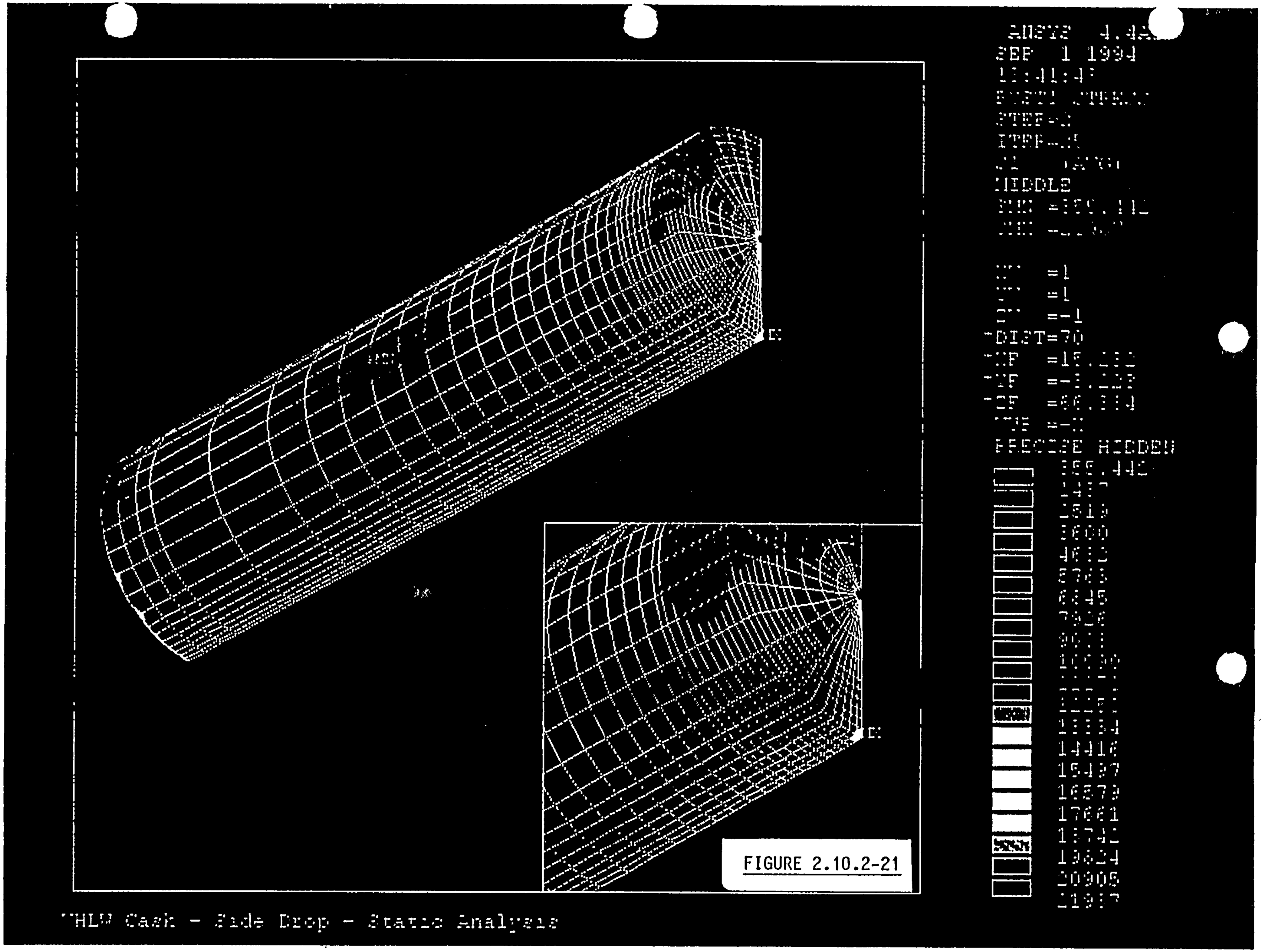


FIGURE 2.10.2-21

HLW Cask - Side Drop - Static Analysis

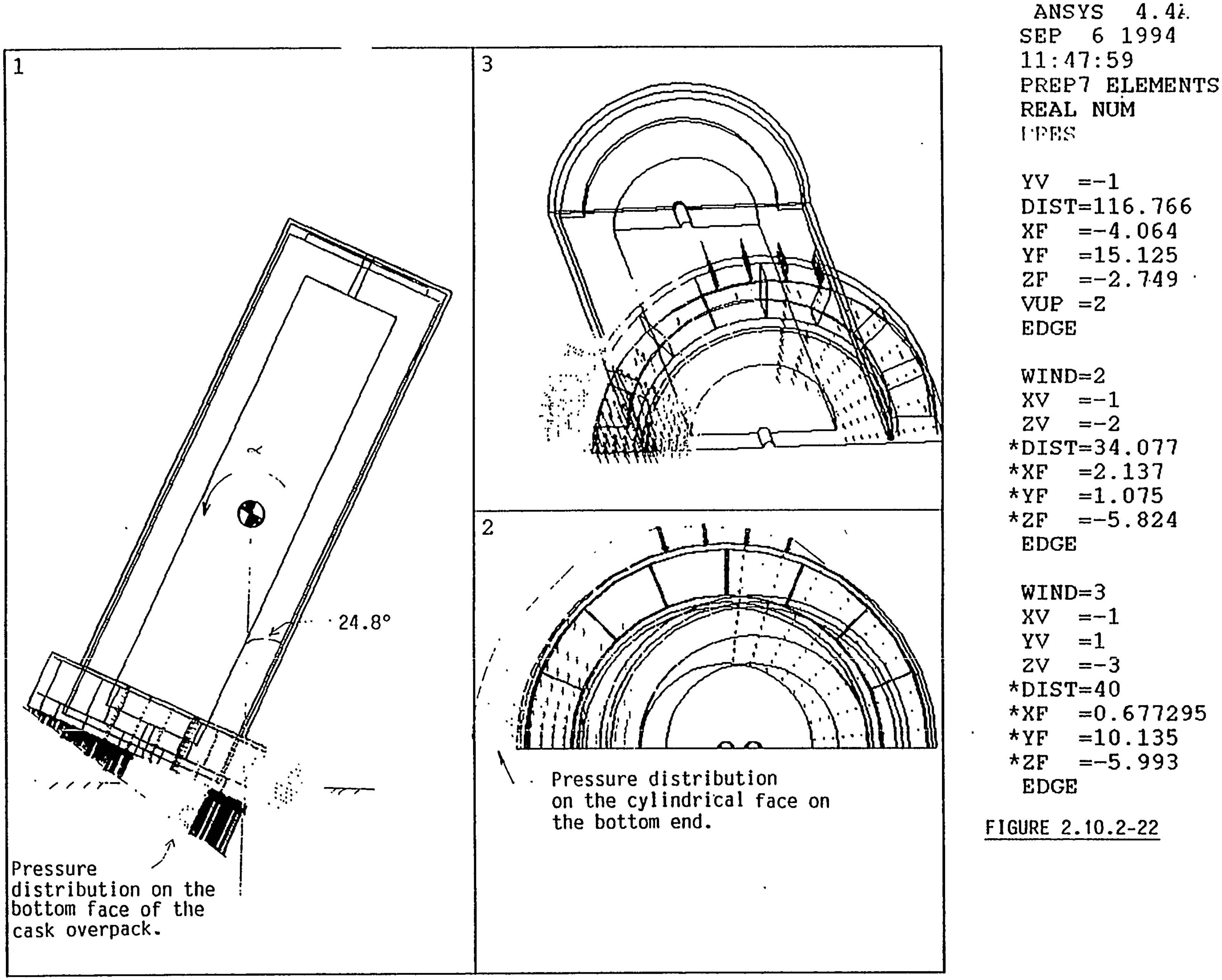


FIGURE 2.10.2-22

VHLW Cask - Corner Drop - Bottom down - Static Analysis

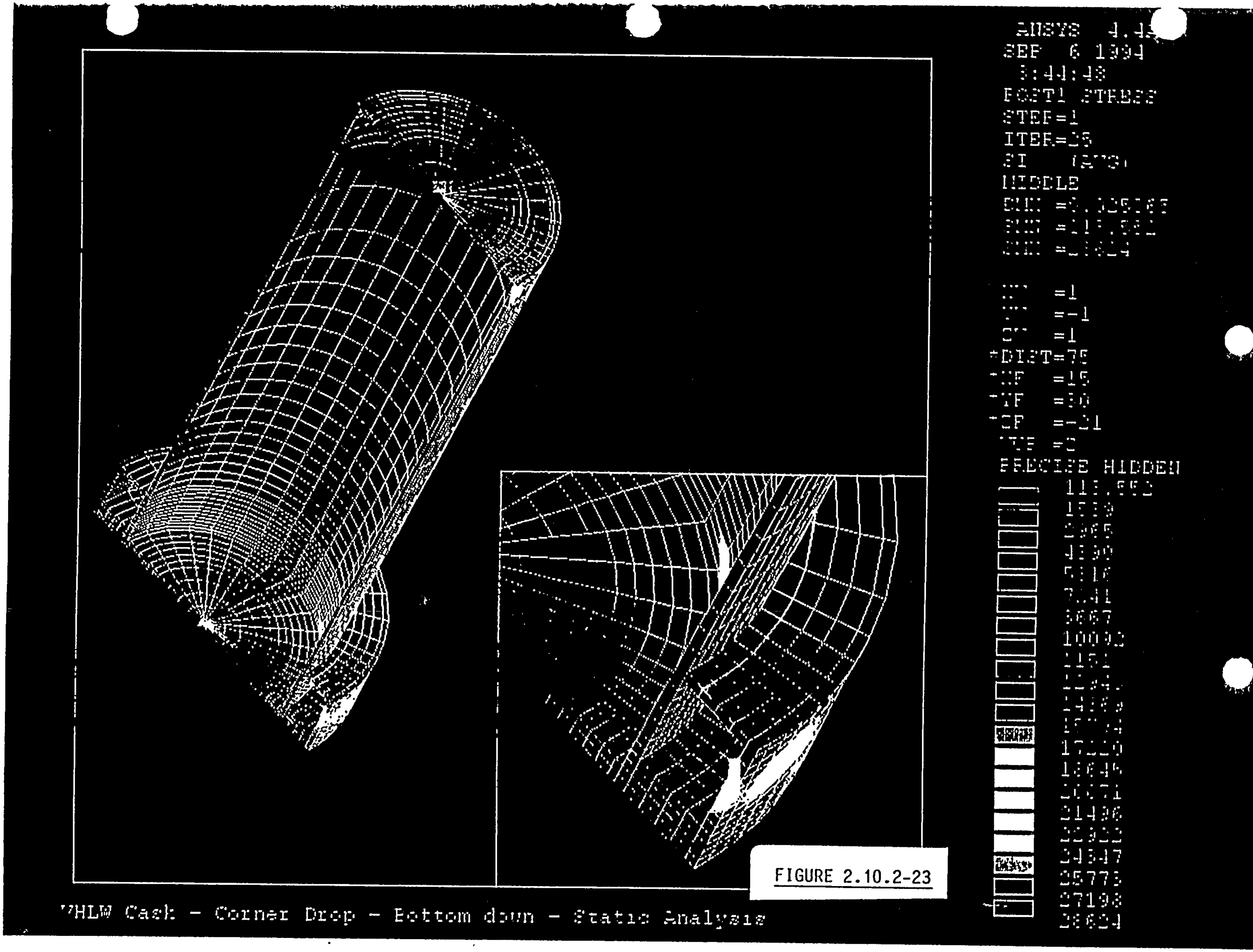


FIGURE 2.10.2-23

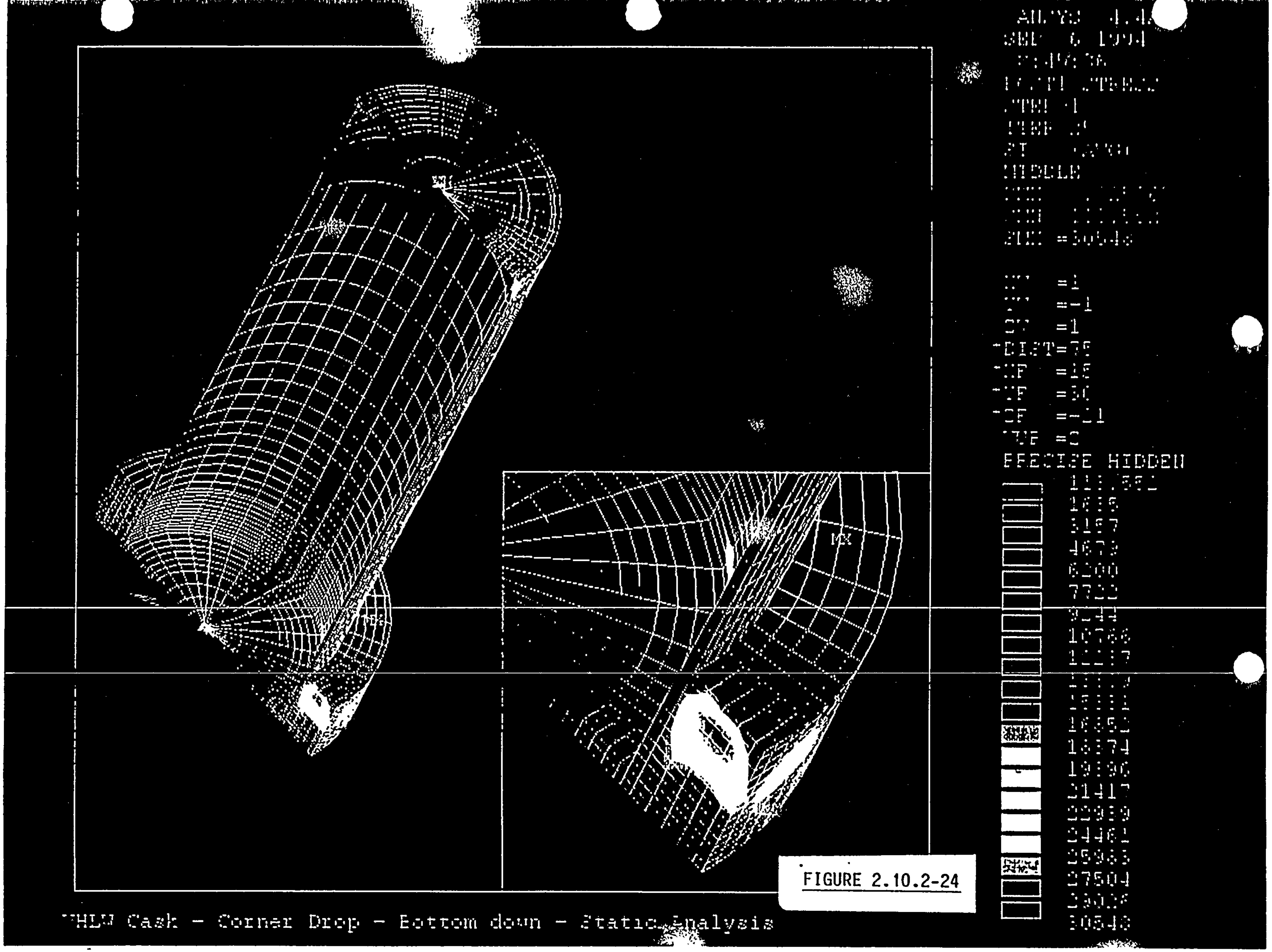


FIGURE 2.10.2-24

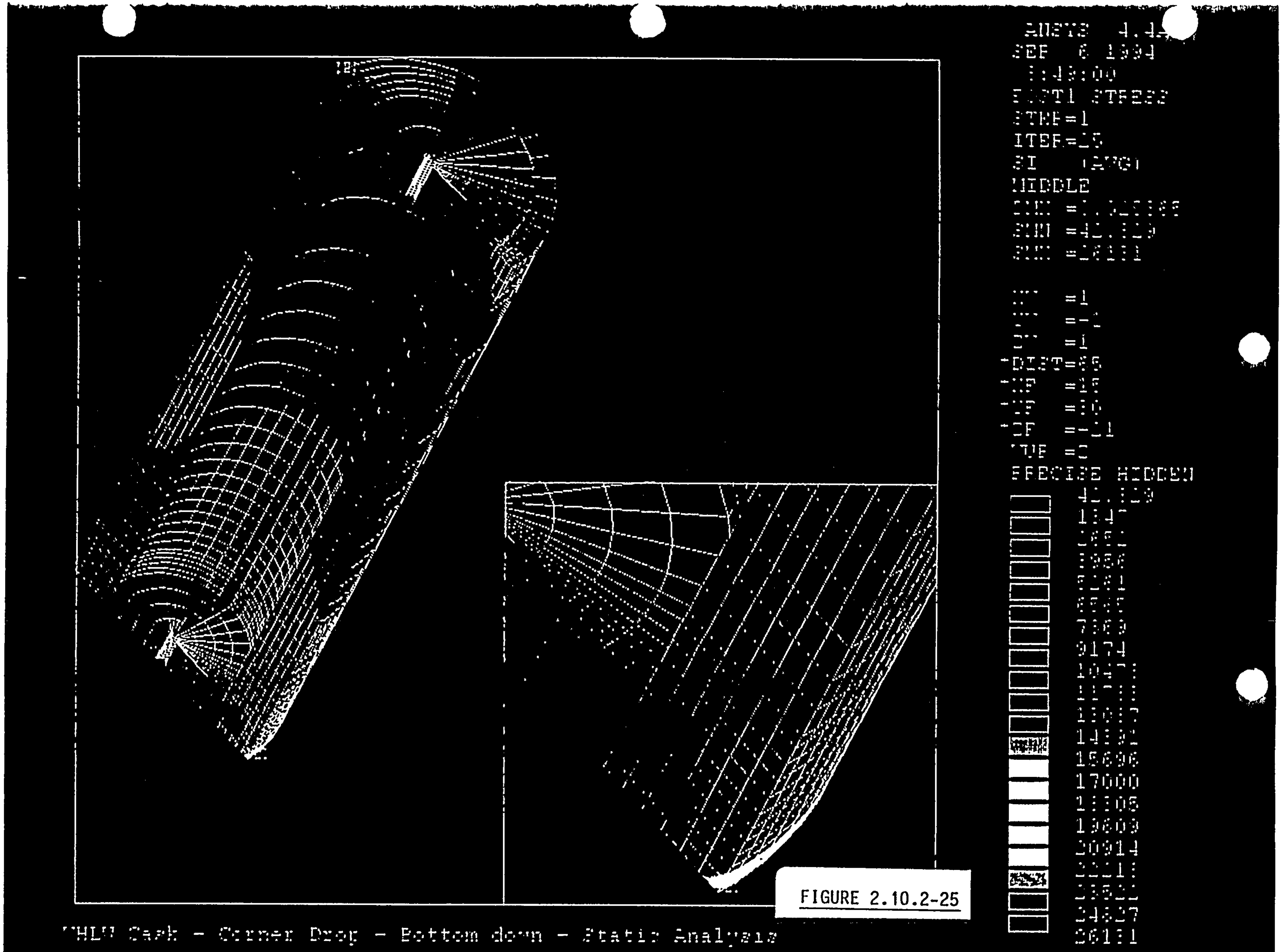
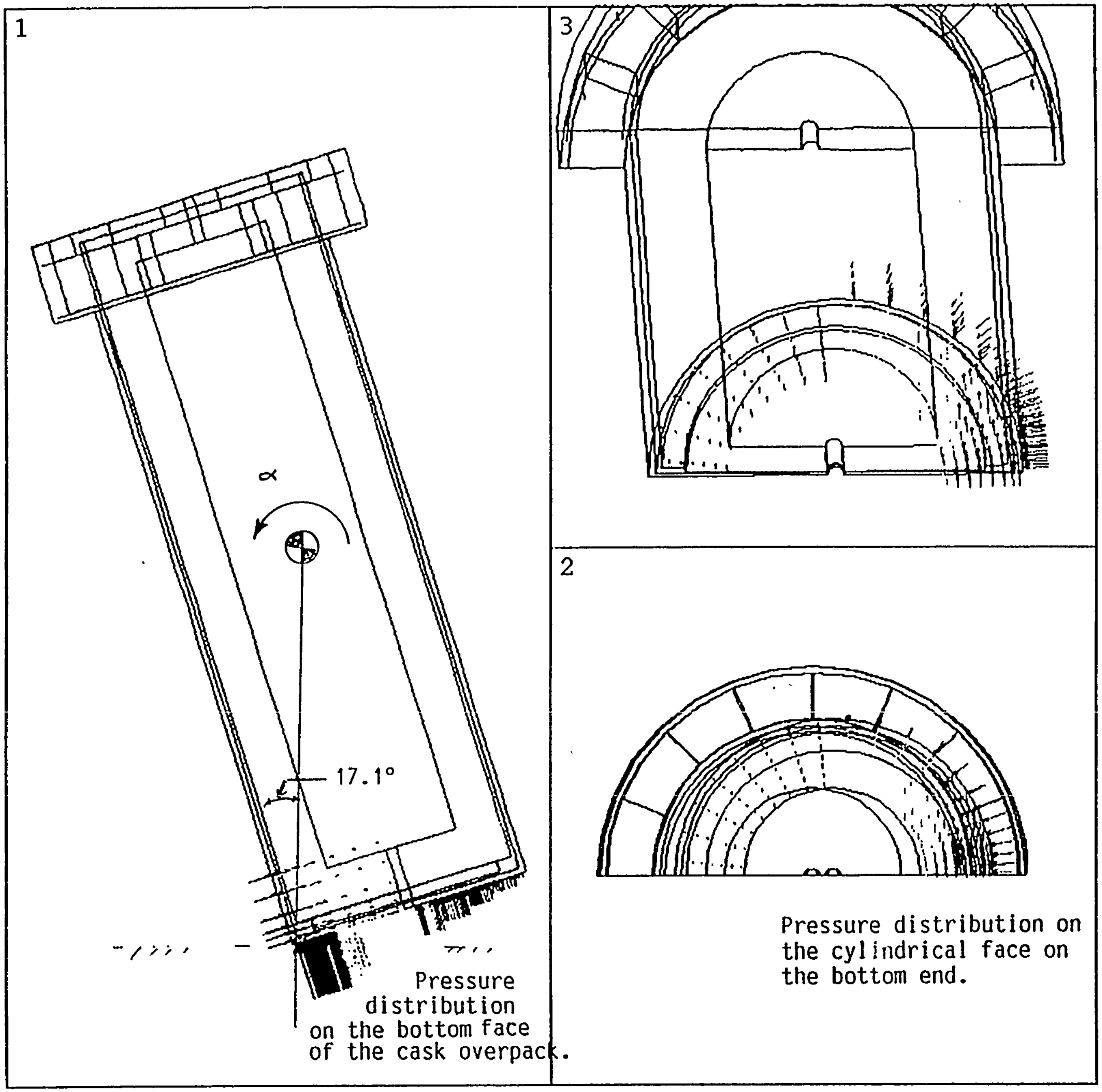


