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Waste Package Tip-Over of 5-DHLW/DOE SNF Short
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	Print Name	Signature	Date
6. Originator	Timothy Schmitt	Tim Schmitt	3/23/01
7. Checker	Adam Scheider	Adam K. Scheider	MAR 23, 2001
8. Lead	Scott Bennett	Scott M. Bennett	03/26/01
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1. PURPOSE

The objective of this calculation was to determine the structural response of the 5-defense high-level waste/ Department of Energy (DHLW/DOE) spent nuclear fuel (SNF) short Waste Package (WP) subjected to tip-over onto an unyielding surface (US) (see Ref. 6, Section 1.2.2.1.6). The scope of this calculation was limited to reporting the calculation results in terms of maximum stress intensities. The information regarding the type of WP used in this calculation is based on proposed/potential sketches in Attachments I and II. This calculation is associated with the waste package design and was performed by the Waste Package Design Section in accordance with *Technical Work Plan for: Waste Package Design Description for LA* (Ref. 9). AP-3.12Q, *Calculations*, was used to perform the calculation and develop the document (Ref. 14).

2. METHOD

The finite element calculation was performed by using the commercially available ANSYS Version (V) 5.4 and LS-DYNA V950 finite element codes. The results of this calculation were provided in terms of maximum stress intensities.

With regard to the development of this calculation, the control of the electronic management of data was accomplished in accordance with *Technical Work Plan for: Waste Package Design Description for LA* (Ref. 9) and is evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Information* (Ref. 15). The evaluation (Addendum B of Ref. 9) determined that current work processes and procedures are adequate for the control of electronic management of data for this activity.

3. ASSUMPTIONS

In the course of developing this document, the following assumptions were made regarding the WP structural calculations.

3.1 Some of the temperature-dependent material properties were not available for SB-575 N06022 (Alloy 22), SA-240 S31600 (316NG [nuclear grade] stainless steel [SS]), SA-516 K02700 (516 carbon steel [CS]), and SA-240 S30400 (304L SS). Therefore, room-temperature (20 °C) material properties were assumed for all materials. The impact of using room-temperature material properties was anticipated to be small. The rationale for this assumption was that the mechanical properties of these materials do not change significantly at the temperatures experienced during handling and lifting operations. This assumption was used in Section 5.1.

3.2 Some of the rate-dependent material properties were not available for the materials used. Therefore, the material properties obtained under the static loading conditions were assumed for all materials. The impact of using material properties obtained under static loading conditions was anticipated to be small. The rationale for this assumption was that the mechanical properties of subject materials do not significantly change at the peak strain rates in the course of the tip-over. This assumption was used in Section 5.1.

3.3 The Poisson's ratio of Alloy 22 was not available in literature. Therefore, the Poisson's ratio of Alloy 625 (SB-443 N06625) was assumed for Alloy 22. The impact of this assumption was anticipated to be negligible. The rationale for this assumption was that the chemical compositions of Alloy 22 and Alloy 625 are similar (see Ref. 4 and Ref. 2, respectively). This assumption was used in Section 5.1.

3.4 The target surface was conservatively assumed to be unyielding with a large elastic modulus compared to the WP materials. The rationale for this assumption was that a bounding set of results was required in terms of stresses, and it was known that the use of an US with high stiffness ensures slightly higher stresses in the WP. This assumption was used in Section 5.6.

3.5 The exact geometry of the high-level waste (HLW) glass assembly was simplified for the purpose of this calculation in such a way that its total mass, 2500 *kg* (see Section 5.3), was assumed to be distributed within a cylinder with uniform mass density and constructed of 304L SS. The rationale for this conservative assumption was to provide the set of bounding results, while simplifying the finite element representation (FER). This assumption was used in Section 5.6.

3.6 The exact geometry of the DOE canister was simplified for the purpose of this calculation in such a way that its total mass, 2270 *kg* (see Section 5.4), was assumed to be distributed within a cylinder with uniform mass density and constructed of SA-312 (316L SS). The rationale for this conservative assumption was to provide the set of bounding results, while simplifying the FER. This assumption was used in Section 5.6.

3.7 Poisson's ratio was not available for 516 CS. Therefore, Poisson's ratio of cast carbon steel was assumed for 516 CS. The impact of this assumption was anticipated to be negligible. The rationale for this assumption was that the elastic constants of cast carbon steels are only slightly affected by changes in composition and structure (Ref. 3). This assumption was used in Section 5.1.

3.8 The Poisson's ratio of 304L SS was not available in literature. Therefore, the Poisson's ratio of 304 SS was assumed for 304L SS. The impact of this assumption was anticipated to be negligible. The rationale for this assumption was that the chemical compositions of 304L SS and 304 SS are similar (Ref. 4). This assumption was used in Section 5.1.

3.9 The Poisson's ratio of 316L SS was not available in literature. Therefore, the Poisson's ratio of 316 SS was assumed for 316L SS. The impact of this assumption was anticipated to be negligible. The rationale for this assumption was that the chemical compositions of 316L SS and 316 SS are similar (Ref. 4). This assumption was used in Section 5.1.

3.10 The technical information related to the DOE glass canister is only used to determine the bounding values and identify items that are important to criticality control for this fuel group. The technical information used establishes the bounds for acceptance. The rationale for this assumption is that it was designated by the DOE SNF grouping to demonstrate before acceptance of SNF by the CRWMS that characteristics identified as important to criticality control or other analyses are not exceeded. This assumption was used in Section 5.4.

3.11 The uniform strain of Alloy 22 is not available in literature. Therefore, it is conservatively assumed that the uniform strain is 90% of the elongation. The rationale for this assumption is the character of stress-strain curve for Alloy 22 (Ref. 16). This assumption is used in Section 5.1.2.

3.12 The uniform strain of 316NG is not available in literature. Therefore, it is conservatively assumed that the uniform strain is 90% of the elongation. The rationale for this assumption is the character of stress-strain curve for 316NG SS (Ref. 16). This assumption is used in Section 5.1.2.

3.13 The change of minimum elongation with increase of temperature for the materials used in this calculation is not available in literature. The percent difference between elongations at room temperature and elevated temperatures can be normalized and applied to the data available from accepted codes (Refs. 1 and 12). The rationale for this conservative assumption is that the relative change of typical elongation should be bounding for the relative change of minimum elongation. This assumption is used in Section 5.1.1.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE

One of the finite element analysis computer codes used for this calculation is ANSYS V5.4 (Ref. 20), which was obtained from Software Configuration Management in accordance with appropriate procedures, and is identified by the Computer Software Configuration Item (CSCI) 30040 V5.4. ANSYS V5.4 is a commercially available finite element analysis code and is appropriate for structural calculations of waste packages as performed in this calculation. The calculation using the ANSYS V5.4 software was executed on the Hewlett-Packard (HP) 9000 series UNIX workstation identified with YMP (Yucca Mountain Project) tag number 700315, located in Las Vegas, NV. The software qualification of ANSYS V5.4 was summarized in Reference 7. Qualification of ANSYS V5.4 on the Waste Package Operations (WPO) HP UNIX workstations was documented in Reference 11. The ANSYS evaluation performed for this calculation is fully within the range of the validation performed for the ANSYS V5.4 code. Access to the code was granted by the Software Configuration Secretariat in accordance with the appropriate procedures.

The input files (identified by .inp file extensions) and output files (identified by .out file extensions) for ANSYS V5.4 are provided in Attachments IV, and V.

The second finite element analysis computer code used for this calculation is Livermore Software Technology Corporation (LSTC) LS-DYNA V950 (Ref. 8), which was obtained from Software Configuration Secretariat in accordance with appropriate procedures, and is identified by the Software Tracking Number (STN) 10300-950-00. LS-DYNA V950 is a commercially available finite element analysis code and is appropriate for structural calculations of waste packages as performed in this calculation. The calculation using the LS-DYNA V950 software was executed on the Hewlett-Packard (HP) 9000 series UNIX workstation identified with YMP (Yucca Mountain Project) tag number 117161, located in Las Vegas, NV. The LS-DYNA evaluation performed for this calculation is fully within the range of the validation performed for the LS-DYNA V950 code. Access to the code was granted by the Software Configuration Secretariat in accordance with the appropriate procedures.

The input files (identified by .k and .inc file extensions) and output files (d3hsp) for LS-DYNA V950 are provided in Attachments IV, and V.

4.2 SOFTWARE ROUTINES

None used.

4.3 MODELS

None used.

5. CALCULATION

5.1 MATERIAL PROPERTIES

Material properties used in these calculations are listed in this section. Some of the temperature-dependent and rate-dependent material properties are not available for Alloy 22, 316NG SS, 516 CS, 304L SS, and 316L SS. Therefore, room-temperature density and Poisson's ratio obtained under the static loading conditions are used for Alloy 22, 316NG SS, 516 CS, 304L SS, and 316L SS (see Assumption 3.1 and 3.2).

- Density = 8690 kg/m^3 (0.314 lb/in^3) (at room temperature) (Ref. 4, Section II, SB-575 Section 7.1)

- Yield strength = 310 MPa (45 ksi) (at room temperature) (Ref. 4, Section II, Table Y-1)
  Yield strength = 236 MPa (34.3 ksi) (at $400\ ^oF = 204\ ^oC$) (Ref. 4, Section II, Table Y-1)
  Yield strength = 211 MPa (30.6 ksi) (at $600\ ^oF = 316\ ^oC$) (Ref. 4, Section II, Table Y-1)

- Tensile strength = 690 MPa (100 ksi) (at room temperature) (Ref. 4, Section II, Table U)
  Tensile strength = 657 MPa (95.3 ksi) (at $400\ ^oF = 204\ ^oC$) (Ref. 4, Section II, Table U)
  Tensile strength = 628 MPa (91.1 ksi) (at $600\ ^oF = 316\ ^oC$) (Ref. 4, Section II, Table U)

- Elongation = 0.45 (at room temperature) (Ref. 4, Section II, SB-575 Table 3)

- Poisson's ratio = 0.278 (at room temperature) (Ref. 2, p. 143; see Assumption 3.3)

- Modulus of elasticity = 206 GPa (at room temperature) (Ref. 12, p. 14)
  Modulus of elasticity = 196 GPa (at $400\ ^oF = 204\ ^oC$) (Ref. 12, p. 14)
  Modulus of elasticity = 190 GPa (at $600\ ^oF = 316\ ^oC$) (Ref. 12, p. 14)

SA-240 S31600 (See Ref. 3) (Identical to ASTM A 240) (316NG SS, which is 316 SS with tightened control on carbon and nitrogen content and has the same material properties as 316 SS [see Ref. 13, page 931 and Ref. 4, Section II, SA-240 Table 1]) (Inner shell, inner shell lids, and inner shell lifting feature):

- Density = 7980 kg/m^3 (at room temperature) (Ref. 5, Table X1, p. 7)

- Yield strength = 207 *MPa* (30 *ksi*) (at room temperature) (Ref. 4, Section II, Table Y-1)
  Yield strength = 148 *MPa* (21.4 *ksi*) (at 400 $^{\circ}F = 204\ ^{\circ}C$) (Ref. 4, Section II, Table Y-1)
  Yield strength = 130 *MPa* (18.9 *ksi*) (at 600 $^{\circ}F = 316\ ^{\circ}C$) (Ref. 4, Section II, Table Y-1)

- Tensile strength = 517 *MPa* (75 *ksi*) (at room temperature) (Ref. 4, Section II, Table U)
  Tensile strength = 496 *MPa* (71.9 *ksi*) (at 400 $^{\circ}F = 204\ ^{\circ}C$) (Ref. 4, Section II, Table U)
  Tensile strength = 495 *MPa* (71.8 *ksi*) (at 600 $^{\circ}F = 316\ ^{\circ}C$) (Ref. 4, Section II, Table U)

- Elongation = 0.40 (at room temperature) (Ref. 4, Section II, SA-240 Table 2)

- Poisson's ratio = 0.298 (at room temperature) (Ref. 2, Figure 15, p. 755)

- Modulus of elasticity = 195 *GPa* ($28.3 \cdot 10^6$ *psi*) (at room temperature) (Ref. 4, Section II, Table TM-1)
  Modulus of elasticity = 183 *GPa* ($26.5 \cdot 10^6$ *psi*) (at 400 $^{\circ}F = 204\ ^{\circ}C$) (Ref. 4, Section II, Table TM-1)
  Modulus of elasticity = 174 *GPa* ($25.3 \cdot 10^6$ *psi*) (at 600 $^{\circ}F = 316\ ^{\circ}C$) (Ref. 4, Section II, Table TM-1)

SA-516 K02700 (516 CS) (Divider plates, brackets, and support tube):

- Density = 7850 kg/m^3 (at room temperature) (Ref. 4, SA-20/SA20M, Section 14.1)

- Yield strength = 262 *MPa* (38 *ksi*) (at room temperature) (Ref. 4, Section II, Table Y-1)
  Yield strength = 224 *MPa* (32.5 *ksi*) (at 400 $^{\circ}F = 204\ ^{\circ}C$) (Ref. 4, Section II, Table Y-1)
  Yield strength = 201 *MPa* (29.1 *ksi*) (at 600 $^{\circ}F = 316\ ^{\circ}C$) (Ref. 4, Section II, Table Y-1)

- Tensile strength = 483 *MPa* (70 *ksi*) (at room temperature) (Ref. 4, Section II, Table U)
  Tensile strength = 483 *MPa* (70 *ksi*) (at 400 $^{\circ}F = 204\ ^{\circ}C$) (Ref. 4, Section II, Table U)
  Tensile strength = 483 *MPa* (70 *ksi*) (at 600 $^{\circ}F = 316\ ^{\circ}C$) (Ref. 4, Section II, Table U)

- Elongation = 0.21 (at room temperature) (Ref. 4, Section II , SA-240 Table 2)

