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Calculation Cover Sheet

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1. PURPOSE

The purpose of this analysis is to determine the structural response of a TRIGA Department of Energy (DOE) spent nuclear fuel (SNF) codisposal canister placed in a 5-Defense High Level Waste (DHLW) waste package (WP) and subjected to a tipover design basis event (DBE) dynamic load (see Ref. 7.1, p. 44); the results will be reported in terms of displacements and stress magnitudes. This activity is associated with the WP design.

2. METHOD

A finite element solution was performed by making use of the commercially available ANSYS V5.4 finite element code. The results of this analysis were provided in terms of displacements and maximum stresses.

3. ASSUMPTIONS

In the course of developing this document, assumptions were made regarding the DOE SNF codisposal canister structural analysis. The basis for the dimensional assumptions identified below (3.5 through 3.17, 3.19 through 3.21, and 3.25 through 3.31) are the sketches provided in the Attachment I. No additional basis for the dimensional assumptions, other than the dimensional reasoning, is deemed to be necessary in this document, since future analyses will be performed to determine the adequacy of the current design and dimensions.

3.1 Some of the rate-dependent material properties were not available for the materials used. Therefore, the material properties obtained under the static loading conditions were assumed for all materials. In general, this is notably conservative assumption, nonetheless, in this case, the impact of using material properties obtained under the static loading conditions is anticipated to be small. The basis for this assumption is that the mechanical properties of subject materials do not significantly change at the peak strain rates in the course of the tipover DBE. This assumption is used in Section 5.1.2.

3.2 Some of the temperature-dependent material properties were not available for SA-516 K02700 and SB-575 N06022. Therefore, room temperature (20 °C) material properties were assumed for all materials. The impact of using room temperature material properties is anticipated to be small. The basis for this assumption is that the mechanical properties of subject materials do not significantly change at the WP temperatures experienced during handling and lifting operations. This assumption is used in Section 5.1.2.

3.3 The containment barriers are assumed to have solid connections at the adjacent surfaces. The basis for this assumption is that the inner and outer barriers will either be shrunk fit or the inner barrier will be weld clad onto the outer barrier inner surface (Ref. 7.2, p. 26). For each one of these fabrication processes it is reasonable to assume solid contact between the barriers. This assumption is used in Section 5.2.

3.4 The target surface is conservatively assumed to be essentially unyielding by using a large elastic modulus for the target surface compared to the waste package. The basis for this assumption is that a bounding set of results is required in terms of stresses and displacements and it is known that the use of an essentially unyielding surface ensures slightly higher stresses and displacements in the waste package. This assumption is used in Section 5.2.

3.5 Inner barrier inner diameter = 1.880 *m* (Attachment I-1). This assumption is used in Section 5.2 and Section 5.3.

3.6 Inner barrier outer diameter = outer barrier inner diameter = 1.920 *m* (Attachment I-1). This assumption is used in Section 5.2 and Section 5.3.

3.7 Outer barrier outer diameter = 2.120 *m* (Attachment I-1). This assumption is used in Section 5.2 and Section 5.3.

3.8 Outer barrier skirt inner diameter = 2.000 *m* (Attachment I-1). This assumption is used in Section 5.2.

3.9 Divider plate thickness = 0.0127 *m*. (Attachment I-1). This assumption is used in Section 5.2.

3.10 Support tube (canister guide) thickness = 0.03175 *m* (Attachment I-1). This assumption is used in Section 5.2.

3.11 Inner bracket thickness = 0.0254 *m* (Attachment I-1). This assumption is used in Section 5.2.

3.12 Inner bracket inner tip distance from origin = 0.354 *m* (Attachment I-1). This assumption is used in Section 5.2.

3.13 Corner angle of brackets (angle irons) = 90° (Attachment I-1). This assumption is used in Section 5.2.

3.14 Outer bracket inner tip distance from the origin = 0.6135 *m* (Attachment I-1). This assumption is used in Section 5.2.

3.15 Support tube outer diameter = 0.565 *m* (Attachment I-1). This assumption is used in Section 5.2.

3.16 Fuel pipe outer diameter = 0.0603 *m* (Attachment I-2). This assumption is used in Section 5.2.

3.17 Fuel pipe wall thickness = 0.00554 *m* (0.218 *in.*) (Attachment I-2). This assumption is used in Section 5.2.

3.18 For the vitrified waste, ambient material properties of general borosilicate glass, taken from Ref. 7.13, p. 189, are assumed to be applicable. The basis for this assumption is that the vitrified waste is primarily borosilicate glass. This information is the best available at the time of the calculation. The calculation does not specifically report any results from the glass, but it is included in the finite element representation and has some effect on the reaction of the pour canisters. This assumption is used in Section 5.1.2.

3.19 Outer barrier length = 3.79 *m* (Attachment I-1). This assumption is used in Section 5.3.

3.20 Distance from the skirt end surface to the inner lid outer surface = 0.335 *m* (Attachment I-1). This assumption is used in Section 5.3.

3.21 Inner barrier length = 3.09 *m* (Attachment I-1). This assumption is used in Section 5.3.

3.22 Base plates, pipes, and basket support bracket are assumed to be made of 316L stainless steel (Attachment I-2). This assumption is based on manufacturing purposes such as the necessity to ensure welding compatibility. This assumption is used in Section 5.1.2.

3.23 The magnitudes of the contact stiffnesses between: the waste package and the target surface, the 18 in. canister and the support tube, the pour canister and the inner bracket, the pipes and the 18 in. canister, and the basket support bracket and the 18 in. canister, are assumed to be $2 \cdot 10^9 \ N/m$. The basis for this assumption is explained below:
The magnitude of the contact stiffness between surfaces is one of parameters that affects the results. If the contact stiffness value is very large, stiffness matrix ill-conditioning and divergence occur. On the other hand an extremely small contact stiffness value results in compatibility violations. Therefore, an optimum value for the contact stiffness is one that is between and is arrived at iteratively. The result of iterations revealed that the contact stiffness that works best is $2 \cdot 10^9 \ N/m$. This magnitude of the contact stiffness is used to model all contacts. This assumption is used in Section 5.2.

3.24 The coefficients of static and dynamic friction values have been provided for steel on steel contact, which have been obtained from the limited data in the literature. The basis for this

assumption is that since there is no significant relative displacement between the contact surfaces in this analysis, the friction coefficients do not have significant effect on the results. However, the following numbers had to be specified in order to meet the computational requirements:
Coefficient of static friction = 0.6 (Ref. 7.21, Table D/1 Properties)
Coefficient of kinetic friction = 0.4 (Ref. 7.21, Table D/1 Properties)
This assumption is used in Section 5.2.

3.25 Basket support bracket width = 0.0682 *m* (Attachment I-2). This assumption is used in Section 5.2.

3.26 Basket support bracket height = 0.025 *m* (Attachment I-2). This assumption is used in Section 5.2.

3.27 Basket support bracket thickness = 0.0079375 *m* (5/16 *in.*) (Attachment I-2). This assumption is used in Section 5.2.