FIGURE 2.10.2-25



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EDGE

FIGURE 2.10.2-26

VHLW Cast - Corner Drop - Top Down - Static Analysis

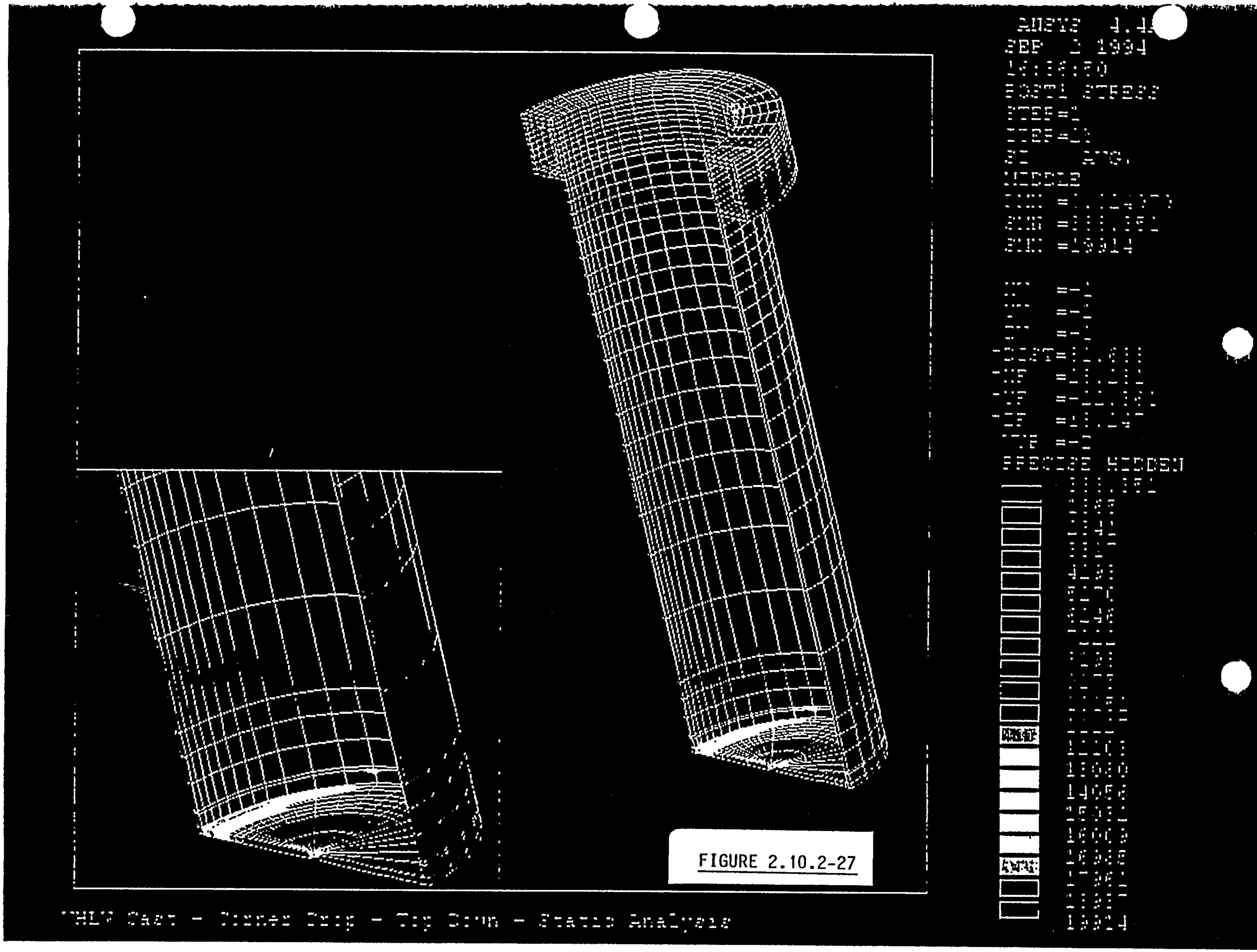


FIGURE 2.10.2-27

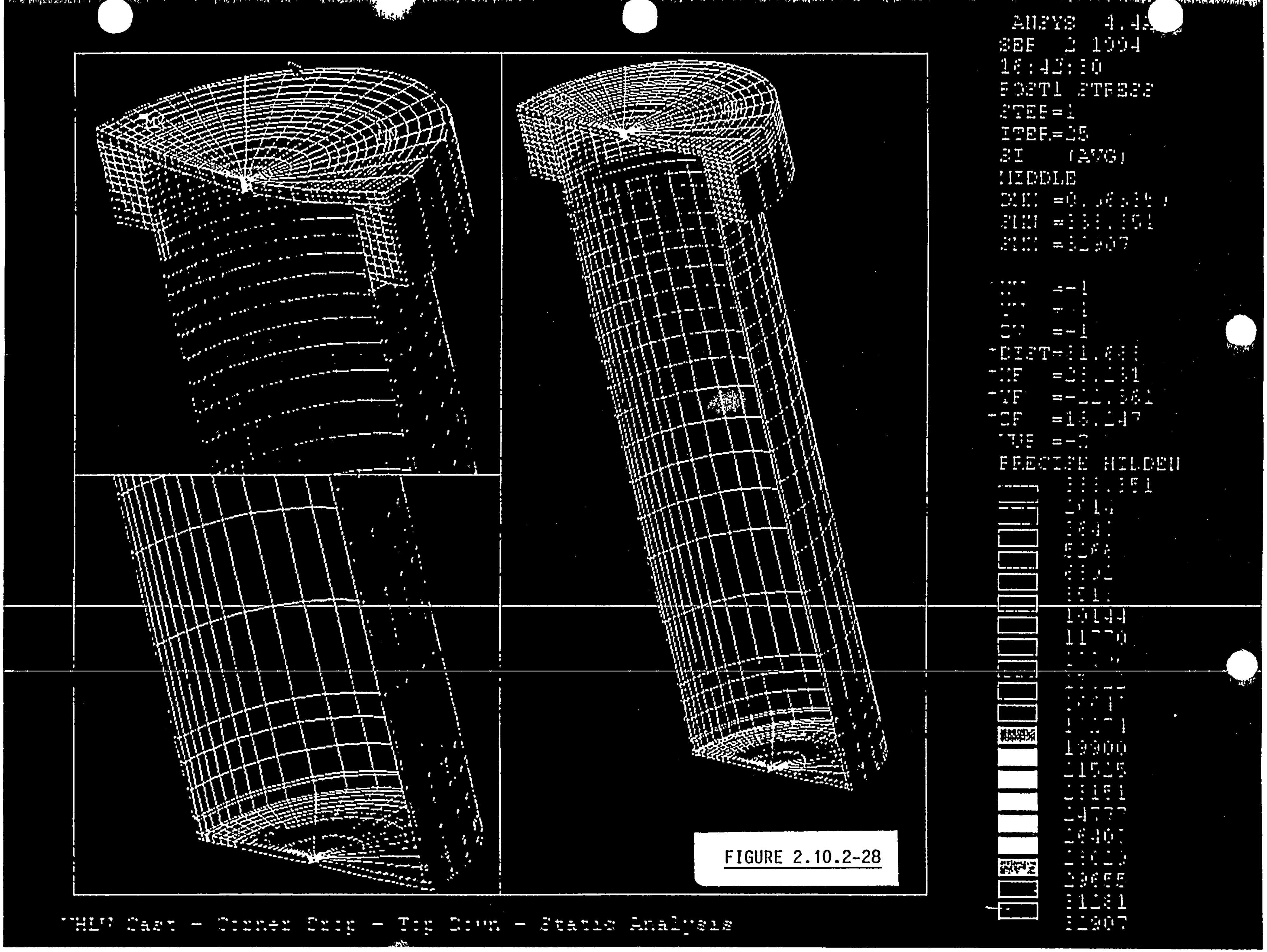


FIGURE 2.10.2-28

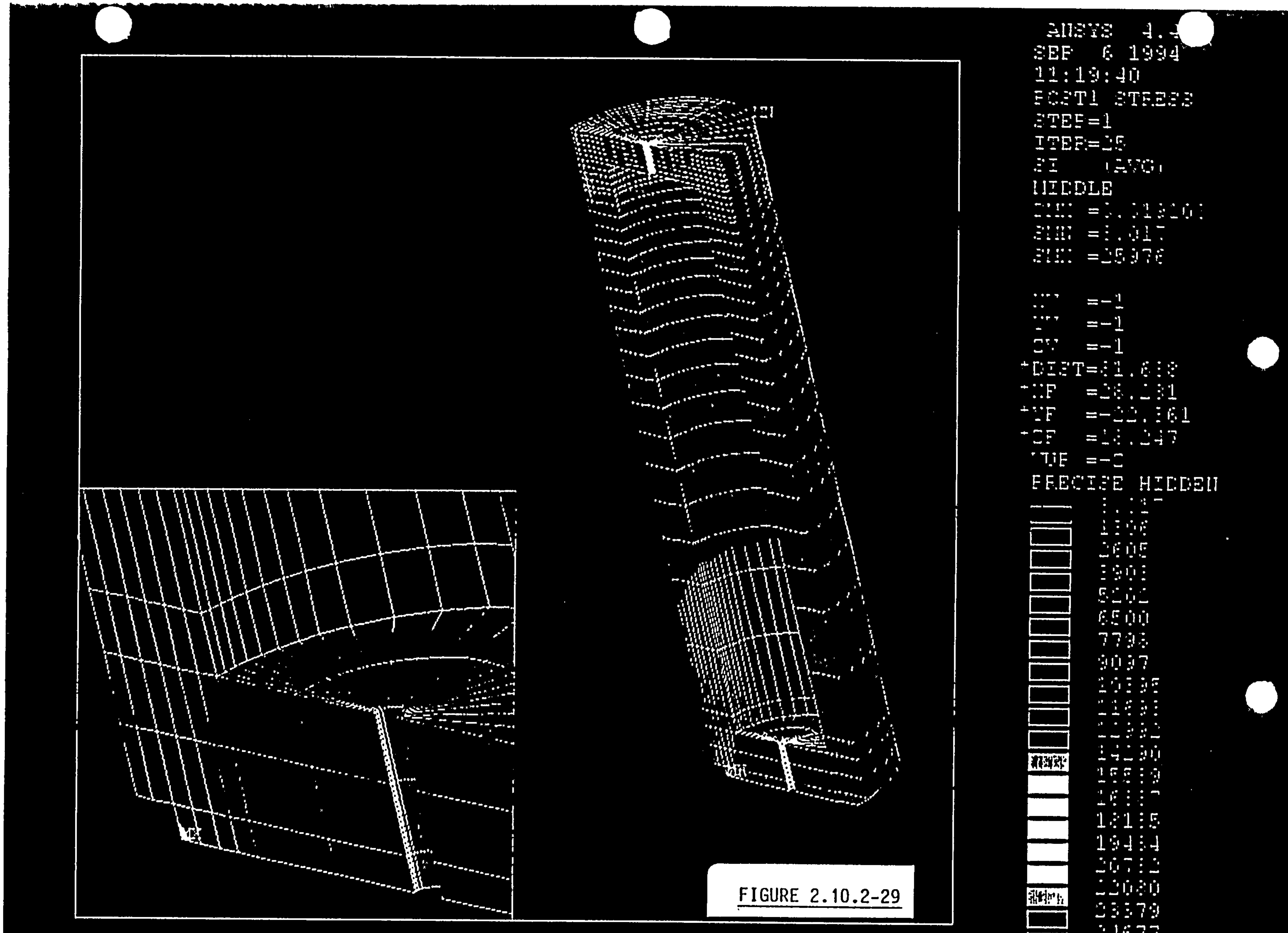


FIGURE 2.10.2-29

HLW Cast - Corner Drop - Top Down - Static Analysis

2.10.3 Pressure and Thermal Stress Analyses Results

A finite element model similar to the one used for the drop analysis was employed to perform the pressure and thermal stress evaluation during the fire accident. The main difference between the two models is that the pressure/thermal stress model consisted of only the overpack of the VHLW package and it extended to 22½° in the circumferential direction whereas the drop model consisted of the entire package and extended to 180° in the circumferential direction. The finite element model is shown in Figure 2.10.3-1.

Surface pressures were applied to the appropriate elements of the finite element model to simulate the internal and external pressure on the VHLW overpack. The stress intensities under internal pressure of 26 psi and external pressure of 21 psi are listed in Table 2.10.3-1.

To obtain the thermal stresses in the VHLW overpack under fire accident conditions, first a conservative temperature profile in the overpack was established from the maximum temperature and maximum temperature gradient at overpack barrel. The temperature on the surface of the overpack covered by the impact limiter was conservatively taken to be 275°F, the maximum temperature of the seal region. Fig. 2.10.3-2 shows the temperature profile used in the thermal stress computation. To combine the internal pressure with the fire transient, surface pressures were applied to the finite elements representing the internal cavity of overpack. The combined (thermal and pressure) stress intensity plot is shown in Figure 2.10.3-3. A maximum stress intensity of 28,347 psi (see Figure 2.10.3-3) results in the flange at the bolt locations. This is caused mainly by the bolt preload as well as due to the differential thermal expansion between the stainless steel overpack and carbon steel bolts.

TABLE 2.10.3-1

STRESS INTENSITY IN THE VHLW OVERPACK UNDER INTERNAL AND EXTERNAL PRESSURE LOADING

Overpack Component	Stress Intensity (psi) Under 26 psi Internal Pressure		Stress Intensity (psi) Under 21 psi External Pressure	
	Membrane	Membrane +Bending	Membrane	Membrane + Bending
Endplate	7,309	11,532	5,920	9,292
Barrel	1,013	5,136	828	4,139
Outer Cover	791	2,015	808	1,242
Annular Ring	218	416	149	351
Baseplate	2,435	4,550	1,266	2,518

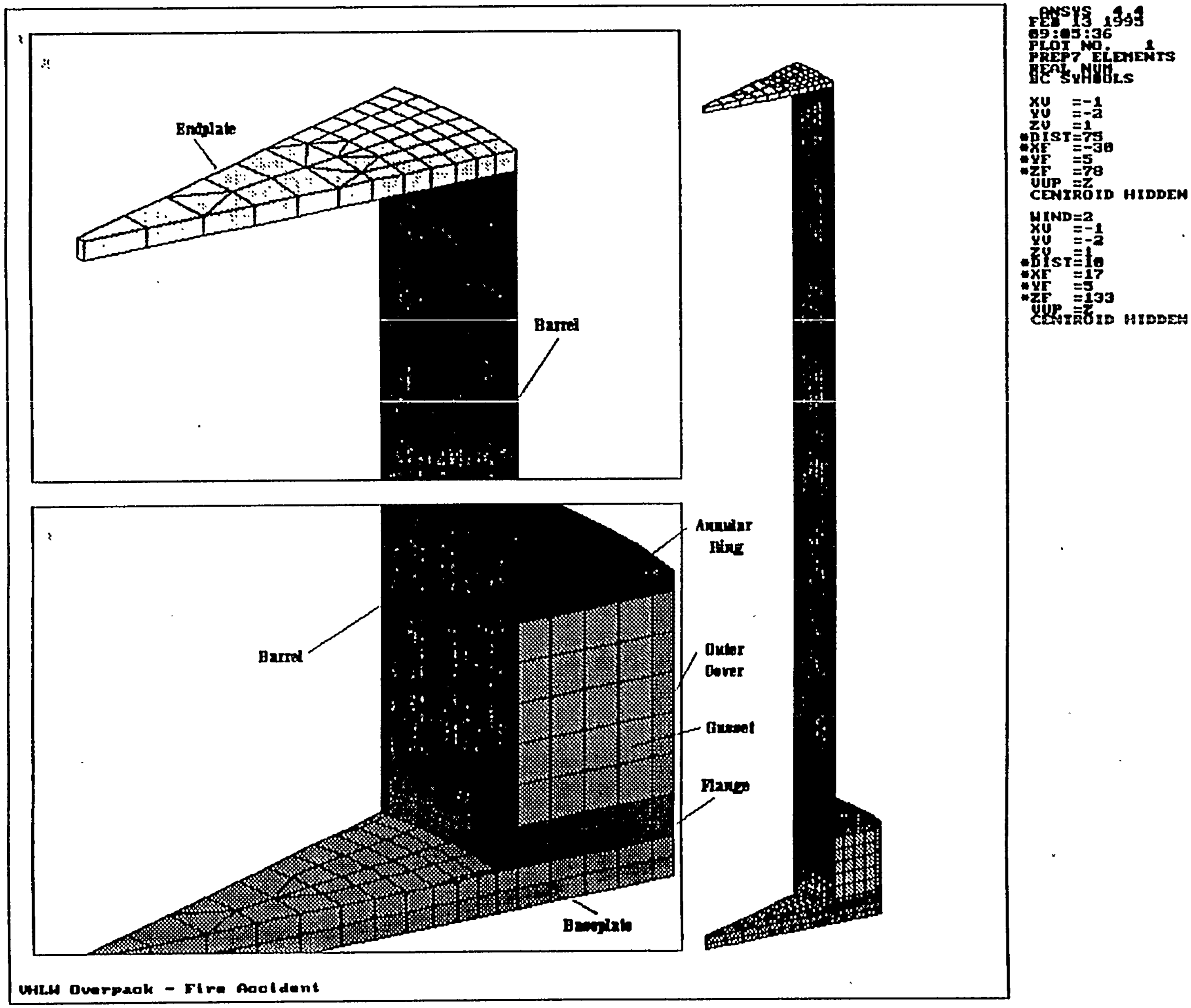


FIGURE 2.10.3-1

FINITE ELEMENT MODEL USED FOR PRESSURE/THERMAL STRESS EVALUATION

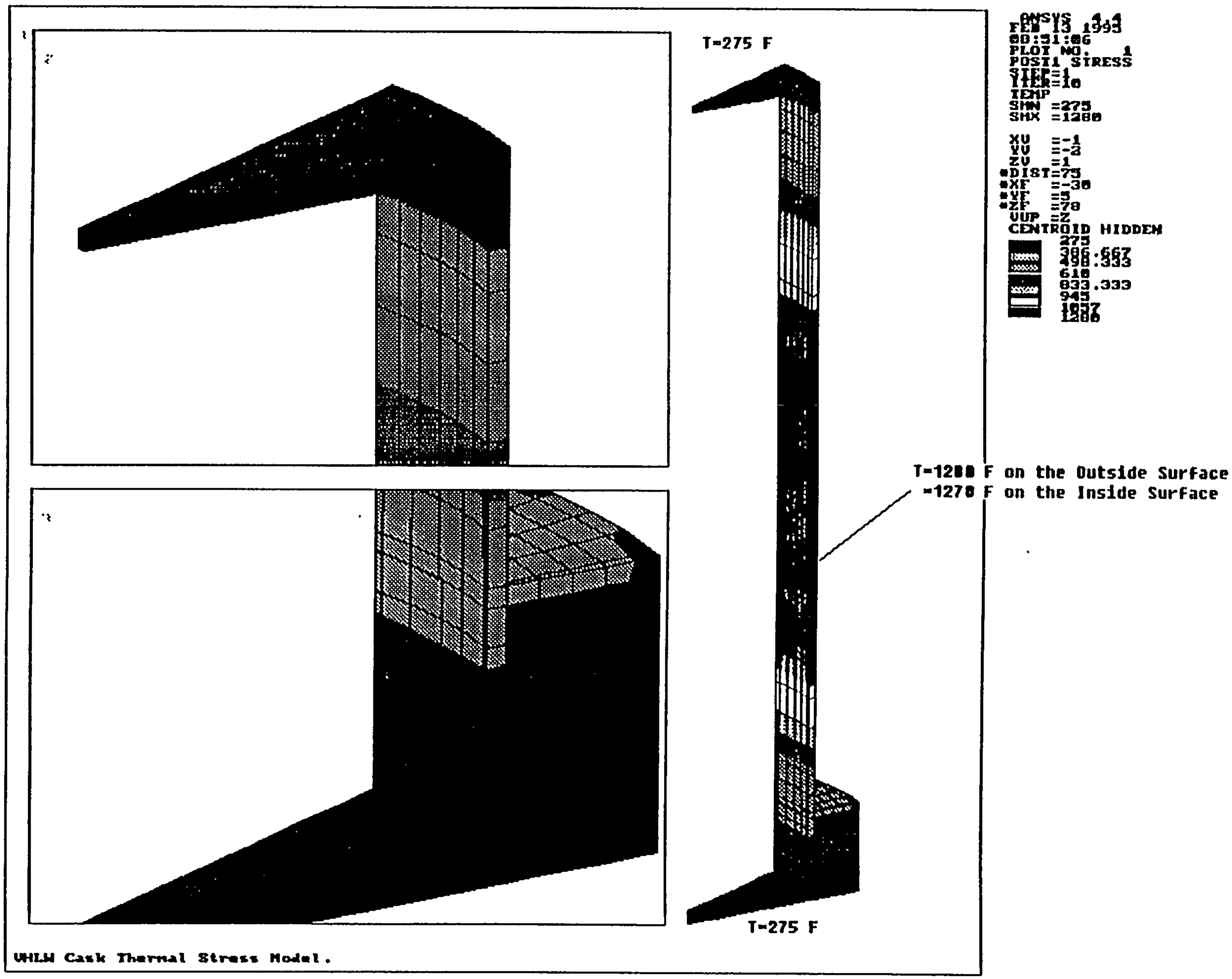
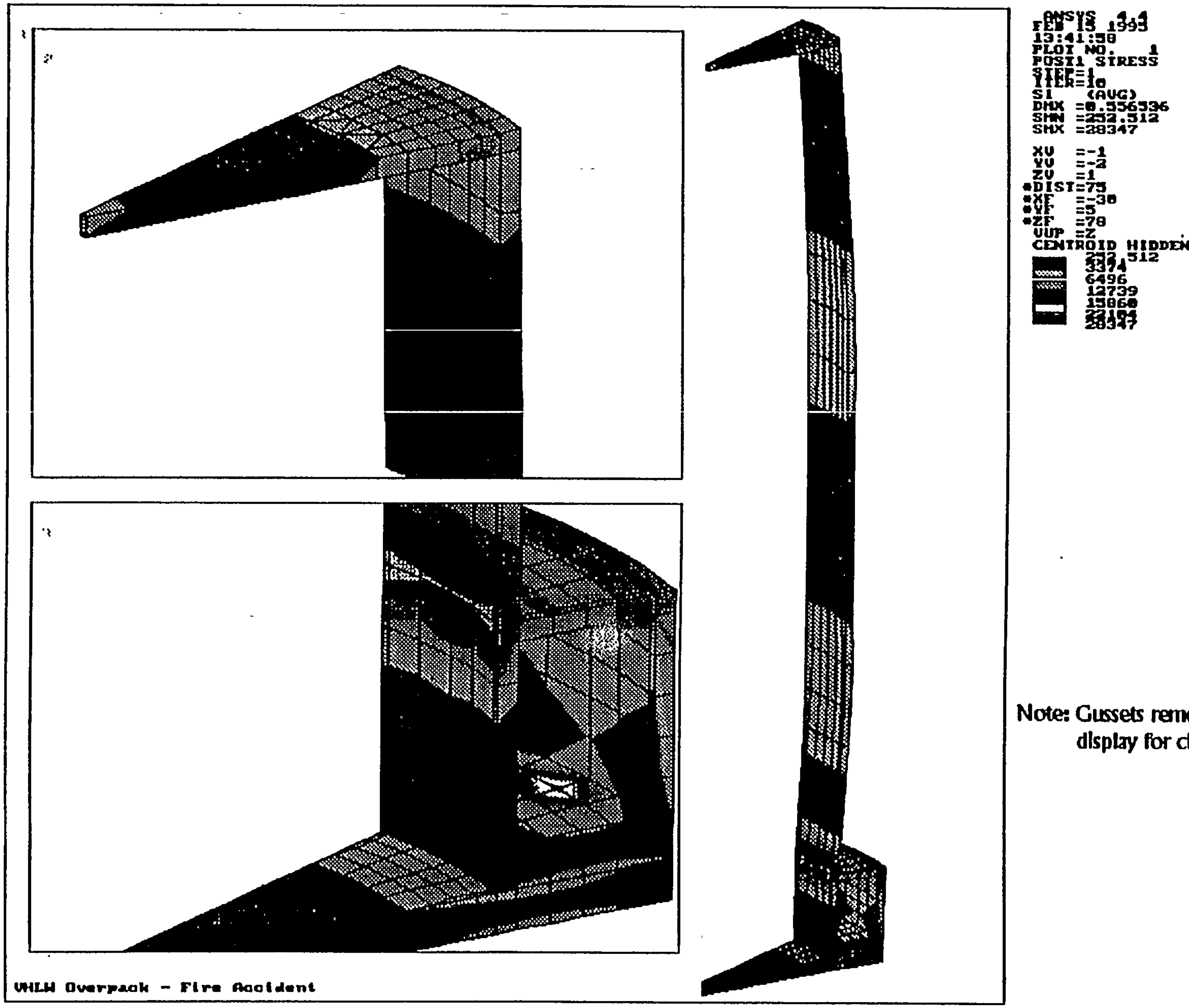


FIGURE 2.10.3-2
TEMPERATURE PROFILE IN THE OVERPACK UNDER FIRE ACCIDENT



Note: Gussets removed from the display for clarity.

