

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT  
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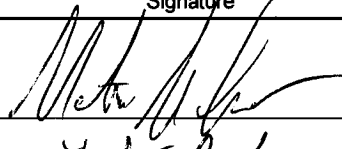
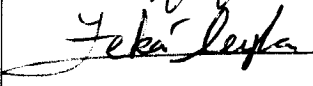

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**CONTENTS**

	<b>Page</b>
1. PURPOSE.....	5
2. METHOD .....	5
3. ASSUMPTIONS.....	5
4. USE OF COMPUTER SOFTWARE AND MODELS .....	7
4.1 SOFTWARE.....	7
4.2 MODELS .....	7
5. CALCULATION .....	8
5.1 CALCULATION DATA .....	8
5.1.1 Inner Shell Properties .....	8
5.1.2 Outer Shell Properties.....	8
5.1.3 Shell Dimensions.....	9
5.1.4 Temperature Range .....	9
5.1.5 Overall Heat Transfer Rate.....	10
5.2 TECHNICAL APPROACH .....	10
5.3 THERMAL EXPANSION CALCULATIONS.....	10
6. RESULTS .....	12
6.1 MAXIMUM OUTER SHELL TANGENTIAL STRESS .....	12
6.2 TANGENTIAL STRESS RELATION TO TEMPERATURE .....	13
6.2.1 21-PWR WP .....	14
6.2.2 44-BWR WP .....	16
6.2.3 24-BWR WP .....	18
6.2.4 12-PWR LONG WP .....	20
6.2.5 5 DHLW/DOE SNF - Short WP.....	22
6.2.6 2-MCO/2-DHLW WP .....	24
6.2.7 NAVAL SNF-Long WP .....	26
7. REFERENCES .....	28
8. ATTACHMENTS.....	30

**FIGURES**

	<b>Page</b>
1. The Locations of the Outer Shell Inner Surface and Outer Surface Maximum Tangential Stresses.....	12
2. 21-PWR WP Outer Shell Outer Surface Tangential Stress .....	14
3. 21-PWR WP Outer Shell Inner Surface Tangential Stress.....	15
4. 44-BWR WP Outer Shell Outer Surface Tangential Stress.....	16
5. 44-BWR WP Outer Shell Inner Surface Tangential Stress .....	17
6. 24-BWR WP Outer Shell Outer Surface Tangential Stress.....	18
7. 24-BWR WP Outer Shell Inner Surface Tangential Stress .....	19
8. 12-PWR Long WP Outer Shell Outer Surface Tangential Stress.....	20
9. 12-PWR Long WP Outer Shell Inner Surface Tangential Stress .....	21
10. 5 DHLW/DOE SNF - Short WP Outer Shell Outer Surface Tangential Stress .....	22
11. 5 DHLW/DOE SNF - Short WP Outer Shell Inner Surface Tangential Stress.....	23
12. 2-MCO/2-DHLW WP Outer Shell Outer Surface Tangential Stress .....	24
13. 2-MCO/2-DHLW WP Outer Shell Inner Surface Tangential Stress.....	25
14. Naval SNF-Long WP Outer Shell Outer Surface Tangential Stress .....	26
15. Naval SNF-Long WP Outer Shell Inner Surface Tangential Stress .....	27

**TABLES**

	<b>Page</b>
1. Dimensions of the Inner and Outer Shell for Various Waste Packages .....	9
2. Inner Cavity Length of the Inner Shell for Various Waste Packages.....	9
3. Overall Heat Transfer Rates .....	10
4. Outer Shell Maximum Tangential Stress at the Outer Surface.....	13
5. Outer Shell Maximum Tangential Stress at the Inner Surface .....	13

## 1. PURPOSE

The objective of this activity is to determine the tangential stresses of the outer shell, due to uneven thermal expansion of the inner and outer shells of the current waste package (WP) designs. Based on the results of the calculation *Waste Package Barrier Stresses Due to Thermal Expansion*, CAL-EBS-ME-000008 (Ref. 10), only tangential stresses are considered for this calculation. The tangential stresses are significantly larger than the radial stresses associated with thermal expansion, and at the WP outer surface the radial stresses are equal to zero. The scope of this activity is limited to determining the tangential stresses the waste package outer shell is subject to due to the interference fit, produced by having two different shell coefficients of thermal expansions. The inner shell has a greater coefficient of thermal expansion than the outer shell, producing a pressure between the two shells. This calculation is associated with Waste Package Project.

The calculations are performed for the 21-PWR (pressurized water reactor), 44-BWR (boiling water reactor), 24-BWR, 12-PWR Long, 5 DHLW/DOE SNF - Short (defense high-level waste/Department of Energy spent nuclear fuel), 2-MCO/2-DHLW (multi-canister overpack), and Naval SNF Long WP designs. The information provided by the sketches attached to this calculation is that of the potential design for the types of WPs considered in this calculation.

This calculation is performed in accordance with the *Technical Work Plan for: Waste Package Design Description for SR* (Ref. 7). The calculation is documented, reviewed, and approved in accordance with AP-3.12Q, *Calculations* (Ref. 1).

## 2. METHOD

The method and the analytical approach for this calculation are performed through the use of basic equations of solid mechanics. With regard to the development of this calculation, the control of electronic management of data was evaluated in accordance with AP-SV.1Q, *Control of the Electronic Management of Information* (Ref. 3). The electronic management of data is controlled in accordance with Ref. 7, Section 10.

## 3. ASSUMPTIONS

In the course of developing this document, assumptions were made regarding the thermal expansion calculations. These are identified below.

- 3.1 One temperature range (20°C – 239°C) (Ref. 9, Table 6-7) is used throughout this calculation for all the waste packages in this study. Although this temperature range pertains to the 21-PWR, it is the largest range among all the waste packages. The rationale for this assumption is that the interference created from thermal expansion with this temperature range will be larger, compared to the interference created from the smaller

temperature ranges associated with the other waste packages. This assumption provides bounding results in terms of tangential stresses in the outer shell due to thermal expansion. This assumption is used in Section 5.1.4.

- 3.2 The 21-PWR WP overall heat transfer rates are used throughout this calculation for all the waste packages in this study. Although these overall heat transfer rates pertain to the 21-PWR WP, they are the greatest among all the waste packages (Ref. 9, Table 6-7). The rationale for this assumption is that larger overall heat transfer rates produce a larger difference in temperature between the inner and outer shells. The inner shell results in having a higher temperature than the outer shell, causing the thermal expansion to be greater for the former. This leads to a greater interference between the shells, yielding higher tangential stresses in the outer shell. This assumption provides bounding results in terms of tangential stresses in the outer shell due to thermal expansion. This assumption is used in Section 5.1.5.
- 3.3 Room temperature elastic moduli are used for calculating the pressure due to the interference. The rationale for this assumption is that the pressure calculation yields greater pressures when the elastic moduli are larger. At the maximum temperature, the elastic moduli are less than those at room temperature, resulting in a smaller pressure. Therefore, using the larger elastic moduli will provide a higher pressure along with higher stresses in the outer shell. This assumption provides bounding results in terms of tangential stresses in the outer shell due to thermal expansion. This assumption is used in Sections 5.1.1 and 5.1.2.
- 3.4 The initial temperature of the waste packages is room temperature, at 20°C (68°F and 293 K). The rationale for this assumption is that the waste packages are manufactured at room temperature or warmer. Room temperature will provide a low initial temperature for the waste package shells, yielding a greater change in temperature than that at a higher temperature. This assumption provides bounding results in terms of tangential stresses in the outer shell due to thermal expansion. This assumption is used in Section 5.1.4.
- 3.5 When calculating the inner shell inner surface temperature, the inner shell outer surface and the outer shell inner surface have the same radius and are in complete contact with each other. The rationale for this assumption is that there is no stress associated with thermal expansion if the two surfaces are not in contact with each other. Calculating the temperature of the inner shell when the shells are not in contact is not of concern for this calculation. This assumption is used in Attachments II through VIII.

#### 4. USE OF COMPUTER SOFTWARE AND MODELS

##### 4.1 SOFTWARE

Section 8 contains computations using the standard functions of a commercial-off-the-shelf software program, Mathcad 2000 Professional. The results of the computation can be reproduced and checked by hand; therefore, the software use is considered exempt from the requirements of AP-SI.1Q, *Software Management* (Ref. 2) (see Ref. 1, Attachment 2, Section 4.A). These computations are performed using Mathcad 2000 Professional on a personal computer. The filenames for each computation are documented in the header for the attachments. Formulas, algorithms, listings of inputs and outputs, and numerical solution techniques are described in comments in the calculation itself, as applicable. The form of the computation files is such that the routines lend themselves to easy verification by visual inspection.

##### 4.2 MODELS

None used.



## 5. CALCULATION

### 5.1 CALCULATION DATA

The material properties of the inner and outer shell are given below.

#### 5.1.1 Inner Shell Properties

- 316 SS NG (Stainless Steel Nuclear Grade), SA-240, inner shell material (Attachment I) 316 NG SS, which is 316 SS [SA-240 S31600] with tightened control on carbon and nitrogen content and has the same material properties as 316 SS (Ref. 5, page 931 and Ref. 6, Section II, SA-240 Table 1)
- Modulus of elasticity,  $E_i = 195.1 \text{ GPa}$  at  $20^\circ\text{C}$  ( $28.3 \cdot 10^6 \text{ psi}$ ) (Ref. 6, Table TM-1, Material Group G) (Assumption 3.3)
- Poisson's ratio,  $\nu_i = 0.298$  at  $20^\circ\text{C}$  (Ref. 4, page 755, Fig. 15)
- Mean coefficient of thermal expansion,  $\alpha_{ss} = 17 \cdot 10^{-6} \text{ m/m}\cdot\text{K}$  at  $260^\circ\text{C}$  ( $9.7 \cdot 10^{-6} \text{ in/in}\cdot^\circ\text{F}$ ) (Ref. 6, Table TE-1, 16CR-12Ni-2Mo at  $500^\circ\text{F}$ , Coefficient B)
- Thermal conductivity,  $K_i = 17.3 \text{ W/m}\cdot\text{K}$  at  $232^\circ\text{C}$  ( $10.0 \text{ BTU/hr}\cdot\text{ft}\cdot^\circ\text{F}$ ) (Ref. 6, Table TCD, 16CR-12Ni-2Mo at  $450^\circ\text{F}$ ).

#### 5.1.2 Outer Shell Properties

- Alloy 22, SB-575 N06022, outer shell material (Attachment I)
- Modulus of elasticity,  $E_o = 206 \text{ GPa}$  at  $20^\circ\text{C}$  ( $29.9 \cdot 10^6 \text{ psi}$ ) (Ref. 15, page 14, Average Dynamic Modulus of Elasticity) (Assumption 3.3)
- Poisson's ratio,  $\nu_o = 0.278$  at  $21^\circ\text{C}$  (Ref. 4, page 143, Mechanical Properties)
- Mean coefficient of thermal expansion,  $\alpha_{\text{alloy22}} = 12.6 \cdot 10^{-6} \text{ m/m}\cdot\text{K}$  from  $24^\circ$  to  $316^\circ\text{C}$  ( $7.0 \cdot 10^{-6} \text{ in/in}\cdot^\circ\text{F}$ ) (Ref. 15, page 13, Average Physical Properties, Mean Coefficient of Thermal Expansion)
- Thermal conductivity,  $K_o = 13.4 \text{ W/m}\cdot\text{K}$  at  $200^\circ\text{C}$  ( $7.75 \text{ BTU/hr}\cdot\text{ft}\cdot^\circ\text{F}$ ) (Ref. 15, page 13, Average Physical Properties, Thermal Conductivity)

- Yield strength  $\sigma_y = 222 \text{ MPa}$  at  $260^\circ\text{C}$  ( $32.2 \cdot 10^3 \text{ psi}$ ) (Ref. 6, Table Y-1, 55Ni-21Cr-13.5Mo at  $500^\circ\text{F}$ ).

### 5.1.3 Shell Dimensions

The dimensions of the inner and outer shells for various waste packages (Attachment I) are given in Table 1.

Table 1. Dimensions of the Inner and Outer Shell for Various Waste Packages

Waste Package Type	Inner Shell Inner Radius		Inner Shell Thickness		Outer Shell Thickness	
	(m)	(in.)	(m)	(in.)	(m)	(in.)
21-PWR	0.712	28.0	0.050	1.97	0.020	0.79
44-BWR	0.727	28.6	0.050	1.97	0.020	0.79
24-BWR	0.549	21.6	0.050	1.97	0.020	0.79
12-PWR Long	0.555	21.9	0.050	1.97	0.020	0.79
5 DHLW/DOE SNF - Short	0.940	37.0	0.050	1.97	0.025	0.98
2-MCO/2-DHLW	0.792	31.2	0.050	1.97	0.025	0.98
Naval SNF Long	0.8595	33.8	0.050	1.97	0.025	0.98

Table 2 provides the inner cavity length of the inner shell for various waste packages (Attachment I).

Table 2. Inner Cavity Length of the Inner Shell for Various Waste Packages

Waste Package Type	Inner Cavity Length	
	(m)	(in.)
21-PWR	4.585	180.5
44-BWR	4.585	180.5
24-BWR	4.585	180.5
12-PWR Long	5.121	201.6
5 DHLW/DOE SNF - Short	3.590	141.3
2-MCO/2-DHLW	4.617	181.8
Naval SNF Long	5.415	213.2

### 5.1.4 Temperature Range

The upper boundary of the temperature range for the 21-PWR WP is  $239^\circ\text{C}$  (462 degrees F and 512 K) at the outer shell outer surface, occurring 35 years after emplacement (Ref. 9, Table 6-7). This waste package outer surface upper boundary temperature is the maximum among all the waste packages and will be used for all the thermal expansion calculations (Assumption

3.1). The lower boundary temperature is room temperature at 20°C (68°F and 293 K) (Assumption 3.4) representing the shells before the spent nuclear fuel is inserted.

### 5.1.5 Overall Heat Transfer Rate

The overall heat transfer rates for the 21-PWR WP are presented in Table 3 along with the corresponding outer shell outer surface temperatures (Ref. 9). These values are used throughout this calculation for all the waste packages in this study (Assumption 3.2).

Table 3. Overall Heat Transfer Rates

Heat, $q_r$ (W)	Outer Shell Outer Surface Temperature, $T_{os}$	
	(K)	(°C)
0.0	293	20
11799.9	330	57
11762.5	357	84
10846.7	381	108
7192.8	411	138
7191.7	426	153
7182.4	443	170
7102.3	468	195
6856.1	493	220
6540.6	502	229
6158.3	512	239

## 5.2 TECHNICAL APPROACH

Seven different potential WP designs are evaluated in this document: 21-PWR, 44-BWR, 24-BWR, 12-PWR Long, 5 DHLW/DOE SNF - Short, 2-MCO/2-DHLW, and Naval SNF Long. For each one of these potential WP designs, a parametric study is performed by calculating the interference produced by the thermal expansion of the inner and outer shells. The interference between the two shells causes a pressure at the interface of the two shell surfaces. This pressure is used to calculate the outer shell tangential stresses at the inner and outer surfaces.

## 5.3 THERMAL EXPANSION CALCULATIONS

Thermal expansion occurs with a change in temperature and is represented by the following equation:  $\delta = \alpha R \Delta T$ ; where  $\delta$  is the change in radial length;  $\alpha$  is the coefficient of thermal expansion;  $R$  is the radial length; and,  $\Delta T$  is the change in temperature (see Attachments II through VIII). Attachment IX verifies this equation for thermal expansion. This calculation is a parametric study that determines the resulting interference between the waste package shells due to thermal expansion based on various gap sizes at room temperature. The calculations for

the tangential stresses of the outer shell at the outer and inner surfaces are presented in Attachments II through VIII. The results are presented in Section 6.

## 6. RESULTS

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### 6.1 MAXIMUM OUTER SHELL TANGENTIAL STRESS

At the maximum temperature, the waste package shells are subject to the greatest pressure created by the interference fit caused by uneven thermal expansion of the waste package inner and outer shells. This interference fit subjects the shells to a tangential stress. The locations of these outer shell stresses are depicted in Figure 1.

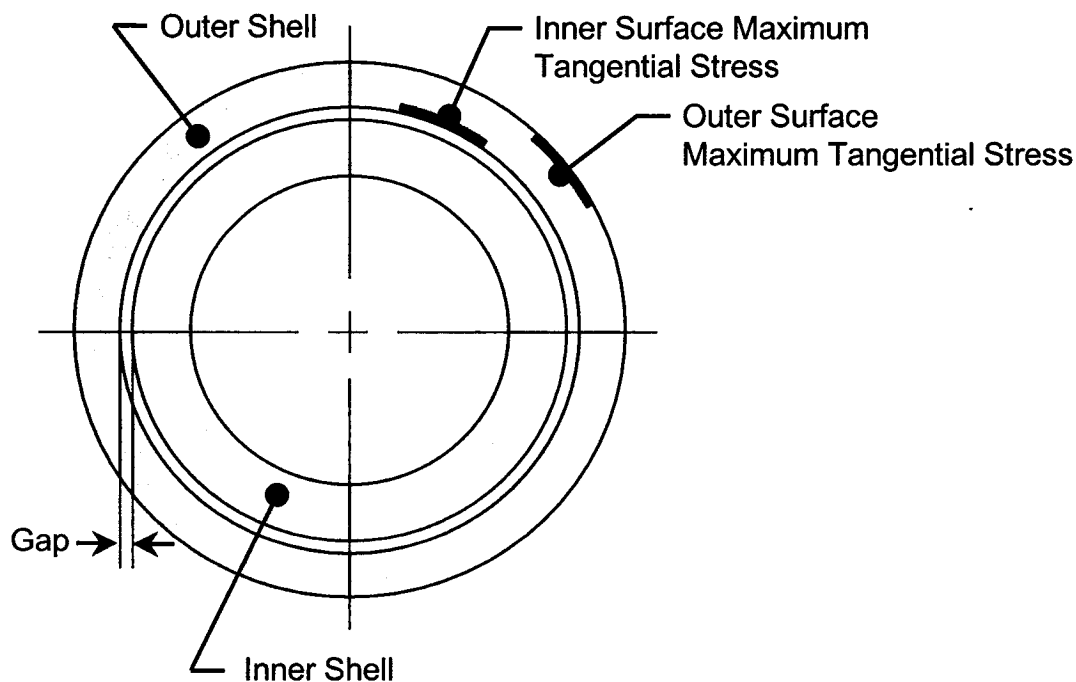


Figure 1. The Locations of the Outer Shell Inner Surface and Outer Surface Maximum Tangential Stresses

The outer shell maximum tangential stresses at the outer and inner surfaces for a corresponding gap size (Attachments II through VIII) are shown in Table 4 and Table 5.

Table 4. Outer Shell Maximum Tangential Stress at the Outer Surface

Waste Package Type	Maximum Tangential Stress at the Outer Surface, $\sigma_{os}$ (MPa)										
	Gap Size (mm)										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
21-PWR	140.9	122.1	103.2	84.4	65.6	46.8	27.9	9.1	0.0	0.0	0.0
44-BWR	140.9	122.4	103.9	85.5	67.0	48.5	30.1	11.6	0.0	0.0	0.0
24-BWR	141.3	117.4	93.5	69.6	45.8	21.9	0.0	0.0	0.0	0.0	0.0
12-PWR Long	140.8	117.2	93.6	69.9	46.3	22.7	0.0	0.0	0.0	0.0	0.0
5 DHLW/DOE SNF - Short	131.4	117.9	104.4	90.9	77.4	63.9	50.4	36.9	23.4	9.9	0.0
2-MCO/2-DHLW	130.9	115.0	99.2	83.4	67.5	51.7	35.8	20.0	4.2	0.0	0.0
Naval SNF Long	130.4	115.7	101.1	86.4	71.7	57.0	42.4	27.7	13.0	0.0	0.0

Table 5. Outer Shell Maximum Tangential Stress at the Inner Surface

Waste Package Type	Maximum Tangential Stress at the Outer Surface, $\sigma_{is}$ (MPa)										
	Gap Size (mm)										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
21-PWR	144.6	125.3	106.0	86.6	67.3	48.0	28.7	9.4	0.0	0.0	0.0
44-BWR	144.5	125.6	106.6	87.7	68.7	49.8	30.8	11.9	0.0	0.0	0.0
24-BWR	146.1	121.4	96.7	72.0	47.3	22.7	0.0	0.0	0.0	0.0	0.0
12-PWR Long	145.6	121.1	96.7	72.3	47.8	23.4	0.0	0.0	0.0	0.0	0.0
5 DHLW/DOE SNF - Short	134.8	120.9	107.1	93.2	79.4	65.5	51.7	37.9	24.0	10.2	0.0
2-MCO/2-DHLW	134.8	118.5	102.2	85.9	69.5	53.2	36.9	20.6	4.3	0.0	0.0
Naval SNF Long	134.1	119.0	103.9	88.8	73.7	58.6	43.5	28.5	13.4	0.0	0.0

## 6.2 TANGENTIAL STRESS RELATION TO TEMPERATURE

The calculation results (Attachments II through VIII) are reported in the following sections for each WP. The waste package outer shell tangential stresses at the inner and outer surfaces due to thermal expansion are reported using plots, illustrating the tangential stress (MPa) with respect to temperature ( $^{\circ}\text{C}$ ). The plots depict the stress/temperature curves for a range of shell gap sizes.

6.2.1 21-PWR WP

Figure 2 illustrates the 21-PWR WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa (see Section 5.1.2), respectively, for informational purposes.

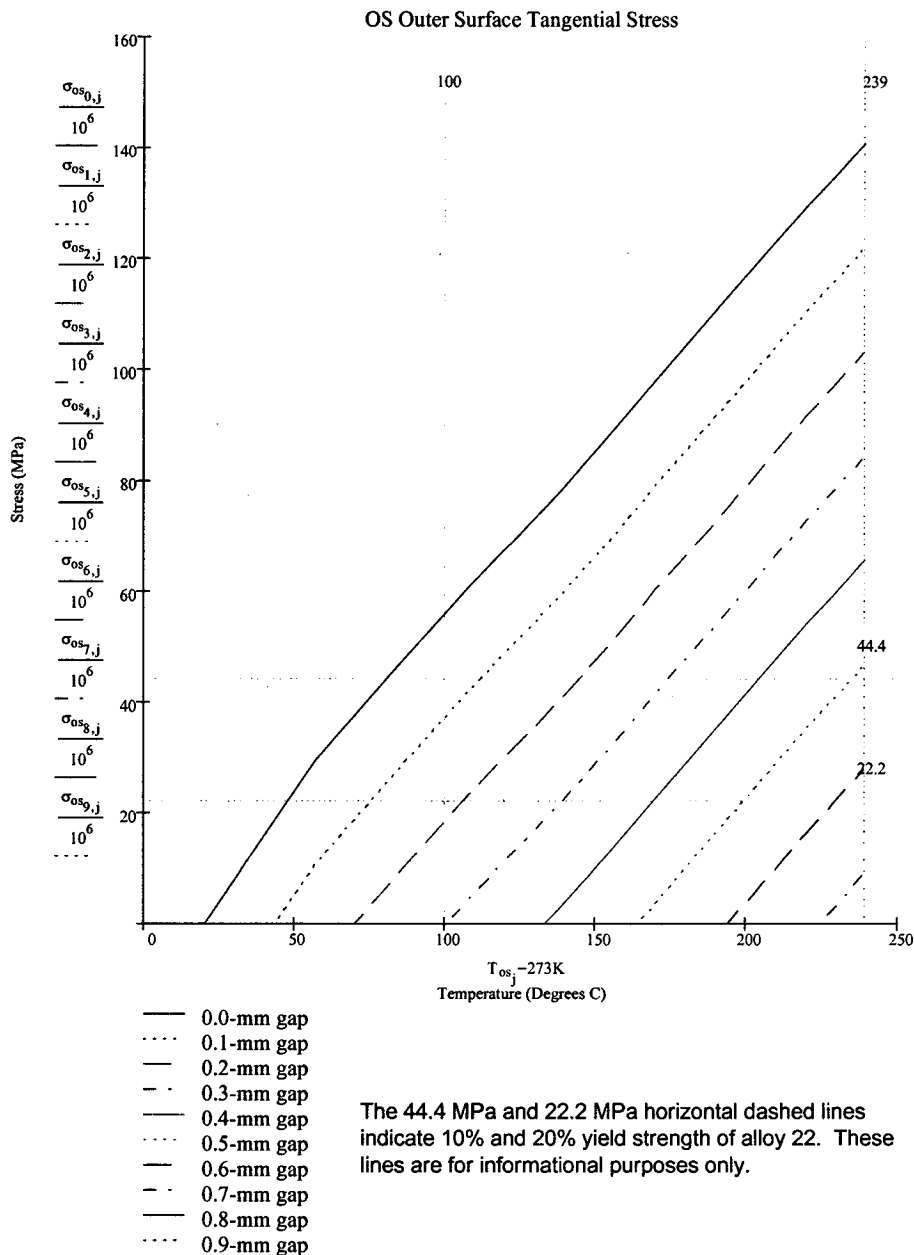


Figure 2. 21-PWR WP Outer Shell Outer Surface Tangential Stress

Figure 3 illustrates the 21-PWR WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

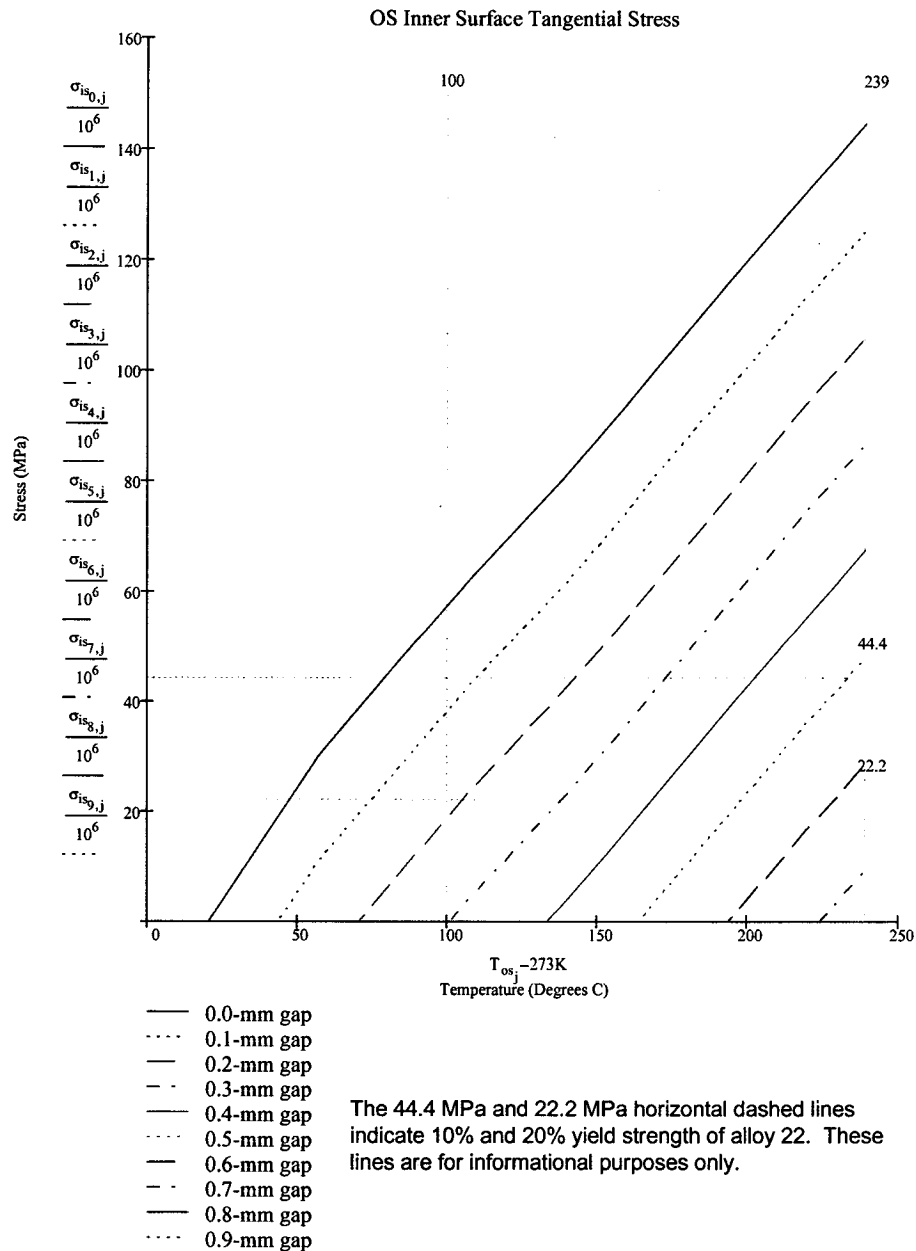


Figure 3. 21-PWR WP Outer Shell Inner Surface Tangential Stress



6.2.2 44-BWR WP

Figure 4 illustrates the 44-BWR WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

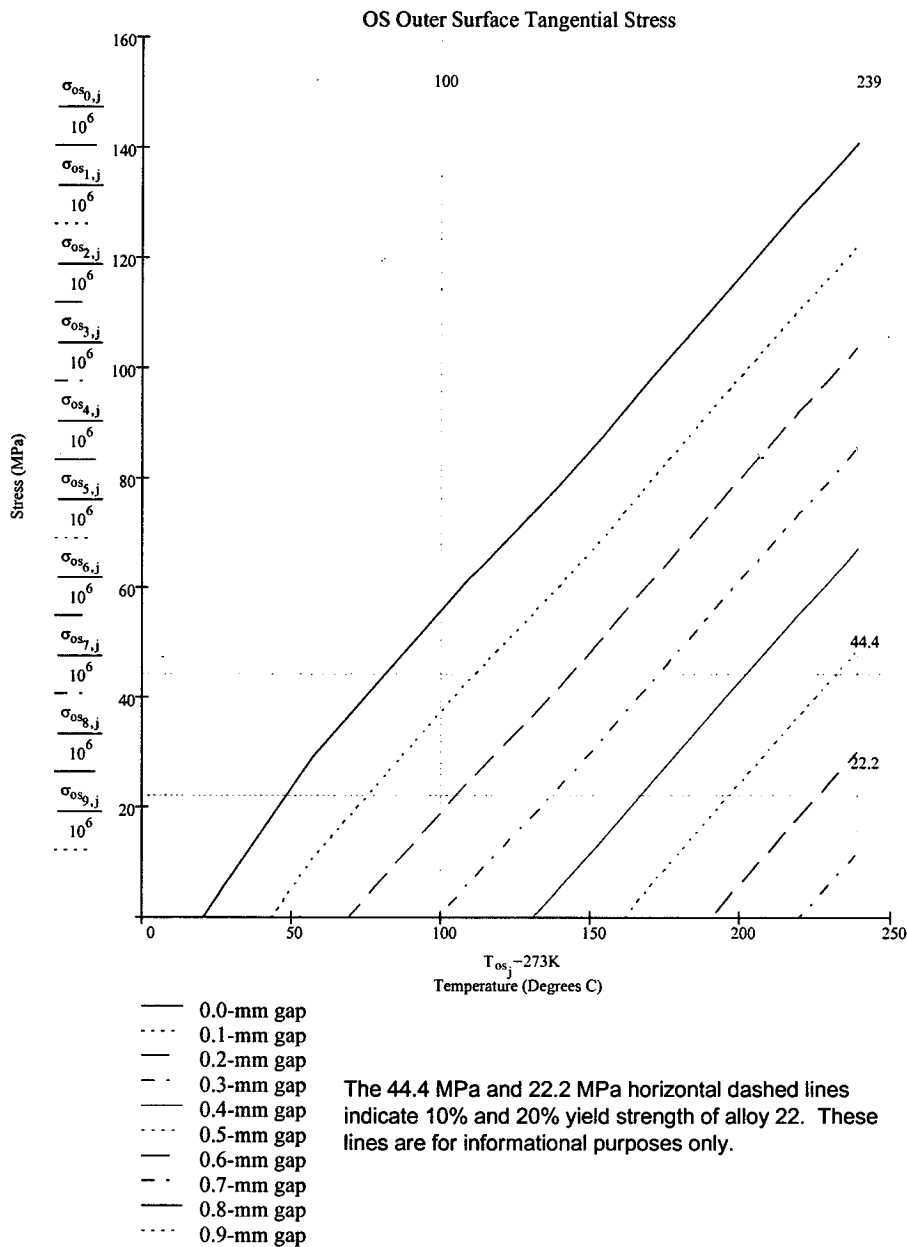


Figure 4. 44-BWR WP Outer Shell Outer Surface Tangential Stress

Figure 5 illustrates the 44-BWR WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

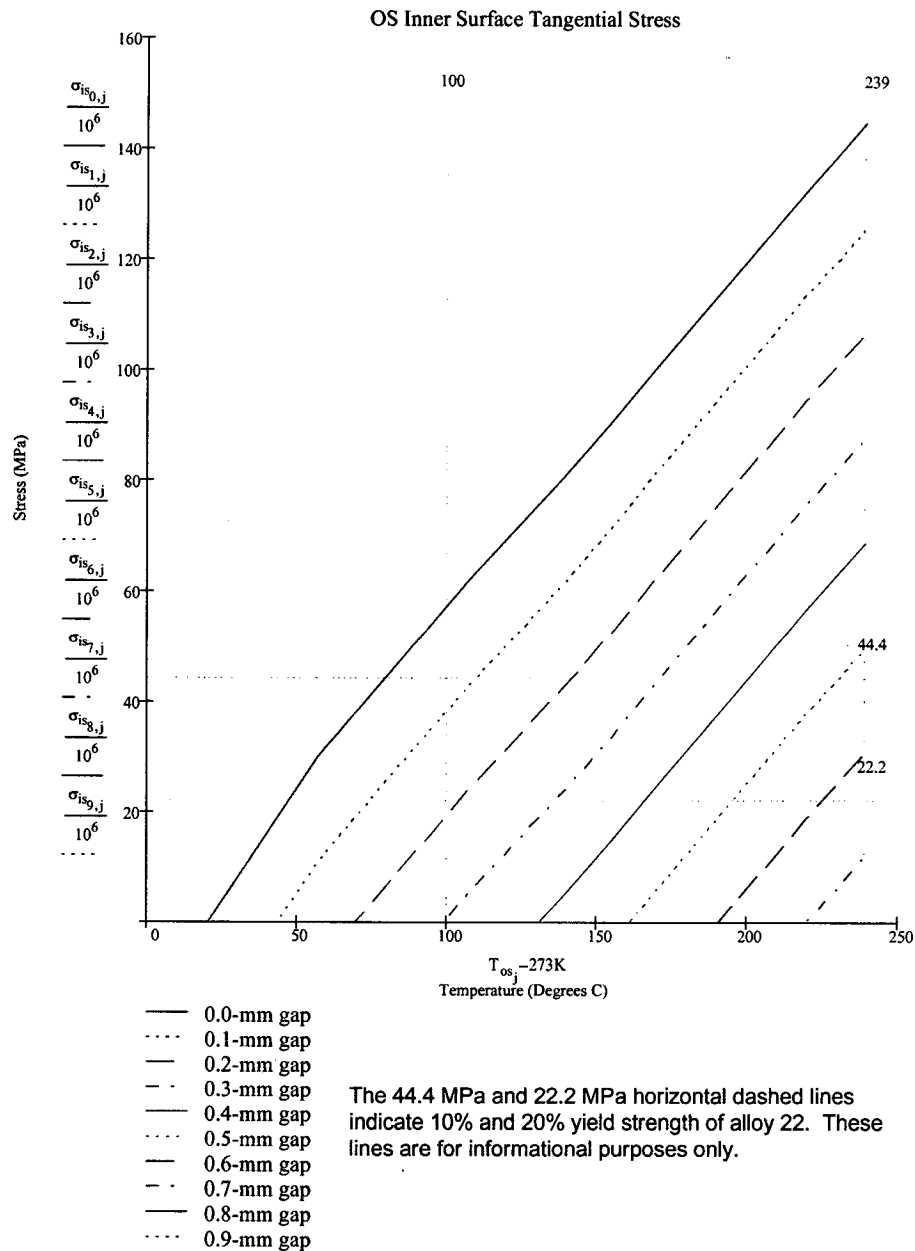


Figure 5. 44-BWR WP Outer Shell Inner Surface Tangential Stress

6.2.3 24-BWR WP

Figure 6 illustrates the 24-BWR WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

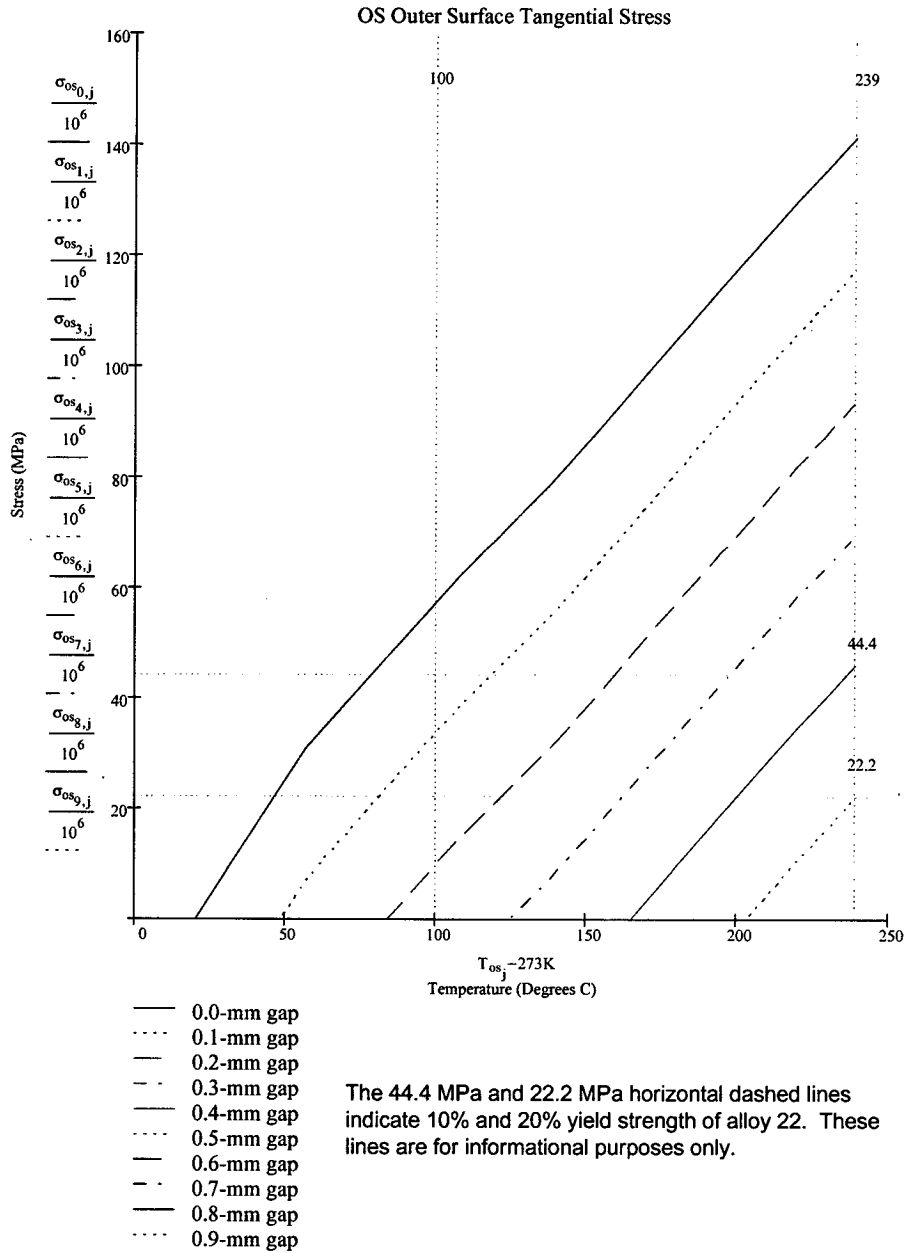


Figure 6. 24-BWR WP Outer Shell Outer Surface Tangential Stress

Figure 7 illustrates the 24-BWR WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

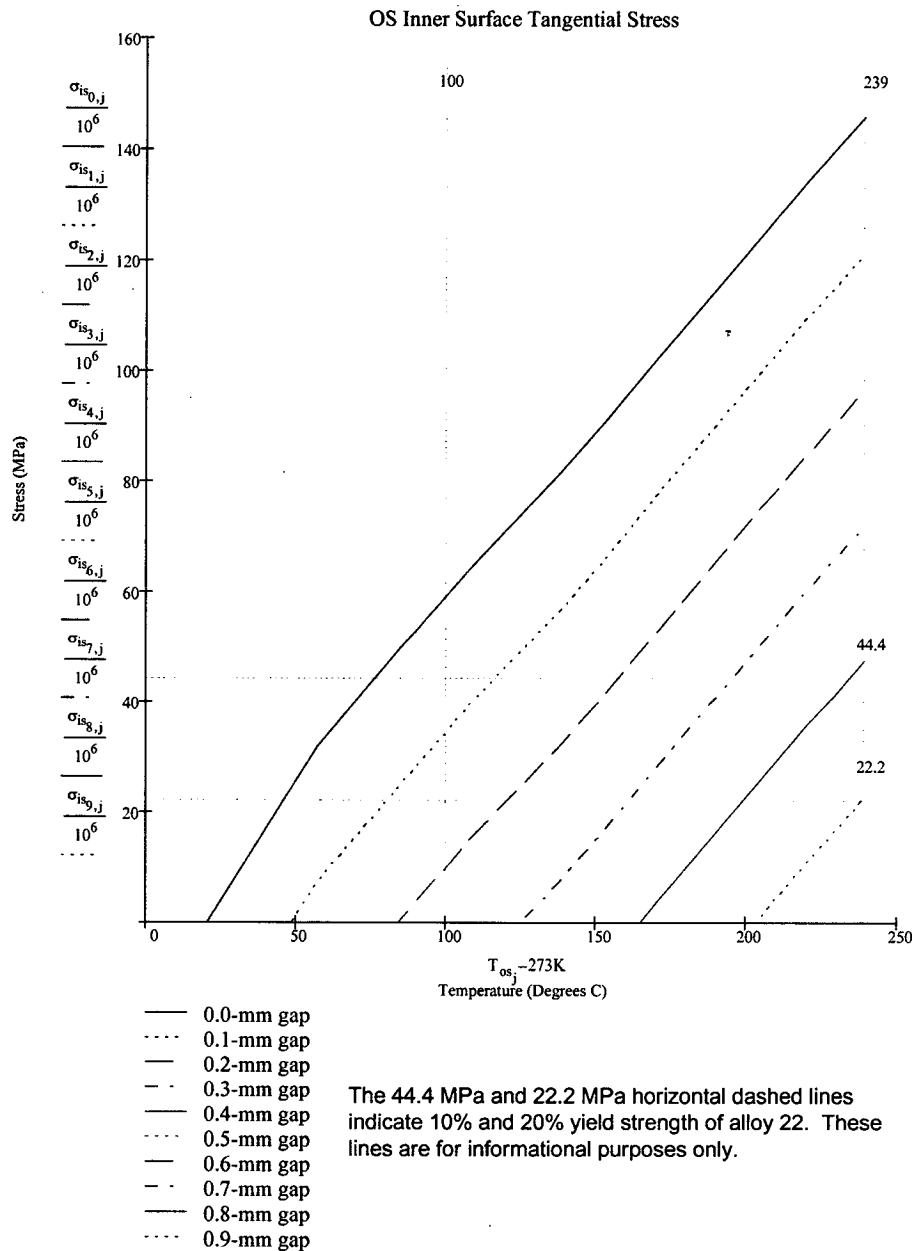


Figure 7. 24-BWR WP Outer Shell Inner Surface Tangential Stress

6.2.4 12-PWR LONG WP

Figure 8 illustrates the 12-PWR Long WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

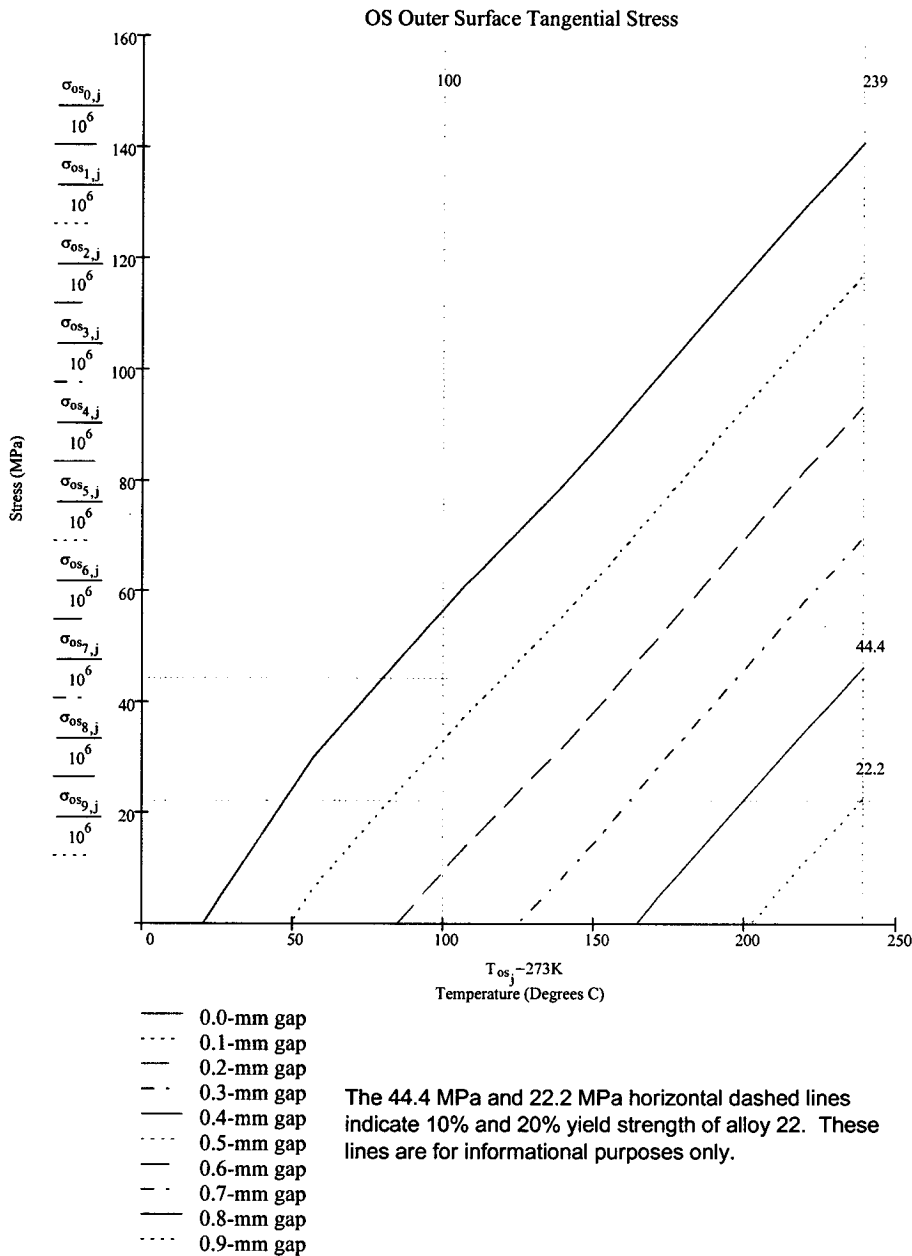


Figure 8. 12-PWR Long WP Outer Shell Outer Surface Tangential Stress

Figure 9 illustrates the 12-PWR Long WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

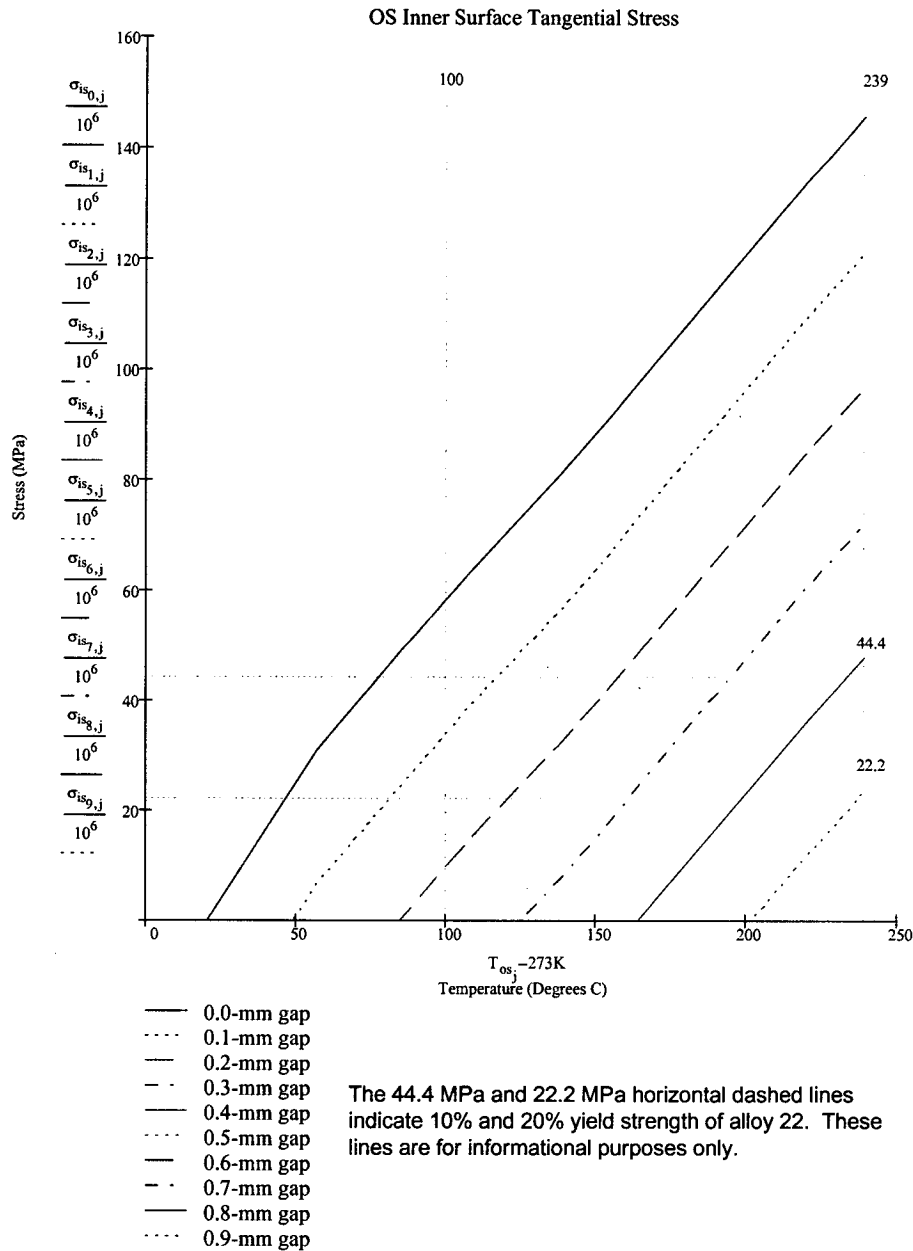


Figure 9. 12-PWR Long WP Outer Shell Inner Surface Tangential Stress

6.2.5 5 DHLW/DOE SNF - Short WP

Figure 10 illustrates the 5 DHLW/DOE SNF - Short WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

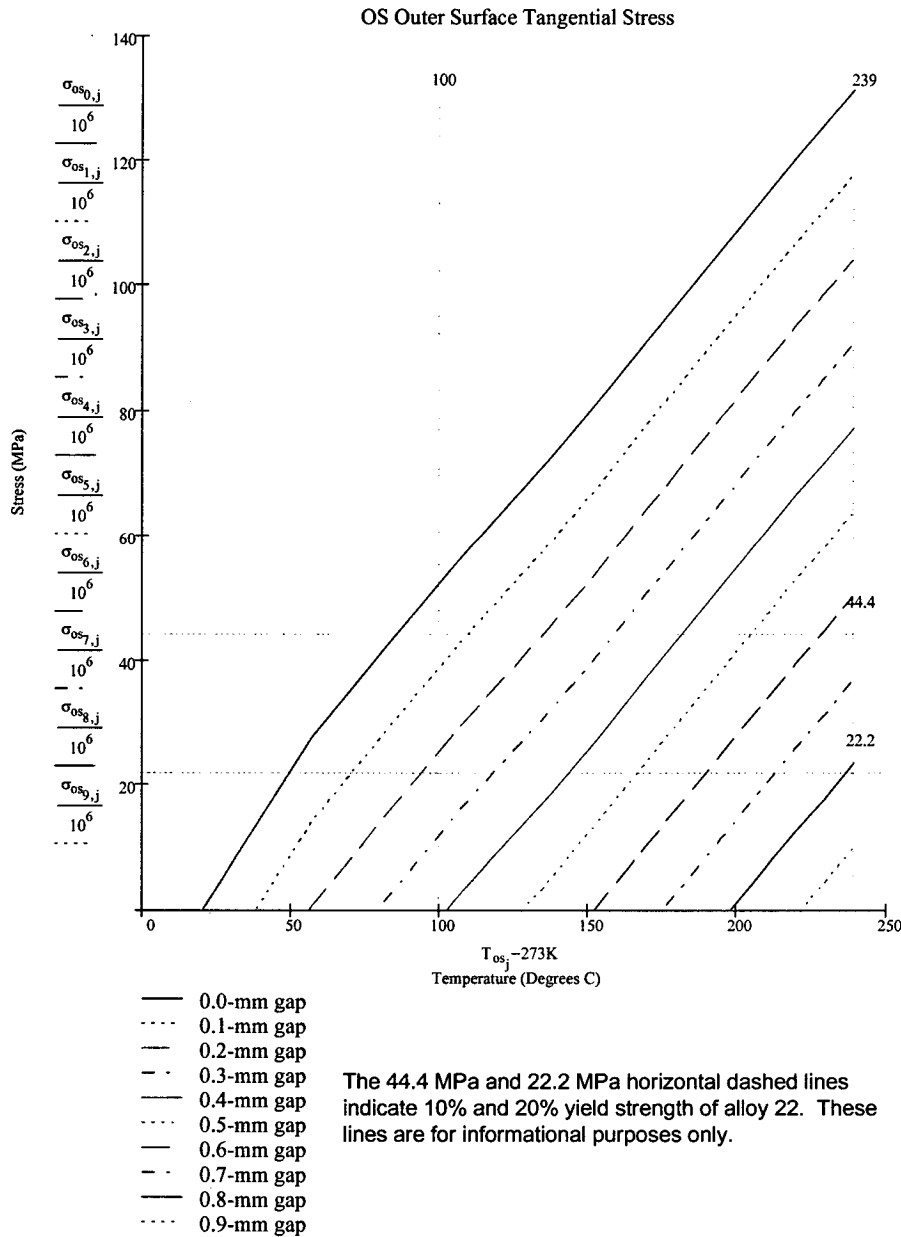


Figure 10. 5 DHLW/DOE SNF - Short WP Outer Shell Outer Surface Tangential Stress

Figure 11 illustrates the 5 DHLW/DOE SNF - Short WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