3.28 Distance from the skirt end surface to the inner lid inner surface = 0.36 *m* (Attachment I-1). This assumption is used in Section 5.3.

3.29 Inner barrier lid thickness = 0.025 *m* (Attachment I-1). This assumption is used in Section 5.3.

3.30 Distance (gap) between inner barrier lid and outer barrier lid = 0.03 *m* (Attachment I-1). This assumption is used in Section 5.3.

3.31 Five-fold symmetry angle of the basket assembly = $360^\circ/5 = 72^\circ$ (Attachment I-1). This assumption is used in Section 5.3.

3.32 In the course of calculation of the total mass moment of inertia about the rotation axis (pivot) the support tube (canister guide), the 18 in. canister, and the basket assembly (divider plates, inner and outer brackets) are considered as one WP component. The length of this component is approximated by the minimum length of the three parts, which is 3.00 *m*. This is conservative assumption. The basis for this simplifying assumption is that although the lengths of constituents are slightly different (3.02 *m* and 3.0 *m*) the use of the minimum length results in the conservative estimate of the impact velocity. This assumption is used in Section 5.3.

4. USE OF COMPUTER SOFTWARE AND MODELS

The finite element analysis computer code used for this calculation is ANSYS version (V) 5.4 which is identified with the Computer Software Configuration Item (CSCI) 30040 V5.4 and was obtained from Software Configuration Management in accordance with appropriate procedures. ANSYS V5.4 is a commercially available finite element analysis code and is appropriate for structural analysis of waste packages as performed in this analysis. The calculations using the ANSYS V5.4 software were executed on a Hewlett-Packard (HP) workstation identified with Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O) tag number 115288. The software qualification of the ANSYS V5.4 software, including problems of the type analyzed in this report, is summarized in the Software Qualification Report for ANSYS V5.4 (Ref. 7.3). Qualification of ANSYS V5.4 on the Waste Package Operations (WPO) HP UNIX workstations is documented in Ref. 7.22. The ANSYS evaluations performed for this design are fully within the range of the validation performed for the ANSYS V5.4 code. Access to and use of the code for the analysis were granted and performed in accordance with the appropriate procedures.

Industry standard software used in this calculation is Pro/Engineer Version 20.0. This software is executed on the HP workstation identified with CRWMS M&O tag number 700887. Pro/Engineer Version 20.0 is not controlled computer software, has not been qualified under the AP-SI series of M&O procedures, and will not be qualified under the M&O procedures.

Attachment I contains the input/output data obtained from Pro/Engineer Version 20.0. The mass densities given in Section 5.1.2 are used as inputs to Pro/Engineer Version 20.0 and corresponding masses of WP components are obtained for the use in structural evaluations. There are no equations of mathematical models, algorithms, or numerical solution techniques applicable to the software routine since Pro/Engineer Version 20.0 is an engineering drawing software package and the subject mass calculations are performed by the source code, based on the dimensions of structural components and the mass density of materials. Verification of this software is accomplished by two test cases, as described in Section 5.1.1. The range of input parameter values is limited to the dimensions of the structural components used in those cases; all mass calculations depend on specific geometry of the subject components. No limitations are identified on software routine applications or validity.

5. CALCULATION

A number of data used in this calculation are based on the existing information from the current waste package designs and the literature available for material properties. Therefore, all data excluding data considered as established fact because of the nature of the publication (e.g., codes and standards, engineering handbooks), shall be treated as existing (unqualified) data. Use of any data from this analysis for input into documents supporting construction, fabrication, or procurement is required to be controlled with TBV (to be verified) tracking in accordance with the appropriate procedures.

When converting values from English to metric units, the added digits of significance are an artifact of the conversion process and do not reflect actual precision of the value as expressed in metric.

The corrosion allowance shell will be referred to as the outer barrier; the corrosion resistant shell will be referred to as the inner barrier; the DOE SNF canister will be referred to as 18 in. canister; the Savannah River Plant High Level Waste (HLW) canister will be referred to as the pour canister throughout this document.

5.1 Calculation Data

5.1.1 Mass and Length of Canisters and Fuel Element

Outer Barrier mass = 17984 *kg* (Attachment I-1)
Inner Barrier mass = 3202 *kg* (Attachment I-1)

Savannah River Plant HLW total canister mass = 2182 *kg* (Ref. 7.19, Table 3.1.1)
Savannah River Plant HLW canister length = 3.00 *m* (Ref. 7.19, Table 3.1.1)
Savannah River Plant HLW canister outer diameter = 0.610 *m* (Ref. 7.19, Table 3.1.1)
Savannah River Plant HLW canister thickness = 0.009525 *m* (0.375 *in.*) (Ref. 7.19, Table 3.1.1)

DOE SNF canister maximum mass = 2270 *kg* (Ref. 7.4, Table 3.2)
DOE SNF canister length = 3.00 *m* (Ref. 7.4, Table 3.1)
DOE SNF canister diameter = 0.4572 *m* (18 *in.*) (Ref. 7.4, p. 5)
DOE SNF canister thickness = 0.009525 *m* (0.375 *in.*) (Ref. 7.4, p. 5)
Total Mass of Stainless Steel Clad TRIGA fuel element (FLIP-L-II) = 4.09 *kg* (Ref. 7.23, Table 5-3)
Length of Standard Streamline Type Rods = 29.68 *in.* = 0.7539 *m* (Ref. 7.14, p. 12)
Outer Diameter of Standard Streamline Type Rods = 1.478 *in.* = 0.0375 *m* (Ref. 7.14, p. 12)

One of the 5-DHLW/DOE spent fuel disposal container structural components, the support tube, is selected for verification of the mass obtained from Pro/Engineer Version 20.0. The mass of this component is determined as product of the mass density (see Section 5.1.2) and the volume, using the dimensions provided on p. I-1:

$$Mass = 7850\left[(3.04 - 0.01)\cdot\left(0.565^2 - 0.5015^2\right)\pi/4\right] = 1265.1347\,kg$$

The mass obtained by preceding calculation is identical to the mass provided on p. I-4.

The same verification procedure is applied for the base plate of the TRIGA DOE SNF basket assembly using the appropriate mass density (see Section 5.1.2) and the dimensions provided on p. I-2:

$$Mass = 7980\left(0.0095 \cdot 0.426^2\ \pi/4\right) = 10.805269\,kg$$

The mass obtained is identical to the mass presented on p. I-11.

5.1.2 Material Properties

Waste package material properties used in the calculations are listed in this section. Some of the temperature-dependent material properties were not available for SA-516 K02700 and SB-575 N06022; therefore, room temperature material properties were used in calculations (Assumption 3.2). Also, the rate-sensitive material properties were not available; therefore, the material properties obtained from static tests were used in calculations (Assumption 3.1).