FIGURE 2.10.3-3
<u>STRESS INTENSITY IN THE OVERPACK UNDER FIRE ACCIDENT</u>

2.10.4 References

2-1 USNRC Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels", March 1978.

2-2 USNRC Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks for Irradiated fuel", July 1988.

2-3 ASME Boiler and Pressure Vessel Code, Section II and III, 1992 Edition.

2-4 USNRC Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with Maximum Wall Thickness of 4 inches (0.1 m)", June 1991.

2-5 "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick", NUREG/CR-1815, UCRL-53013, June 15, 1981.

2-6 CNSI Proprietary Program CASKDROP Users Manual.

2-7 CNSI Proprietary Program CASKDROP Technical Manual.

2-8 CNSI Proprietary Program CASKDROP Verification Manual.

2-9 John H. Bickford, *An Introduction to the Design and Behavior of Bolted Joints*, Marcel Dekker Inc. Publication, 1981.

2-10 Nelms, "Structural Analysis of Shipping Casks, Vol. 3, Effects of Jacket Physical Properties and Curvature on Puncture Resistance", June 1968.

2-11 Swanson Analysis Systems, Inc. "ANSYS Engineering Analysis User's Manual," March 1983.

2-12 Rao, P. N. and Hoffer K. E., "The Mechanical Behavior of Flexible Polyurethance Foams under High Rate Loading" Journal of Materials, JMLSA, Vol. 8, No. 3, Sept 1971, pp. 704-717.

2-13 DeGisi, S. L. and Neet, Thomas E., "Predicting the Compressive Properties of Ridgid Urethane Foam", Journal of Applied Polymer Science, Vol. 20, 1976, pp. 2011-2029.

2-14 Neet, T. E., "Predicting Compressive Strength of Urethane Foams at High Strains, Bendix Kansas City Division, Report BDX-613-1103, Contract AT(29-1)-613 USAEC, May 1974.

2-15 McConnel, P., Ritchey G. and Adler, W., "Effect of Loading Rate on the Compressive Strength of Constrained Impact Limiter Materials", General Research Corporation, Report CR-86-1063 for Sandia National Laboratories (TTC), July 1986.

CHAPTER THREE

THERMAL EVALUATION

3.0 THERMAL EVALUATION

This chapter identifies, describes, discusses, and analyzes the principal thermal engineering design of the VHLW cask. Compliance with the performance requirements of 10 CFR 71 is demonstrated.

3.1 Discussion

The VHLW cask is a right circular cylinder with a removable lid, enclosed for transport in a cylindrical overpack and removable impact limiters at each end.

Decay heat from the VHLW contents is transferred through the VHLW canister to the inner wall of the shield insert by radiation, convection, and conduction through the air gap. The heat is transferred though the shield insert by conduction, then across the gap between the shield insert and the overpack by radiation, convection, and conduction through the air in the gap. Then, the heat is conducted across the overpack wall, and transmitted to the environment via convection and radiation.

The impact limiters are metal enclosures filled with polyurethane foam and are used to absorb impact energy during an accident involving impact. These impact limiters act as insulating barriers to heat flow, reducing the heat flow through the regions covered by the impact limiters to essentially zero. During the hypothetical fire transient accident condition specified in 10 CFR 71.73, these limiters serve to provide thermal protection to the top and bottom ends of the package.

The results of the thermal analyses are summarized in Table 3-1. These analyses results are discussed in detail in Sections 3.4 and 3.5.

3.2 Summary of Thermal Properties of Materials

Thermal properties of the materials included in the thermal model of the package are shown in Tables 3-2, 3-3 and 3-4. Temperature independent thermal properties were used for the materials since the properties vary slightly with temperature.

3.2.1 Overall Surface Heat Transfer Coefficient

The exposed outer surface of the cask transfers heat to the environment by natural convection and thermal radiation. These heat transfer mechanisms can be quantified using correlations given in typical heat transfer texts. Reference 3-1 gives a correlation for natural convection flows tangential to the heat transfer surface, such as along the horizontal surface of the VHLW cask during transport. A calculation that derives this overall heat transfer coefficient is presented in Appendix 3.6.1. The overall heat transfer coefficients calculated for the VHLW cask are presented in Table 3-4.

3.3 Technical Specifications of Components

Not Applicable.

3.4 Thermal Evaluation for Normal Conditions of Transport

The regulatory requirements for the normal conditions of transport are given in 10 CFR 71.71. This section demonstrates how the VHLW cask and contents responds to the thermal loadings specified in 10 CFR 71.71 and listed in Table 3-5.

These loadings must be considered in the worst case scenario for the feature under consideration. The normal hot and cold loadings specified in 10 CFR 71.71(b) are considered here only to determine the temperature distributions to be used in accordance with the other loadings specified in the subpart. The hot and cold loadings specified in 10 CFR 71.71(c)(1) and (2), respectively, result in the worst case normal condition temperature distributions. The normal hot loading case is used as the initial condition loading for the hypothetical accident conditions thermal analyses, described in Section 3.5.

3.4.1 Thermal Model

3.4.1.1 Analytical Model

The steady-state temperature distributions through the VHLW cask and contents during the various normal conditions of transport loading conditions are analyzed by means of a two-dimensional, axisymmetric finite element model of the cask. The model is shown in Figure 3-1. This model is evaluated using the ALGOR finite element analysis system (Ref. 3-2).

This model represents the major components of the cask, as well as the VHLW and canister. A number of conservatisms are built into the analysis model. The gaps between the VHLW canister and the shield insert wall and between the shield insert and overpack are represented by the conduction of air only, neglecting the radiation and convection contributions to the transfer of heat out of the cask. Also, the impact limiters are represented on the cask as perfect insulators, allowing no heat to travel out the areas of the cask covered by the limiters.

The overall surface heat transfer coefficient applied to all exposed surfaces is detailed in Appendix 3.6.1, and the temperature-dependent thermal properties are presented in Table 3-3. These values are calculated for the shield insert and overpack in a horizontal transport orientation. The values used in the Appendix 3.10.1 evaluation are chosen to be conservative whenever possible.

As shown in the assumptions listed in Table 3-5, there are two load cases considered in this section. The first load case is performed for an ambient temperature of 100°F. The results of this load case analysis are used as the initial temperature distribution for the hypothetical accident discussed in Section 3.5. The second case, normal conditions of transport, is also performed at 100°F ambient, and also includes a solar insolation factor on the curved surfaces based on the 10 CFR 71.71 requirement of 400 gcal/sq cm per 12-hour period. For conservatism, the average solar insolance over the 12-hour application period is applied in the steady-state, resulting in higher temperatures. The results of these analyses are summarized in Table 3-1.

3.4.1.2 Test Model

Not Applicable.

3.4.2 Maximum Temperatures

The maximum temperature calculated during the normal conditions of transport analyses is 587°F (308.3°C), and occurs at the center of the model in the VHLW itself for the load case with solar insolance. The maximum temperatures in other components also occurs in the load case with solar insolance.

Maximum temperatures are conservative due to the assumption of a 1000 watt decay heat load. This decay heat value is significantly higher than any expected value for canisters of VHLW. The decay heat from a reference VHLW - SR canister is 690 watts (Ref. 3-4, page 10) and the decay heat from a VHLW - WV canister is a maximum of 390 watts (Ref. 3-7, page 9).

The maximum surface temperatures of the cask, as shown in Table 3-1, are 114.1°F (45.6°C) without solar insolation and 169.9°F (76.6°C) with solar insolation. The maximum temperature without solar insolation does not exceed the 122°F (50°C) value given in 10 CFR 71.43(g), allowing the cask to be transported in non-exclusive use shipment from a thermal standpoint. Other maximum temperatures also do not exceed their maximum allowable service temperatures, as shown in Table 3-1.

3.4.3 Minimum Temperatures

The waste transported in the cask may not be a heat source, so the minimum temperature the cask could reach under these circumstances would be the minimum ambient temperature, -40°F (-40°C). All components used in the cask are serviceable at this temperature.

3.4.4 Maximum Internal Pressure

The maximum internal pressure of the cask is calculated assuming that the gas within the cask (air or inert gas) behaves as an ideal gas. The cask is assumed to be completely dry.

The temperature of the gas mixture within the cask is assumed to be equal to the average temperatures of the canister surface and the cavity wall. From Table 3-1, the maximum canister surface temperature is 538.9°F, and the cavity wall temperature is 253.3°F, giving a mean temperature of about 396.1°F for the gas. Assuming that the cask is initially filled with atmospheric pressure gas at a temperature of -20°F, the maximum pressure in the cask is calculated based on the ideal gas law as follows:

$$P_{max} = \left(\frac{396.1°F + 460°F}{-20°F + 460°F} \right) (14.7 \text{ psia}) = 28.6 \text{ psia}$$

Additional pressure buildup due to gas production in the VHLW by radioactive decay has been calculated in Section 4.2.2 to be less than 0.01 psia. Although the gas temperatures between the ductile iron shielding and the transport overpack are lower, the temperature within the ductile iron shielding are used in order to be conservative.

The gauge pressure in the cask under normal conditions of transport is equal to the absolute pressure of the gas mixture within the cask minus the outside ambient pressure. The maximum gauge pressure for this cask during normal conditions of transport (reduced external pressure conditions per 10 CFR 71.1(c)(3)) is therefore:

28.6 psia - 3.5 psia = 25.1 psig

Section 2.10.2.9 discusses the impact of the 25.1 psig internal pressure on cask performance.

3.4.5 Maximum Thermal Stresses

The temperature gradient through the side wall of the cask under normal conditions of transport is due to the 1000 watt decay heat load of the VHLW. Under normal conditions of transport, the temperature difference between the inside and the outside walls of the overpack is only 0.3°F, and the difference between the inside and outside walls of the shield insert is a maximum of 2.3°F. The stresses resulting from this temperature gradient will be insignificant. Section 2.10 provides further discussions of the effect of these thermal stresses.

3.4.6 Evaluation of Package Performance for Normal Conditions of Transport

All temperatures and stresses within the package due to normal conditions of transport loading conditions have been demonstrated to be within allowable service ranges for all components and materials used in the cask. Seal temperatures range from -40°F (-40°C) to 204.1°F (95.6°C) and are within the silicone operating range of -60°F to 450°F (Ref. 3-3). The temperatures that all structural materials experience are below their melting points.

The maximum temperature gradient in any single component of the cask occurs in the shield insert, and is 2.3°F. The stresses resulting from this thermal gradient are discussed in Section 2.10.

The temperature gradient across the cask cavity is calculated to be 284°F. This value is quite conservative, and results from the use of the minimum VHLW canister diameter and the maximum tolerated shield insert cavity diameter at the same time. Actual temperature gradients across this gap are likely to be smaller.

3.5 Hypothetical Accident Thermal Evaluation

The regulatory requirements for the hypothetical accident conditions of transport are given in 10 CFR 71.73. This section demonstrates how the VHLW cask and contents respond to the thermal loadings specified in 10 CFR 71.73, and listed in Table 3-5.

Specifically, 10 CFR 71.73(c)(3) requires that the transport package be evaluated for exposure to a heat flux equivalent to that of a 1475°F (800°C) radiation environment with an emissivity of at least 0.9 for a period of at least 30 minutes. This loading is meant to simulate an accident in which the package is completely surrounded by fire. Additionally, the convective effects of still air must be considered, if significant. Following this transient, the package must be evaluated for a cooldown period during which no artificial cooling may be assumed.

The initial temperature distribution within the package is assumed to be that calculated from the same boundary conditions as used in the normal conditions of transport analysis presented in Section 3.4 except insolation is not included. Furthermore, these loadings are required to be applied to a package that has been previously subjected to the events specified in 10 CFR 71.73(c)(1) and (2).

3.5.1 Thermal Model

3.5.1.1 Analytical Model

The model used to evaluate the loadings applied during the hypothetical accident is the same as that used in the normal conditions of transport analyses. Proper convergence during the transient is assured by reducing the size of the timesteps and re-analyzing until temperatures do not change significantly.

The package initial surface loadings and ambient temperature values are applied as listed in Table 3-6, in accordance with the 10 CFR 71.73 requirements stated above. The impact limiters are assumed to remain attached to the package after the free drop and puncture accident events as discussed in Section 2.6. Then, transient temperatures are calculated by exposing the package to a 1475°F (800°C) thermal radiation environment for 30 minutes which simulates a fire transient.

After the 30 minute fire transient, the package surface loadings and ambient temperature values are returned to their pre-fire values. A 12-hour transient is then analyzed, allowing time for all cask components, as well as the VHLW, to reach maximum temperatures and begin to decline in value. These maximum temperatures are listed in Table 3-1, along with the time at which they occur.

maximum average gas temperature is 750°F and occurs at approximately the end of the fire transient. Assuming that the cask is initially filled with atmospheric pressure gas at a temperature of -20°F, the maximum pressure in the cask is calculated based on the ideal gas law as follows:

$$P_{max} = \left(\frac{750\,°F + 460\,°F}{-20\,°F + 460\,°F} \right) (14.7 \text{ psia}) = 40.4 \text{ psia}$$

The maximum gauge pressure in the cask under accident condition loadings is equal to the absolute pressure of the gas mixture within the cask minus the outside ambient pressure. The maximum gauge pressure for this cask during the fire transient is therefore:

40.4 psia - 14.7 psia = 25.7 psig

Section 2.7.3 discusses the impact of the 25.7 psig internal pressure on cask performance.

3.5.5 Maximum Thermal Stresses

The maximum temperature differential across the stainless steel overpack of the VHLW cask is 36°F, and occurs at approximately 10 minutes after the beginning of the fire transient. The maximum temperature difference across the ductile iron shield insert is 12°F, and occurs at about 30 minutes after the end of the fire transient.

The maximum average wall temperatures for the transport overpack and shield insert wall are 1275°F and 239°F, respectively. The thermal stresses resulting from temperature gradients during the hypothetical accident conditions are discussed in Section 2.0.

3.5.6 Evaluation of Package Performance of the Hypothetical Accident Conditions

All temperatures and stresses within the package due to normal conditions of transport loading conditions have been demonstrated to be within allowable service ranges for all components and materials used in the cask. Seal temperatures range from 152.1°F (66.7°C) at the start of the fire to 204.1°F (95.6°C) at 6.3 hours after the end of the 30-minute fire, and are within the silicone operating range of -60°F to 450°F (Ref. 3-3). The temperatures that all structural materials experience are below their melting points.

3.6 Appendices

3.6.1 Convection and Radiation Heat Transfer Coefficients for Horizontal Cylinders

3.6.1.1 Introduction

Calculations discussed in this section are prepared using the Mathcad, Version 4.0 computer

A major conservatism in this calculation involves the application of thermal radiation during the 30-minute fire transient. The ALGOR finite element code transient analysis module is not capable of handling non-linear equations such as that presented by the Stefan-Boltzmann law of radiation, which includes a fourth-order temperature factor. To linearize the calculation, the code bases the surface heat flux calculation on the initial surface and ambient temperatures. This conservatism could be minimized by performing a series of calculations over the 30-minute evaluation interval, updating the model with the newly calculated temperatures before running the next step to reduce the net heat flux into the package. However, the transient has been performed using only one step, so that the heat flux entering the package is based on the temperature differential between the overpack surface (~114°F) and the fire (1475°F) at the start of the transient, resulting in a conservative heat flux throughout the transient.

During the cooldown phase, the value used for the overall heat transfer coefficient is the same as that used during the original normal condition steady-state analysis, which was chosen based on the expected surface temperature of 114°F. This results in a lower heat transfer coefficient, and a lower rate of heat removal from the cask, allowing the heat to travel deeper into the cask and contents.

3.5.1.2 Test Model

Not applicable.

3.5.2 Package Conditions and Environment

As demonstrated in Section 2.6, damage to the package caused by free drop and puncture tests will not significantly alter the thermal characteristics of the package. Even after crushing, the impact limiters continue to act as thermal barriers.

3.5.3 Package Temperatures

Maximum temperatures and their time of occurrence during the hypothetical fire transient and subsequent cooldown transient are listed in Table 3-1. Additionally, a time-history plot of the maximum temperatures of important cask components and cask contents is shown in Figure 3-2. The maximum calculated temperatures are less than the maximum allowable temperatures of each component, as shown in Table 3-1.

3.5.4 Maximum Internal Pressures

As in Section 3.4.4, the maximum internal pressure of the cask is calculated assuming that the gas within the cask (air or inert gas) behaves as an ideal gas. The cask is assumed to be completely dry.

The temperature of the gas mixture within the cask is assumed to be equal to the average temperatures of the ductile iron shielding surface and the transport overpack wall. The based on the Prandtl number "Pr", and the Rayleigh number, "Ra" which is in turn a function of the Grashof and Prandtl numbers. The definition of "b" and the Rayleigh, Grashof, and Prandtl numbers are presented below:

$$b = \frac{1.17}{\left[1 + \left(\frac{0.5}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}$$

$$Ra_L = Gr_L \cdot Pr$$

$$Gr_L = \frac{g\,\beta\,(T_s - T_e)\,L^3}{\nu^2}$$

$$P_r = \frac{\nu}{\alpha}$$

where:

g = gravitational constant (9.8 m/sec^2)
β = Boussinesq approximation ($\sim 1/T$)
T_s = cask surface temperature
T_e = environment (ambient) temperature (100°F)
ν = kinematic viscosity
α = thermal diffusivity

Next, the material properties for air can be defined. As shown above, the ambient temperature is conservatively assumed to be 100°F (311°K):

T_e = 311°K

The properties will be evaluated at the bulk (average) temperature, T_{av}, and the surface temperature will be varied to produce a set of temperature-dependent values for input to the computer model. To demonstrate the calculational method the surface temperature (T_s) will be assumed to be 125°F (325°K):

$$T_{av} = \frac{T_s + T_e}{2}$$

Now, the Boussinesq approximation, or thermal expansion coefficient, can be defined, using program. All calculations have been verified using hand calculations.

3.6.1.2 Overall Heat Transfer Coefficient

To determine the rate of heat removal on the surface of the cask using the ALGOR finite element analysis system, an overall heat removal coefficient must be determined and then applied to the finite element model as a boundary condition on the cask surface elements. Heat is removed from the cask by two modes: convection and thermal radiation. These factors are separately calculated and summed to determine the overall heat transfer coefficient for the cask surface as shown below:

$$h_t = h_c + h_r$$

where:

h_t = total heat transfer coefficient
h_c = convection coefficient
h_r = radiation coefficient

The values of the convection and radiation coefficients are calculated in the following sections.

3.6.1.3 Convection Heat Transfer Coefficient

The mean coefficient of convective heat transfer, h_c, is generally represented in terms of the mean Nusselt number according to the following equation (Ref.: 3-1, page 570):

$$h_c = \frac{N_L k}{L}$$

where:

N_L = Nusselt number
k = thermal conductivity of air
L = characteristic length of heat flow surface (approximately cask circumference)

Reference 3-1 page 577 presents a general correlation applicable to a wide variety of natural convection flows for which the primary buoyant driving force is directed tangential to the heat transfer surface. This correlation is given by:

$$N_L = \left(a + 0.331\ b \cdot Ra_L^{\frac{1}{6}}\right)^2$$

where "a" is a geometry dependent coefficient, "b" is an empirically defined coefficient

$$b = \frac{1.17}{\left[1 + \left(\frac{0.5}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} = 0.979$$

$$Ra_L = Gr_L \cdot Pr = (3.803 \times 10^{10})(0.704) = 2.677 \times 10^{10}$$

$$N_L = \left(a + 0.331\ b \cdot Ra^{\frac{1}{3}}\right)^2 = \left(1.06 + (0.331)(0.979)(2.677 \times 10^{10})^{0.1667}\right)^2 = 352.83$$

We can now define the convection coefficient as a function of the Nusselt number, thermal conductivity, and length, "L":

$$h_c = \frac{N_L k}{L} = \frac{(352.83)(0.028\ \text{watt}/\text{m-}^\circ\text{K})}{3\ \text{m}} = 3.25\ \text{watt}/\text{m}^2\text{-}^\circ\text{K}$$

The value of the convection coefficient in metric and English units are stated below:

$$h_c = 3.25\ \frac{\text{watt}}{\text{m}^2 \circ \text{K}}$$

$$h_c = 0.0040\ \frac{\text{BTU}}{\text{hr inch}^2 \circ \text{R}}$$

3.6.1.4 Thermal Radiation Heat Transfer Coefficient

The calculation of the radiation heat transfer coefficient is more straightforward, and can be accomplished using the Stefan-Boltzmann law for radiation heat transport as follows:

$$q_r = \sigma \epsilon \left(T_s^4 - T_e^4\right)$$

where:

σ = Stefan-Boltzmann constant
ϵ = Cask surface emissivity

These values are defined as follows:

the average temperature:

$$\beta = \frac{1}{T_{av}}$$

$$T_{av} = 316.5° K$$

A table of values for the properties of air, including the Prandtl number, are presented in the appendices of Reference 3-1. These values are used to linearly interpolate for properties at T_{av} = 318°K, calculated above. Linear interpolation yields:

υ = 1.751×10^{-5} m^2/s
Pr = 0.704
k = 0.028 watt/m-°K

For the horizontal cylinder representation of the VHLW cask, the values for "a" and "L" are defined as follows:

a = 1.06 (Ref. 3-1)
L = πD (Ref. 3-1, page 578)
D ≈ 1 m (cask diameter is 1 m)
L ≈ 3 m

Now that the air and cask properties have been defined, the solution can be calculated, starting with the Grashof number as follows:

$$Gr_L = \frac{g\beta(T_s - T_e)L^3}{v^2}$$

$$Gr_L = \frac{(9.8\ m/s^2)\left(\frac{1}{318° K}\right)(325 °K - 311 °K)(3\ m)^3}{(1.751 \times 10^{-5}\ m^2/s)^2} = 3.803 \times 10^{10}$$

The Nusselt number can also be calculated using values for "b" and the Rayleigh number as calculated below:

By varying the value of the surface temperature, the values of the heat transfer coefficient can be determined as a function of temperature, providing data for the temperature-dependant thermal properties. Table 3-4 shows the overall heat transfer coefficient calculated using this method for various cask surface temperatures.