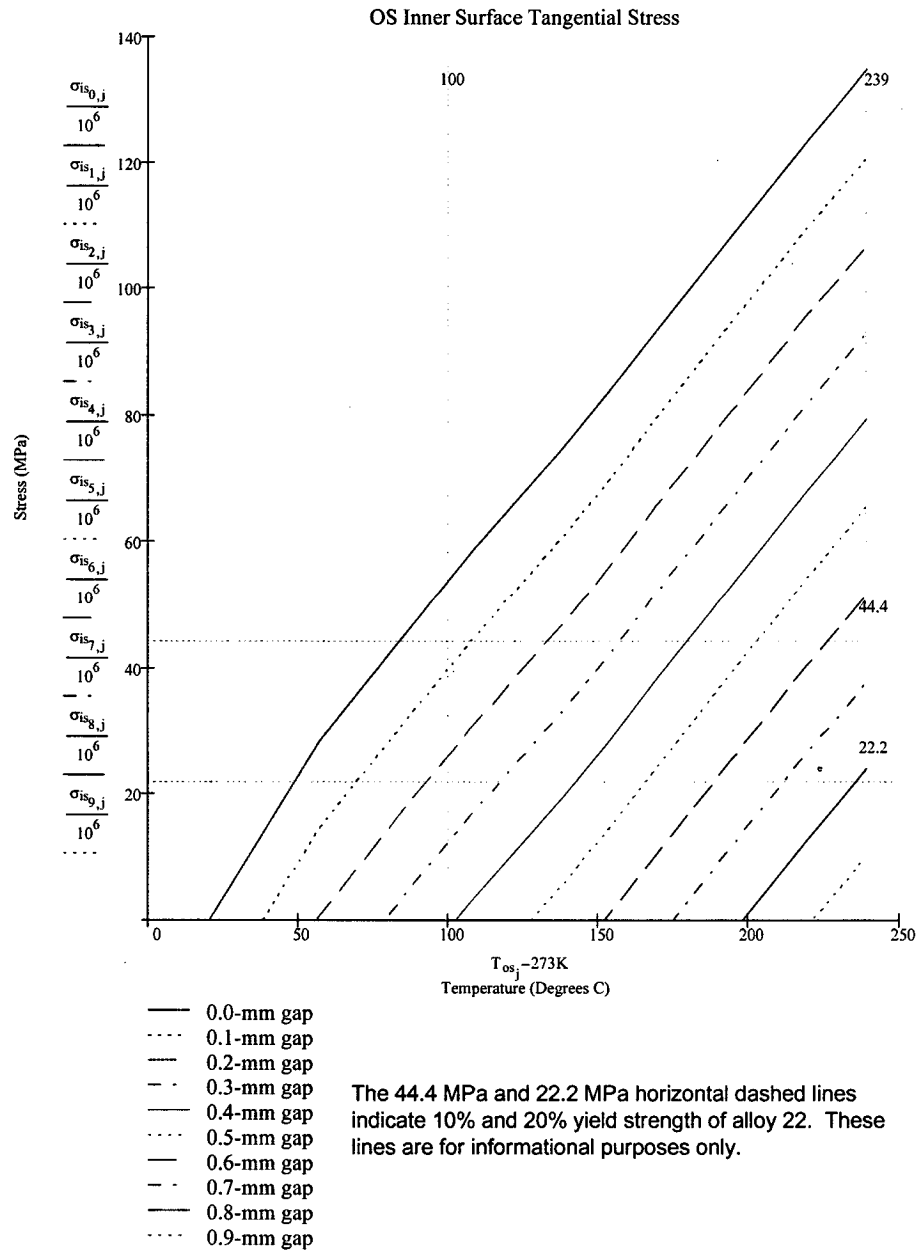


Figure 11. 5 DHLW/DOE SNF - Short WP Outer Shell Inner Surface Tangential Stress



6.2.6 2-MCO/2-DHLW WP

Figure 12 illustrates the 2-MCO/2-DHLW WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

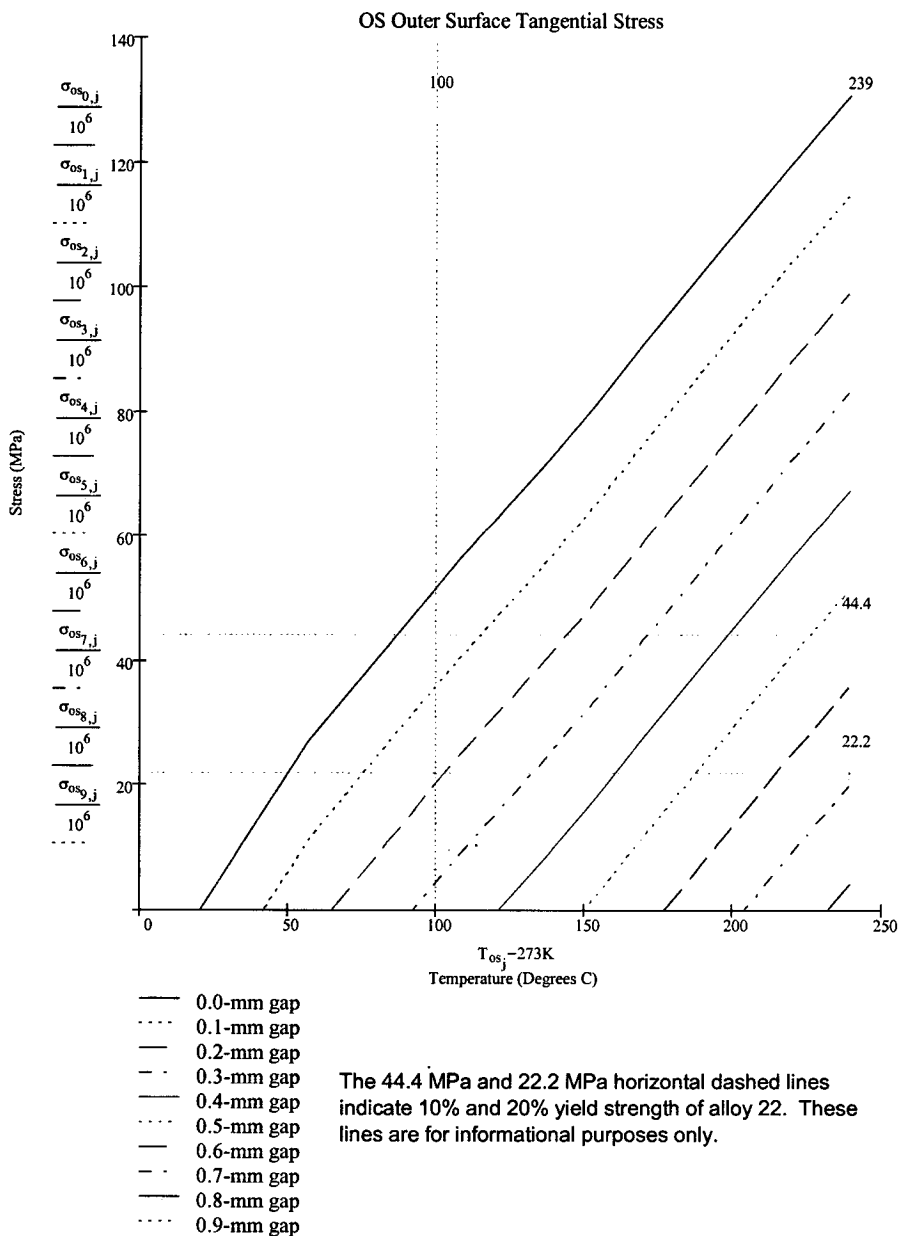


Figure 12. 2-MCO/2-DHLW WP Outer Shell Outer Surface Tangential Stress

Figure 13 illustrates the 2-MCO/2-DHLW WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

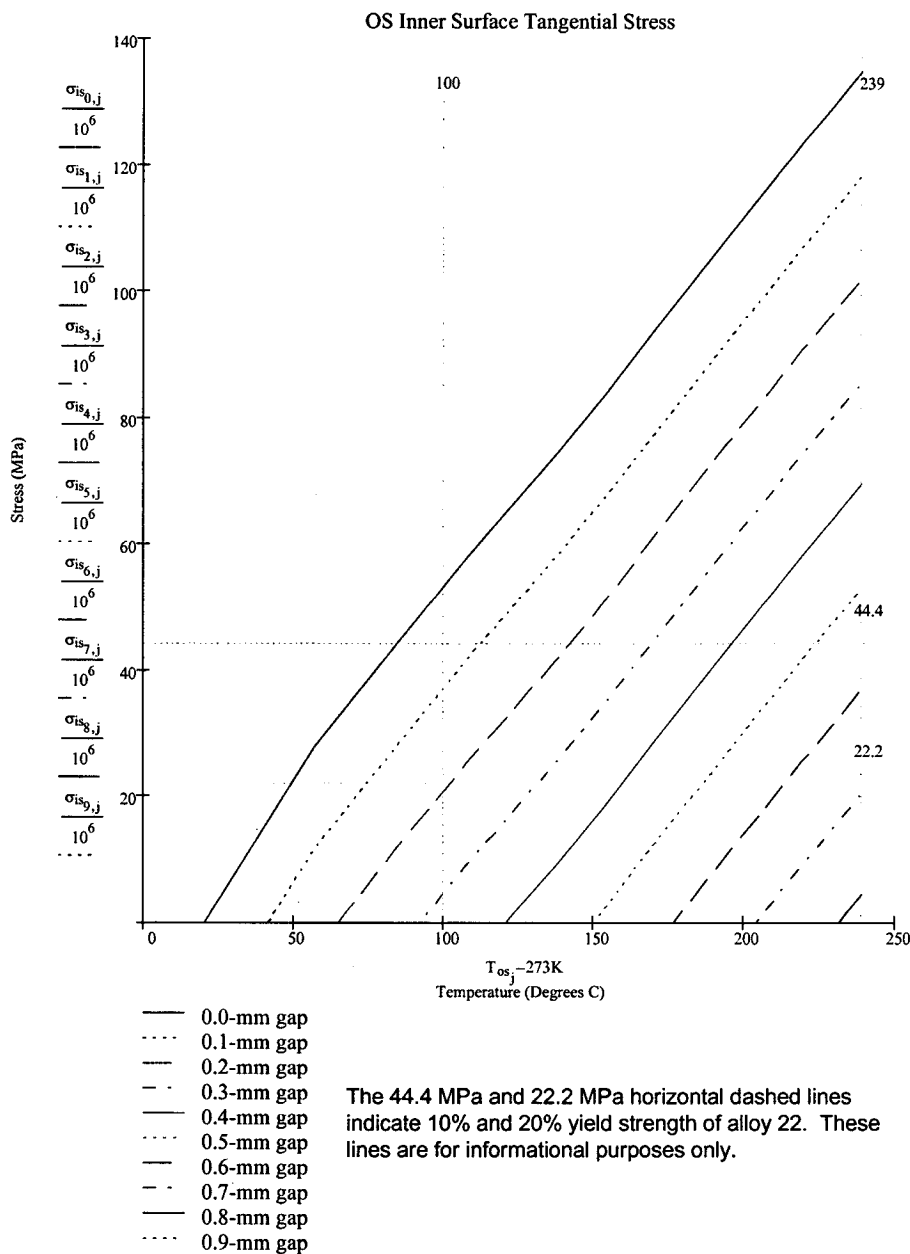


Figure 13. 2-MCO/2-DHLW WP Outer Shell Inner Surface Tangential Stress

6.2.7 NAVAL SNF-Long WP

Figure 14 illustrates the Naval SNF-Long WP outer shell outer surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

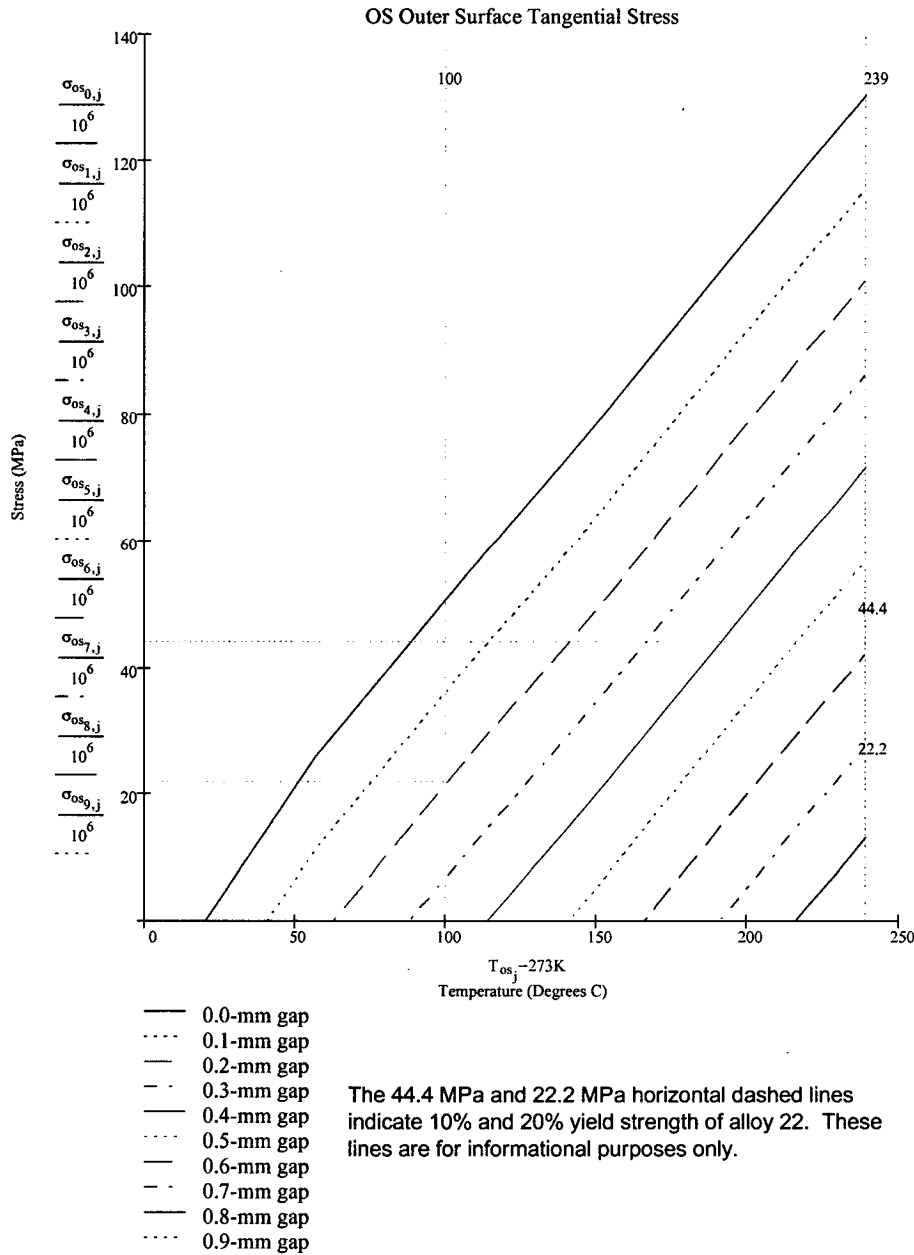


Figure 14. Naval SNF-Long WP Outer Shell Outer Surface Tangential Stress

Figure 15 illustrates the Naval SNF-Long WP outer shell inner surface tangential stress (MPa) with respect to temperature (°C) for a range of gap sizes. The Alloy 22 yield strength 10% and 20% levels are indicated on the plots at 22.2 and 44.4 MPa, respectively, for informational purposes.

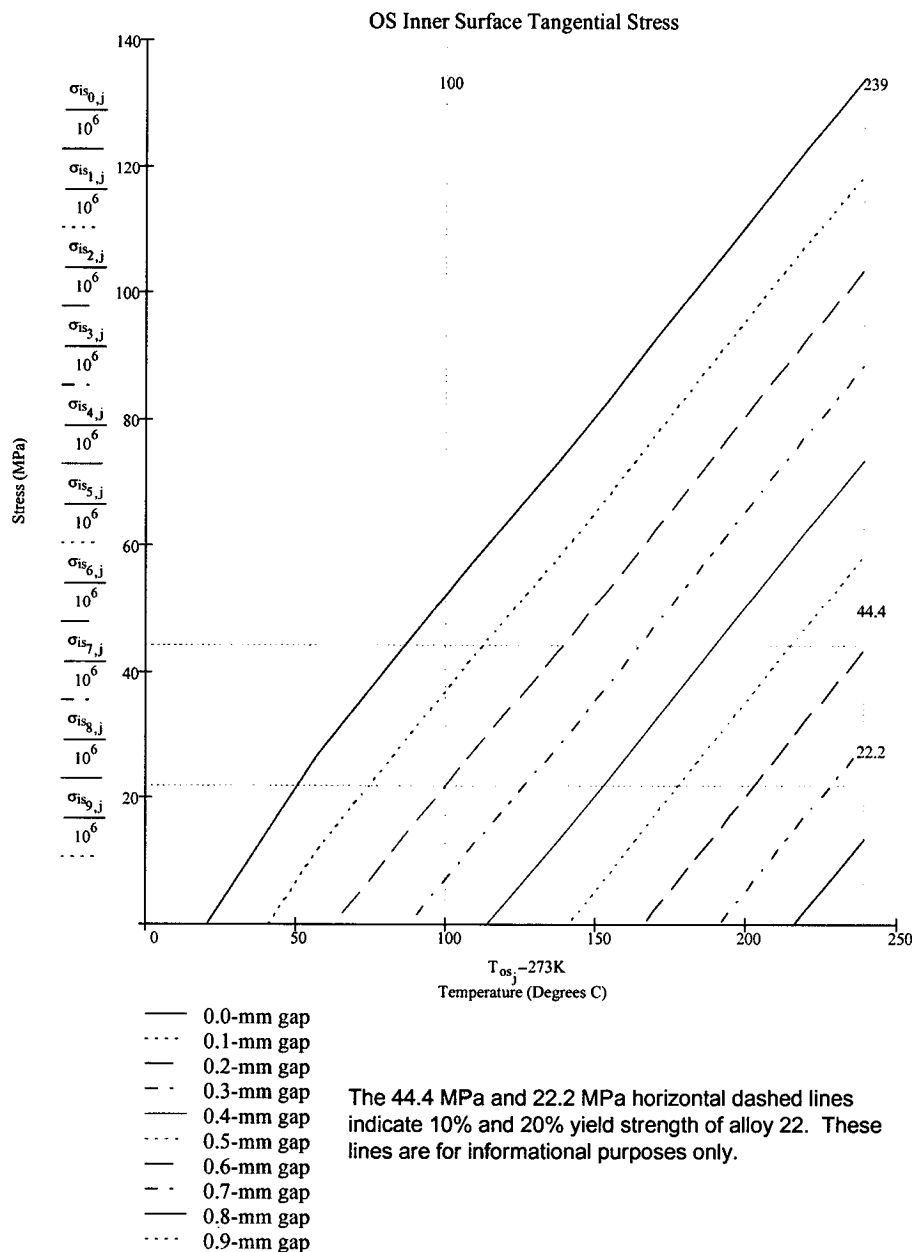


Figure 15. Naval SNF-Long WP Outer Shell Inner Surface Tangential Stress

## 7. REFERENCES

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## 8. ATTACHMENTS

Attachment I (22 pages): Design sketches. Table 4 lists the potential design sketches used in this calculation.

Table 4. Potential Design Sketches Used

Design Sketch Title	Sketch Number	Rev.	Pages
<i>21-PWR Waste Package Configurations for Site Recommendation</i>	SK-0175	02	I-1 to I-2
<i>21-PWR Waste Package Weld Configuration</i>	SK-0191	00	I-3
<i>44-BWR Waste Package Configuration for Site Recommendation</i>	SK-0192	00	I-4 to I-5
<i>44-BWR Waste Package Assembly Weld Configuration</i>	SK-0193	00	I-6
<i>24-BWR Waste Package Configuration for Site Recommendation</i>	SK-0184	00	I-7 to I-8
<i>24-BWR Waste Package Assembly Weld Configuration</i>	SK-0202	00	I-9
<i>12-PWR Long Waste Package Configuration for Site Recommendation</i>	SK-0183	01	I-10 to I-11
<i>12-PWR Long Waste Package Weld Configuration</i>	SK-0205	00	I-12
<i>5 DHLW/DOE SNF - Short WP Assembly Configuration for Site Recommendation</i>	SK-0196	03	I-13 to I-14
<i>5 DHLW/DOE SNF - Short Weld Configuration</i>	SK-0197	00	I-15
<i>2-MCO/2-DHLW Waste Package Configuration for Site Recommendation</i>	SK-0198	04	I-16 to I-18
<i>2-MCO/2-DHLW Waste Package Weld Configuration</i>	SK-0199	01	I-19
<i>Naval SNF Long Waste Package Configuration for Site Recommendation</i>	SK-0194	01	I-20 to I-21
<i>Naval SNF Long Waste Package Weld Configuration</i>	SK-0195	00	I-22

Attachment II (10 pages): Mathcad thermal expansion calculations for the 21-PWR WP

Attachment III (10 pages): Mathcad thermal expansion calculations for the 44-BWR WP

Attachment IV (10 pages): Mathcad thermal expansion calculations for the 24-BWR WP

Attachment V (10 pages): Mathcad thermal expansion calculations for the 12-PWR Long WP

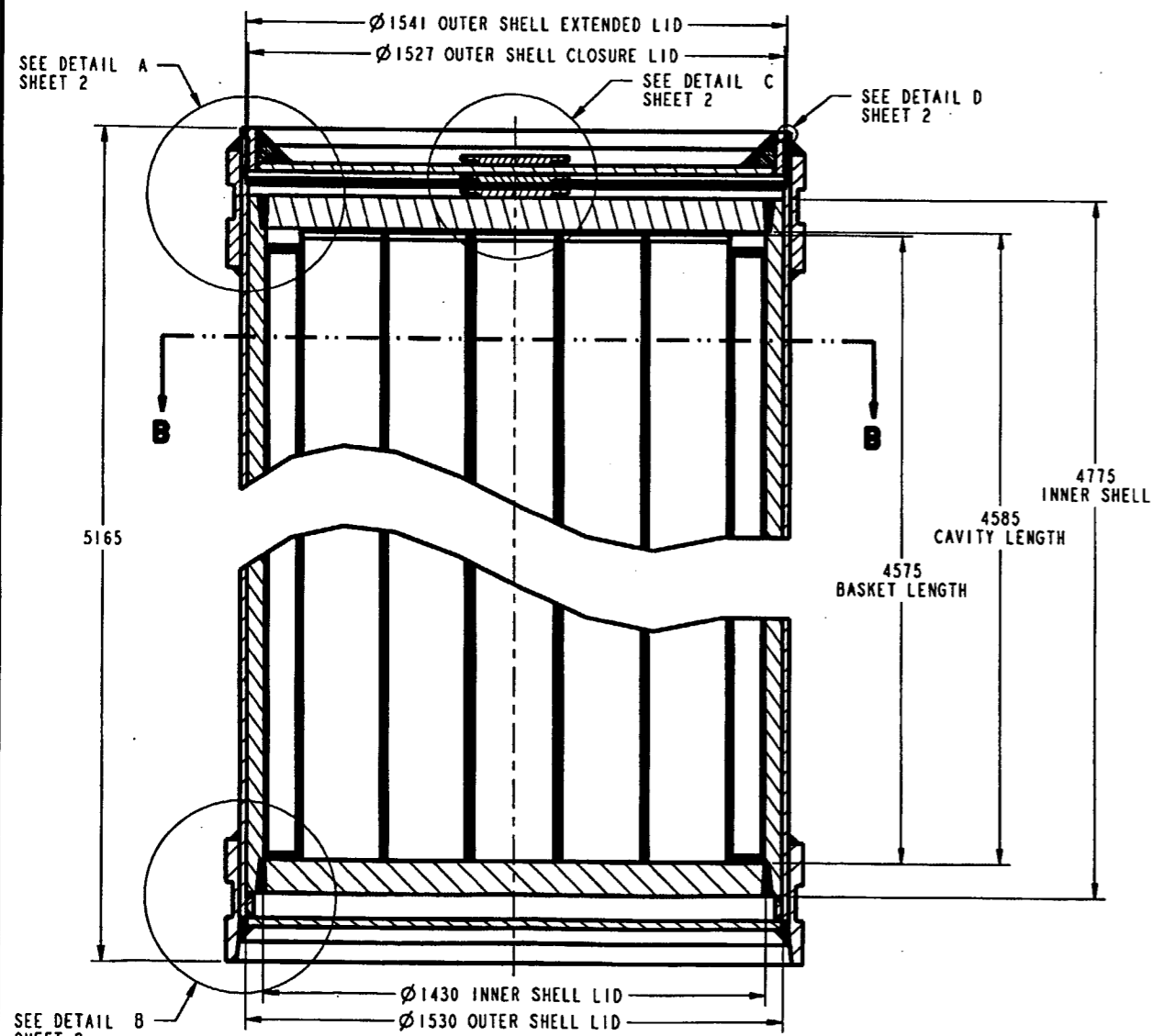
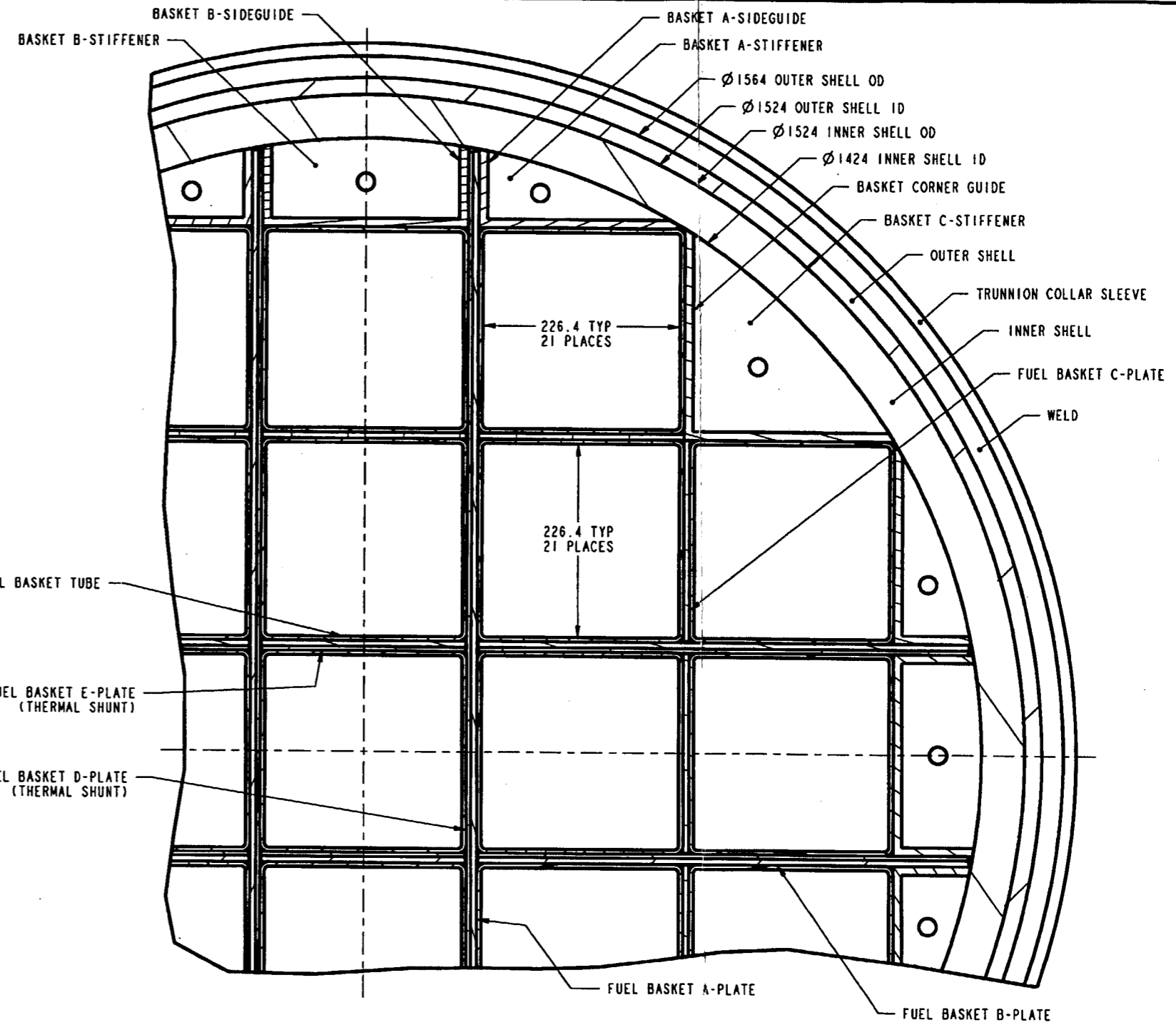
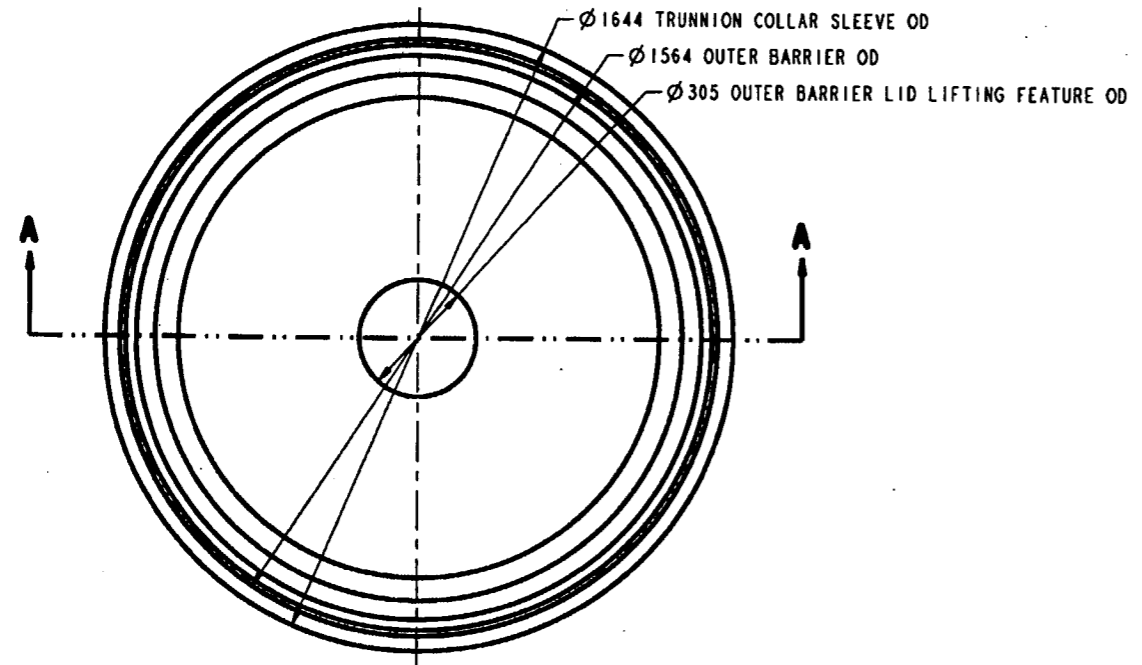
Attachment VI (10 pages): Mathcad thermal expansion calculations for the 5 DHLW/DOE SNF - Short WP

Attachment VII (10 pages): Mathcad thermal expansion calculations for the 2-MCO/2-DHLW WP

Attachment VIII (10 pages): Mathcad thermal expansion calculations for the Naval SNF Long WP

Attachment IX (5 pages): Mathcad verification for the equation of thermal expansion through a radius, using the theory of elasticity.





SECTION B-B

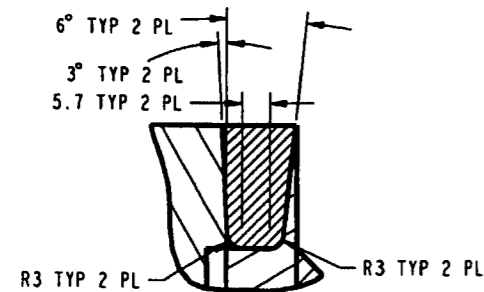
SECTION A-A

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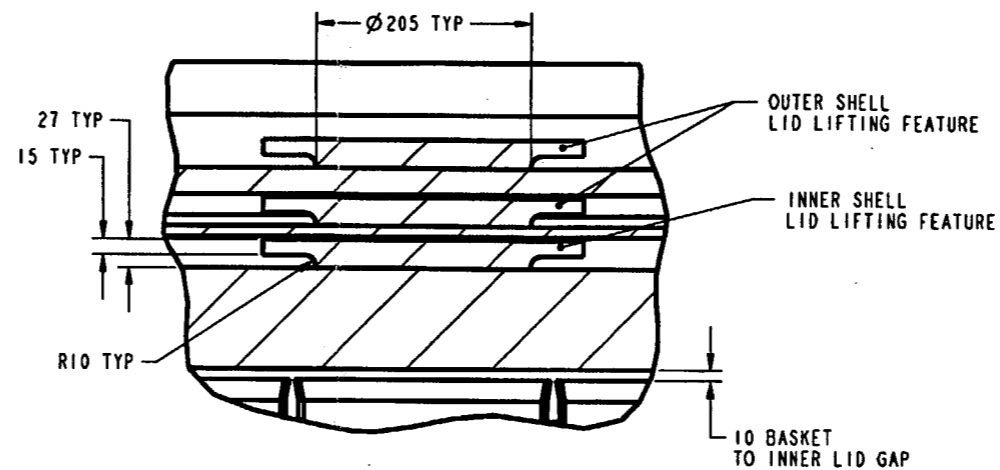
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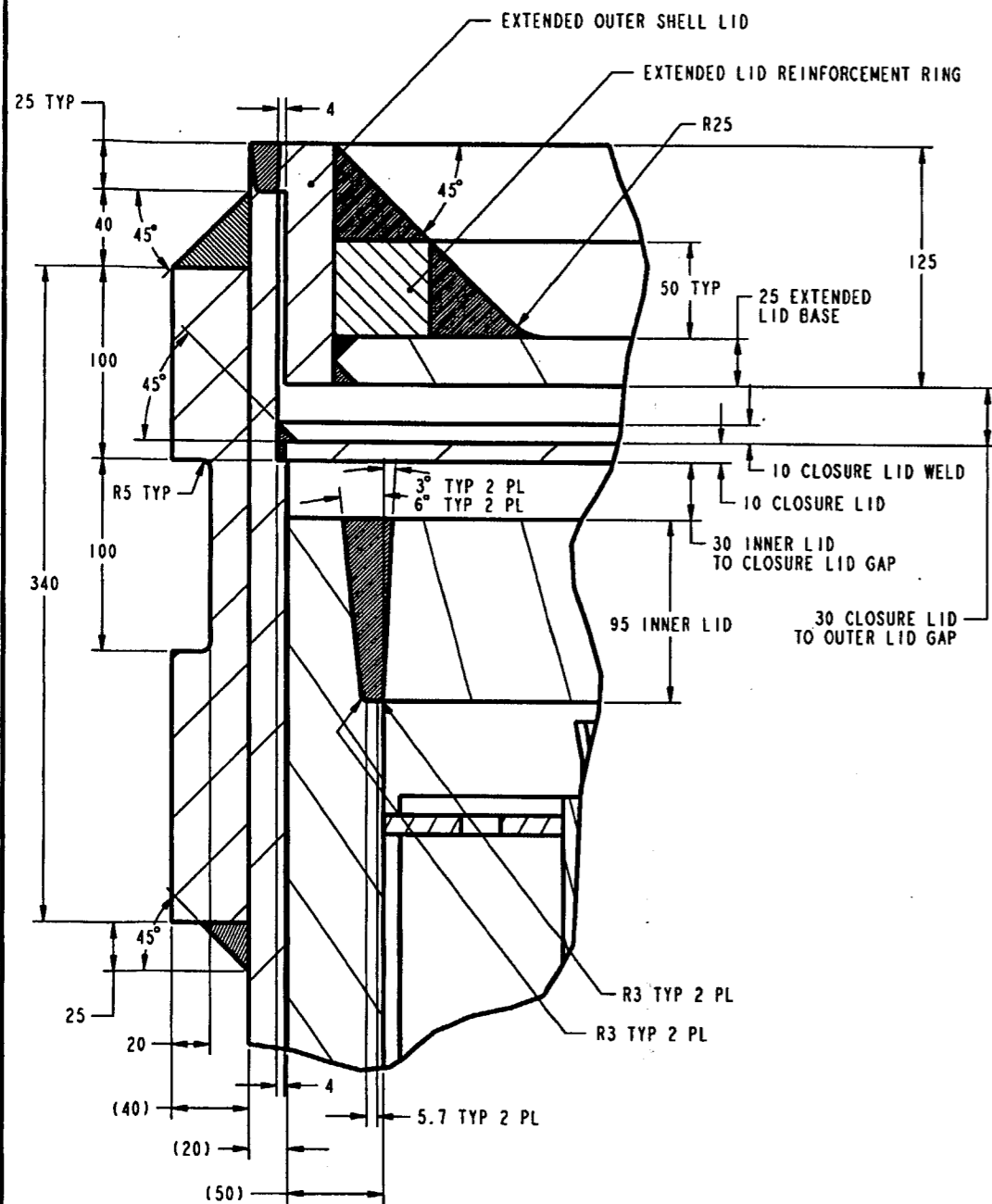
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DETAIL D



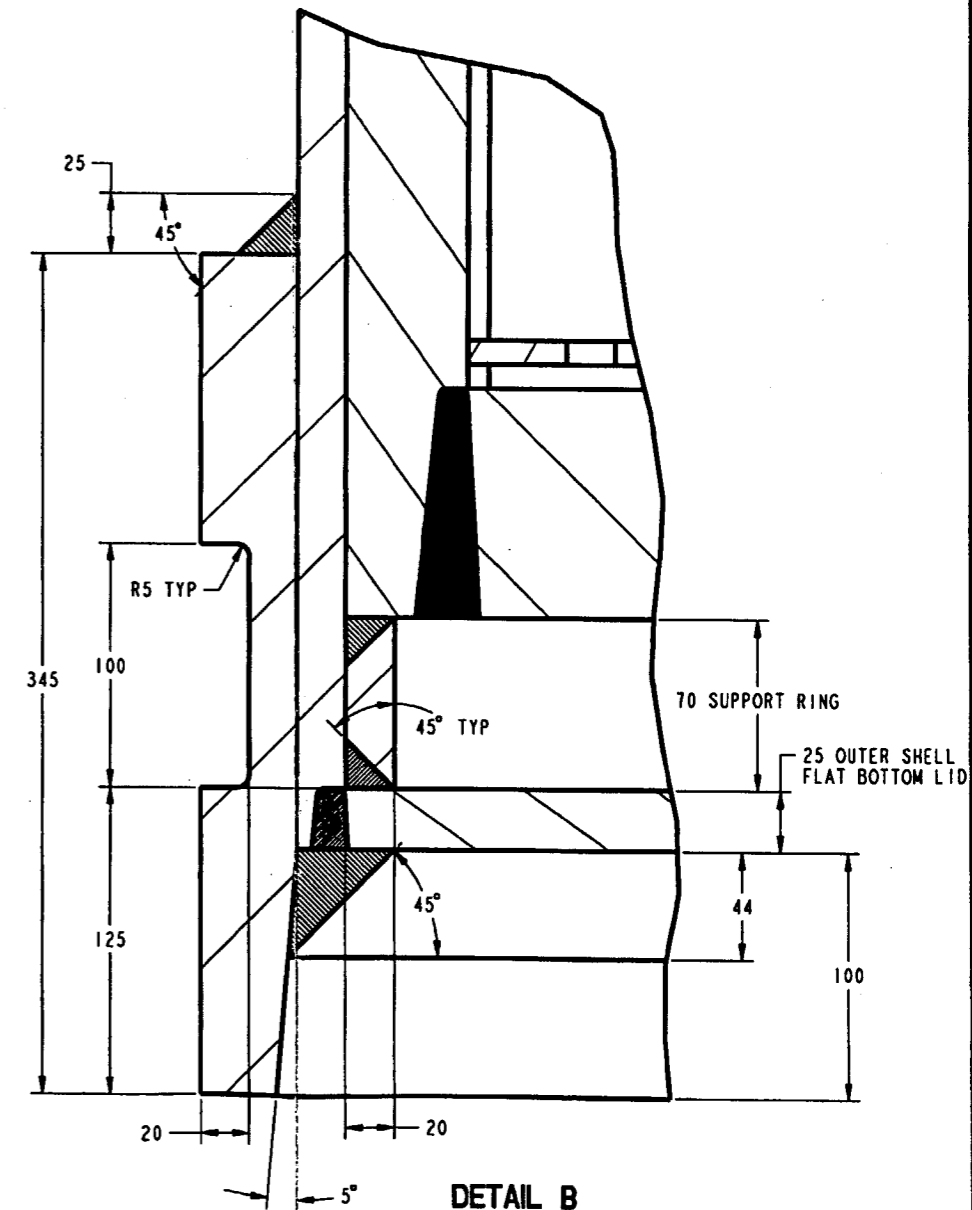
DETAIL C



DETAIL A

21-PWR WASTE PACKAGE ASSEMBLY WITH STAINLESS STEEL/BORON PLATES  
 ‡ 21-PWR CONTROL ROD WASTE PACKAGE ASSEMBLY WITH CARBON STEEL PLATES

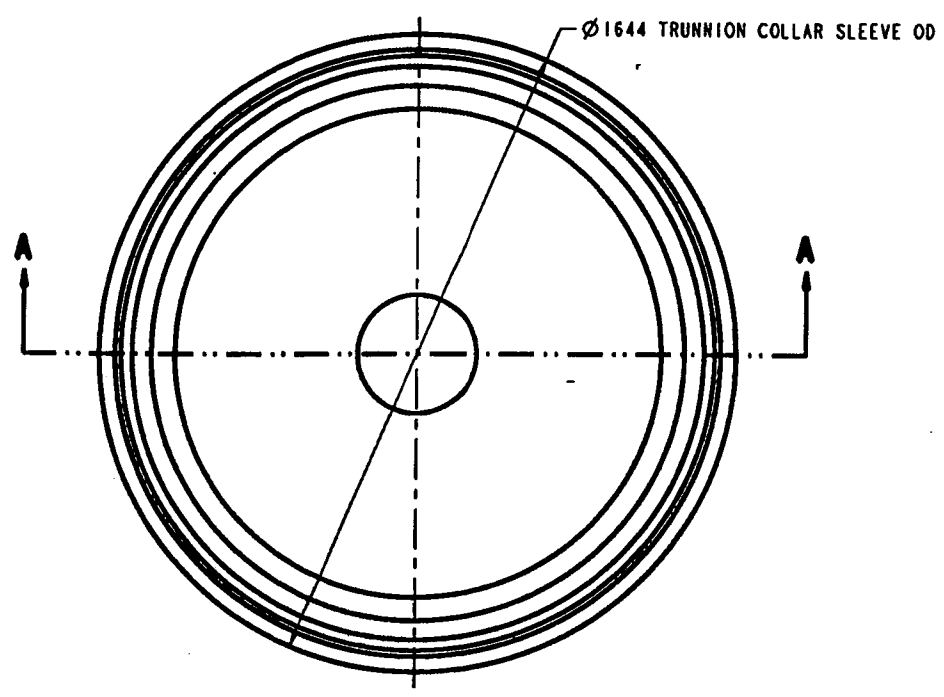
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BASKET A-SIDEGUIDE	SA-516 K02700	10	27	32
BASKET A-STIFFENER	SA-516 K02700	10	0.72	64
BASKET B-SIDEGUIDE	SA-516 K02700	10	36	16
BASKET B-STIFFENER	SA-516 K02700	10	1.5	32
BASKET C-STIFFENER	SA-516 K02700	10	2.3	32
BASKET CORNERGUIDE	SA-516 K02700	10	42	16
FUEL BASKET A-PLATE	NEUTRONIT A 978	7	85	8
	‡SA-516 K02700	#7	#86	#8
FUEL BASKET B-PLATE	NEUTRONIT A 978	7	85	8
	‡SA-516 K02700	#7	#86	#8
FUEL BASKET C-PLATE	NEUTRONIT A 978	7	44	16
	‡SA-516 K02700	#7	#45	#16
FUEL BASKET D-PLATE	SB-209 A96061 T4	5	21	8
FUEL BASKET E-PLATE	SB-209 A96061 T4	5	21	8
FUEL BASKET TUBE	SA-516 K02700	5	164	21
INNER SHELL	SA-240 S31600	50	8709	1
INNER SHELL LID	SA-240 S31600	95	1200	2
INNER LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	20	4193	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	132	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	366	1
OUTER LID LIFTING FEATURE	SB-575 N06022	27	13	2
EXTENDED LID REINFORCEMENT RING	SB-575 N06022	50	97	1
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	159	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N0-6022	25	396	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	507	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	497	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	41	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	249	**
TOTAL 316 WELDS	SFA-5.9 S31680	-	128	**
WASTE PACKAGE ASSEMBLY	-	-	26035	1
	-	-	#26059	#1
PWR FUEL ASSEMBLY	-	-	773.4*	21
WP ASSEMBLY WITH SNF	-	-	42277	1
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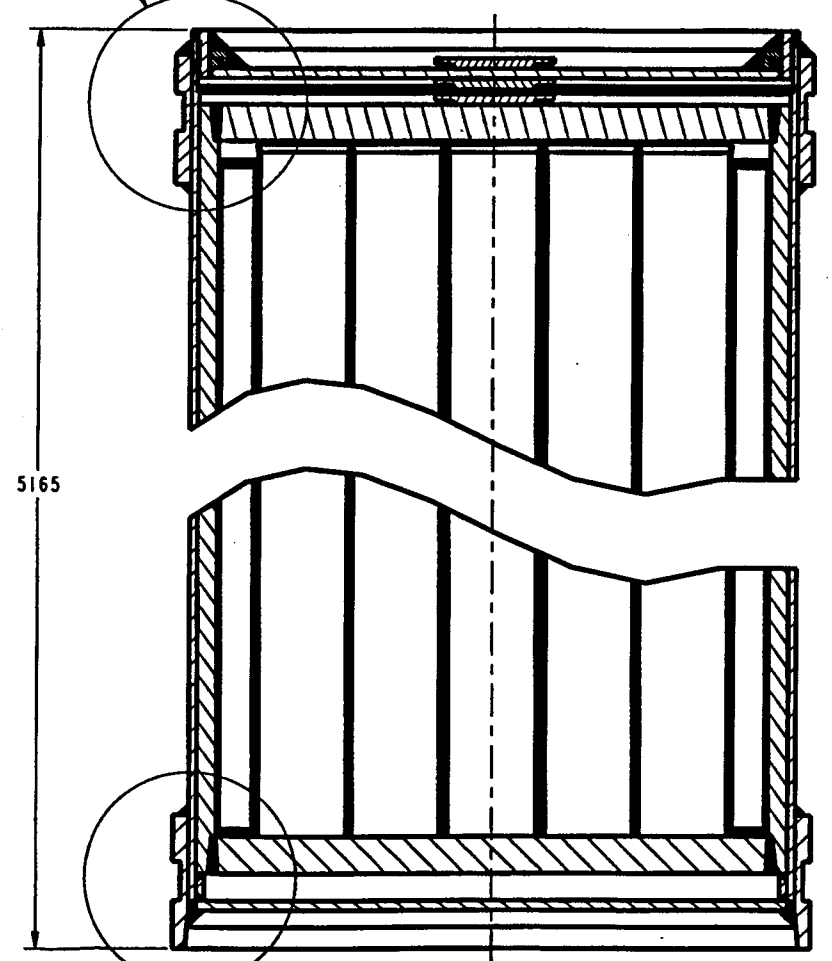
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\* CRWMS M&O 1997. WASTE CONTAINER CAVITY SIZE DETERMINATION. BBAA00000-01717-0200-00026 REV 00. LAS VEGAS, NV: CRWMS M&O. ACC: MOL.19980106.0061

\*\* REFER TO SK-0191 REV 00 "21-PWR WASTE PACKAGE WELD CONFIGURATION"

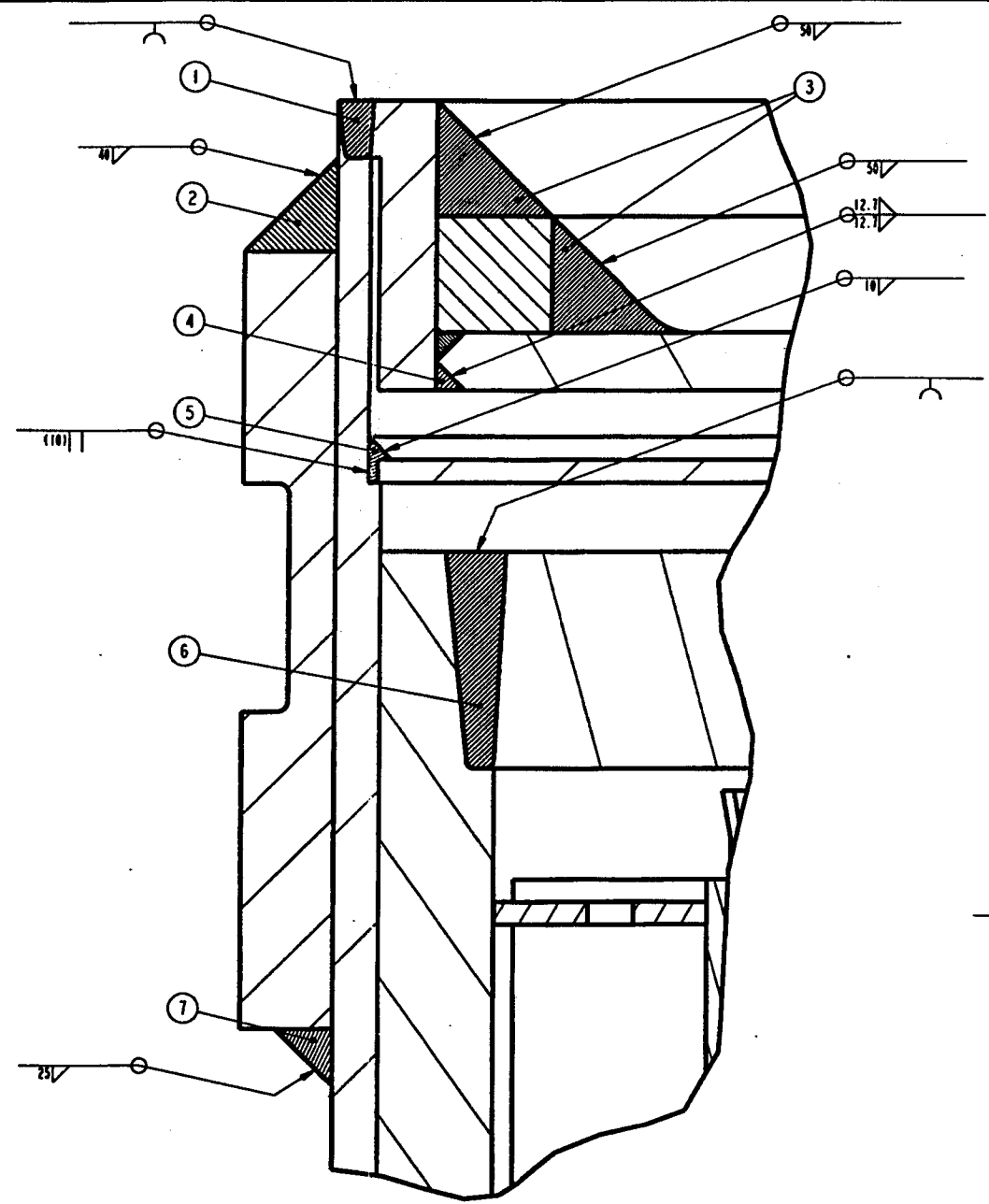


SEE DETAIL A

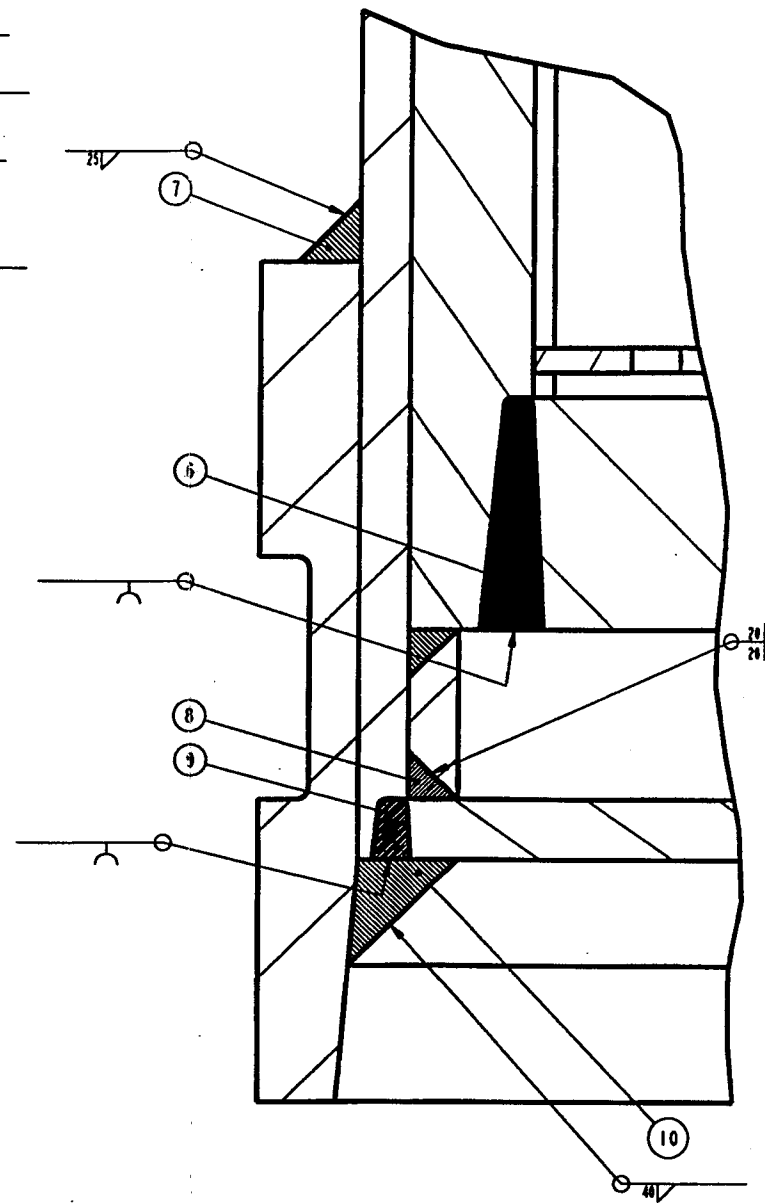


SEE DETAIL B

SECTION A-A



DETAIL A



DETAIL B

WELD	MATERIAL	MASS (KG)	QTY ROD	
1	SFA-5.14 N06022	14	1	
2	SFA-5.14 N06022	35	1	
3	SFA-5.14 N06022	96	1	
4	SFA-5.14 N06022	3.1	2	
5	SFA-5.14 N06022	3.8	1	
6	SFA-5.9 S31680	64	2	
7	SFA-5.14 N06022	13	2	
8	SFA-5.14 N06022	8.2	2	
9	SFA-5.14 N06022	14	1	
10	SFA-5.14 N06022	37	1	
TOTAL ALLOY 22 WELDS		SFA-5.14 N06022	249	-
TOTAL 316 WELDS		SFA-5.9 S31680	128	-