- Poisson's ratio = 0.3 (at room temperature) (Ref. 2, Figure 15, p. 755; see Assumption 3.7)

- Modulus of elasticity = 203 *GPa* ($29.5 \cdot 10^6$ *psi*) (at room temperature) (Ref. 4, Section II Table TM-1)

Modulus of elasticity = 191 GPa ($27.7 \cdot 10^6$ psi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II Table TM-1)
Modulus of elasticity = 184 GPa ($26.7 \cdot 10^6$ psi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II Table TM-1)

SA-240 S30403 (304L SS) (HLW Canisters):

- Yield strength = 170 MPa (25 ksi) (at room temperature) (Ref. 4, Section II , Table Y-1)
  Yield strength = 121 MPa (17.5 ksi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II , Table Y-1)
  Yield strength = 107 MPa (15.5 ksi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II , Table Y-1)

- Tensile strength = 485 MPa (70 ksi) (at room temperature) (Ref. 4, Section II , Table U)
  Tensile strength = 405 MPa (58.7 ksi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II , Table U)
  Tensile strength = 392 MPa (56.9 ksi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II , Table U)

- Elongation = 0.40 (at room temperature) (Ref. 4, Section II , SA-240 Table 2)

- Poisson's ratio = 0.29 (at room temperature) (Ref. 2, Figure 15, p. 755; see Assumption 3.8)

- Modulus of elasticity = 195 GPa ($28.3 \cdot 10^6$ psi) (at room temperature) (Ref. 4, Section II Table TM-1)
  Modulus of elasticity = 183 GPa ($26.5 \cdot 10^6$ psi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II Table TM-1)
  Modulus of elasticity = 174 GPa ($25.3 \cdot 10^6$ psi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II Table TM-1)

SA-312 S31603 (316L SS) (DOE SNF Canister):

- Yield strength = 170 MPa (25 ksi) (at room temperature) (Ref. 4, Section II , Table Y-1)
  Yield strength = 121 MPa (17.5 ksi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II , Table Y-1)
  Yield strength = 108 MPa (15.6 ksi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II , Table Y-1)

- Tensile strength = 483 MPa (70 ksi) (at room temperature) (Ref. 4, Section II , Table U)
  Tensile strength = 429 MPa (62.2 ksi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II , Table U)
  Tensile strength = 425 MPa (61.7 ksi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II , Table U)

- Elongation = 0.40 (at room temperature) (Ref. 4, Section II, SA-240 Table 2)

- Poisson's ratio = 0.3 (at room temperature) (Ref. 2, Figure 15, p. 755) (see Assumption 3.9)

- Modulus of elasticity = 195 GPa ($28.3 \cdot 10^6$ psi) (at room temperature) (Ref. 4, Section II Table TM-1)
  Modulus of elasticity = 183 GPa ($26.5 \cdot 10^6$ psi) (at 400 $°F$ = 204 $°C$) (Ref. 4, Section II Table TM-1)
  Modulus of elasticity = 174 GPa ($25.3 \cdot 10^6$ psi) (at 600 $°F$ = 316 $°C$) (Ref. 4, Section II Table TM-1)

5.1.1 Calculations for Elevated-Temperature Material Properties

The values for elongation at elevated temperatures are not listed in conventional listings such as American Society for Testing and Materials (ASTM) Standards or American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. However, the elongation values at elevated temperatures are available from vendor data. This vendor data will be used to estimate elevated temperature elongation normalized to the room temperature values from accepted codes (see Assumptions 3.13).

For Alloy 22, the vendor data shows a 6.1% increase in elongation values between 400 °F and room temperature and a 9.7% increase between 600 °F and room temperature (Ref. 12).

Therefore, the elongation values for Alloy 22 at elevated temperatures will be as follows:

Elongation = $0.45 \cdot 1.061 = 0.48$ (at 400 $°F$ = 204 $°C$)
Elongation = $0.45 \cdot 1.097 = 0.49$ (at 600 $°F$ = 316 $°C$)

For 316NG SS, the vendor data shows a 25% decrease in elongation values between 400 °F and room temperature and a 29% decrease between 600 °F and room temperature (Ref. 1).

Therefore, the elongation values for 316NG SS at elevated temperatures will be as follows:

Elongation = $0.40 \cdot (1 - 0.25) = 0.30$ (at 400 $°F$ = 204 $°C$)
Elongation = $0.40 \cdot (1 - 0.29) = 0.28$ (at 600 $°F$ = 316 $°C$)

Since the components made of 516 CS, 304 SS, and 316L SS will not be analyzed for stresses, their elongations are not needed at elevated temperatures. The 516 CS, 304 SS, and 316L SS components are only needed for their density.

5.1.2 Calculations for True Measures of Ductility

The material properties in Section 5.1 refer to engineering stress and strain definitions (see Ref. 20):

$$s = \frac{P}{A_0} \text{ and } e = \frac{L - L_0}{L_0}$$

Where P stands for the force applied during static tensile test, L is the deformed-specimen length, and L_0 and A_0 are original length and cross-sectional area of specimen, respectively. It is generally accepted that the engineering stress-strain curve does not give a true indication of the deformation characteristics of a material during the plastic deformation since it is based entirely on the original dimensions of the specimen. Therefore, the LS-DYNA V950 finite element code requires input in terms of true stress and strain definitions:

$$\sigma = \frac{P}{A} \text{ and } \varepsilon = \ln\left(\frac{L}{L_0}\right)$$

The relationships between the true stress and strain definitions and engineering stress and strain definitions can be readily derived based on constancy of volume ($A_0 \cdot L_0 = A \cdot L$) and strain homogeneity during plastic deformation:

$$\sigma = s \cdot (1 + e) \text{ and } \varepsilon = \ln(1 + e)$$

These expressions are applicable only in the hardening region of stress-strain curve that is limited by the onset of necking.

The following parameters are used in the subsequent calculations:

$s_y \approx \sigma_y$ = yield strength
s_u = engineering tensile strength
σ_u = true tensile strength
$e_y \approx \varepsilon_y$ = strain corresponding to yield strength
e_u = engineering strain corresponding to tensile strength (engineering uniform strain)
ε_u = true strain corresponding to tensile strength (true uniform strain)

In absence of the uniform strain data in available literature, it needs to be estimated based on stress-strains curves and elongation (strain corresponding to rupture of the tensile specimen).

The stress-strain curves for Alloy 22, 304 SS and 316NG SS do not manifest three-stage deformation character (see Ref. 16). Therefore, the elongation, reduced by 10% for the sake of conservativism can be used in place of uniform strain.

In the case of Alloy 22 the true measures of ductility are:

$e_u = 0.9 \cdot elongation = 0.41$ (at room temperature)

$e_u = 0.9 \cdot 0.48 = 0.43$ (at $400\ ^oF = 204\ ^oC$)

$e_u = 0.9 \cdot 0.49 = 0.44$ (at $600\ ^oF = 316\ ^oC$)

$\varepsilon_u = \ln(1+e_u) = \ln(1+0.41) = 0.34$ (at room temperature)

$\varepsilon_u = \ln(1+e_u) = \ln(1+0.43) = 0.36$ (at $400\ ^oF = 204\ ^oC$)

$\varepsilon_u = \ln(1+e_u) = \ln(1+0.44) = 0.36$ (at $600\ ^oF = 316\ ^oC$)

$\sigma_u = s_u \cdot (1+e_u) = 690 \cdot (1+0.41) = 973\ MPa$ (at room temperature)

$\sigma_u = s_u \cdot (1+e_u) = 657 \cdot (1+0.43) = 940\ MPa$ (at $400\ ^oF = 204\ ^oC$)

$\sigma_u = s_u \cdot (1+e_u) = 628 \cdot (1+0.44) = 904\ MPa$ (at $600\ ^oF = 316\ ^oC$)

For 316NG SS:

$e_u = 0.9 \cdot elongation = 0.36$ (at room temperature)

$e_u = 0.9 \cdot 0.30 = 0.27$ (at $400\ ^oF = 204\ ^oC$)

$e_u = 0.9 \cdot 0.28 = 0.25$ (at $600\ ^oF = 316\ ^oC$)

$\varepsilon_u = \ln(1+e_u) = \ln(1+0.36) = 0.31$ (at room temperature)

$\varepsilon_u = \ln(1+e_u) = \ln(1+0.27) = 0.24$ (at $400\ ^oF = 204\ ^oC$)

$\varepsilon_u = \ln(1+e_u) = \ln(1+0.25) = 0.22$ (at $600\ ^oF = 316\ ^oC$)

$\sigma_u = s_u \cdot (1+e_u) = 515 \cdot (1+0.36) = 700\ MPa$ (at room temperature)

$\sigma_u = s_u \cdot (1+e_u) = 496 \cdot (1+0.27) = 630\ MPa$ (at $400\ ^oF = 204\ ^oC$)

$\sigma_u = s_u \cdot (1+e_u) = 495 \cdot (1+0.25) = 619\ MPa$ (at $600\ ^oF = 316\ ^oC$)

5.2 CALCULATIONS FOR TANGENT MODULI

The results of this simulation were required to include elastic and plastic deformations for Alloy 22, 316NG SS, 516 CS, 304L SS, and 316L SS. When the materials are driven into the plastic range, the slope of stress-strain curve continuously changes. Thus, a simplification for this curve was needed to incorporate plasticity into the FER. A standard approximation commonly used in engineering is to use a straight line that connects the yield point and the ultimate tensile strength point of the material. The parameters used in the subsequent calculations in addition to those defined in Section 5.1.2 are modulus of elasticity (E) and tangent modulus (E_1). The tangent (hardening) modulus represents the slope of the stress-strain curve in the plastic region.

In the case of 316NG SS, the strain corresponding to the yield strength is:

$\varepsilon_y = \sigma_y / E = 207 \cdot 10^6 / 195 \cdot 10^9 = 1.06 \cdot 10^{-3}$ (at room temperature) (see Section 5.1 and Section 5.1.1)

Hence, the tangent modulus is:

$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \varepsilon_y) = (0.703 - 0.207)/(0.31 - 1.06 \cdot 10^{-3}) = 1.6\ GPa$ (at room temperature) (see Section 5.1, 5.1.1, and 5.1.2)
$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \varepsilon_y) = (0.630 - 0.148)/(0.24 - 0.148/183) = 2.0\ GPa$ (at $400\ ^\circ F = 204\ ^\circ C$) (see Section 5.1, 5.1.1, and 5.1.2)
$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \varepsilon_y) = (0.619 - 0.130)/(0.22 - 0.130/174) = 2.2\ GPa$ (at $600\ ^\circ F = 316\ ^\circ C$) (see Section 5.1, 5.1.1, and 5.1.2)

Similarly, for Alloy 22:

$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \varepsilon_y) = (0.973 - 0.310)/(0.34 - 0.310/206) = 2.0\ GPa$ (at room temperature) (see Section 5.1, 5.1.1, and 5.1.2)
$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \varepsilon_y) = (0.940 - 0.236)/(0.36 - 0.236/196) = 2.0\ GPa$ (at $400\ ^\circ F = 204\ ^\circ C$) (see Section 5.1, 5.1.1, and 5.1.2)
$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \varepsilon_y) = (0.904 - 0.211)/(0.36 - 0.211/190) = 1.9\ GPa$ (at $600\ ^\circ F = 316\ ^\circ C$) (see Section 5.1, 5.1.1, and 5.1.2)

For 516 CS:

$E_1 = (S_u - S_y)/(e_u - e_y) = (0.483 - 0.262)/(0.21 - 0.262/203) = 1.1\ GPa$ (at room temperature) (see Section 5.1, 5.1.1, and Section 5.1.2)

For 304L SS:

$E_1 = (S_u - S_y)/(e_u - e_y) = (0.485 - 0.170)/(0.40 - 0.170/195) = 0.79\ GPa$ (at room temperature) (see Section 5.1, 5.1.1, and Section 5.1.2)

For 316L SS:

$E_1 = (S_u - S_y)/(e_u - e_y) = (0.483 - 0.170)/(0.40 - 0.170/195) = 0.78\ GPa$ (at room temperature) (see Section 5.1 and Section 5.1.1)

Again, since the components made of 516 CS, 304L SS, and 316L SS will not be analyzed for stresses, the tangent moduli for these materials are not needed at elevated temperatures. The 516 CS, 304L SS, and 316L SS components are only needed for their density.

5.3 MASS AND GEOMETRIC DIMENSIONS OF HLW CANISTERS

This calculation was performed by using the following mass and geometric dimensions of the HLW canisters:

Total mass $= 2500\ kg$ (Ref. 18, Section 4.2.3.1, p. 18)
Width $= 610\ mm$ (Ref. 18, Section 4.2.3.1, p. 18)
Overall length $= 3.000\ m$ (Ref. 18, Section 4.2.3.1, p. 18)

5.3.1 Calculation of Density of HLW Canisters

This calculation was performed by using the following density for the HLW Canisters.

Volume $= \pi \cdot r^2 \cdot h = \pi \cdot \left(\dfrac{0.61}{2}\right)^2 \cdot 3.0 = 0.877\ m^3$

Density $= \dfrac{m}{v} = \dfrac{2500}{0.877} = 2850.627\ \dfrac{kg}{m^3}$

5.4 MASS AND GEOMETRIC DIMENSIONS OF DOE SNF CANISTER

This calculation was performed by using the following mass and geometric dimensions of the DOE SNF canister (see Assumption 3.10):

Total mass $= 2270\ kg$ (Ref. 6, Table 5, p. 12)
Width $= 457\ mm$ (Ref. 6, Table 5, p. 12)
Overall length $= 3.000\ m$ (Ref. 6, Table 5, p. 12)

5.4.1 Calculation of Density of DOE SNF Canister

This calculation was performed by using the following density for the DOE SNF Canister.

$$\text{Volume} = \pi \cdot r^2 \cdot h = \pi \cdot \left(\frac{0.457}{2}\right)^2 \cdot 3.0 = 0.492\ m^3$$

$$\text{Density} = \frac{m}{v} = \frac{2270}{0.492} = 4613.821\ \frac{kg}{m^3}$$

5.5 INITIAL VELOCITY OF WASTE PACKAGE

To reduce the computer execution time while preserving all features of the problem relevant to the structural calculation, the WP is set in a position just before impact and given an appropriate initial angular velocity.