σ = 5.67×10^{-8} watt/m^2-K^4
ϵ = 0.9 (Approximate value for painted or dull surface)

Expressed in terms of a heat transfer coefficient, the equation becomes:

$$q_r = h_r(T_s - T_e)$$

By equating the two definitions for heat transfer rate, the value of the radiation heat transfer coefficient can be defined as follows:

$$h_r = \frac{\sigma\epsilon(T_s^4 - T_e^4)}{(T_s - T_e)}$$

Substituting T_e = 311°K and T_s = 325°K yields the following values for the radiation coefficient in metric and English units:

$$h_r = 6.57 \frac{\text{watt}}{\text{m}^2 \ °\text{K}}$$

$$h_r = 0.00803 \frac{\text{BTU}}{\text{hr inch}^2 \ °\text{R}}$$

3.6.1.5 Total Heat Transfer Coefficient

The total heat transfer coefficient can be determined by summing the convection and radiation heat transfer coefficients as follows:

$$h_t = h_c + h_r$$

Substituting yields the following values in metric and English units:

$$h_t = 3.25 \frac{\text{watt}}{\text{m}^2 \cdot \text{K}} + 6.57 \frac{\text{watt}}{\text{m}^2 \ °\text{K}} = 9.82 \frac{\text{watt}}{\text{m}^2 \cdot \text{K}}$$

$$h_t = 0.0040 \frac{\text{BTU}}{\text{hr inch}^2 \ °\text{R}} + 0.00803 \frac{\text{BTU}}{\text{hr inch}^2 \ °\text{R}} = 0.012 \frac{\text{BTU}}{\text{hr inch}^2 \ °\text{R}}$$

TABLE 3-2
THERMAL PROPERTIES OF MATERIALS FOR VHLW CASK

Material (Zone)	Density (lb/in^3)	Conductivity (BTU/hr-in-F)	Specific Heat (BTU/lb-F)	Data Source
VHLW (Contents)	0.0976	0.0457	0.1815	Ref. 3-7
Stainless Steel (Overpack)	0.285	0.77	0.1194	Ref. 3-5
Ductile Iron (Shield insert)	0.253	1.69	0.129	Ref. 3-6

TABLE 3-1
SUMMARY OF THERMAL ANALYSIS RESULTS

Location	Normal Conditions: Max. Temp. w/o Solar °F (°C)	Normal Conditions: Max. Temp. w/ Solar °F (°C)	Hypothetical Accident Conditions: Max. Temp. °F (°C)	Hypothetical Accident Conditions: Time (hours)	Max. Allowable °F (°C)
VHLW	548.6 (287.0)	587.0 (308.3)	572 (300)	12.4	844 (451) (Note 1)
VHLW Canister	500.8 (260.4)	538.9 (281.6)	523 (273)	11.6	801 (427) (Note 2)
Shield insert	202.7 (94.8)	253.3 (122.9)	240 (116)	6.3	1341 (727) (Note 3)
Transport Overpack	114.3 (45.7)	170.2 (76.8)	1280 (693)	0.5	2000 (1095) (Note 4)
Outer Surface	114.1 (45.6)	169.9 (76.6)			
O-Rings (Transport Overpack)	152.1 (66.7)	204.1 (95.6)	275 (135)	2.7	450 (232) (Note 5)

Notes:
(1) Glass transition temperature (Ref. 3-7, page 5).
(2) Maximum canister wall temperature analyzed that gives good structural strength (Ref. 3-4, p. 16).
(3) Temperature at which the crystalline structure of iron changes (Ref. 3-8, p. 6-17).
(4) Maximum temperature without excessive scaling (Ref. 3-8, p. 6-37).
(5) Ref. 3-3, page A3-35.

TABLE 3-4
OVERALL HEAT TRANSFER COEFFICIENT FOR VHLW CASK SURFACE

Surface Temperature (deg F)	Surface Heat Transfer Coefficient (BTU/hr-in^2-F)
100	1.240×10^{-5}
102	9.319×10^{-3}
104	9.774×10^{-3}
106	1.013×10^{-2}
108	1.042×10^{-2}
110	1.066×10^{-2}
112	1.088×10^{-2}
114	1.109×10^{-2}
116	1.127×10^{-2}
118	1.144×10^{-2}
120	1.160×10^{-2}
140	1.288×10^{-2}
160	1.389×10^{-2}
170	1.440×10^{-2}
180	1.479×10^{-2}
200	1.562×10^{-2}

TABLE 3-3
TEMPERATURE-DEPENDENT THERMAL PROPERTIES FOR AIR

Temperature		Density (lb/in^3)	Conductivity (BTU/hr-in-F)	Specific Heat (BTU/lb-F)
°F	°K			
80	300	4.25e-05	1.26e-03	0.2402
90	*	4.19e-05	1.28e-03	0.2403
110	*	4.04e-05	1.32e-03	0.2405
130	*	3.90e-05	1.36e-03	0.2406
150	*	3.75e-05	1.40e-03	0.2408
170	350	3.61e-05	1.45e-03	0.241
190	*	3.52e-05	1.48e-03	0.2413
210	*	3.42e-05	1.52e-03	0.2415
230	*	3.33e-05	1.56e-03	0.2418
250	*	3.24e-05	1.60e-03	0.2421
260	400	3.19e-05	1.62e-03	0.2422
350	450	2.83e-05	1.79e-03	0.2439
440	500	2.55e-05	1.94e-03	0.246
530	550	2.32e-05	2.10e-03	0.2482
620	600	2.12e-05	2.24e-03	0.252
710	650	1.96e-05	2.39e-03	0.2541
800	700	1.82e-05	2.52e-03	0.2568
890	750	1.70e-05	2.65e-03	0.2594
980	800	1.59e-05	2.78e-03	0.2623

All values are from Reference 3-1, page 833 except where noted by "*" in the °K column in which case they are linearly interpolated.

TABLE 3-5
10 CFR 71.73 THERMAL LOADING REQUIREMENTS FOR HYPOTHETICAL ACCIDENT CONDITIONS

Parameter	Initial Conditions	Load Case	
		30-Minute Fire Transient	12-Hour Cooldown Transient
Ambient Temperature °F (°C)	100°F (38°C)	1475°F (800°C)	100°F(38°C)
Environment Emissivity	0.9	0.9	(Note 1)
Cask Surface Absorptivity	1	1	(Note 1)

Notes:
(1) Radiation heat transfer to the environment was conservatively ignored during cooldown.

TABLE 3-5
10 CFR 71.71 THERMAL LOADING REQUIREMENTS FOR NORMAL CONDITIONS OF TRANSPORT

Parameter	Load Case			
	Normal Hot	Normal Cold	Hot	Cold
Ambient Temperature °F (°C)	100°F (38°C)	-20°F (-29°C)	100°F (38°C)	-40°F (-40°C)
Solar Insolation (Curved Surfaces)	none	none	400 g-cal/cm^2 per 12 hours	none

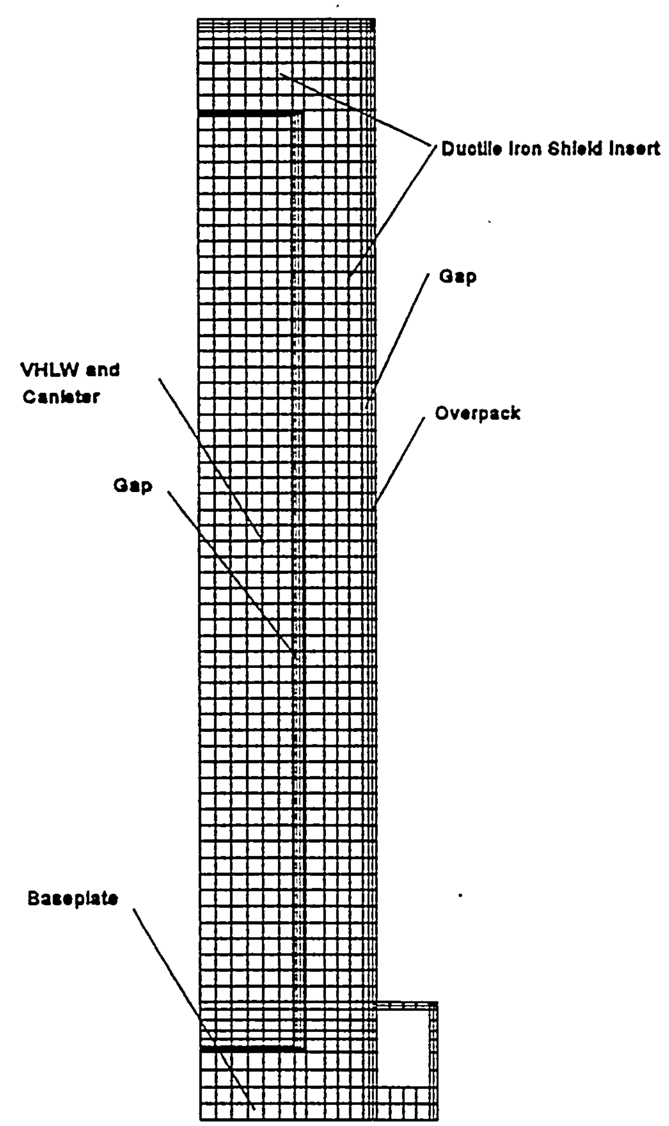


Figure 3-1
VHLW Cask Finite Element Thermal Model

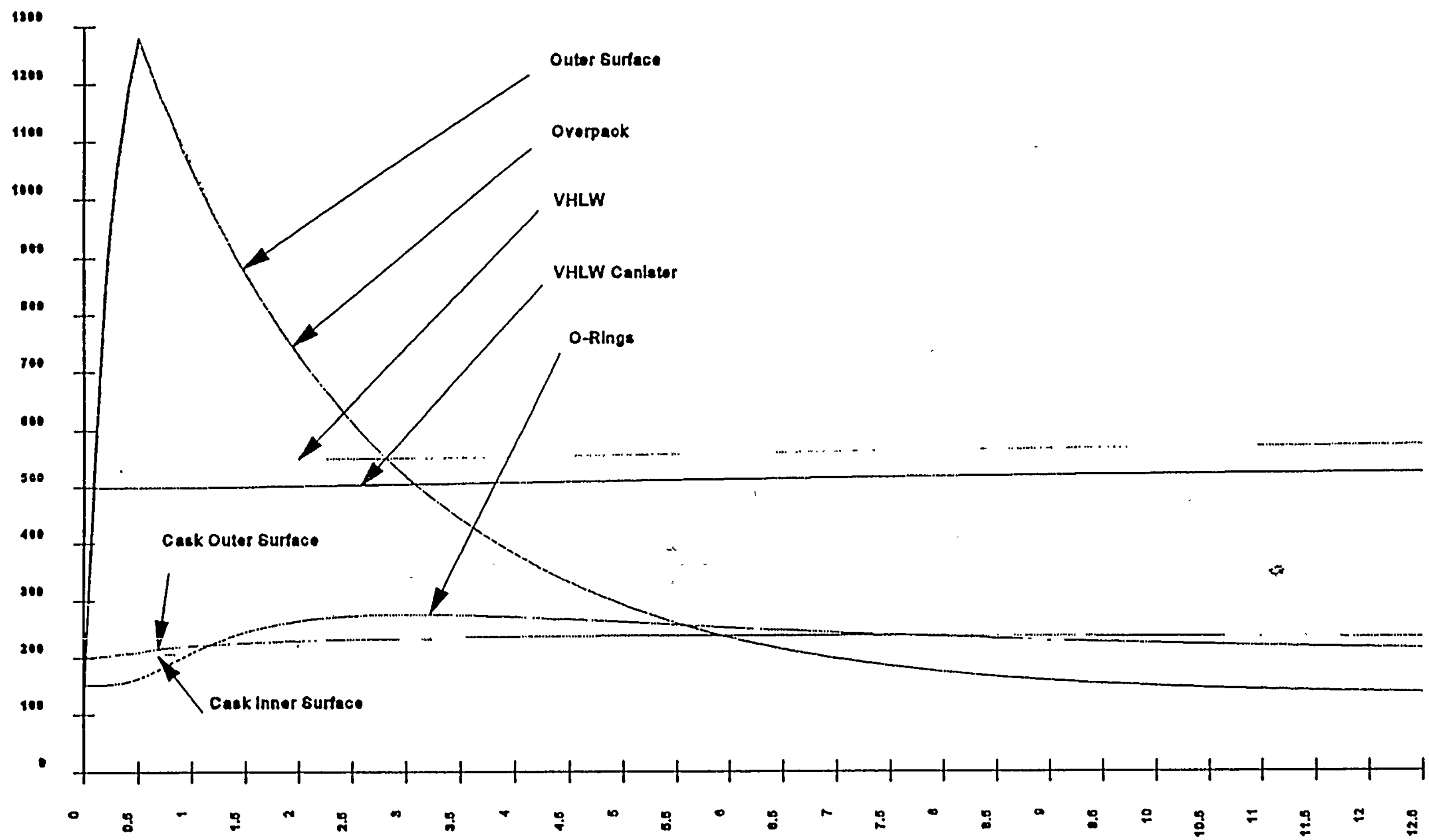


Figure 3-2
Hypothetical Accident Transient
(Temperature in °F Vs. Time in Hours)

REFERENCES

3-1 Tomas, L. C., *Heat Transfer*, Professional Version, Prentice-Hall, 1993.

3-2 *ALGOR Finite Element Analysis System*, ALGOR Inc., Pittsburgh, PA, 1994.

3-3 *Parker O-Ring Handbook*, Parker Seal Group, 1992.

3-4 Baxter, R. G., *Defense Waste Processing Facility Waste Form and Canister Description*, National Technical Information Service, Springfield, Virginia, December 1988, DP-1606, Revision 2.

3-5 *Stahlschlüssel*, Verlag Stahlschlüssel, Wegst KG Marbach, 1983.

3-6 *Iron Castings Handbook*, Iron Castings Society, Inc.

3-7 Eisenstatt, Larry R., *Description of the West Valley Demonstration Project Reference High-Level Waste Form and Canister*, National Technical Information Service, Springfield, Virginia, July 28, 1986, DOE/NE/44139-26.

3-8 Baumeister, Theodore, et. al., *Mark's Standard Handbook for Mechanical Engineers*, eds., Eighth Edition, McGraw-Hill Book Company, New York, 1978.

CHAPTER FOUR
CONTAINMENT

4.0 CONTAINMENT

This chapter describes the containment configuration and test requirements for the VHLW package. Both normal conditions of transport and hypothetical accident conditions per 10CFR71 (Ref.4-1) are discussed.

4.1 Containment Boundary

The containment boundary for the package consists of the package overpack barrel and barrel base, the package overpack base plate, the seal plate, the test port closure, and the associated seals. The containment boundary is shown in Figure 4-1. Each is described in more detail in the following sections.

4.1.1 Containment Vessel

The package overpack barrel consists of a 1.00 inch (25.4 mm) to 1.50 inch (38.1 mm) thick cylindrical shell, a 1.00 inch (25.4 mm) thick end plate, a 2.00 inch (50.8 mm) thick barrel base, a 1.00 inch (25.4 mm) thick seal plate, and a 2.00 inch (50.8 mm) thick base plate. The vessel has an inside diameter of 43.00 inches (1092 mm) and an inside length of 136.00 inches (3454 mm). It is fabricated from stainless steel plate. The containment vessel configuration is shown in Figure 1-1.

4.1.2 Containment Penetrations

The only penetration into the containment boundary is the overpack seal test port, which penetrates to the space between the two seals on the seal plate. The test port is sealed with a tapered plug.

4.1.3 Seals and Welds

4.1.3.1 Seals

Containment seals are located between the seal plate (located in the overpack base plate) and the overpack ring plate. All seals used in the containment boundary are static face seals. The seal areas are designed to experience no significant plastic deformation under hypothetical accident conditions, as demonstrated in Section 2. Any of several different silicone compounds can be used for the seals, depending on availability. The specific silicone compound used must have a manufacturer-specified normal recommended temperature range encompassing the range shown in Table 4-1. Typical hardness of silicone seals falls in the range of 40 to 70 durometers (Ref.4-2).

Minimum manufacturer recommended O-ring compression is 0.007 inches (Ref. 4-2), or 1.4%, and the maximum recommended compression for static seals is 30% (Ref.4-2). The compression for the O-rings in the VHLW package has been set to 25%. Groove dimensions prevent overcompression of the O-rings by the base plate closure screw preload forces and by hypothetical accident forces. Table 4-1 shows design parameters for the seals.

A summary of seal testing prior to first use, during routine maintenance, and assembly for transportation is provided below.

4.1.3.1.1 Fabrication Verification Leak Test

Upon completion of fabrication, the containmentboundary shall be tested in accordance with the Fabrication Verification Leak Test, delineated in Section 8.1.3. This test verifies the sealing integrity of the package to a leak rate less than 3.05×10^{-4} std cm^3/s.

4.1.3.1.2 Maintenance Verification Leak Test

After the third use, annually (i.e. within one year of use), or at the time of damaged seal replacement, the containment shall be tested per the Maintenance Verification Leak Test, delineated in Section 8.2.2. This test verifies the sealing integrity of the package to a leak rate less than 3.05×10^{-4} std cm^3/s.

4.1.3.1.3 Assembly Verification Leak Test

Prior to shipment of the loaded VHLW Package, the containment shall be leak tested in accordance with the Assembly Verification Leak Test, delineated in Section 4.5.1.7. This test verifies the proper assembly of the package with a test sensitivity of 1×10^{-3} std cm^3/s or better.

4.1.3.2 Welds

All containment boundary welds, except the weld between the base plate and the seal plate, are full penetration bevel or groove welds to ensure structural and sealing integrity. These full penetration welds are designed per ASME Section III Subsection NB and are fully radiographically examined where possible. Where radiographic examination is not practical, multi-pass liquid penetrant examination is performed.

The weld between the base plate and seal plate is a 1/8 inc[illegible] partial penetration groove weld on both radii of the seal plate. These welds are sized to minimize distortion of the seal plate, which has the machined grooves and face for containment sealing. These welds are examined by the liquid penetrant method.

4.1.4 <u>Closure</u>

Closure of the package overpack is accomplished by sixteen (16) SA 193, Grade B7 socket head cap screws. The screw size and tightening requirements are provided in Table 4-2.

4.2 Requirements for Normal Conditions of Transport

The VHLW package is designed, fabricated, and leak tested to preclude a release of radioactive material in excess of the limits prescribed in 10CFR71.51 (a) (1) (Ref.4-1).

4.2.1 Containment of Radioactive Material

The radioactive material is held within a glass matrix, and this glass matrix is confined within a sealed, stainless steel canister. The canister is located inside the VHLW shield insert cavity, which in turn is contained within the VHLW Package overpack. Despite these multiple levels of containment, it is conservatively assumed for purposes of this containment evaluation that no containment is provided by the VHLW shield insert or the sealed stainless steel canister. The package overpack and its seals are exclusively relied upon as the containment boundary for purposes of the containment evaluation.

Containment testing is based on ensuring that no leak paths with an equivalent diameter greater than 20 microns exist, as described in Appendix 4.5.1. By doing so, the release rate of activity will be within the regulatory limits of $A_2 \times 10^{-6}$.

4.2.2 Pressurization of Containment Vessel

Because the VHLW is solid glass, no vapors or gases other than helium from radioactive decay form in the containment vessel. Thus, pressurization of the containment vessel is calculated by summing the pressure increase due to thermal expansion of air and the pressure increase due to helium production.

4.2.2.1 Thermal Expansion of Air

Containment vessel pressurization due to thermal expansion of air occurs when the package temperature increases after filling and sealing the package. The maximum internal pressure due to thermal expansion of air is calculated in Section 3.4.4.

4.2.2.2 Gas Production

Another contributor toward pressure increase inside the VHLW canister is alpha decay within the glass matrix which results in helium gas production. The gas production rate is approximately 30 cm^3/yr (standard conditions) (Ref. 4-3). As discussed above, this gas is assumed to be diffuse out of the canister and shield insert into the package overpack cavity. The pressure increase is dependent on the overpack and shield insert free volume. It is conservative to ignore any free volume within the shield insert cavity and to include only the volume between the shield insert and the overpack.

The free volume between the shield insert and the overpack is calculated as the difference in volume of two cylinders: the inside boundary of the overpack and the outside boundary of the shield insert. Then, the volume of the secondary lid is subtracted. The dimensions of the shield insert and overpack are:

$$d_{\text{overpack, inside, minimum}} = 42.99 \text{ inches}$$

$$h_{\text{overpack, inside, minimum}} = 135.88 \text{ inches}$$

$$d_{\text{shield insert, outside, maximum}} = 41.50 \text{ inches}$$

$$h_{\text{shield insert, outside, maximum}} = 133.63 \text{ inches}$$

The volume difference between the overpack inner boundary and the shield insert outer boundary is:

$$V = \frac{\pi}{4}(42.99 \ inches)^2(135.88 \ inches) - \frac{\pi}{4}(41.50 \ inches)^2(133.63 \ inches)$$

$$V_{insert-overpack} = 16{,}478 \ inches^3 = 270.0 \ liters$$

Subtracting the secondary lid volume from the volume calculated above yields the free volume. T.. secondary lid is at most 2-1/8" thick and 35-1/8" in diameter.

$$V_{secondary\ lid} = (\frac{\pi}{4})(35.125)^2(2.125)$$

$$V_{secondary\ lid} = 2059.1 \ inches^3 = 33.7 \ liters$$

$$V_{free} = 270.0 \ liters - 33.7 \ liters = 236.3 \ liters$$

The annual increase in pressure due to helium production can now be calculated from the gas produc... ..te, 30 cm^3/year, the minimum free volume, 236.3 liters, the initial pressure, 14.70 psia, and the ideal gas law. Therefore the annual pressure increase due to gas production is:

$$\Delta P = \frac{(14.70 \ psia)(30 \ cm^3)}{(236{,}300 \ cm^3)}$$

This pressure increase is three orders of magnitude smaller than the maximum pressure increase due to thermal expansion of air. Thus, it has an insignificant effect on the package.