SA-516 K02700 (ASTM A 516 Grade 70 carbon steel) (Outer barrier, basket, and support tube material, Ref. 7.6, pp. 125-126):
Material supplied to ASTM A 516/A 516M-90 specification conforms to specification A 20/A 20 M-95a (Ref. 7.7, Section 3.1). Therefore, density = 7850 kg/m^3 (Ref. 7.8, Section 14.1)
Poisson's ratio was not available for ASTM A 516 carbon steel. Since the elastic constants of cast carbon steels are only slightly affected by changes in composition and structure, Poisson's ratio of cast carbon steel can be used for A 516 carbon steel: Poisson's ratio = 0.3 (Ref. 7.12, p. 393)
Since the carbon content of A 516 Grade 70 can be up to 0.31% (Ref. 7.7, p. 2) and the difference between the elastic moduli for steels with carbon contents less than or greater than 0.30% specified at the temperature of interest is negligibly small (Ref. 7.10, Table TM-1),
Modulus of elasticity = 202 *GPa* (29.3 * 10^6 *psi*) (Ref. 7.10, Table TM-1) (at 20 ℃)
Yield strength = 262 *MPa* (38 *ksi*) (Ref. 7.10, Table Y-1) (at 20 ℃)
Tensile strength = 483 *MPa* (70 *ksi*) (Ref. 7.10, Table U) (at 20 ℃)
% elongation = 21 (Ref. 7.7) (at 20 ℃)
SB-575 N06022 (ASTM B 575) (Inner barrier material, Ref. 7.6, p. 125):
Density = 8690 kg/m^3 (0.314 lb/in^3) (Ref. 7.11, p. 2)
Poisson's ratio was not available for SB-575 N06022. Since the chemical compositions of SB-575 N06022 and Alloy 625 are similar (see Ref. 7.11, p. 2 and Ref. 7.9, p. 143), Poisson's ratio of Alloy 625 is used for SB-575 N06022: Poisson's ratio = 0.278 (Ref. 7.9, p. 143) (at 20 ℃)
Modulus of elasticity = 206 *GPa* (29.9 * 10^6 *psi*) (Ref. 7.5, p. 14) (at 20 ℃)

Yield strength = 310 *MPa* (45 *ksi*) (Ref. 7.11, p. 3) (at 20 °C)
Tensile strength = 690 *MPa* (100 *ksi*) (Ref. 7.11, p. 3) (at 20 °C)
% elongation = 45 (Ref. 7.11, p. 3) (at 20 °C)

304L Stainless steel (Pour canister shell (Ref. 7.19, p. 3.3-1) material):
Density = 7940 kg/m^3 (Ref. 7.20, p. 7)
Poisson's ratio = 0.29 (Ref. 7.9, Figure 15, p. 755) (at 20 °C)
Modulus of elasticity = 195 *GPa* (28.3 * 10^6 *psi*) (Ref. 7.10, Table TM-1, p. 614) (at 20 °C)
Yield strength = 172 *MPa* (25 *ksi*) (Ref. 7.10, Table Y-1, p. 526) (at 20 °C)
Tensile strength = 483 *MPa* (70 *ksi*) (Ref. 7.10, Table U, p. 441) (at 20 °C)
% elongation = 40 (Ref. 7.15, Table 2, p. 5) (at 20 °C)

316L Stainless steel (18 in. canister shell (Ref. 7.4), pipe, base plate, and basket support bracket material (Assumption 3.22)):
Density = 7980 kg/m^3 (Ref. 7.20, p. 7)
Poisson's ratio for 316L stainless steel was not available in the literature. Since the composition of 316 stainless steel is closest to 316L stainless steel, Poisson's ratio of 316 stainless steel is used:
Poisson's ratio = 0.298 (Ref. 7.9, Figure 15, p. 755) (at 20 °C)
Modulus of elasticity = 195 *GPa* (28.3 * 10^6 *psi*) (Ref. 7.10, Table TM-1, p. 614) (at 20 °C)
Yield strength = 172 *MPa* (25 *ksi*) (Ref. 7.10, Table Y-1, p. 514) (at 20 °C)
Tensile strength = 483 *MPa* (70 *ksi*) (Ref. 7.10, Table U, p. 437) (at 20 °C)
% elongation = 40 (Ref. 7.15, Table 2, p. 5) (at 20 °C)

Vitrified waste (see Ref. 7.16 and Assumption 3.18):
Density = 2850 kg/m^3 (Ref. 7.16, Table 6.4)
Poisson's ratio = 0.2 (Ref. 7.13, p. 189) (at 20 °C)
Modulus of elasticity = 62.7 *GPa* (9.1 * 10^6 *psi*) (Ref. 7.13, p. 189) (at 20 °C)

5.2 Finite Element Representation

A two-dimensional (2-D) finite element representation of the 5-DHLW DOE SNF waste package is developed in order to determine the effects of tipover design basis event loads on the structural contents of the 18 in. canister. The 2-D finite element representation is developed using the dimensions provided in Assumptions 3.5 through 3.17 and 3.25 through 3.27. The finite element representation includes the outer and inner barriers, basket assembly (inner and outer brackets and divider plate), support tube, uppermost pour canister, mass of the four pour canisters, 18 in. canister shell, pipes, basket support brackets, and the mass of the fuel (see Figure II-1). A one half-symmetry finite element representation is developed for the waste package. The barriers are assumed to have solid connections at the adjacent surfaces (Assumption 3.3) and are constrained in a direction perpendicular to the symmetry plane. One of the pour canisters, which is located over the 18 in.

canister, is created using 2-D elements. The remaining pour canisters were included in the representation by placing point mass elements at the points of contact of the pour canisters with the basket assembly. This is the most realistic approach to simulate the effect of each pour canister in contact with the WP internals if 2-D elements are not used to create the remaining pour canisters; the benefit of using this approach is to reduce the computer execution time.

The target surface is conservatively assumed to be essentially unyielding by using a large elastic modulus for the target surface compared to the waste package (Assumption 3.4). The target surface is constrained at the bottom to prevent its motion in horizontal and vertical direction. Contact elements are defined between: the top pour canister and the inner bracket, the lower and upper corner (apex) pipe and the 18 in. canister, the lower and upper basket support bracket and the 18 in. canister, the 18 in. canister and the support tube and finally, the outer barrier and the target surface. The initial configuration of the finite element representation of WP internals includes the maximum possible gap for each contact element in order to account for the worst case scenario (Figure II-1). On the other hand, the initial gap between the entire WP and the target surface is small in comparison with the others. This allows enough time and displacement for the WP and its internals to ramp up to the specified initial velocity before the impact. With this initial velocity, the simulation is then continued throughout the impact until the WP and its internals begin to rebound (Figure II-2), at which time the stress peaks and the maximum displacements have been obtained.