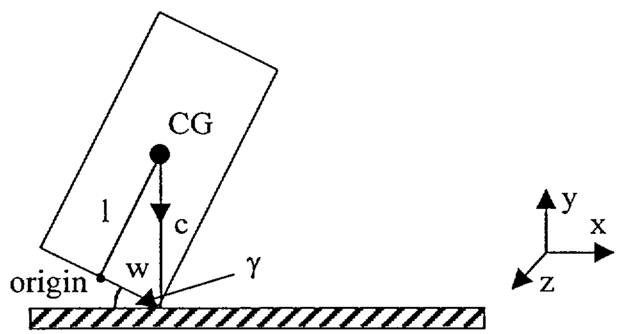

Figure 1. Tip-Over Geometry

Using the following parameters:

g = acceleration due to gravity $= 9.81\ m/s^2$
M = total mass $= 3.813 \cdot 10^4\ kg$ (See Attachment I-1)

mass moment of inertia about z axis located at the center of gravity (Iz) was calculated using LS-DYNA V950 with the unyielding surface omitted (see Attachment VI). LS-DYNA V950 calculates the mass properties of the FER prior to solving the problem. The following results block was taken in the exact format from Attachment V, d3hsp, lines 64669 through 64678:

```
m a s s   p r o p e r t i e s   o f   b o d y
     total mass of body           =     .3748E+05
     x-coordinate of mass center =     .1817E+01
     y-coordinate of mass center =     .4161E-02
     z-coordinate of mass center =     .6292E-05

     inertia tensor of body
     row1=        .2164E+05     -.5573E+02      .5113E-01
     row2=       -.5573E+02      .5411E+05     -.1460E-01
     row3=        .5113E-01     -.1460E-01      .5414E+05
```

NOTE: The mass calculated from LS-DYNA V950 is slightly lower than that listed in Attachment I, due to the 4-*mm* radial gap between the inner and outer shells, as opposed to the 0-*mm* radial gap in Attachment I. The difference was less than 2% and the impact was anticipated to be negligible, however the mass listed in Attachment I was used in the subsequent calculations as the bounding mass.

In this case, the WP is rotating about the z axis, thus Iz = Izz = $5.414 \cdot 10^4 \; kg \cdot m^2$

The following geometric parameters were also used in subsequent calculations:

x = 1.817 *m* = distance in the x direction to the center of gravity from the origin
y = 0.0042 *m* = distance in the y direction to the center of gravity from the origin

Since this forms a right triangle:

$$l = \sqrt{x^2 + y^2} = \sqrt{1.817^2 + 0.0042^2} = 1.817 \; m$$

w = ½ the outer diameter of the trunnion collar sleeve = 1.055 *m* (Attachment I-1)

Again, since this forms a right triangle:

$$c = \sqrt{l^2 + w^2} = \sqrt{1.817^2 + 1.055^2} = 2.101 \; m$$

Also,

$$\gamma = \text{angle necessary for tip-over} = \tan^{-1}\left(\frac{w}{l}\right) = 30.1°$$

Using the parallel axis thereom, the mass moment of inertia about the point of rotation:

$$I = Iz + Mc^2 = 5.414 \cdot 10^4 + 3.813 \cdot 10^4 \cdot 2.101^2 = 2.225 \cdot 10^5 \; kg \cdot m^2$$

Using Newton's second law of motion:

$$\sum M = I \cdot \alpha$$

$M \cdot g \cdot c \cdot \cos\theta = I \cdot \alpha$, where θ is the angle of rotation and α is the rotational acceleration it follows that:

$$\alpha = \frac{M \cdot g \cdot c \cdot \cos\theta}{I} = \frac{3.813 \cdot 10^4 \cdot 9.81 \cdot 2.101 \cdot \cos\theta}{2.225 \cdot 10^5} = 3.542 \cdot \cos\theta$$

Knowing:

$v = \dfrac{ds}{dt}$ and $a = \dfrac{dv}{dt}$, where s is displacement, v is velocity, and a is acceleration, velocity in terms of acceleration can be found by rearranging and substituting:

$$dt = \frac{dv}{a}$$

$$v = \frac{ds}{\frac{dv}{a}}$$

$$v \cdot \frac{dv}{a} = ds$$

Thus: $v \cdot dv = a \cdot ds$ or for rotational velocity: $\omega \cdot d\omega = \alpha \cdot d\theta$
Integrating over angle of tip-over:

$$\int_0^{\omega} \omega \cdot d\omega = \int_{\frac{\pi}{2}}^{\gamma} \alpha \cdot d\theta$$

$$\frac{\omega^2}{2} = 3.542 \cdot (\sin\theta)\Big|_{\frac{\pi}{2}}^{\gamma} = 3.542 \cdot \left[-\sin\left(30.1 \cdot \frac{\pi}{180}\right) + \sin\left(\frac{\pi}{2}\right)\right] = 1.77$$

$$\omega = 1.88 \ \frac{rad}{s}$$

5.6 FINITE ELEMENT REPRESENTATION

A full three-dimensional (3-D) FER of the WP was developed in ANSYS V5.4 by using the dimensions provided in Attachment I. The FER was created with the largest possible radial gap of 4 *mm* between the inner and outer shells (Ref. 10). The initial orientation of the inner shell maintains this 4-*mm* gap around the circumference of the shell. The internal structure of the WP was simplified in several ways. First the support tube, brackets, and divider plates were combined and created as shell elements with an assigned thickness of 31.75, 25.4, 12.7 *mm* in the respective regions. Next, the structure of the HLW canisters and DOE SNF canister, were reduced to cylinders of uniform mass density, and assumed to be constructed of 304L SS and 316L SS, respectively (Assumptions 3.5 and 3.6). The total mass and geometric dimensions of the HLW canisters and DOE SNF canisters (see Sections 5.3 and 5.4) define the density. The benefit of using this approach was to reduce the computer execution time while preserving all features of the problem relevant to the structural calculation.

The target surface was conservatively assumed to be unyielding with a large elastic modulus (Assumption 3.4).

The mesh of the FER was appropriately generated and refined in the contact region according to standard engineering practice. Thus, the accuracy and representativeness of the results of this calculation were deemed acceptable.

The initial tip-over angle was reduced to $0.1°$ and the WP was given an initial angular velocity corresponding to the rigid-body motion of the WP (see Section 5.4).

The FER was then used in LS-DYNA V950 to perform the transient dynamic analysis for the 5-DHLW/DOE WP tip-over design basis event at room temperature, $204\ °C$, and $316\ °C$.

6. RESULTS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the technical product input information quality may be confirmed by review of the DIRS database.

The results of this calculation were obtained using elongation values from unverified test data (see Assumption 3.8).

The results obtained from LS-DYNA V950 were reported in terms of maximum shear stress. Since the maximum stress intensities were desired, the results needed to be converted. The maximum shear stress is defined as one half the difference between maximum and minimum principal stress. Stress intensity is defined as the difference between maximum and minimum principal stress. Therefore, the results obtained from LS-DYNA V950 were multiplied by two, to obtain the corresponding stress intensities.

The maximum stresses were found by carefully examining each time step taken by LS-DYNA V950, which outputs the element with the highest magnitude of stress, at each step, for each defined part. Table 1 lists the maximum stress intensities in the outer shell and inner shell at room temperature, $204\ °C$, and $316\ °C$.

Table 1. Maximum Stress Intensities

	Outer Shell	Inner Shell
Room Temperature	519 MPa (see Figure III-3)	394 MPa (see Figure III-4)
204 °C	419 MPa (see Figure III-6)	373 MPa (see Figure III-7)
316 °C	397 MPa (see Figure III-9)	211 MPa (see Figure III-10)

The above table shows that for each temperature condition, each part exceeded the yield strength, but the magnitude was less than the tensile strength of the corresponding material (see Sections 5.1 and 5.1.2).

It should be noted that the mass calculated from LS-DYNA V950 was slightly lower than that listed in Attachment I. This is due to the 4-*mm* radial gap between the inner and outer shells, as opposed to the 0-*mm* radial gap in Attachment I. The difference was less than 2% and was anticipated to be negligible.

7. REFERENCES

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8. ATTACHMENTS

Attachment I (2 pages): Design sketches (*5 DHLW/DOE SNF – Short WP Assembly Configuration for Site Recommendation* [SK-0196 REV 03]; two sheets)
(This attachment uses References 17, 18, and Attachment II)

Attachment II (1 page): Weld configuration sketches (*5-DHLW/DOE SNF - Short Weld Configuration* [SK-0197 REV 00]; one sheet)

Attachment III (10 pages): Figures obtained from LS-DYNA V950

Attachments IV, V, VI, and VII (Compact Disc):
ANSYS V5.4 and LS-DYNA V950 electronic files (Attachments VI and VII use the same .inc, .inp, and .out files as Attachment V)

Table 2 contains the file names, dates, times, and sizes in Attachments IV, V, VI, and VII.

Table 2. File Name, Date, Time, and Size

Attachment IV (modeled without unyielding surface for calculating mass moment of inertia)

Name	Date	Time	Size
nouy1.inp	11/06/2000	1:29 pm	26 KB
mainnou.k	11/06/2000	1:31 pm	2 KB
element.inc	11/06/2000	1:29 pm	1,874 KB
nodes.inc	11/06/2000	1:29 pm	1,821 KB
bcnodes.inc	11/06/2000	1:29 pm	2 KB
d3hsp	11/08/2000	2:16 pm	4,482 KB
nouy.out	11/06/2000	1:29 pm	433 KB

Attachment V (tip-over at room temperature)

hlwtip.inp	11/06/2000	1:02 pm	27 KB
mainroom.k	2/12/2000	9:13 am	3 KB
element.inc	2/12/2000	9:13 am	1,888 KB
nodes.inc	2/12/2000	9:13 am	1,838 KB
bcnodes.inc	2/12/2000	9:13 am	1 KB
d3hsp	2/12/2000	9:13 am	8,498 KB
hlwtip.out	11/06/2000	1:02 pm	441 KB

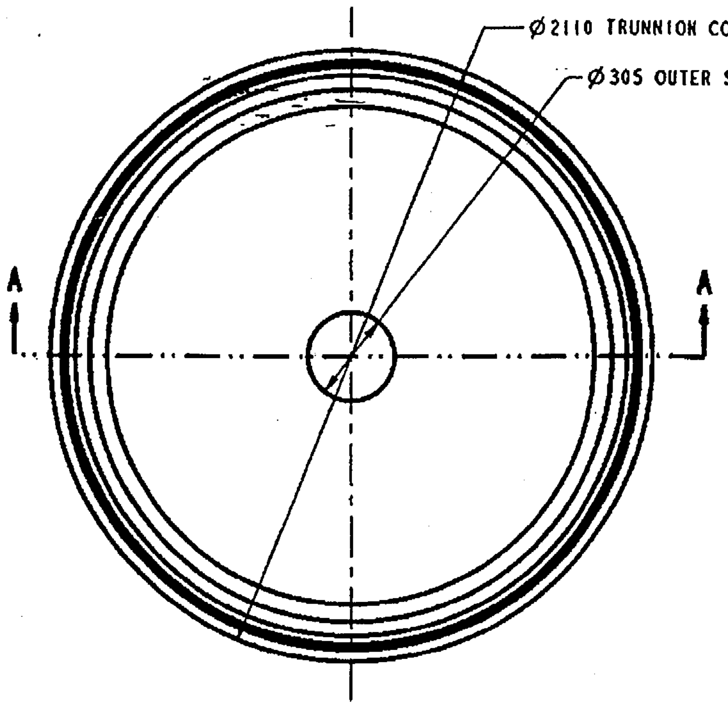
Attachment VI (tip-over at $400\ ^{o}F = 204\ ^{o}C$)