4.2.3 Containment Criterion

The VHLW package containment is verified by means of leak test. The test criterion is developed in Section 4.5.1. The procedures used for acceptance testing and assembly verification testing is discussed in Section 4.1.3.

4.3 Containment Requirements for Hypothetical Accident Conditions

The VHLW package is designed, fabricated, and leak tested to preclude a release of radioactive material in excess of the limits prescribed in 10CFR71.51 (a) (2) (Ref. 4-1).

4.3.1 Fission Gas Products

There are no fission gas products in the defense high level waste (DHLW) as produced at the Defense Waste Processing Facility or West Valley Demonstration Project.

4.3.2 Containment of Radioactive Material

The radioactive material is held within a glass matrix, and this glass matrix is confined within a sealed, stainless steel canister. The canister is inside the sealed VHLW shield insert, which is contained inside the VHLW package overpack cavity, where the cavity containment boundary seals limit the release of particles.

Containment testing is based on ensuring that no leak paths with an equivalent diameter greater than 20 microns exist, as described in Appendix 4.5.1. By doing so, the release rate of activity will be within the regulatory limit of A_2 in one week.

4.3.3 Containment Criterion

The VHLW package containment is verified by means of leak test. The test criterion is developed in Section 4.5.1. The procedures used for acceptance testing and assembly verification testing is discussed in Section 4.1.3.

4.4 Special Requirements

The VHLW package is designed for a single level of containment. A separate, second level of containment is not provided within the package cavity for several reasons:

- A relatively small amount of respirable-sized plutonium fines are produced by the waste.
- The waste, being vitrified and producing only modest amounts of fines, is minimally dispersible.
- The canister itself, as demonstrated in numerous tests, is a strong, safe containment for the waste and capable of withstanding the regulatory impact tests.

Table 10 of Reference (Ref. 4-5) shows that 239 g of glass particles less than 10 microns in diameter (i.e., respirable particles) were generated during impact testing of a bare canister dropped from 9 m (30 feet). For a VHLW-WV canister filled with 3700 lb. of VHLW this corresponds to a mass fraction of 1.42×10^{-4}. Since the total plutonium activity contained in the VHLW-SR canister is 3595 Ci (refer to Table 4-2), a maximum activity of 0.51 Ci of plutonium will present in the package in respirable form. This is well below the 20 Ci of plutonium maximally permitted under 10CFR71.63 for single containment.

In a similar test (Ref. 4-6), a DWPF canister was also dropped 9 m (30 feet) onto a bottom corner. In this test, less than 50 g of particles 10 microns or smaller were collected, which corresponds to less than 0.11 Ci of plutonium.

Also, Table 10 of Reference (Ref. 4-5) shows that 532 g of glass particles less than 20 microns in diameter (i.e., dispersible) were generated during the 9 m drop test. This corresponds to 0.024% of the mass of the waste.

Numerous, rigorous tests have demonstrated the capability of the DHLW canisters to survive impacts intact and without loss of containment:

- Testing is described in Reference 4-7 in which 13 canisters of varying designs were impact tested. Three were constructed of 304L stainless steel, as is the current design, but were different dimensionally. Two of these three were dropped from 9 m (30 feet), and the third from 32 m (104 feet). No visible cracks were found in any of the three 304L canisters after the impact testing.

- Reference 4-8 describes testing of four canisters with the same dimensions as the present design. One of the canisters was constructed of wrought 304L, the other three of a centrifugally cast equivalent. Each of the canisters was successively dropped from 9 m (30 feet) onto the bottom corner, from a side orientation 1 m onto a pin, and 9 m (30 feet) onto the fill nozzle. The canisters were filled with borosilicate glass during the drop tests. Following the impact test, each canister was subjected to a helium leak and dye-penetrant test. No leakage greater than instrument sensitivity was observed, and no cracks were revealed by the dye-penetrant test.

- Reference 4-9 describes impact testing of three glass-filled canisters of the present design, two of which were fabricated from 304L stainless steel. One of these two was dropped from 9 m (30 feet) onto its nozzle. The other was dropped from 9 m (30 feet) onto a bottom corner, and then from a side orientation 1 m (40 inches) onto a pin. After the impact testing, both canisters were Helium leak tested. No leakage was detected from either canister. The canister subjected to the two drops was dye-penetrant checked, and no cracks were found near the welds nor on the surfaces on either side of the weld.

- In testing described in Reference 4-6, a glass-filled DWPF canister was dropped 9 m (30 feet) onto its bottom corner. Helium leak and dye-penetrant testing after the impact showed no leaks or cracks.

- In Reference 4-5, two DWPF canisters were impact tested. One was dropped from 9 m (30 feet), and the other from 0.3 m (1 foot). Helium leak and dye-penetrant testing after the impact showed no leaks or cracks.

Thus, these tests have shown that only small amounts of dispersible plutonium fines, and even smaller amounts of respirable fines, are generated by the regulatory impact scenarios. Furthermore, these small amounts are contained in the canister that has demonstrated its capability to survive impacts for the 10 CFR 71 specified hypothetical drop accidents, structurally intact and without loss of integrity. Therefore, the VHLW waste and canister can be classified as an "other plutonium bearing solid," as described in 10CFR71.63b(3) (Ref. 4-1), and the VHLW package can be exempt from the requirement for a separate inner container.

4.5 Appendix

4.5.1 Determination of Containment Leakage Acceptance Criterion

This appendix establishes the maximum permissible leakage rates for normal conditions of transport and hypothetical accident conditions for the VHLW package. The cal-culational methods provided in this appendix follow the guidance of ANSI N14.5-1987 (Ref. 4-4) and NRC Regulatory Guide 7.4 (Ref. 4-10) to satisfy the requirements of 10 CFR 71 (Ref. 4-1).

The maximum permissible leakage rates calculated will form the basis for establishing the leakage rate to be utilized in performing the VHLW Containment System Fabrication Verification Test and the Containment System Periodic Leak Test Verification.

4.5.1.1 Containment Requirements

Containment requirements for transportation of radioactive waste package have been established by 10 CFR 71 (Ref. 4-1). The following limits on release of radioactive materials during transport are imposed:

Normal Conditions: Limit R_N = $A_2 \times 10^{-6}$ per hour,

Accident Conditions: Limit R_A = A_2 in one week.

Individual radionuclide A_2 values are obtained from Appendix A of 10 CFR 71 (Ref. 4-1).

4.5.1.2 Determination of A_2 for Mixture of Radionuclides

The value for A_2 for the radionuclide mixture to be transported in this package is determined using the following formula from Appendix A of 10 CFR 71 (Ref. 4-1):

$$A_2(mixture) = \frac{1}{\sum_i (f(i)/A_2(i))}$$

where f(i) is the fraction of activity of the isotope i in the mixture and $A_2(i)$ is the appropriate A_2 value for isotope i.

Table 4-3 lists the activity for each isotope in the mixture, as defined in Ref. 4-3 and Ref. 4-11, and the appropriate A_2 value for each isotope. The total activity per canister is 130,000 Ci for West Valley (WV) canisters and 265,000 Ci for Savannah River (SR) canisters.

From the data in Table 4-3, an A_2 for the mixture is calculated for the VHLW-WV and VHLW-SR wastes:

A_2(mixture) = 0.64 Ci (VHLW-WV)
= 0.32 Ci (VHLW-SR)

An A_2 value of 0.32 Ci will be used for determination of leakage limits and leak testing requirements, since this is the more restrictive limit.

4.5.1.3 Radioactive Material Available for Release

The radioactive materials of concern in the VHLW package are small particles of glassified waste that have been liberated from the essentially monolithic waste matrix. These particles can arise from cool down processes after pouring, normal handling and transport loads, and hypothetical accident loads.

At the temperatures attained in the package at normal or hypothetical accident conditions there are no radioactive gases or volatile substances in the package.

In order to determine the quantities of fine particles which would be present in the VHLW package during normal conditions of transport and hypothetical accident conditions, testing of the VHLW canister and its contents was performed. Measurements of the size distribution of fine particles generated in VHLW canisters due to impact loads are documented in Reference 4-5. These tests were performed by dropping the bare canister vertically onto its bottom end from a predesignated height. For actual transport, the canister will be housed in the VHLW package and its associated overpack. The maximum impact load for the package transportation configuration will be significantly reduced due to the package impact limiters.

As documented in Reference 4-5, two DWPF (VHLW-SR) canisters were drop-tested; one from 1 foot (0.3 m), and the other from 30 feet (9 m). Each canister contained 3700 pounds of vitrified material. Subsequent non-destructive examination by helium leak check and dye penetrant showed no breach of canister integrity.

4.5.1.3.1 Normal Conditions of Transport

Subsequent to the drop tests, four 0.11 inch (0.28 cm) diameter holes were drilled in the canister that had been dropped one foot (0.3 m). The canister was then transported a distance of 2069 miles. During transport, fines released through the four holes were collected on filters. These fines were analyzed and characterized by size. A total of 24.44 mg of particles $\leq$ 20 microns in diameter were released. Assuming that the quantity of particles is directly proportional to the amount of vitrified waste, the maximum quantity of particles would be generated in the VHLW-WV canister, which has a total VHLW weight of 4952 lb. (2246 kg). Factoring the VHLW-SR canister particulate quantity by the ratio of the VHLW-WV to VHLW-SR canister content weights results in a total quantity of particles $\leq$ 20 microns of 32.71 mg. It is conservatively assumed that 50 mg of particles are available for release for both the VHLW-WV and VHLW-SR canisters. Since the VHLW-SR activity is much higher than that for the VHLW-WV, the VHLW-SR activity values are used.

Total Activity in the canisters = 265,000 Ci (Table 4-3)

Weight of waste in canister = 4200 lb. (Table 4-3)

Therefore, the activity of particles 20 microns in size or smaller that could potentially be released from the VHLW canister during normal conditions of transport which would be available for release from the VHLW package overpack is:

$$A_N = (50 \times 10^{-3}\ \text{g})(265{,}000\ \text{Ci})(1/4200\ \text{lb.})(1\ \text{lb.}/454\ \text{g})$$
$$= 6.95 \times 10^{-3}\ \text{Ci}$$

4.5.1.3.2 Hypothetical Accident Conditions

Subsequent to the drop tests (Ref. 4-5), the canister that had been dropped 30 feet (9 m) was disassembled and the quantity and size-distribution of glass particles present in the canister were measured. It was determined that 535 g of particles $\leq$ 20 microns were present (Ref. 4-5). As discussed above under normal conditions, again factor the particle quantity by the VHLW-WV to VHLW-SR weight ratio. This results in a total particle quantity sized _ 20 microns of 716 g. For hypothetical accident conditions, it is conservatively assumed that all of these particles are released from the canister. Therefore, activity available for release from the VHLW package overpack, using the VHLW-SR activity, will be:

$$A_A = (716\ \text{g})(265{,}000\ \text{Ci})(1/4200\ \text{lb.})(1\ \text{lb.}/454\ \text{g})$$
$$= 99.5\ \text{Ci}$$

4.5.1.3.3 Normal and Accident Conditions Activity Concentrations

For determination of the activity concentrations, it is again conservatively assumed that all materials available for release are in the volume of the void between the VHLW shield insert and the package overpack. Using the above activities and the volume of the overpack void (236,300 cm^3 per Section 4.2.2), the activity concentrations (i.e. activity per unit volume) can be calculated.

$$C_N = \frac{6.95 \times 10^{-3}}{236{,}300\ cm^3} = 2.94 \times 10^{-8}\ Ci/cm^3$$

$$C_A = \frac{99.5\ Ci}{236{,}300\ cm^3} = 4.21 \times 10^{-4}\ Ci/cm^3$$

4.5.1.4 Maximum Permissible Leak Rates

The maximum permissible leak rates are:

$$R_N = A_2 \times 10^{-6} \text{ in one hour}$$
$$= 0.32 \times 10^{-6}\ Ci/hr. \quad = 3.2 \times 10^{-7}\ Ci/hr.$$

$$R_A = A_2 \text{ in one week}$$
$$= 0.32\ Ci/week \quad = 3.2 \times 10^{-1}\ Ci/week$$

The maximum permissible leakage rate for the VHLW package containment for normal conditions is:

$$L_N = \frac{R_N}{C_N} x \frac{1}{360}$$

Therefore:

$$L_N = \frac{3.2 x 10^{-7}\ Ci/sec}{2.94\ x 10^{-8}\ Ci/cm^3} x 1/3600$$

$$= 3.02\ x 10^{-3}\ cm^3/sec$$

The maximum permissible leakage rate for the VHLW package containment for hypothetical accident conditions is:

$$L_A = \frac{R_A}{C_A} x 1.65\ x 10^{-6}$$

Therefore:

$$L_A = \frac{3.2 x 10^{-1}\ Ci/sec}{4.21 x 10^{-4}\ Ci/cm^3} x 1.65 x 10^{-6}$$

$$= 1.26 x 10^{-3}\ cm^3/sec$$

L_N and L_A are the maximum permissible volumetric leak rates assuming only particles $\leq$ 20 microns are releasable from the cavity.

4.5.1.5 Leak Path Diameters Verification

Using the leak rates established above, the equivalent leakage hole diameter can be determined. If this hole diameter is $\leq$ 20 microns, then the leakage limits are suitable. If the corresponding leakage hole diameter is > 20 microns, then a lower leakage limit will need to be developed for testing purposes.

For normal conditions, the following are applicable:

T = 396.1°F = 202°C = 475°K (Section 3.5.4)

P_u = Upstream pressure = 28.6 psia = 1.95 atm (Section 3.5.4)

P_d = Downstream pressure = 3.5 psia = 0.24 atm (Ref. 4-1)

The leakage hole length is estimated as 25% of the seal minor diameter. Therefore the estimated hole length is:

$a_{closure}$ = Leakage hole length = 0.25 × 0.50 in × 2.54 cm/in = 0.32 cm

As will be shown later, the leakage is choked flow, which is independent of the leakage hole length. Therefore an approximation of the leakage hole length is acceptable.

For air, the following properties are used:

$r_c = 0.528$ $M = 29$ $k = 1.4$ (Ref. 4-4)

Reference 4-4 only gives properties at room temperature. Since the viscosity is sensitive to temperature, use Sutherland's Viscosity Formula to determine the viscosity at the normal conditions temperature:

$$\mu = \frac{T(^{\circ}R)^{3/2}}{T(^{\circ}R) + 198.6} x 2.27 x 10^{-8} \ lb\text{-}sec/ft^2$$

To convert to centipoise, apply the following relationships:

1 lb.-s / ft^2 = 4.7880258 × 10^4 cP

1°R = 1.8°K

Substituting:

$$\mu = \frac{[1.8T(^{\circ}K)]^{3/2}}{1.8T(^{\circ}K) + 198.6} x\ 1.087\ x 10^{-3}\ cP \quad \text{(Eqn. 1)}$$

$$= 0.0258\ cP$$

Since $P_d / P_u = 0.123 < r_c$, the possibility of choked flow exists. To determine if the flow is choked, check the ratio of continuum flow to free molecular flow (r_f) per equation B5 of Reference 4-4 as follows:

$$L = (F_c + F_m)(P_u + P_d) \quad cm^3/s \qquad \text{(Eqn. B2, Ref. 4-4)}$$

where:

$$F_c = \frac{2.49 \times 10^6 D^4}{a \mu} cm^3/atm - s \qquad \text{(Eqn. B3, Ref. 4-4)}$$

$$= 3.02 \times 10^8 D^4$$

and

$$F_m = \frac{3.81 \times 10^3 D^3 \sqrt{T/M}}{a P_a} cm^3/atm - s \qquad \text{(Eqn. B4, Ref. 4-4)}$$

$$= 4.40 \times 10^4 D^3$$

Substituting:

$$L = (3.02 \times 10^8 D^4 + 4.40 \times 10^4 D^3)(1.95 - 0.24) = 3.02 \times 10^{-3} \ cm^3/sec$$

Solving for D by iteration:

$$D = 1.52 \times 10^{-3} \ cm$$

The ratio r_f is found from equation B5, Ref. 4-4:

$$r_f = \frac{654 \ D \ P_a}{\mu \sqrt{T/M}} = 10.43$$

Since $r_f > 1$ and $P_d/P_u < r_c$, the flow is choked. Therefore the leakage hole diameter must be solved using equation B7 of (Ref. 4-4), which is rearranged as follows to solve directly for D:

$$D = \left(\frac{4L}{\pi}\right)^{1/2} \left(\frac{M(k+1)}{2kR_o T_u}\right)^{1/4} \left(\frac{k+1}{2}\right)^{1/2(k-1)} \qquad \text{(Eqn. 2)}$$

Substituting:

$$D = 3.90 \times 10^{-4} \ cm = 3.90 \ microns$$

For the accident condition, the following apply:

T = 750°F = 399°C = 672°K (Section 3.5.4)

P_u = Upstream pressure = 40.4 psia = 2.75 atm (Section 3.5.4)

P_d = Downstream pressure = 1.00 atm

μ = 0.0325 cP (per Eqn. 1)

Since $P_d / P_u = 0.364 < r_c$, the possibility of choked flow exists. To determine if the flow is choked, check the ratio of continuum to free molecular flow (r_f) per equation B5 of Ref. 4-4 as follows:

$$L = (F_c + F_m)(P_u + P_d) \quad cm^3/s$$ (Eqn. B2, Ref. 4-4)

where

$$F_c = \frac{2.49 \times 10^6 D^4}{a \mu} cm^3/atm-s$$ (Eqn. B3, Ref. 4-4)

$$= 2.04 \times 10^8 D^4$$

and

$$F_m = \frac{3.81 \times 10^3 D^3 \sqrt{T/M}}{a P_a} cm^3/atm-s$$ (Eqn. B4, Ref. 4-4)

$$= 3.06 \times 10^4 D^3$$

Substituting:

$$L = (2.40 \times 10^8 D^4 + 3.06 \times 10^4 D^3)(2.75 - 1.00) = 1.26 \times 10^{-3} cm^3/sec$$

Solving for D by iteration:

$$D = 1.29 \times 10^{-3} cm$$

The ratio r_f is found from equation B5, Ref.4-4:

$$r_f = \frac{654 \, D \, P_a}{\mu \sqrt{T/M}} = 10.09$$

Since $r_f > 1$ and $P_d/P_u < r_c$, the flow is choked. Therefore the leakage hole diameter must be solved using Eqn. 2, resulting in:

$$D = 2.31 \times 10^{-4} cm = 2.31 \text{ microns}$$

Since the leakage limits result in a leakage hole size < 20 microns, the leakage test limits established on the basis of releaseable particles less than 20 microns in size is acceptable and conservative.

The reference air leakage rate, L_R, is defined in Section 5.4 of Ref. 4-4 as equivalent to the maximum of L_N or L_A expressed in standard cubic centimeters per second. Per equation B13 of (Ref. 4-4), for choked flow,

$$L_R = L\sqrt{\left(\frac{0.583}{k/k+1}\right)\left(\frac{M}{29}\right)\left(\frac{298}{T}\right)} \times \left(\frac{1}{P_u}\right)\left[\frac{0.634}{(2/k+1)^{1/(k-1)}}\right] \; std\ cm^3/s$$

Substituting the above values for normal and accident conditions into this equation yields

$L_{RN} = 1.23 \times 10^{-3}$ std cm^3/s

$L_{RA} = 3.05 \times 10^{-4}$ std cm^3/s

Therefore

$L_R = 1.23 \times 10^{-3}$ std cm^3/s

Per Section 5.4 of Reference 4-4, this leak rate requires that all testing be performed per Sections 6.2 through 6.5 of Reference 4-4. Also, per Table A1 of Reference 4-4, the use of the Halogen detector test is adequate. Sulfur hexafluoride (SF_6) will be used as the testing gas.

4.5.1.6 Containment System Fabrication and Periodic Verification Leakage Rate Determination

Since the leakage limits result in a leakage hole size < 20 microns, the leakage test limits will be specified based upon the above computed leakage limits. The allowable test leakage rate, L_T, is the more restrictive of L_N or L_A at standard conditions:

$L_T = 3.05 \times 10^{-4}$ std cm^3/s

Per 7.3.2 of Reference 4-4, the sensitivity of the test procedure must be no more than one-half the allowable test leakage rate. Therefore a procedure sensitivity, L_y, of 1.52×10^{-4} std cm^3/s of dry air at standard conditions is required.

4.5.1.6.1 Closure Seal Verification Test

It is assumed that testing will be performed using sulfur hexafluoride, which will be added to the annular space between the O-rings to a pressure of 25 psig. Therefore closure seal verification testing is assumed at the following conditions:

$T = 25°C = 298°K$

P_u = Upstream pressure = 25 psig = 39.7 psia = 2.70 atm

P_d = Downstream pressure = 1.0 atm

P_a = Average pressure = 1.85 atm

a = Leakage hole length = 0.32 cm

D = Leakage hole diameter = 2.31 microns = 2.31×10^{-4} cm

The Acceptance Leak Test will be performed with sulfur hexafluoride, which has the following properties:

$r_c = 0.585$ $M = 146$ $k = 1.1$ $\mu = 0.0151$ (Ref. 4-4)

Since the sulfur hexafluoride gas is added to the annulus, which is already filled with air at 1.0 atm, the resulting test will actually be performed with a gas mixture. Per Reference 4-4, the following properties are computed for the gas mixture:

$P_{u,air}$ = 1.0 atm, $P_{u,SF6}$ = 1.70 atm, P_m = 1.0 + 1.70 = 2.70 atm

$$M_m = \sum_{i=1}^{n} \frac{P_i M_i}{P_m}$$ (Eqn. B10, Ref. 4-4)

$$= \left(\frac{1.0}{2.70}\right) 29 + \left(\frac{1.70}{2.70}\right) 146 = 102$$

$$\mu_m = \sum_{i=1}^{n} \frac{\mu_i M_i}{P_m}$$ (Eqn. B11, Ref. 4-4)

$$= \left(\frac{1.0}{2.70}\right) 0.0185 + \left(\frac{1.70}{2.70}\right) 0.0151 = 0.0164\ cP$$

Since P_d/P_u = 0.37, which is less than r_c (0.585 for sulfur hexafluoride and 0.528 for air), it is necessary to determine if the flow is choked with a 2.31 micron hole. Substituting the above values into equation B5 of Ref. 4-4:

$r_f = 10.0 > 1$

Therefore the flow is choked. The solution for choked flow involves the ratios of specific heat, k. The value of k for the mixture will be between that of air, 1.40, and that of sulfur hexafluoride, 1.10. Since a lower value of k_m will result in a lower permissible leakage rate, conservatively use the value of k for sulfur hexafluoride for k_m.