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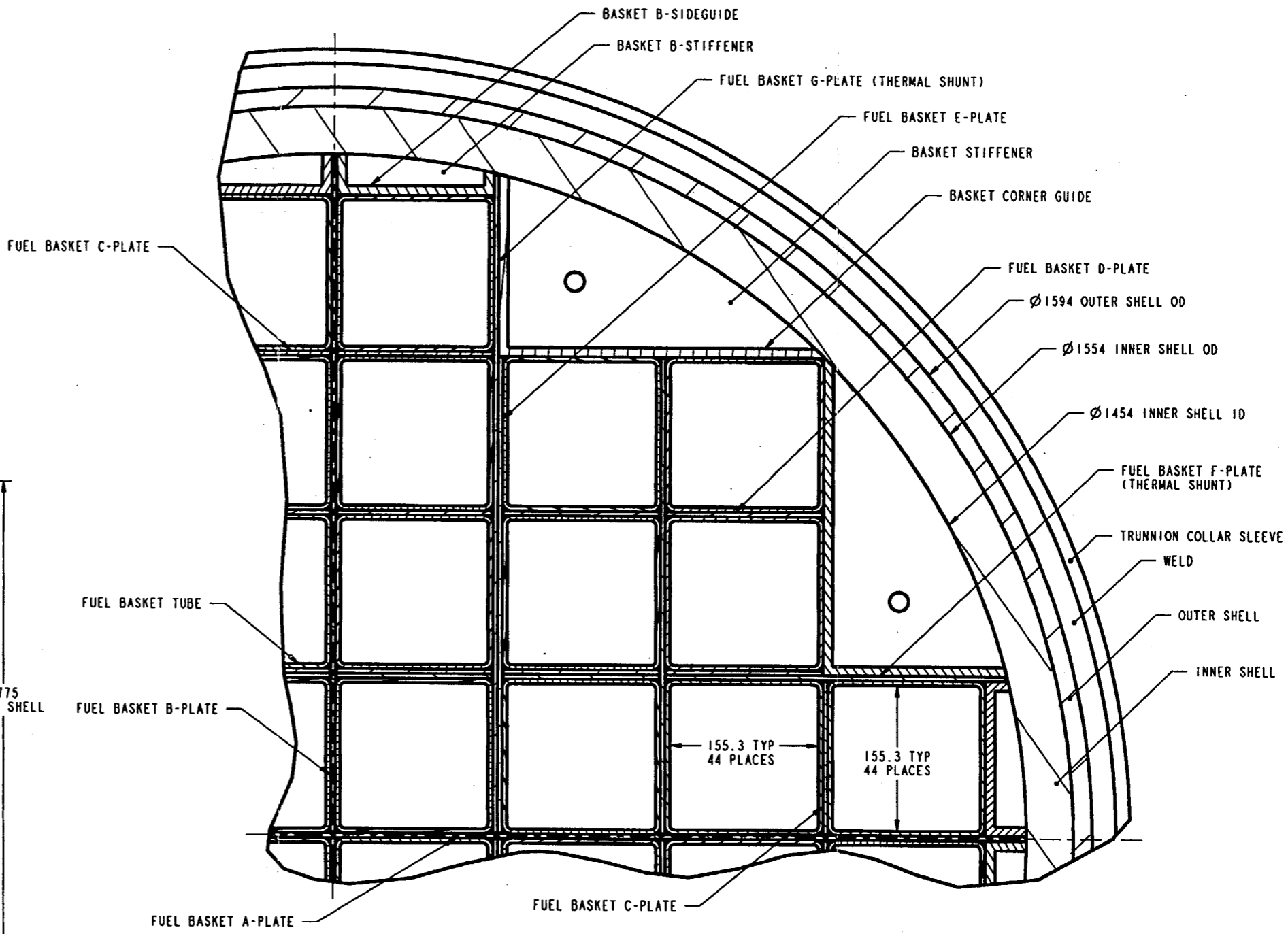
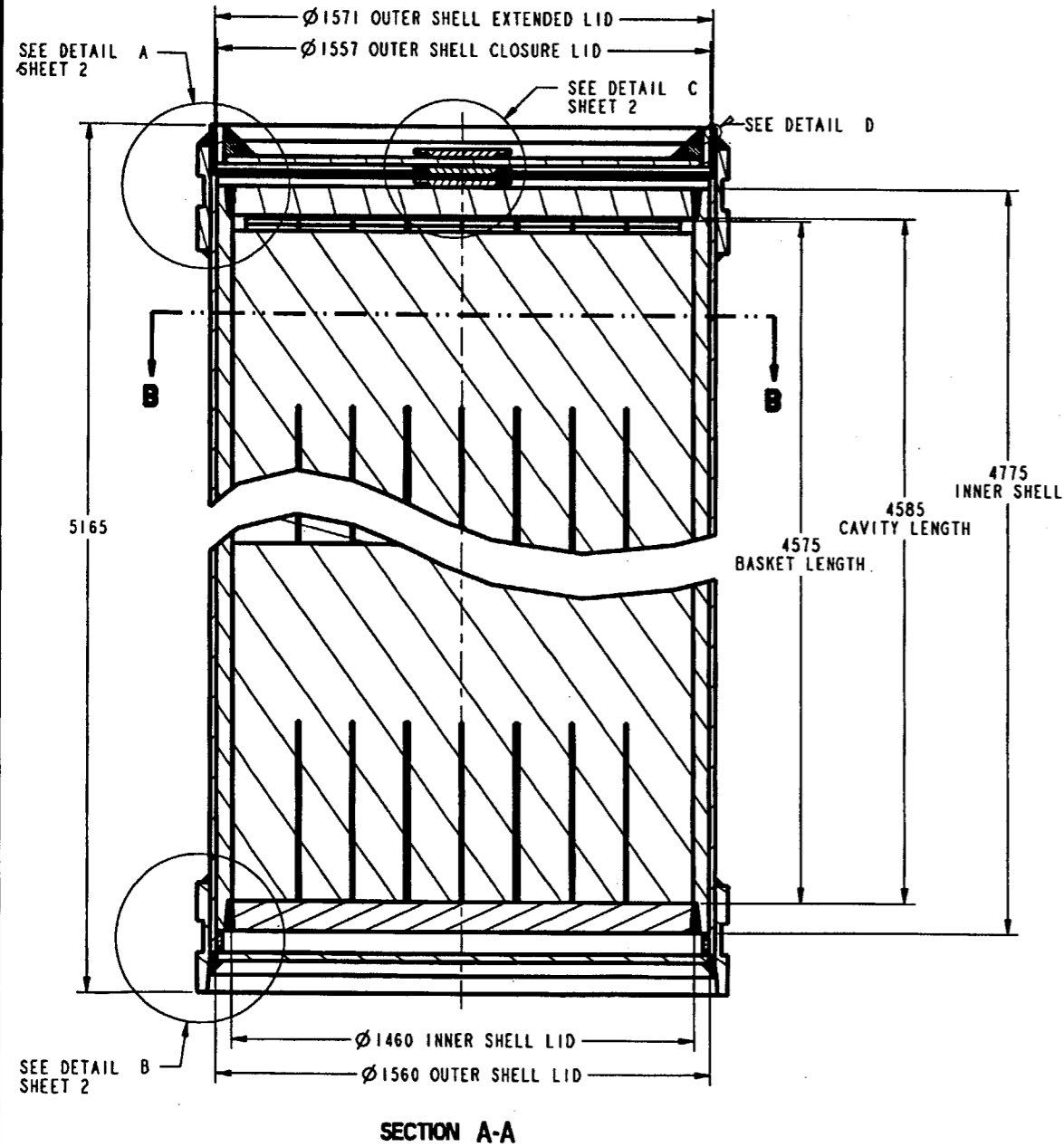
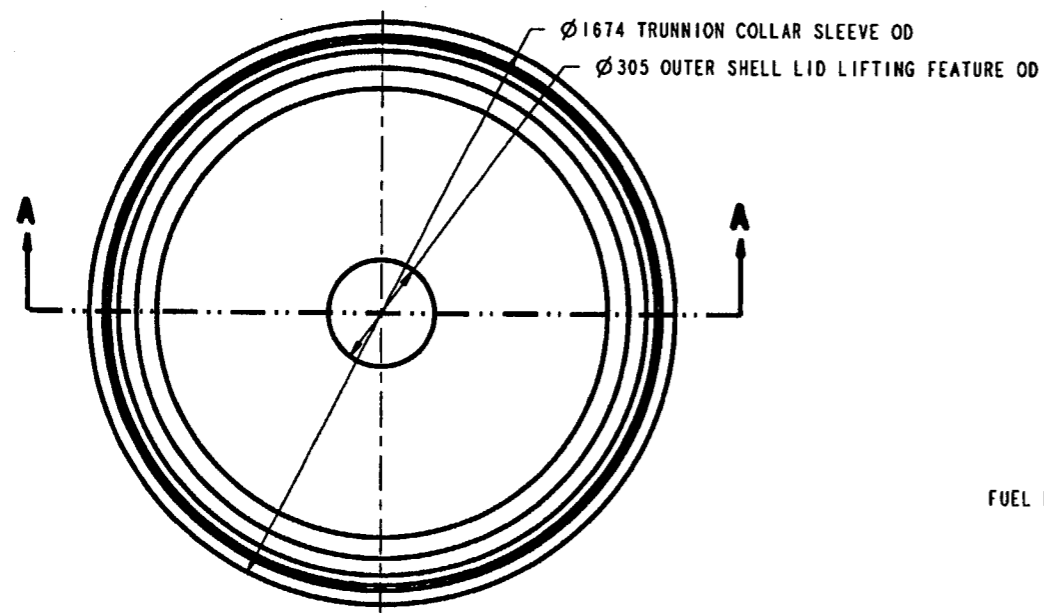
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 SMB 03/15/00  
 JOC 3/13/00  
 TJA 00



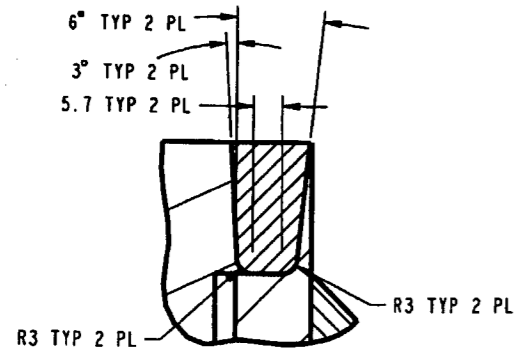
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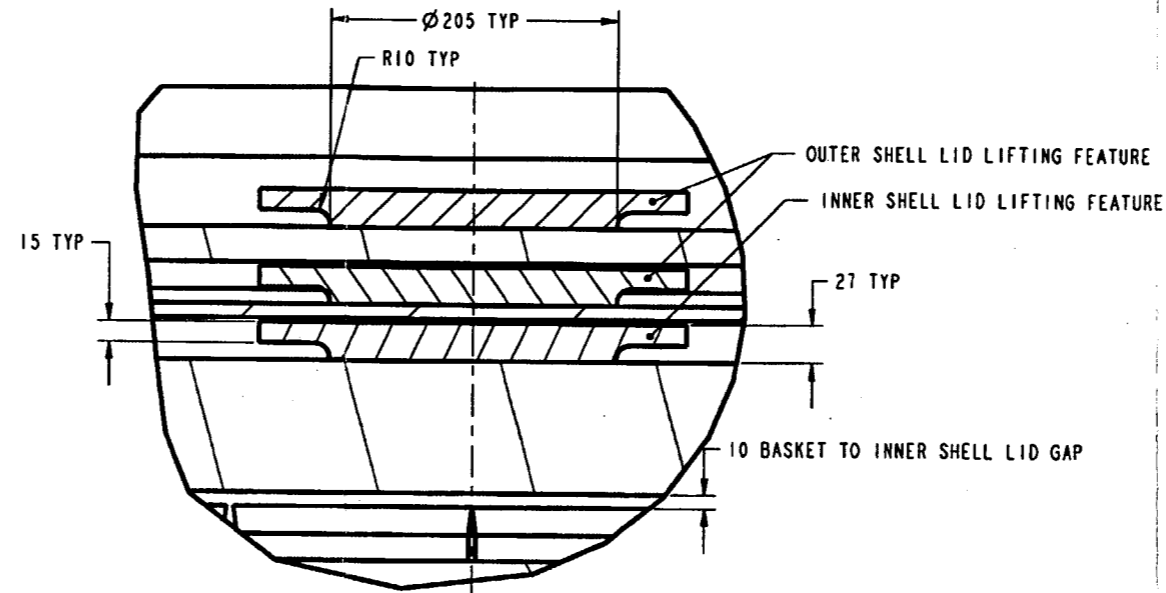
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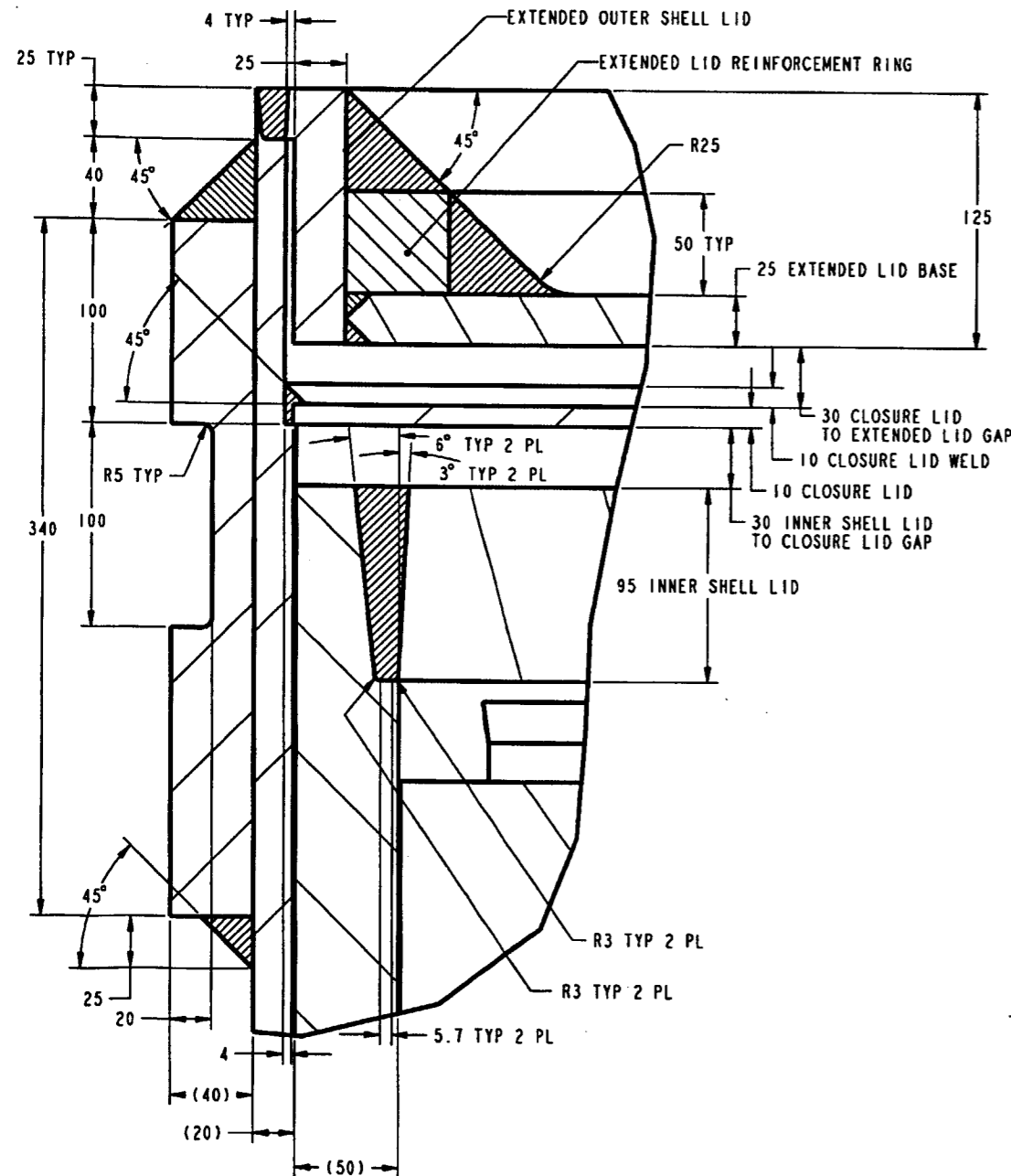
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DETAIL C

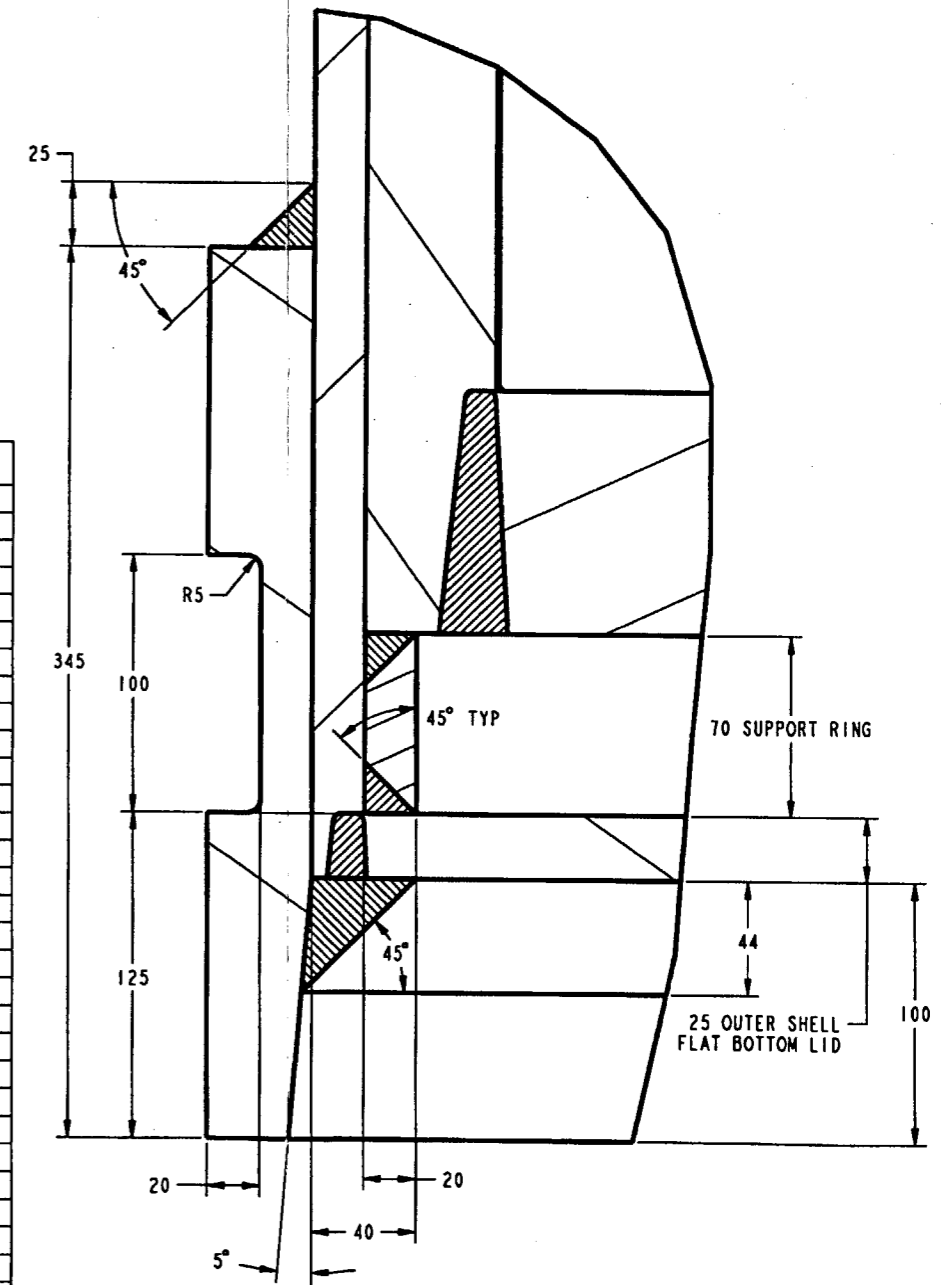


DETAIL A

COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
BASKET B-SIDEGUIDE	SA-516 K02700	10	19	32
BASKET B-STIFFENER	SA-516 K02700	10	0.31	64
BASKET CORNERGUIDE	SA-516 K02700	10	46	32
BASKET STIFFENER	SA-516 K02700	10	2.7	64
FUEL BASKET A-PLATE	NEUTRONIT A 978	5	63	4
FUEL BASKET B-PLATE	NEUTRONIT A 978	5	63	4
FUEL BASKET C-PLATE	NEUTRONIT A 978	5	15	16
FUEL BASKET D-PLATE	NEUTRONIT A 978	5	44	16
FUEL BASKET E-PLATE	NEUTRONIT A 978	5	44	16
FUEL BASKET F-PLATE	SB-209 A96061 T4	5	21	8
FUEL BASKET G-PLATE	SB-209 A96061 T4	5	21	8
FUEL BASKET TUBE	SA-516 K02700	5	113	44
INNER SHELL	SA-240 S31600	50	8886	1
INNER SHELL LID	SA-240 S31600	95	1251	2
INNER SHELL LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	20	4275	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	135	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	381	1
OUTER SHELL LID LIFTING FEATURE	SB-575 N06022	27	13	2
EXTENDED LID REINFORCEMENT RING	SB-575 N06022	50	99	1
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	165	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	412	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	517	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	507	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	42	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	253	**
TOTAL 316 WELDS	SFA-5.9 S31680	-	131	**
WASTE PACKAGE ASSEMBLY	-	-	28068	1
BWR FUEL ASSEMBLY	-	-	328.4*	44
WASTE PACKAGE ASSEMBLY WITH SNF	-	-	42517	1

\* CRWMS M&O 1997. WASTE CONTAINER CAVITY SIZE DETERMINATION. BBAA00000-01717-0200-00026 REV 00 LAS VEGAS, NV; CRWMS M&O. ACC: MOL.19980106.0061

\*\* REFER TO SK-0193 REV 00 "SINGLE CRM 44-BWR WASTE PACKAGE ASSEMBLY WELD CONFIGURATION"

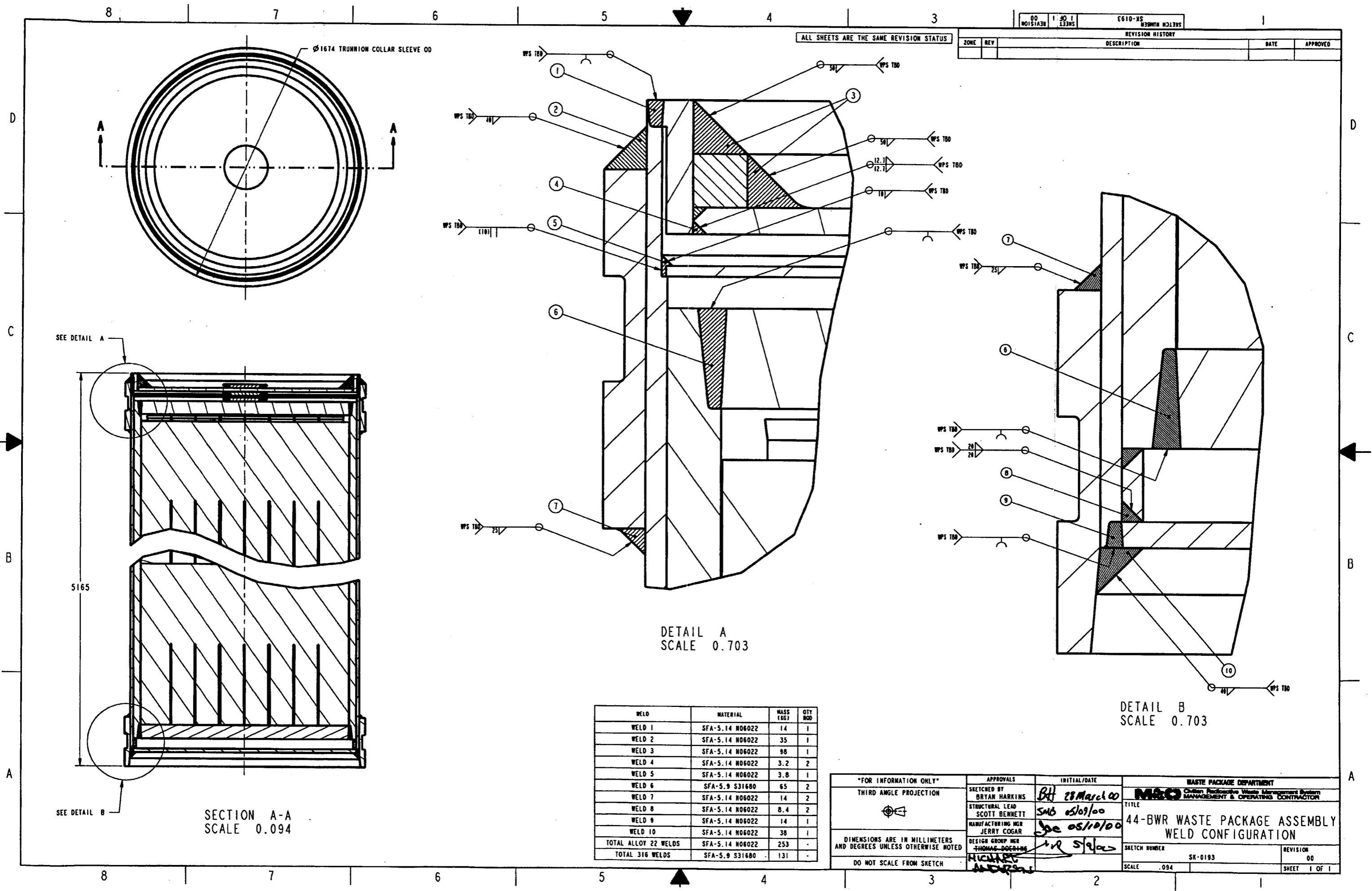


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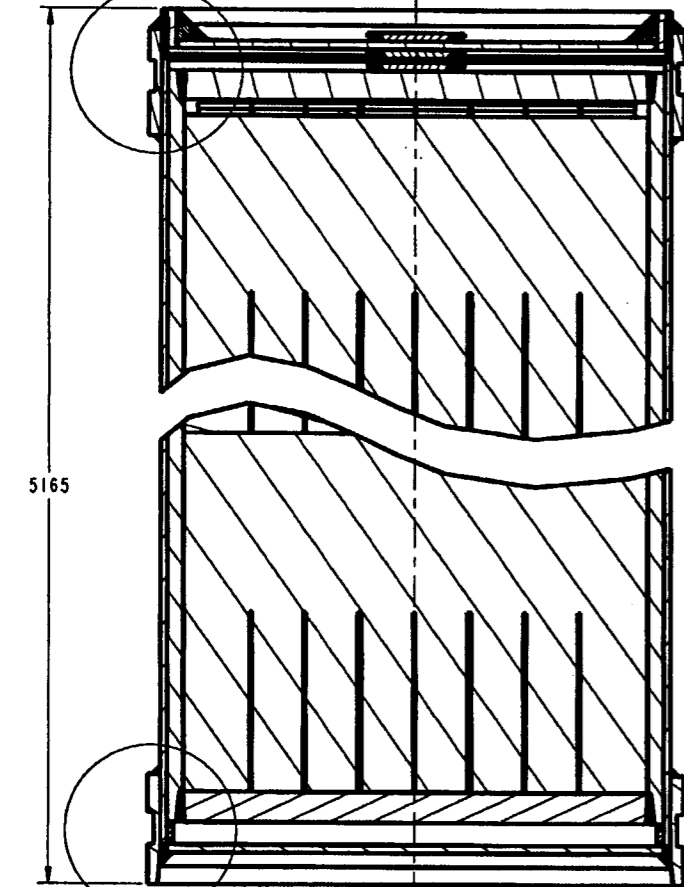
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REVISION  
6610-NS  
WASTE MANAGEMENT SYSTEMS

REVISION HISTORY				
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ALL SHEETS ARE THE SAME REVISION STATUS



SEE DETAIL A



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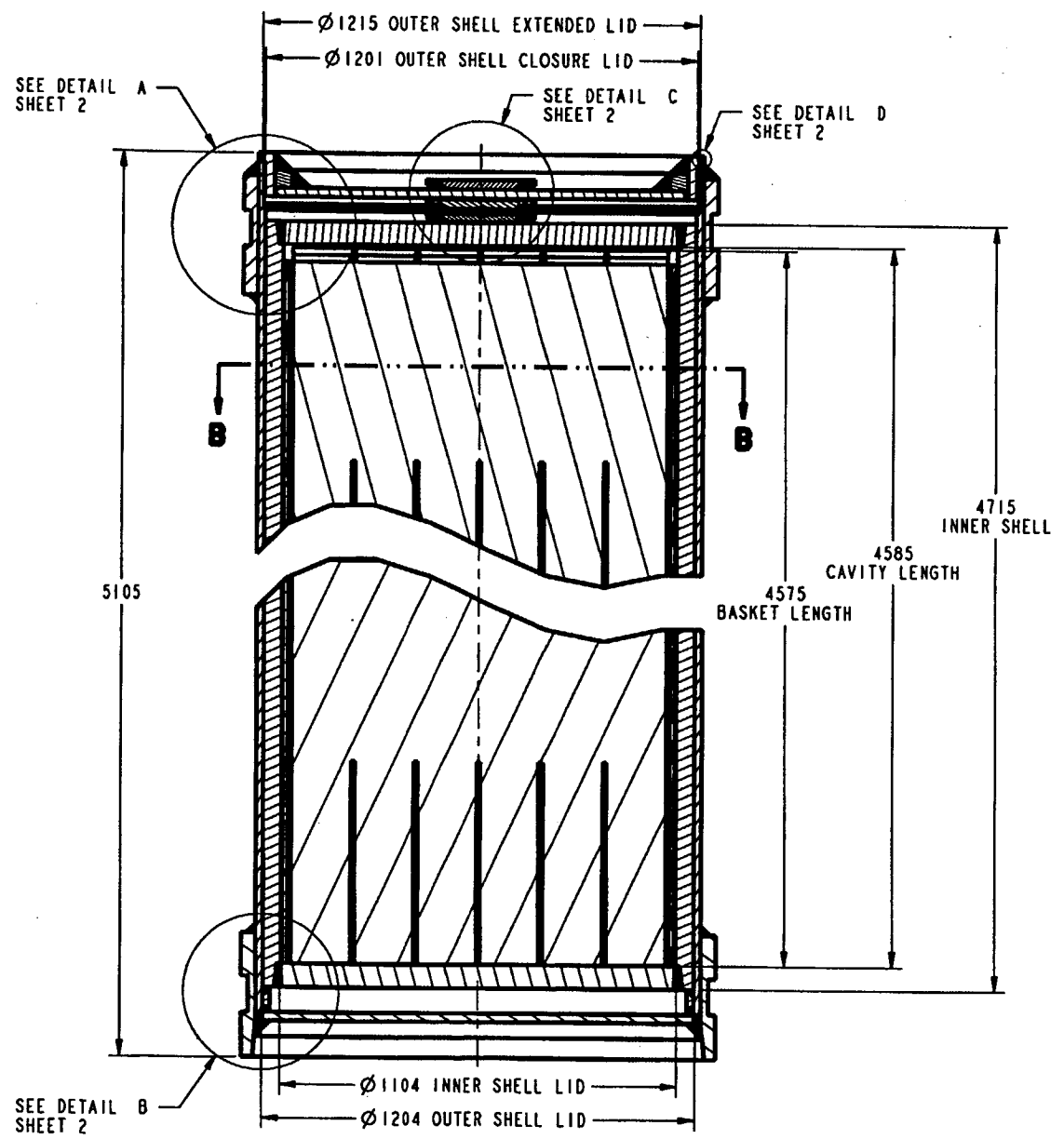
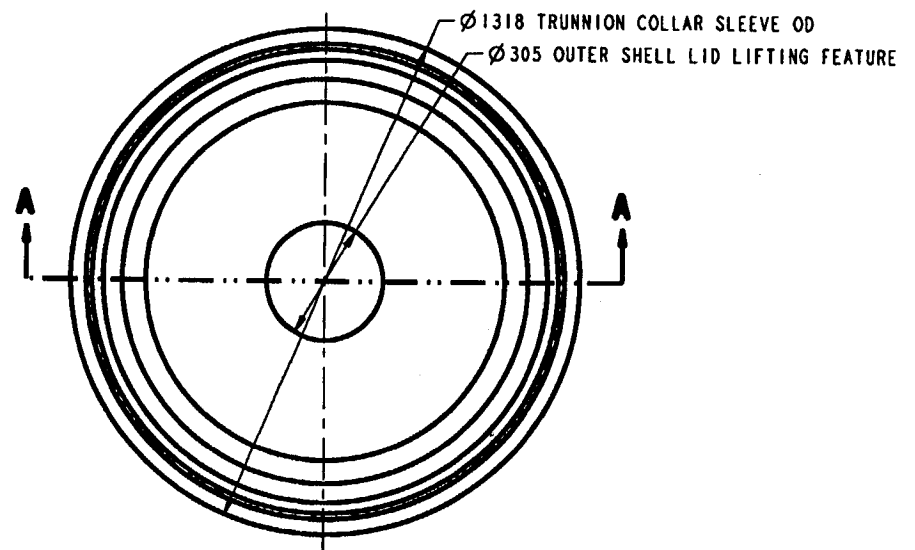
SEE DETAIL B

DETAIL A  
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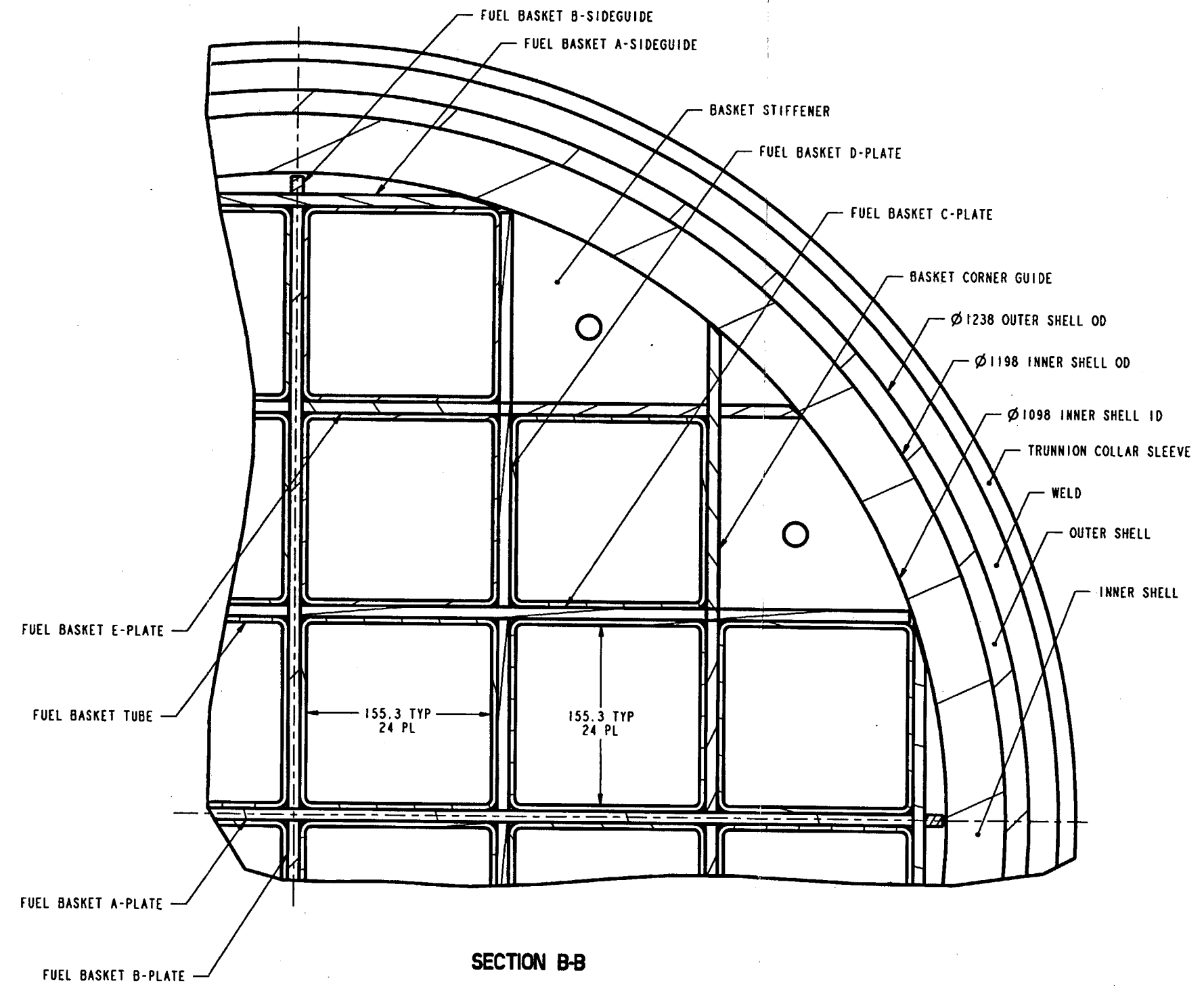
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WELD	MATERIAL	MASS (KG)	QTY ROD
WELD 1	SFA-5.14 N06022	14	1
WELD 2	SFA-5.14 N06022	35	1
WELD 3	SFA-5.14 N06022	98	1
WELD 4	SFA-5.14 N06022	3.2	2
WELD 5	SFA-5.14 N06022	3.8	1
WELD 6	SFA-5.9 S31680	65	2
WELD 7	SFA-5.14 N06022	14	2
WELD 8	SFA-5.14 N06022	8.4	2
WELD 9	SFA-5.14 N06022	14	1
WELD 10	SFA-5.14 N06022	38	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	253	-
TOTAL 316 WELDS	SFA-5.9 S31680	131	-

<p>"FOR INFORMATION ONLY"</p> <p>THIRD ANGLE PROJECTION</p> <p>DIMENSIONS ARE IN MILLIMETERS AND DEGREES UNLESS OTHERWISE NOTED</p> <p>DO NOT SCALE FROM SKETCH</p>	<p>APPROVALS</p> <p>SKETCHED BY BRYAN HARKINS</p> <p>STRUCTURAL LEAD SCOTT BENNETT</p> <p>MANUFACTURING MGR JERRY COGAR</p> <p>DESIGN GROUP MGR THOMAS DOERING</p> <p>NICHOLE ANDERSON</p>	<p>INITIAL/DATE</p> <p>BH 28 March 00</p> <p>SMB 05/09/00</p> <p>JPC 05/10/00</p> <p>TH ST 02/00</p>	<p>WASTE PACKAGE DEPARTMENT</p> <p>M&amp;O Civilian Radioactive Waste Management System MANAGEMENT &amp; OPERATING CONTRACTOR</p> <p>TITLE</p> <p>44-BWR WASTE PACKAGE ASSEMBLY WELD CONFIGURATION</p> <p>SKETCH NUMBER</p> <p>SK-0193</p> <p>REVISION</p> <p>00</p> <p>SHEET 1 OF 1</p>
	<p>SCALE .094</p>	<p>SCALE 0.094</p>	<p>SCALE 0.094</p>
	<p>SCALE 0.094</p>	<p>SCALE 0.094</p>	<p>SCALE 0.094</p>
	<p>SCALE 0.094</p>	<p>SCALE 0.094</p>	<p>SCALE 0.094</p>



SECTION A-A



SECTION B-B

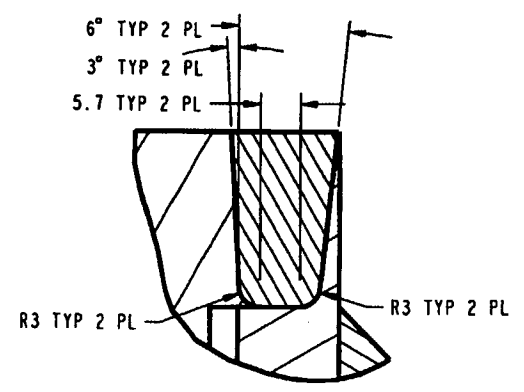
FOR INFORMATION ONLY

24-BWR WASTE PACKAGE CONFIGURATION FOR SITE RECOMMENDATION

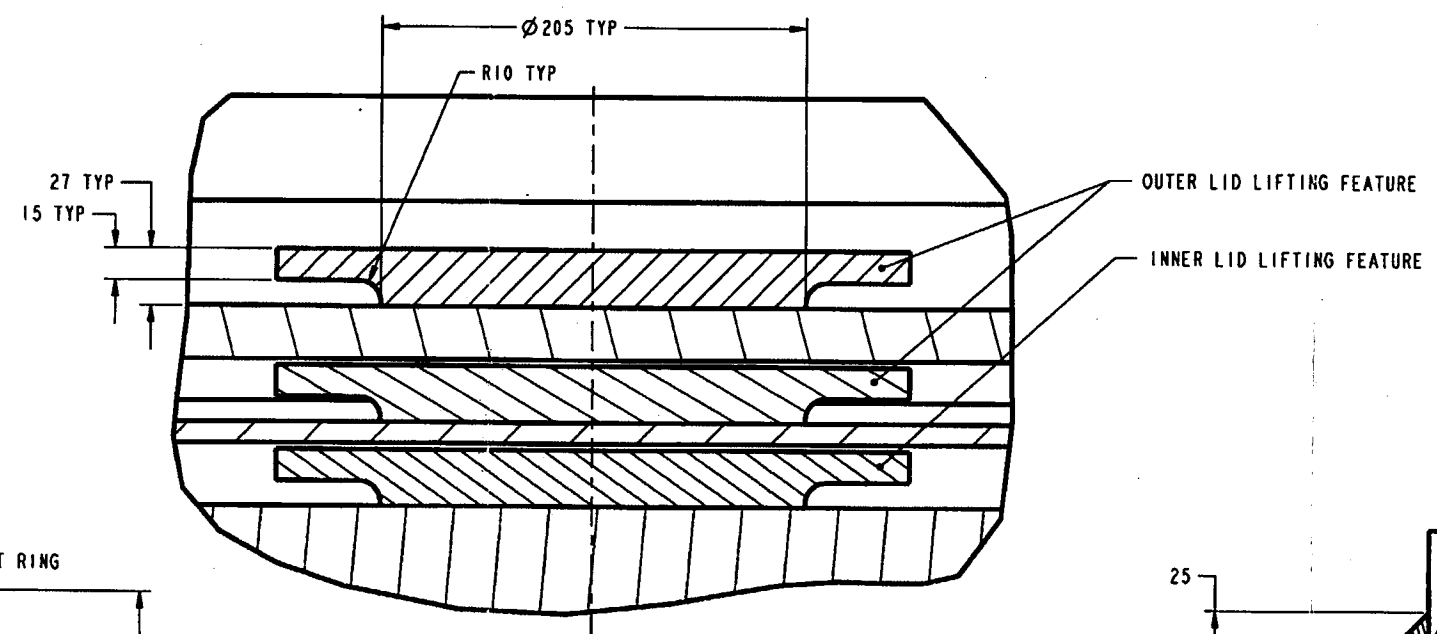
SKETCH NUMBER:	SK-0184 REV 00	SHEET 1 OF 2
SKETCHED BY:	BRYAN HARKINS	
DATE:	01/25/00	
FILE:	/home/pro_library/checkout/sketches/24-bwr/sk-0184.dwg	

*BH*  
*25 Jan 00*  
*Jac*  
*1/25/00*  
*SMB*  
*01/25/00*  
*1:26:00*

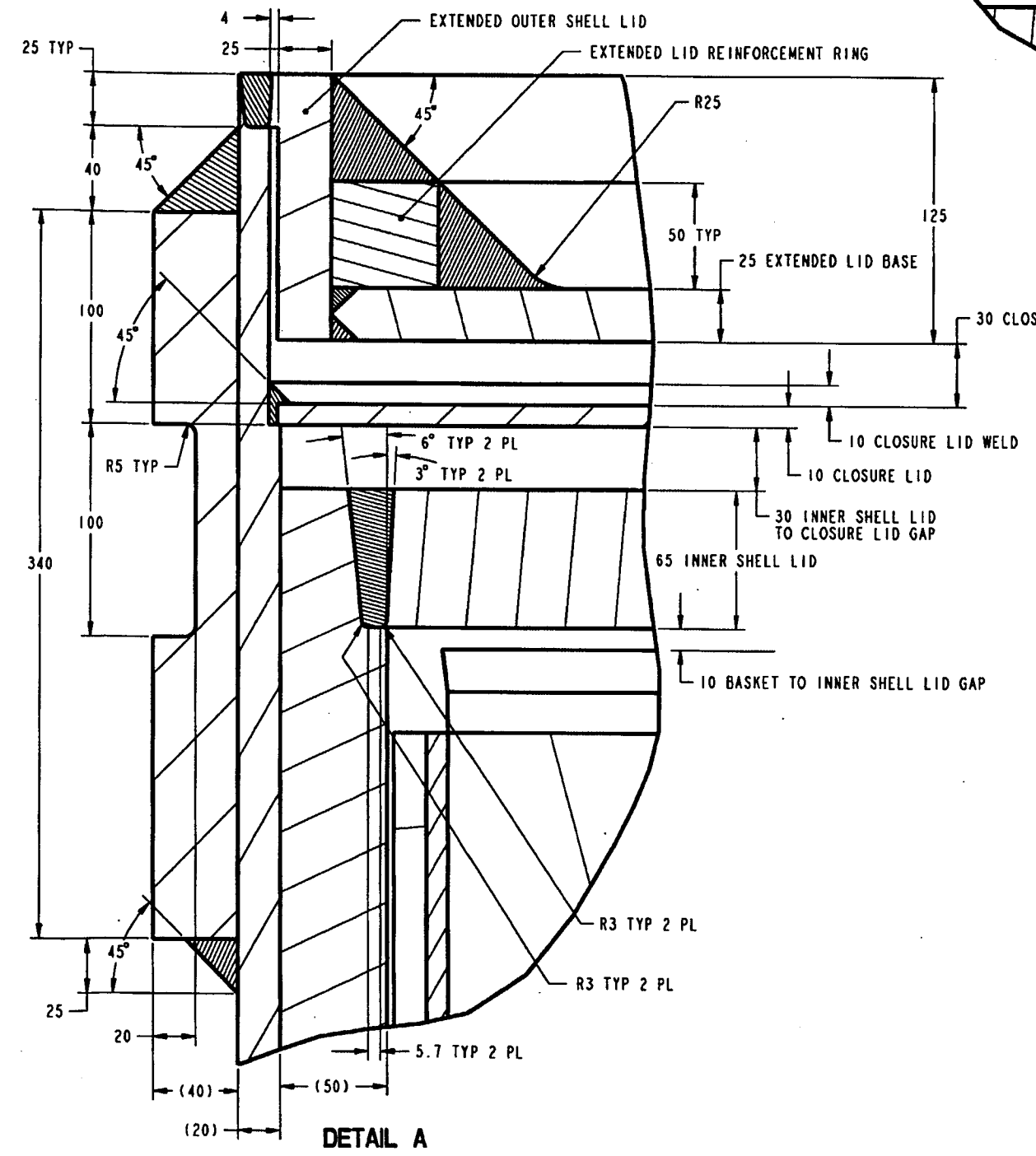
UNITS: mm  
DO NOT SCALE FROM SKETCH



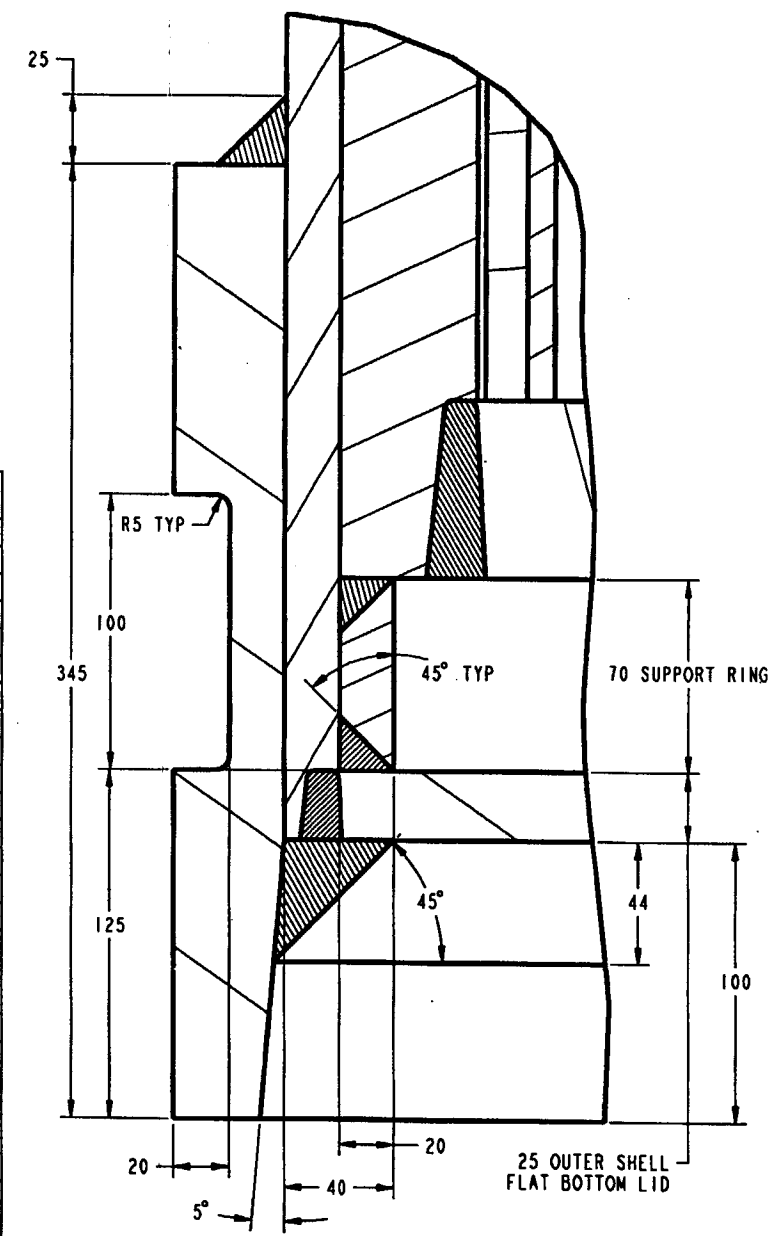
DETAIL D



DETAIL C



DETAIL A



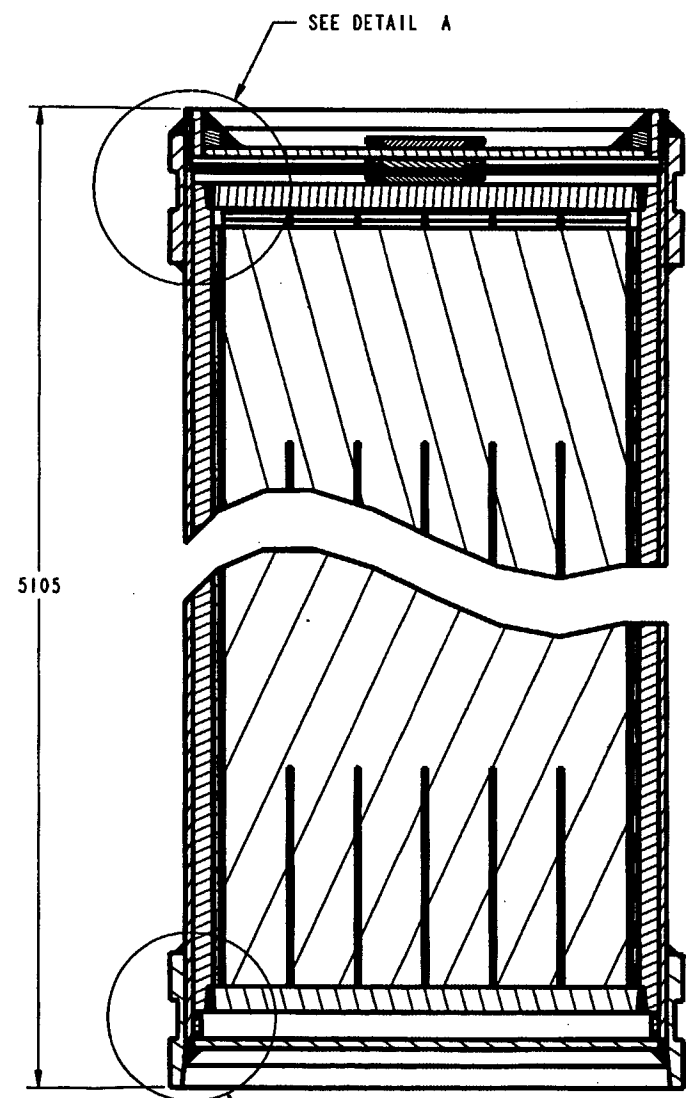
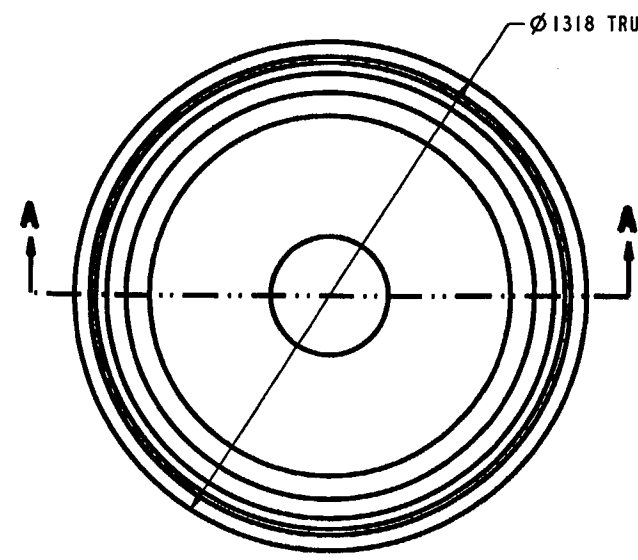
DETAIL B

COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
BASKET A-GUIDE	SA-516 K02700	10	27	16
BASKET B-GUIDE	SA-516 K02700	10	1.3	16
BASKET CORNER GUIDE	SA-516 K02700	10	22	32
BASKET STIFFENER	SA-516 K02700	10	1.6	64
FUEL BASKET A-PLATE	NEUTRONIT A 978	10	89	4
FUEL BASKET B-PLATE	NEUTRONIT A 978	10	89	4
FUEL BASKET C-PLATE	NEUTRONIT A 978	10	90	8
FUEL BASKET D-PLATE	NEUTRONIT A 978	10	90	8
FUEL BASKET E-PLATE	NEUTRONIT A 978	10	30	16
FUEL BASKET TUBE	SA-516 K02700	5	113	24
INNER SHELL	SA-240 S31600	50	6731	1
INNER SHELL LID	SA-240 S31600	65	489	2
INNER SHELL LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	20	3268	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	103	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	221	1
OUTER SHELL LID LIFTING FEATURE	SB-575 N06022	27	13	2
EXTENDED LID REINFORCEMENT RING	SB-575 N06022	50	75	1
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	98	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	245	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	404	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	396	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	32	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	194	**
TOTAL 316 WELDS	SFA-5.9 S31680	-	59	**
WASTE PACKAGE ASSEMBLY	-	-	19437	1
BWR FUEL ASSEMBLY	-	-	*328.4	24
WASTE PACKAGE ASSEMBLY WITH SNF	-	-	27318	1

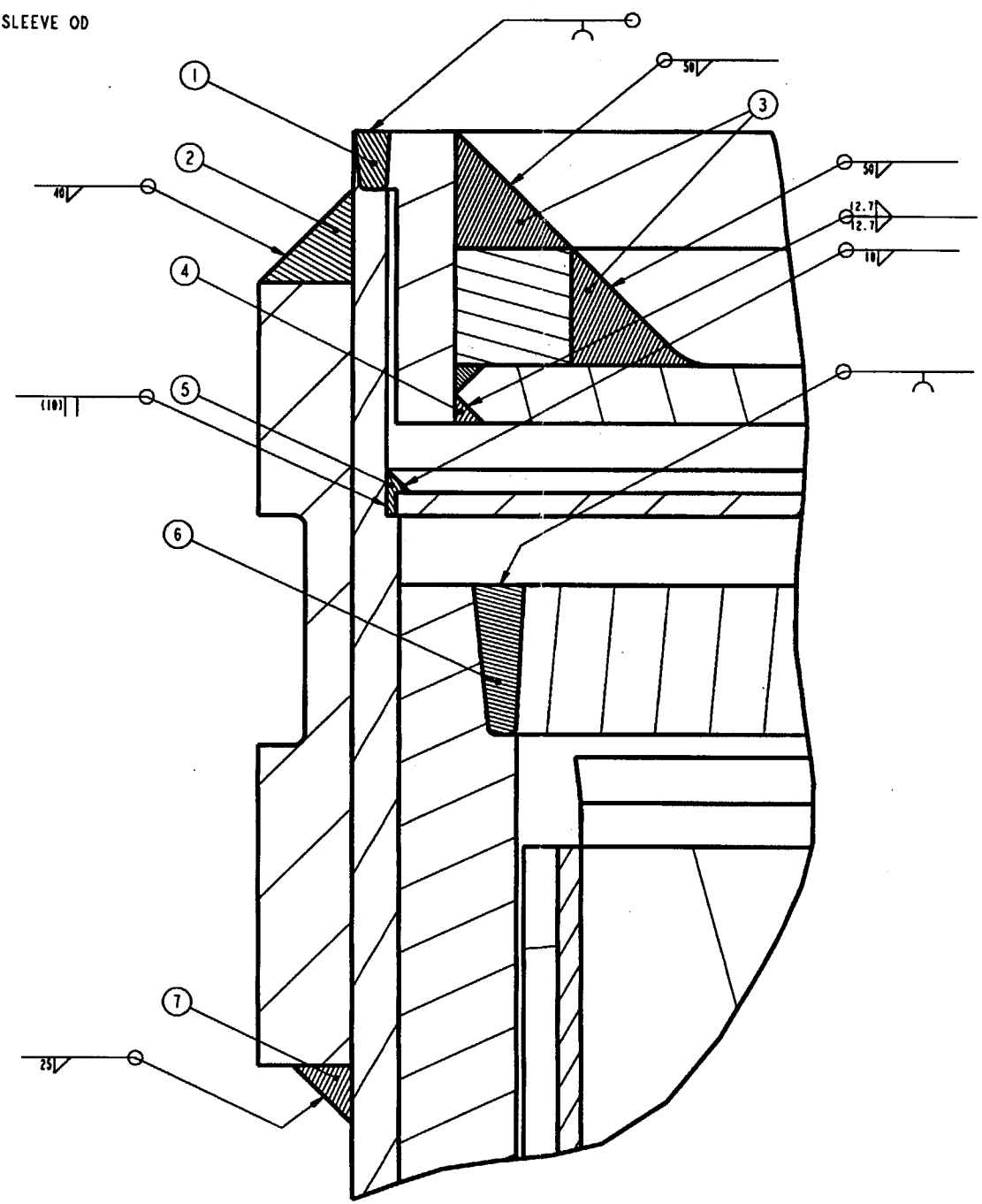
\* CRWMS M&O 1997. WASTE CONTAINER CAVITY SIZE DETERMINATION. BBAA00000-01717-0200-00026 REV 00 LAS VEGAS, NV: CRWMS M&O. ACC: MOL.19980106.0061

\*\* REFER TO SK-0202 REV 00 \*24-BWR WASTE PACKAGE ASSEMBLY WELD CONFIGURATION\*

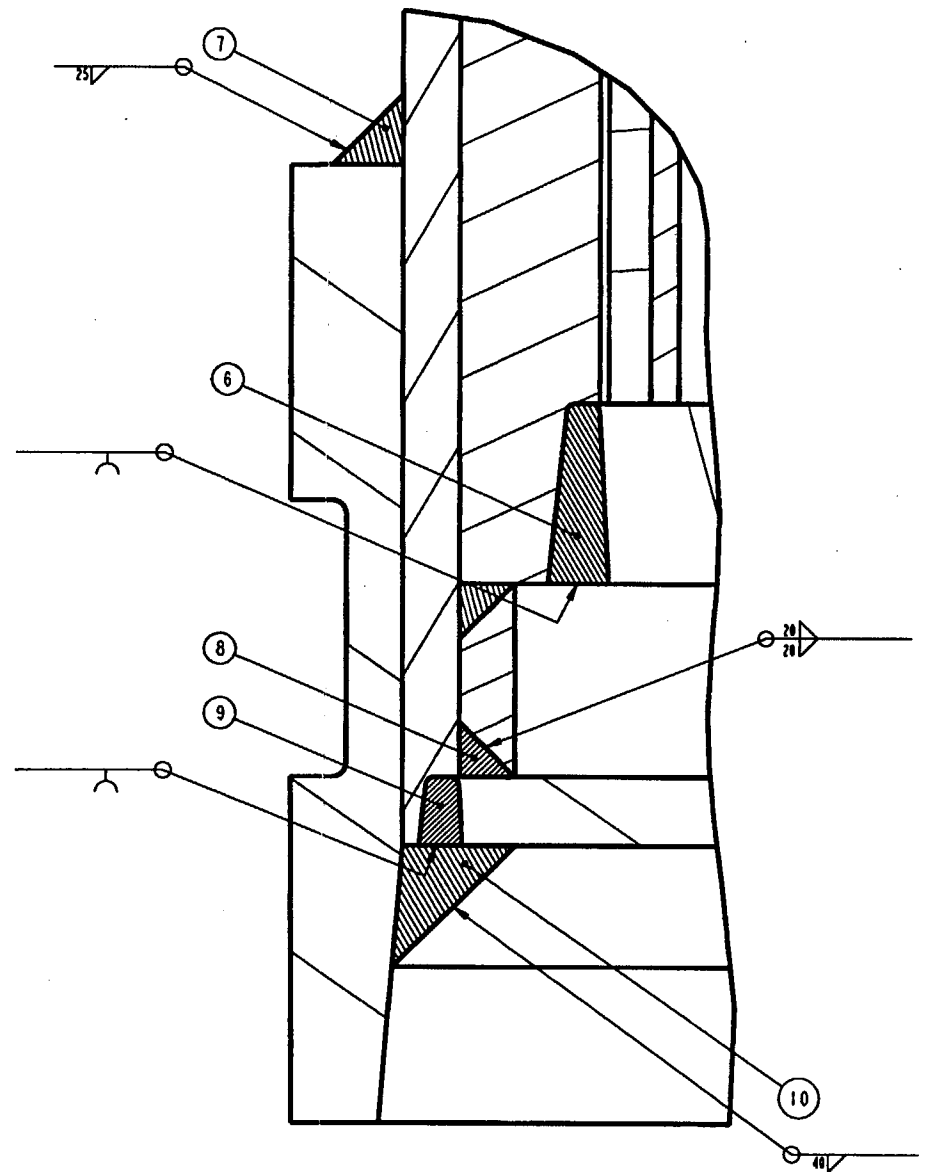




SECTION A-A



DETAIL A



DETAIL B

WELD	MATERIAL	MASS (KG)	QTY ROD	
1	SFA-5.14 N06022	11	1	
2	SFA-5.14 N06022	28	1	
3	SFA-5.14 N06022	73	1	
4	SFA-5.14 N06022	2.4	2	
5	SFA-5.14 N06022	3.0	1	
6	SFA-5.9 S31680	30	2	
7	SFA-5.14 N06022	11	2	
8	SFA-5.14 N06022	6.5	2	
9	SFA-5.14 N06022	11	1	
10	SFA-5.14 N06022	29	1	
TOTAL ALLOY 22 WELDS		SFA-5.14 N06022	194	-
TOTAL 316 WELDS		SFA-5.9 S31680	59	-

UNITS: mm  
DO NOT SCALE FROM SKETCH

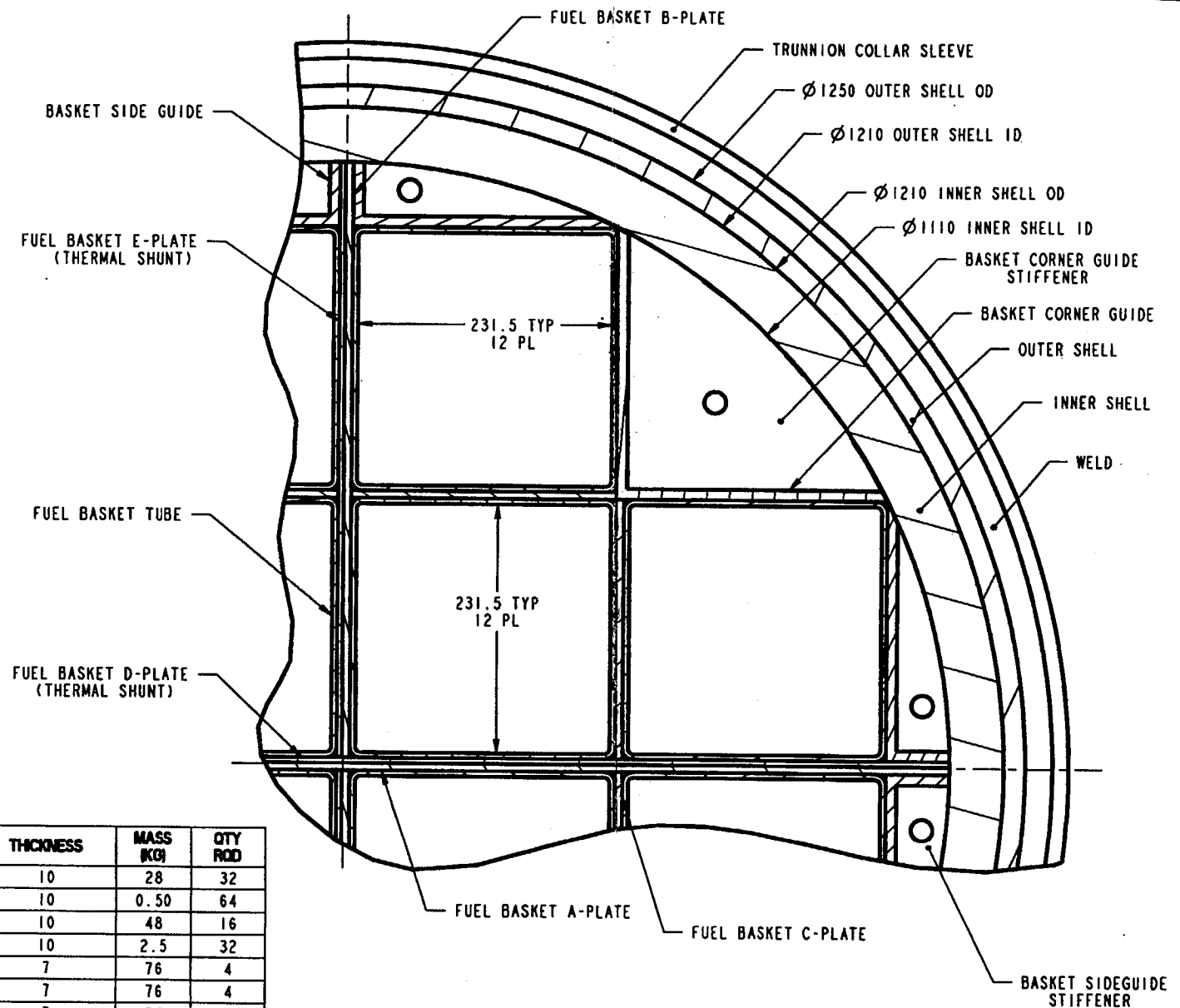
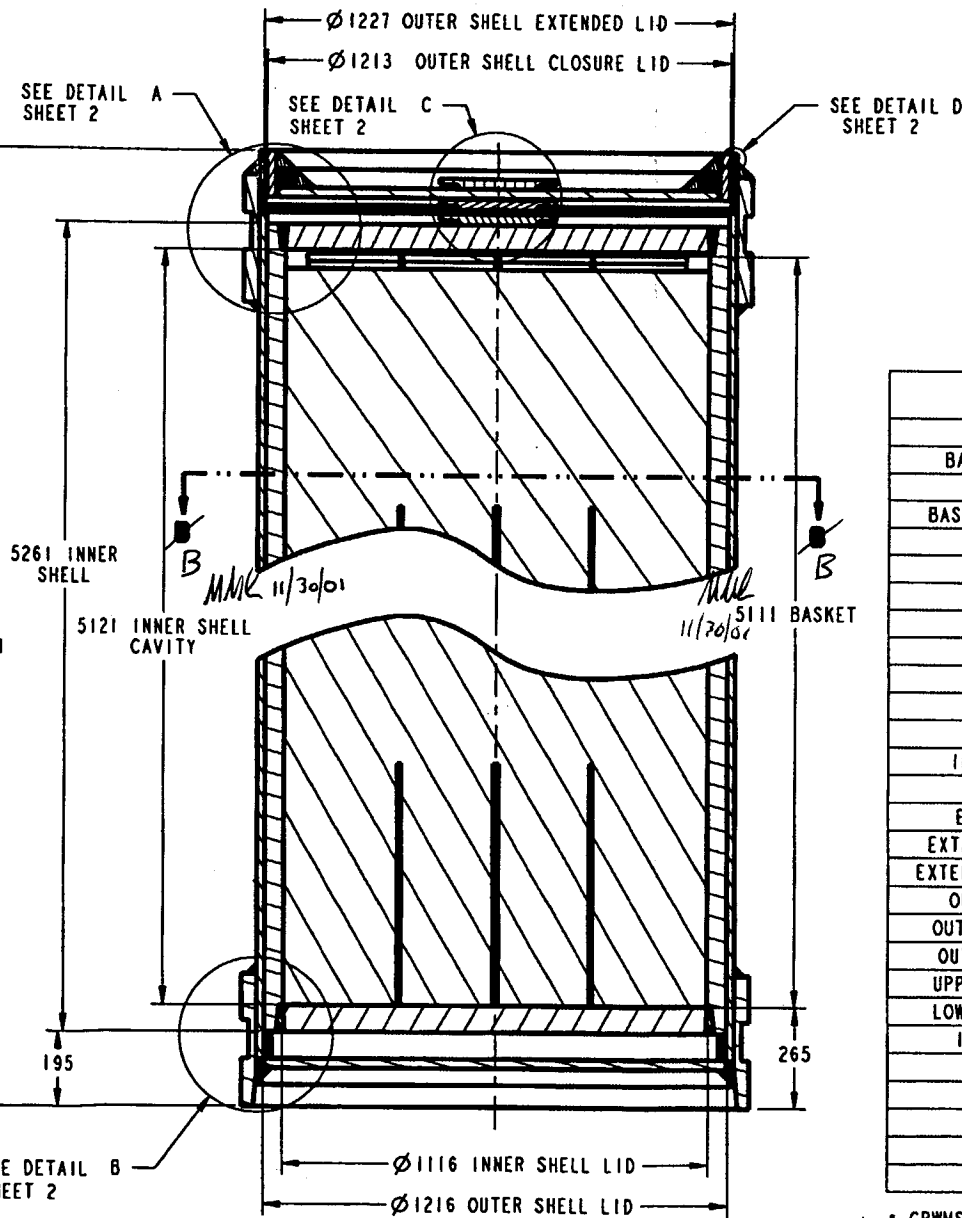
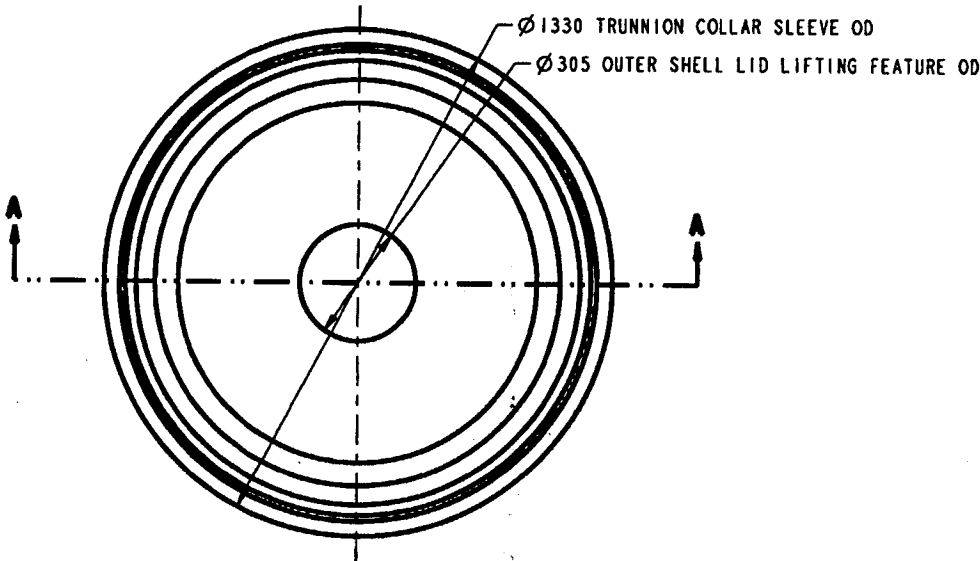
REVISIONS			
REV	DESCRIPTION	DRN BY	DATE
00	ISSUED APPROVED	BH	03/07/00

"FOR INFORMATION ONLY"

24-BWR WASTE PACKAGE ASSEMBLY WELD CONFIGURATION

SKETCH NUMBER: SK-0202 REV 00  
 SKETCHED BY: BRYAN HARKINS  
 DATE: 03/07/00  
 FILE: /home/pro\_library/checkout/sketches/24bwr/sk-0202.dwg

*BA*  
*13 March 00*  
*SMB*  
*03/03/00*  
*3.18.00*



COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
BASKET SIDEGUIDE	SA-516 K02700	10	28	32
BASKET SIDEGUIDE STIFFENER	SA-516 K02700	10	0.50	64
BASKET CORNER GUIDE	SA-516 K02700	10	48	16
BASKET CORNER GUIDE STIFFENER	SA-516 K02700	10	2.5	32
FUEL BASKET A-PLATE	NEUTRONIT A 978	7	76	4
FUEL BASKET B-PLATE	NEUTRONIT A 978	7	76	4
FUEL BASKET C-PLATE	NEUTRONIT A 978	7	34	16
FUEL BASKET D-PLATE	SB-209 A96061 T4	5	19	4
FUEL BASKET E-PLATE	SB-209 A96061 T4	5	19	4
FUEL BASKET TUBE	SA-516 K02700	5	187	12
INNER SHELL	SA-240 S31600	50	7589	1
INNER SHELL LID	SA-240 S31600	70	538	2
INNER LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	(01) 20	3666	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	104	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	226	1
EXTENDED LID REINFORCEMENT RING	SB-575 N06022	50	76	1
OUTER LID LIFTING FEATURE	SB-575 N06022	27	13	2
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	100	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	250	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	408	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	400	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	32	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	196	**
TOTAL 316 WELDS	SFA-5.9 S31680	-	67	**
WASTE PACKAGE ASSEMBLY	-	-	19541	1
PWR FUEL ASSEMBLY	-	-	882.2*	12
WP ASSEMBLY WITH SNF	-	-	30127	1

\* CRWMS M&O 1997. WASTE CONTAINER CAVITY SIZE DETERMINATION. BBAA00000-01717-0200-00026 REV 00 LAS VEGAS, NEVADA: CRWMS M&O. ACC: MOL. 19980106-0061  
 \*\* REFER TO SK-0205 REV 00 "12-PWR LONG PACKAGE WELD CONFIGURATION"

UNITS: mm

DO NOT SCALE FROM SKETCH

SECTION B-B

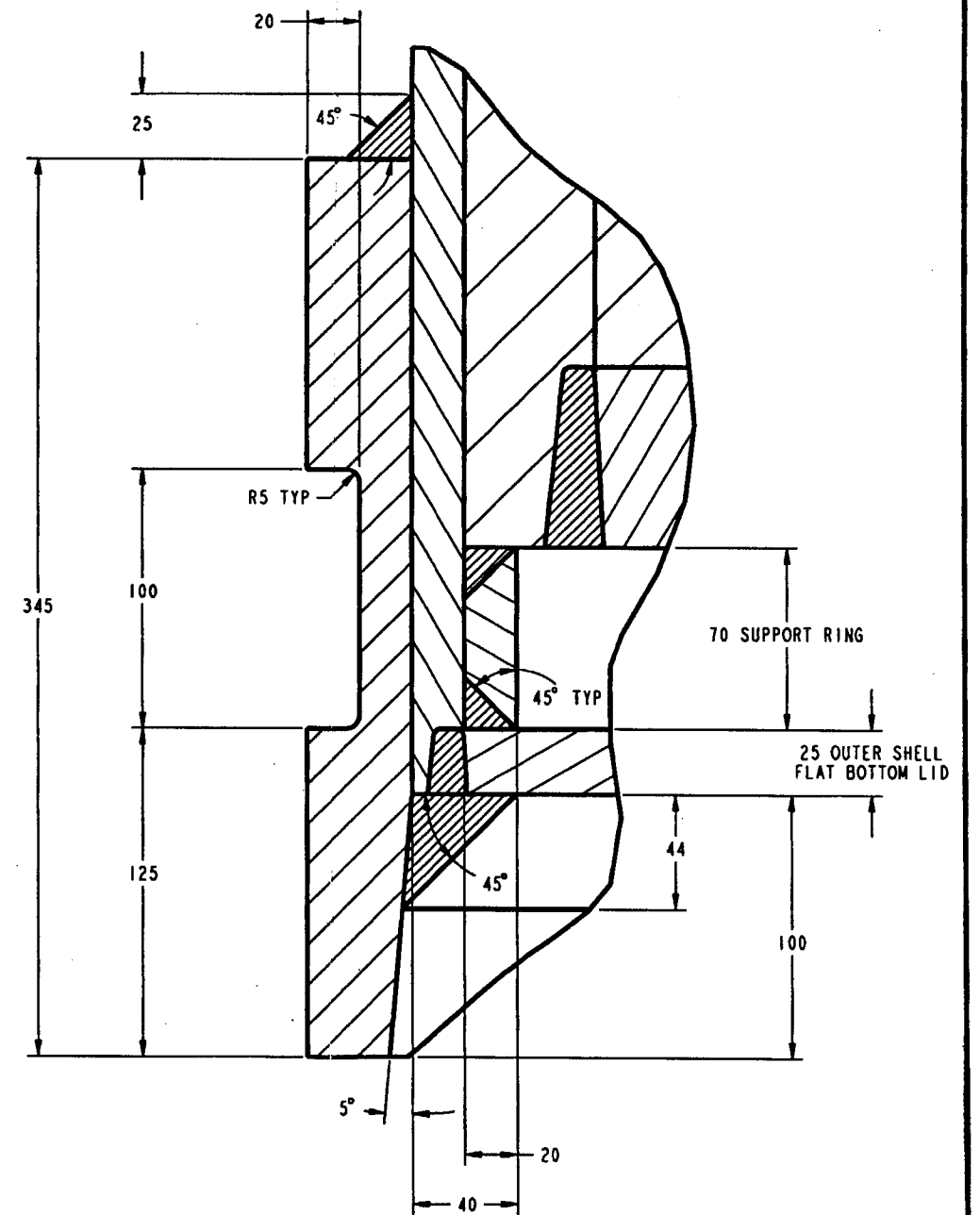
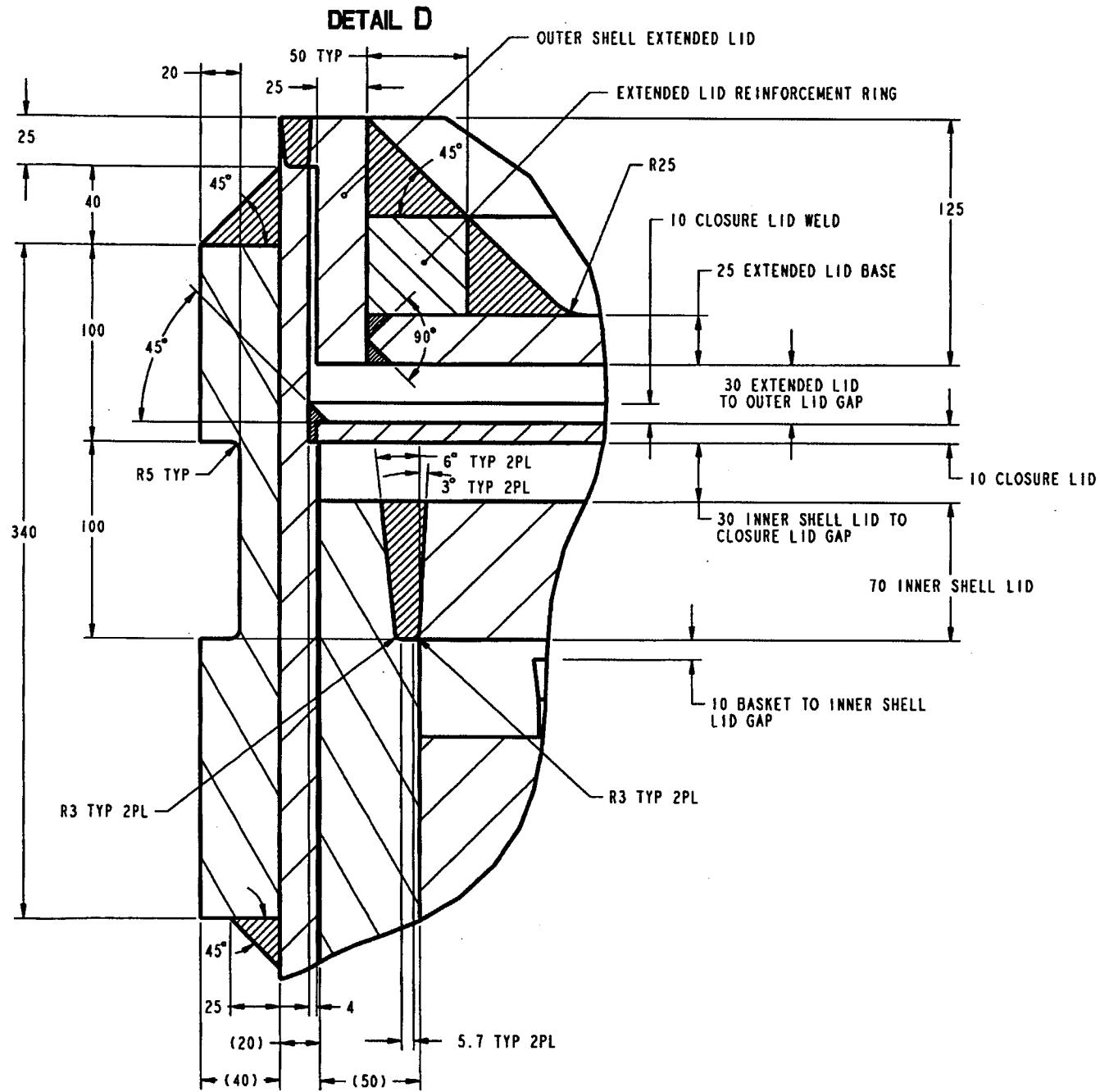
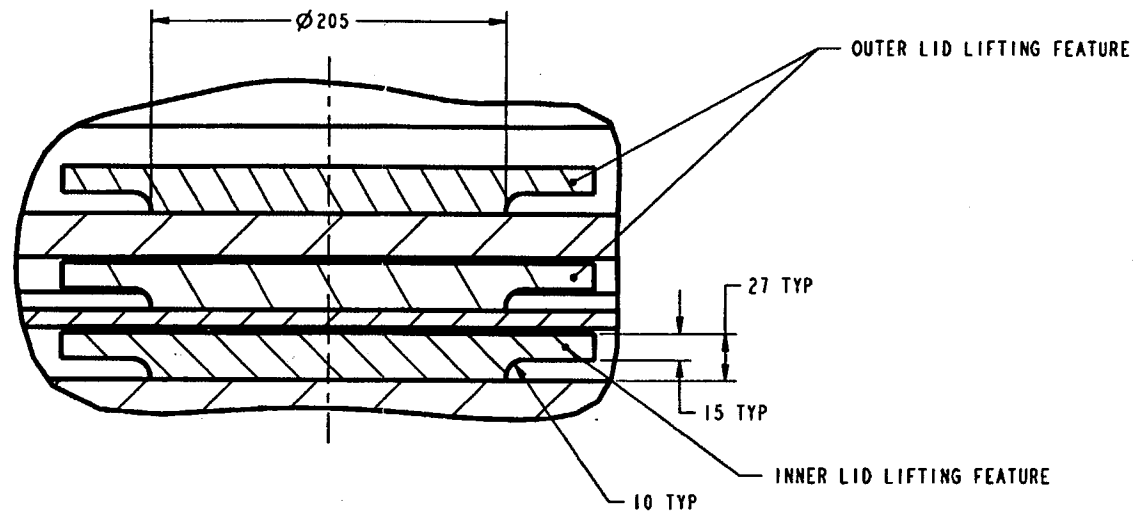
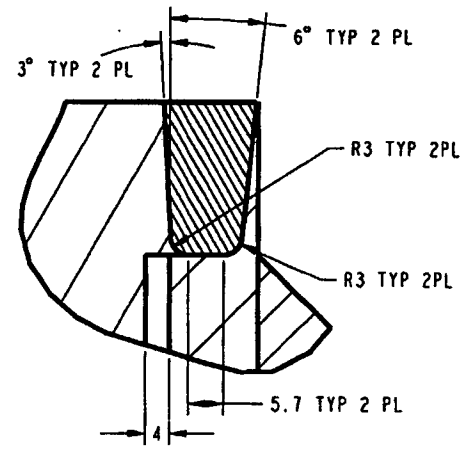
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REVISIONS			
REV	DESCRIPTION	DRN BY	DATE
00	ISSUED APPROVED	GC	01/26/00
01	20 OUTER SHELL THICKNESS "WAS" 25, REVISION TABLE "ADDED"	BH	03/23/00

"FOR INFORMATION ONLY"

12-PWR LONG WASTE PACKAGE CONFIGURATION FOR SITE RECOMMENDATION

SKETCH NUMBER: SK-0183 REV 01 SHEET 1 OF 2  
 SKETCHED BY: BRYAN HARKINS *BH*  
 DATE: 03/23/00 *23 March 00* z.c. for SMB *3/23/00*  
 FILE: /home/pro\_library/checkout/sketches/12pwr/12pwr long/SK-0183.dwg *323.00*



DETAIL A

DETAIL C

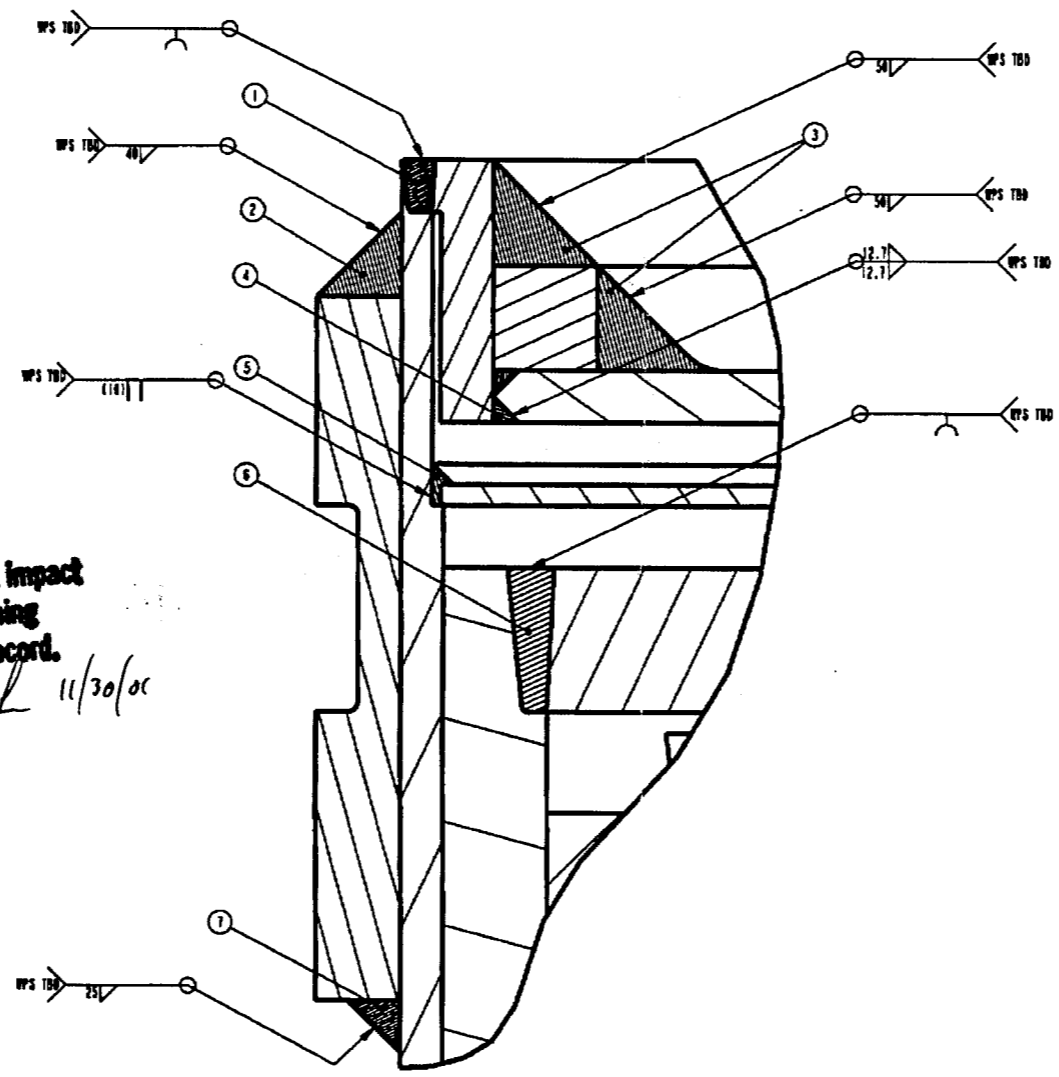
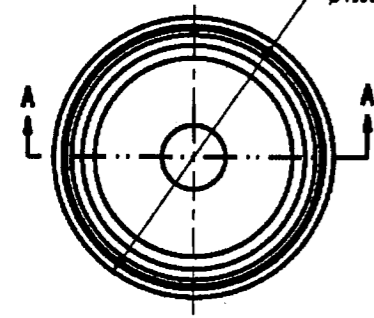
DETAIL B

5020-MS  
SHEET 1 OF 1  
REVISION NUMBER

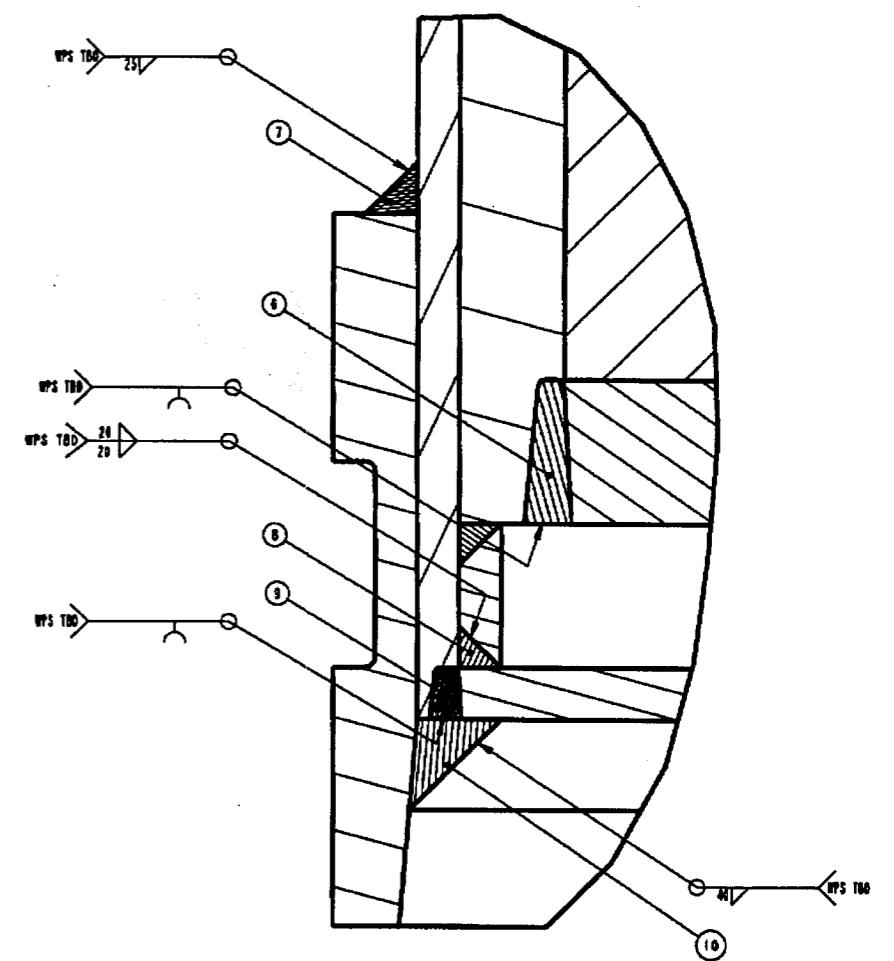
ALL SHEETS ARE THE SAME REVISION STATUS

ZONE	REV	DESCRIPTION	DATE	APPROVED

Ø1330 TRUNNION COLLAR SLEEVE OD



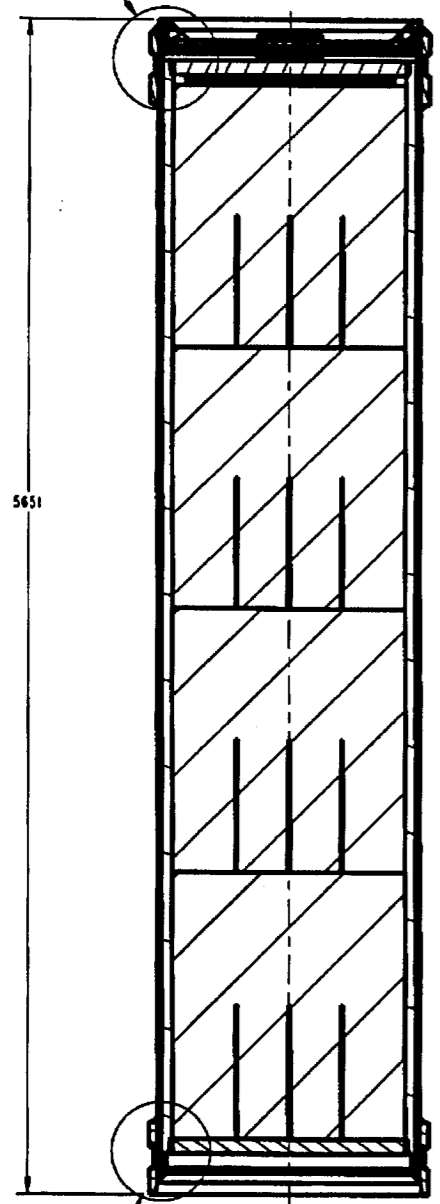
Weldability does not impact the technical meaning or content of the record.  
*MMZ 11/30/00*



DETAIL A  
SCALE 0.625

DETAIL B  
SCALE 0.625

SEE DETAIL A



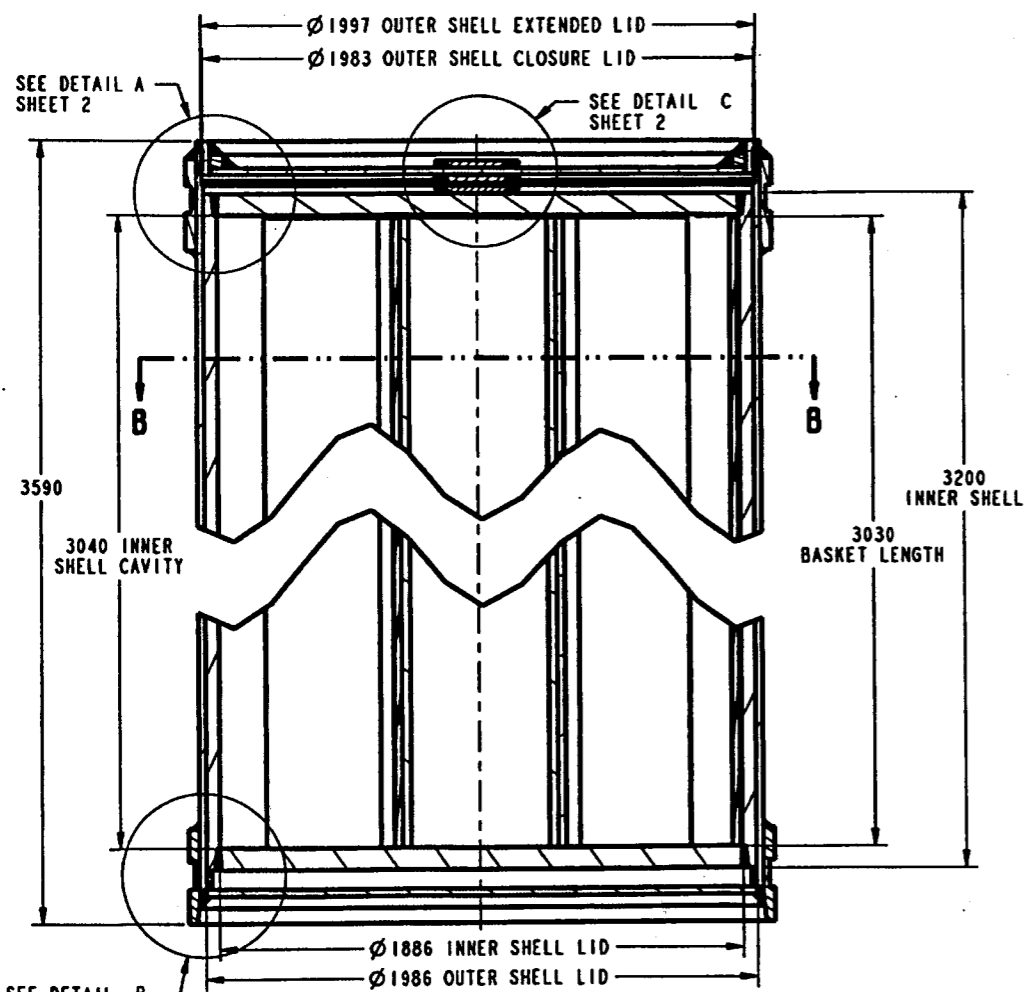
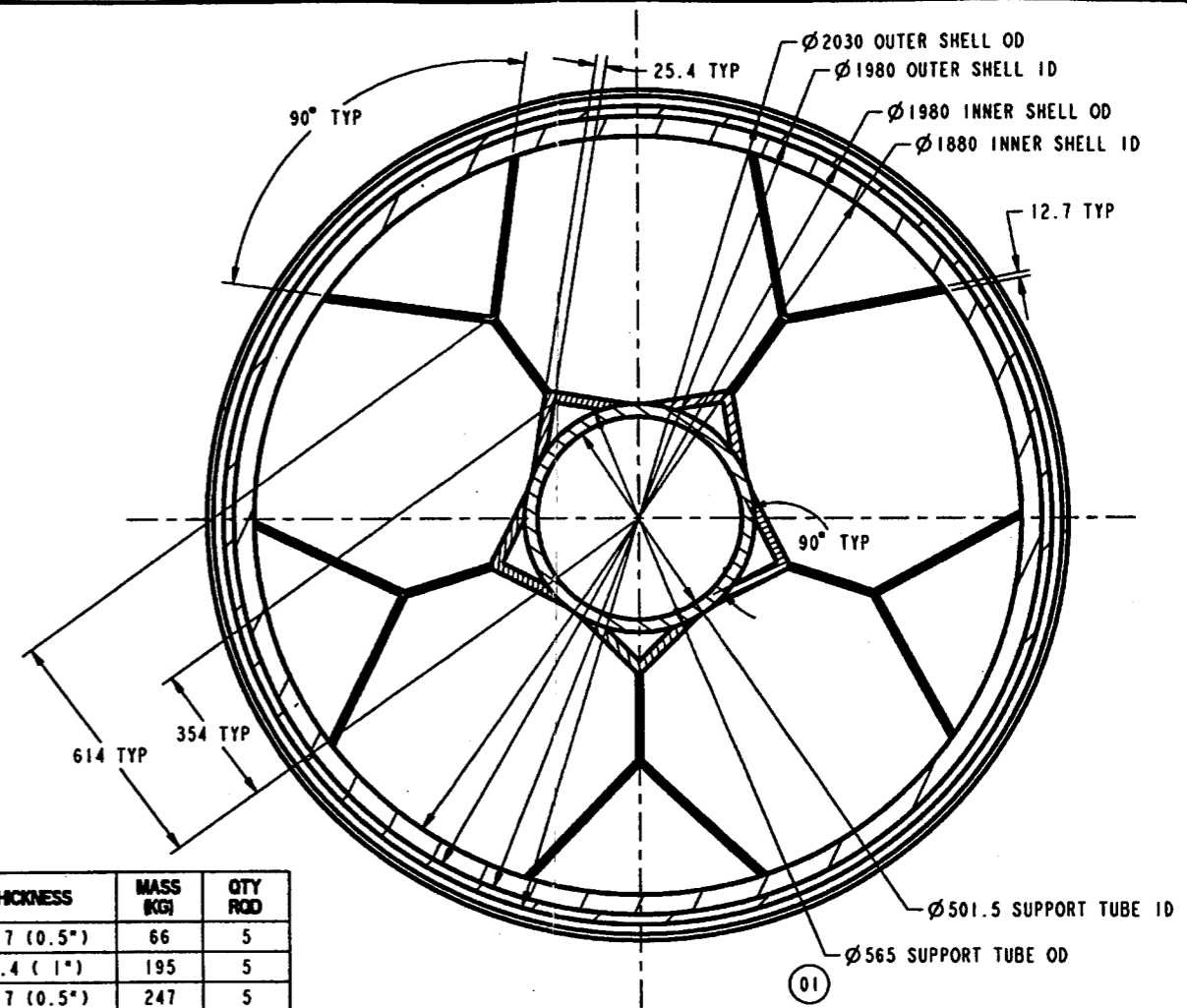
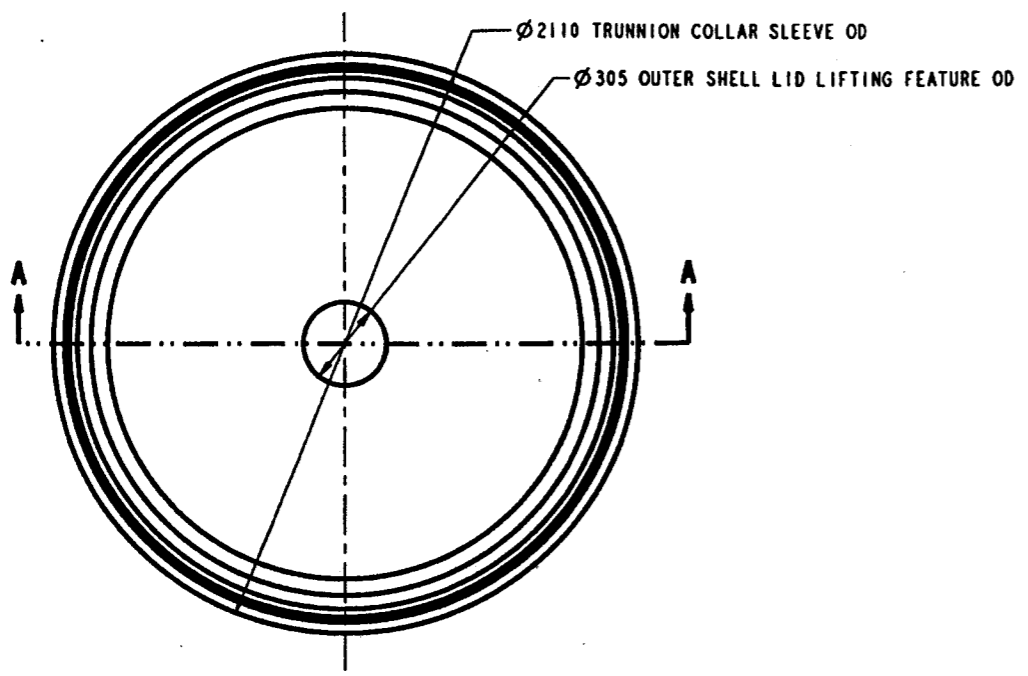
SECTION A-A  
SCALE 0.062

SEE DETAIL B

WELDS	MATERIAL	MASS (KG)	QTY BOP
WELD 1	SFA-5.14 N06022	11	1
WELD 2	SFA-5.14 N06022	28	1
WELD 3	SFA-5.14 N06022	74	1
WELD 4	SFA-5.14 N06022	2.5	2
WELD 5	SFA-5.14 N06022	3.0	1
WELD 6	SFA-5.9 S31680	34	2
WELD 7	SFA-5.14 N06022	11	2
WELD 8	SFA-5.14 N06022	6.5	2
WELD 9	SFA-5.14 N06022	11	1
WELD 10	SFA-5.14 N06022	29	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	186	-
TOTAL 316 WELDS	SFA-5.9 S31680	67	-

For Information and Completeness, No Approvals Required. *SMB 12/06/00*

"FOR INFORMATION ONLY"		APPROVALS	INITIAL/DATE	WASTE PACKAGE DEPARTMENT		
THIRD ANGLE PROJECTION		SKETCHED BY BRYAN HARKINS	N/A	M&O California Radioactive Waste Management System MANAGEMENT & OPERATIONS CONTRACTOR		
		STRUCTURAL LEAD SCOTT BENNETT		TITLE	12-PWR LONG WASTE PACKAGE WELD CONFIGURATION	
		MANUFACTURING MGR JERRY COGAR		SKETCH NUMBER	SK-0265	
		DESIGN GROUP MGR THOMAS DOERING		REVISION	00	
DIMENSIONS ARE IN MILLIMETERS AND DEGREES UNLESS OTHERWISE NOTED		DO NOT SCALE FROM SKETCH		SCALE	0.625	
				SHEET	1 OF 1	



COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
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	-

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 DHLW/DOE SNF - SHORT WP ASSEMBLY CONFIGURATION FOR SITE RECOMENDATION**

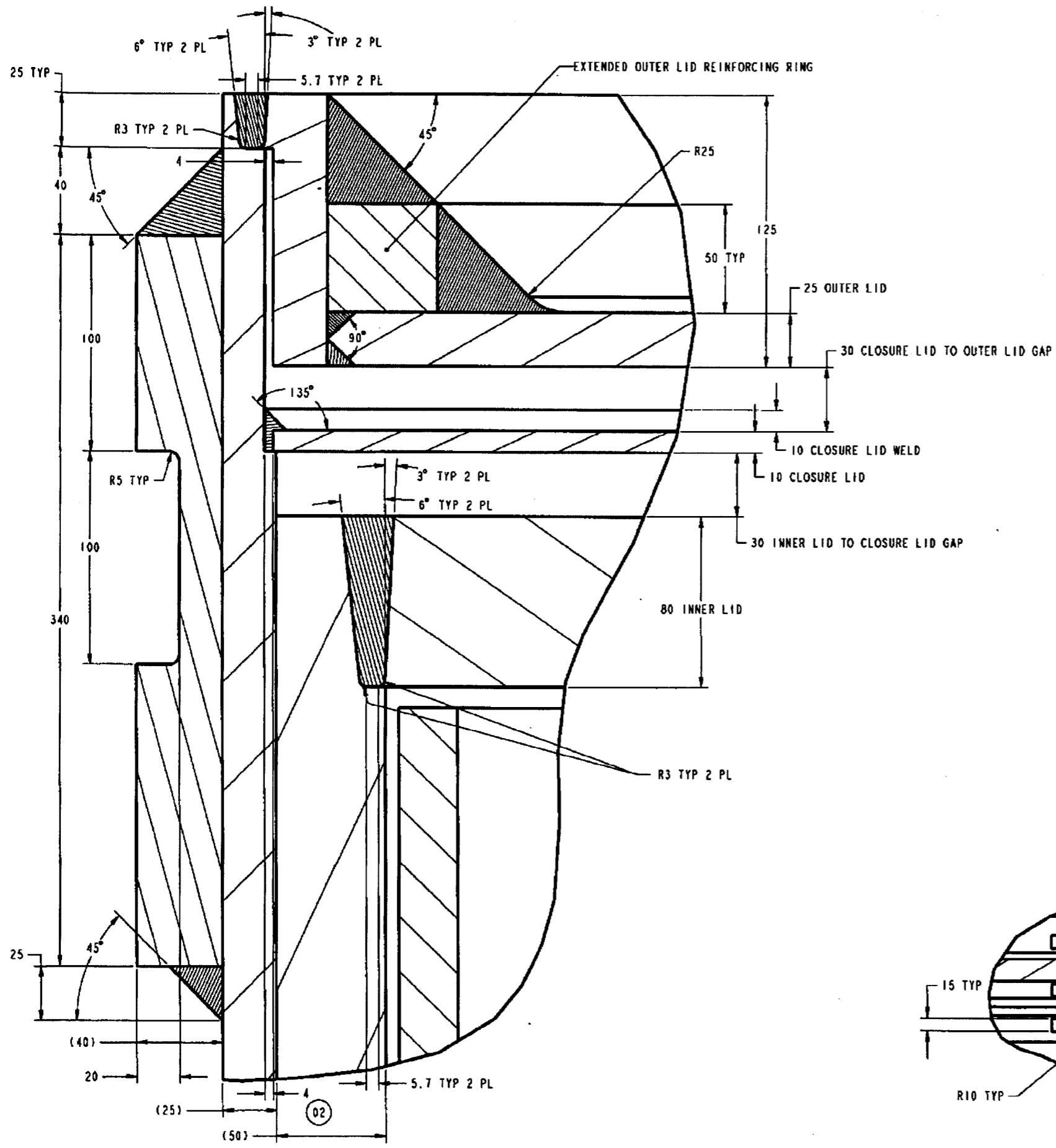
SKETCH NUMBER: SK-0196 REV 03 SHEET 1 OF 2  
 SKETCHED BY: EUGENE CONNELL *EJC* *SMB* *SMB For MJA*  
 DATE: 06/05/00 *06/06/00* *06/06/00* *06/06/00*  
 FILE: /home/pro.library/checkout/sketches/5dhlw\_short/sk-0196\_rev03.dwg

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.