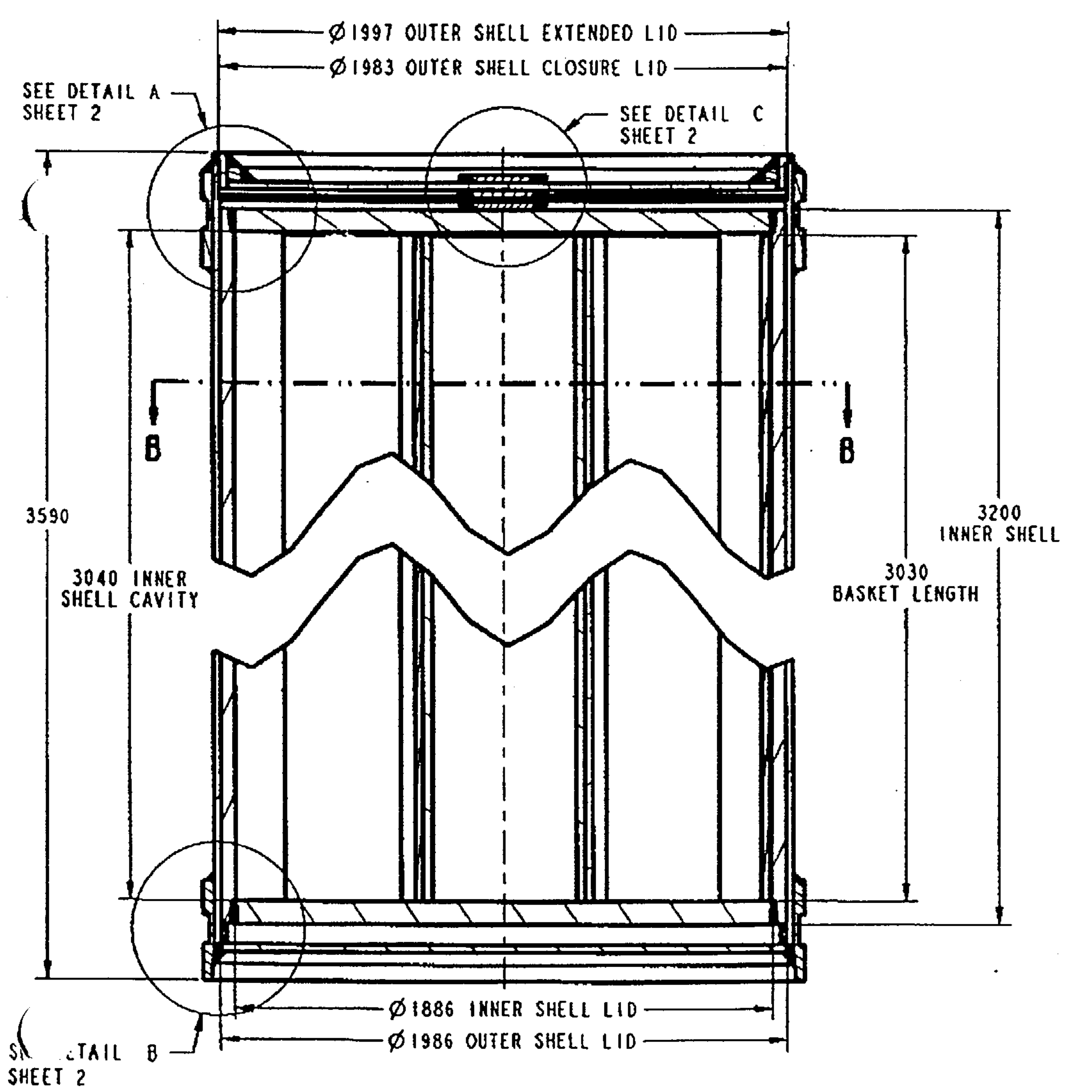
main400.k	2/12/2000	9:14 am	3 KB
d3hsp	2/12/2000	9:14 am	8,490 KB

Attachment VII (tip-over at $600\ ^{o}F = 316\ ^{o}C$)

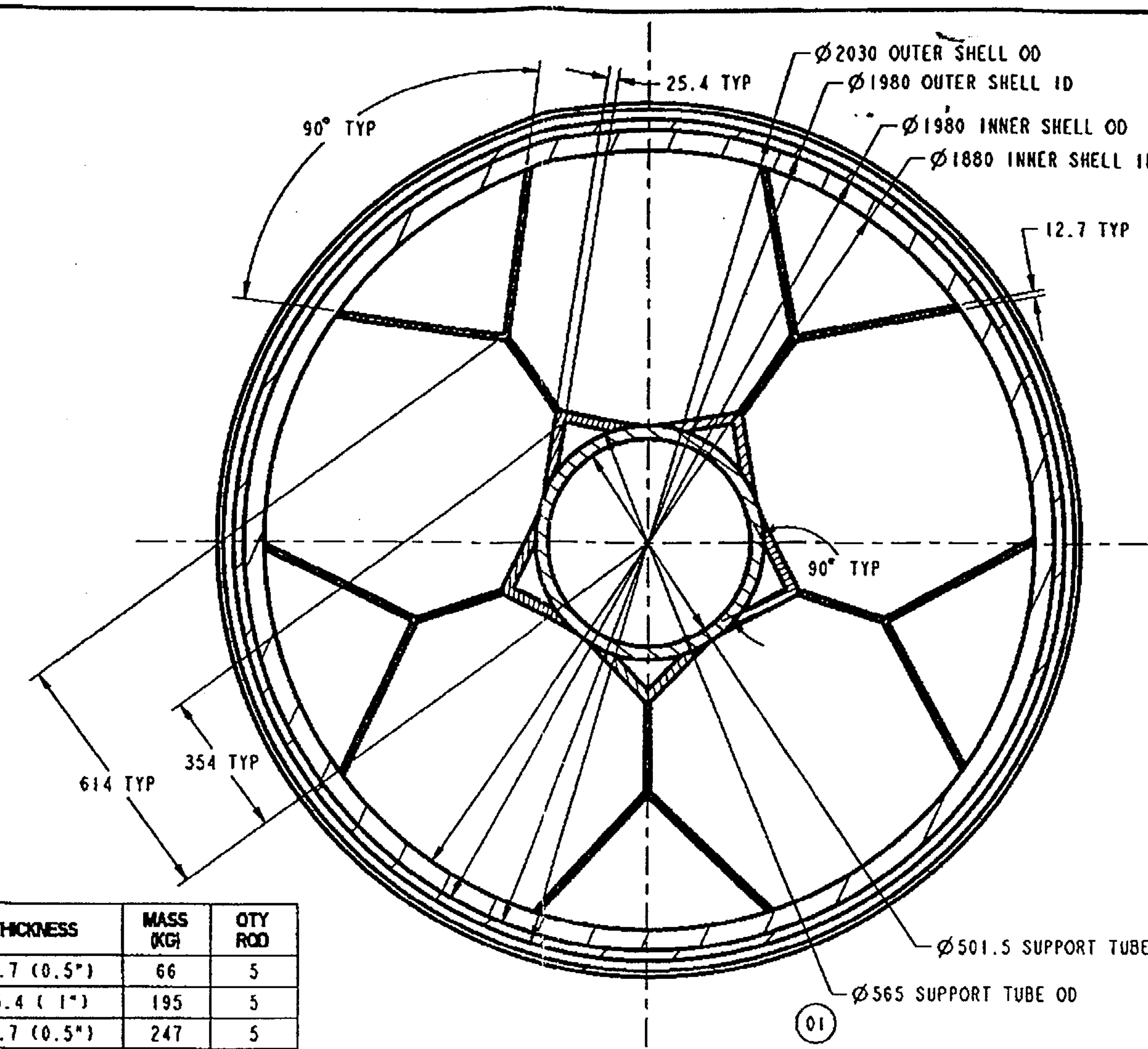
main600.k	2/12/2000	9:15 am	3 KB
d3hsp	2/12/2000	9:15 am	8,475 KB

NOTE: The file sizes may vary with operating system.





SECTION A-A



SECTION B-B

COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY RQD
DIVIDER PLATE	SA-516 K02700	12.7 (0.5")	66	5
INNER BRACKET	SA-516 K02700	25.4 (1")	195	5
OUTER BRACKET	SA-516 K02700	12.7 (0.5")	247	5
SUPPORT TUBE	SA-516 K02700	31.75 (1.25")	1265	1
INNER SHELL	SA-240 S31600	50	7621	1
INNER SHELL LID	SA-240 S31600	80	1765	2
INNER LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	25	4692	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	172	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	629	1
EXTENDED OUTER LID REINFORCING RING	SB-575 N06022	50	129	1
OUTER LID LIFTING FEATURE	SB-575 N06022	27	13	2
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	268	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	669	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	655	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	642	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	53	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	325	***
TOTAL 316 WELDS	SFA-5.9 S31680	-	133	***
WASTE PACKAGE ASSEMBLY	-	-	23360	1
HLW GLASS ASSEMBLY	-	-	2500*	5
18" CANISTER SHORT	-	-	2270**	1
WP ASSEMBLY WITH SNF	-	-	38130	-

03 * WASTE ACCEPTANCE SYSTEM REQUIREMENTS DOCUMENT. E00000000-00811-1708-00001 REV 03, DOE/RW-0351. ACC: HQO.19990226.0001, PAGE 18, SECTION 4.2.3.1.A.4.

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*** SEE SK-0197 FOR WELD CONFIGURATION AND MASSES

UNITS: mm

DO NOT SCALE FROM SKETCH

REVISIONS			
REV	DESCRIPTION	DRW BY	DATE
00	ISSUED APPROVED	DGM	1/26/00
01	IN SECTION B-B Ø 565 SUPPORT TUBE OD "WAS" ID	DGM	4/21/00
02	"MODIFIED" REVISION TABLE, "ADDED" DIMENSION 4 TO DETAIL A, "MODIFIED" CROSS HATCHING ON DETAIL A	BH	4/25/00
03	IN NOTE **, DOE/RW-0351 "WAS" DOE/RW-315P, IN REVISION BLOCK REV 00, 1/26/00 "WAS" 1/25/00, "ADDED" REVISION BALLOONS TO SECTION B-B AND DETAIL "A"	EJC	6/5/00

"FOR INFORMATION ONLY"

5 CHLW/DOE SNF - SHORT WP ASSSEMBLY CONFIGURATION FOR SITE RECOMENDATION

SKETCH NUMBER: SK-0196 REV 03 SHEET 1 OF 2

SKETCHED BY: EUGENE CONNELL EJC 06/06/00 SMB 06/06/00 SMB for MJA 06/06/00

DATE: 06/05/00

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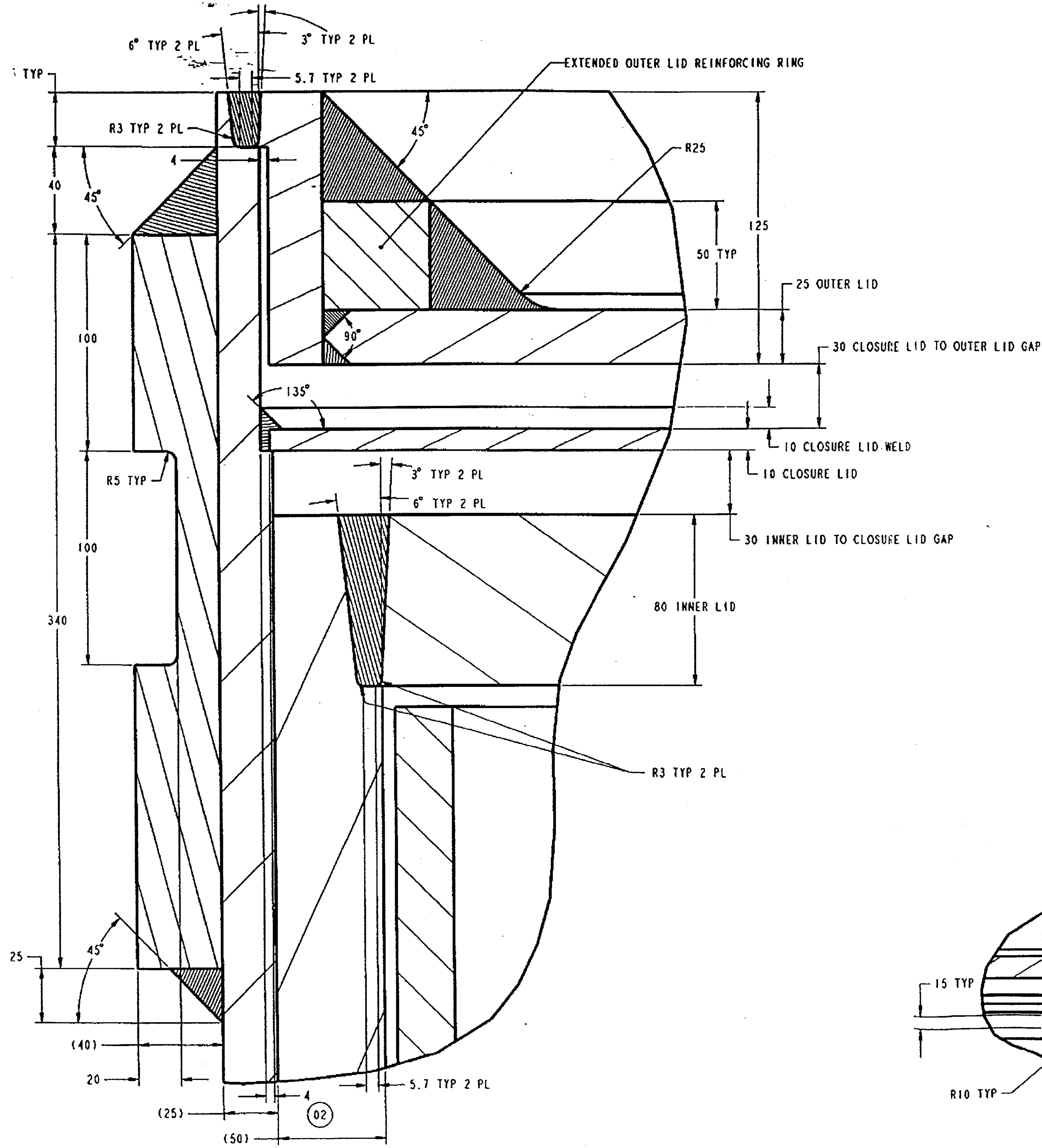