Since both the allowable leakage rate and the test leakage rate are choked flow, use equation B8 of Ref. 4-4 to solve for the sulfur hexafluoride - air mixture leak rate, L_m.

$$L_m = L_T \sqrt{\left(\frac{\left(\frac{k}{k+1}\right)_m}{\left(\frac{k}{k+1}\right)_{air}}\right)\left(\frac{M_{air}}{M_m}\right)\left(\frac{T_{u,m}}{T_{u,air}}\right)} \times \left[\frac{\left(\frac{2}{k+1}\right)_m^{1/(k-1)}}{\left(\frac{2}{k+1}\right)_{air}^{1/(k-1)}}\right] cm^3/s$$

Substituting the above properties for the sulfur hexafluoride - air mixture and the properties for air at standard conditions:

$$L_m = 3.05 \times 10^{-4} \sqrt{\left(\frac{\left(\frac{1.10}{1.10+1}\right)}{\left(\frac{1.40}{1.40+1}\right)}\right)\left(\frac{29}{1023}\right)\left(\frac{298}{298}\right)} \times \left[\frac{\left(\frac{2}{1.10+1}\right)^{1/(1.10-1)}}{\left(\frac{2}{1.40+1}\right)^{1/(1.40-1)}}\right] cm^3/s$$

$$= 1.49 \times 10^{-4} cm^3/s$$

The detector to be used to measure the leak will only measure the tracer gas quantity. As such, the acceptable tracer gas leak rate is computed by rearranging Eq B20 of Reference 4-4 as:

$$L_t = L_m \times (P_{u,SF6} \;/\; P_m)$$

$$= (1.49 \times 10^{-4}\ cm^3/s)\ (1.70 / 2.70) = 9.37 \times 10^{-5}\ cm^3/s$$

Since the detector that will be used for the VHLW cask is calibrated in oz/yr, it is necessary to convert the leakage rate. This is based on the ideal gas law:

$$PV = nRT$$

The number of moles of gas, n, can be expressed as the mass of the gas divided by the molar mass:

$$n = m / M$$

Substituting and dividing by time and rearranging yields:

$$\frac{m}{t} = \frac{V}{t}\frac{PM}{RT} = Q \qquad \text{(Eqn. [illegible])}$$

where

Q = m/t = mass leakage rate

V/t = volumetric leakage rate = 9.37×10^{-5} cm³/s

P = upstream pressure = 2.70 atm

M = molar weight of sulfur hexafluoride - air mixture = 102.3 g / mol

R = universal gas constant = 82.056 cm³ atm / mol °K

T = temperature at test conditions = 25°C = 298°K

Substituting the closure verification test conditions into Eqn. 3 yields:

$$Q = (9.37\times 10^{-5})\,(2.70)\,(102.3)\,/\,(82.056)\,(298)$$

$$= 1.06 \times 10^{-6} \text{ g / s}$$

Converting to the detector units:

$$Q = (1.06 \times 10^{-6} \text{ g / s})\,(0.035274 \text{ oz / g})\,(3.1557 \times 10^{7} \text{ s / yr})$$

$$= 1.18 \text{ oz / yr of } SF_6 \text{ at } 25°C \text{ and } 25.0 \text{ psig}$$

4.5.1.6.2 Test Port Leakage Verification Test

Since the annular space between the closure seals is pressurized via the test port, the test port plug cannot be tested by the method discussed above. The test port plug leakage test will be done after the closure seal test, using a halogen leak detector and a vacuum system. After testing of the closure seals is complete, the pressure (25 psig) will be released and the test port closed. Therefore the remaining gas in the annulus will be a sulfur hexafluoride - air mixture at 1 atm pressure. The gas mixture is assumed to remain in proportion to the mixture used in the closure seal test. Therefore test port leakage verification testing is assumed at the following conditions:

T = 25°C = 298°K

P_u = Upstream pressure = 0 psig = 14.7 psia = 1.00 atm

P_d = Downstream pressure = 0.01 atm

P_a = Average pressure = 0.495 atm

D = Leakage hole diameter = 2.31 microns = 2.31×10^{-4} cm

The test port plug is tapered and nests in a taper in the test port. The contact between the port and the plug is relied upon to provide the necessary seal. It is assumed that the test port contact surface is 1/16 inch wide. Therefore the leakage hole length is:

a = Leakage hole length = (1/16 in) (2.54 cm/in) = 0.16 cm

The test port seal Acceptance Leak Test will be performed with the sulfur hexafluoride - air mixture from the closure seal leak test. The properties for the gas mixture are:

$$P_m = 1.00 \text{ atm}$$

$$P_{u,air} = (1.00 / 2.70)1.00 = 0.37 \text{ atm}$$

$$P_{u,SF6} = (1.70 / 2.70)1.00 = 0.63 \text{ atm}$$

$$M_m = 102.3$$

$$\mu_m = 0.0164 \text{ cP}$$

Since $P_d/P_u = 0.01$, which is less than r_c (0.585 for sulfur hexafluoride and 0.528 for air), it is necessary to determine if the flow is choked with a 2.53 micron hole. Substituting the above values into equation B5 of Reference 4-4:

$$r_f = 2.73 > 1$$

Therefore the flow is choked. Since the leakage rate for choked flow is independent of the leak path length, the permissible leakage rate for the test port seal is identical to that for the closure seal, i.e.

$$L_m = 1.49 \times 10^{-4} \text{ cm}^3/\text{s}$$

$$L_t = 9.37 \times 10^{-5} \text{ cm}^3/\text{s}$$

Substituting the test port verification test conditions into Eqn. 3 yields:

$$Q = (9.37 \times 10^{-5}) (1.00) (102.3) / (82.056) (298)$$
$$= 3.94 \times 10^{-7} \text{ g / s}$$

Converting to the detector units:

$$Q = (3.94 \times 10^{-7} \text{ g / s}) (0.035274 \text{ oz / g}) (3.1557 \times 10^{7} \text{ s / yr})$$
$$= 0.44 \text{ oz / yr}$$ of SF_6 at 25°C and 0.01 atm (7.6 torr) vacuum

4.5.1.6.3 Effects of Temperature and Pressure

The temperature at which the test is performed affects the test leakage rate. Therefore, the temperature dependency of the test must be determined. For choked flow, the leak rate is independent of the pressure.

For choked flow for the specified Containment System Fabrication and Periodic Verification Tests specified above, the following table provides a summary of acceptable leak rates for sulfur hexafluoride at the specified backfill pressures at different temperatures.

4.5.1.7 Containment System Assembly Verification Leakage Rate Determination

As stated in Reference 4-4, the containment system of each Type B package shall be assembled and tested to verify that it has been properly assembled and that the containment function has been established. The test is dependent upon the normal conditions of transport.

The assembly procedure test sensitivity, L_u, in std cm^3 / s, need only be 4200 × L_N to verify proper assembly of the package, but shall be at least 10^{-1} std cm^3 / s. Substituting and solving:

$$L_u = 4200 \times 1.23 \times 10^{-3} = 5.17 \text{ std cm}^3 / \text{s}$$

which is greater than 10^{-1} std cm^3 / s. Therefore the assembly verification leak test sensitivity shall be 10^{-1} std cm^3 / s. Per Table A1 of Reference 4-4, the gas pressure drop test is suitable for this leakage rate. Two separate tests will be required, one for the closure seals and one for the test port seal. The applied pressure is assumed to be 3.0 atm abs (28.4 psig) of air.

4.5.1.7.1 Closure Seal Assembly Verification Test

The volume of the test space must be determined to perform the pressure drop test. The volume of the test space is equal to the volume of the annular space plus the volume of the test port and testing apparatus. For this evaluation it is assumed that the test apparatus is a one-half inch pipe with 12 inches of length before the valve. The pressure gage will be installed into this length of pipe. The resulting volume is:

$$\begin{aligned} V &= \pi(48.50)(.25)(.25) + \pi((.25)^2/4)(2.00\text{-}0.56) + \pi((.375)^2/4)(0.56) \\ &\quad + \pi((.50)^2/4)(12.00) \\ &= 9.523 + 0.071 + 0.062 + 2.356 \\ &= 12.01 \text{ in}^3 \\ &= 196.8 \text{ cm}^3 \end{aligned}$$

Per Reference 4-4, the required test sensitivity is:

$$S \leq 10^{-1} \text{ cm}^3 / \text{s} \qquad \text{(6.5.2, Ref. 4-4)}$$

For the pressure drop test, the maximum permissable leakage rate is

$$L \leq S/2 \text{ cm}^3 / \text{s} \qquad \text{(Eq B23, Ref. 4-4)}$$

where L is equal to L_R, which is defined as

$$L_R = \frac{V T_S}{3600\ H P_S} \left(\frac{P_1}{T_1} - \frac{P_2}{T_2} \right) \ std\ cm^3/sec \qquad \text{(Eq B19, Ref. 4-4)}$$

It is assumed that testing will be performed at standard pressure and temperature, i.e. 1 atm and 25°C. Furthermore, assume that the temperature at the beginning and end of the test are the same, i.e. $T_1 = T_2 = T_s$. Substituting and rearranging:

$$\frac{P_1 - P_2}{H} = \frac{3600\ P_S L_R}{V} \qquad \text{(Eqn. 4)}$$

Substituting $\Delta P = P_1 - P_2$, $L_R = S/2 = 5.0 \times 10^{-2}$, and the pressure and volume:

$$\Delta P/H = 0.91 \text{ atm / hr} = 13.4 \text{ psi / hr}$$

This high value means the test can be completed quickly, validating the constant temperature assumption. For example, if the test is done for 3 minutes, the maximum permissible pressure drop is 0.67 psi.

4.5.1.7.2 Test Port Plug Assembly Verification Test

This test is essentially identical to the closure seal test, except that the volume of the test will be the test apparatus volume outside the test port plug. This test should be done after the closure assembly verification test. For this set up the test volume will be

$$V = 2.356 \text{ in}^3 = 38.6 \text{ cm}^3$$

With the same assumptions as identified above for the closure seal test, substitution into Eqn. 4 yields:

$$\Delta P/H = 4.66 \text{ atm / hr} = 68.5 \text{ psi / hr}$$

This high value means the test can and must be completed quickly, validating the constant temperature assumption. For example, if the test is done for 3 minutes, the maximum permissible pressure drop is 3.4 psi.

4.5.1.7.3 Effects of Temperature and Pressure

Since the pressure drop test leaks are in the choked flow regime, they are independent of pressure effects. Tests must ensure that pressure does not drop below the critical pressure for the test to remain valid. For air, $r_c = 0.528$, which corresponds to a minimum upstream pressure of 1.89 atm abs, or 13.1 psig.

However, temperature will effect the acceptable leak rate. If the test temperatures are equal at the beginning and end of the test (i.e. $T_1 = T_2 = T$), but not the same as the standard temperature, the leak rate equation (Eqn. 4) will be

$$\frac{P_1 - P_2}{H} = \frac{3600\ P_s L_R}{V} \frac{T}{T_S}$$

$$\begin{aligned} \Delta P &= 12.08\ (L_R\ T\ /\ V)\ \ \text{atm / hr} \\ &= 177.6\ (L_R\ T\ /\ V)\ \ \text{psi / hr} \end{aligned}$$

In addition, the permissable leakage rate will be affected by the temperature. Since the leak test is being done with air, the leak rate adjustment of Eq B8 of Reference 4-4 simplifies to:

$$L_R = L_T \sqrt{\frac{T}{29}}$$ where $L_T = S/2 = 5.00 \times 10^{-2}\ cm^3 / s$

Acceptable leak rates, in cm^3/s and in psi/hr, are summarized in Table 4-5 for the closure and test port seal assembly verification tests.

TABLE 4-1
SEAL DESIGN PARAMETERS

Design Parameter	Value
Normal recommended temperature range (Ref. 4-2)	-60_F to 450_F (-50_C to 232_C)
Compression	25%

TABLE 4-2
SCREW TORQUE REQUIREMENTS

Location	Size	Torque Values ($\pm$10%, lubricated) (ft-lb.)
Overpack base	1" - 8UNCx 3-1/2"	500

TABLE 4-3
CALCULATION OF VHLW A_2

Isotope	A2 (Ci) (per 10CFR71)	VHLW-SR Specific Activity (Ci/lb.) (Ref.4-11)	Activity per Canister (Ci)		VHLW - WV f(i)	VHLW - SR f(i)	VHLW - WV f(i)/A2(i)	VHLW- SR f(i)/A2(i)
			VHLW-WV (Ref.4-3)	VHLW-SR (Note 1)				
Cr-51	600	2.51e-20		1.05e-16		3.97e-22		6.62e-25
Fe-55	1000		2.10e+00		1.68e-05		1.68e-08	
Co-60	7	4.58e-02	3.60e+00	1.92e+02	2.88e-05	7.25e-04	4.11e-06	1.[illegible]e-04
Ni-59	900	6.46e-06	3.60e-01	2.71e-02	2.88e-06	1.02e-07	3.20e-09	1.14e-10
Ni-63	100	8.02e-04	2.70e+01	3.37e+00	2.16e-04	1.27e-05	2.16e-06	1.27e-07
Se-79	0.05	4.58e-05	1.60e-02	1.92e-01	1.28e-07	7.25e-07	2.56e-06	1.45e-05
Rb-87	Unlimited	2.35e-10		[illegible].87e-07		3.72e-12		
Sr-89	10	1.15e-08		4.83e-05		1.82e-10		1.82e-11
Sr-90	0.4	1.26e+01	3.00e+04	5.29e+04	2.40e-01	1.99e-01	5.99e-01	4.99e-01
Y-90	10	1.29e+01	3.00e+04	5.42e+04	2.40e-01	2.04e-01	2.40e-02	2.04e-02
Y-91	30	2.04e-07		8.57e-04		3.23e-09		1.08e-10
Zr-93	200	3.01e-04	1.10e+00	1.26e+00	8.79e-06	4.76e-06	4.39e-08	2.38e-08
Zr-95	20	2.71e-06		1.14e-02		4.29e-08		2.14e-09
Nb-93m	200		8.60e-01		6.87e-06		3.44e-08	
Nb-94	0.002	2.60e-08		1.09e-04		4.12e-10		2.06e-07
Nb-95	20	5.70e-06		2.39e-02		9.02e-08		4.51e-09
Nb-95m	0.002	3.36e-08		1.41e-04		5.32e-10		2.66e-07
Tc-99	25	8.30e-04	7.40e+00	3.49e+00	5.91e-05	1.31e-05	2.37e-06	5.25e-07
Ru-103	25	4.54e-12		1.91e-08		7.19e-14		2.87e-15
Ru-106	7	6.07e-01	3.60e-02	2.55e+03	2.88e-07	9.61e-03	4.11e-08	1.37e-03
Rh-103m	1000	4.41e-12		1.85e-08		6.98e-14		6.98e-17
Rh-106	3	6.09e-0[illegible]	[illegible].60e-02	2.56e+03	2.88e-07	9.64e-03	9.59e-08	3.21e-03
Pd-107	0.002	3.97e-06	5.30e-03	1.67e-02	4.23e-08	6.28e-08	2.12e-05	3.14e-05
Ag-110m	7	3.39e-05		1.42e-01		5.37e-07		7.67e-08
Cd-113	0.002	1.35e-17		5.67e-14		2.14e-19		1.07e-16
Cd-115m	30	3.27e-13		1.37e-09		5.18e-15		1.73e-16
Sn-121m	0.002	2.13e-05		8.95e-02		3.37e-07		1.69e-04
Sn-123	0.002	6.87e-05		2.89e-01		1.09e-06		5.44e-04
Sn-126	0.002	1.19e-04	1.80e-01	5.00e-01	1.44e-06	1.88e-06	7.19e-04	9.42e-04
Sb-124	5	1.92e-11		8.06e-08		3.04e-13		6.08e-14
Sb-125	25	2.29e-01	9.30e+00	9.62e+02	7.43e-05	3.62e-03	2.97e-06	1.45e-04
Sb-126	0.002	1.66e-05	2.50e-01	6.97e-02	2.00e-06	2.63e-07	9.99e-04	1.31e-04
Sb-126m	0.002	1.19e-04	1.80e-01	5.00e-01	1.44e-06	1.88e-06	7.19e-04	9.42e-04
Te-125m	100	7.44e-02	2.10e+00	3.12e+02	1.68e-05	1.18e-03	1.68e-07	1.18e-05
Te-127	20	3.24e-05		1.36e-01		5.13e-07		2.56e-08
Te-127m	20	3.31e-05		1.39e-01		5.24e-07		2.62e-08
Te-129	20	8.23e-16		3.46e-12		1.30e-17		6.51e-19
Te-129m	10	1.28e-15		5.38e-12		2.03e-17		2.03e-18
Cs-134	10	9.09e-02	1.60e+01	3.82e+02	1.28e-04	1.44e-03	1.28e-05	1.44e-04
Cs-135	25	2.68e-05	7.00e-01	1.13e-01	5.59e-06	4.24e-07	2.24e-07	1.70e-08
Cs-136	7	2.11e-43		8.86e-40		3.34e-45		4.77e-46
Cs-137	10	1.17e+01	3.20e+04	4.91e+04	2.56e-01	1.85e-01	2.56e-02	1.85e-02
Ba-136m	0.002	2.32e-42		9.74e-39		3.67e-44		1.84e-41

Isotope	A2 (Ci) (per 10CFR71)	VHLW-SR Specific Activity (Ci/lb.) [4-11]	Activity per Canister (Ci)		VHLW - WV f(i)	VHLW - SR f(i)	VHLW - WV f(i)/A2(i)	VHLW- SR f(i)/A2(i)
			VHLW-WV [4-3]	VHLW-SR (Note 1)				
Ba-137m	3	1.12e+01	3.00e+04	4.70e+04	2.40e-01	1.77e-01	7.99e-02	5.91e-02
Ba-140	20	2.76e-40		1.16e-36		4.37e-42		2.18e-43
La-140	30	1.16e-40		4.87e-37		1.84e-42		6.12e-44
Ce-141	25	9.68e-15		4.07e-11		1.53e-16		6.13e-18
Ce-142	0.002	2.59e-09		1.09e-05		4.10e-11		2.05e-08
Ce-144	7	2.66e+00	4.30e-03	1.12e+04	3.44e-08	4.21e-02	4.91e-09	6.01e-03
Pr-143	20	3.23e-38		1.36e-34		5.11e-40		2.56e-41
Pr-144	3	2.66e+00	4.30e-03	1.12e+04	3.44e-08	4.21e-02	1.15e-08	1.40e-02
Pr-144m	0.002	3.20e-02		1.34e+02		5.06e-04		2.53e-01
Nd-144	0.002	1.31e-13		5.50e-10		2.07e-15		1.04e-12
Nd-147	20	3.40e-48		1.43e-44		5.38e-50		2.69e-51
Pm-147	25	6.52e+00	6.30e+02	2.74e+04	5.03e-03	1.03e-01	2.01e-04	4.13e-03
Pm-148	0.002	1.88e-14		7.90e-11		2.98e-16		1.49e-13
Pm-	0.002	2.72e-13		1.14e-09		4.31e-15		2.15e-12
Sm-147	Unlimited	5.39e-10		2.26e-06		8.53e-12		
Sm-148	0.002	1.56e-15		6.55e-12		2.47e-17		1.23e-14
Sm-149	0.002	4.80e-16		2.02e-12		7.60e-18		3.80e-15
Sm-151	90	6.68e-02	9.00e+02	2.81e+02	7.19e-03	1.06e-03	7.99e-05	1.17e-05
Eu-152	10	9.94e-04	1.60e+00	4.17e+00	1.28e-05	1.57e-05	1.28e-06	1.57e-06
Eu-154	5	1.67e-01	4.50e+02	7.01e+02	3.60e-03	2.64e-03	7.19e-04	5.29e-04
Eu-155	60	1.28e-01	6.50e+01	5.38e+02	5.19e-04	2.03e-03	8.66e-06	3.38e-05
Eu-156	0.002	1.41e-35		5.92e-32		2.23e-37		1.12e-34
Tb-160	10	3.02e-10		1.27e-06		4.78e-12		4.78e-13
Tl-208	0.002	3.04e-07		1.28e-03		4.81e-09		2.41e-06
Th-232	Unlimited		8.00e-03		6.39e-08			
U-232	0.03	3.61e-06		1.52e-02		5.71e-08		1.90e-06
U-233	0.1	4.27e-10	4.20e-02	1.79e-06	3.36e-07	6.76e-12	3.36e-06	6.76e-11
U-234	0.1	9.24e-06	1.90e-02	3.88e-02	1.52e-07	1.46e-07	1.52e-06	1.46e-06
U-235	0.2	4.24e-08	4.40e-04	1.78e-04	3.52e-09	6.71e-10	1.76e-08	3.36e-09
U-236	0.2	3.04e-07	1.20e-03	1.28e-03	9.59e-09	4.81e-09	4.79e-08	2.41e-08
U-238	Unlimited	2.83e-06	3.50e-03	1.19e-02	2.80e-08	4.48e-08		
Np-236	0.002	4.70e-12		1.97e-08		7.44e-14		3.72e-11
Np-237	0.005	2.40e-06	6.90e-02	1.01e-02	5.51e-07	3.80e-08	1.10e-04	7.60e-06
Np-239	25		1.50e+01		1.20e-04		4.79e-06	
Pu-236	0.002	3.29e-05		1.38e-01		5.21e-07		2.60e-04
Pu-237	0.002	2.41e-15		1.01e-11		3.81e-17		1.91e-14
Pu-238	0.003	4.00e-01	3.00e+01	1.68e+03	2.40e-04	6.33e-03	7.99e-02	2.11E+0
Pu-239	0.002	3.48e-03	7.60e+00	1.46e+01	6.07e-05	5.51e-05	3.04e-02	2.75e-02
Pu-240	0.002	2.34e-03	1.90e+01	9.83e+00	1.52e-04	3.70e-05	7.59e-02	1.85e-02
Pu-241	0.1	4.50e-01	3.30e+02	1.89e+03	2.64e-03	7.12e-03	2.64e-02	7.12e-02
Pu-242	0.003	3.30e-06	7.50e-03	1.39e-02	5.99e-08	5.22e-08	2.00e-05	1.74e-05
Am-241	0.008	2.97e-03	5.00e+02	1.25e+01	4.00e-03	4.70e-05	4.99e-01	5.88e-03
Am-242	0.002	3.87e-06	1.30e-01	1.63e-02	1.04e-06	6.13e-08	5.19e-04	3.06e-05
Am-	0.002	3.90e-06	1.30e-01	1.64e-02	1.04e-06	6.17e-08	5.19e-04	3.09e-05
Am-243	0.008	1.56e-06	1.50e+01	6.55e-03	1.20e-04	2.47e-08	1.50e-02	3.09e-06
Cm-242	0.2	9.42e-06	1.30e-01	3.96e-02	1.04e-06	1.49e-07	5.19e-06	7.45e-07

Isotope	A2 (Ci) (per 10CFR71)	VHLW-SR Specific Activity (Ci/lb.) [4-11]	Activity per Canister (Ci) VHLW-WV [4-3]	VHLW-SR (Note 1)	VHLW - WV f(i)	VHLW - SR f(i)	VHLW - WV f(i)/A2(i)	VHLW-SR f(i)/A2(i)
Cm-243	0.009	1.50e-06	1.00e+00	6.30e-03	7.99e-06	2.37e-08	8.88e-04	2.64e-06
Cm-244	0.01	2.90e-02	1.20e+02	1.22e+02	9.59e-04	4.59e-04	9.59e-02	4.59e-02
Cm-245	0.006	1.81e-09	6.30e-02	7.60e-06	5.03e-07	2.86e-11	8.39e-05	4.77e-09
Cm-246	0.006	1.44e-10	2.70e-02	6.05e-07	2.16e-07	2.28e-12	3.60e-05	3.80e-10
Cm-247	0.002	1.78e-16		7.48e-13		2.82e-18		1.41e-15
Cm-248	0.002	1.85e-16		7.77e-13		2.93e-18		1.46e-15
Total			1.30e+05	2.65e+05	1.00e+00	1.00e+00	1.56e+00	3.16E+0
						A2 Mix:	6.40e-01	3.20e-01

Note:
(1) Based on maximum VHLW-SR glass weight = 4200 pounds (Ref. 4-11)

TABLE 4-4
ALLOWABLE LEAK RATES AT VARIOUS TEMPERATURES FOR SF_6

TEMPERATURE			LEAK RATE		
°C	°F	°K	L_t Volumetric (10^{-5} cm^3/s)	Q Closure (oz/yr)	Q Test Port (oz/yr)
-10	14	263	8.8	1.11	0.41
0	32	273	8.96	1.13	0.42
10	50	283	9.13	1.15	0.43
20	68	293	9.29	1.17	0.43
25	77	298	9.37	1.18	0.44
30	86	303	9.44	1.19	0.44
40	104	313	9.6	1.21	0.45
50	122	323	9.75	1.23	0.46

Note:

Meeting the above demonstrates satisfaction of the allowable test leakage rate of 3.05×10^{-4} std cm^3/s.