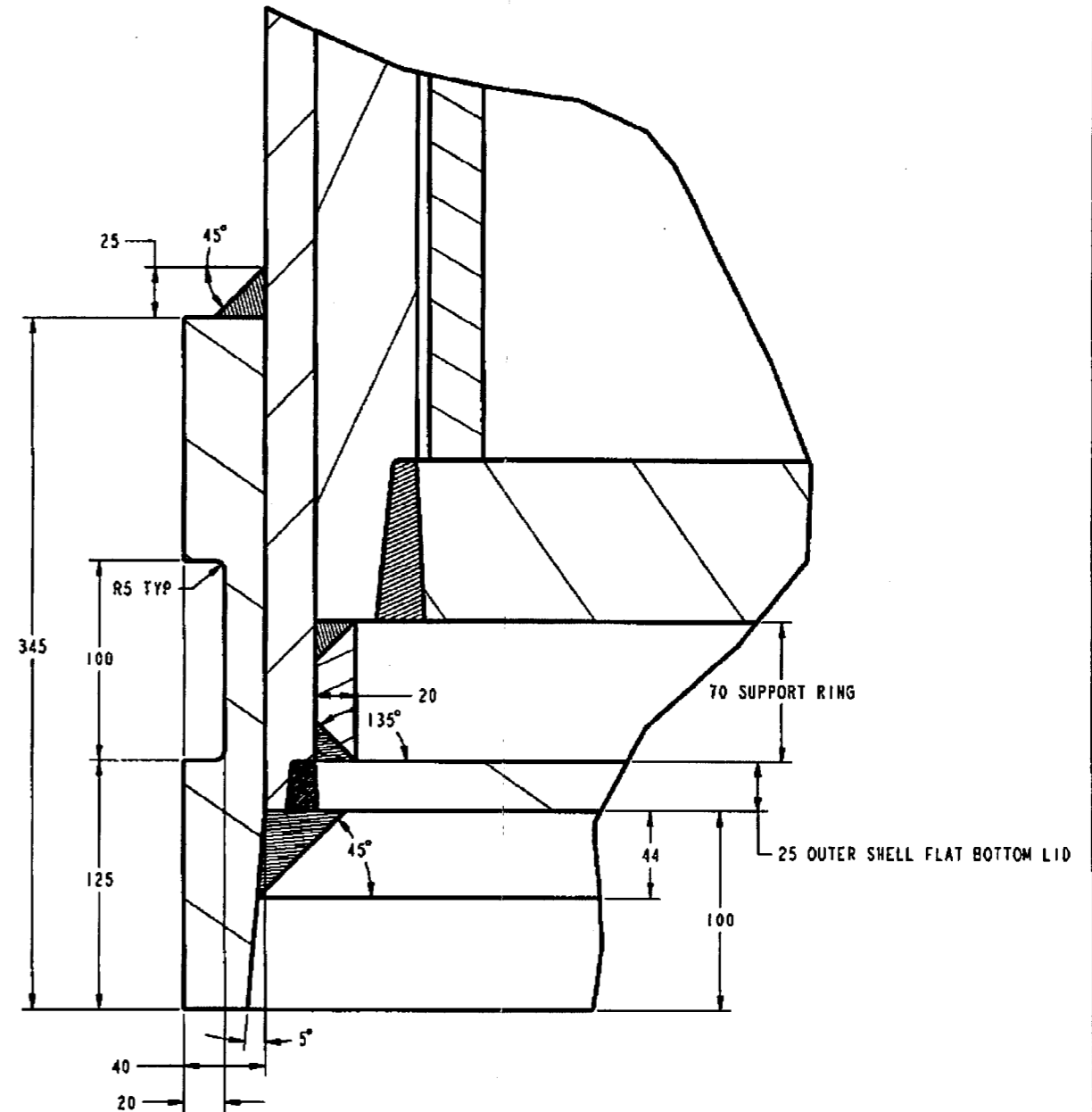
\*\* UNITED STATES DEPARTMENT OF ENERGY 1998. DESIGN SPECIFICATION FOR DEPARTMENT OF ENERGY STANDARDIZED SPENT NUCLEAR FUEL CANISTERS, VOLUME 1, DESIGN SPECIFICATION, REV 01. WASHINGTON D.C.: UNITED STATES DEPARTMENT OF ENERGY. TIC: 241528

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

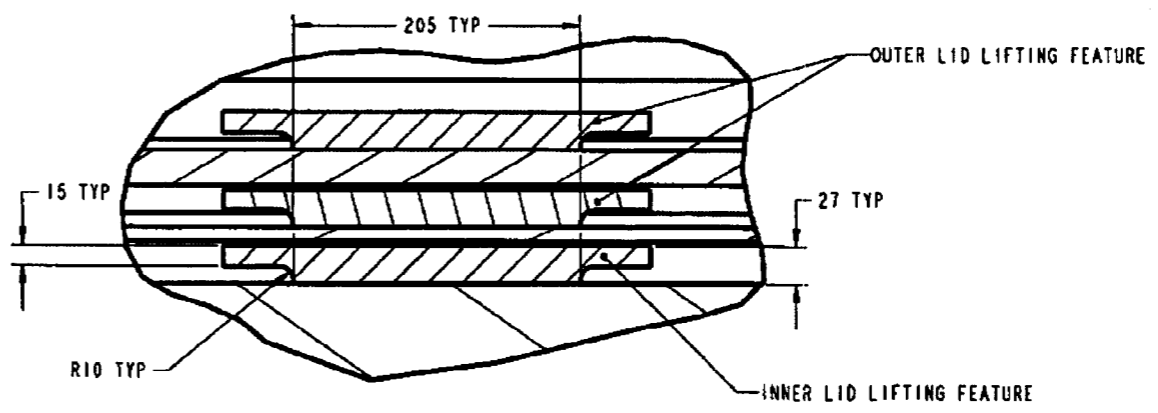
UNITS: mm  
DO NOT SCALE FROM SKETCH



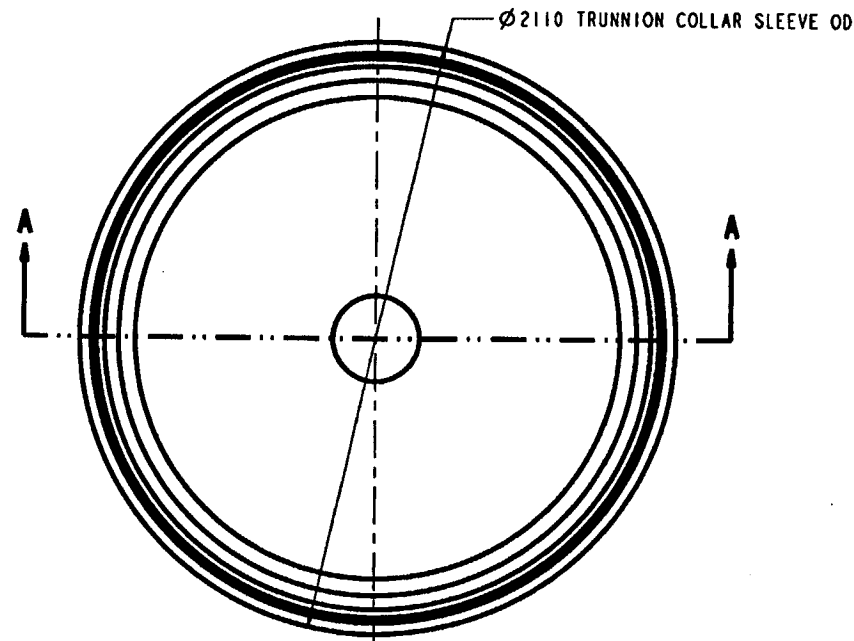
DETAIL A



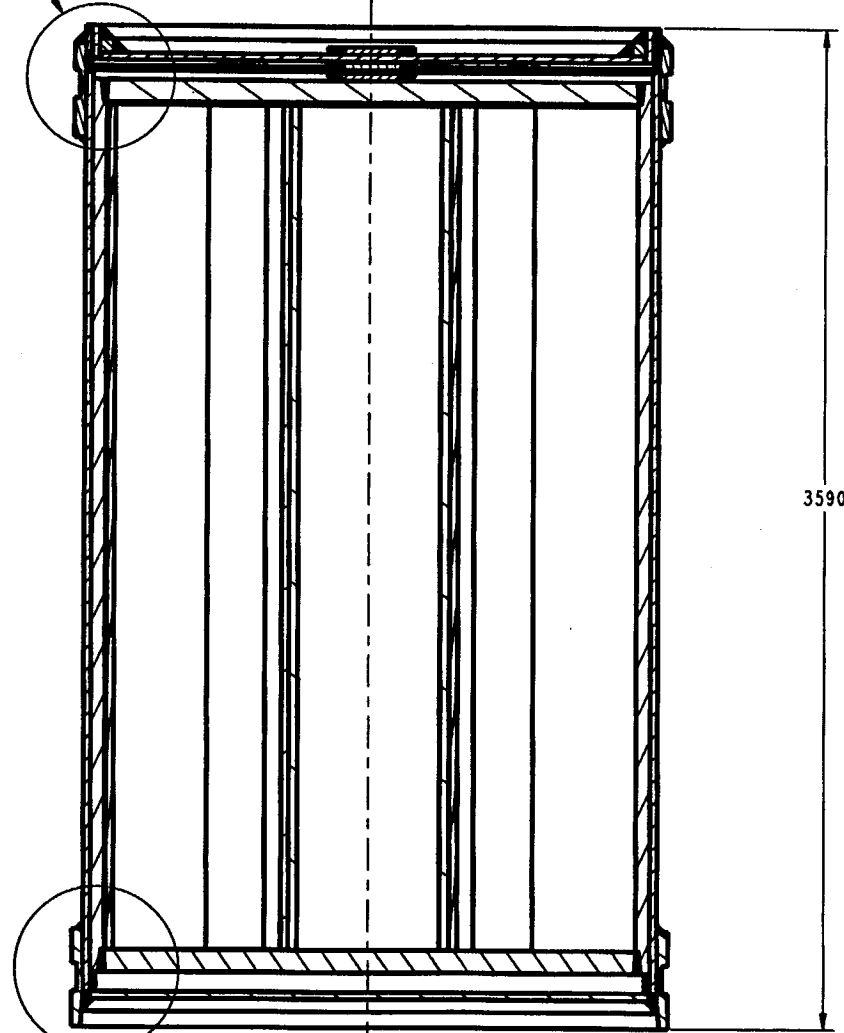
DETAIL B



DETAIL C

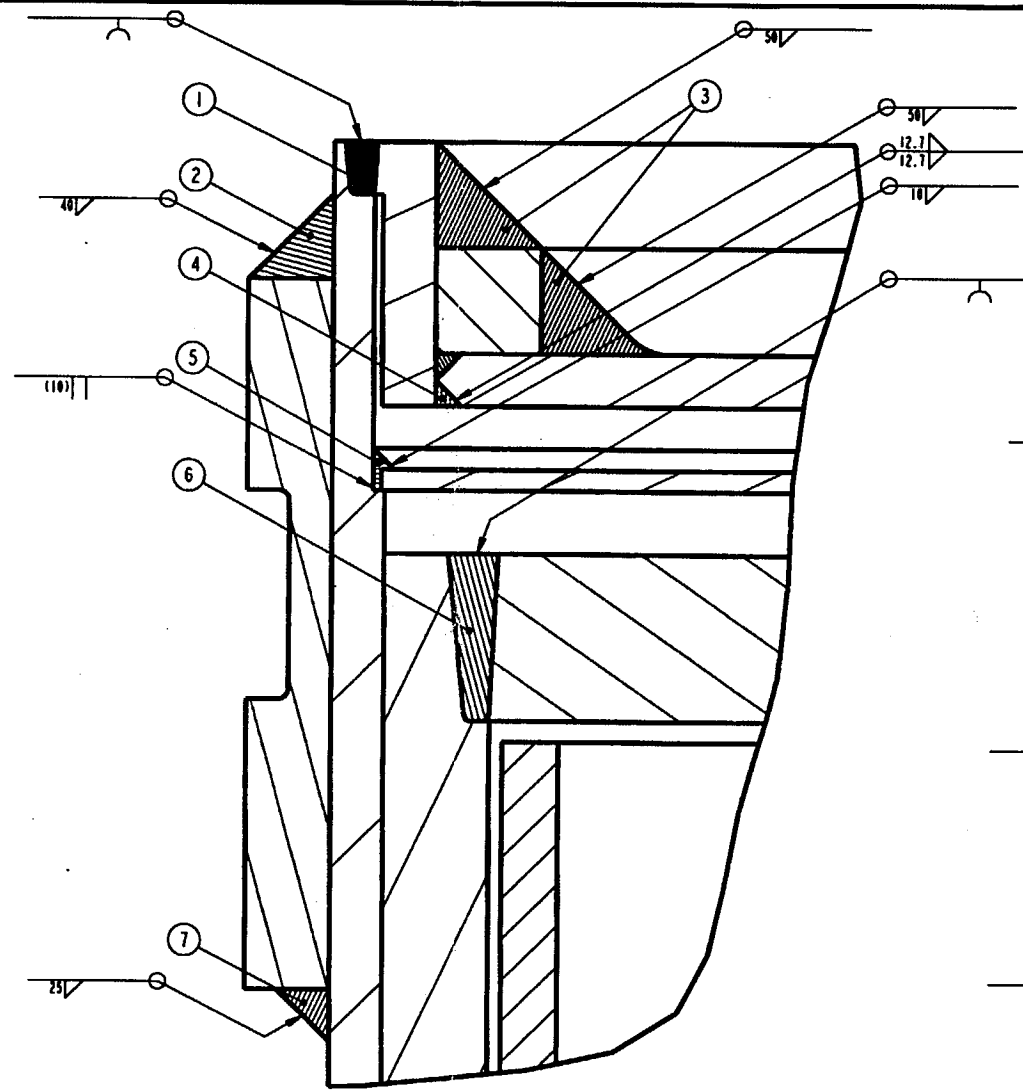


SEE DETAIL A

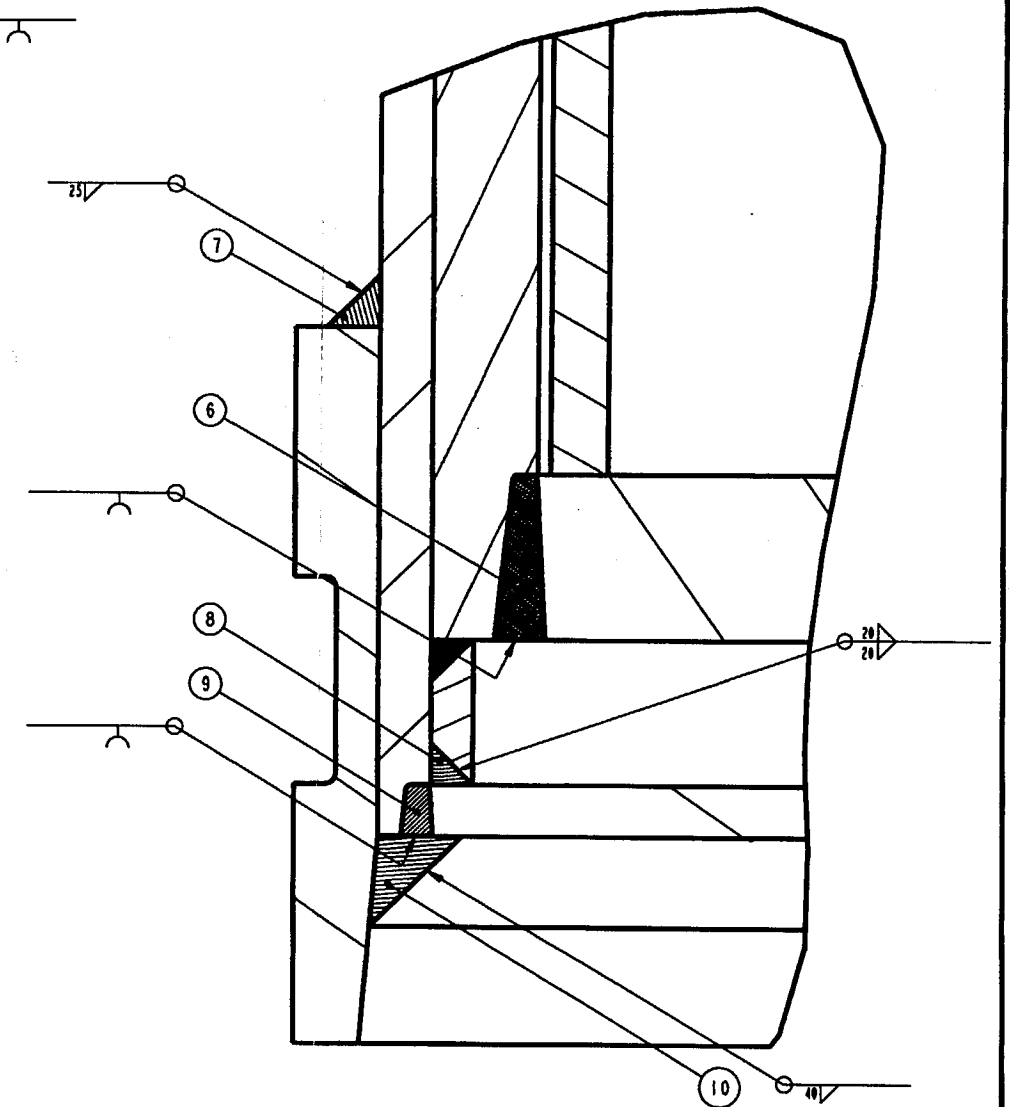


SECTION A-A

SEE DETAIL B



DETAIL A



DETAIL B

WELD	MATERIAL	MASS (KG)	QTY ROD
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**

SKETCH NUMBER: SK-0197 REV 00

SKETCHED BY: BRYAN HARKINS

DATE: 03/10/00

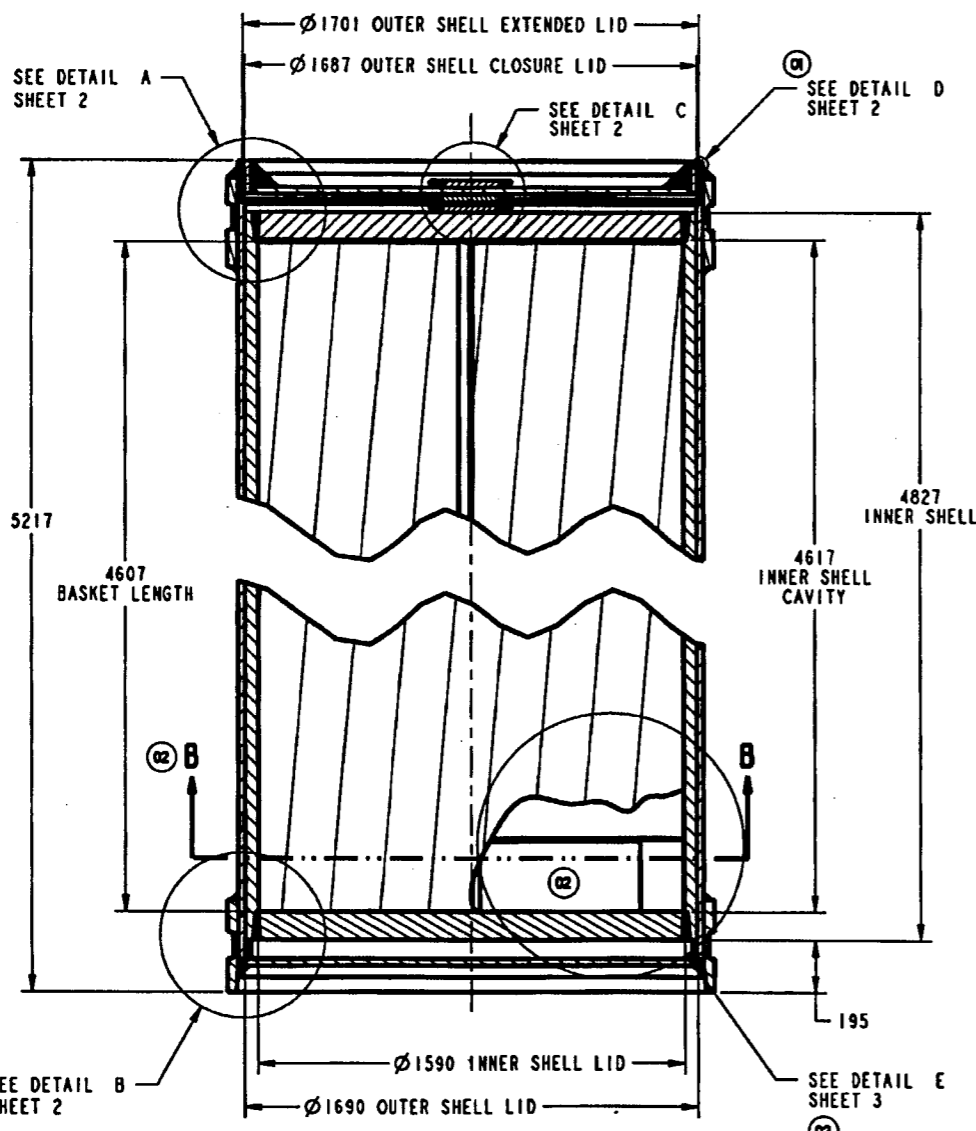
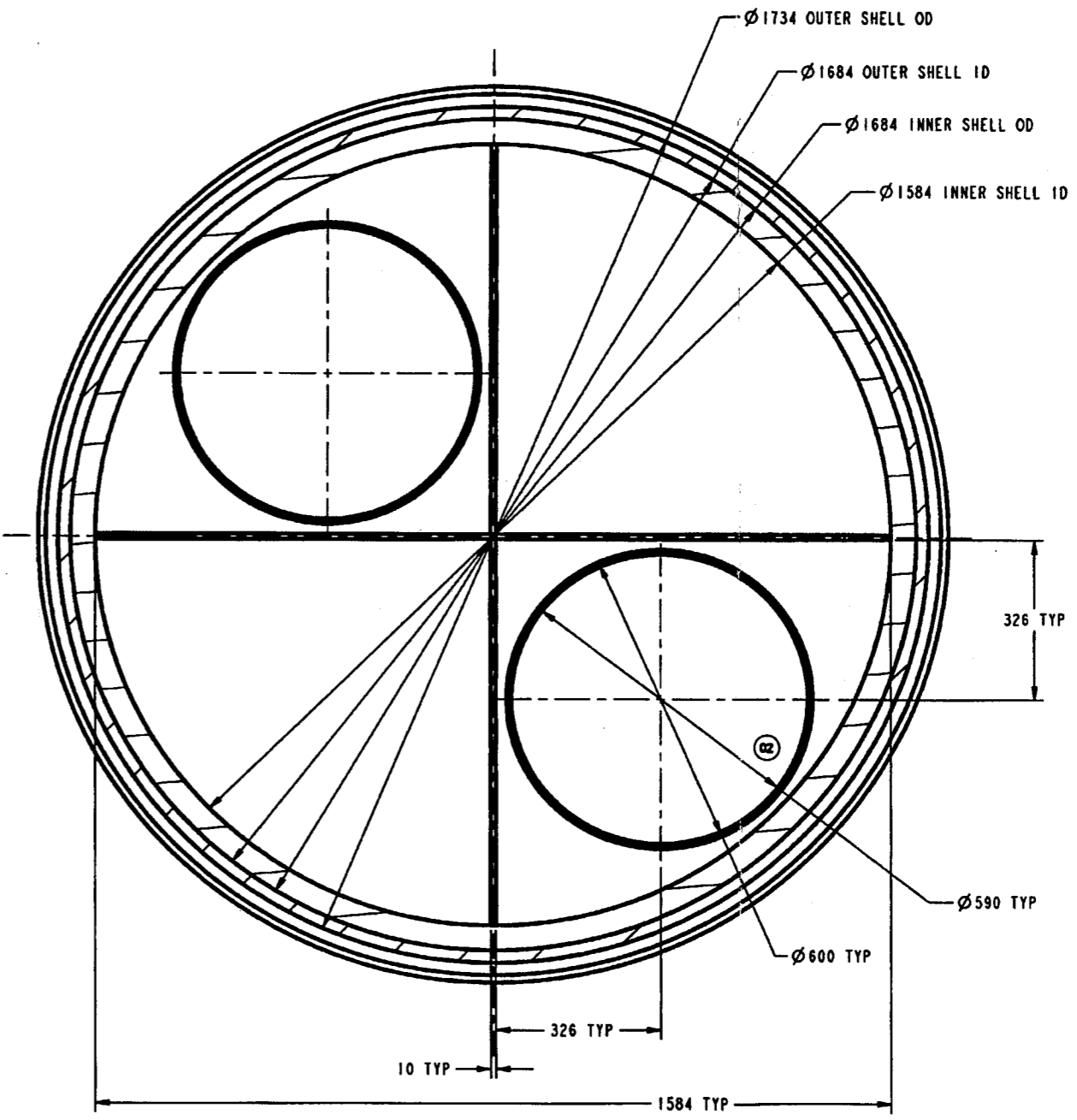
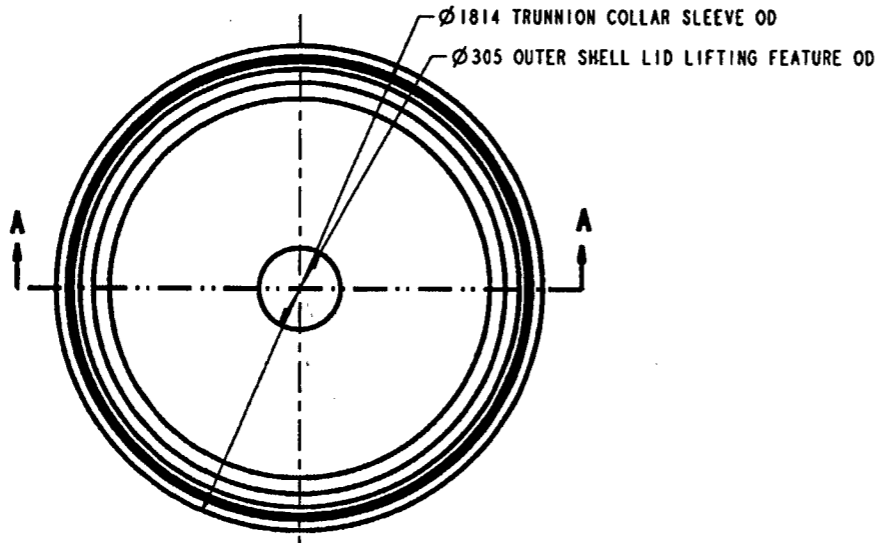
FILE:

/home/pro\_library/checkout/sketches/5dhlw/5dhlw\_short/sk-0197rev00.dwg

*BH*  
10 March 00  
Sms  
03/13/00  
Joe  
3/13/00  
TWB, B.00

ALL SHEETS ARE THE SAME REVISION STATUS

SKETCH NUMBER SK-0198	SHEET 1	NO. OF SHEETS 1	
REV	DESCRIPTION	DATE	APPROVED
	FOR REVISIONS SEE SHEET 3		



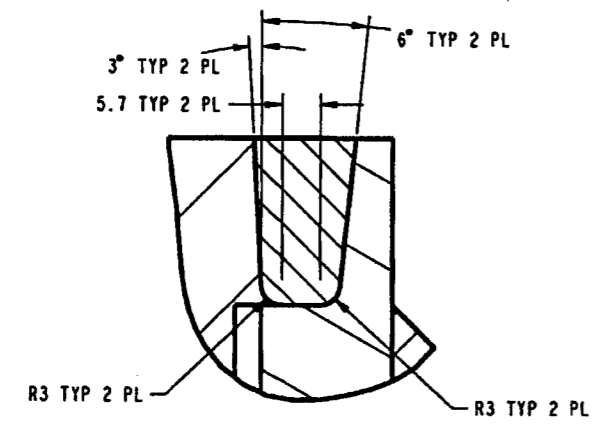
SECTION B-B

SECTION A-A

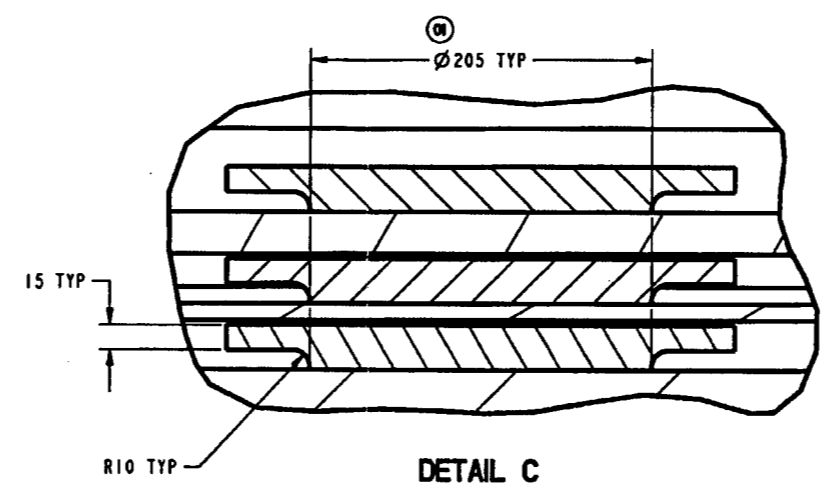
FOR INFORMATION ONLY

<p>"FOR INFORMATION ONLY"</p> <p>THIRD ANGLE PROJECTION</p> <p>DIMENSIONS ARE IN MILLIMETERS AND DEGREES UNLESS OTHERWISE NOTED</p> <p>DO NOT SCALE FROM SKETCH</p>	<p>APPROVALS</p> <p>SKETCHED BY BRYAN HARKINS</p> <p>STRUCTURAL LEAD SCOTT BENNETT</p> <p>MANUFACTURING MGR JERRY COGAR</p> <p>DESIGN GROUP MGR MICHAEL ANDERSON</p>	<p>INITIAL/DATE</p> <p>BA 10/26/00</p> <p>SUB 11/10/00</p> <p>JSC 11/10/00</p> <p>MA 11/15/00</p>	<p>WASTE PACKAGE DEPARTMENT</p> <p><b>M&amp;O</b> <small>Calicut Remediation Waste Management System Management &amp; Operations CONTRACTOR</small></p> <p>TITLE</p> <p>2-MCO/2-DHLW WASTE PACKAGE CONFIGURATION FOR SITE RECOMMENDATION</p> <p>SKETCH NUMBER</p> <p>SK-0198</p> <p>SCALE .08</p>	<p>REVISION</p> <p>04</p> <p>SHEET 1</p>
	<p>WASTE PACKAGE DEPARTMENT</p> <p>2-MCO/2-DHLW WASTE PACKAGE CONFIGURATION FOR SITE RECOMMENDATION</p> <p>SKETCH NUMBER</p> <p>SK-0198</p> <p>SCALE .08</p>			<p>REVISION</p> <p>04</p> <p>SHEET 1</p>

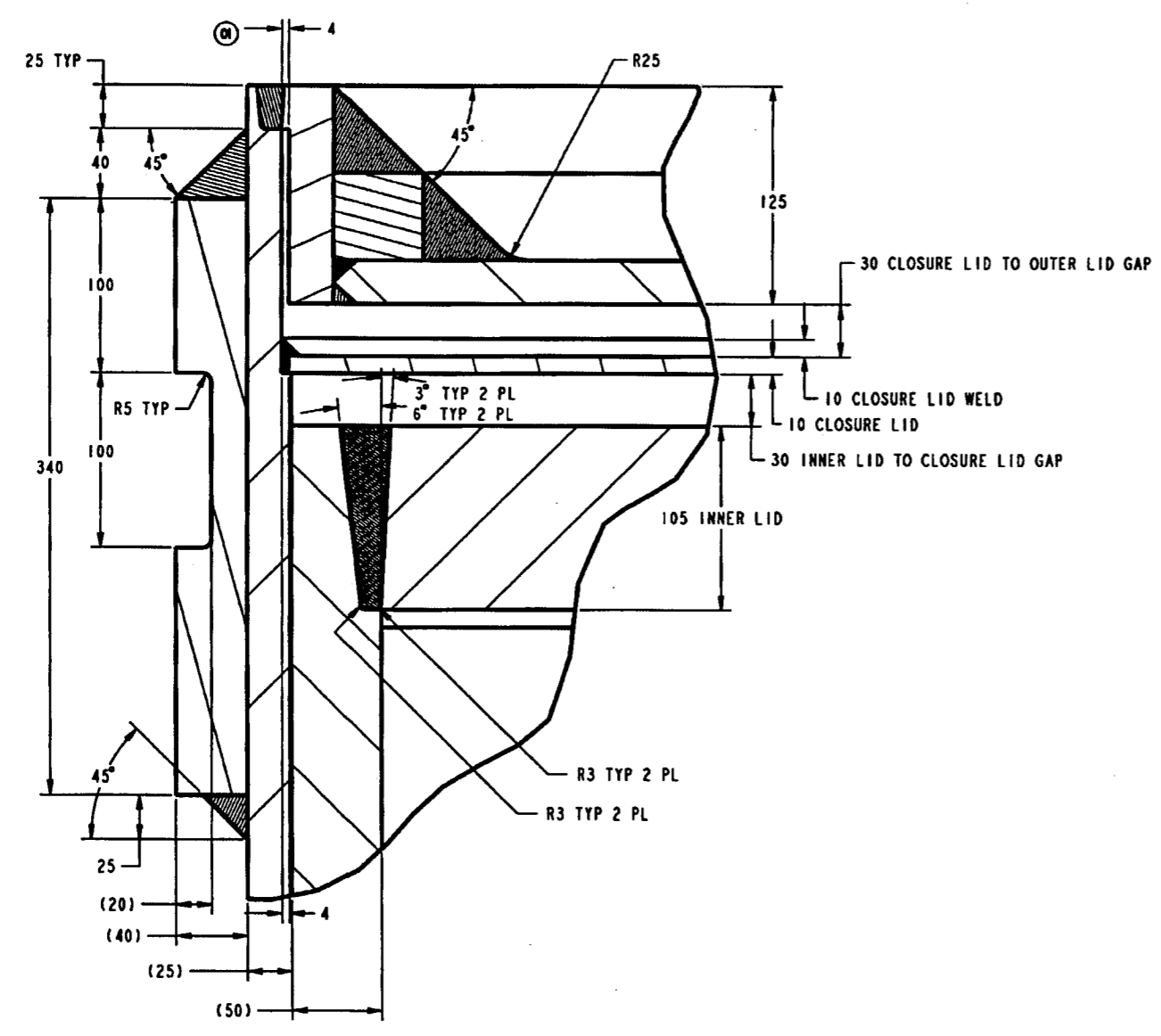




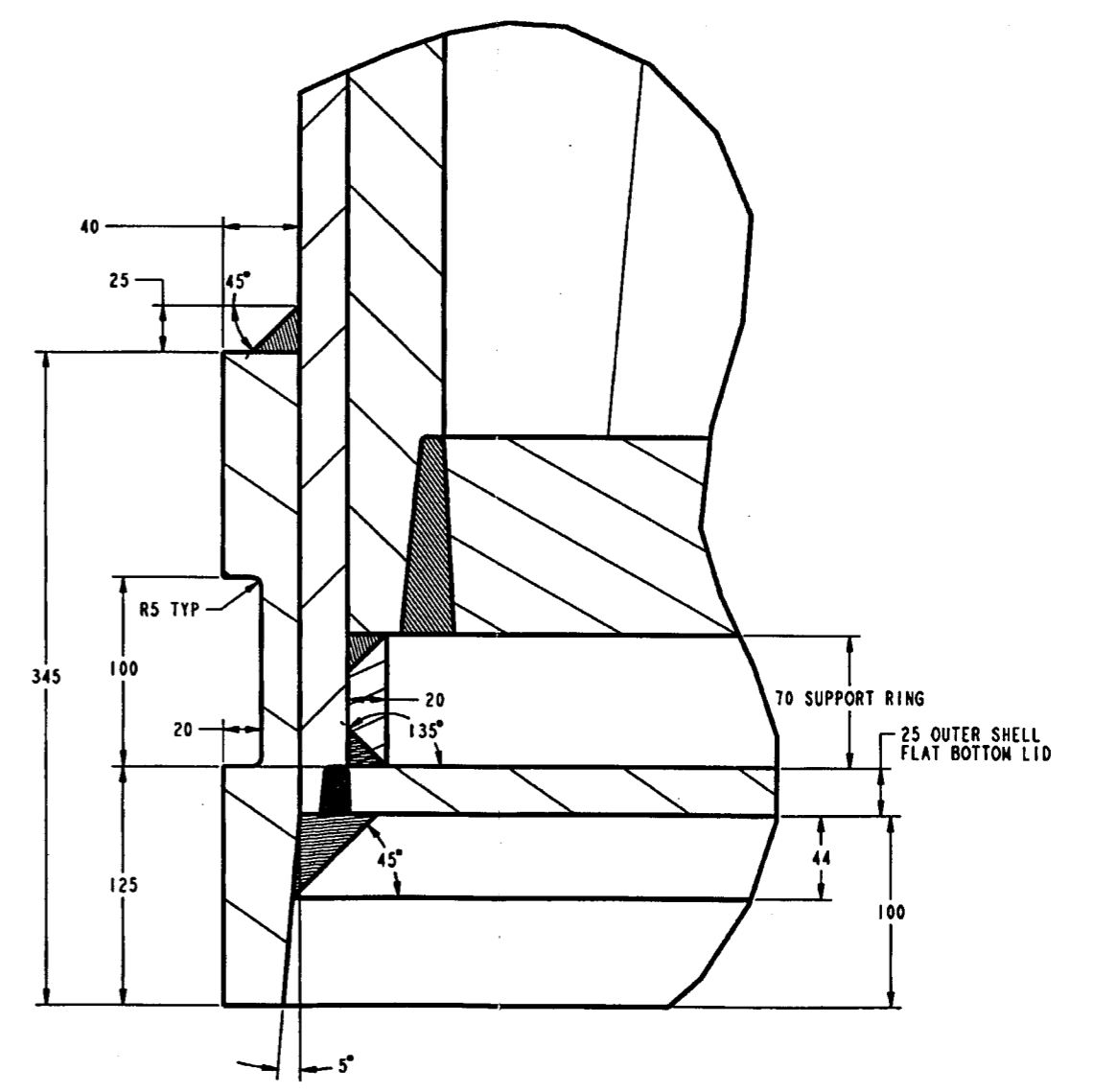
DETAIL D



DETAIL C



DETAIL A

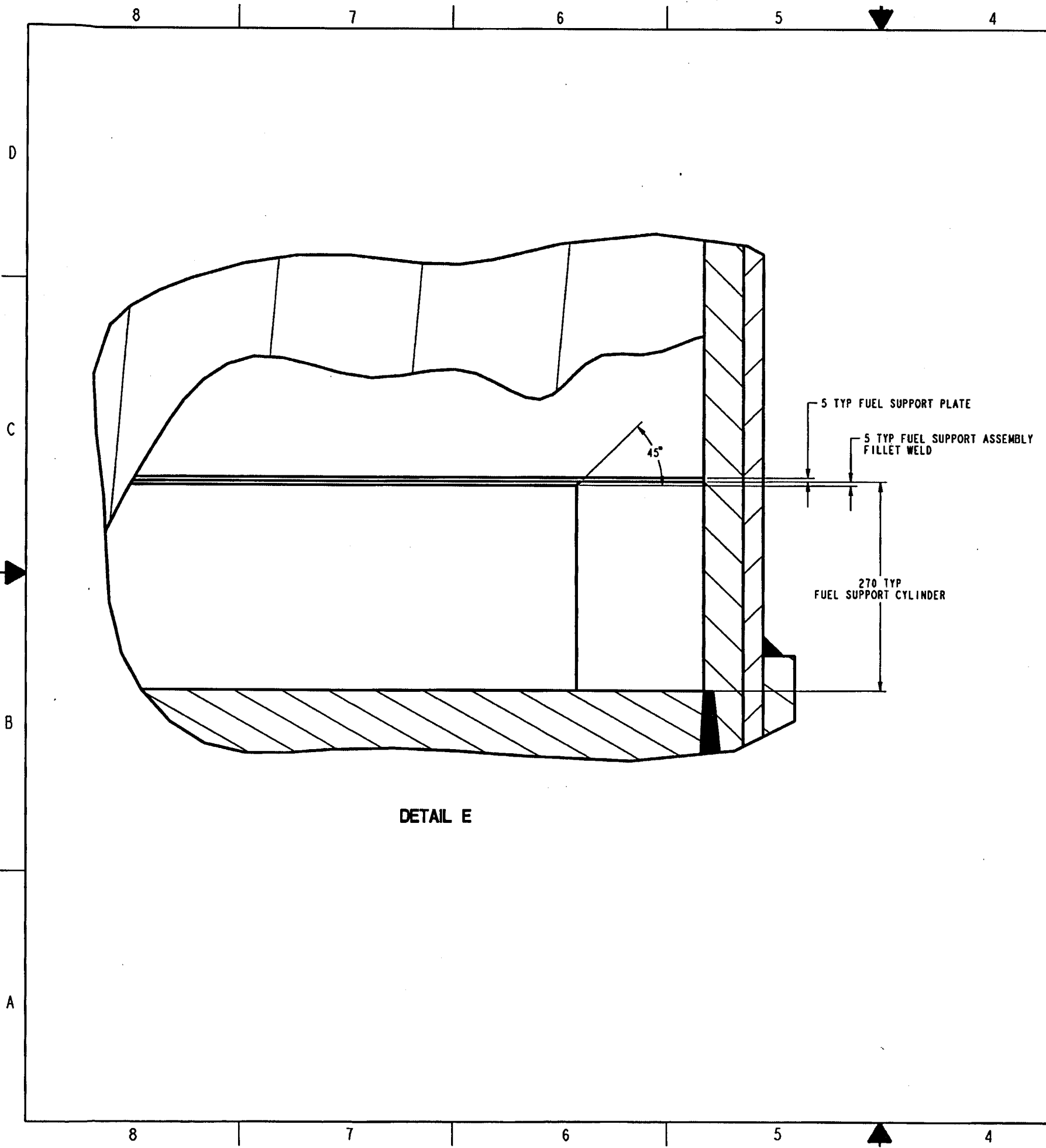


DETAIL B

WASTE PACKAGE DEPARTMENT	
M&O Civilian Radioactive Waste Management System MANAGEMENT & OPERATING CONTRACTOR	
SKETCH NUMBER	REVISION
SK-0198	04
SCALE	SHEET
00	2

SECTION NUMBER  
8610-XS  
233MS  
DOE/RW-0351

REVISION TABLE			
REV	DESCRIPTION	DRW BY	DATE
00	ISSUED APPROVED	DM	01/25/00
01	MASS 9743 "WAS" 9730, MASS 1641 "WAS" 1647, MASS 5897 "WAS" 4670, MASS 561 "WAS" 558, MASS 550 "WAS" 547, MASS 276 "WAS" 274, MASS 23801 "WAS" 21846, MASS 49300 "WAS" 48066, THICKNESS 25 "WAS" 20, SKETCHED BY "WAS" ORIGINATOR, "CREATED" DETAIL D, "ADDED" Ø TO DETAIL C, "DELETED" WELD DIMENSIONS FROM DETAIL A	BH	03/09/00
02	MASS 23159 "WAS" 23081, MASS 49378 "WAS" 49300, "ADDED" FUEL SUPPORT ASSEMBLY, "MODIFIED" COMPONENTS LIST, "CREATED" DETAIL E, MOVED COMPONENTS LIST TO SHEET 3, "MOVED" REVISION TABLE TO SHEET 3, "MODIFIED" REVISION TABLE FORMAT, "ADDED" DIMENSIONS TO SECTION B-B.	BH	05/18/00
03	DOE/RW-0351 "WAS" DOE/RW-0315P, "ADDED" NEW FORMAT, "MODIFIED" REVISION TABLE	EJC	06/09/00
04	8746.4 MCO MASS WAS 8909.6, REFERENCE CHANGED, 49052 LOADED WP MASS WAS 49378	BH	11/10/00



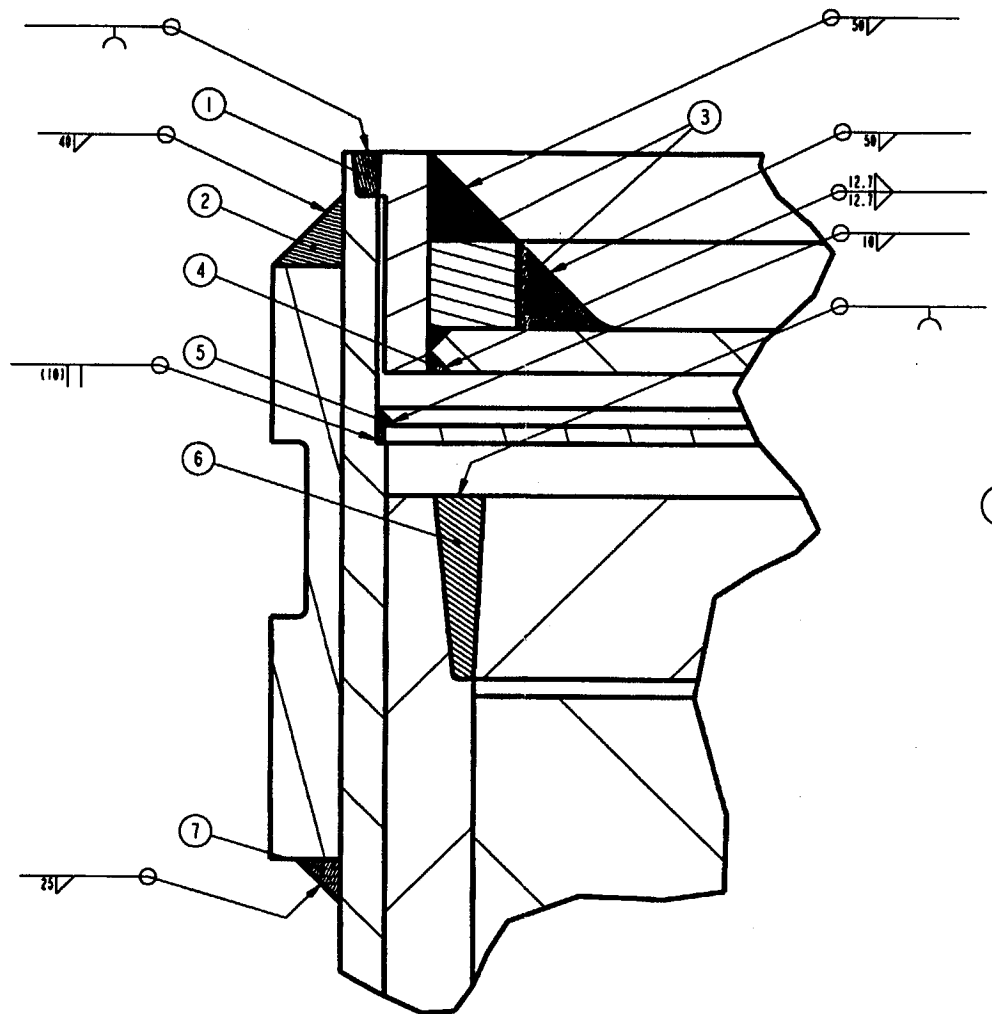
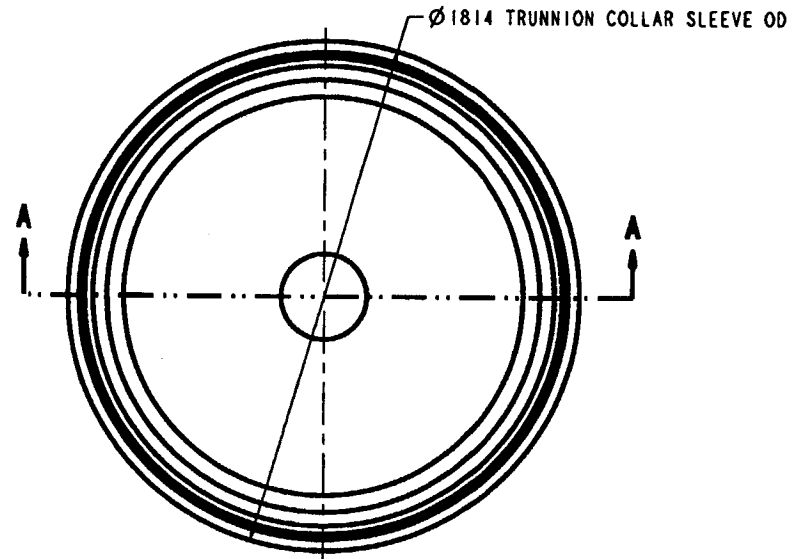
COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
A-PLATE	SA-516 K02700	10	571	2
02 FUEL SUPPORT PLATE	SA-516 K02700	5	19	2
02 FUEL SUPPORT CYLINDER	SA-516 K02700	5	20	2
INNER SHELL	SA-240 S31600	50	01 9743	1
INNER SHELL LID	SA-240 S31600	105	01 1641	2
INNER LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	01 25	01 5897	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	146	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	450	1
EXTENDED OUTER LID REINFORCING RING	SB-575 N06022	50	108	1
OUTER LID LIFTING FEATURE	SB-575 N06022	27	13	2
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	194	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	484	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	01 561	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	01 550	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	45	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	01 276	***
TOTAL 316 WELDS	SFA-5.9 S31680	-	164	***
02 TOTAL CARBON STEEL WELDS	SFA-5.18 K10726	-	0.37	***
WASTE PACKAGE ASSEMBLY	-	-	01 02 23159	1
HLW GLASS ASSEMBLY	-	-	4200*	2
MCO	-	-	04 8746.4**	2
WP ASSEMBLY WITH SNF	-	-	01 02 49052 04	1

03 \* WASTE ACCEPTANCE SYSTEM REQUIREMENTS DOCUMENT. E0000000-00811-1708-00001 REV 03, DOE/RW-0351. ACC: HQO.19990226.0001, PAGE 18, SECTION 4.2.3.1.A.4.