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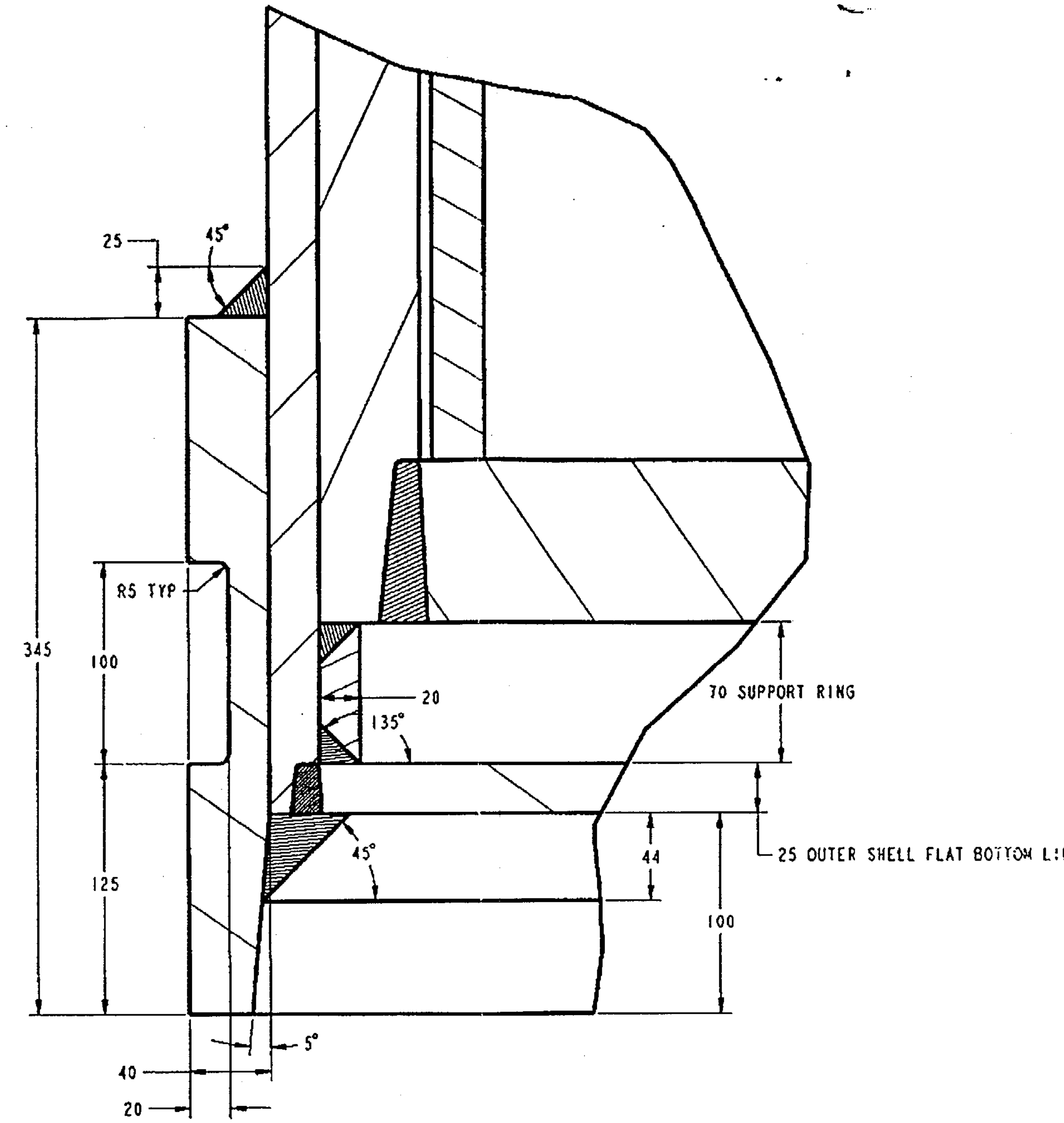

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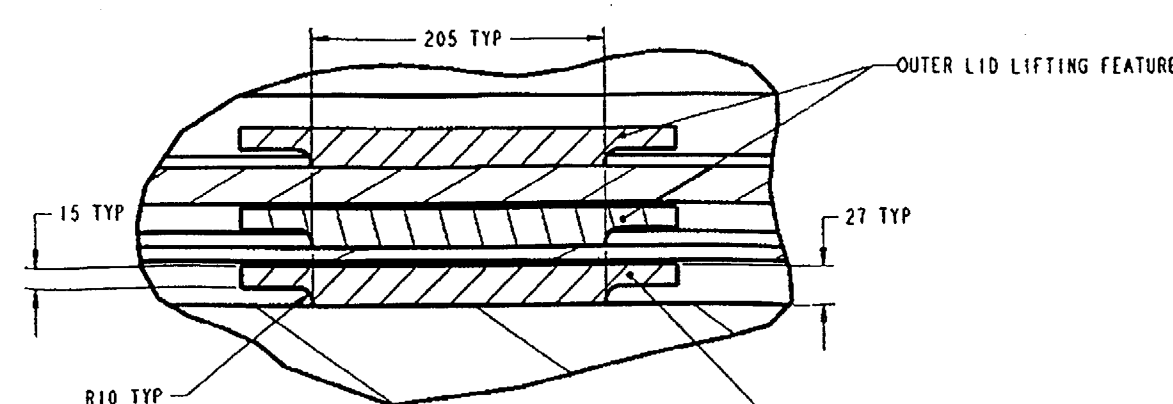
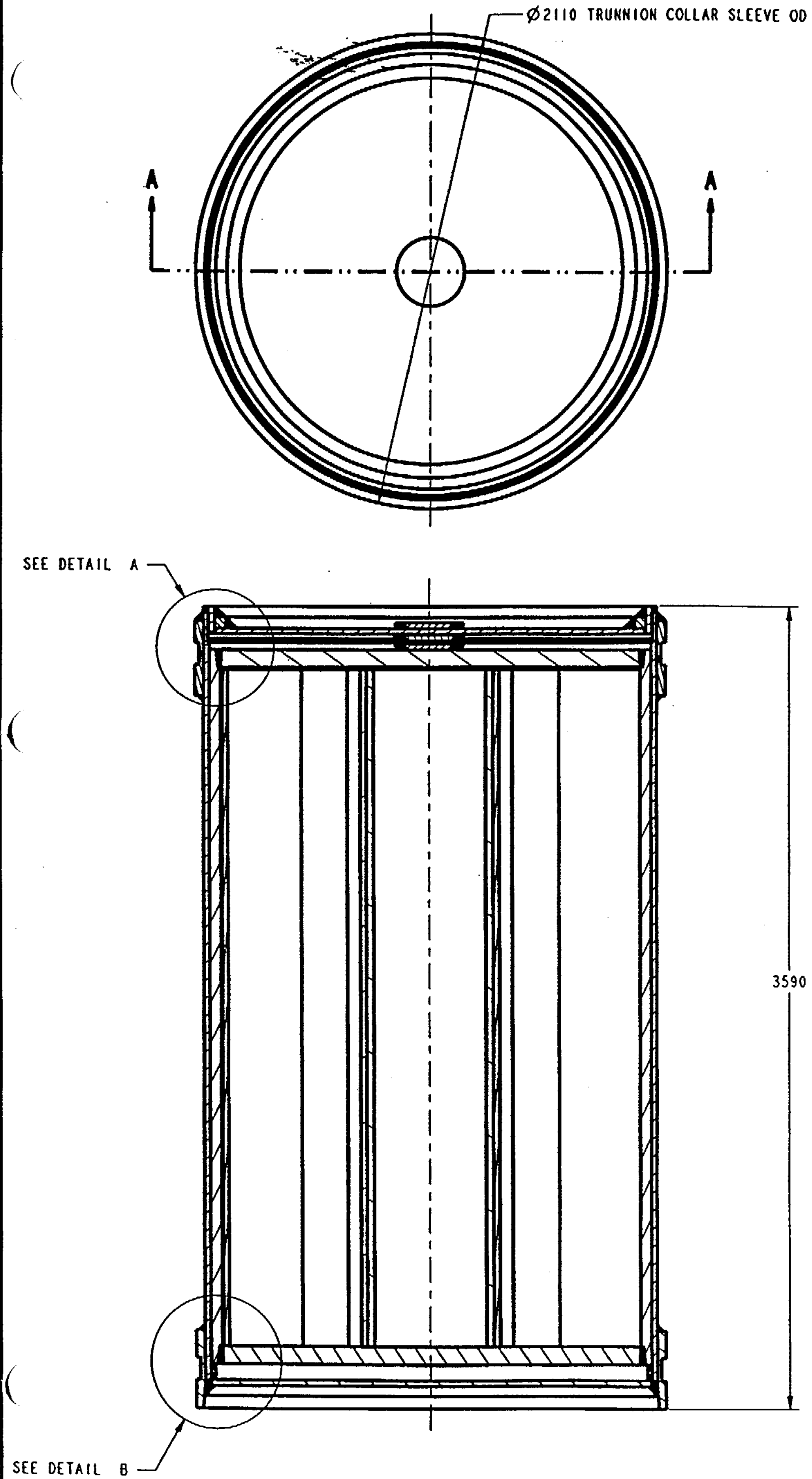
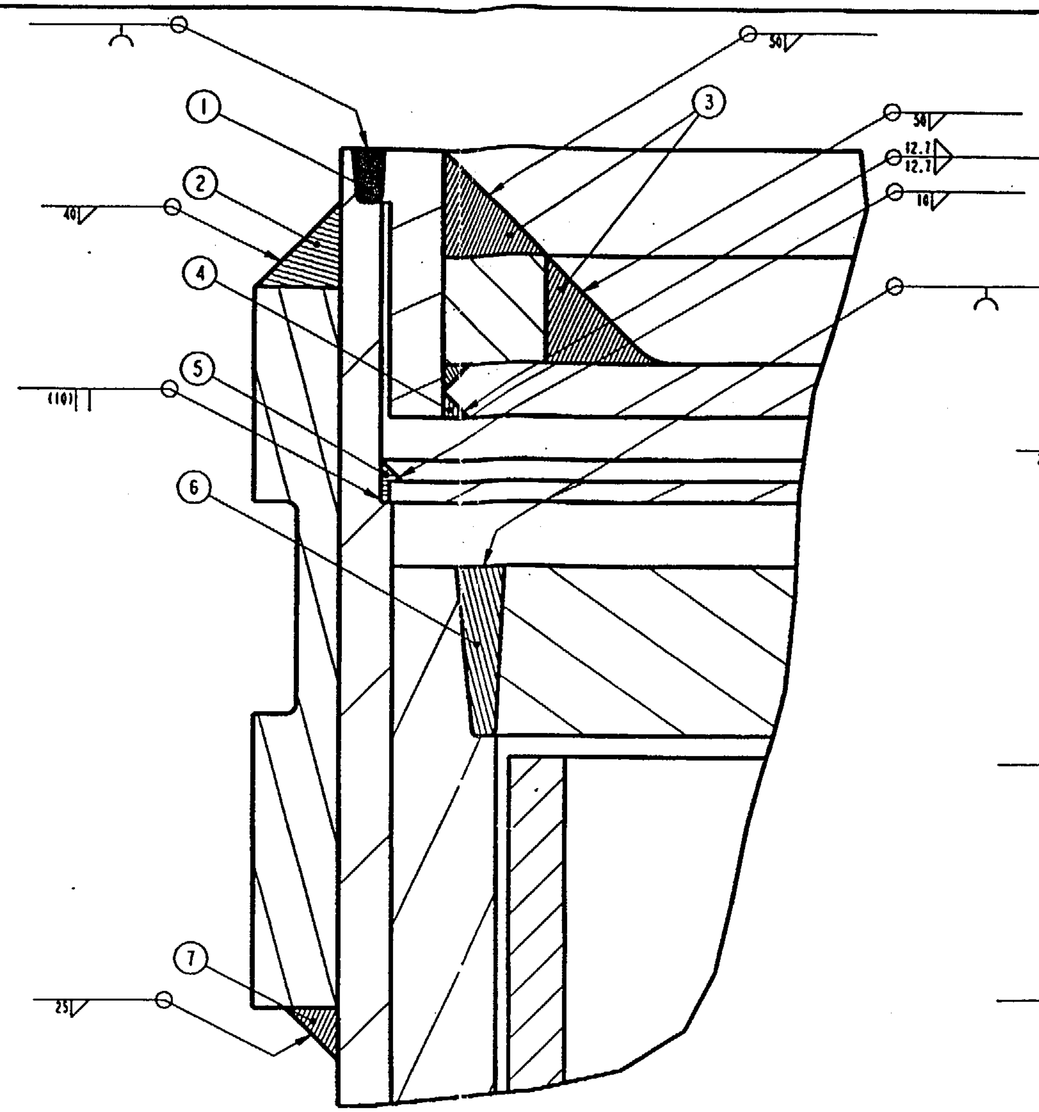


DETAIL C

SK-0196 REV 03 | SHEET 2 OF 2



SECTION A-A



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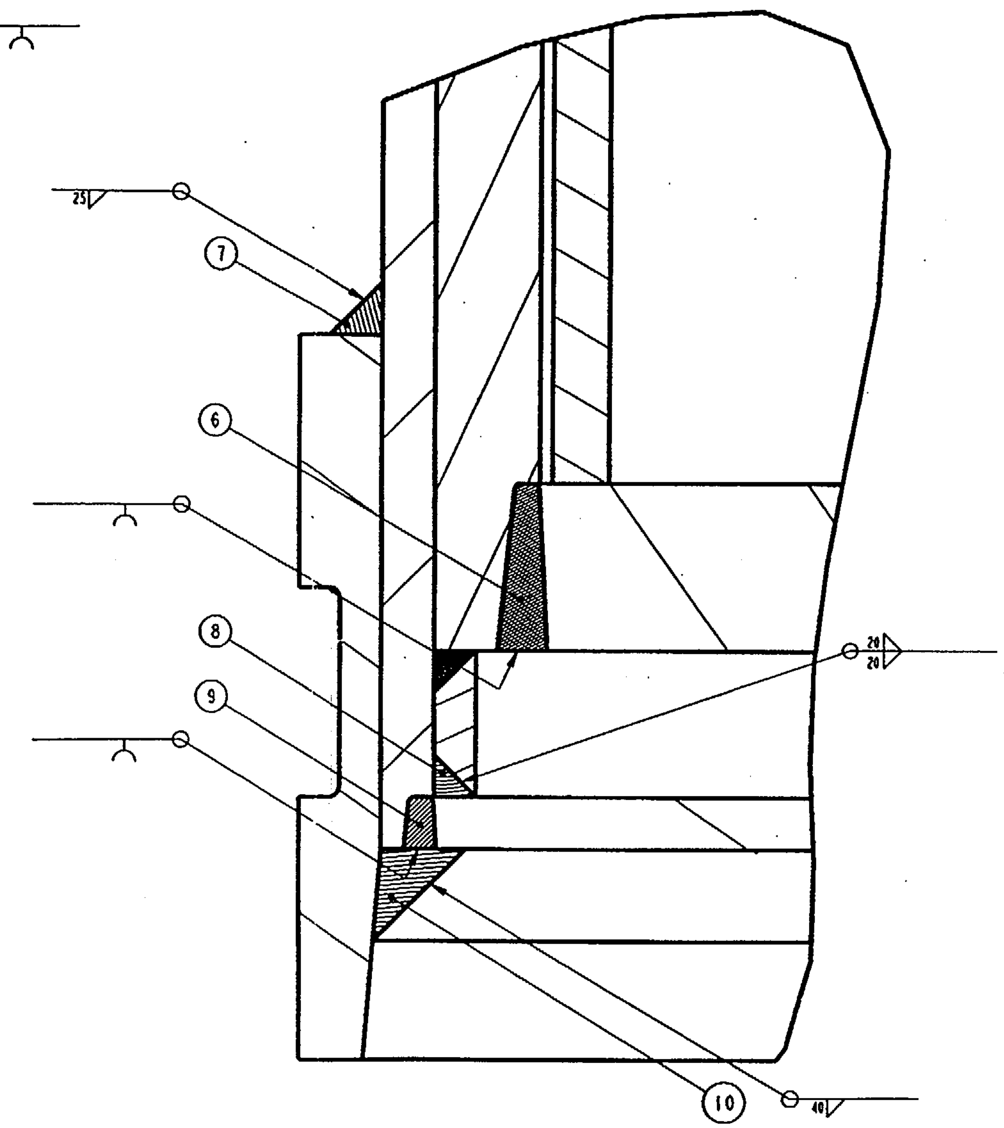