The magnitude of the contact stiffness is one of the parameters that affect results, as discussed in Assumption 3.23. The result of succesive iterations revealed that the contact stiffness that works best is $2 \cdot 10^9\ N/m$. Further increase of the value of the contact stiffness does not influence the results significantly. This magnitude of the contact stiffness is used to model contacts between all contact surfaces.

5.3 Impact Velocity Calculations

The center of gravity of the WP is not perfectly aligned with the line passing through the points at the skirt ends (right-circular cylinder diagonal) on the plane of symmetry. One of the reasons is that pour canisters are not symmetric along the waste package length and they are not filled 100%. In addition, there is a small gap between the inner and outer barrier upper lids. Since the effect is small and it is conservative to use a higher location for the center of gravity, the following calculations make use of a simplification that the center of gravity lies on the diagonal. The WP is created in such a way that the center of gravity of the WP is directly above the vertical line passing through the WP corner at the end of the skirt.
The following parameters are defined which will be used in the calculations:

m_T = total mass of WP

I_T = total mass moment of inertia about the axis of rotation (pivot) of WP

m = mass of WP component

I = mass moment of inertia about the axis of rotation (pivot) of WP component
L = length of WP component
r_m = mean radius of WP shells
g = gravitational acceleration
c = change in WP center of gravity height during the tipover
r = distance of the WP center of gravity from one corner on the WP half-symmetry plane
r_o = outer barrier outer radius
r_i = inner barrier inner radius
r_g = canister guide (support tube) outer radius
ω = WP angular velocity
v = linear impact velocity at the inner barrier outer surface (upper lid)
q = radial distance from the longitudinal centroidal axis of WP to the longitudinal centroidal axis of the pour canisters
β = five-fold symmetry angle defining the position of the pour canisters
d = distance from the bottom centroid of any WP component (see Ref. 7.17, p. 630) to the rotation axis (pivot)
h = component of d parallel to the basal plane (bottom) of every WP component.

Consider a simple planar geometry of the right circular cylinder (WP barriers) cut by a plane passing through its axis of symmetry. Then:

$$r = \sqrt{(3.79)^2 + (2.12)^2}/2 = 2.17\ m \text{ (see Assumptions 3.7 and 3.19)}$$

$$\alpha = \tan^{-1}(3.79/2.12) = 60.8^\circ$$

$$c = r\,[1 - \cos(\alpha)] = 2.17\,[1 - \cos(60.8^\circ)] = 1.11\ m$$

$$q = (r_i + r_g)/2 = (0.94 + 0.2825)/2 = 0.611\ m \text{ (see Assumptions 3.5 and 3.15, and Attachment I-1)}$$

The total mass of WP is sum of the masses of following components: outer and inner barrier, support tube, basket assembly (divider plates, and inner and outer brackets), 18 in. canister, pour canisters, and outer and inner barrier lids. The total mass moment of inertia is, in the same manner, sum of the mass moments of inertia of the same WP components.

The general formula for the mass moment of inertia for any of components is given by (Ref. 7.17, p. 630):

$$I = m\left(r_m^2/2 + L^2/3 + d^2\right)$$

Note that the third term in the previous equation, $m \cdot d^2$, takes into account the relative position of the component with respect to the rotation axis (pivot). Parameter d is, accordingly, the distance from the bottom centroid of any WP component (see Ref. 7.17, p. 630) to the rotation axis (pivot). In the following calculation this parameter will be, for the sake of brevity, referred to as distance, and all calculation results will be presented with three digit accuracy.

Outer barrier:
mass = 17984 kg (see Attachment I-1)
mean radius = (2.12+1.92)/4=1.01 m (Assumptions 3.6 and 3.7)
length = 3.79 m (Assumption 3.19)
distance = 2.12/2 = 1.06 m (see Assumption 3.7 and Attachment I-1)
Therefore,
mass moment of inertia = $17984\left(1.01^2/2+3.79^2/3+1.06^2\right)=115000\ kg\cdot m^2$

Inner barrier:
mass = 3202 kg (see Attachment I-1)
mean radius = (1.92+1.88)/4=0.95 m (Assumptions 3.5 and 3.6)
length = 3.09 m (Assumption 3.21)
distance = $\sqrt{1.06^2+0.335^2}=1.11\ m$ (see Assumptions 3.7 and 3.20, and Attachment I-1)
Therefore,
mass moment of inertia = $3202\left(0.95^2/2+3.09^2/3+1.11^2\right)=15600\ kg\cdot m^2$

Support tube, 18 in. canister and basket assembly (see Assumption 3.32):
mass = $1265+2270+5\left(66+195+247\right)=6075\ kg$ (see Attachment I-1, and Section 5.1.1)
length = 3.00 m (Assumption 3.32)
distance = $\sqrt{1.06^2+0.36^2}=1.12\ m$ (see Assumptions 3.7 and 3.28, and Attachment I-1)
Therefore,
mass moment of inertia = $6075\left(3.00^2/3+1.12^2\right)=25800\ kg\cdot m^2$
Note that in the preceding calculation the first term in the general mass moment of inertia equation is not included since the mean radius is much smaller than the length and distance.

Pour canister:
mass = $5\left(2182\right)=10910\ kg$ (Section 5.1.1)
length = 3.00 m (Section 5.1.1)
The distance components parallel to the WP basal plane, of the five pour canisters, are:

$$h_1=r_0-q=1.06-0.611=0.449\ m$$

$$h_2=h_3=r_o-q\cos(\beta)=1.06-0.611\cos\left(72^\circ\right)=0.871\ m$$

$$h_4=h_5=r_o+q\cos(\beta/2)=1.06+0.611\cos\left(36^\circ\right)=1.55\ m$$

Since the vertical component of the distance is the same for all five pour canisters, 0.36 m (Assumption 3.28) the corresponding distances are:

$$d_1 = \sqrt{0.449^2 + 0.360^2} = 0.576\ m$$

$$d_2 = d_3 = \sqrt{0.871^2 + 0.360^2} = 0.942\ m$$

$$d_4 = d_5 = \sqrt{1.55^2 + 0.360^2} = 1.59\ m$$

Therefore,

mass moment of inertia = $2182\left\{5\,(3.0)^2/3 + \left[2\,(0.942)^2 + 2\,(1.59)^2 + 0.576^2\right]\right\} = 48400\ kg \cdot m^2$
Note that in the preceding calculation the first term in the general mass moment of inertia equation is neglected since the mean radius is much smaller than the length and distance.

Outer barrier lid:

mass = $2\,(2508) = 5016\ kg$ (see Attachment I-1)

distance = $\sqrt{1.06^2 + (0.335 + 3.09 + 0.0300)^2} = 3.61\ m$ (see Assumptions 3.7, 3.21 and 3.30, and Attachment I-1)

Therefore,

mass moment of inertia = $2508\,(3.61)^2 = 32700\ kg \cdot m^2$

Note that in the preceding calculation of the mass moment of inertia the lower outer barrier lid is not included since its contribution is small in comparison with the upper lid. Furthermore, the first two terms in the general mass moment of inertia equation are considered unsignificant since both the radius and the length (in this case lid thickness) are much smaller than the distance.