TABLE 4-5
ASSEMBLY VERIFICATION TEST
ALLOWABLE LEAK RATES AT VARIOUS TEMPERATURES

TEMPERATURE			LEAK RATE		
°C	°F	°K	L_R Volumetric (10^{-2} cm^3/s)	ΔP/H Closure (psi/hr)	ΔP/H Test Port (psi/hr)
-10	14	263	4.7	11.1	56.8
0	32	273	4.79	11.8	60.1
10	50	283	4.87	12.4	63.4
20	68	293	4.96	13.1	66.8
25	77	298	5	13.4	68.5
30	86	303	5.04	13.8	70.3
40	104	313	5.12	14.5	73.8
50	122	323	5.21	15.2	77.4

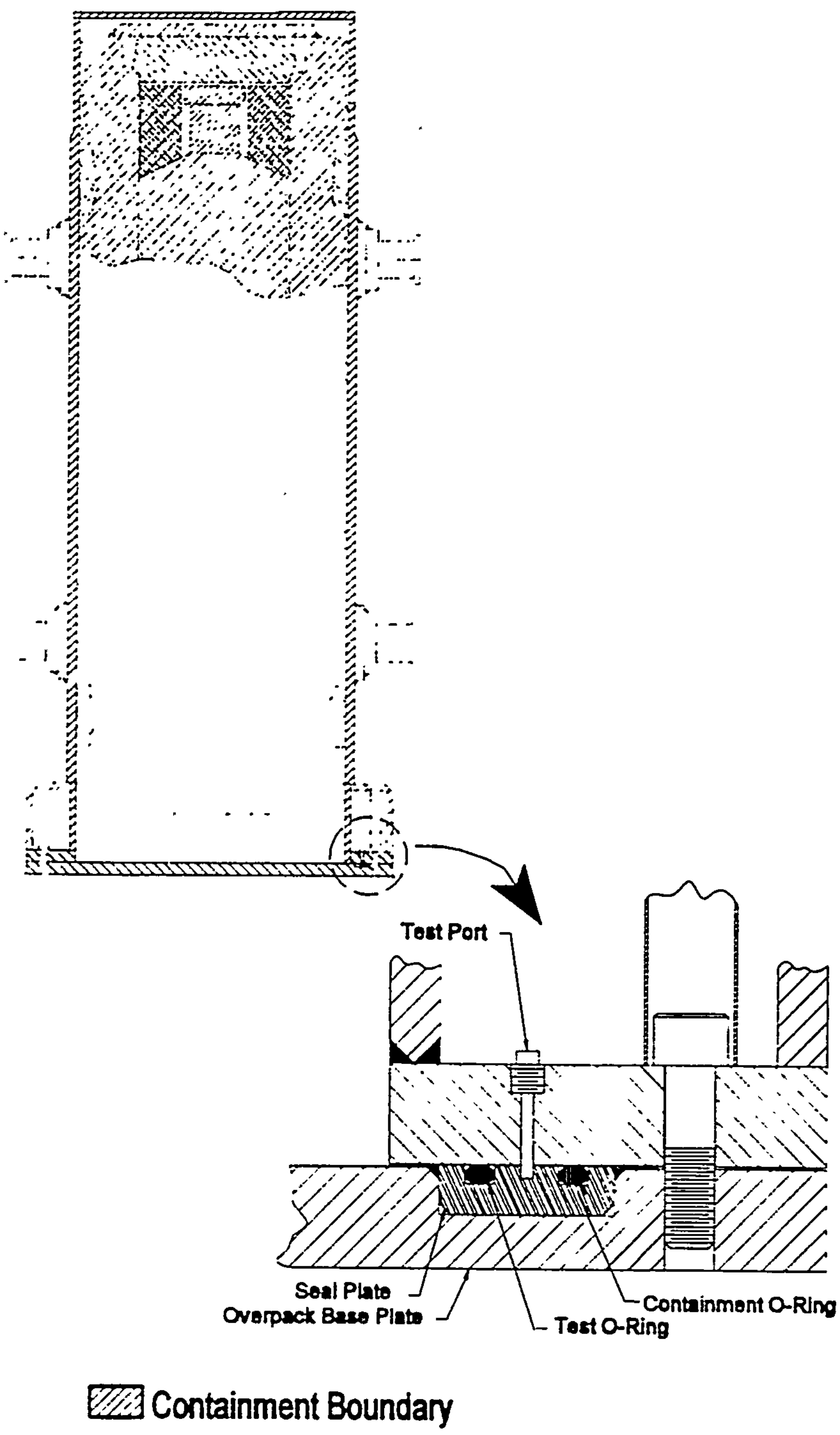


Figure 4-1
VHLW Package Containment Boundary

REFERENCES

4-1 Code of Federal Regulations, Title 10, Part 71, *Packaging and Transportation of Radioactive Materials*, U.S. Nuclear Regulatory Commission, U.S. Government Printing Office, Washington, DC, May 31, 1988.

4-2 *Parker O-Ring Handbook*, Parker Seal Group, Lexington, Kentucky, 1992.

4-3 Eisenstatt, Larry R., *Description of the West Valley Demonstration Project Reference High-Level Waste Form and Canister*, National Technical Information Service, DOE/NE/44139-26, Springfield, Virginia, July 28, 1986.

4-4 ANSI N14.5-1987, *American National Standard for Radioactive Materials-Leakage Tests on Packages for Shipment*, American National Standards Institute, Inc., New York, 1987.

4-5 R.K. Farnsworth, J. Mishima, *DWPF Canister Impact Testing and Analyses for the Transportation Technology Center*, PNL, DOE/DE-AC06-76RLO 1830, September 1987

4-6 S.C. Slate, B.A. Pulsipher, P.A. Scott, *MCC-15: Waste/Canister Accident Testing and Analysis Method*, Proceedings of Waste Management 1985, Tucson, Arizona, March 1985.

4-7 F.A. Simonen and S.C. Slate, *Stress Analysis of High-Level Waste Canisters: Methods, Applications, and Design Data*, PNL-3036, Pacific Northwest Laboratory, October 1979.

4-8 M.E. Peterson and J.M. Alzheimer, *Impact Testing of Centrifugally Cast Canisters of Simulated Waste Glass*, PNL-5250, Pacific Northwest Laboratory, 1984.

4-9 M.E. Peterson, J.M. Alzheimer, and S.C. Slate, *Impact Testing of Simulated High-Level Waste Glass Canisters*, PNL-5251, Pacific Northwest Laboratories, January 1985.

4-10 *Leakage Tests on Packages for Shipment of Radioactive Materials*, Regulatory Guide 7.4, U.S. Nuclear Regulatory Commission, Office of Standards Development, Washington, DC, June 1975.

4-11 Baxter, R. G., *Defense Waste Processing Facility Waste Form and Canister Description*, National Technical Information Service, Springfield, Virginia, DP-1606, Revision 2, December 1988.

4-12 M.H. Burgess, J.P. Mitchell, M.H.E. Ball, R.T. Edwards, *Leak-Testing to Demonstrate Retention of Particles*, PATRAM 1989 Proceedings, pp. 365-372.

4-13 J. Higson, R.J. Moulton, R.A. Vaughan, *Containment of Radioactive Powders by Seals*, PATRAM 1989 Proceedings, pp. 670-679.

CHAPTER FIVE
SHIELDING EVALUATION

5.0 SHIELDING EVALUATION

This chapter identifies, describes, discusses, and analyzes the principal shielding design of the VHLW cask. Compliance with §§ 71.47 "External radiation standards for all packages" and 71.51 "Additional requirements for Type B packages" of 10 CFR Part 71 is demonstrated. Note that each shipment of the cask and fuel will be exclusive use.

5.1 Discussion and Results

5.1.1 Operating Design

The VHLW cask consists of ductile iron shield walls, a ductile iron primary lid, a ductile iron secondary lid, and a stainless steel overpack. Neutron shielding plugs are provided at the top and bottom of the cask. These components provide the necessary shielding for the various radioactive materials to be shipped within the package. (Refer to Section 1.2.3 for packaging contents.) Tests and analysis performed under Sections 2.0 and 3.0 have demonstrated the abilit; the containment vessel to maintain its shielding integrity under normal conditions of transpo.. and after the hypothetical accident. Prior to each shipment, radiation readings will be taken based on individual loadings to assure compliance with applicable regulations as determined in 10 CFR 71.47 (refer to Section 7.1).

The VHLW cask will be operated such that the contents in the cask will not create a dose rate exceeding 200 mr/hr on the cask surface, or 10 mr/hr at two meters from the vehicle. The package shielding must be sufficient to satisfy the dose rate limit of 10 CFR 71.51(a)(2) which states that any shielding loss resulting from the hypothetical accident will not increase the external dose rate to more than 1000 mr/hr at one meter from the external surface of the cask.

The VHLW cask has been designed to accommodate the West Valley and Savannah River waste canisters as described in Reference 5-1. Based on the information contained in this database, the Savann.. River waste from the Defense Waste Processing Facility (DWPF) produces the strongest source term. This DWPF source term will therefore be used for this shielding analysis. From the information provided in Reference 5-1, the West Valley waste could be accommodated with no decay.

5.1.2 Shielding Design Features

The cask side wall consists of 7.25-inch thick ductile iron shielding and a 1.50-inch thick stainless steel overpack. The top shielding consists of an 8.00-inch thick ductile iron primary lid, a 1.00-inch thick secondary lid, and a 1.00-inch thick stainless steel overpack. The bottom shielding consists of 6.25 inches of ductile iron and a 2.00-inch thick stainless steel overpack.

5.1.3 Maximum Dose Rate Calculations

Table 5-1 gives the highest possible normal and accident condition dose rates resulting from the maximum source which may be transported within the cask and compares them with maximum allowable dose rates given in 10 CFR 71. This payload is one vitrified high level waste canister from the DWPF assumed to be decayed 10 years as presented in Reference 5-1.

The source is modeled as being uniformly distributed within the waste glass volume. The shielding capabilities of the VHLW cask are unaffected by the hypothetical accident as demonstrated in Chapter 2. Table 5-1 shows that each of the calculated maximum dose rates is below its corresponding maximum permissible limit.

5.2 Source Specification

The source assumed in the VHLW cask is the 10 year decayed DWPF source term provided in Reference 5-1 Gamma and neutron sources from this waste form are described in this section. Other vitrified waste forms, such as West Valley, can also be accommodated in the VHLW cask.

5.2.1 Gamma Source

Reference 5-1 gives the gamma energy spectra and source in database form. This source term is shown in Table 5-2 for 10 years decayed. This source distribution considers contributions from all radionuclides within the waste.

5.2.2 Neutron Source

The neutron source strength assumed for the VHLW cask shielding analyses is taken from Table 3.3.6 of Reference 5-1. This source strength is a combination of alpha,n and spontaneous fission sources within the waste. This source strength is assumed to have a typical fission source spectrum (Table 2 of Reference 5-2). The neutron source term is shown in Table 5-3.

5.3 Model Specification

5.3.1 Description of Radial and Axial Shielding Configuration

Figure 5-1 shows a sketch of the radial and axial shielding materials. This configuration has been modeled with the XSDRNPM discrete-ordinates computer code (Reference 5-3). Figure 5-2 shows the radial model and Figure 5-3 shows the top and bottom axial models of the VHLW cask and contents. Table 5-4 gives the canister nominal dimensions and references used in these models. Minimum thicknesses (within tolerances) of the cask wall materials are used in all models for conservatism.

The DWPF canister fill height is assumed to be 91 inches as provided in Reference 5-1.

5.3.2 Shield Regional Densities

5.3.2.1 VHLW Waste Canister and Cask Shielding

The primary VHLW cask shielding material is ductile iron. Stainless Steel is used to fabricate the Defense Waste Processing Facility canister (Reference 5-1). The density of Ductile Iron is assumed to be 7.0 g/cc (Reference 5-4). The density of stainless steel Type 304L is 8.03 g/cc (Ref. 5-5 Mark's, page 6-44). The atom densities for ductile iron and stainless steel are shown in Table 5-5.

5.3.2.2 Defense Waste Processing Facility Waste Glass

The composition of DWPF glass is given in Reference 5-1. Tables 5-6 and 5-7 show the material composition of the glass taken from this reference. The atom densities for the glass is shown in Table 5-8

5.4 Shielding Evaluation

5.4.1 Method and Data

The shielding evaluation is performed using the NITAWL, XSDRNPM , and XSDOSE computer codes of the SCALE code package (Reference 5-3). A working cross-section library is prepared using NITAWL for the 22 neutron - 18 gamma energy group library. This working library is used by the XSDRNPM code to calculate the surface fluxes for each shielding geometry. These surface fluxes are used by the XSDOSE code to calculate integrated dose rates at the various detector locations based on ANSI standard flux-to-dose conversion factors.

XSDRNPM is a one-dimensional code, and cannot directly represent finite cylindrical geometries. Therefore, the code provides a method for representing the leakage of gamma or neutron particles in the direction considered infinite by the code, i.e. axial for radial geometries, and radially for axial geometries). For conservatism, no leakage correction is used for the radial calculations. However, the leakage of particles can be significant in an axial model, as the code assumes the model to be infinite in the planar direction. Therefore, leakage corrections are used for the top and bottom axial shielding calculations. As discussed in Reference 5-6, care must be taken in choosing the appropriate buckling correction factor to be used. As described in Reference 5-7, the diameter of the waste canister is used for gamma calculations, while the diameter of the VHLW cask is used for neutron calculations. The larger dimension is used for the neutron analyses due to the scattering nature of neutron radiation.

5.4.2 Dose Rates for Normal Conditions of Transport

Table 5-1 shows the dose rates calculated for a VHLW cask containing a canister of DWPF waste which has been decayed for 10 years from the canister specification isotopics as given in Reference 5-1. The surface dose rates are less than 100 mr/hr, with the largest dose rate being

94.2 mr/hr at the bottom of the VHLW cask. The two meter dose rates are all less than 10 mr/hr, with the largest dose rate being 8.3 mr/hr at the bottom of the cask.

5.4.3 Dose Rates for Hypothetical Accident Conditions

As discussed in Section 2.7, no breach in the containment occurs as a result of the hypothetical accident However, the polyethylene neutron shielding at the ends of the cask would melt during the fire accident. The one-meter dose rates for the cask after accident conditions are listed in Table 5-1, including the increased dose rates resulting from a loss of neutron shielding at the top and bottom ends of the cask. The maximum one-meter accident dose rate is 43.8 mr/hr at the bottom of the VHLW cask, well below the 1000 mr/hr limit.

TABLE 5-1

SUMMARY OF MAXIMUM DOSE RATES (MR/HR)

	Package Surface			2 Meters From Vehicle (1)			1 Meter From Surface of Package (Accident)		
	Side	Top	Bottom	Side	Top	Bottom	Side	Top	Bottom
Gamma	33.3	53.9	91.1	3.5	5.0	8.1	10.4	20.8	40.3
Neutron	17.8	7.0	2.9	1.2	0.4	0.2	4.5	3.1	3.5
Secondary Gamma	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Total	51.2	61.1	94.2	4.7	5.4	8.3	14.9	23.9	43.8

Notes:

(1) The top and bottom dose rates at 2 M from the vehicle have been conservatively calculated at 2 M from the cask surface to allow flexibility in placing the cask on the trailer.

TABLE 5-2

DEFENSE WASTE PROCESSING FACILITY WASTE GAMMA SOURCE TERM GROUP STRUCTURE (SCALE 18-GROUP FORMAT)

Energy Group	Mean Energy (MeV)	Gamma Source (particles/sec) (1)
1	9	7.70E3
2	7.25	6.14E4
3	5.75	4.80E5
4	4.5	0.0
5	3.5	7.65E7
6	2.75	7.69E8
7	2.25	3.63E10
8	1.83	4.46E11
9	1.5	1.47E13
10	1.17	0.0
11	0.9	1.66E11
12	0.7	1.17E15
13	0.5	4.04E13
14	0.35	0.0
15	0.25	1.07E14
16	0.15	1.60E14
17	0.08	3.07E14
18	0.03	6.17E14

(1) Due to differences between the source structure presented in Reference 5-1 and the SCALE 18-group structure, some energy groups have zero source strengths. All energy groups were re-binned upwards for conservatism, and the total energy of the source is conserved.

TABLE 5-3

DWPF WASTE NEUTRON SOURCES (NEUTRONS/SEC)

Radionuclide	Alpha, N	Spontaneous Fission	Total
U-238	0.0	3.96E2	3.96E2
Pu-238	5.79E7	2.30E5	5.81E7
Pu-239	3.97E5	5.69E0	3.97E5
Pu-240	2.68E5	3.47E4	3.03E5
Pu-242	0.0	5.40E3	5.40E2
Am-241	4.25E5	3.98E0	4.25E5
Cm-242	1.98E3	2.28E2	2.20E3
Cm-244	5.11E6	1.48E7	1.99E7
Totals	**6.41E7**	**1.51E7**	**7.92E7**

TABLE 5-4

DWPF WASTE CANISTER DIMENSIONS
(REFERENCE 5-1)

Description	Value (Inches)
Canister fill height	91
Canister outside diameter	24.00
Canister wall thickness	0.375

TABLE 5-5

ATOMIC DENSITIES OF DUCTILE IRON AND STAINLESS STEEL TYPE 304L

Element	Ductile Iron (1) (atoms/barn-cm)	Stainless Steel (2) (atoms/barn-cm)
Cr	--	1.74E-2
Ni	7.15E-4	7.72E-3
Fe	7.02E-2	5.94E-2
Si	3.46E-3	--
C	1.23E-2	--

(1) Reference 5-4.
(2) Reference 5-5.

TABLE 5-6

DWPF GLASS COMPOSITION

Component	Weight Percent	Component	Weight Percent
Al_2O_3	3.96	MnO	2
B_2O_3	10.28	SiO_2	46.72
CaO	0.85	TiO_2	0.99
Fe_2O_3	7.04	U_3O_8	2.2
FeO	3.12	Na_2O	12.15
K_2O	3.58	NiO	0.93
Li_2O	3.16	Zeolite	1.67
MgO	1.36		

TABLE 5-7

DWPF ZEOLITE COMPOSITION

Component	Weight Percent
SiO_2	48
H_2O	19.1
Al_2O_3	18.6
CaO	10.2
Na_2O	4.1

TABLE 5-8

ATOMIC DENSITIES OF DWPF WASTE GLASS

Element	Density (atoms/barn-cm)
Al	1.38E-3
B	4.85E-3
Ca	3.01E-4
Fe	2.16E-3
K	1.25E-3
Li	3.44E-3
Mg	5.52E-4
Mn	4.60E-4
Si	1.31E-2
Ti	2.01E-4
U	1.29E-4
Na	6.49E-3
Ni	2.04E-4
H	6.02E-4
O	4.66E-2

REFERENCES

5-1 Characteristics Database System, High-Level Waste Database, DOE/RW-0184, Revision 1, July 1992.

5-2 CASK-81, 22 Neutron, 18 Gamma-Ray Group, P3, Cross Sections for Shipping Cask Analysis, ORNL Radiation Shielding Information Center ID # DLC-23, July 29, 1987.

5-3 SCALE 4.2, Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation, ORNL Radiation Shielding Information Center ID # CCC-545, September 1994.

5-4 GNS Material Data Sheet No. WB 02, 1982.

5-5 Baumeister, Theodore, et. al., *Mark's Standard Handbook for Mechanical Engineers*, eds., Eighth Edition, McGraw-Hill Book Company, New York, 1978.

5-6 Carbajo, J. J., "Comparison of Spent Fuel Cask Radiation Doses Calculated by One-and Two-Dimensional Shielding Codes," Trans. Am. Nucl. Society, 65, 365-366, June 1992.

CHAPTER SIX
CRITICALITY EVALUATION

6.0 CRITICALITY EVALUATION

This chapter identifies, describes, discusses and analyzes the criticality design of the VHLW cask. Compliance with the performance requirements of 10 CFR Part 71 is demonstrated for a Type B transport package.

6.1 Discussion and Results

The VHLW cask holds a single canister of either VHLW-WV or -SR waste. The maximum content of fissile nuclides per each of these waste types is shown in Table 6-1.

Criticality safety is assured by:

- the limited maximum inventory of fissile nuclides per canister
- the homogeneous distribution of the fissile nuclides in the glass matrix.

Nuclear criticality safety assessments for VHLW canisters show that the infinite array neutron multiplication factor k_{eff} will be less than 0.4, as shown in Table 6-2. Due to its thick, neutron-absorbing ductile iron walls, the VHLW cask has additional criticality safety. Also, the volume of water possible in the cavity is limited, even in the unlikely event of flooding of an open cask, by the small annulus between canister and cavity wall (nominally 0.5") and between cask surface and overpack wall (nominally 0.75").

6.2 Package Fuel Loading

The maximum inventory of thermally fissile nuclides in vitrified waste is shown in Table 6-1. These values have been taken from the waste form descriptions in Table 23, Reference 6-1, and Table 12, Reference 6-2, based on 3700 lbs. per glass canister.