DETAIL B

WELD	MATERIAL	MASS (KG)	QTY RQD
1	SFA-5.14 N06022	18	1
2	SFA-5.14 N06022	45	1
3	SFA-5.14 N06022	127	1
4	SFA-5.14 N06022	4.1	2
5	SFA-5.14 N06022	4.9	1
6	SFA-5.9 S31680	67	2
7	SFA-5.14 N06022	17	2
8	SFA-5.14 N06022	11	2
9	SFA-5.14 N06022	18	1
10	SFA-5.14 N06022	48	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	325	-
TOTAL 316 WELDS	SFA-5.9 S31680	133	-

UNITS: mm

DO NOT SCALE FROM SKETCH

REVISIONS			
REV	DESCRIPTION	DRW BY	DATE
00	ISSUED APPROVED	BH	03/10/00

"FOR INFORMATION ONLY"

5-DHLW/DOE SNF - SHORT WELD CONFIGURATION

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SKETCHED BY:	BRYAN HARKINS BH 10 March 00
DATE:	03/10/00
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3/13/00
TWD 3.13.00

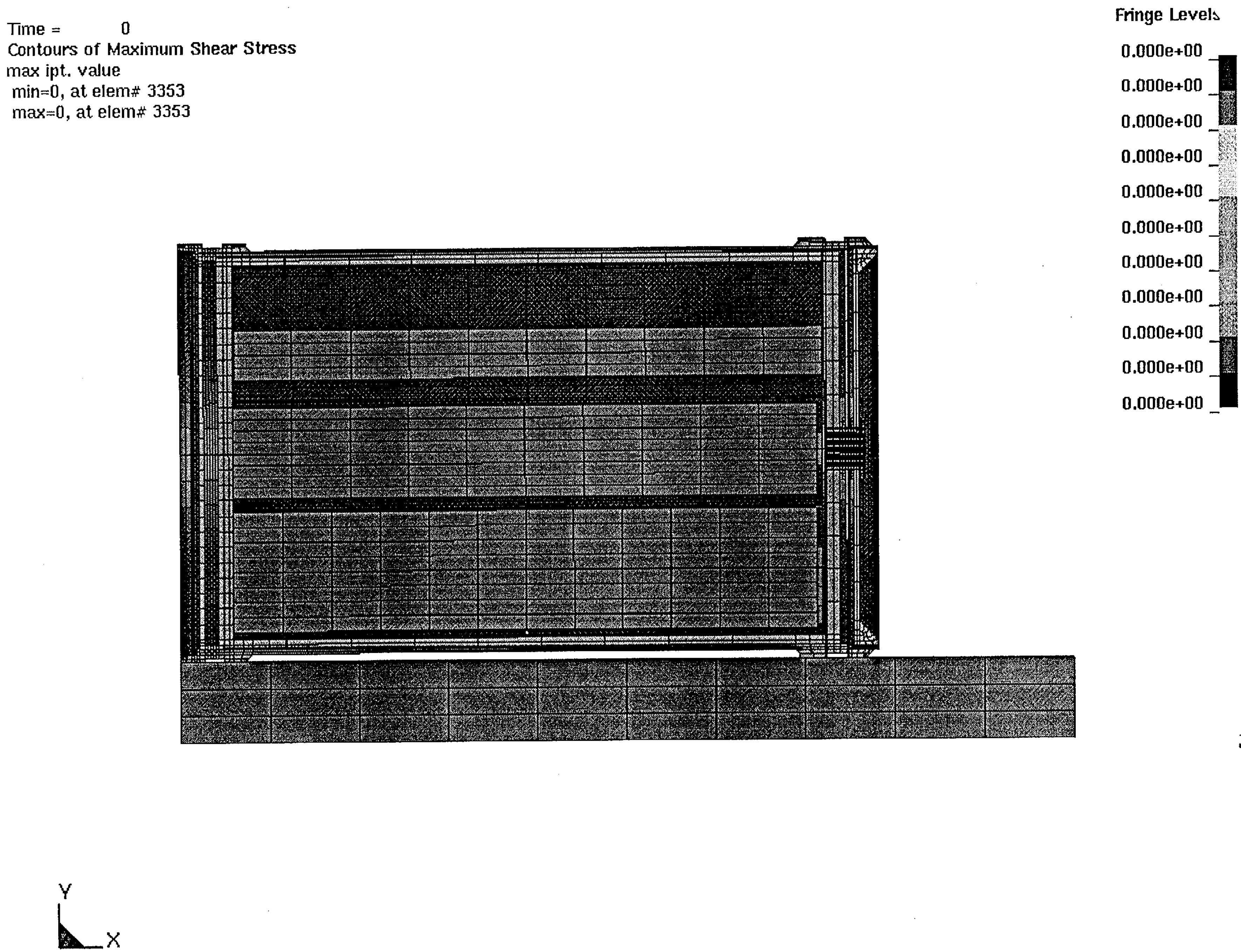

Figure III-1. Cross-Sectional View of Finite Element Representation of the 5-DHLW/DOE SNF Short WP

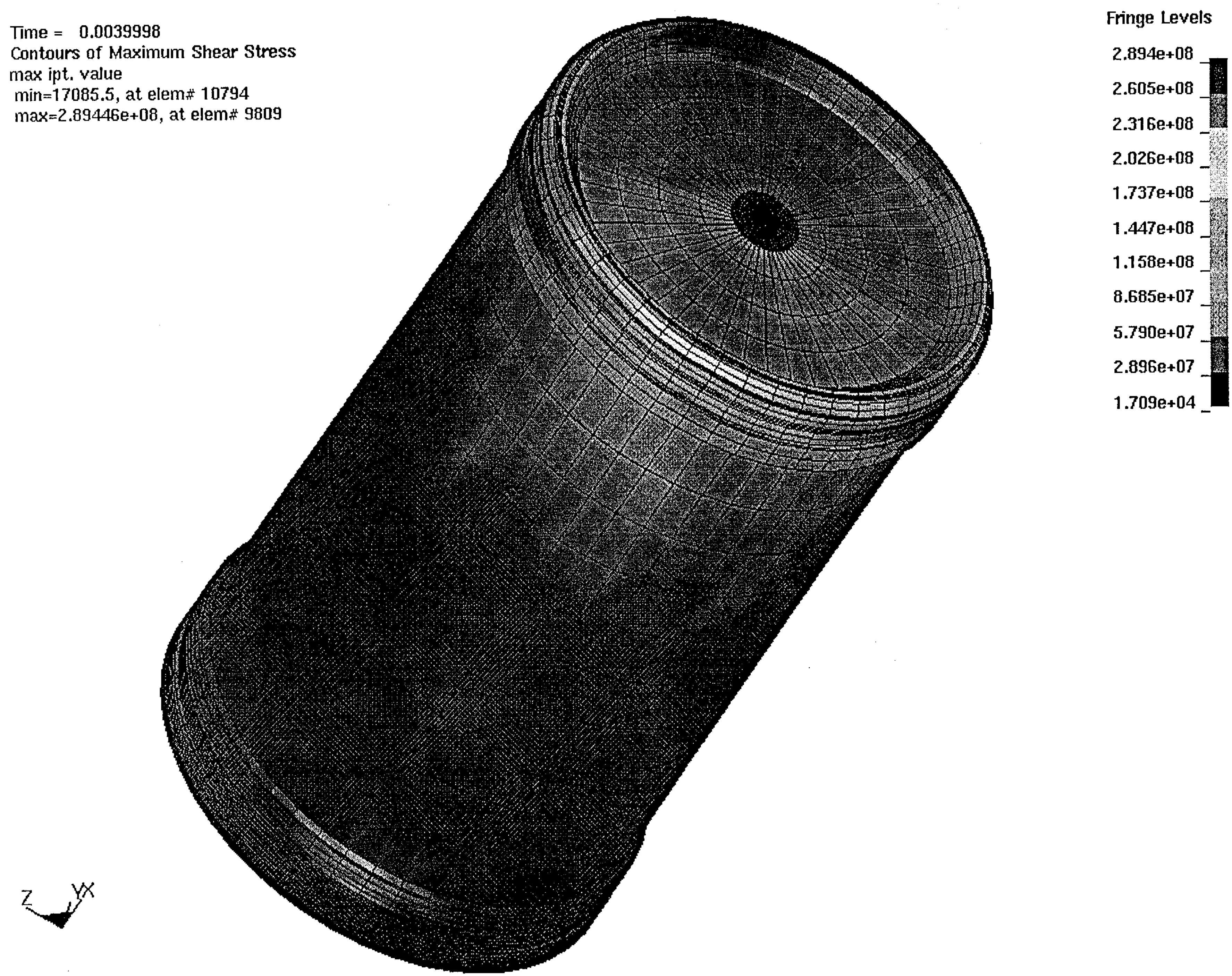

Figure III-2. Shear Stress Plot of Complete Waste Package (at room temperature)

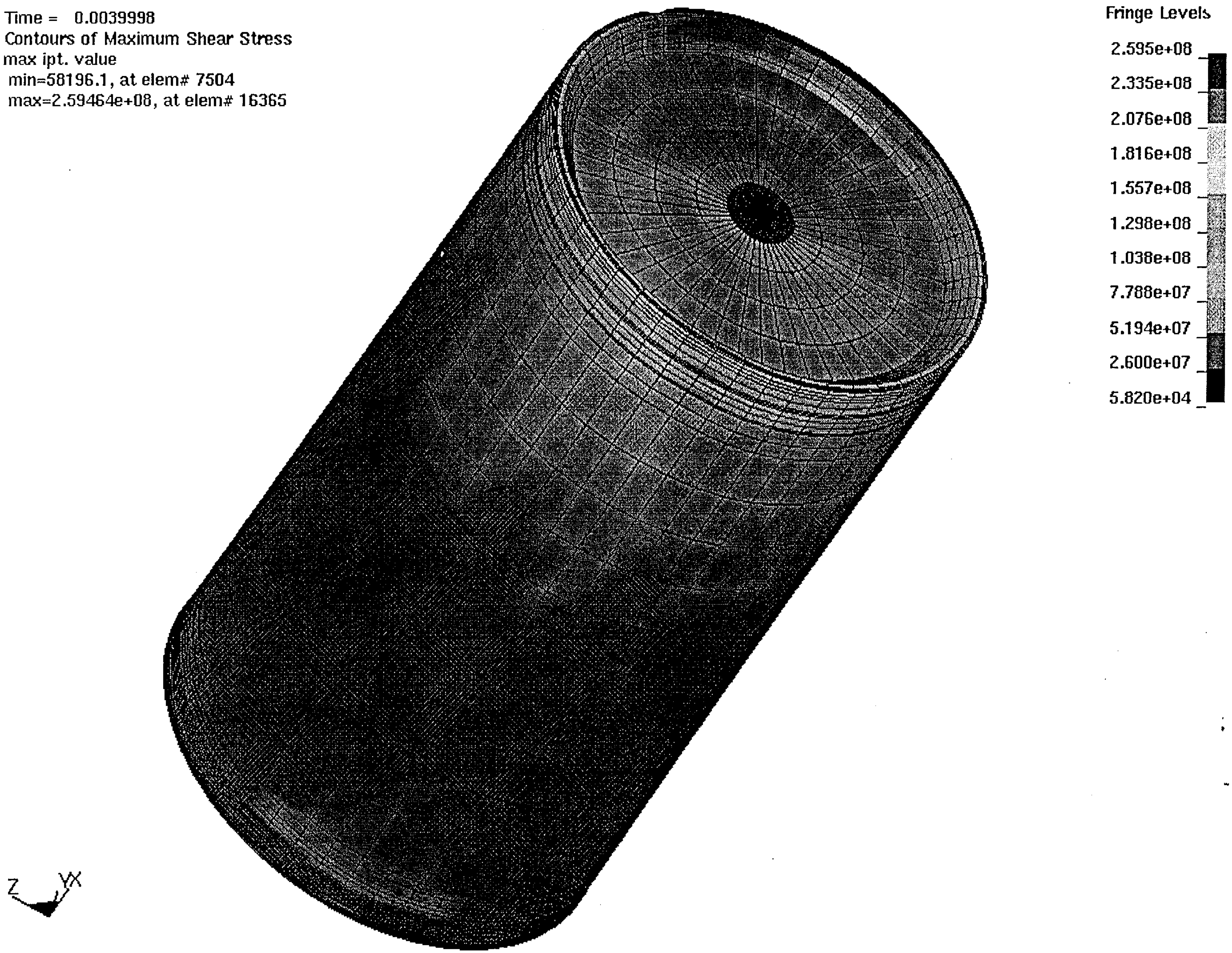

Figure III-3. Shear Stress Plot of Outer Shell and Lids (at room temperature)