Inner barrier lid:

mass = $2\,(605) = 1210\ kg$ (see Attachment I-1)

distance = $\sqrt{1.06^2 + (0.335 + 3.09 - 0.0250)^2} = 3.56\ m$ (see Assumptions 3.7, 3.21 and 3.29, and Attachment I-1)

Therefore,

mass moment of inertia = $605\,(3.56)^2 = 7670\ kg \cdot m^2$

Note that in the preceding calculation of the mass moment of inertia, the lower outer barrier lid is not included since its contribution is small in comparison with the upper lid. Furthermore, the first two terms in the general mass moment of inertia equation are considered negligible since both the radius and the length (lid thickness) are much smaller than the distance.

Total mass of WP is: $m_T = 17984 + 3202 + 6075 + 10910 + 5016 + 1210 = 44397\ kg$

Total mass moment of inertia of WP:

$I_T = 115000 + 15600 + 25800 + 48400 + 32700 + 7670 = 245000\ kg \cdot m^2$

Kinetic energy for fixed-axis rotation is $KE = I_T \omega^2 / 2$

Potential energy is $PE = m_T\ g\ h$

By conservation of energy: $KE = PE$

Therefore the angular velocity is:

$$\omega = \sqrt{\frac{2\ m_T\ g\ h}{I_T}} = \sqrt{\frac{2\,(44397)(9.81)(1.11)}{245000}} = 1.99\ \ s^{-1}$$

Inner lid outer surface impact velocity will be conservatively used for the 2-D finite element representation. The impact velocity is defined as a product of the angular velocity of WP, and the distance between the upper basal plane of the inner lid and the rotation axis (pivot). Since there is no lid in the 2-D representation, more deflection and stress is ancipated to take place in the WP components. The impact velocity in a tipover event is, therefore:

$v = (0.335 + 3.09)\,1.99 = 6.82\ m/s$ (see Assumptions 3.20 and 3.21)

The velocity $6.9\,m/s$ is used as a bounding approximation in the finite element simulation.

5.4 Calculations for Dependent Parameters and Mass

The total mass of the stainless steel clad fuel element (FLIP-L-II) is applied to the bottom inner surface of each one of the pipes. Total mass per unit length inside an individual pipe is calculated below:

Fuel mass per unit length = 4.090 / 0.7539 = 5.42 *kg/m* (see Section 5.1.1)
Thus, total mass inside a single pipe per unit length = 5.42 *kg/m*

For the pour canister point masses in the finite element representation:
Savannah River Plant HLW canister mass per unit length = 2182 / 3.00 = 727 *kg/m* (see Section 5.1.1)
These dimensions and mass values are used in the finite element representation to obtain the results for a bounding tipover DBE.

5.5 Calculations for Tangent Moduli

The results of this impact simulation are required to include elastic and plastic deformations for all materials. When the materials are driven into the plastic range, the slope of the stress-strain curve continuously changes. Thus, a simplification for this curve is needed to incorporate plasticity into the finite element solution. A standard approximation is commonly used in engineering by assuming a straight line that connects the yield point to the ultimate tensile strength point of the material. The ultimate tensile strength and the ultimate elongation are, in general, strain rate sensitive material properties. This effect was neglected due to the lack of data (see Assumption 3.1). The following parameters will be used in subsequent calculations:

S_y = Yield strength of the material
S_u = Ultimate tensile strength
e_1, e_2, e_3 = strain magnitudes
E = Elastic modulus (slope of the line in the elastic region)
E_l = Tangent modulus (slope of the line in the plastic region)

The slope, E_l is determined by :
$e_l = S_y / E$ and $e_2 = e_3 - e_l$ where e_3 = elongation specified for material

Hence, for SA-516 K02700:
$E_l = (S_u - S_y) / e_2 = (0.483 - 0.262) / (0.21 - (0.262 / 202))$ (see Section 5.1.2)
Calculated value is given as, $E_l = 1.059$ *GPa*

Similarly, for SB-575 N06022:
$E_l = (0.690 - 0.310) / (0.45 - (0.310 / 206)) = 0.847$ *GPa* (see Section 5.1.2)

For 304L stainless steel:
$E_l = (0.483 - 0.172) / (0.40 - (0.172 / 195)) = 0.779$ *GPa* (see Section 5.1.2)

For 316L stainless steel:
$E_l = (0.483 - 0.172) / (0.40 - (0.172 / 195)) = 0.779$ *GPa* (see Section 5.1.2)

6. RESULTS

The results obtained in this calculation are based on the existing information from the current waste package designs and the literature available for material properties. Although some data are obtained from qualified sources such as American Society of Mechanical Engineers (ASME) Code or American Society for Testing and Materials (ASTM) Specifications, all results provided in this document are to be verified (TBV). Use of any data or results from this analysis for input into documents supporting construction, fabrication, or procurement is required to be controlled with TBV tracking in accordance with the appropriate procedures.

The structural response of the waste package to tipover accident loads is reported using maximum stress values and displacements obtained from the finite element solution to the problem. The results show that the maximum cavity closure inside the fuel pipe is 8.28 *mm* (see Ref. 7.18, Attachment V, line #549), consequently the minimum inner diameter of the pipe is 40.9 *mm* (Ref. 7.18, Attachment V, line #551). Since the maximum outer diameter of the fuel element is 37.5 *mm* (see Section 5.1.1), available space between the most deformed apex pipe and the fuel rod is 3.44 *mm* (Ref. 7.18, Attachment V, line #553). Hence, there will be no interference between the two components as a result of tipover DBE. The maximum stress intensity in the pipe is determined to be 350 *MPa* (see Ref. 7.18, Attachment IV, line #645). The maximum stress intensity in the 18 in. canister shell is determined to be 238 *MPa* (see Ref. 7.18, Attachment IV, line #643). These stress intensity magnitudes are less than the tensile strength of 316L stainless steel, 483 *MPa* (see Section 5.1.2).

7. REFERENCES

7.1 Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O) 1997. *Waste Package Design Basis Events.* BBA000000-01717-0200-00037 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971006.0075.

7.2 CRWMS M&O 1997. *Waste Package Fabrication Process Report.* BBA000000-01717-2500-00010 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971218.0275.

7.3 CRWMS M&O 1998. *Software Qualification Report for ANSYS V5.4, A Finite Element Code* (CSCI: 30040 V5.4). 30040-2003 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980609.0847.

7.4 U. S. Department of Energy National Spent Nuclear Fuel Program 1998. *Preliminary Design Specification for Department of Energy Standardized Spent Nuclear Fuel Canisters, Volume I – Design Specification.* DOE/SNF/REP-011, REV 1. Washington, DC: DOE. TIC: 241528.