The calculations are for canisters (see Fig. 6-2) of limited glass height of 102.36" for VHLW-WV and 84.25" for VHLW-SR.

6.3 Model Specification

6.3.1 Description of Calculational Model

The VHLW cask loaded with a canister is modelled in three-dimensional cylindrical geometry as shown in Fig. 6-1 (radial section) and Fig. 6-2 (axial section). The active glass height of the canisters is taken into account with a height of 2140 mm (84.25"), corresponding to 3700 lbs of VHLW-SR at 2.75 g/cm^3 and a height of 2600 mm (102.36"), corresponding to 2006 kg of VHLW-WV at 2.70 g/cm^3. On the outer overpack-side-wall surface, mirror reflection was used for the neutrons. The multiplication factors k_{eff} thus calculated correspond to an unlimited array of this kind of cask.

The gaps between the outer canister surface and the cavity wall and between the cask surface and overpack wall are conservatively assumed with vacuum. This was shown by results of parameter calculations, in which the gaps were alternatively considered to be filled with water and/or vacuum. The most reactive arrangement resulted from the unflooded, dry gaps in the VHLW cask. Results of the parametric analysis are provided in Table 6-4.

Also, no external water is considered since external moderation would decrease the neutron multiplication due to increased absorption of the reflected neutrons in the cask wall.

The calculation for an infinite block of VHLW glass (k_{inf}) considers a cylinder of infinite height which is a conservative approach since neutron absorption in both the lid and bottom of the cask is neglected. In this case, only the nuclide concentration is of importance for criticality safety.

6.3.2 Package Regional Densities

Densities corresponding to average composition were assumed for the different zones. Densities and composition of the VHLW glass are taken from Tab. 7 of (Ref. 6-1) and Tab. 21 of (Ref. 6-2) respectively, neglecting minor constituents which contribute less than 0.5 wt% (except fissile nuclides). Tab. 6-3 shows the densities and compositions for the four material zones considered in the model.

The concentrations of fissile nuclides have been calculated from Tab. 6-1 for canisters filled with 3700 lbs (1678 kg) of VHLW (SR), and 2006 kg (90 % full) of VHLW (WV) respectively.

All constituents are assumed to be mixed homogeneously throughout their respective material zones.

6.4 Criticality Calculation

6.4.1 Calculation Method

The criticality safety analysis was performed with the aid of the SCALE 4.2 program system (Ref. 6-3). For criticality calculations, this program contains various cross-sectional libraries, from which the 27 group library used in this calculation was selected. The program utilizes routines for treating self-shielding according to Bondarenko's method (Ref. 6-4), or according to Nordheim's method (Ref. 6-5) for these cross sections. The programs are called according to the resonance data given.

Also integrated in this program is the code XSDRNPM (Ref. 6-6) which can be used to generate the cell-weighted cross-sections. The self-shielded or cell-weighted cross-sections are then treated by the Monte Carlo program KENO-Va (Ref. 6-7) to calculate the multiplication factors. In addition, the program system has several auxiliary routines to calculate, for example, the Dancoff factor of the nuclide number densities or for the automated transfer of the cross-sections.

With the generated self-shielding cross-sections, a one-dimensional transport calculation is performed by the code XSDRNPM (Ref. 6-6), which iteratively solves Boltzmann's equation by the S_n-method, to determine the infinite multiplication factor for the VHLW glass.

The multiplication factor for the infinite array of VHLW casks is calculated with KENO-Va, using the SCALE control sequence CSAS25 of the CSAS4 module (Ref. 6-3).

The neutron statistics to determine the multiplication factors k_{eff} with the KENO-Va program are based on 103 iterations with 300 neutrons each, whereby the first 3 iterations are not counted.

6.4.2 Criticality Results

The results of the criticality calculations are summarized in Tab. 6-2 for the model described above. Additionally, the neutron multiplication factor of an infinite block of VHLW is given in Tab. 6-2.

The effective neutron multiplication factor of an infinite array of casks, k_{eff}, is well below the design limit of 0.95, even for the very conservative calculational model used in these calculations, and even if allowance is made for tolerances, temperature effects, etc.

6.5 Critical Benchmark Experiments

The SCALE system has been extensively validated by calculations for critical benchmark experiments. For details see (Ref. 6-3).

TABLE 6-1
MAXIMUM FISSILE NUCLIDE INVENTORY OF VHLW CASK

Maximum Fissile Inventory	VHLW-WV g/cask	VHLW-SR g/cask
U-233	440	< .001
U-235	210	85.6
Pu-239	120	245
Pu-241	3.5	19.5
Cu-244	1.7	1.6

TABLE 6-2
NEUTRON MULTIPLICATION FACTOR
FOR VHLW CASK WITH MAXIMUM FISSILE INVENTORY

Neutron-Multiplication Factor	VHLW-WV	VHLW-SR
k_{eff} (1)	0.249 (1)	0.110 (3)
k_{inf} (2)	0.383	0.163

1) infinite array of unflooded (dry) casks
2) infinite block of VHLW glass
3) standard deviation < 0.001

TABLE 6-3a
COMPOSITION OF MATERIAL ZONES
FOR CRITICALITY CALCULATIONS

Zone: VHLW-glass		
	VHLW-WV	VHLW-SR
Density, g/cm^3	2.70	2.75
Compound	wt%	
U-233	0.0222	---
U-235	0.0106	0.0044
Al_2O_3	2.83	3.96
B_2O_3	9.95	10.28
CaO	0.60	0.85
Fe_2O_3	12.16	7.04
FeO	-----	3.12
K_2O	3.57	3.58
Li_2O	3.03	3.16
MgO	1.30	1.36
MnO_2	1.31	-----
Zeolite	-----	1.67
SiO2	----	48.0
H_2O	-----	19.1
Al_2O_3-	-----	18.6
CaO	-----	10.2
Na_2O	-----	4.1
Pu-239	0.0060	0.0126
Pu-241	0.0002	0.0010
MnO	----	2.0000
Na_2O	10.9300	12.1500
NiO	-----	0.9300
P_2O_5	2.51	-----
SiO_2	46.65	46.72
ThO_2	3.58	-----
TiO_2	0.98	0.99
UO_2	0.56	-----
U_3O_8	-----	2.2

TABLE 6-3b
COMPOSITION OF MATERIAL ZONES FOR CRITICALITY CALCULATIONS

	Zone		
	Overpack & Canister Wall	Gaps	Lid & Cask Wall
Material	SS304	Vacuum	Ductile Iron, ASTM A-874
Density, g/cm³	7.8	0	7.0
Composition, wt %			
	Cr 19.0	—	C 3.6
	Mn 2.0		Si 1.9
	Fe 69.5		Fe 92.6
	Ni 9.5		Ni 1.3

TABLE 6-4
CRITICALITY ANALYSES FOR VHLW CASK

				k_{eff}[3]	
Case	Gap 1[1]	Gap 2[2]	Surroundings	VHLW - SR	VHLW - WV
1	water	water	water	0.1000	0.2190
2	water	water	vacuum	0.1004	0.2194
3	water	vacuum	vacuum	0.1008	0.2220
4	vacuum	vacuum	vacuum	0.1103	0.2494
5	vacuum	water	water	0.1052	0.2375
6	vacuum	vacuum	water	0.1056	0.2393
7	vacuum	water	vacuum	0.1061	0.2398

Notes:

(1) Gap 1 is the space between the inside of the ductile iron shielding walls and the outside of the VHLW canister.

(2) Gap 2 is the space between the inside of the stainless steel overpack and the outside of the ductile iron shielding.

(3) Standard deviation less than 0.001

References

6-1 Eisenstatt, Larry R., *Description of the West Valley Demonstration Project Reference High-Level Waste Form and Canister*, DOE/NE/44139-26 (DE 87008691), July 1986.

6-2 Baxter,R.G., *Defense Waste Processing Facility Waste Form and Canister Description*, DP-1606, Rev. 2, December 1988

6-3 SCALE 4.2, *Modular Code System for Perfoming Standardized Computer Analysis for Licensing Evaluation*, ORNL/RSIC CCC-545, December 1993

6-4 Freene, N.M., *BONAMI-S: Resonance Self-Shielding by the Bondarenko Method*, NUREG/CR-200 Rev. 4, Vol. 2, Sect. F1, ORNL/NUREG/CSD-2/V2/R4, November 1993

6-5 Greene, N.M., Petrie, L.M., and Westfall, R.M. *NITAWL-II, SCALE System Module for Performing Resonance*, Shielding and Working Library Production, NUREG/CR-0200 Rev. 0, Vol. 2, Sect. F2, ORNL/NUREG/CSD-2/V2/R3

6-6 Greene, N.M., and PetrieL.M., *XSDRNPM-S: A One-Dimensional Discrete-Ordinates*, Code for Transport Analysis, NUREG/CR-0200 Rev. 4, Vol. 2, Sect. F3, ORNL-NUREG/CSD-2/V2/R4, November 1993

6-7 Petrie, L.M., and Landers, N.F., *KENO-Va: An Improved Monte Carlo Criticality Program with Supergrouping*, NUREG/CR-200 Rev. 4, Vol. 2, Sect. F11, ORNL/NUREG/CSD-2/R4, November 1993

CHAPTER SEVEN

OPERATING PROCEDURES

7.0 OPERATING PROCEDURES

7.1 Procedure for Removing Package from Trailer and Disassembly

Note: Radiation surveys performed on the loaded casks, prior to the cask being transported, should included neutron detectors as well as beta-gamma to ensure the limits of Chapter 5 are not exceeded.

7.1.1 Remove the eight ¾" bolts that attach the upper impact limiter to the cask overpack, and the eight ¾" bolts that attach the lower impact limiter to the overpack.

7.1.2 Attach suitable equipment to the lifting lugs on the upper impact limiter and remove it from the cask overpack. Remove the lower impact limiter from the overpack. Care should be taken to prevent damage to the impact limiter during handling and storage.

7.1.3 Disconnect cask to trailer tiedown equipment.

7.1.4 Attach the cask lifting yoke to the upper set of overpack lifting trunnions. Rotate the cask to the vertical orientation and remove it from the trailer. Place the cask on level ground resting in the vertical orientation on its base plate.

7.1.5 Loosen and remove the sixteen 1"-8 socket head cap screws that attach the overpack barrel to the overpack base plate.

7.1.6 Using the cask lifting yoke attached to the upper overpack lifting trunnions, lift the overpack barrel vertically until it clears the top of the shield insert. Place the overpack barrel aside.

Note: Before lifting the overpack barrel and during lifting, ensure the lifting yoke is directly above the centerline of the cask to prevent lateral movement of the barrel.

Note: During handling of the overpack barrel, especially when resting it on the ground, care should be taken to prevent damage to the seal sealing surfaces on the barrel base plate flange.

7.1.7 Remove the three 1" bolts from the four trunnion shipping plugs and remove the four plugs from the shield insert. Install the four shield insert lifting trunnions in the same locations by bolting the trunnions in place with twelve 1" bolts. These bolts should be torqued to 200 ± 20 ft-lbs.

Note: If only the upper two trunnions are to be used for moving the shield insert, then only these two shipping plugs need to be removed.

7.1.8 The shield insert can now be positioned for loading the defense high level waste canisters.

7.2 Package Assembly for Shipment

Note: Preparation for shipment can begin after the defense high level waste canister has been placed in the cavity of the shielding insert, the primary lid is in place, and the secondary lid is in position and the closure weld for the secondary lid performed.

Note: Before preparing the package for shipment, inspect the exterior of the shield insert and the interior of the overpack for damage, loose materials or moisture. Clean and inspect the overpack seals and seal surfaces. Replace the overpack seals if defects or damage is found. When seals are replaced, the Maintenance Verification Leak Test must be performed as specified in Section 8.1.3.

7.2.1 Place the overpack base plate on a flat, level surface where the cask assembly is to be performed.

7.2.2 Lift the shield insert by the upper trunnions using a suitable lift yoke and place in position on the overpack base plate. The insert should be centered on the black target on the overpack base plate to prevent interference with the overpack barrel.

Note: The outer diameter of the black target on the overpack base plate corresponds to the inner diameter of the overpack barrel.

Note: Ensure the alignment pins in the base plate are in place and unbent before installing the overpack barrel.

7.2.3 Remove the four shield insert lifting trunnions and in their place bolt the four shield insert plugs. Install each shield insert plug by bolting it in place with three 1" bolts. Torque the bolts to 200 $\pm$ 20 ft-lbs.

7.2.4 Lift the overpack barrel using a suitable lift yoke attached to the upper overpack lifting trunnions. Center the overpack barrel above the shield insert and align match marks on the upper and lower parts of the overpack. Lower the overpack barrel down over the shield insert until it seats on the overpack base, ensuring alignment pins in the overpack base are seated in their holes on the barrel base plate.

7.2.5 Secure the overpack barrel to the overpack base plate by using the sixteen 1" socket head cap screws. The bolts should be tightened in a star pattern, and torqued to 500 $\pm$ 50 ft-lbs.

7.2.6 Perform the Assembly Verification Leak Test in accordance with Section 8.2.2.

Note: The procedure for performing the Assembly Verification Leak Tests requires installation of the $3/8$" vent plug after the seals have been tested, and leak testing of the plug. When the vent plug is installed it should be torqued to 50 ± 5 ft-lbs.

7.2.6 The cask is ready to be loaded on the trailer for transport.

7.3 Procedure for Loading Cask Onto Trailer

7.3.1 Attach the cask lifting yoke to the upper set of overpack lifting trunnions.

7.3.2 Lift the cask and set the lower set of overpack trunnions into the lower trunnion supports on the trailer. Rotate the cask into the horizontal position until the upper set of trunnions rest in the upper trunnion supports.

7.3.3 Attach the cask-to-trailer tiedown equipment and remove the lifting yoke from the overpack lifting trunnions.

7.3.4 Attach suitable equipment to the lifting lugs on the upper impact limiter and lift it into position on the upper (overpack barrel) end of the cask overpack. Slide the overpack over the end of the overpack and bolt it into position with eight ¾" bolts. Tighten each bolt until the spring washer is compressed.

Note: Rotate the impact limiter radially so that tabs on the upper impact limiter are bolted to ones on the overpack that are color-coded the same color.

7.3.5 Attach suitable equipment to the lifting lugs on the lower impact limiter and lift it into position on the lower (baseplate) end of the cask overpack. Slide the overpack over the end of the overpack and bolt it into position with eight ¾" bolts. Tighten each bolt until the spring washer is compressed.

Note: Rotate the impact limiter radially until the match mark on the lower impact limiter aligns with the one on the overpack.

7.3.6 Attach the tamperproof seals (two) between the lower impact limiter and overpack in the locations provided.

CHAPTER EIGHT

ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

8.0 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

8.1 Acceptance Tests

Note: Inspections and tests in Section 8.1 shall be performed before first use of the package.

8.1.1 Visual Examination

The package will be examined for adverse conditions in materials or fabrication. Seal surfaces shall be examined for proper finish. Nameplates must be in place and legible.

8.1.2 Structural Tests

Welds that form part of the containment structure, as identified in the drawings in Appendix 1.3, are to be inspected per ASME Code, Section III, Div. 1, Subsection NB, Article NB-5000.

Welds that are not part of the containment structure are to be inspected per SAME Code, Section III, Div. I, Subsection NF.

Welds on lifting and tiedown lugs and trunnions are to be inspected before and after 150% load testing in accordance with SAME Code requirements for MT or PT examinations discussed above.

8.1.3 Leak Tests

Note: The leak test described in this section must be performed with the package assembled, including with the shield insert in place in the overpack cavity. A simulated shield insert can be used that is equal in volume for the test.

Prior to acceptance of the package it is to be assembled and leak tested according to the requirements of this section and Chapter 4. Two separate leak tests are required; one for the overpack O-rings, and then one for the test port plug. Leak testing of the seals is performed by pressurizing the annulus between the O-rings to 25 psig with sulfur hexafluoride (R-134a) using the test port on the overpack barrel base plate provided for this purpose. The detector probe is moved along the exterior surface of the outer seal to check for any R-134a that may be leaking out. The test port plug is tested by installing the plug and testing the void above the plug for leaking R-134a.

The detector used for performing the leak test shall be a General Electric H-25B leak detector along with a Yokogawa Model LS-20 leak standard containing R-134a halogen gas.

Note: Equivalent leak detectors and leak standards are permissible provided they have the minimum sensitivity specified in Chapter 4.

The maximum permissible leak rate for the testing described in this section is:

O-rings: 3.05×10^{-4} std-cm^3/sec, which corresponds to 1.18 oz/year at a temperature of 77°F

Test Port Plug: 9.37×10^{-5} std-cm^3/sec, which corresponds to 0.44 oz/yr at a temperature of 77°F

Table 8-1 provides the maximum permissible leakage rate at different temperatures.

8.1.4 Component Tests

Components of cask identified as being critical to its performance shall be procured and examined in accordance with an approved Quality Assurance program.

8.1.5 Test for Shielding Integrity

Shielding integrity of the package shall be verified by gamma scan or gamma probe methods of the shield insert to assure the shield insert is free of significant voids. All gamma scanning shall be performed on a 4-inch square or less grid system. The acceptance criteria shall be that voids resulting in shield loss in excess of 10% of the normal ductile iron thickness in the direction measured shall not be acceptable.

8.1.6 Thermal Acceptance Tests

No thermal acceptance testing is required for the VHLW packaging. Chapter 3, Thermal Evaluation does not identify any critical components requiring evaluation by testing.

8.2 Maintenance Program

Note: The VHLW Cask shall be subjected to routine and periodic inspections and tests in accordance with this section and approved procedures.

8.2.1 Routine Maintenance

8.2.1.1 Fasteners

Fasteners shall be inspected for defects prior to each use. Replacement bolts shall be procured only through an approved QA program.

The plug used for the vent port in the overpack barrel base plate shall be inspected for defects prior to each use.

8.2.1.2 Seals

The O-ring seals shall be visually inspected prior to each use to ensure they are in the proper position and free of cuts or cracks. The seal seating surfaces shall be inspected to ensure they are clean and undamaged.

8.2.2 Periodic Maintenance

8.2.2.1 Periodic Leak Tests

The package shall be assembled and leak tested as described in Section 8.1.3 after its third use. In addition, the leak test described in Section 8.1.3 shall have been performed within the preceding 12-month period prior to any use.

Prior to the cask being used, the overpack containment seal O-rings in the overpack shall have been replaced within the preceding 12-month period.

8.2.2.2 Assembly Verification Leak Test

Note: This test is performed to verify proper assembly of the package. It shall be performed after assembly of the package and prior to each shipment.

Two separate leak tests are required; one for the overpack O-rings, and one for the test port. The overpack O-rings are tested by pressurizing the annulus between the O-rings with air and measuring the drop in pressure over time. The test port is tested by pressurizing the void above the test port with air, and measuring any pressure drop. The test shall be performed using a pressure gauge calibrated to a maximum error of 1% of full scale.

The test pressure for the test of the O-rings shall be at least 30 psig and the test shall last a minimum of 30 minutes. The allowable drop in pressure at an ambient temperature of 77°F is five psi. The test pressure for the test port is 30 psig and the test shall last a minimum of ten minutes. The allowable drop in pressure at an ambient temperature of 77°F is five psi. Table 8-2 shows the allowable pressure drops for the O-rings and test port for a range of other ambient temperatures.

Any condition which results in a pressure drop of more than five psi shall be corrected and the test performed again.

The sensitivity of the assembly verification test described in this section is greater than the required 10^{-1} atm-cm^3/sec as described in Section 4.4.

8.2.3 Subsystem Maintenance

The VHLW Cask contains no subsystem assemblies.

8.2.4 Valves, Rupture Discs, and Gaskets on Containment Vessel

Prior to the cask being used, the containment O-ring seal in the overpack shall have been replaced within the preceding 12-month period.

8.2.5 Shielding

No shielding maintenance is required after acceptance testing described in Section 8.1.5, unless repair to a damaged area is necessary. Any testing required after repair shall be performed in accordance with Section 8.1.5.

8.3 Appendix

8.3.1 Documentation

All records pertaining to maintenance and repair of the VHLW Cask shall be maintained for the life of the package. This shall include records pertaining procurement documents, vendor material certifications, certificates of compliance, and inspection and test results.

8.3.2 Operation

8.3.2.1 If the cask is unused for more than 12 months, operational checks of all cask components shall be performed.

8.3.2.2 Prior to each use and during loading, inspections of all components shall be performed to ensure the package is properly loaded and sealed.

8.3.3 Maintenance

A maintenance schedule for the cask shall be established. Procedures shall be established for performing each maintenance item that detail the proper method for performing the maintenance and the corrective actions for any defects found.

8.3.4 Repair

8.3.4.1 Repair of the VHLW Cask shall return the cask to its original condition or better. Repairs shall be performed using procedures prepared by qualified personnel and approved by QA.

8.3.4.2 Materials and components purchased for the cask that are critical to its performance shall equivalent to or better than originals. Material certification or certificates of conformance shall be required for all such materials or components.

8.3.4.3 Repair work shall be inspected by qualified personnel that did not originally perform the work. Results from the inspection shall be documented and become part of the cask records.

8.3.4.3 Tests shall be performed on repaired casks as necessary to show compliance with the original requirements for the cask. These tests shall follow the original test procedures, or if there are none, shall follow approved testing procedures. All test procedures and results shall be fully documented and become part of the cask records.

8.3.5 Corrective Action Program

Any conditions in the operation, maintenance, or repair of the cask shall be promptly detected and repaired. The cause of such a condition shall be determined and corrective action taken. Identification, cause, and corrective action for adverse conditions shall be documented and become part of the cask records.

TABLE 8-1
ALLOWABLE LEAK RATES AT VARIOUS TEMPERATURES FOR SF_6

TEMPERATURE			LEAK RATE		
°C	°F	°K	L_t Volumetric (10^{-5} cm^3/s)	Q Closure (oz/yr)	Q Test Port (oz/yr)
-10	14	263	8.8	1.11	0.41
0	32	273	8.96	1.13	0.42
10	50	283	9.13	1.15	0.43
20	68	293	9.29	1.17	0.43
25	77	298	9.37	1.18	0.44
30	86	303	9.44	1.19	0.44
40	104	313	9.6	1.21	0.45
50	122	323	9.75	1.23	0.46

<u>Note:</u>

Meeting the above demonstrates satisfaction of the allowable test leakage rate of 3.05×10^{-4} std cm^3/s.

TABLE 8-2
ASSEMBLY VERIFICATION TEST
ALLOWABLE LEAK RATES AT VARIOUS TEMPERATURES

TEMPERATURE			LEAK RATE		
°C	°F	°K	L_R Volumetric (10^{-2} cm^3/s)	ΔP/H Closure (psi/hr)	ΔP/H Test Port (psi/hr)
-10	14	263	4.7	11.1	56.8
0	32	273	4.79	11.8	60.1
10	50	283	4.87	12.4	63.4
20	68	293	4.96	13.1	66.8
25	77	298	5	13.4	68.5
30	86	303	5.04	13.8	70.3
40	104	313	5.12	14.5	73.8
50	122	323	5.21	15.2	77.4