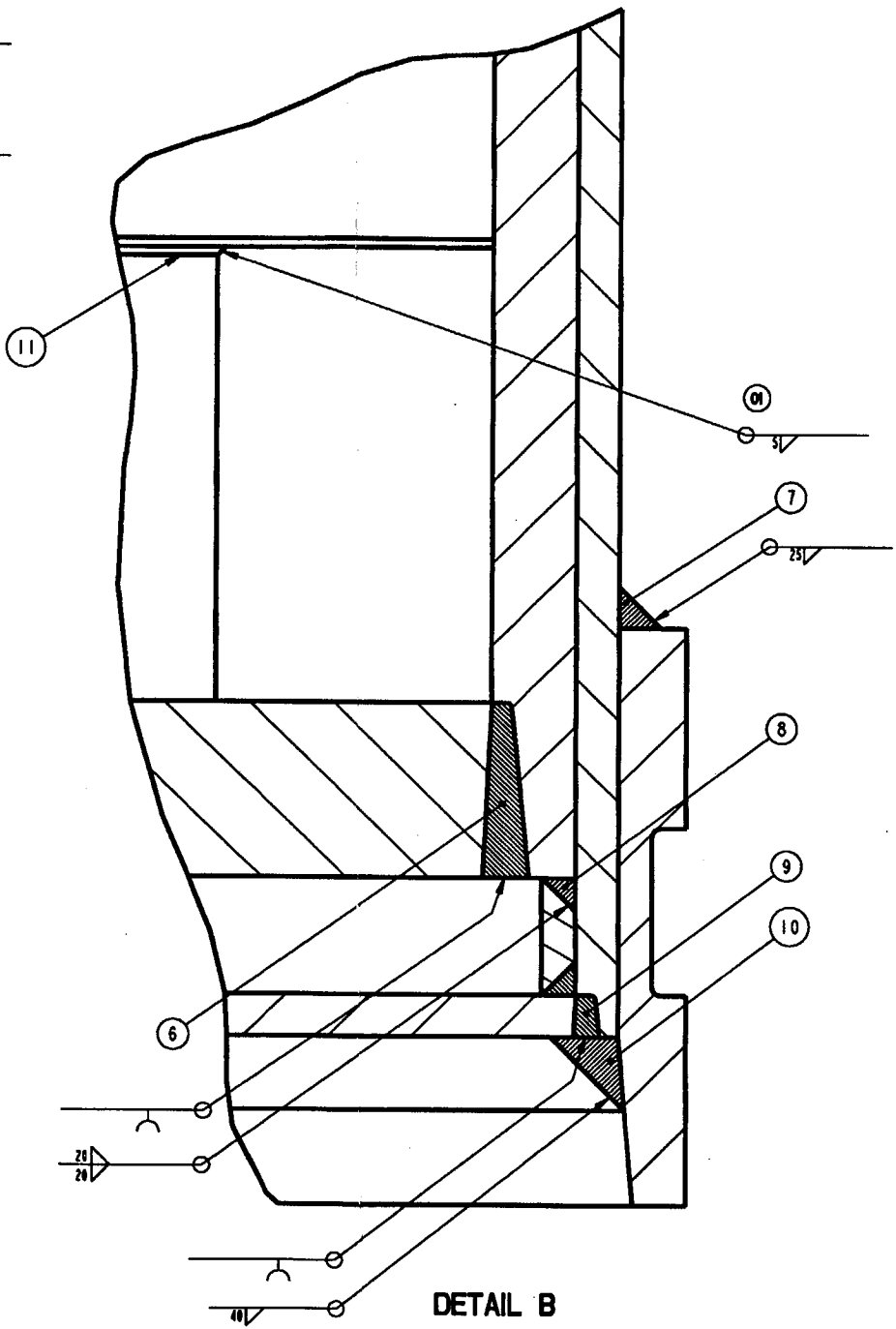
04 \*\* U.S. DEPARTMENT OF ENERGY 2000. N REACTOR (U-METAL) FUEL CHARACTERISTICS FOR DISPOSAL CRITICALITY ANALYSIS. DOE/SNF/REP-056 REV 0. U.S. DEPARTMENT OF ENERGY. TIC: 247956

\*\*\* SEE SK-0199 FOR WELD CONFIGURATION AND MASSES.

WASTE PACKAGE DEPARTMENT  
**M&O** Clinton Radiologic Waste Management System  
MANAGEMENT & OPERATING CONTRACTOR  
 SKETCH NUMBER: SK-0198  
 REVISION: 04  
 SCALE: .08  
 SHEET: 3

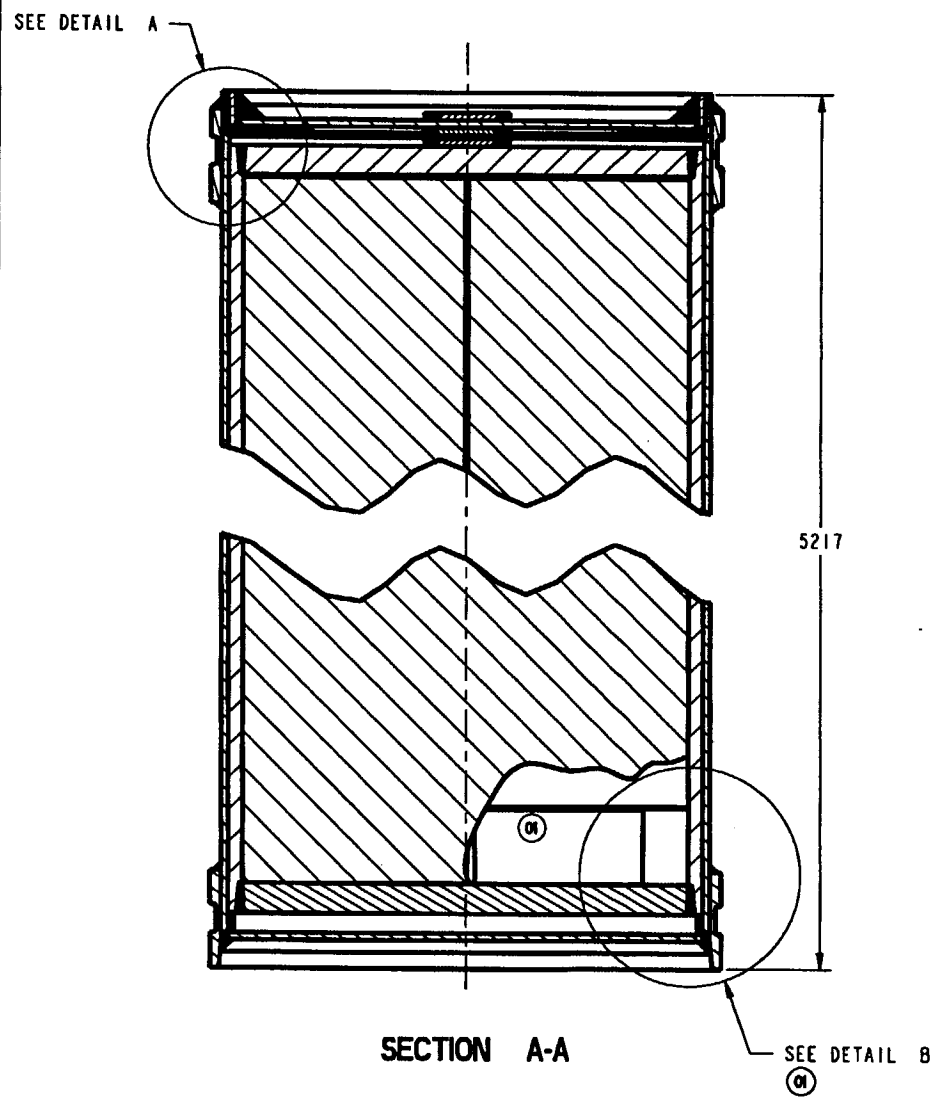


DETAIL A



DETAIL B

"FOR INFORMATION ONLY"



REVISION TABLE			
REV	DESCRIPTION	CHK BY	DATE
00	ISSUED APPROVED	BH	03/08/00
01	FUEL SUPPORT ASSEMBLY WELD ADDED TO WP ASSEMBLY	BH	05/09/00
01	WELD SYMBOL FOR FUEL SUPPORT ASSEMBLY WELD ADDED TO DETAIL B	BH	05/09/00
01	FUEL SUPPORT ASSEMBLY WELD ADDED TO WELD TABLE AS WELD 11	BH	05/09/00
01	TOTAL CARBON STEEL WELDS ADDED TO WELD TABLE	BH	05/09/00
01	LOCATION OF DETAIL B FROM SECTION A-A WAS MODIFIED	BH	05/09/00

WELD	MATERIAL	MASS (KG)	QTY ROD
1	SFA-5.14 N06022	15	1
2	SFA-5.14 N06022	38	1
3	SFA-5.14 N06022	107	1
4	SFA-5.14 N06022	3.5	2
5	SFA-5.14 N06022	4.2	1
6	SFA-5.9 S31680	82	2
7	SFA-5.14 N06022	15	2
8	SFA-5.14 N06022	9.1	2
9	SFA-5.14 N06022	15	1
10	SFA-5.14 N06022	41	1
⑪	SFA-5.18 K10726	0.19	2
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	276	-
TOTAL 316 WELDS	SFA-5.9 S31680	164	-
⑪ TOTAL CARBON STEEL WELDS	SFA-5.18 K10726	0.38	-

UNITS: mm

DO NOT SCALE FROM SKETCH

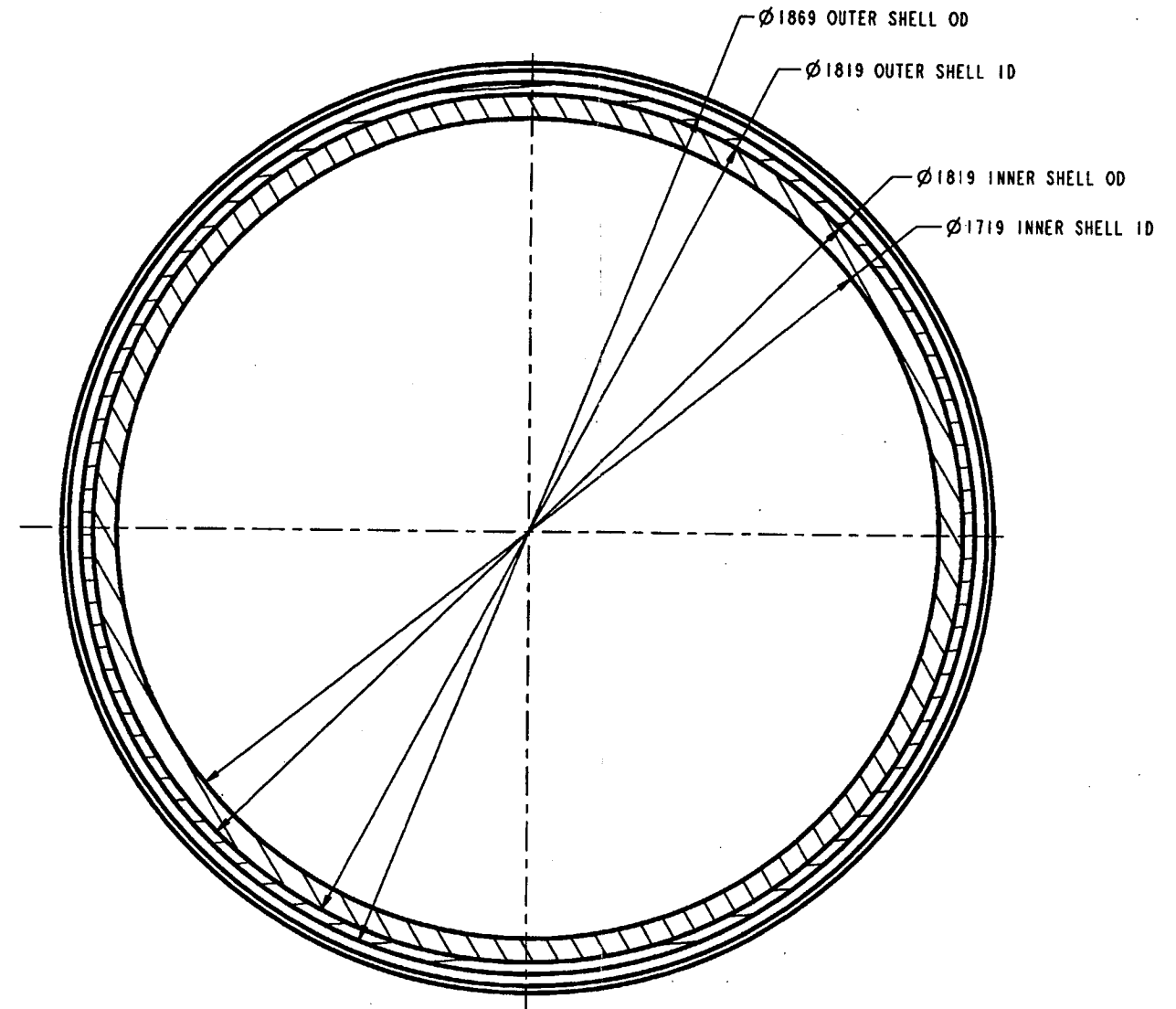
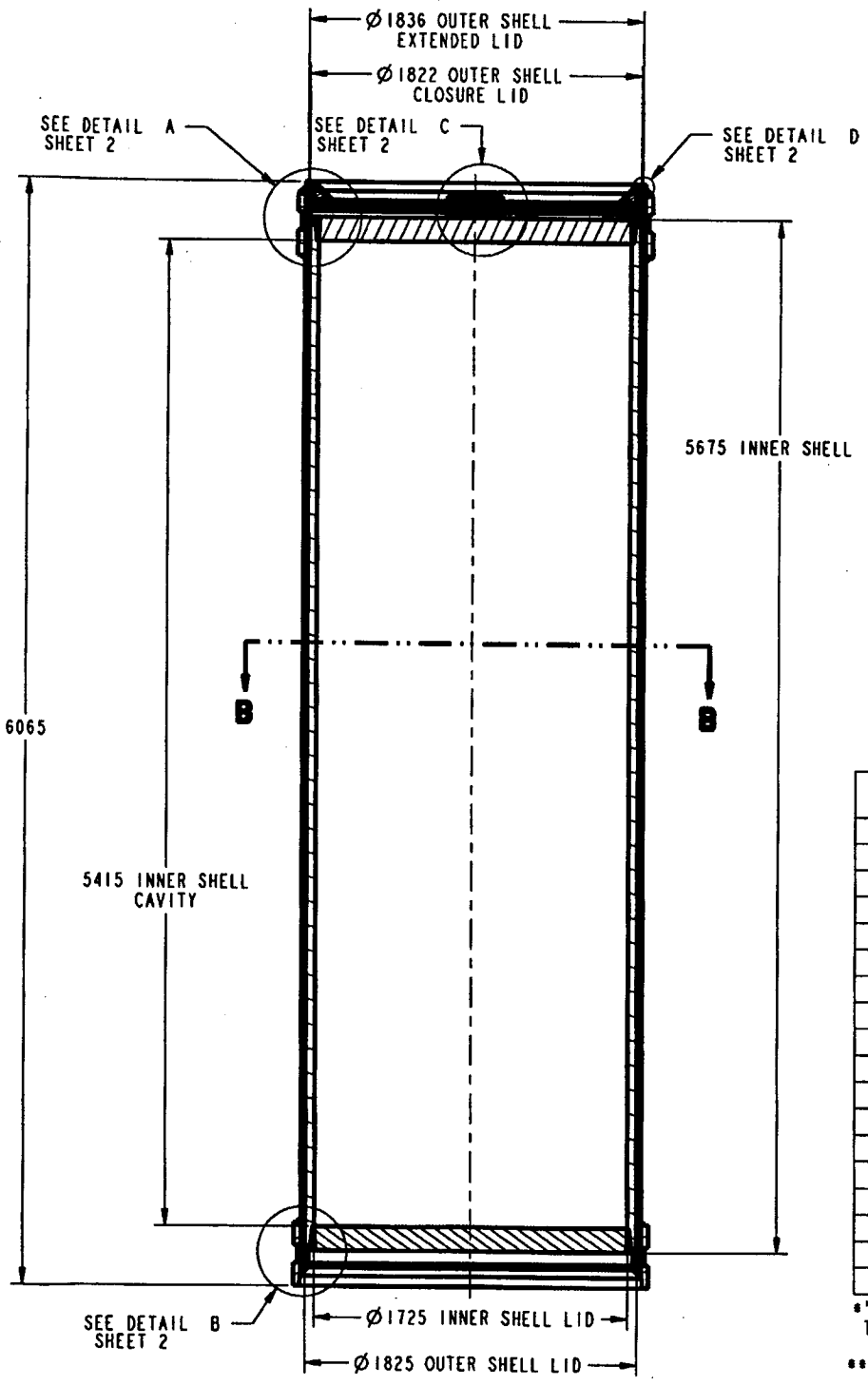
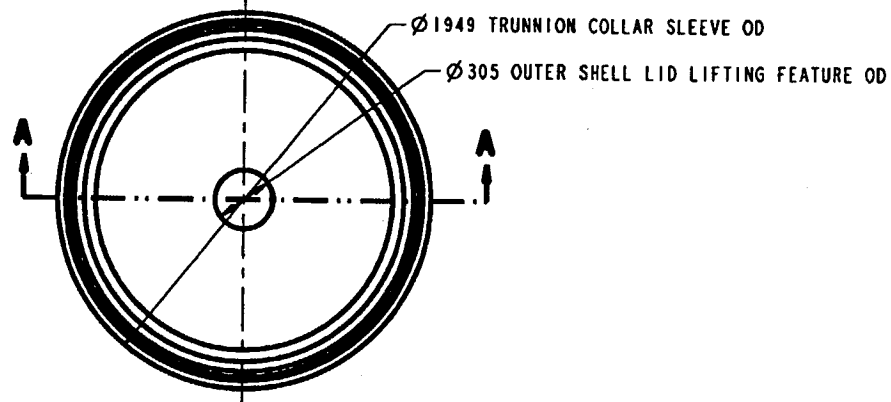
**2-MCO / 2-DHLW WASTE PACKAGE WELD CONFIGURATION**

SKETCH NUMBER: SK-0199 REV 01

SKETCHED BY: BRYAN HARKINS *BH*

DATE: 05/09/00 *24/05/00 SMO*

FILE: /home/pro\_library/checkout/sketches/2mco\_2dhlw/sk-0199rev01.dwg *WES/24/05*



SECTION B-B

COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
INNER SHELL	SA-240 S31600	50	12372	1
INNER SHELL LID	SA-240 S31600	130	2390	2
INNER LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	25	7430	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	158	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	528	1
EXTENDED LID REINFORCEMENT RING	SB-575 N06022	50	118	1
OUTER LID LIFTING FEATURE	SB-575 N06022	27	13	2
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	227	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	564	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	604	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	592	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	49	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	298	**
TOTAL 316 WELDS	SFA-5.9 S31680	-	243	**
WASTE PACKAGE ASSEMBLY	-	-	28005	1
NAVAL SNF	-	-	44452*	1
WASTE PACKAGE WITH SNF	-	-	72457	1

\*MAXIMUM EXPECTED PARAMETERS FOR NAVAL REACTORS CANISTERS\* 10/29/97 FROM: RICHARD GUIDA TO: RUSSELL DYER. MOL.19980121.0011

\*\*REFER TO SK-0195 REV 00 "NAVAL SNF LONG WASTE PACKAGE WELD CONFIGURATION"

UNITS: mm

DO NOT SCALE FROM SKETCH

"FOR INFORMATION ONLY"

NAVAL SNF LONG WASTE PACKAGE CONFIGURATION FOR SITE RECOMMENDATION

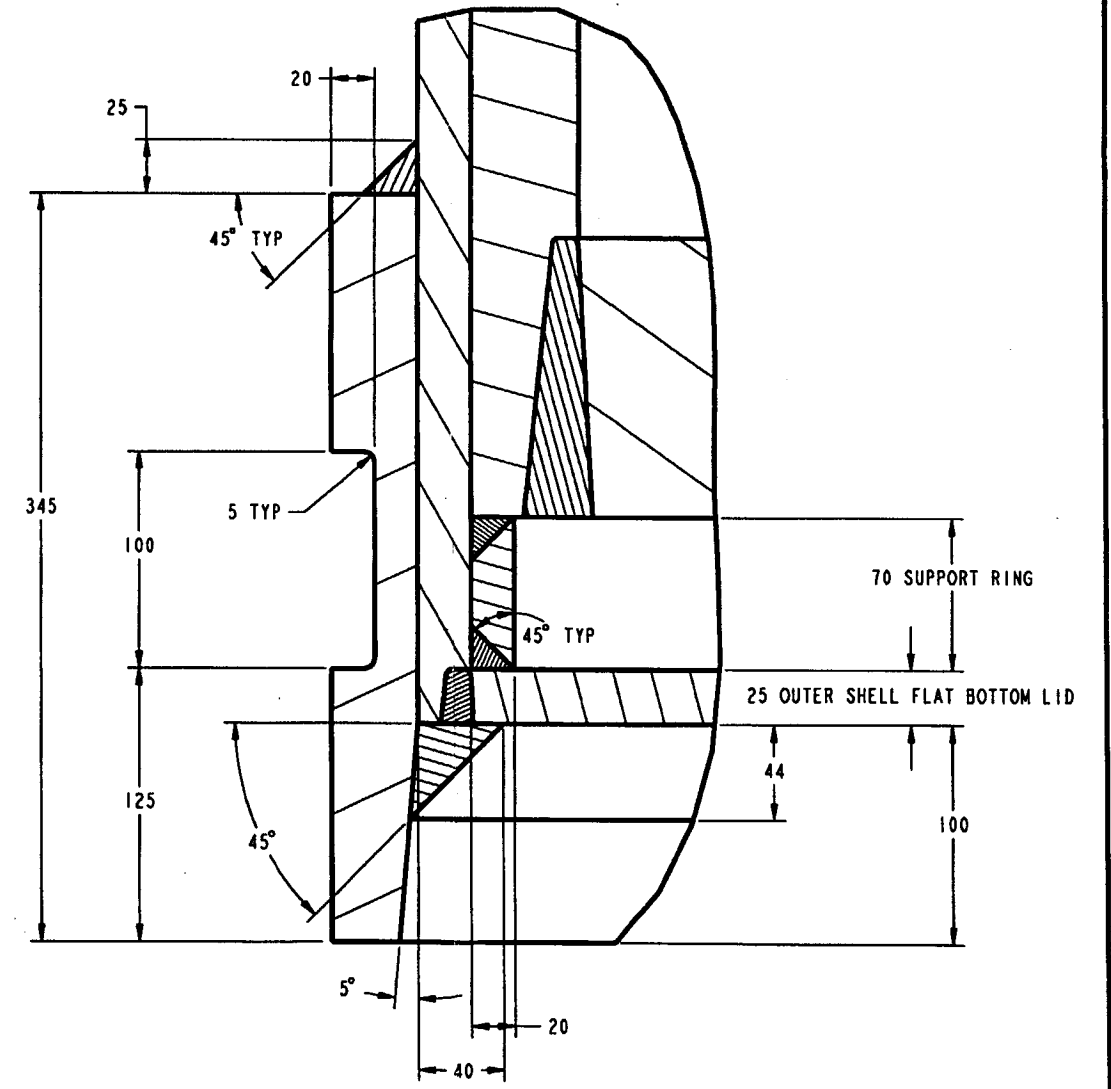
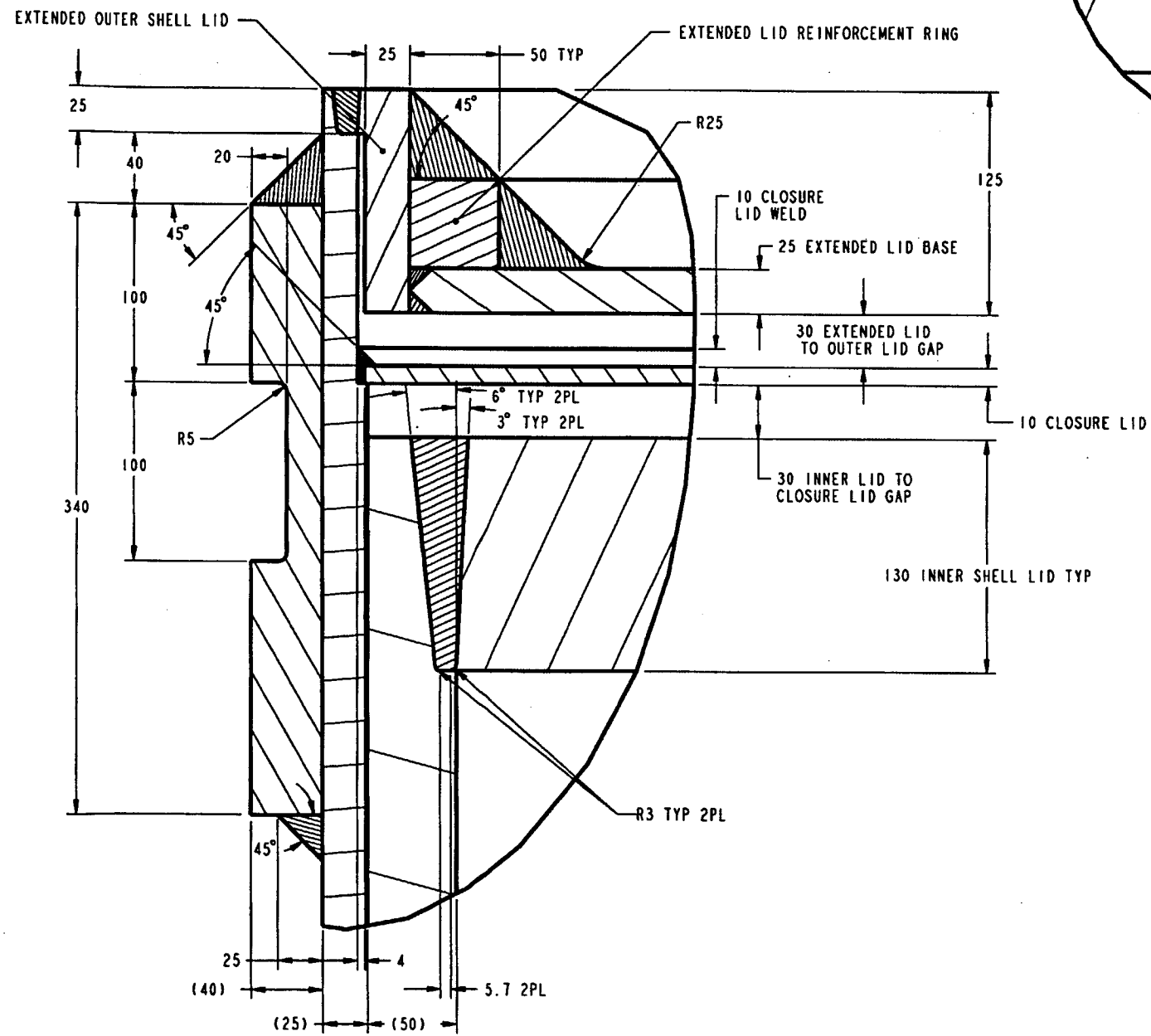
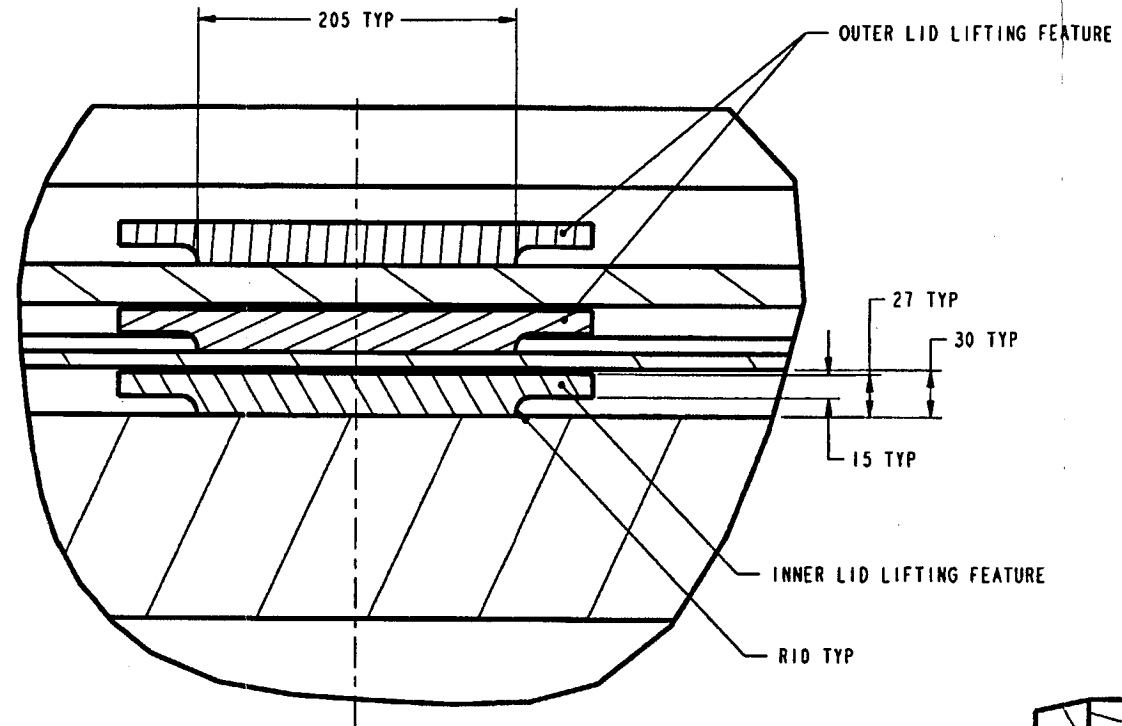
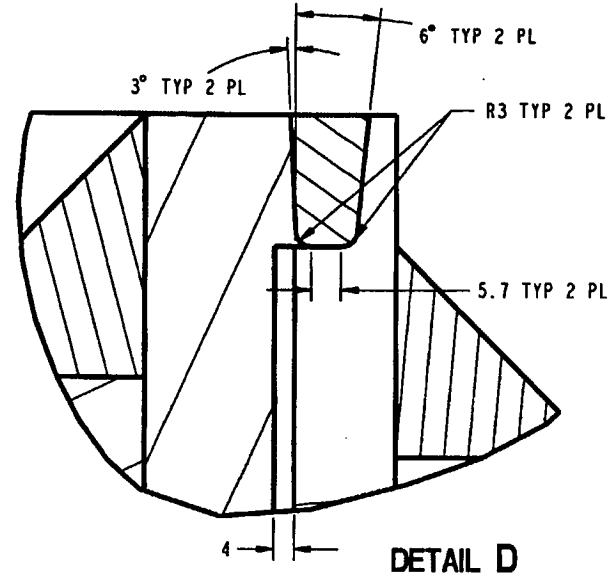
SKETCH NUMBER: SK-0194 REV 01 SHEET 1 OF 2

SKETCHED BY: GENE CONNELL *gpc 01/26/00*

DATE: 01/11/00

FILE: /home/pro\_library/checkout/sketches/naoal/naoal snf long/SK-0194.dwg

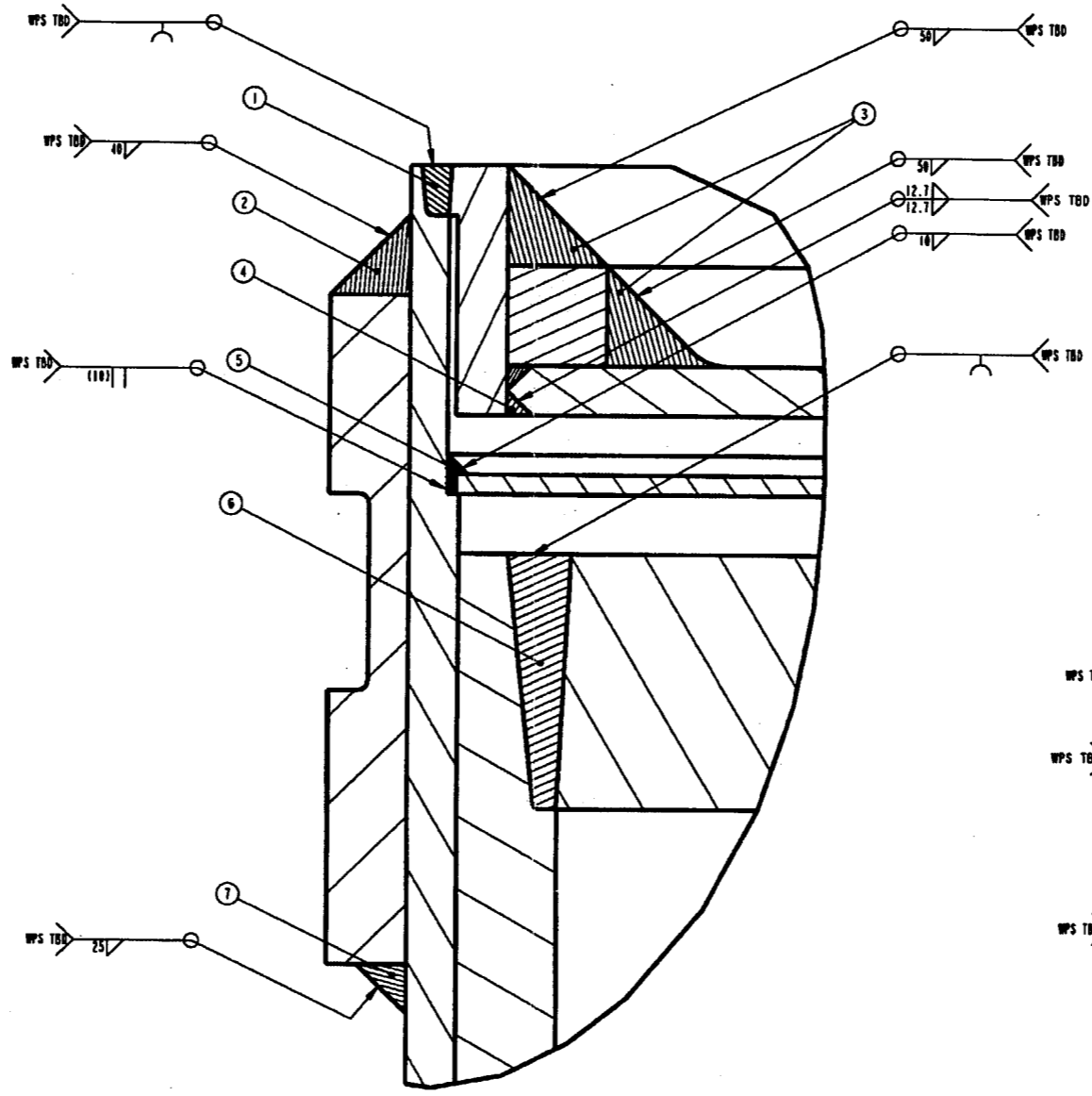
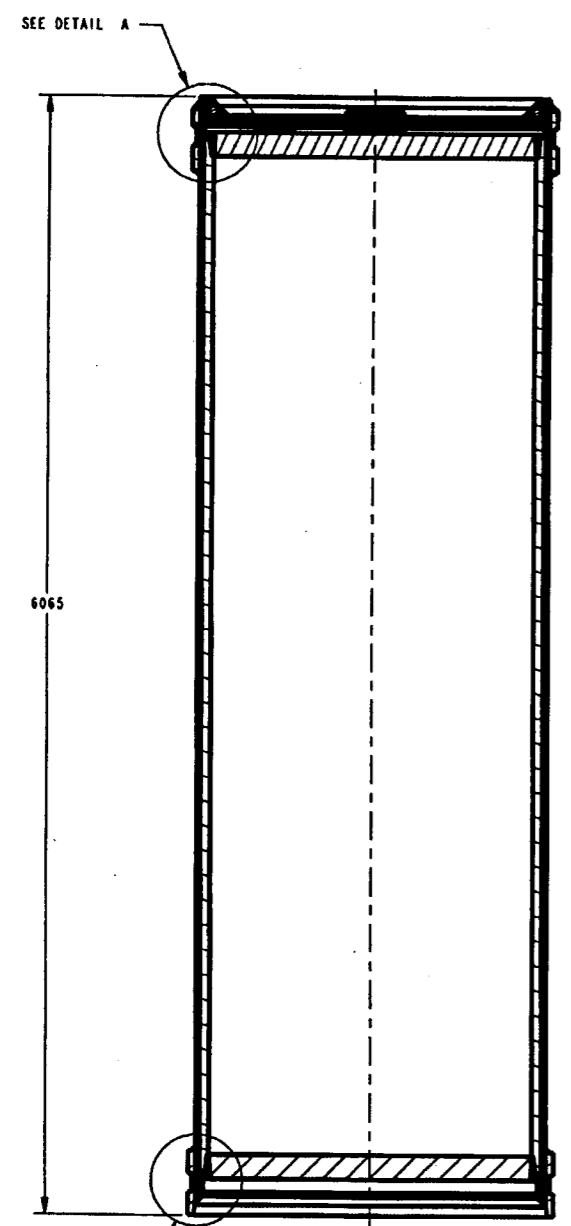
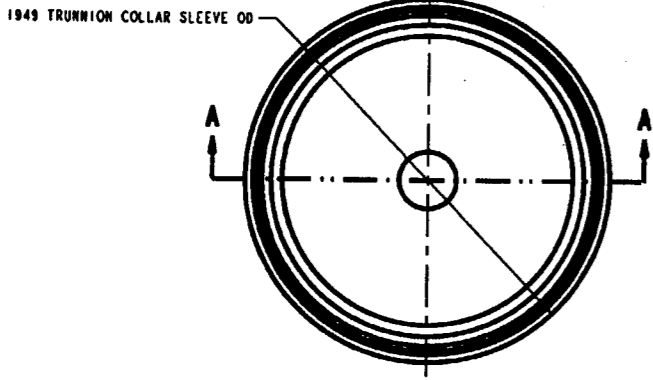
*SMB 01/26/00 Joe 1/26/00 700,2600*



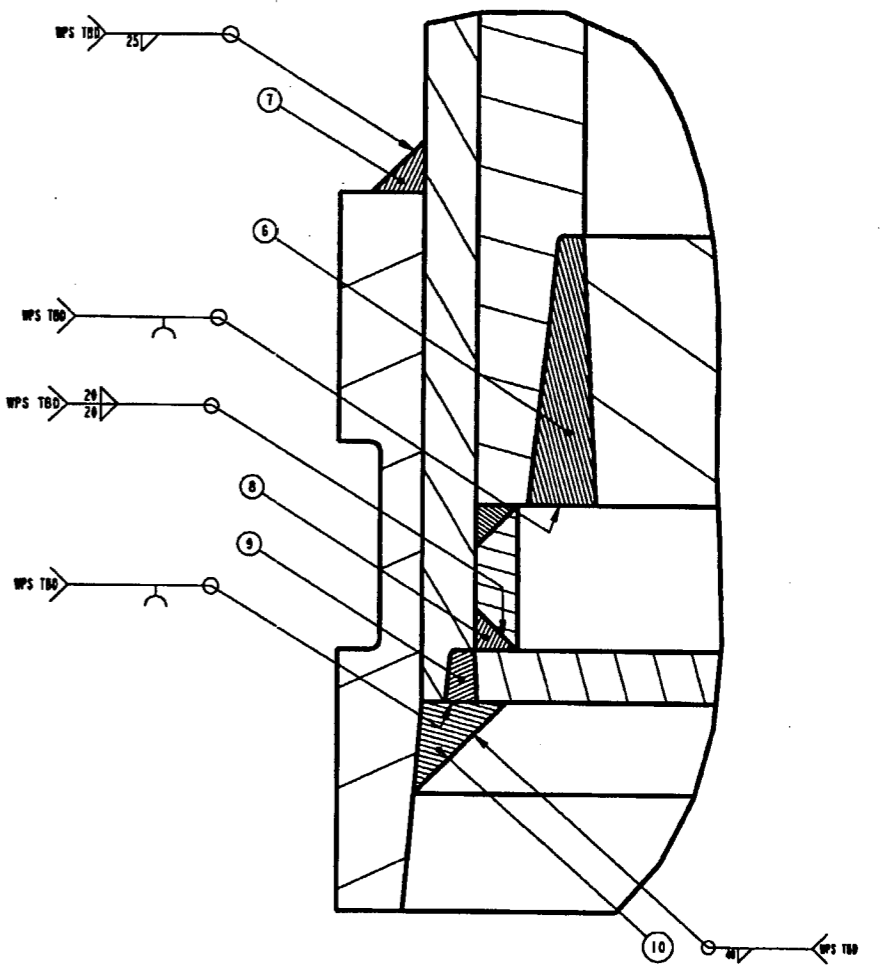
NO. 00131231 SHEET 1 OF 1 5610-MS 230000 H03203

REVISION HISTORY			
ZONE	REV	DESCRIPTION	DATE

ALL SHEETS ARE THE SAME REVISION STATUS




DETAIL A  
SCALE 0.625




DETAIL B  
SCALE 0.625

WELDS	MATERIAL	MASS (KG)	QTY ROD
WELD 1	SFA-5.14 N06022	16	1
WELD 2	SFA-5.14 N06022	41	1
WELD 3	SFA-5.14 N06022	116	1
WELD 4	SFA-5.14 N06022	3.8	2
WELD 5	SFA-5.14 N06022	4.5	1
WELD 6	SFA-5.9 S31680	123	2
WELD 7	SFA-5.14 N06022	16	2
WELD 8	SFA-5.14 N06022	9.9	2
WELD 9	SFA-5.14 N06022	16	1
WELD 10	SFA-5.14 N06022	44	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	298	-
TOTAL 316 WELDS	SFA-5.9 S31680	246	-

"FOR INFORMATION ONLY"  
THIRD ANGLE PROJECTION  
  
DIMENSIONS ARE IN MILLIMETERS AND DEGREES UNLESS OTHERWISE NOTED  
DO NOT SCALE FROM SKETCH

APPROVALS	INITIAL/DATE
SKETCHED BY BRYAN HARKINS	<i>BH</i> 28 March 00
STRUCTURAL LEAD SCOTT BENNETT	<i>SAB</i> 05/19/00
MANUFACTURING MGR JERRY COGAR	<i>JC</i> 05/19/00
DESIGN GROUP MGR THOMAS DOERING	<i>TD</i> 5/19/00

WASTE PACKAGE DEPARTMENT	
 M&O Civilian Radioactive Waste Management System MANAGEMENT & OPERATING CONTRACTOR	
TITLE	NAVAL SNF LONG WASTE PACKAGE WELD CONFIGURATION
SKETCH NUMBER	SK-0195
REVISION	00
SCALE	.055
SHEET	1 OF 1

## Various Shell Gap Sizes for the 21-PWR WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter  $j$  provides a range from 0 to 10 with an interval of 1.

$j := 0..10$

range from 0 to 10 with an interval of 1

$gap_j := j \cdot 0.0001 \cdot m$

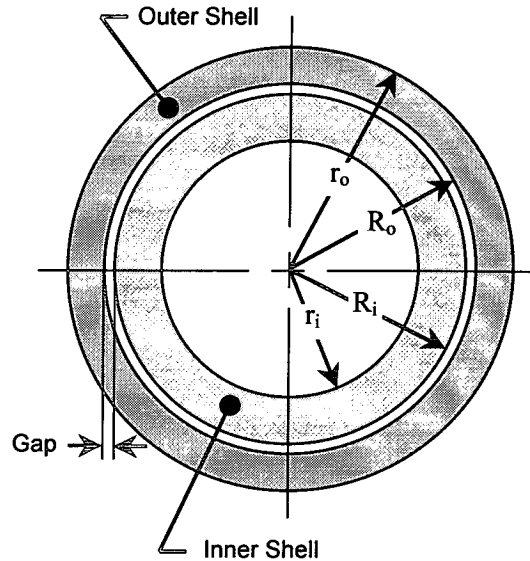
range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

	0	
0	0.0	
1	0.1	
2	0.2	
3	0.3	
4	0.4	
5	0.5	
6	0.6	
7	0.7	
8	0.8	
9	0.9	
10	1.0	

$gap_j =$  mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.712\text{-m}$	inner shell inner radius
$th_i := 0.050\text{-m}$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + \text{gap}$	outer shell inner radius
$th_o := 0.020\text{-m}$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 4.585\text{m}$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$	mean coefficient of thermal expansion for 316NG SS $\left( 9.7 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$ (Section 5.1.1)
$\alpha_{\text{alloy22}} := 12.6 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$	mean coefficient of thermal expansion for Alloy 22 $\left( 7.0 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$ (Section 5.1.2)

$\text{GPa} := 10^9 \cdot \text{Pa}$	$\text{MPa} := 10^6 \cdot \text{Pa}$	$\text{ksi} := 10^3 \cdot \text{psi}$
$E_o := 206 \cdot \text{GPa}$	$E_o = 29.9 \cdot 10^6 \cdot \text{psi}$	outer shell elastic modulus (Section 5.1.2)
$E_i := 195.1 \cdot \text{GPa}$	$E_i = 28.3 \cdot 10^6 \cdot \text{psi}$	inner shell elastic modulus (Section 5.1.1)
$\nu_o := 0.278$		outer shell Poisson's ratio (Section 5.1.2)
$\nu_i := 0.298$		inner shell Poisson's ratio (Section 5.1.1)



$$K_i := 17.3 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot\text{deg F}} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot\text{deg F}} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y,\text{alloy22}} := 222\text{MPa} \quad \sigma_{y,\text{alloy22}} = 32.2 \text{ ksi} \quad \text{outer shell yield strength at 260 degrees C (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

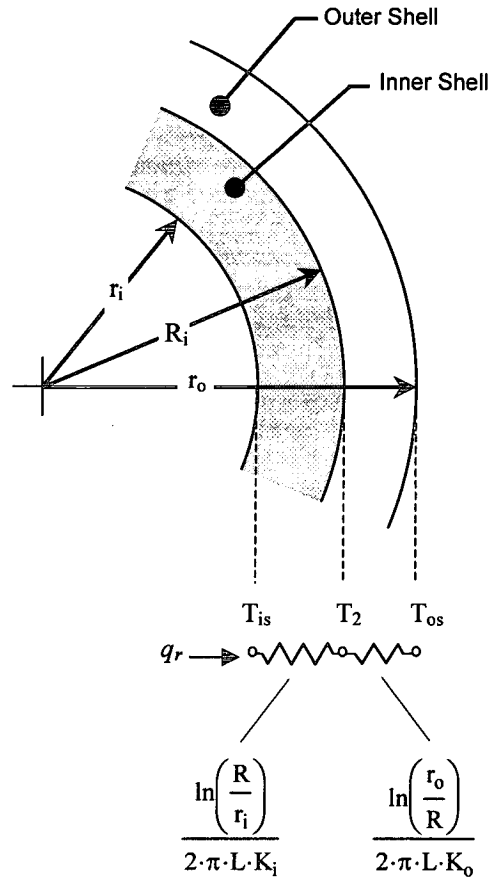
$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

$T_{os} :=$	$\left( \begin{array}{c} 293 \\ 330 \\ 357 \\ 381 \\ 411 \\ 426 \\ 443 \\ 468 \\ 493 \\ 502 \\ 512 \end{array} \right) \text{ K}$	outer shell outer surface temperature	$q_r :=$	$\left( \begin{array}{c} 0.0 \\ 11799.9 \\ 11762.5 \\ 10846.7 \\ 7192.8 \\ 7191.7 \\ 7182.4 \\ 7102.3 \\ 6856.1 \\ 6540.6 \\ 6158.3 \end{array} \right) \text{ W}$	overall heat transfer rates (Section 5.1.5)
-------------	---	--	----------	--	--

Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

	0	
$T_{is} =$	0	293.0
	1	332.4
	2	359.4
	3	383.2
	4	412.5
	5	427.5
	6	444.5
	7	469.4
	8	494.4
	9	503.3
	10	513.3
		K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$                       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$                       outer shell outer surface temperature change

Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\varepsilon = \alpha (\Delta T) \quad \text{where } \varepsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\varepsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} R_i \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} R_o \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\frac{R_o}{E_o} \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right)} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \quad \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \quad \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad \text{10\% yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

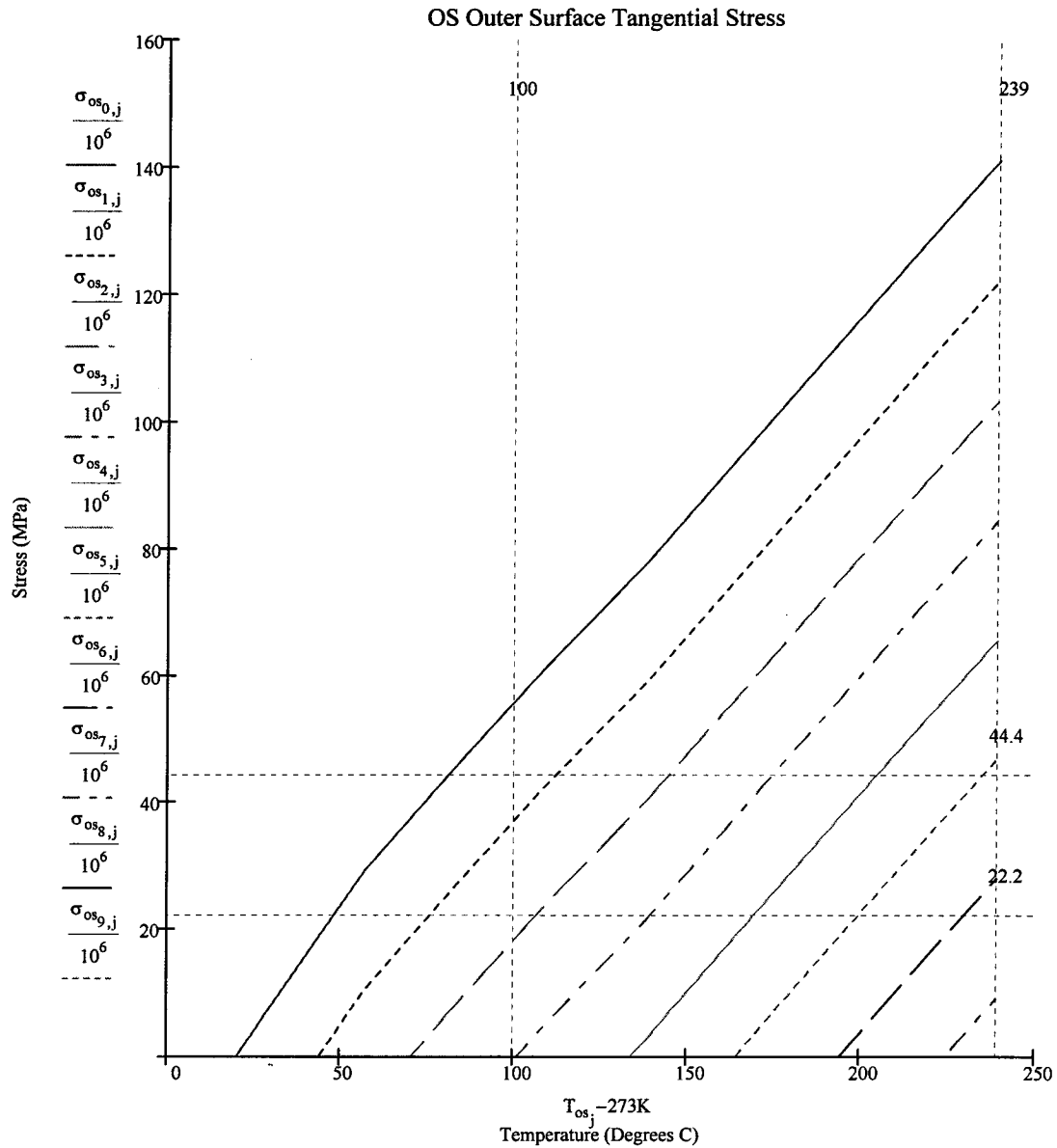
$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad \text{20\% yield strength}$$

$$\sigma_{20\%} = 44.4 \text{ MPa}$$

Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{j,10}^{os}$ =	
0.0	mm	140.9	MPa
0.1		122.1	
0.2		103.2	
0.3		84.4	
0.4		65.6	
0.5		46.8	
0.6		27.9	
0.7		9.1	
0.8		-9.7	
0.9		-28.5	
1.0		-47.3	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



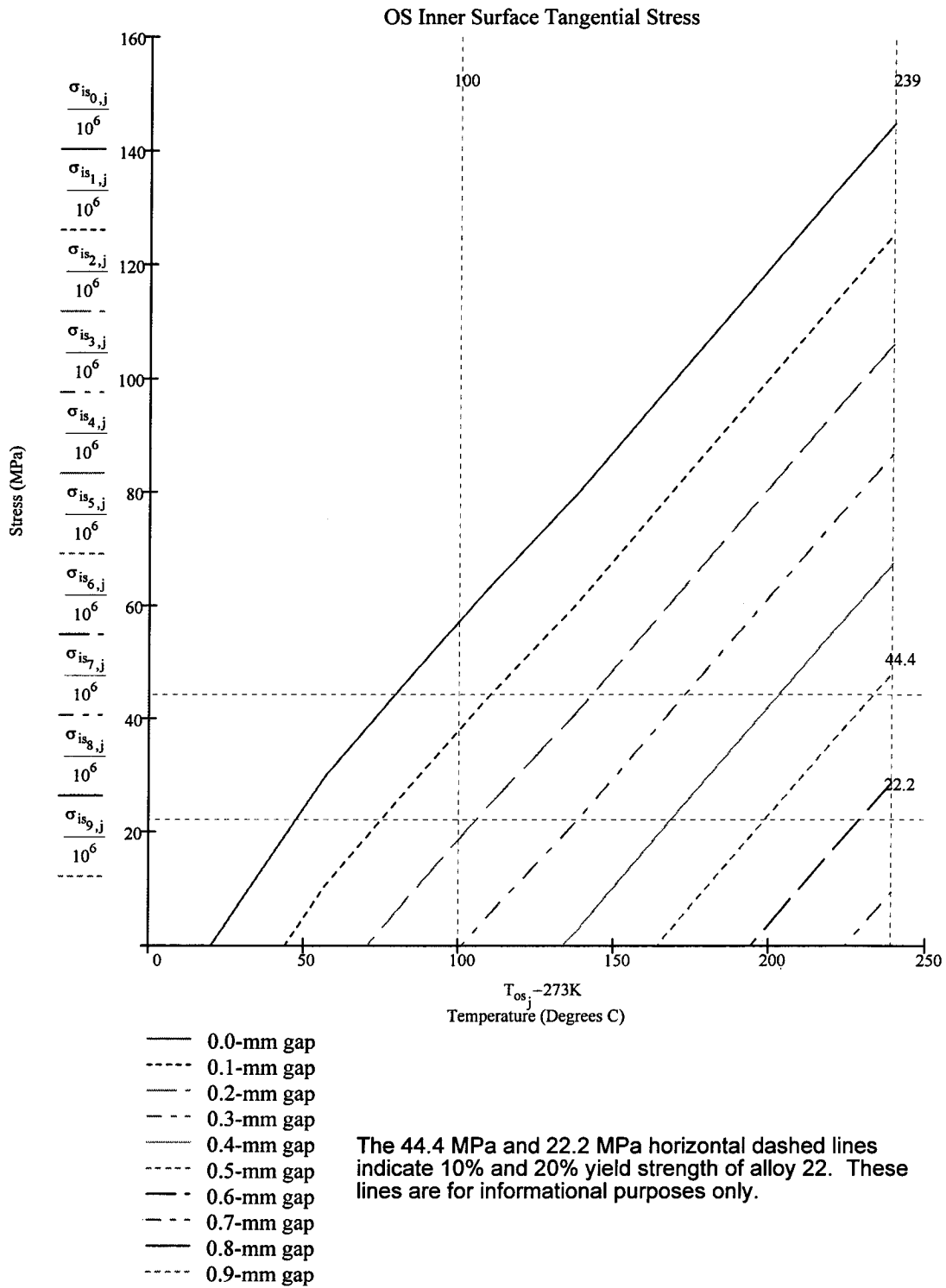
- 0.0-mm gap
- - - 0.1-mm gap
- - - 0.2-mm gap
- - - 0.3-mm gap
- - - 0.4-mm gap
- - - 0.5-mm gap
- - - 0.6-mm gap
- - - 0.7-mm gap
- - - 0.8-mm gap
- - - 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	144.6	MPa
0.1		125.3	
0.2		106.0	
0.3		86.6	
0.4		67.3	
0.5		48.0	
0.6		28.7	
0.7		9.4	
0.8		-10.0	
0.9		-29.3	
1.0		-48.6	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.