7.5 HAYNES International 1997. *Hastelloy Alloy C-22.* Kokomo, Indiana. TIC: 238121.

7.6 CRWMS M&O 1997. *Waste Package Materials Selection Analysis.* BBA000000-01717-0200-00020 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980324.0242.

7.7 American Society for Testing and Materials 1990. *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service.* ASTM Designation: A 516/A 516M-90. Philadelphia, Pennsylvania: ASTM. TIC: 237681.

7.8 American Society for Testing and Materials 1997. *Standard Specification for General Requirements for Steel Plates for Pressure Vessels.* ASTM Designation: A 20/A 20M-97a. West Conshohocken, Pennsylvania: ASTM. TIC: 242529.

7.9 American Society for Metals (ASM) 1980. *Metals Handbook Ninth Edition, Volume 3, Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals.* Metals Park, Ohio: ASM. TIC: 209801.

7.10 American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Code.* Section II. New York, New York: ASME. TIC: 238901.

7.11 American Society for Testing and Materials 1998. *Standard Specification for Low-Carbon Nickel-Molybdenum-Chromium, Low-Carbon Nickel-Chromium-Molybdenum, Low-Carbon Nickel-Chromium-Molybdenum-Copper and Low-Carbon Nickel-Chromium-Molybdenum-Tungsten Alloy Plate, Sheet, and Strip.* ASTM Designation: B 575-97. West Conshohocken, Pennsylvania: ASTM. TIC: 241816.

7.12 American Society for Metals 1978. *Metals Handbook Ninth Edition, Volume 1, Properties and Selection: Irons and Steels.* Metals Park, Ohio: ASM. TIC: 209799.

7.13 Lewis, Clifford F., ed. 1990. *Materials Engineering, Materials Selector 1991.* Cleveland, Ohio: Penton Publishing. Pages 105, 188, and 189. TIC: 239718.

7.14 DOE 1999. *TRIGA (UZrH) Fuel Characteristics for Disposal Criticality Analysis.* DOE/SNF/REP-048. Revision 0. Washington, DC: U.S. Department of Energy. TIC: 244162.

7.15 American Society for Testing and Materials 1997. *Standard Specification for Heat-Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels.* ASTM Designation: A 240/A 240M-97a. West Conshohocken, Pennsylvania: ASTM. TIC: 239431.

7.16 Stout, R.B. and Leider, H., eds. 1994. *Preliminary Waste Form Characteristics Report Version 1.0.* UCRL-ID-108314 REV 1. Livermore, California: Lawrence Livermore National Laboratory. TIC: 213843.

7.17 Meriam, J.L. and Kraige, L.G. 1987. *Engineering Mechanics Volume 2, Dynamics. Second Edition.* New York, New York: John Wiley and Sons. Page 630. TIC: 239804.

7.18 CRWMS M&O 1999. *Electronic Files for Structural Calculations for the Codisposal of TRIGA Spent Nuclear Fuel in a Waste Package, BBA000000-01717-0210-00052 REV 00.* Las Vegas, Nevada: CRWMS M&O. Floppy disk. ACC: MOL.19990505.0473.

7.19 Oak Ridge National Laboratory (ORNL) 1992. *Characteristics of Potential Repository Wastes, Volume 1.* DOE/RW-0184-R1. Oak Ridge, Tennessee: ORNL. HQO.19920827.0001.

7.20 American Society for Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.* ASTM Designation: G 1-90. Philadelphia, Pennsylvania: ASTM. TIC: 238771.

7.21 Meriam, J.L. and Kraige, L.G. 1987. *Engineering Mechanics Volume 1, Statics. Second Edition.* New York, New York: John Wiley and Sons. Page 441. TIC: 241293.

7.22 CRWMS M&O 1998. *Qualification of ANSYS V5.4 on the WPO HP UNIX Workstations.* Interoffice correspondence, T. W. Doering to Gregory Carlisle, LV.WP.SMB.05/98-100, May 22, 1998. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980730.0147.

7.23 CRWMS M&O 1999. *Volume/Mass of DOE Canister and TRIGA SNF.* BBA000000-01717-0210-00046 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990713.0238.