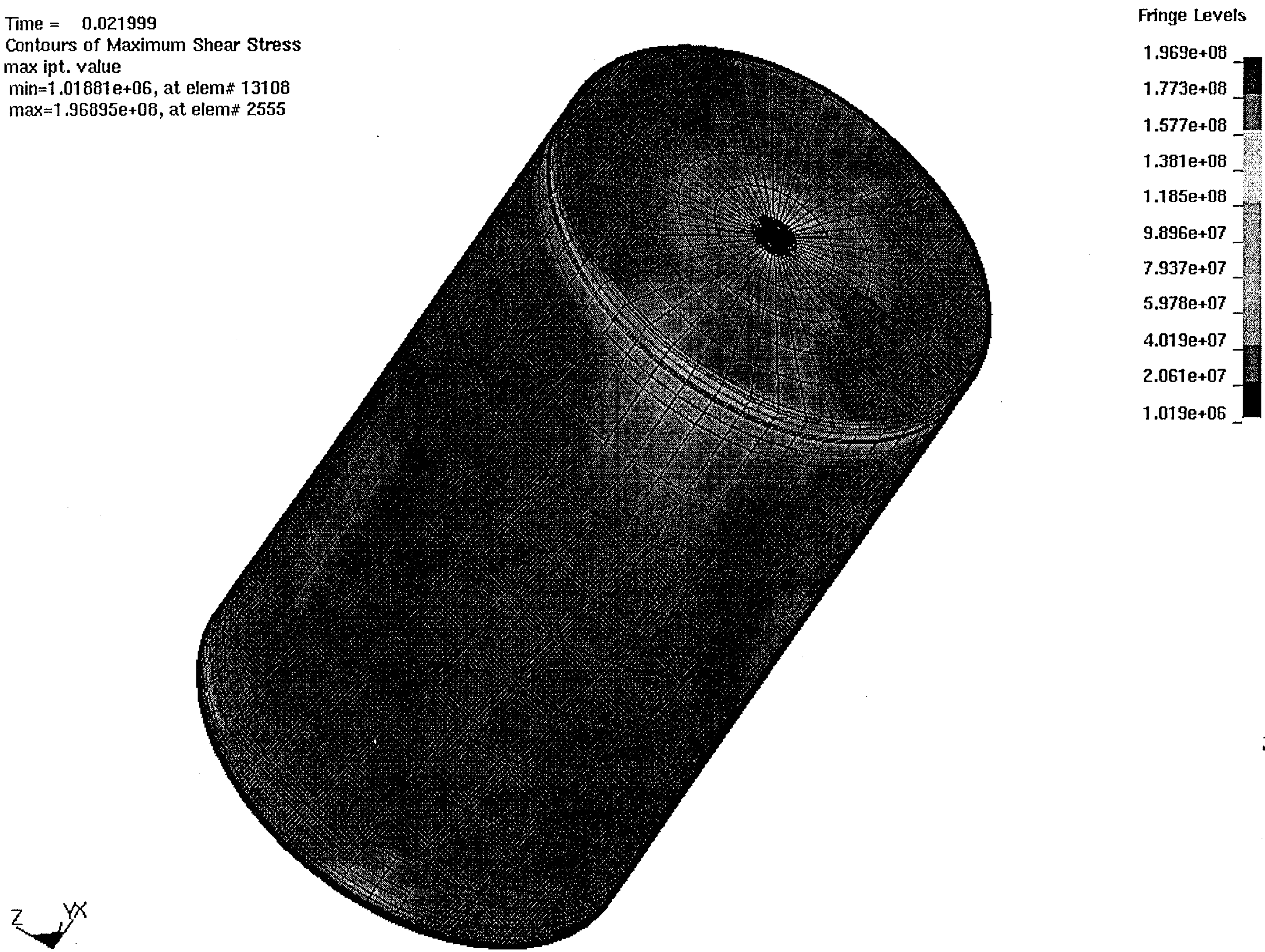

Figure III-4. Shear Stress Plot of Inner Shell and Inner Lid (at room temperature)

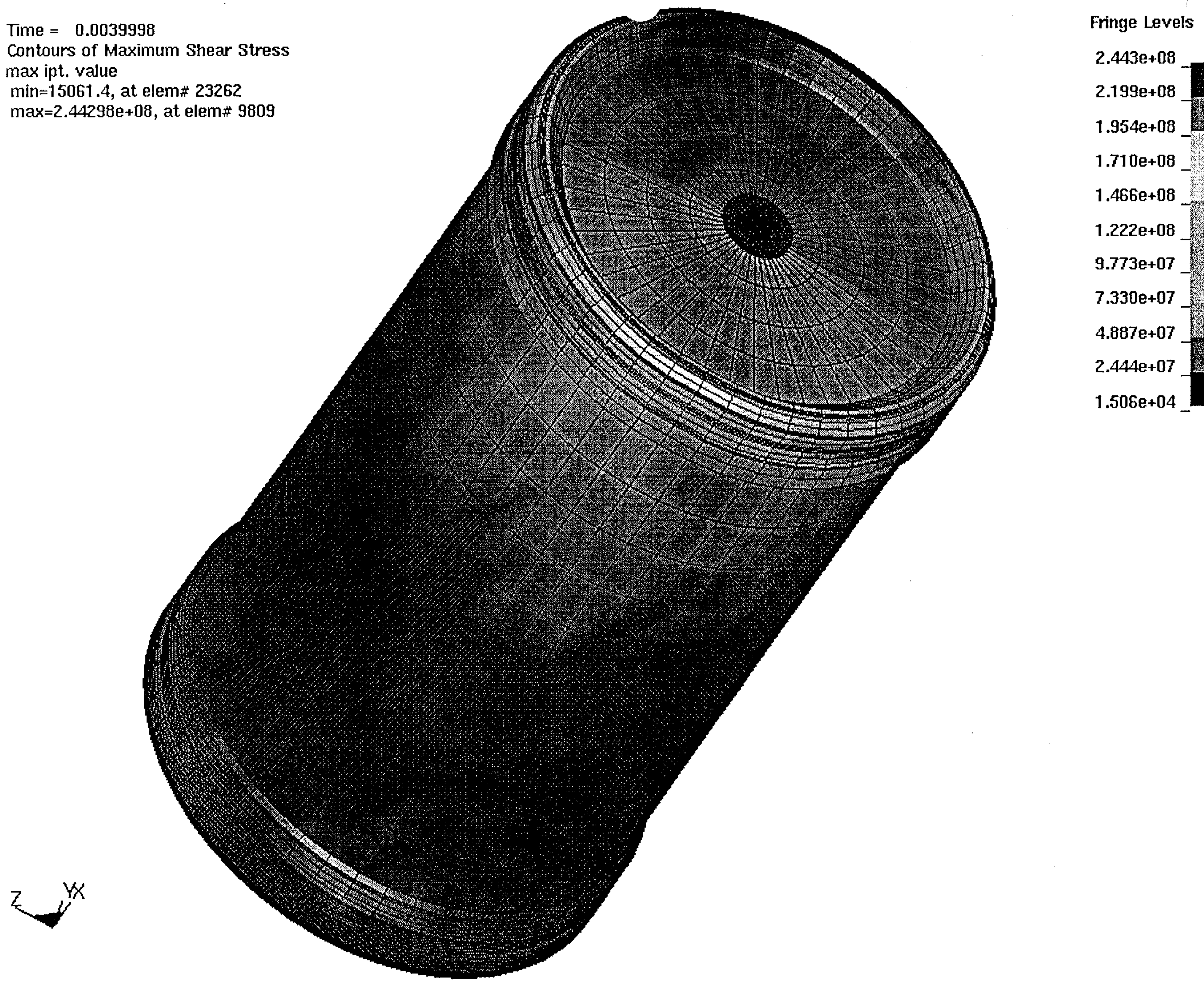

Figure III-5. Shear Stress Plot of Complete Waste Package (at 204 °*C*)

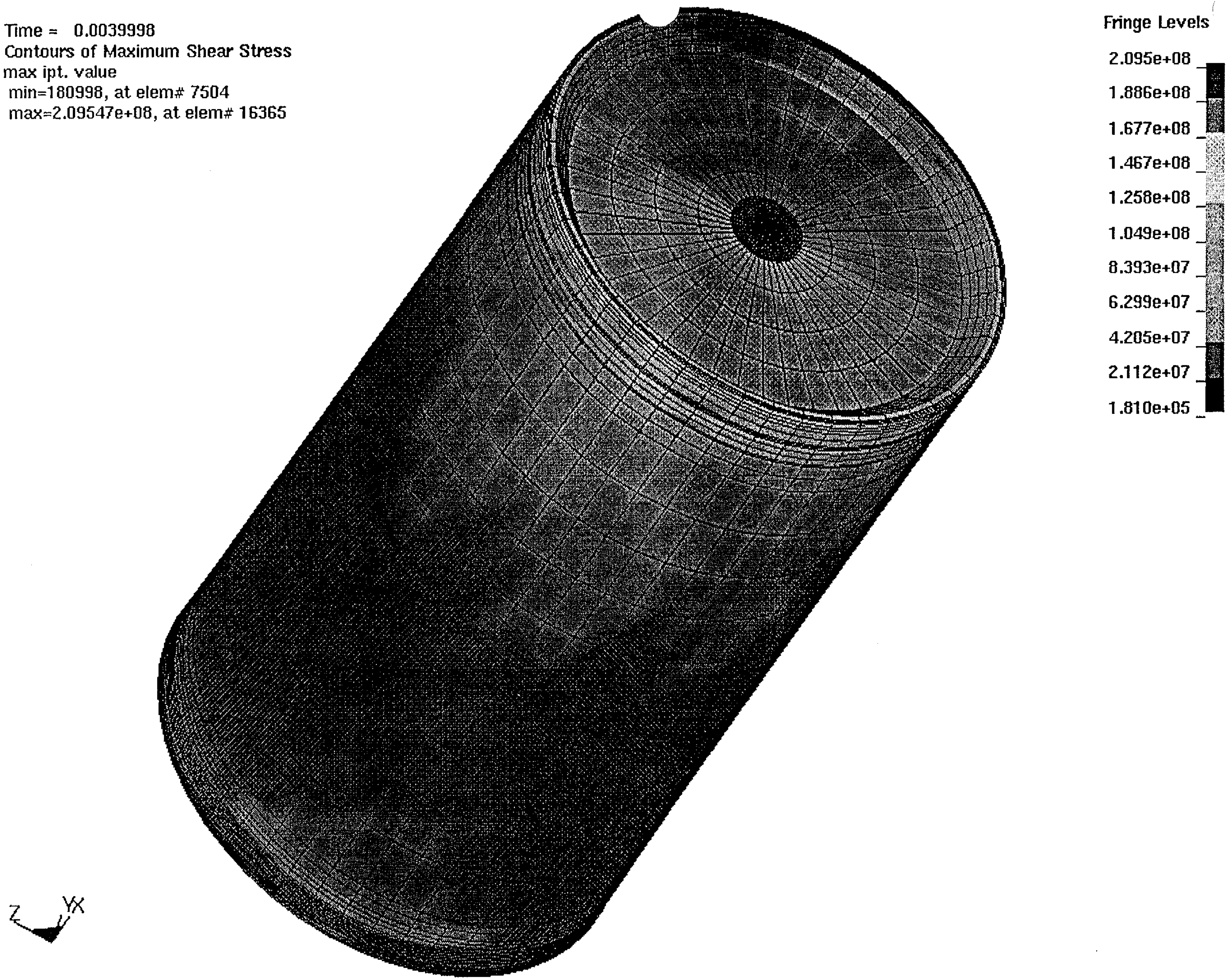

Figure III-6. Shear Stress Plot of Outer Shell and Lids (at 204 °*C*)