### Various Shell Gap Sizes for the 44-BWR WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter j provides a range from 0 to 10 with an interval of 1.

$j := 0..10$

range from 0 to 10 with an interval of 1

$gap_j := j \cdot 0.0001 \cdot m$

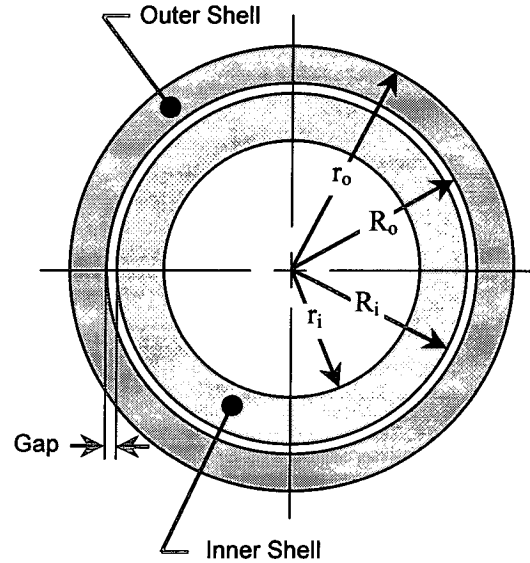
range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

	0	
0	0.0	
1	0.1	
2	0.2	
3	0.3	
4	0.4	
5	0.5	
6	0.6	
7	0.7	
8	0.8	
9	0.9	
10	1.0	

gap<sub>j</sub> = mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.727\text{-m}$	inner shell inner radius
$th_i := 0.050\text{-m}$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + \text{gap}$	outer shell inner radius
$th_o := 0.020\text{-m}$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 4.585\text{m}$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$  mean coefficient of thermal expansion for 316NG SS  
 $\left( 9.7 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$  (Section 5.1.1)

$\alpha_{\text{alloy22}} := 12.6 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$  mean coefficient of thermal expansion for Alloy 22  
 $\left( 7.0 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$  (Section 5.1.2)

$\text{GPa} := 10^9 \cdot \text{Pa}$        $\text{MPa} := 10^6 \cdot \text{Pa}$        $\text{ksi} := 10^3 \cdot \text{psi}$

$E_o := 206 \cdot \text{GPa}$        $E_o = 29.9 \cdot 10^6 \cdot \text{psi}$       outer shell elastic modulus (Section 5.1.2)

$E_i := 195.1 \cdot \text{GPa}$        $E_i = 28.3 \cdot 10^6 \cdot \text{psi}$       inner shell elastic modulus (Section 5.1.1)

$\nu_o := 0.278$       outer shell Poisson's ratio (Section 5.1.2)

$\nu_i := 0.298$       inner shell Poisson's ratio (Section 5.1.1)

$$K_i := 17.3 \frac{W}{m \cdot K} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{W}{m \cdot K} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y, alloy22} := 222 MPa \quad \sigma_{y, alloy22} = 32.2 \text{ ksi} \quad \text{outer shell yield strength at 260 degrees C (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

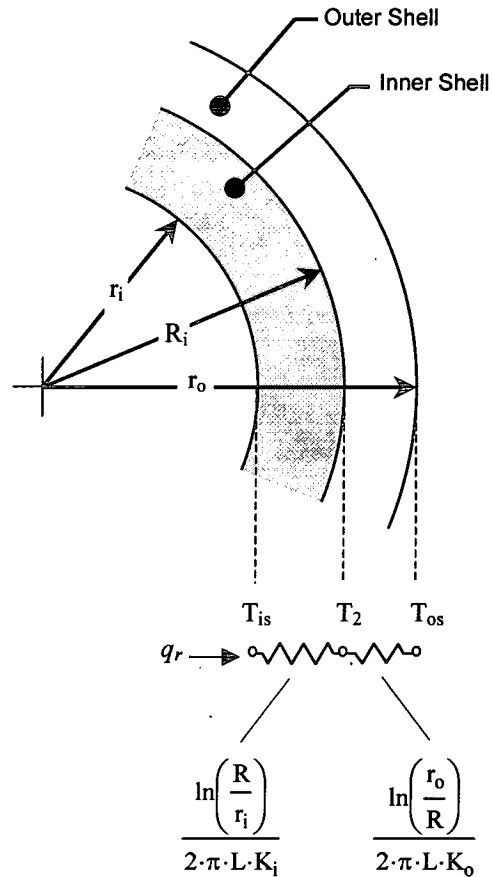
$T_{os} :=$	$\begin{pmatrix} 293 \\ 330 \\ 357 \\ 381 \\ 411 \\ 426 \\ 443 \\ 468 \\ 493 \\ 502 \\ 512 \end{pmatrix}$	K	outer shell outer surface temperature	$q_r :=$	$\begin{pmatrix} 0.0 \\ 11799.9 \\ 11762.5 \\ 10846.7 \\ 7192.8 \\ 7191.7 \\ 7182.4 \\ 7102.3 \\ 6856.1 \\ 6540.6 \\ 6158.3 \end{pmatrix}$	W	overall heat transfer rates (Section 5.1.5)
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Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

$\emptyset$	
0	293.0
1	332.4
2	359.3
3	383.2
4	412.4
5	427.4
6	444.4
7	469.4
8	494.4
9	503.3
10	513.2

$T_{is} =$  K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$                       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$                       outer shell outer surface temperature change

Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\varepsilon = \alpha (\Delta T) \quad \text{where } \varepsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\varepsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} \cdot R_i \cdot \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} \cdot R_o \cdot \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\frac{R_o}{E_o} \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right)} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \quad \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \quad \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad \text{10\% yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

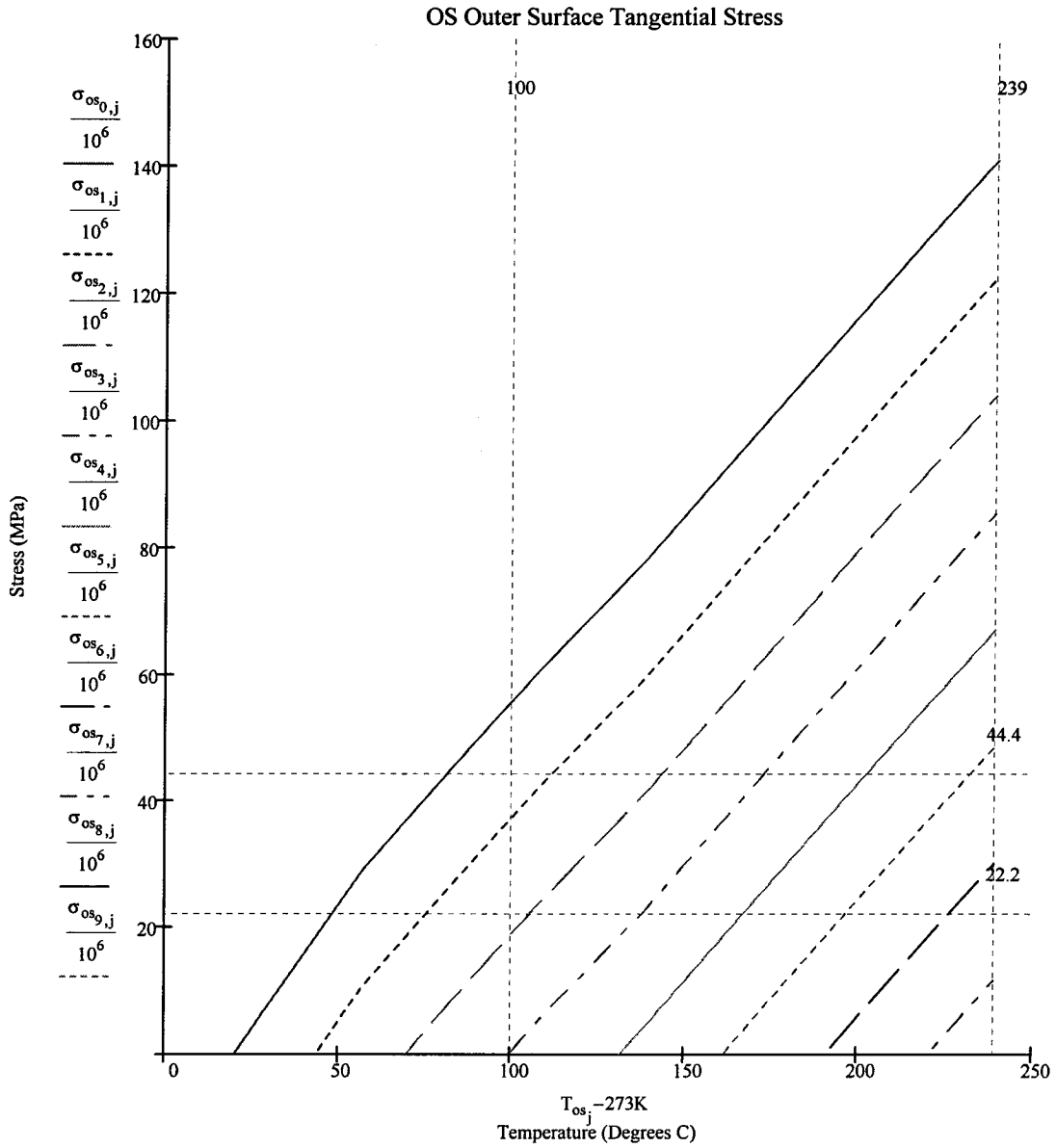
$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad \text{20\% yield strength}$$

$$\sigma_{20\%} = 44.4 \text{ MPa}$$

Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{os_{j,10}}$ =	
0.0	mm	140.9	MPa
0.1		122.4	
0.2		103.9	
0.3		85.5	
0.4		67.0	
0.5		48.5	
0.6		30.1	
0.7		11.6	
0.8		-6.9	
0.9		-25.3	
1.0		-43.8	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- - - 0.2-mm gap
- - - 0.3-mm gap
- - - 0.4-mm gap
- - - 0.5-mm gap
- - - 0.6-mm gap
- - - 0.7-mm gap
- - - 0.8-mm gap
- - - 0.9-mm gap

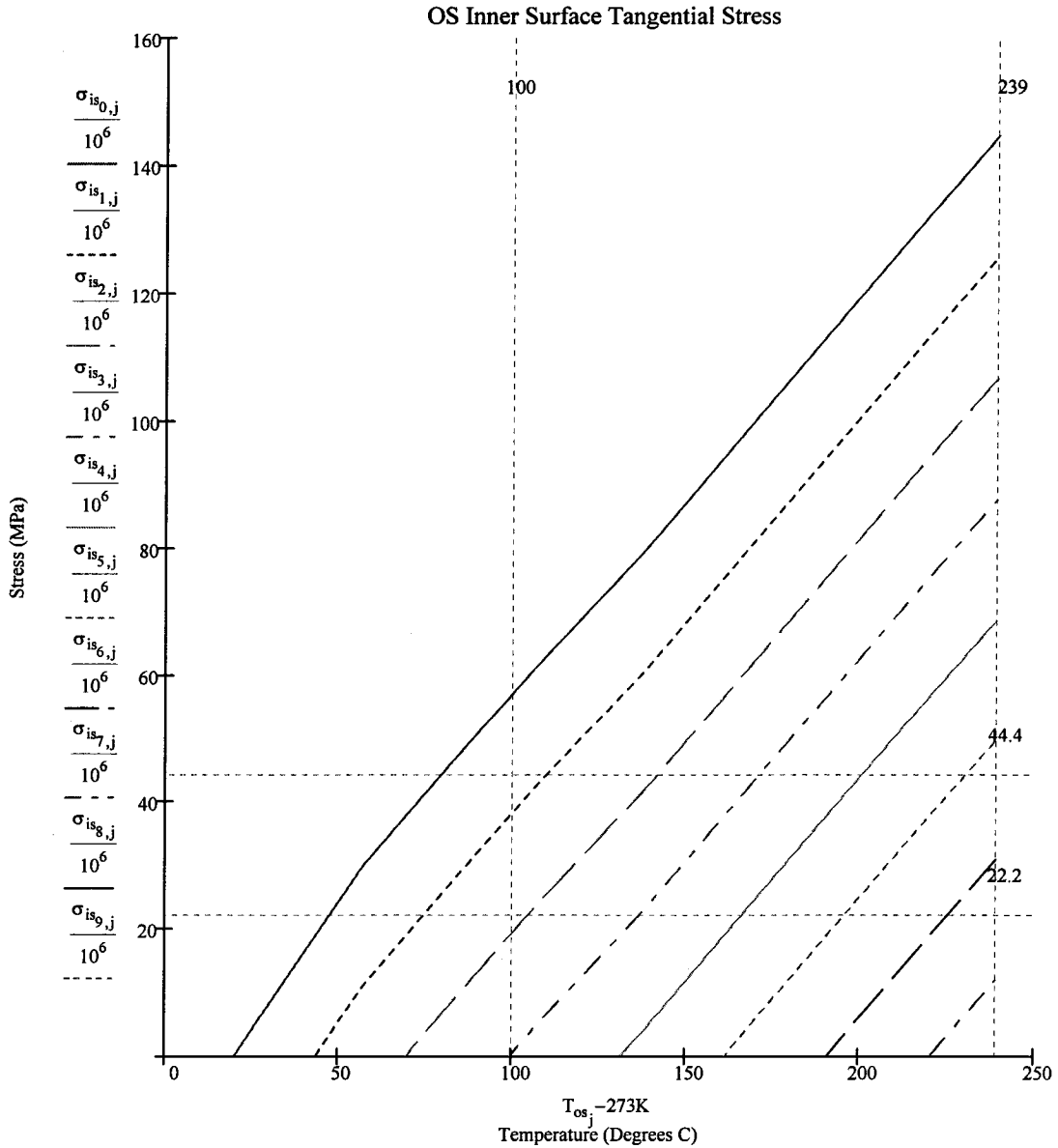
The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.



Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	144.5	MPa
0.1		125.6	
0.2		106.6	
0.3		87.7	
0.4		68.7	
0.5		49.8	
0.6		30.8	
0.7		11.9	
0.8		-7.0	
0.9		-26.0	
1.0		-44.9	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- · - 0.2-mm gap
- · · 0.3-mm gap
- · · · 0.4-mm gap
- · · · · 0.5-mm gap
- · · · · · 0.6-mm gap
- · · · · · · 0.7-mm gap
- · · · · · · · 0.8-mm gap
- · · · · · · · · 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

## Various Shell Gap Sizes for the 24-BWR WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter j provides a range from 0 to 10 with an interval of 1.

$j := 0..10$

range from 0 to 10 with an interval of 1

$gap_j := j \cdot 0.0001 \cdot m$

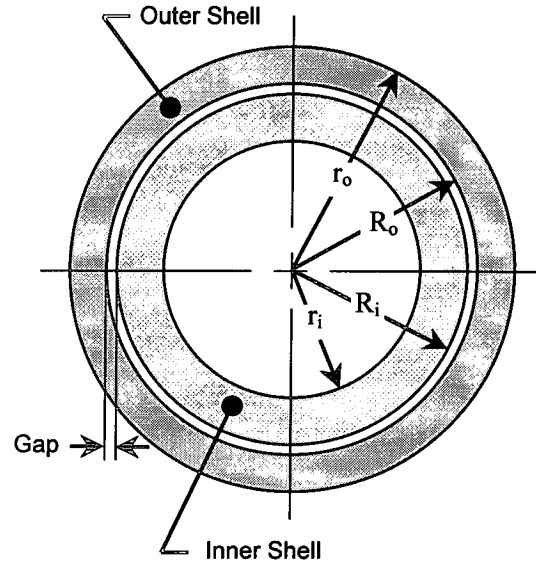
range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

	0	
0	0.0	
1	0.1	
2	0.2	
3	0.3	
4	0.4	
5	0.5	
6	0.6	
7	0.7	
8	0.8	
9	0.9	
10	1.0	

gap<sub>j</sub> = mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.549\text{-m}$	inner shell inner radius
$th_i := 0.050\text{-m}$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + \text{gap}$	outer shell inner radius
$th_o := 0.020\text{-m}$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 4.585\text{m}$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$	mean coefficient of thermal expansion for 316NG SS $\left( 9.7 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$ (Section 5.1.1)
$\alpha_{\text{alloy22}} := 12.6 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$	mean coefficient of thermal expansion for Alloy 22 $\left( 7.0 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$ (Section 5.1.2)

$\text{GPa} := 10^9 \cdot \text{Pa}$	$\text{MPa} := 10^6 \cdot \text{Pa}$	$\text{ksi} := 10^3 \cdot \text{psi}$	
$E_o := 206 \cdot \text{GPa}$	$E_o = 29.9 \cdot 10^6 \cdot \text{psi}$		outer shell elastic modulus (Section 5.1.2)
$E_i := 195.1 \cdot \text{GPa}$	$E_i = 28.3 \cdot 10^6 \cdot \text{psi}$		inner shell elastic modulus (Section 5.1.1)
$\nu_o := 0.278$			outer shell Poisson's ratio (Section 5.1.2)
$\nu_i := 0.298$			inner shell Poisson's ratio (Section 5.1.1)

$$K_i := 17.3 \frac{W}{m \cdot K} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{W}{m \cdot K} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y, alloy22} := 222 MPa \quad \sigma_{y, alloy22} = 32.2 \text{ ksi} \quad \text{outer shell yield strength at 260 degrees C (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

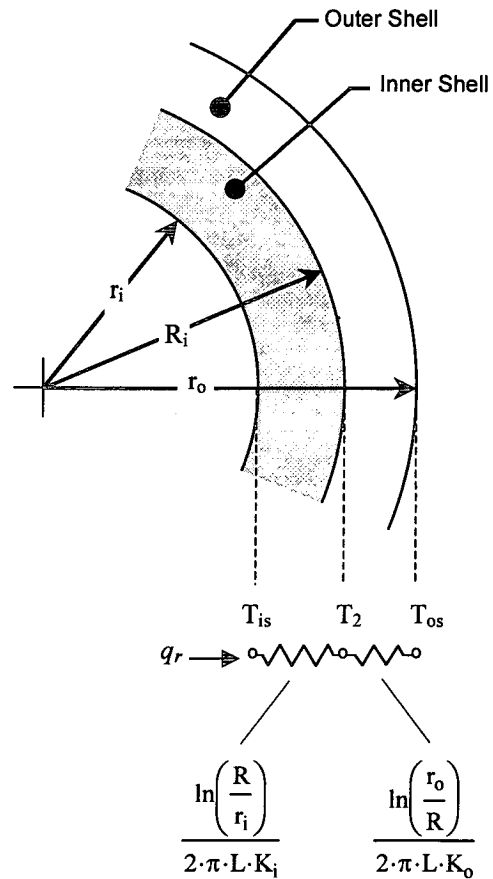
$T_{os} :=$	293 330 357 381 411 426 443 468 493 502 512	K	outer shell outer surface temperature	$q_r :=$	0.0 11799.9 11762.5 10846.7 7192.8 7191.7 7182.4 7102.3 6856.1 6540.6 6158.3	W	overall heat transfer rates (Section 5.1.5)
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Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

	$\theta$
0	293.0
1	333.1
2	360.1
3	383.8
4	412.9
5	427.9
6	444.9
7	469.8
8	494.8
9	503.7
10	513.6

$T_{is} =$  K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$       outer shell outer surface temperature change

Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\varepsilon = \alpha (\Delta T) \quad \text{where } \varepsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\varepsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} R_i \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} R_o \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\frac{R_o}{E_o} \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right)} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \quad \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \quad \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad \text{10\% yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad \text{20\% yield strength}$$

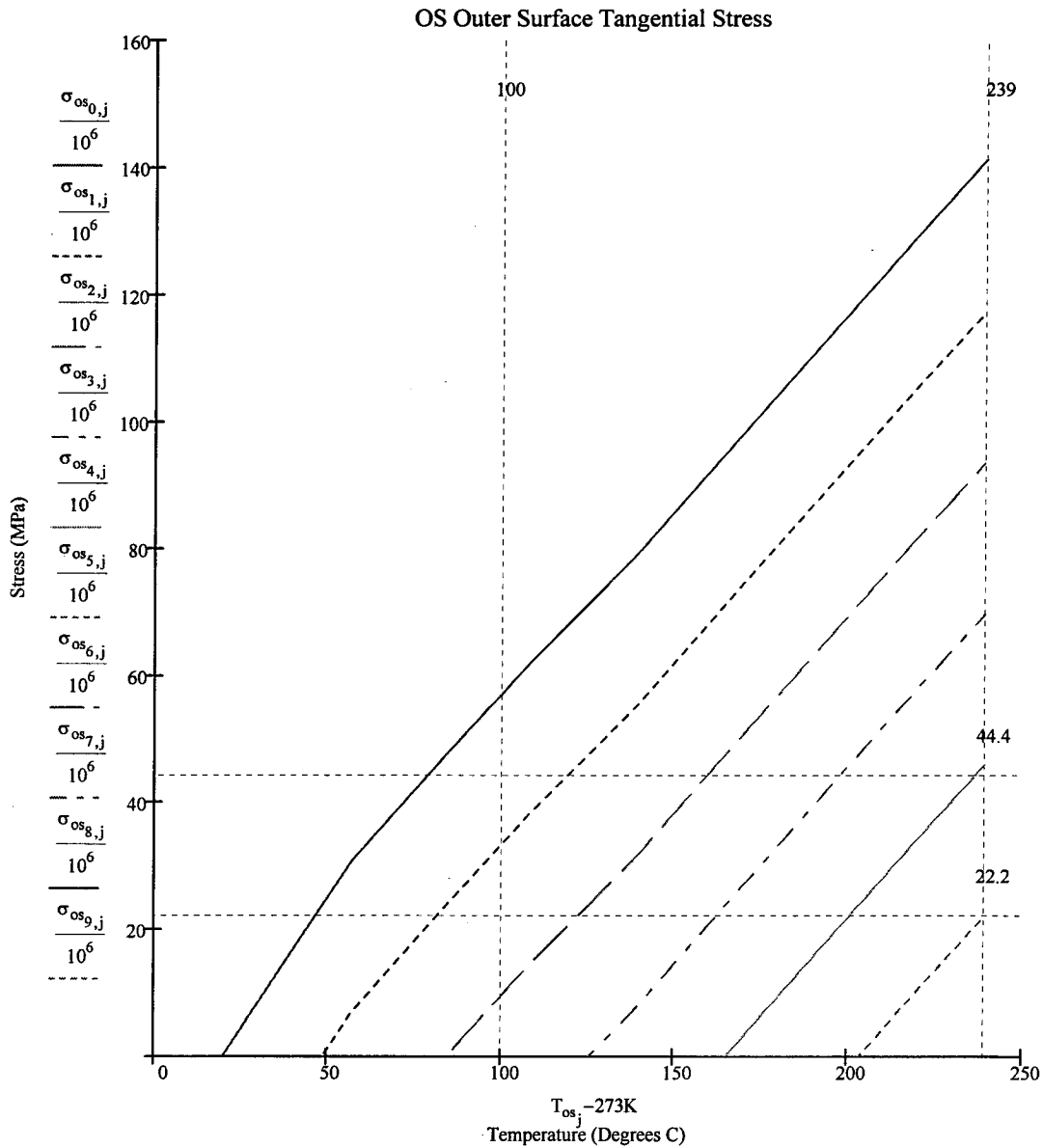
$$\sigma_{20\%} = 44.4 \text{ MPa}$$



Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{os_{j,10}}$ =	
0.0	mm	141.3	MPa
0.1		117.4	
0.2		93.5	
0.3		69.6	
0.4		45.8	
0.5		21.9	
0.6		-1.9	
0.7		-25.8	
0.8		-49.6	
0.9		-73.5	
1.0		-97.3	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



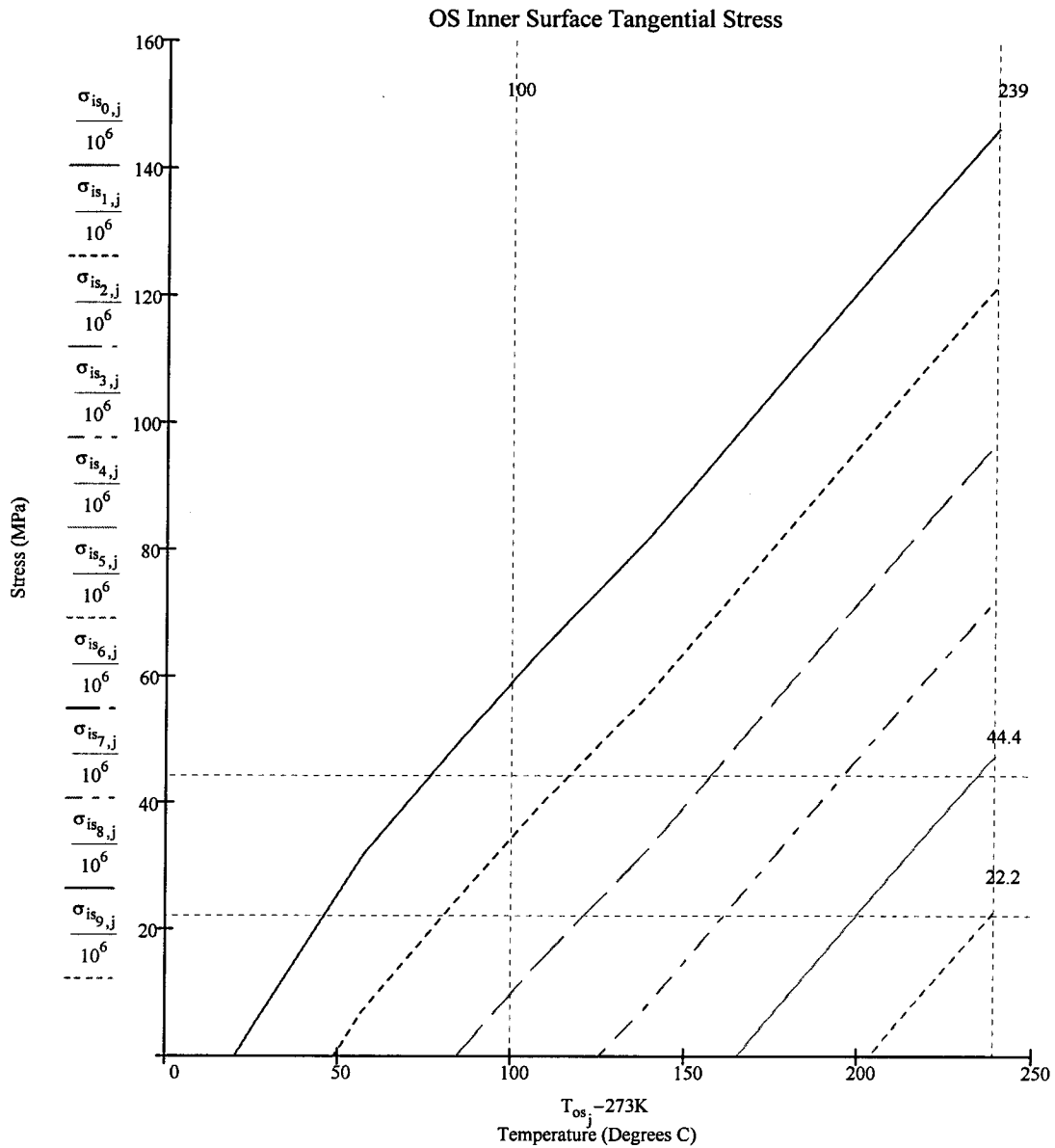
- 0.0-mm gap
- - - 0.1-mm gap
- . - 0.2-mm gap
- . . 0.3-mm gap
- . . . 0.4-mm gap
- . . . . 0.5-mm gap
- . . . . . 0.6-mm gap
- . . . . . . 0.7-mm gap
- . . . . . . . 0.8-mm gap
- . . . . . . . . 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	146.1	MPa
0.1		121.4	
0.2		96.7	
0.3		72.0	
0.4		47.3	
0.5		22.7	
0.6		-2.0	
0.7		-26.7	
0.8		-51.3	
0.9		-76.0	
1.0		-100.6	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- . - 0.2-mm gap
- - - 0.3-mm gap
- . - 0.4-mm gap
- - - 0.5-mm gap
- . - 0.6-mm gap
- - - 0.7-mm gap
- . - 0.8-mm gap
- - - 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

## Various Shell Gap Sizes for the 12-PWR Long WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter  $j$  provides a range from 0 to 10 with an interval of 1.

$j := 0..10$

range from 0 to 10 with an interval of 1

$gap_j := j \cdot 0.0001 \cdot m$

range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

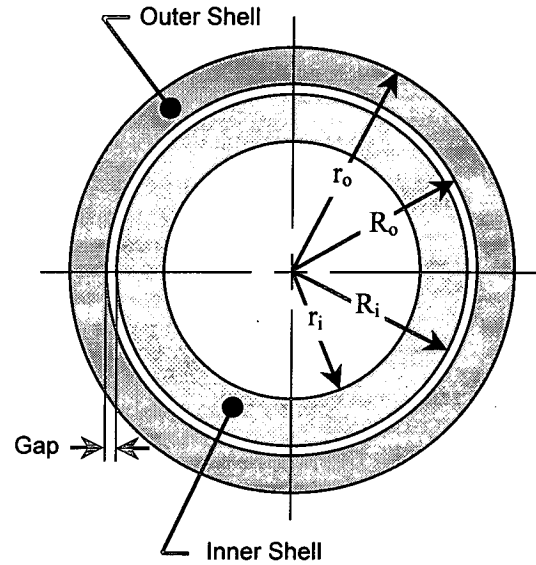
$gap_j =$

0	0.0
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0

mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.555\cdot\text{m}$	inner shell inner radius
$th_i := 0.050\cdot\text{m}$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + \text{gap}$	outer shell inner radius
$th_o := 0.020\cdot\text{m}$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 5.121\text{m}$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{\text{m}}{\text{m}\cdot\text{K}}$	mean coefficient of thermal expansion for 316NG SS $\left( 9.7 \cdot 10^{-6} \frac{\text{in}}{\text{in}\cdot\text{deg F}} \right)$ (Section 5.1.1)
$\alpha_{\text{alloy22}} := 12.6 \cdot 10^{-6} \frac{\text{m}}{\text{m}\cdot\text{K}}$	mean coefficient of thermal expansion for Alloy 22 $\left( 7.0 \cdot 10^{-6} \frac{\text{in}}{\text{in}\cdot\text{deg F}} \right)$ (Section 5.1.2)

$\text{GPa} := 10^9 \cdot \text{Pa}$	$\text{MPa} := 10^6 \cdot \text{Pa}$	$\text{ksi} := 10^3 \cdot \text{psi}$
$E_o := 206 \cdot \text{GPa}$	$E_o = 29.9 \cdot 10^6 \cdot \text{psi}$	outer shell elastic modulus (Section 5.1.2)
$E_i := 195.1 \cdot \text{GPa}$	$E_i = 28.3 \cdot 10^6 \cdot \text{psi}$	inner shell elastic modulus (Section 5.1.1)
$\nu_o := 0.278$		outer shell Poisson's ratio (Section 5.1.2)
$\nu_i := 0.298$		inner shell Poisson's ratio (Section 5.1.1)

$$K_i := 17.3 \frac{W}{m \cdot K} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{W}{m \cdot K} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y, alloy22} := 222 MPa \quad \sigma_{y, alloy22} = 32.2 \text{ ksi} \quad \text{outer shell yield strength at 260 degrees C (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

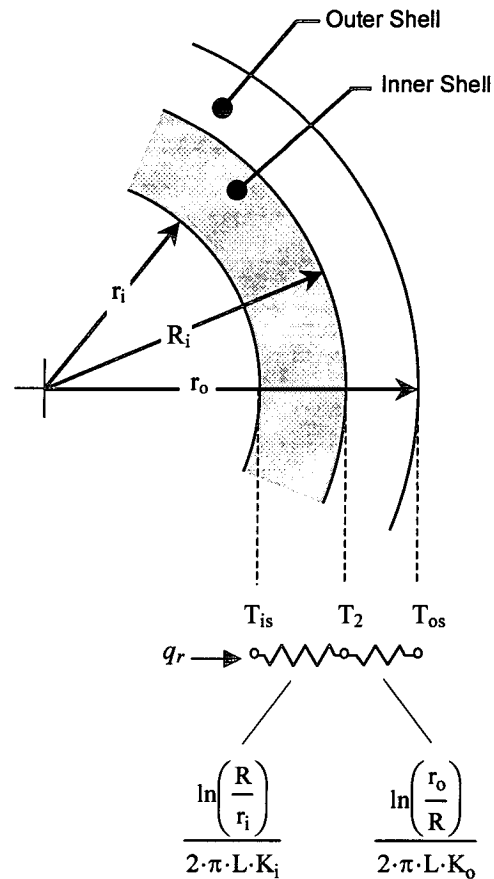
$T_{os} :=$	293 330 357 381 411 426 443 468 493 502 512	K	outer shell outer surface temperature	$q_r :=$	0.0 11799.9 11762.5 10846.7 7192.8 7191.7 7182.4 7102.3 6856.1 6540.6 6158.3	W	overall heat transfer rates (Section 5.1.5)
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Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

	0
0	293.0
1	332.7
2	359.7
3	383.5
4	412.7
5	427.7
6	444.7
7	469.6
8	494.6
9	503.5
10	513.4

$T_{is} =$  K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$                       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$                       outer shell outer surface temperature change



Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\varepsilon = \alpha (\Delta T) \quad \text{where } \varepsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\varepsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} \cdot R_i \cdot \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} \cdot R_o \cdot \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\left[ \frac{R_o}{E_o} \cdot \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \cdot \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right) \right]} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \rightarrow \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \rightarrow \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad 10\% \text{ yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

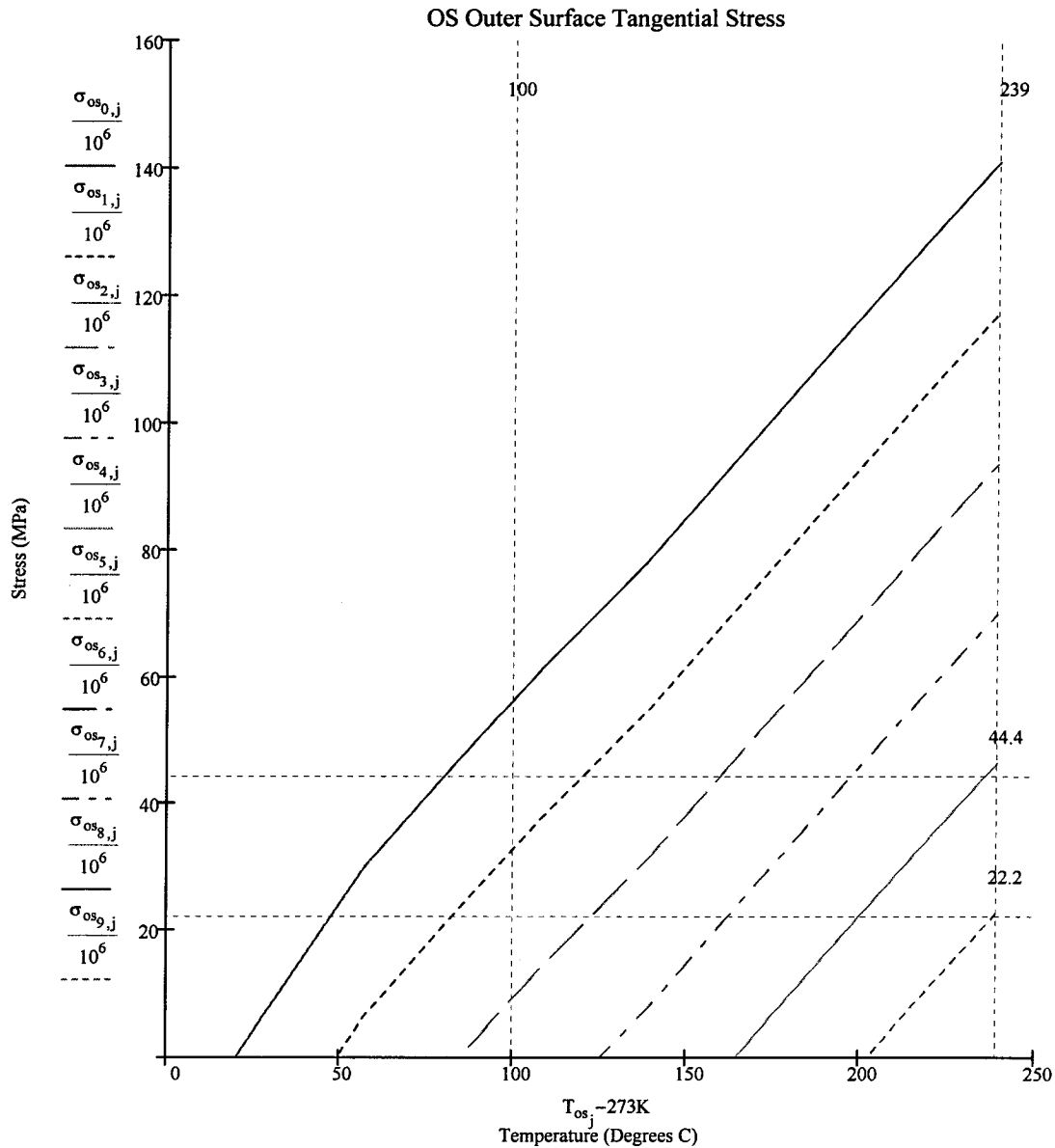
$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad 20\% \text{ yield strength}$$

$$\sigma_{20\%} = 44.4 \text{ MPa}$$

Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{j,10}^{os}$ =	
0.0	mm	140.8	MPa
0.1			
0.2			
0.3			
0.4			
0.5			
0.6			
0.7			
0.8			
0.9			
1.0			

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



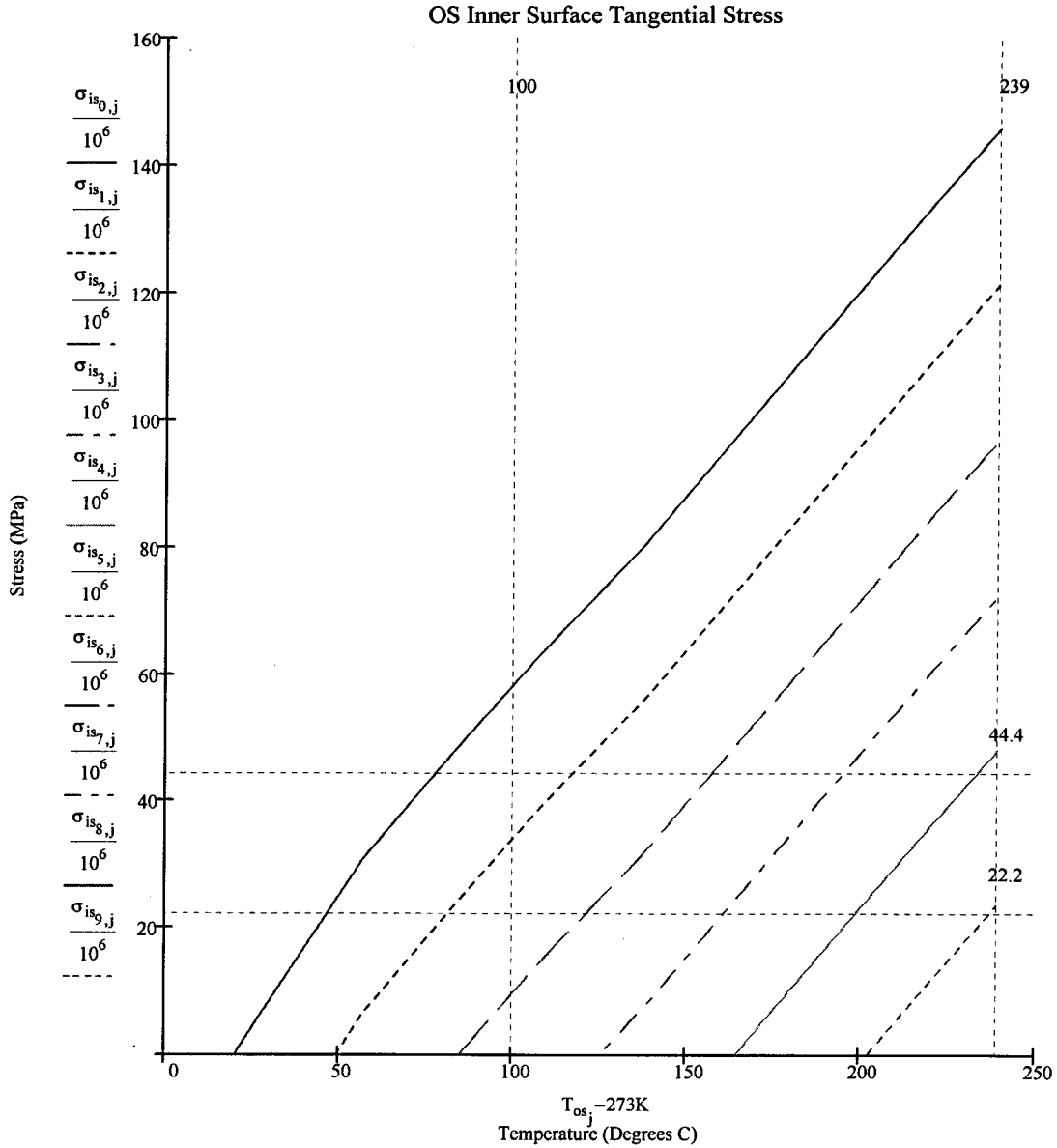
- 0.0-mm gap
- - - 0.1-mm gap
- - - 0.2-mm gap
- - - 0.3-mm gap
- - - 0.4-mm gap
- - - 0.5-mm gap
- - - 0.6-mm gap
- - - 0.7-mm gap
- - - 0.8-mm gap
- - - 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	145.6	MPa
0.1		121.1	
0.2		96.7	
0.3		72.3	
0.4		47.8	
0.5		23.4	
0.6		-1.0	
0.7		-25.4	
0.8		-49.8	
0.9		-74.2	
1.0		-98.6	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- . - 0.2-mm gap
- - - 0.3-mm gap
- . - 0.4-mm gap
- - - 0.5-mm gap
- . - 0.6-mm gap
- - - 0.7-mm gap
- . - 0.8-mm gap
- - - 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

## Various Shell Gap Sizes for the 5-DHLW/DOE SNF-LONG WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter  $j$  provides a range from 0 to 10 with an interval of 1.

$j := 0..10$

range from 0 to 10 with an interval of 1

$gap_j := j \cdot 0.0001 \cdot m$

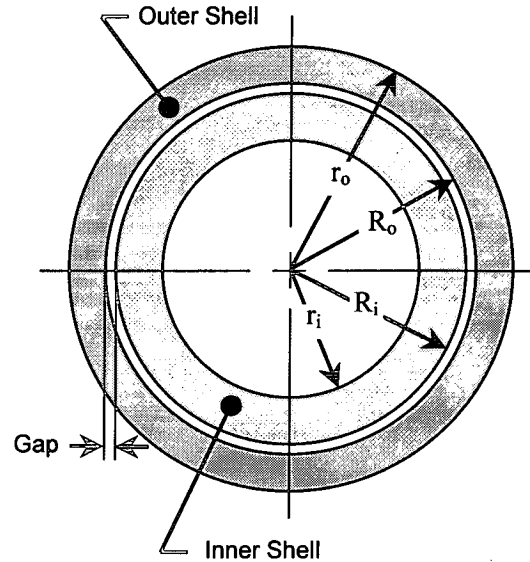
range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

	0	
0	0.0	
1	0.1	
2	0.2	
3	0.3	
4	0.4	
5	0.5	
6	0.6	
7	0.7	
8	0.8	
9	0.9	
10	1.0	

$gap_j =$  mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.940\text{-m}$	inner shell inner radius
$th_i := 0.050\text{-m}$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + \text{gap}$	outer shell inner radius
$th_o := 0.025\text{-m}$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 3.590\text{m}$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$  mean coefficient of thermal expansion for 316NG SS  
 $\left( 9.7 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$  (Section 5.1.1)

$\alpha_{\text{alloy22}} := 12.6 \cdot 10^{-6} \frac{\text{m}}{\text{m} \cdot \text{K}}$  mean coefficient of thermal expansion for Alloy 22  
 $\left( 7.0 \cdot 10^{-6} \frac{\text{in}}{\text{in} \cdot \text{deg F}} \right)$  (Section 5.1.2)

$\text{GPa} := 10^9 \cdot \text{Pa}$        $\text{MPa} := 10^6 \cdot \text{Pa}$        $\text{ksi} := 10^3 \cdot \text{psi}$

$E_o := 206 \cdot \text{GPa}$        $E_o = 29.9 \cdot 10^6 \cdot \text{psi}$       outer shell elastic modulus (Section 5.1.2)

$E_i := 195.1 \cdot \text{GPa}$        $E_i = 28.3 \cdot 10^6 \cdot \text{psi}$       inner shell elastic modulus (Section 5.1.1)

$\nu_o := 0.278$       outer shell Poisson's ratio (Section 5.1.2)

$\nu_i := 0.298$       inner shell Poisson's ratio (Section 5.1.1)



$$K_i := 17.3 \frac{W}{m \cdot K} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{W}{m \cdot K} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{BTU}{hr \cdot ft \cdot deg F} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y, alloy22} := 222 MPa \quad \sigma_{y, alloy22} = 32.2 \text{ ksi} \quad \text{outer shell yield strength at 260 degrees C (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

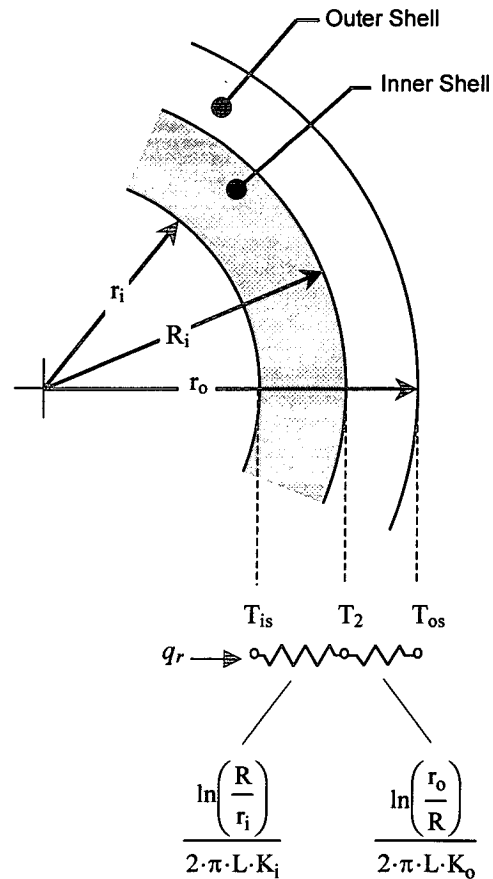
$T_{os} :=$	K	outer shell outer surface temperature	$q_r :=$	W	overall heat transfer rates (Section 5.1.5)
	293			0.0	
	330			11799.9	
	357			11762.5	
	381			10846.7	
	411			7192.8	
	426			7191.7	
	443			7182.4	
	468			7102.3	
	493			6856.1	
	502			6540.6	
	512			6158.3	

Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

	$\theta$
0	293.0
1	332.5
2	359.5
3	383.3
4	412.5
5	427.5
6	444.5
7	469.5
8	494.5
9	503.4
10	513.3

$T_{is} =$  K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$                       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$                       outer shell outer surface temperature change

Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\varepsilon = \alpha (\Delta T) \quad \text{where } \varepsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\varepsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} R_i \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} R_o \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\frac{R_o}{E_o} \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right)} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \quad \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \quad \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad \text{10\% yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

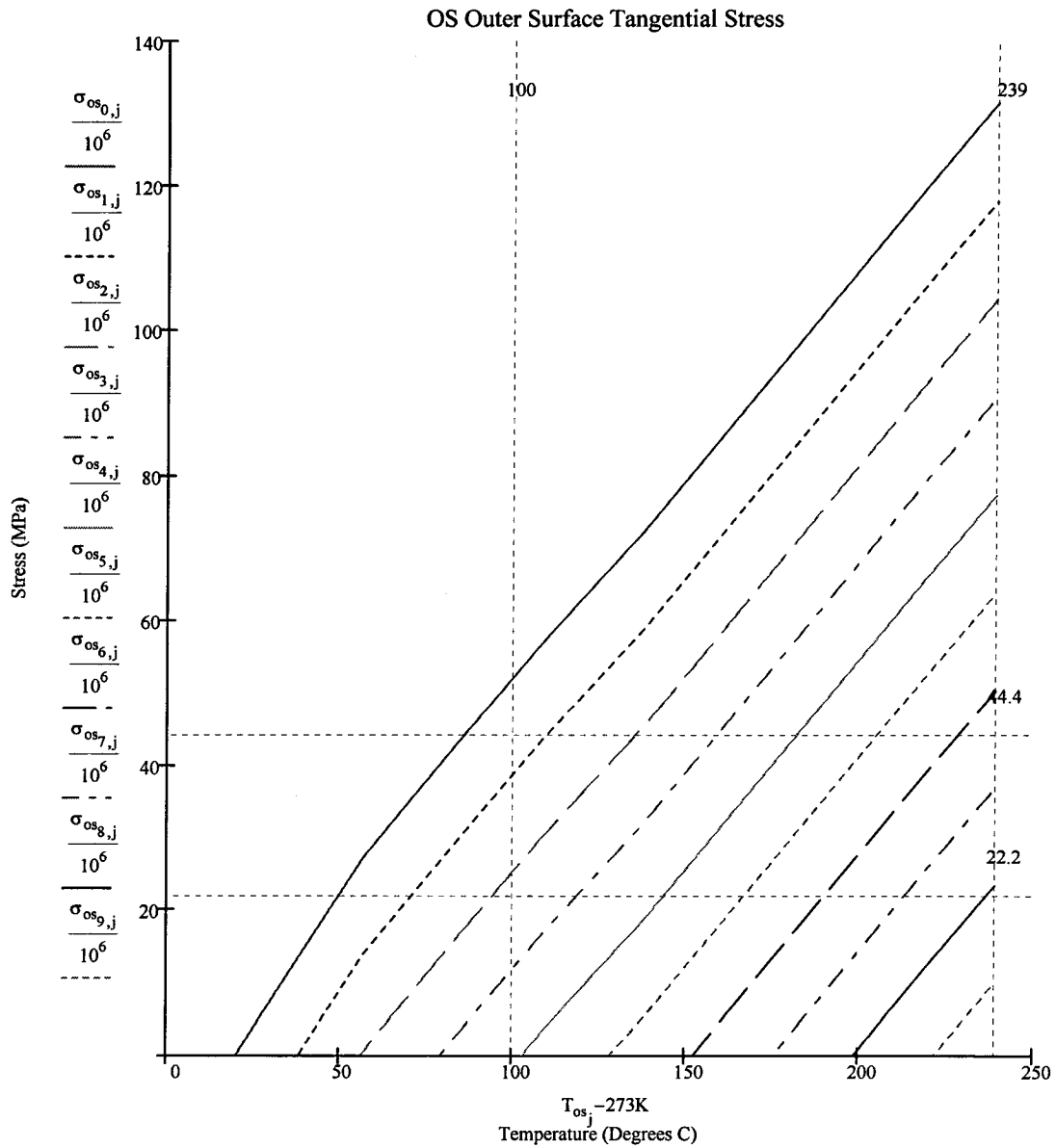
$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad \text{20\% yield strength}$$

$$\sigma_{20\%} = 44.4 \text{ MPa}$$

Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{os_{j,10}}$ =	
0.0	mm	131.4	MPa
0.1		117.9	
0.2		104.4	
0.3		90.9	
0.4		77.4	
0.5		63.9	
0.6		50.4	
0.7		36.9	
0.8		23.4	
0.9		9.9	
1.0		-3.6	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



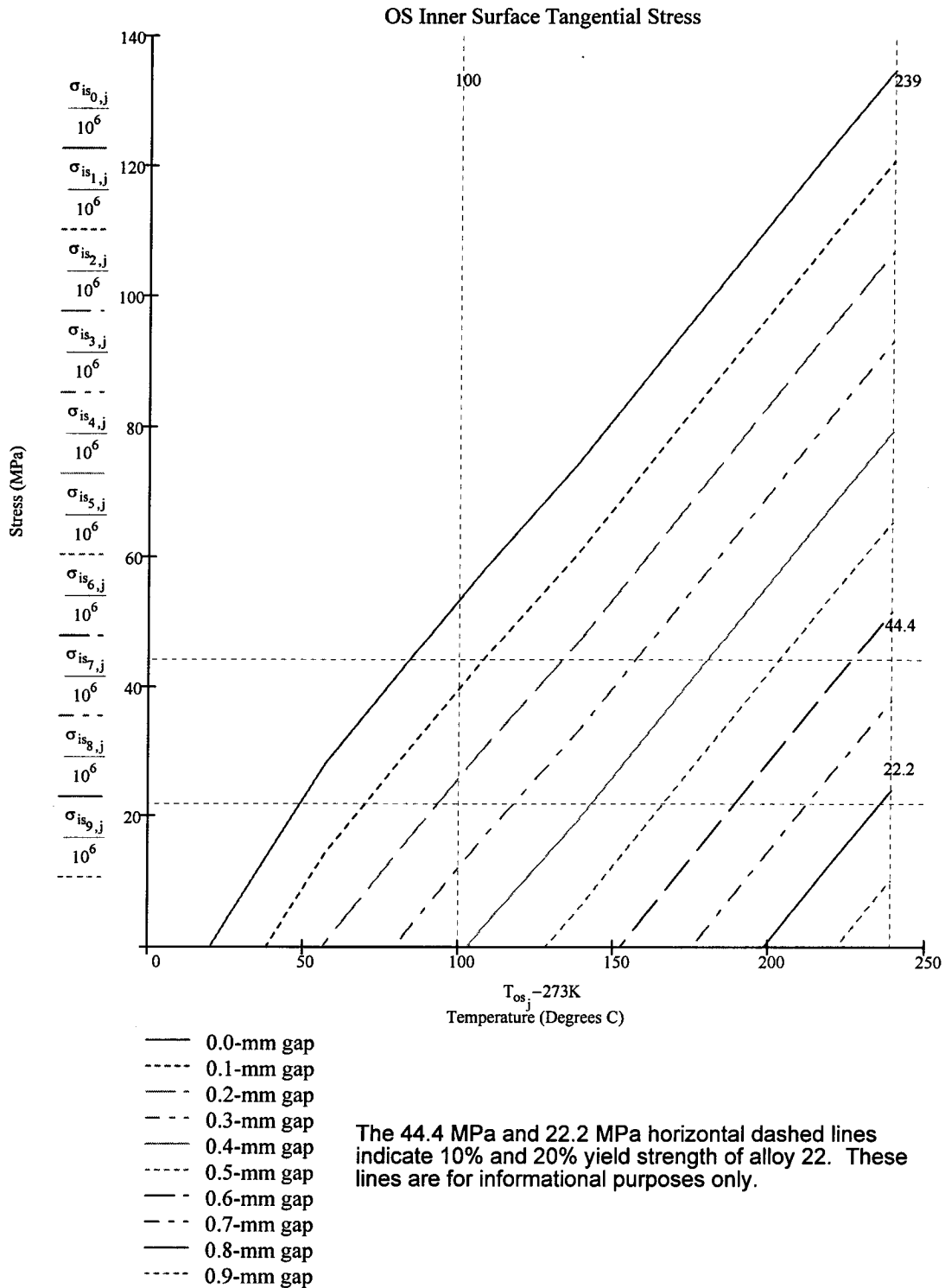
- 0.0-mm gap
- - - 0.1-mm gap
- - - 0.2-mm gap
- - - 0.3-mm gap
- - - 0.4-mm gap
- - - 0.5-mm gap
- - - 0.6-mm gap
- - - 0.7-mm gap
- - - 0.8-mm gap
- - - 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	134.8	MPa
0.1		120.9	
0.2		107.1	
0.3		93.2	
0.4		79.4	
0.5		65.5	
0.6		51.7	
0.7		37.9	
0.8		24.0	
0.9		10.2	
1.0		-3.7	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.