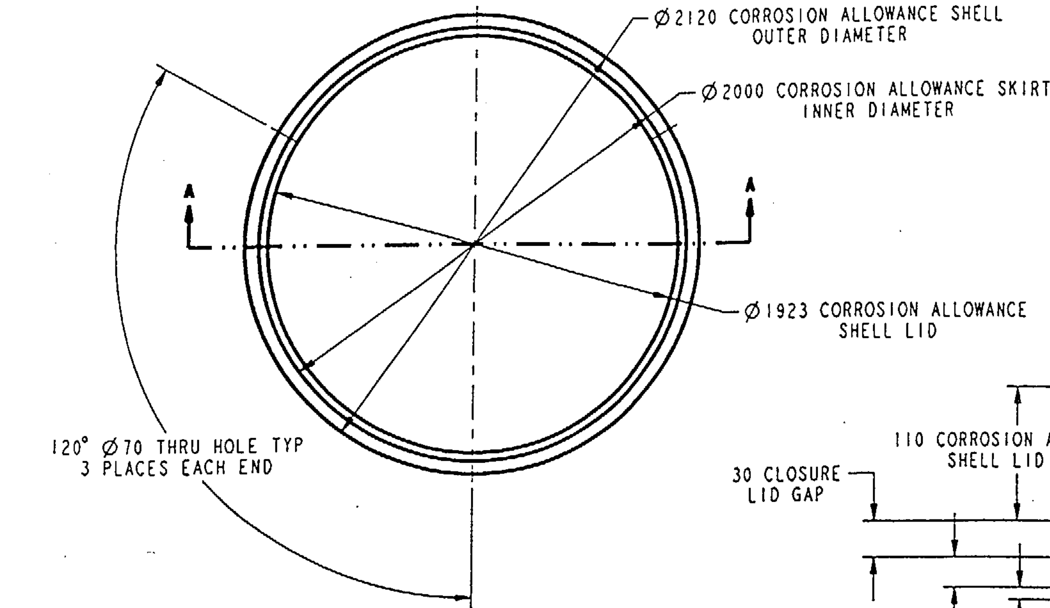
8. ATTACHMENTS

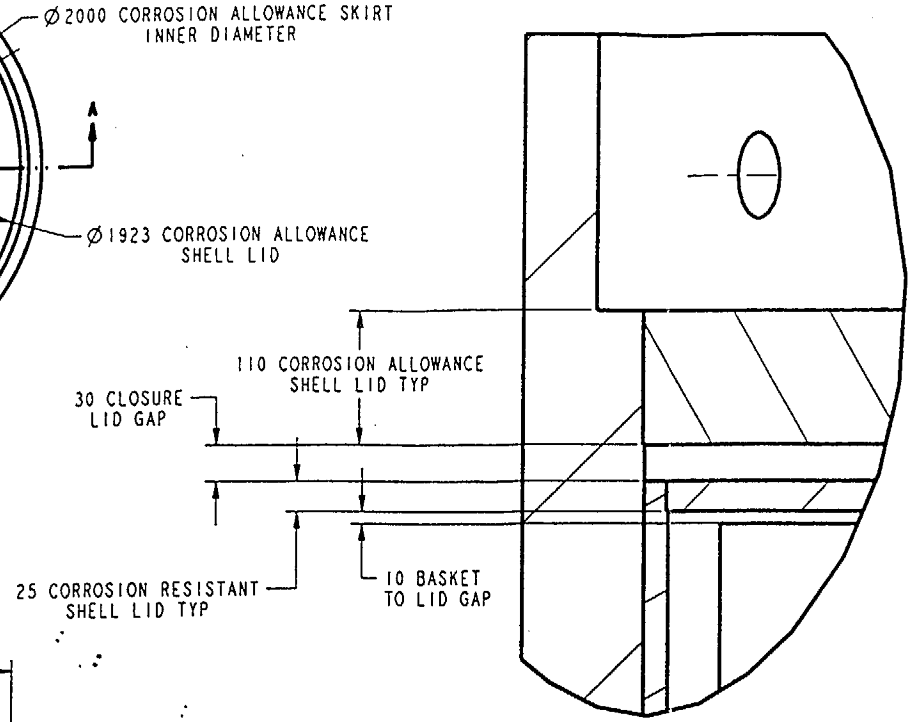
Attachment I (15 pages): Sketches and structural component masses

Attachment II (3 pages): Figures obtained from ANSYS

Attachments III through V have been moved from REV 00A copy of this calculation to Ref. 7.18. The following is the list of electronic files including names, dates, times and sizes available in Ref. 7.18. Note that these are no longer attachments to this document; they are listed for information only.

Description	Date	Time	Size
Attachment III: triga.at3	05/04/99	10:19 am	653 KB
Attachment IV: triga.at4	05/04/99	9:08 am	25 KB
Attachment V: triga.at5	05/04/99	9:07 am	20 KB





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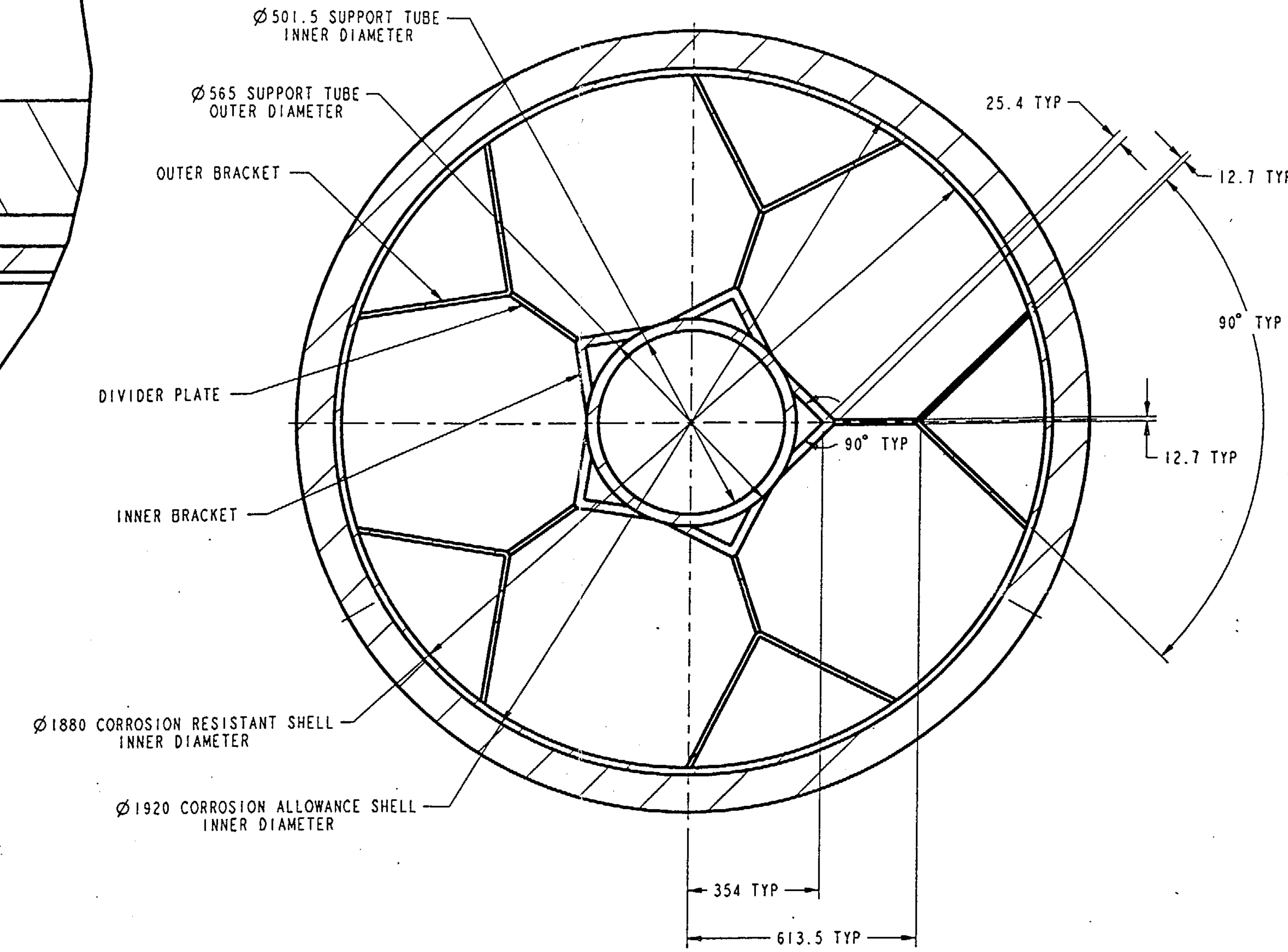