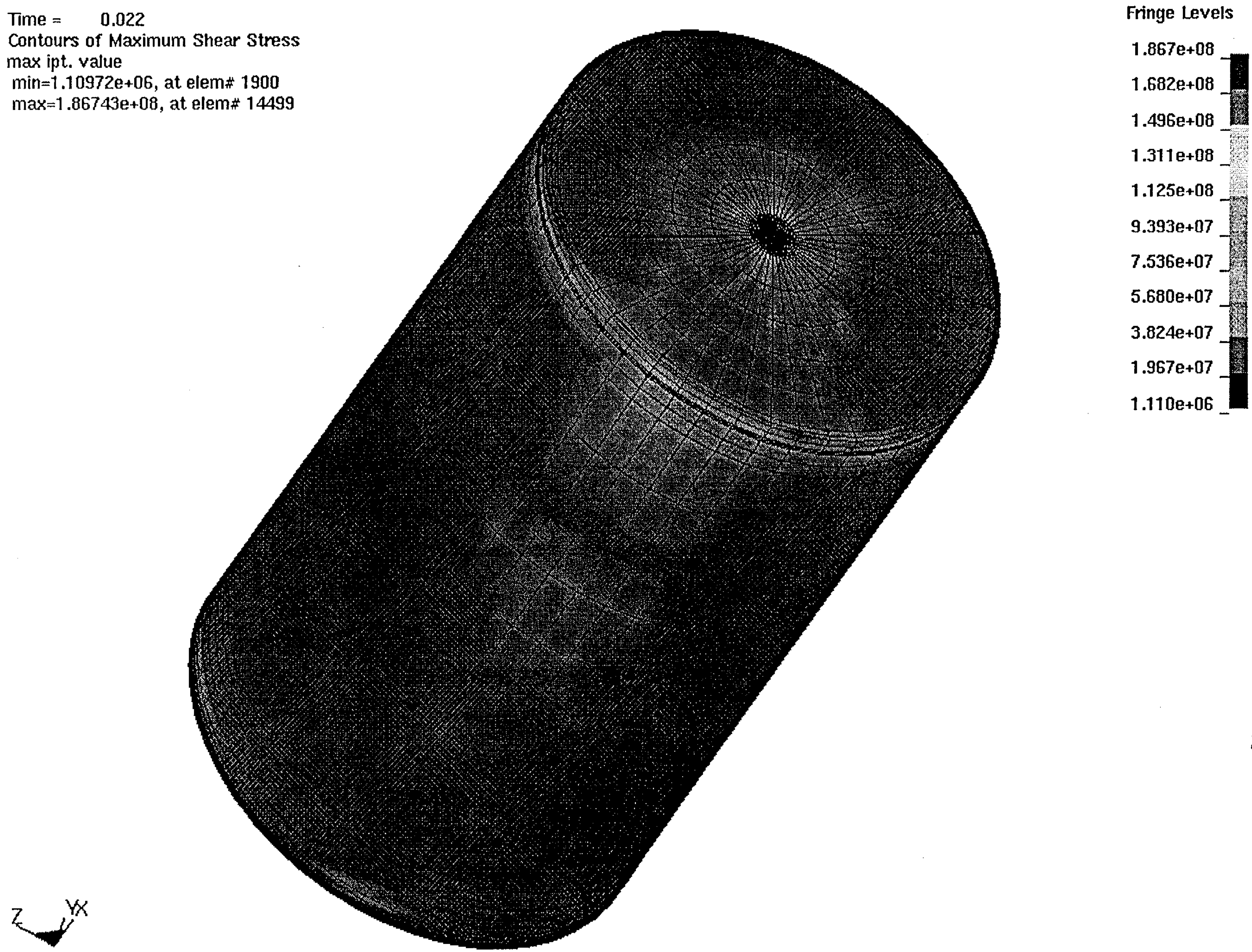

Figure III-7. Shear Stress Plot of Inner Shell and Inner Lid (at 204 °C)

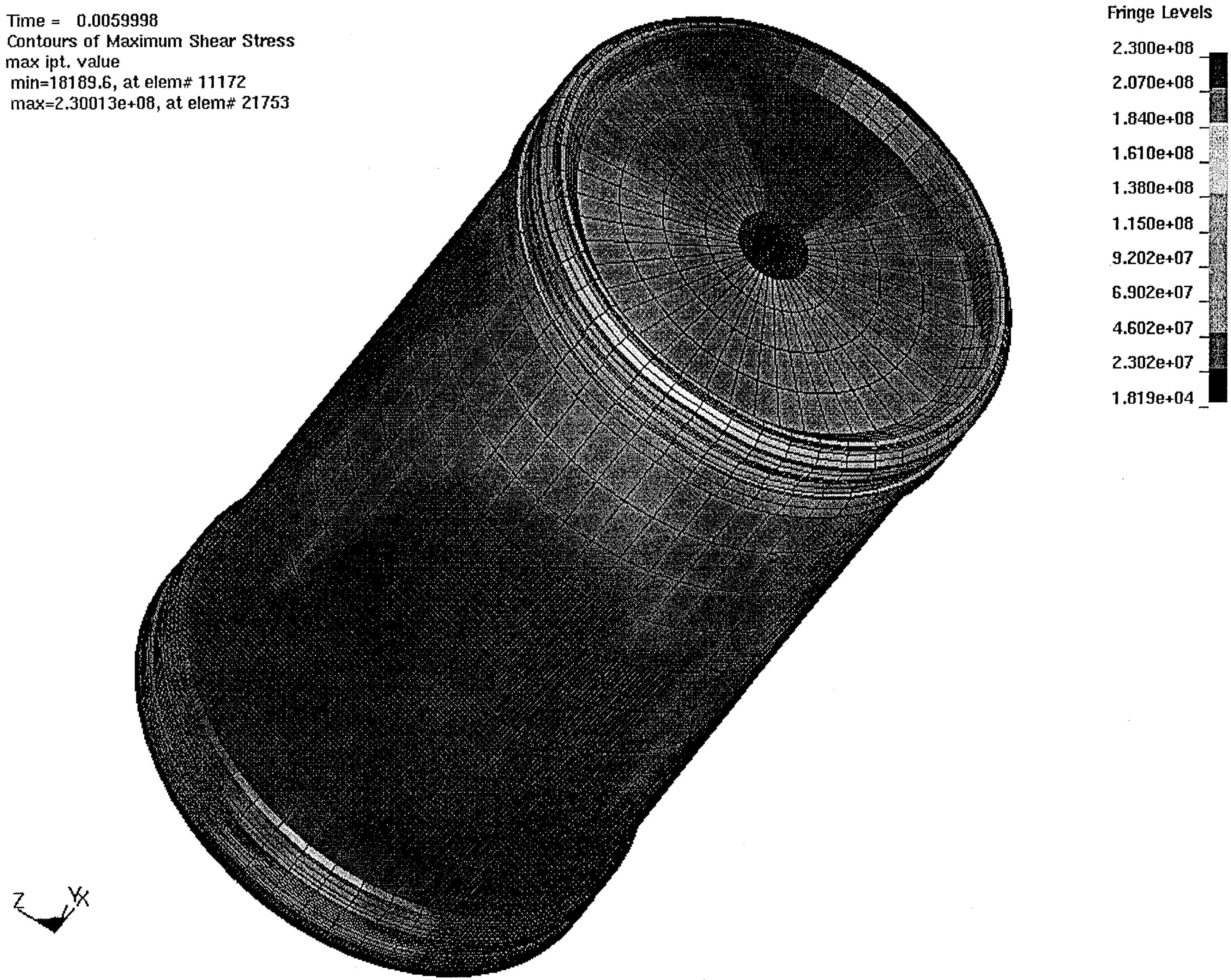

Figure III-8. Shear Stress Plot of Complete Waste Package (at 316 °*C*)

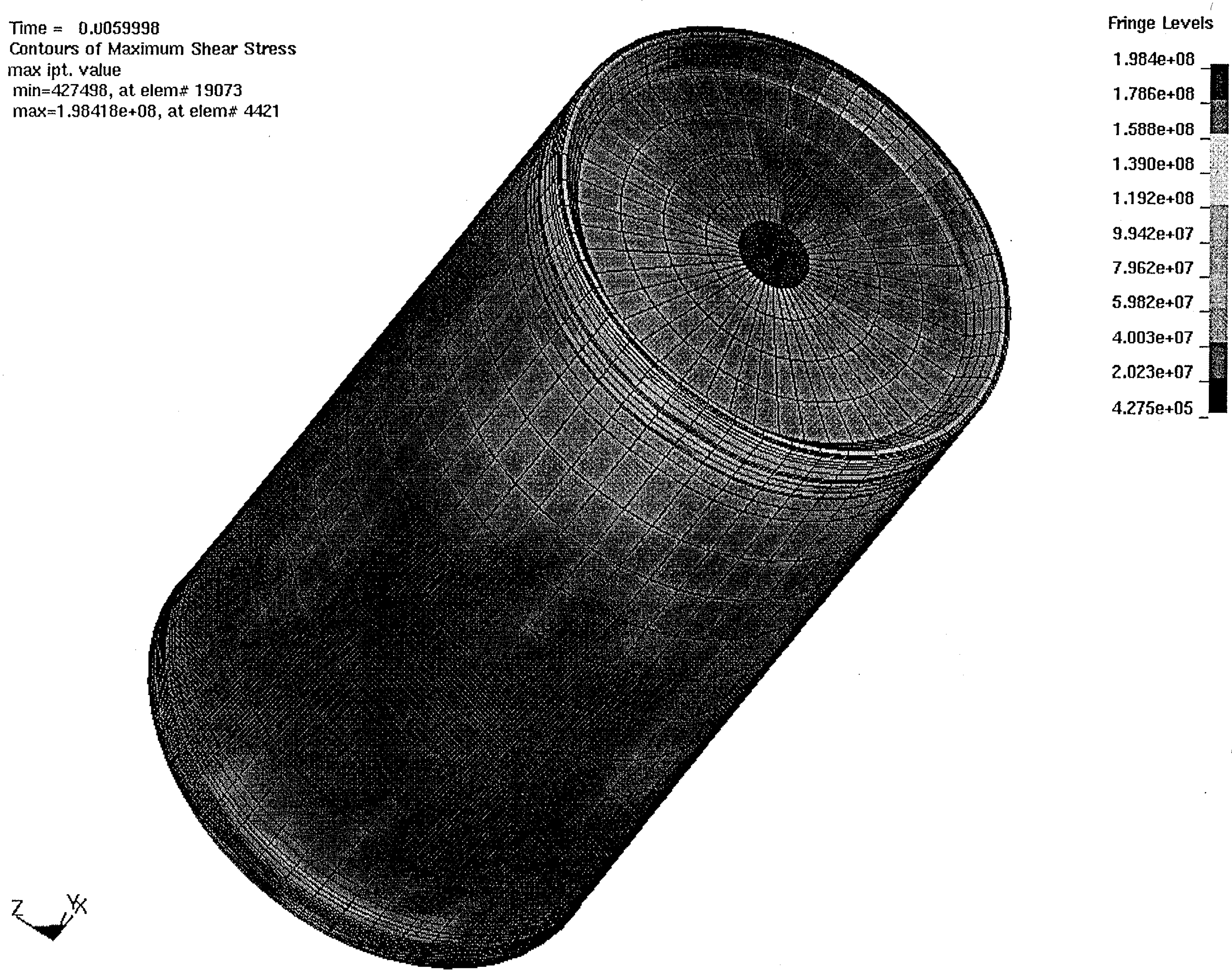

Figure III-9. Shear Stress Plot of Outer Shell and Lids (at 316 °*C*)

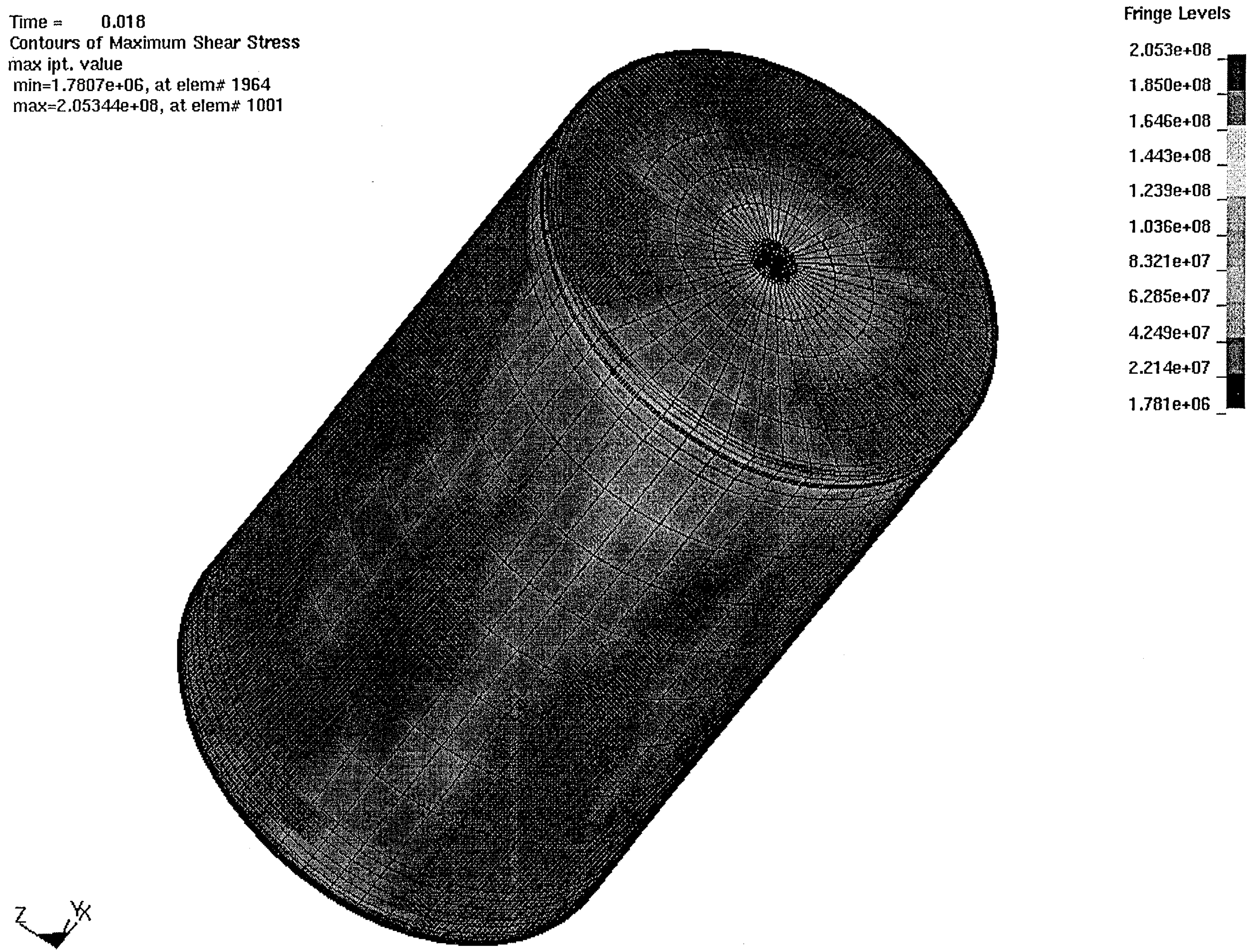

Figure III-10. Shear Stress Plot of Inner Shell and Inner Lid (at 316 °C)