## Various Shell Gap Sizes for the 2-MCO/2-DHLW WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter  $j$  provides a range from 0 to 10 with an interval of 1.

$j := 0..10$

range from 0 to 10 with an interval of 1

$gap_j := j \cdot 0.0001 \cdot m$

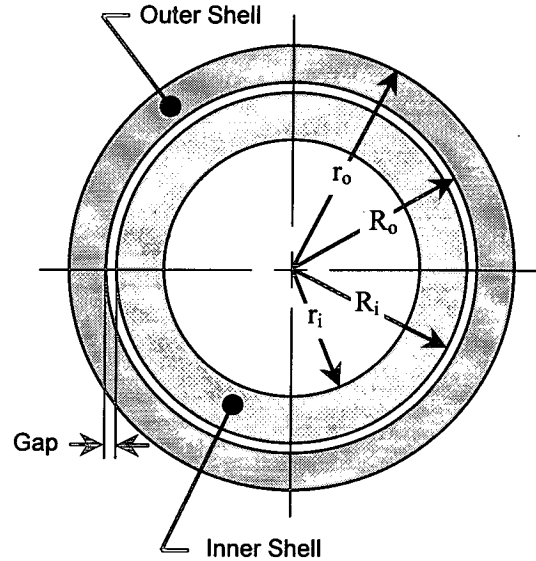
range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

	0	
0	0.0	
1	0.1	
2	0.2	
3	0.3	
4	0.4	
5	0.5	
6	0.6	
7	0.7	
8	0.8	
9	0.9	
10	1.0	

gap<sub>j</sub> = mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.792 \cdot m$	inner shell inner radius
$th_i := 0.050 \cdot m$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + gap$	outer shell inner radius
$th_o := 0.025 \cdot m$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 4.617m$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{m}{m \cdot K}$	mean coefficient of thermal expansion for 316NG SS $\left( 9.7 \cdot 10^{-6} \frac{in}{in \cdot deg F} \right)$ (Section 5.1.1)
$\alpha_{alloy22} := 12.6 \cdot 10^{-6} \frac{m}{m \cdot K}$	mean coefficient of thermal expansion for Alloy 22 $\left( 7.0 \cdot 10^{-6} \frac{in}{in \cdot deg F} \right)$ (Section 5.1.2)

$GPa := 10^9 \cdot Pa$	$MPa := 10^6 \cdot Pa$	$ksi := 10^3 \cdot psi$
$E_o := 206 \cdot GPa$	$E_o = 29.9 \cdot 10^6 \cdot psi$	outer shell elastic modulus (Section 5.1.2)
$E_i := 195.1 \cdot GPa$	$E_i = 28.3 \cdot 10^6 \cdot psi$	inner shell elastic modulus (Section 5.1.1)
$\nu_o := 0.278$		outer shell Poisson's ratio (Section 5.1.2)
$\nu_i := 0.298$		inner shell Poisson's ratio (Section 5.1.1)

$$K_i := 17.3 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot\text{deg F}} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot\text{deg F}} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y,\text{alloy22}} := 222\text{MPa} \quad \sigma_{y,\text{alloy22}} = 32.2\text{ksi} \quad \text{outer shell yield strength at 260 degrees C (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

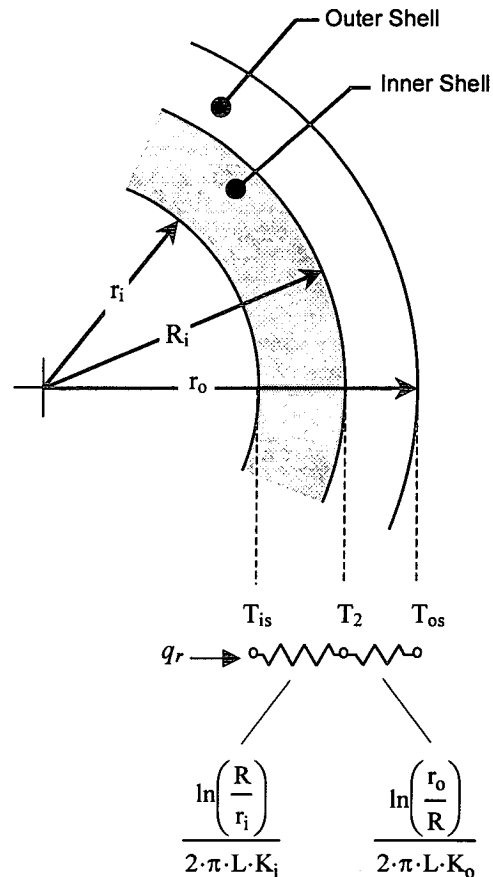
$T_{os} :=$	$\begin{pmatrix} 293 \\ 330 \\ 357 \\ 381 \\ 411 \\ 426 \\ 443 \\ 468 \\ 493 \\ 502 \\ 512 \end{pmatrix}$	K	outer shell outer surface temperature	$q_r :=$	$\begin{pmatrix} 0.0 \\ 11799.9 \\ 11762.5 \\ 10846.7 \\ 7192.8 \\ 7191.7 \\ 7182.4 \\ 7102.3 \\ 6856.1 \\ 6540.6 \\ 6158.3 \end{pmatrix}$	W	overall heat transfer rates (Section 5.1.5)
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Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

	$\theta$
0	293.0
1	332.3
2	359.3
3	383.1
4	412.4
5	427.4
6	444.4
7	469.4
8	494.4
9	503.3
10	513.2

$T_{is} =$  K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$                       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$                       outer shell outer surface temperature change

Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\epsilon = \alpha (\Delta T) \quad \text{where } \epsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\epsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} \cdot R_i \cdot \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} \cdot R_o \cdot \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\frac{R_o}{E_o} \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right)} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \quad \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \quad \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad \text{10\% yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

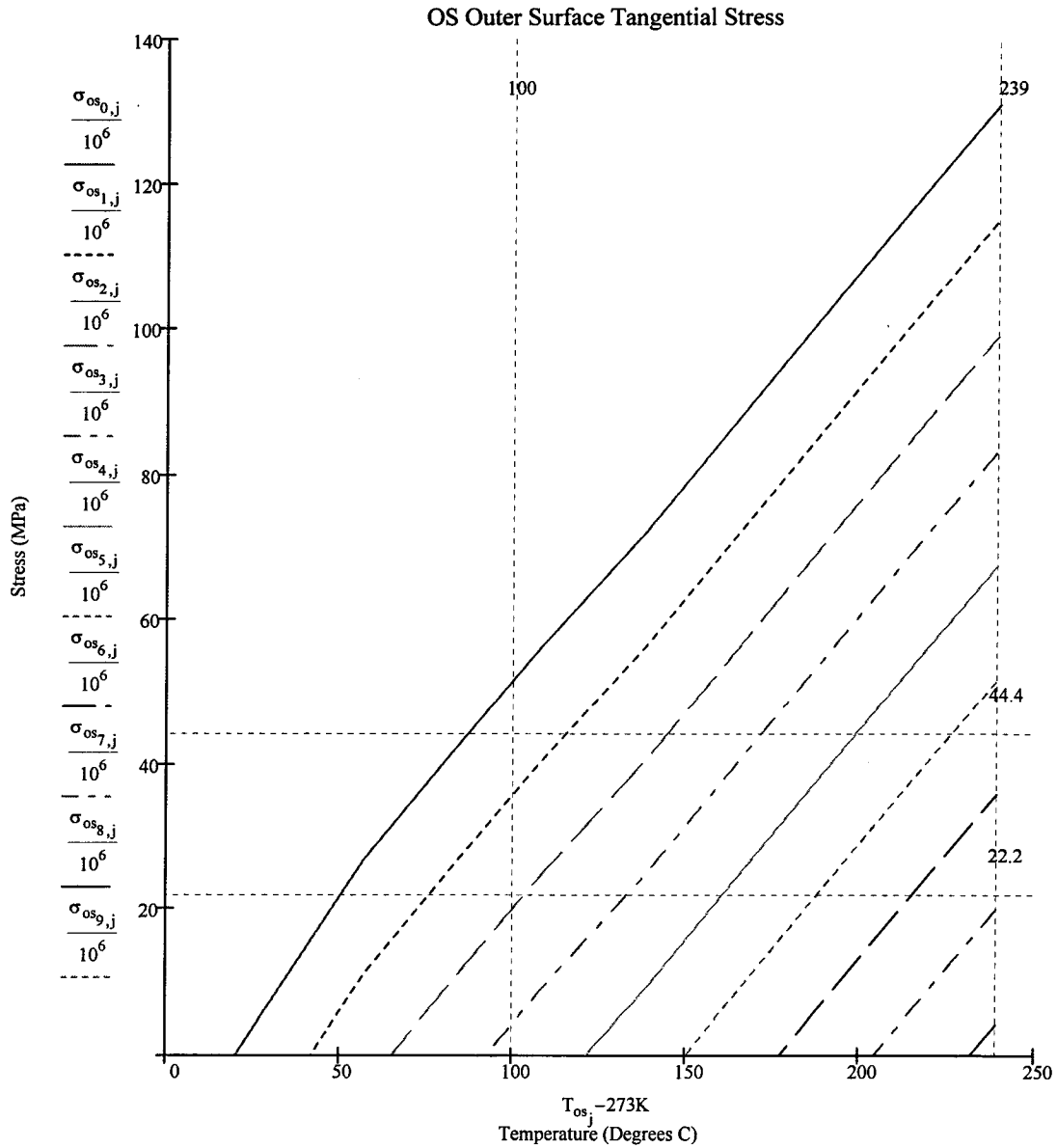
$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad \text{20\% yield strength}$$

$$\sigma_{20\%} = 44.4 \text{ MPa}$$

Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{os_{j,10}}$ =	
0.0	mm	130.9	MPa
0.1		115.0	
0.2		99.2	
0.3		83.4	
0.4		67.5	
0.5		51.7	
0.6		35.8	
0.7		20.0	
0.8		4.2	
0.9		-11.6	
1.0		-27.5	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- - - 0.2-mm gap
- - - 0.3-mm gap
- - - 0.4-mm gap
- - - 0.5-mm gap
- - - 0.6-mm gap
- - - 0.7-mm gap
- - - 0.8-mm gap
- - - 0.9-mm gap

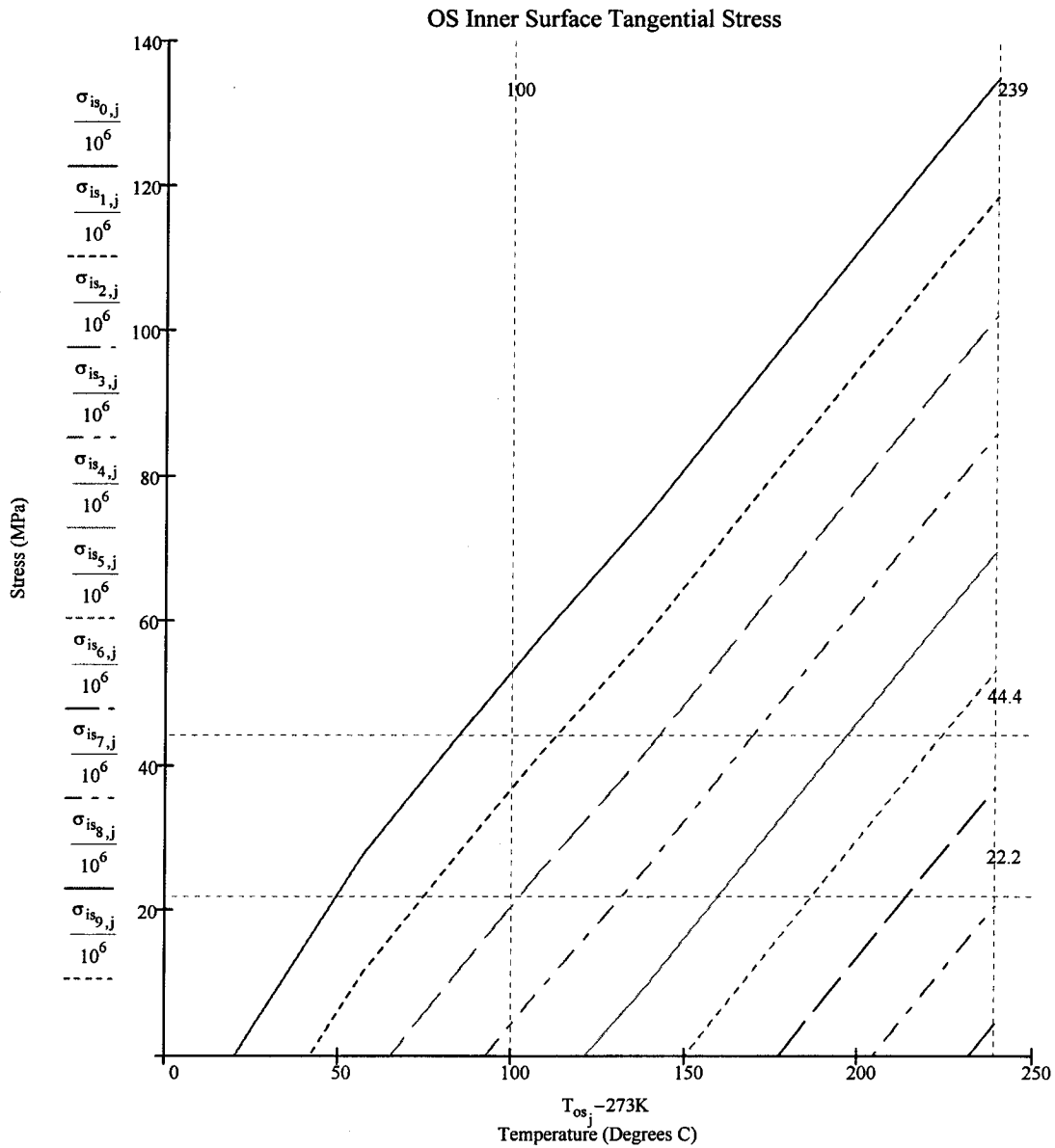
The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.



Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	134.8	MPa
0.1		118.5	
0.2		102.2	
0.3		85.9	
0.4		69.5	
0.5		53.2	
0.6		36.9	
0.7		20.6	
0.8		4.3	
0.9		-12.0	
1.0		-28.3	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- · - 0.2-mm gap
- - - 0.3-mm gap
- 0.4-mm gap
- - - 0.5-mm gap
- · - 0.6-mm gap
- - - 0.7-mm gap
- 0.8-mm gap
- - - 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

## Various Shell Gap Sizes for the Naval SNF Long WP

This calculation determines the outer shell stresses due to uneven thermal expansion of the inner and outer shells. The inner shell is constructed of 316 Stainless Steel Nuclear Grade (Section 5.1.1), and the outer shell is constructed of Alloy 22 (Section 5.1.2). Various shell gap sizes are used to calculate the resulting outer shell stresses.

Parameter  $j$  provides a range from 0 to 10 with an interval of 1.

$j := 0..10$  range from 0 to 10 with an interval of 1

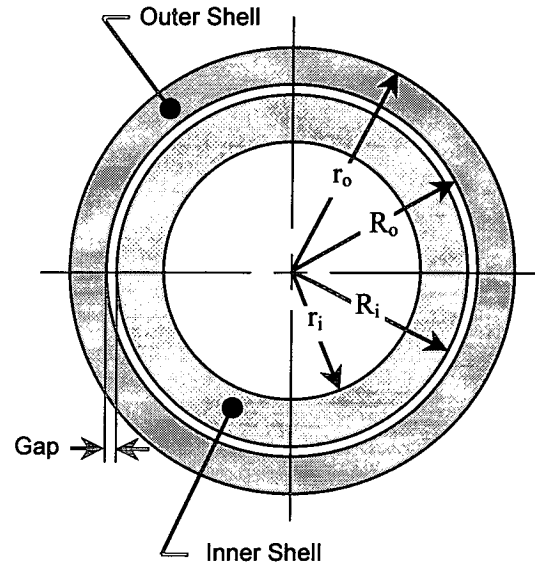
$gap_j := j \cdot 0.0001 \cdot m$  range of shell gap sizes between the shells from which the outer shell stresses are to be calculated

	0	
0	0.0	
1	0.1	
2	0.2	
3	0.3	
4	0.4	
5	0.5	
6	0.6	
7	0.7	
8	0.8	
9	0.9	
10	1.0	

mm

Dimensions of the waste package cross section and the inner cavity length (Section 5.1.3):

$r_i := 0.8595\text{-m}$	inner shell inner radius
$th_i := 0.050\text{-m}$	inner shell thickness
$R_i := r_i + th_i$	inner shell outer radius
$R_o := R_i + \text{gap}$	outer shell inner radius
$th_o := 0.025\text{-m}$	outer shell thickness
$r_o := R_o + th_o$	outer shell outer radius
$L := 5.415\text{m}$	inner cavity length



Material Properties.

$\alpha_{ss} := 17 \cdot 10^{-6} \frac{\text{m}}{\text{m}\cdot\text{K}}$	mean coefficient of thermal expansion for 316NG SS $\left( 9.7 \cdot 10^{-6} \frac{\text{in}}{\text{in}\cdot\text{deg F}} \right)$ (Section 5.1.1)
$\alpha_{\text{alloy22}} := 12.6 \cdot 10^{-6} \frac{\text{m}}{\text{m}\cdot\text{K}}$	mean coefficient of thermal expansion for Alloy 22 $\left( 7.0 \cdot 10^{-6} \frac{\text{in}}{\text{in}\cdot\text{deg F}} \right)$ (Section 5.1.2)

$\text{GPa} := 10^9 \cdot \text{Pa}$	$\text{MPa} := 10^6 \cdot \text{Pa}$	$\text{ksi} := 10^3 \cdot \text{psi}$
$E_o := 206 \cdot \text{GPa}$	$E_o = 29.9 \cdot 10^6 \cdot \text{psi}$	outer shell elastic modulus (Section 5.1.2)
$E_i := 195.1 \cdot \text{GPa}$	$E_i = 28.3 \cdot 10^6 \cdot \text{psi}$	inner shell elastic modulus (Section 5.1.1)
$\nu_o := 0.278$		outer shell Poisson's ratio (Section 5.1.2)
$\nu_i := 0.298$		inner shell Poisson's ratio (Section 5.1.1)

$$K_i := 17.3 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad \text{inner shell thermal conductivity} \left( 10.0 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot\text{deg F}} \right) \text{ (Section 5.1.1)}$$

$$K_o := 13.4 \frac{\text{W}}{\text{m}\cdot\text{K}} \quad \text{outer shell thermal conductivity} \left( 7.75 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot\text{deg F}} \right) \text{ (Section 5.1.2)}$$

$$\sigma_{y,\text{alloy22}} := 222\text{MPa} \quad \sigma_{y,\text{alloy22}} = 32.2 \text{ ksi} \quad \text{outer shell yield strength at 260 degrees C} \text{ (Section 5.1.2)}$$

The upper boundary of the temperature range that the outer shell of the 21-PWR waste package is subject to is 239 degrees C (462 degrees F and 512 K) (Section 5.1.4), occurring 35 years after emplacement. This upper boundary temperature range is used for all waste packages (Section 5.1.4). Room temperature at 20 degrees C (68 degrees F and 293 K) is the initial temperature (Section 5.1.4) of the shells before the spent nuclear fuel is inserted.

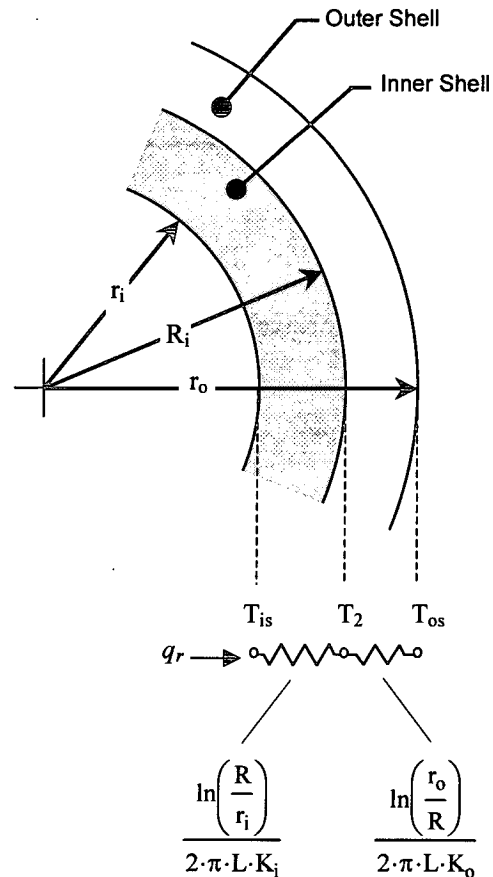
$T_{os}$  represents the temperature range values (Kelvin) of the calculation.  $q_r$  represents the corresponding overall heat transfer rates (Watts) for each temperature (Section 5.1.5). At room temperature the overall heat transfer rate is equal to zero, representing the shells before insertion of the spent nuclear fuel.

$T_{os} :=$	293 330 357 381 411 426 443 468 493 502 512	K	outer shell outer surface temperature	$q_r :=$	0.0 11799.9 11762.5 10846.7 7192.8 7191.7 7182.4 7102.3 6856.1 6540.6 6158.3	W	overall heat transfer rates (Section 5.1.5)
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Using heat transfer methods for a composite cylindrical wall, illustrated here, the inner shell inner surface temperature range,  $T_{is}$ , is found by the following equation (Ref. 16, page 92, eq. (3-29)). These temperature values correspond with  $T_{os}$  values. For this part of the calculation  $R_i$  and  $R_o$  are equal to each other (Assumption 3.5).

$$T_{is} := \left[ \left( \frac{\ln\left(\frac{R_i}{r_i}\right)}{2 \cdot \pi \cdot L \cdot K_i} + \frac{\ln\left(\frac{r_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot K_o} \right) \cdot q_r \right] + T_{os}$$

	0	
$T_{is} =$	293.0	
	1	331.8
	2	358.8
	3	382.7
	4	412.1
	5	427.1
	6	444.1
	7	469.1
	8	494.1
	9	503.0
	10	513.0
		K



The temperature change is found for both the inner shell at the inner surface and outer shell at the outer surface:

$\Delta T_{is} := T_{is} - 293K$                       inner shell inner surface temperature change

$\Delta T_{os} := T_{os} - 293K$                       outer shell outer surface temperature change

Interference between the two shells along the radius is determined using the basic definition of thermal expansion:

$$\varepsilon = \alpha (\Delta T) \quad \text{where } \varepsilon \text{ is the strain (change in length per length), } \alpha \text{ is the coefficient of thermal expansion, and } \Delta T \text{ is the change in temperature (Ref. 17, page 63, eq. (2-61)).}$$

Since  $\varepsilon = \delta / L$  (change in length per length), solving for the change in length,  $\delta$ , yields the equation for thermal expansion along a radius:

$$\delta = \alpha R \Delta T \quad \text{where } \delta \text{ is the change in radial length, } \alpha \text{ is the coefficient of thermal expansion, } R \text{ is the radial length, and } \Delta T \text{ is the change in temperature.}$$

$$\delta_i := \alpha_{ss} R_i \Delta T_{is} \quad \text{change in size of the inner shell outer radius}$$

$$\delta_o := \alpha_{\text{alloy22}} R_o \Delta T_{os}^T \quad \text{change in size of the outer shell inner radius}$$

$$A := (1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1) \quad \text{This 1x11 row vector is used to expand the 11x1 column vectors into matrices compatible with the } \delta_o \text{ 11x11 matrix.}$$

$$\delta := A^T \cdot \delta_i^T - \delta_o - \text{gap} \cdot A \quad \text{interference between shells}$$

$$R_o := R_o \cdot A \quad \text{outer shell inner surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

$$r_o := r_o \cdot A \quad \text{outer shell outer surface radii 11x1 column vector, expanded to an 11x11 matrix}$$

Pressure,  $p$ , due to an interference fit is found by the following equation (Ref. 17, pages 62 to 63, eq. (2-59)):

$$p := \left[ \frac{\delta}{\frac{R_o}{E_o} \left( \frac{r_o^2 + R_o^2}{r_o^2 - R_o^2} + \nu_o \right) + \frac{R_i}{E_i} \left( \frac{R_i^2 + r_i^2}{R_i^2 - r_i^2} - \nu_i \right)} \right]$$

The tangential stresses at the inner and outer surfaces of the outer shell are found in this section.

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the outer surface:

$$\sigma_{os} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{r_o^2} \right) \right] \quad \text{outer shell outer surface tangential stress (MPa)}$$

Outer shell tangential stress (Ref. 17, page 59, eq. (2-50), first equation) at the inner surface:

$$\sigma_{is} := \left[ \frac{p \cdot (R_o)^2}{r_o^2 - R_o^2} \cdot \left( 1 + \frac{r_o^2}{R_o^2} \right) \right] \quad \text{outer shell inner surface tangential stress (MPa)}$$

The following calculations determine the outer shell 10% and 20% yield strength values. These values are marked on the resulting plots and are for informational purposes only.

$$\sigma_{10\%} := 10\% \cdot \sigma_{y, \text{alloy22}} \quad \text{10\% yield strength}$$

$$\sigma_{10\%} = 22.2 \text{ MPa}$$

$$\sigma_{20\%} := 20\% \cdot \sigma_{y, \text{alloy22}} \quad \text{20\% yield strength}$$

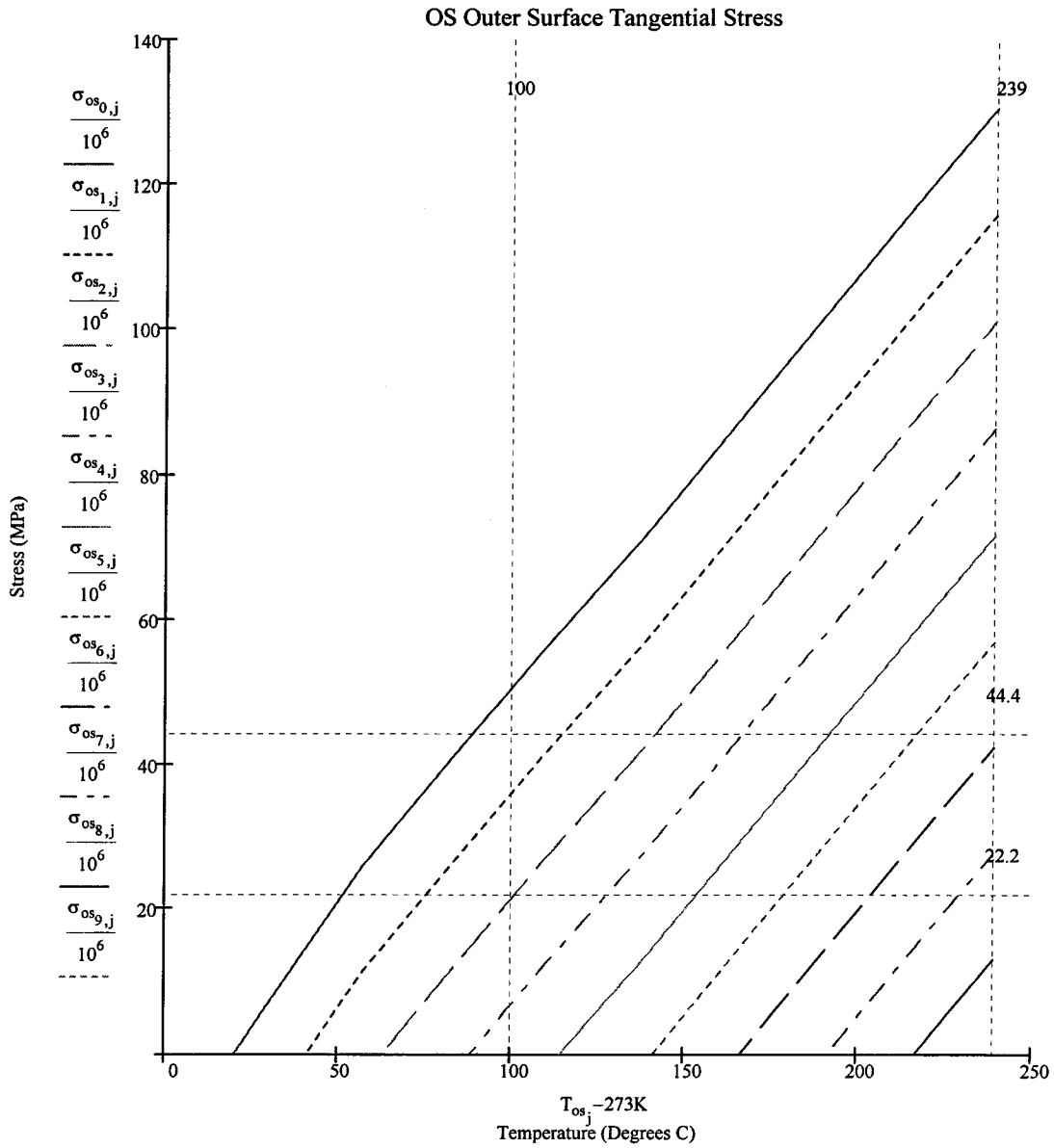
$$\sigma_{20\%} = 44.4 \text{ MPa}$$



Maximum stress at 239 degrees C at the outer surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{os_{j,10}}$ =	
0.0	mm	130.4	MPa
0.1		115.7	
0.2		101.1	
0.3		86.4	
0.4		71.7	
0.5		57.0	
0.6		42.4	
0.7		27.7	
0.8		13.0	
0.9		-1.7	
1.0		-16.3	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the outer surface of the outer shell for various gap sizes.



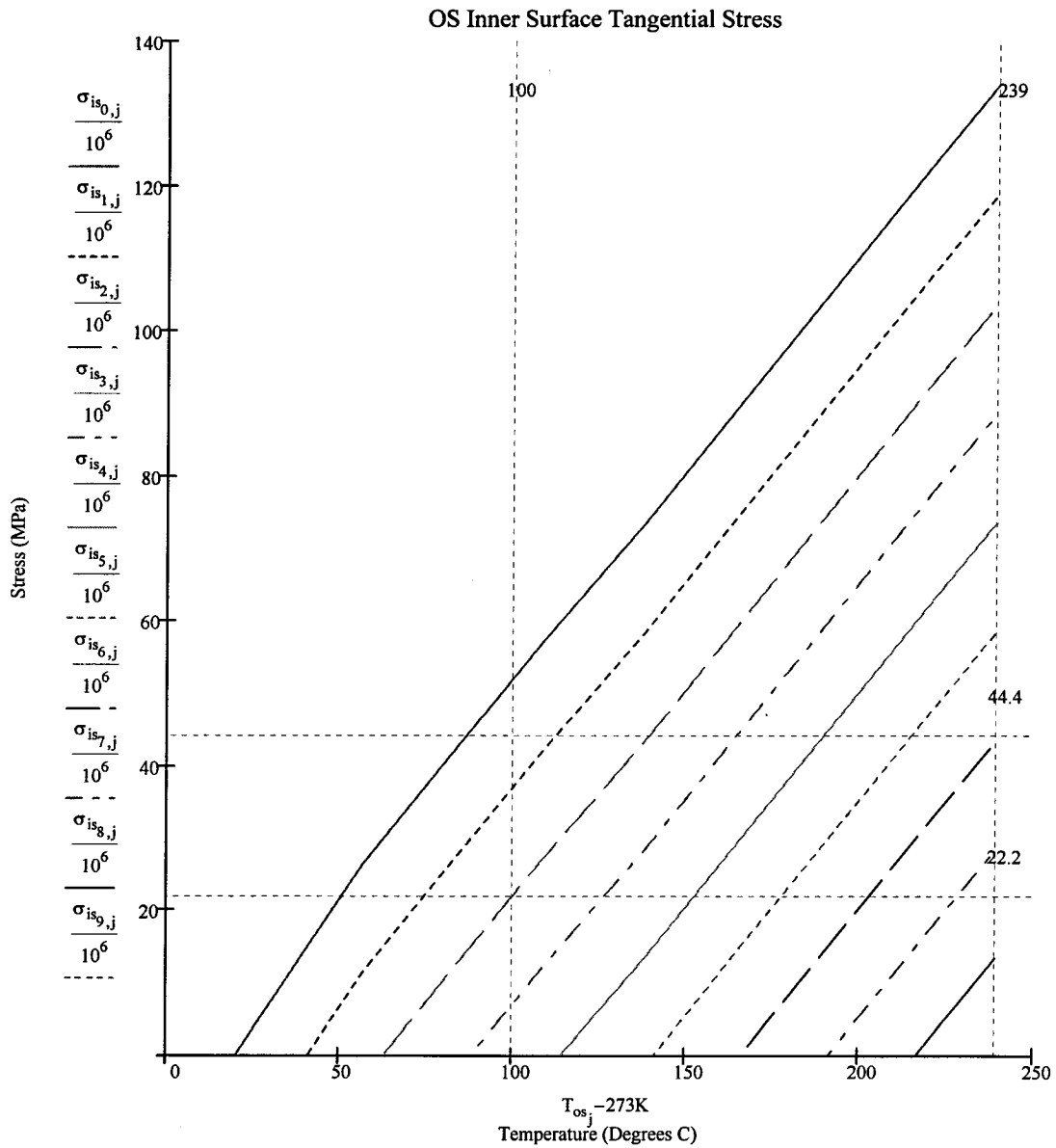
- 0.0-mm gap
- - - 0.1-mm gap
- . - 0.2-mm gap
- . . 0.3-mm gap
- . . . 0.4-mm gap
- . . . . 0.5-mm gap
- . . . . . 0.6-mm gap
- . . . . . . 0.7-mm gap
- . . . . . . . 0.8-mm gap
- . . . . . . . . 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

Maximum stress at 239 degrees C at the inner surface for a corresponding gap size. Negative stresses signify that there is no contact between the shells for the corresponding gap size.

gap <sub>j</sub> =		$\sigma_{is_{j,10}}$ =	
0.0	mm	134.1	MPa
0.1		119.0	
0.2		103.9	
0.3		88.8	
0.4		73.7	
0.5		58.6	
0.6		43.5	
0.7		28.5	
0.8		13.4	
0.9		-1.7	
1.0		-16.8	

This plot illustrates the stress (MPa) with respect to temperature (degrees C) of the inner surface of the outer shell for various gap sizes.



- 0.0-mm gap
- - - 0.1-mm gap
- . - 0.2-mm gap
- . . 0.3-mm gap
- . . . 0.4-mm gap
- . . . . 0.5-mm gap
- . . . . . 0.6-mm gap
- . . . . . . 0.7-mm gap
- . . . . . . . 0.8-mm gap
- . . . . . . . . 0.9-mm gap

The 44.4 MPa and 22.2 MPa horizontal dashed lines indicate 10% and 20% yield strength of alloy 22. These lines are for informational purposes only.

## Thermal Expansion for a Long Circular Cylinder

This attachment will verify the basic equation for thermal expansion through the radius of a cylinder. The equation is as follows:

$$\delta = \alpha \cdot R \cdot \Delta T$$

where

$\delta$  is the change in radial length,  
 $\alpha$  is the coefficient of thermal expansion,  
 $R$  is the radial length,  
and  $\Delta T$  is the change in temperature.

The following equations (Ref. 19, page 444, eq. (c) through (f)) are used to determine the stress in the radial, angular, and axial directions, represented by  $\sigma_r$ ,  $\sigma_\theta$ , and  $\sigma_z$ , respectively. The displacement due to thermal expansion is given by  $u$ . Since the temperature gradient through the barrier thickness is negligibly small,  $\Delta T$  is independent of the radius,  $r$ .

$$u = \frac{1 + \nu}{1 - \nu} \cdot \alpha \cdot \frac{1}{r} \cdot \int_a^r \Delta T \cdot r \, dr + C_1 \cdot r + \frac{C_2}{r} \quad (1)$$

$$\sigma_r = -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{1}{r^2} \int_a^r \Delta T \cdot r \, dr + \frac{E}{1 + \nu} \cdot \left( \frac{C_1}{1 - 2\nu} - \frac{C_2}{r^2} \right) \quad (2)$$

$$\sigma_\theta = \frac{\alpha \cdot E}{1 - \nu} \cdot \frac{1}{r^2} \int_a^r \Delta T \cdot r \, dr - \frac{\alpha \cdot E \cdot \Delta T}{1 - \nu} + \frac{E}{1 + \nu} \cdot \left( \frac{C_1}{1 - 2\nu} + \frac{C_2}{r^2} \right) \quad (3)$$

$$\sigma_z = -\frac{\alpha \cdot E \cdot \Delta T}{1 - \nu} + \frac{2 \cdot \nu \cdot E \cdot C_1}{(1 + \nu)(1 - 2\nu)} \quad (4)$$

where

$\nu$  is Poisson's ratio,  
 $\alpha$  is the coefficient of thermal expansion,  
 $E$  is the elastic modulus,  
 $r$  is the radial length,  
 $a$  is the inner radius,  
and  $\Delta T$  is the change in temperature.

Integrating and simplifying equation (2) gives

$$\sigma_r = -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{1}{r^2} \int_a^r \Delta T \cdot r \, dr + \frac{E}{1 + \nu} \cdot \left( \frac{C_1}{1 - 2\nu} - \frac{C_2}{r^2} \right)$$

$$\sigma_r = -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{1}{r^2} \left( \frac{1}{2} \cdot r^2 \cdot \Delta T - \frac{1}{2} \cdot a^2 \cdot \Delta T \right) + \frac{E}{1 + \nu} \cdot \left( \frac{C_1}{1 - 2\nu} - \frac{C_2}{r^2} \right)$$

$$\sigma_r = -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{\Delta T}{2} \cdot \left( 1 - \frac{a^2}{r^2} \right) + \frac{E}{1 + \nu} \cdot \left( \frac{C_1}{1 - 2\nu} - \frac{C_2}{r^2} \right) \quad (5)$$

Using eq. (5),  $C_2$  is found in terms of  $C_1$  by using the following boundary condition:

For  $r = a$ ,  $\sigma_r = 0$ .

$$C_2 = \frac{1}{1 - 2\nu} \cdot a^2 \cdot C_1 \quad (6)$$

$C_2$  is substituted into eq. (5).

$$\sigma_r = -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{\Delta T}{2} \cdot \left( 1 - \frac{a^2}{r^2} \right) + \frac{E}{1 + \nu} \left[ \frac{C_1}{1 - 2\nu} - \left( \frac{1}{1 - 2\nu} \cdot a^2 \cdot C_1 \right) \frac{1}{r^2} \right]$$

$$\sigma_r = -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{\Delta T}{2} \cdot \left( 1 - \frac{a^2}{r^2} \right) + \frac{C_1 \cdot E}{(1 + \nu) \cdot (1 - 2\nu)} \cdot \left( 1 - \frac{a^2}{r^2} \right)$$

$$\sigma_r = \left[ -\frac{\alpha \cdot E}{1 - \nu} \cdot \frac{\Delta T}{2} + \frac{C_1 \cdot E}{(1 + \nu) \cdot (1 - 2\nu)} \right] \cdot \left( 1 - \frac{a^2}{r^2} \right) \quad (7)$$

Using eq. (7),  $C_1$  is found by using the following boundary condition:

For  $r = b$ ,  $\sigma_r = 0$ , where  $b$  is the outer radius.

$$C_1 = \frac{(1 + \nu) \cdot (1 - 2\nu)}{2(1 - \nu)} \cdot \alpha \cdot \Delta T \quad (8)$$

Substituting  $C_1$  into eq. (6) produces  $C_2$ .

$$C_2 = \frac{1}{1-2\nu} \cdot a^2 \cdot \frac{(1+\nu) \cdot (1-2\nu)}{2(1-\nu)} \cdot \alpha \cdot \Delta T$$

$$C_2 = \frac{(1+\nu)}{2(1-\nu)} \cdot a^2 \cdot \alpha \cdot \Delta T \quad (9)$$

$C_1$  and  $C_2$  are inserted into eq. (5) to determine the radial stress,  $\sigma_r$ .

$$\sigma_r = -\frac{\alpha \cdot E}{1-\nu} \cdot \frac{\Delta T}{2} \cdot \left(1 - \frac{a^2}{r^2}\right) + \frac{E}{1+\nu} \cdot \left[ \frac{1}{1-2\nu} \cdot \frac{(1+\nu) \cdot (1-2\nu)}{2(1-\nu)} \cdot \alpha \cdot \Delta T - \frac{1}{r^2} \cdot \frac{(1+\nu)}{2(1-\nu)} \cdot a^2 \cdot \alpha \cdot \Delta T \right]$$

Reducing the equation yields

$$\sigma_r = -\frac{E}{2(1-\nu)} \cdot \alpha \cdot \Delta T \cdot \left(1 - \frac{a^2}{r^2}\right) + \frac{E}{1+\nu} \cdot \left[ \frac{(1+\nu)}{2(1-\nu)} \cdot \alpha \cdot \Delta T - \frac{(1+\nu)}{2(1-\nu)} \cdot \frac{a^2}{r^2} \cdot \alpha \cdot \Delta T \right]$$

$$\sigma_r = -\frac{E}{2(1-\nu)} \cdot \alpha \cdot \Delta T \cdot \left(1 - \frac{a^2}{r^2}\right) + \frac{E}{2(1-\nu)} \cdot \alpha \cdot \Delta T \cdot \left(1 - \frac{a^2}{r^2}\right)$$

$$\sigma_r = 0 \quad (10)$$

$C_1$  and  $C_2$  are inserted into eq. (3) to determine the angular stress,  $\sigma_\theta$ .

$$\sigma_\theta = \frac{\alpha \cdot E}{1-\nu} \cdot \frac{1}{r^2} \cdot \int_a^r \Delta T \cdot r \cdot dr - \frac{\alpha \cdot E \cdot \Delta T}{1-\nu} + \frac{E}{1+\nu} \cdot \left[ \frac{1}{1-2\nu} \cdot \frac{(1+\nu) \cdot (1-2\nu)}{2(1-\nu)} \cdot \alpha \cdot \Delta T + \frac{(1+\nu)}{2(1-\nu)} \cdot \frac{a^2}{r^2} \cdot \alpha \cdot \Delta T \right]$$

Reducing the equation yields

$$\sigma_{\theta} = \frac{\alpha \cdot E}{1 - \nu} \cdot \frac{1}{r^2} \left[ \frac{1}{2} \cdot \Delta T \cdot (r^2 - a^2) \right] - \frac{\alpha \cdot E \cdot \Delta T}{1 - \nu} + \frac{E}{1 + \nu} \left[ \frac{(1 + \nu)}{2 \cdot (1 - \nu)} \cdot \alpha \cdot \Delta T + \frac{(1 + \nu)}{2 \cdot (1 - \nu)} \cdot \frac{a^2}{r^2} \cdot \alpha \cdot \Delta T \right]$$

$$\sigma_{\theta} = \frac{E}{2(1 - \nu)} \cdot \alpha \cdot \Delta T \cdot \left( 1 - \frac{a^2}{r^2} \right) - \frac{E}{1 - \nu} \cdot \alpha \cdot \Delta T + \frac{E}{2 \cdot (1 - \nu)} \cdot \alpha \cdot \Delta T \cdot \left( 1 + \frac{a^2}{r^2} \right)$$

$$\sigma_{\theta} = \frac{E}{2(1 - \nu)} \cdot \alpha \cdot \Delta T \cdot \left( 1 - \frac{a^2}{r^2} - 2 \right) + \frac{E}{2 \cdot (1 - \nu)} \cdot \alpha \cdot \Delta T \cdot \left( 1 + \frac{a^2}{r^2} \right)$$

$$\sigma_{\theta} = -\frac{E}{2(1 - \nu)} \cdot \alpha \cdot \Delta T \cdot \left( 1 + \frac{a^2}{r^2} \right) + \frac{E}{2 \cdot (1 - \nu)} \cdot \alpha \cdot \Delta T \cdot \left( 1 + \frac{a^2}{r^2} \right)$$

$$\sigma_{\theta} = 0 \tag{11}$$

A uniform axial stress  $\sigma_z = C_3$  is superposed onto eq. (4), choosing  $C_3$  so that the resultant force on the ends is zero (Ref. 19, page 444).

$$\sigma_z = \frac{\alpha \cdot E \cdot \Delta T}{1 - \nu} + \frac{2 \cdot \nu \cdot E \cdot C_1}{(1 + \nu)(1 - 2\nu)} + C_3 = 0 \tag{12}$$

Using eq. (12),  $C_3$  is found by substituting  $C_1$  into the equation.

$$C_3 = \frac{\alpha \cdot E \cdot \Delta T}{1 - \nu} - \frac{2 \cdot \nu \cdot E}{(1 + \nu) \cdot (1 - 2\nu)} \cdot \frac{(1 + \nu) \cdot (1 - 2\nu)}{2(1 - \nu)} \cdot \alpha \cdot \Delta T$$

Reducing the equation yields

$$C_3 = \frac{E}{1 - \nu} \cdot \alpha \cdot \Delta T - \frac{\nu \cdot E}{1 - \nu} \cdot \alpha \cdot \Delta T$$

$$C_3 = \frac{E}{1 - \nu} \cdot \alpha \cdot \Delta T (1 - \nu)$$

$$C_3 = E \cdot \alpha \cdot \Delta T \tag{13}$$



The displacement  $u$ , is affected by the axial stress  $C_3$ . A term  $-vC_3/E$  must be added on the right of eq. (1) (Ref. 19, page 445).

$$u = \frac{1+v}{1-v} \cdot \alpha \cdot \frac{1}{r} \cdot \int_a^r \Delta T \cdot r \, dr + C_1 \cdot r + \frac{C_2}{r} + \left( \frac{v \cdot C_3 \cdot r}{E} \right) \quad (14)$$

$C_1$ ,  $C_2$ , and  $C_3$  are inserted into eq. (14) to determine the radial displacement.

$$u = \frac{1+v}{1-v} \cdot \alpha \cdot \frac{1}{r} \cdot \int_a^r \Delta T \cdot r \, dr + \frac{(1+v) \cdot (1-2 \cdot v)}{2(1-v)} \cdot \alpha \cdot \Delta T \cdot r + \frac{1}{r} \cdot \frac{(1+v)}{2(1-v)} \cdot a^2 \cdot \alpha \cdot \Delta T + \left( \frac{v \cdot E \cdot \alpha \cdot \Delta T \cdot r}{E} \right)$$

Reducing the equation yields

$$u = \frac{1+v}{2(1-v)} \cdot \frac{1}{r} \cdot \alpha \cdot \Delta T \cdot (r^2 - a^2) + \frac{(1+v) \cdot (1-2 \cdot v)}{2 \cdot (1-v)} \cdot \alpha \cdot \Delta T \cdot r + \frac{(1+v)}{2 \cdot (1-v)} \cdot \frac{a^2}{r} \cdot \alpha \cdot \Delta T - v \cdot \alpha \cdot r \cdot \Delta T$$

$$u = \frac{1+v}{2 \cdot (1-v)} \cdot \alpha \cdot \Delta T \cdot \left[ \left( r - \frac{a^2}{r} \right) + (1-2 \cdot v) \cdot r + \frac{a^2}{r} \right] - v \cdot \alpha \cdot r \cdot \Delta T$$

$$u = \frac{1+v}{2 \cdot (1-v)} \cdot \alpha \cdot \Delta T \cdot \left( r - \frac{a^2}{r} + r - 2 \cdot v \cdot r + \frac{a^2}{r} \right) - v \cdot \alpha \cdot r \cdot \Delta T$$

$$u = \frac{1+v}{2 \cdot (1-v)} \cdot \alpha \cdot \Delta T \cdot (2r - 2 \cdot v \cdot r) - v \cdot \alpha \cdot r \cdot \Delta T$$

$$u = \frac{1+v}{(1-v)} \cdot \alpha \cdot r \cdot \Delta T \cdot (1-v) - v \cdot \alpha \cdot r \cdot \Delta T$$

$$u = (1+v) \cdot \alpha \cdot r \cdot \Delta T - v \cdot \alpha \cdot r \cdot \Delta T$$

$$u = \alpha \cdot r \cdot \Delta T \quad (15)$$