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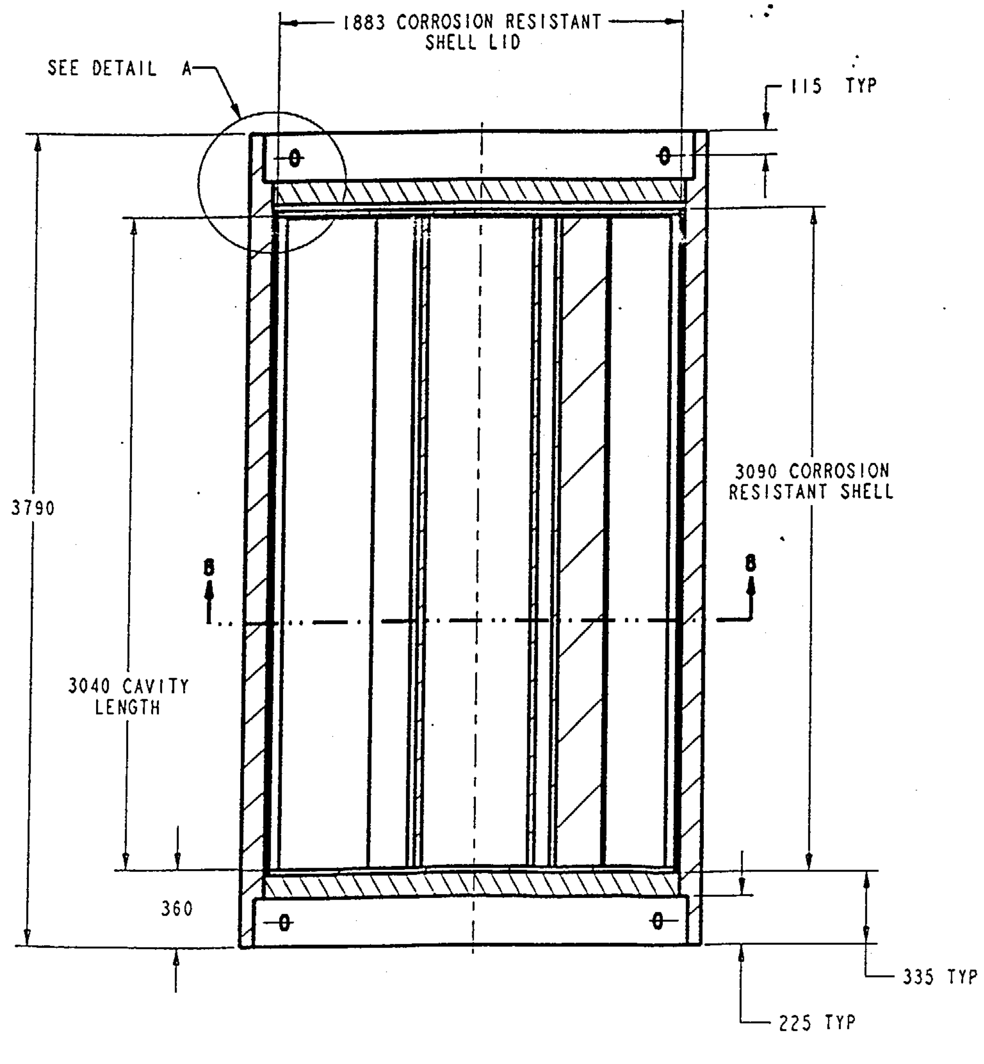


SECTION A-A

COMPONENT NAME	MATERIAL	THICKNESS	MASS (kg)	QTY REQ
CORROSION ALLOWANCE SHELL	SA-516 K02700	100	17984	1
CORROSION ALLOWANCE SHELL LID	SA-516 K02700	110	2508	2
CORROSION RESISTANT SHELL	SB-575 N06022	20	3202	1
CORROSION RESISTANT SHELL LID	SB-575 N06022	25	605	2
DIVIDER PLATE	SA-516 K02700	12.7	66	5
INNER BRACKET	SA-516 K02700	25.4	195	5
OUTER BRACKET	SA-516 K02700	12.7	247	5
SUPPORT TUBE	SA-516 K02700	31.75	1265	1

"FOR INFORMATION ONLY"

UNITS: mm

DO NOT SCALE

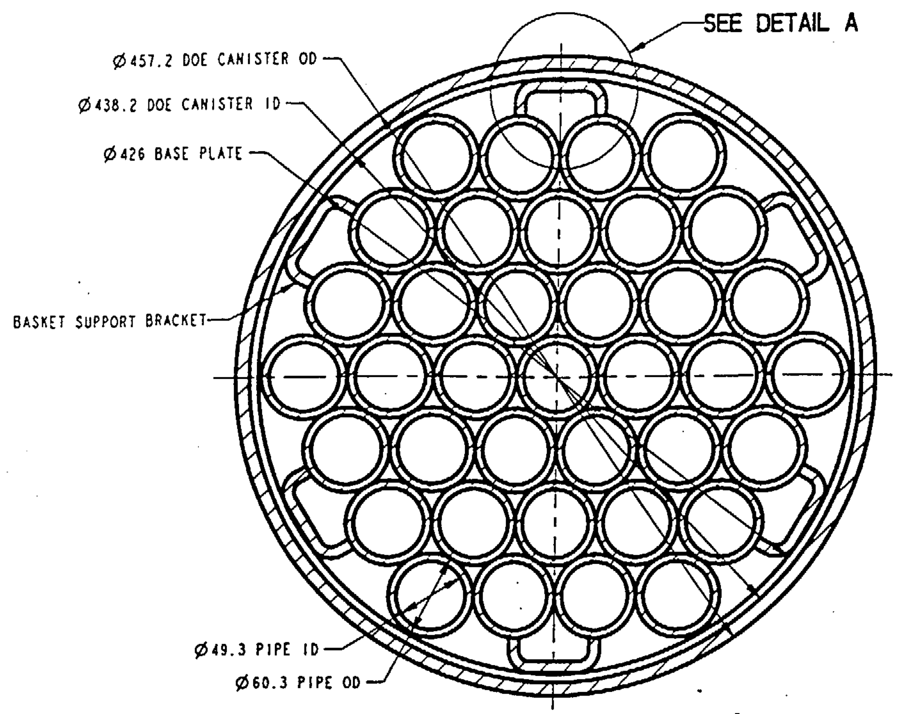
5-DHLW/DOE SPENT FUEL DISPOSAL CONTAINER

SKETCH NUMBER: SK-0069 REV 01

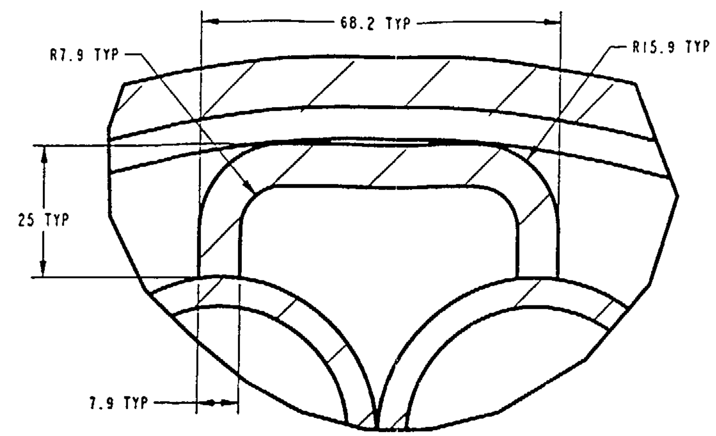
SKETCHED BY: GENE CONNELL

DATE: 10/08/98

FILE: /home/pro_library/checkout/sketches/dhlw_5pk/SK-0069.dwg



SECTION B-B



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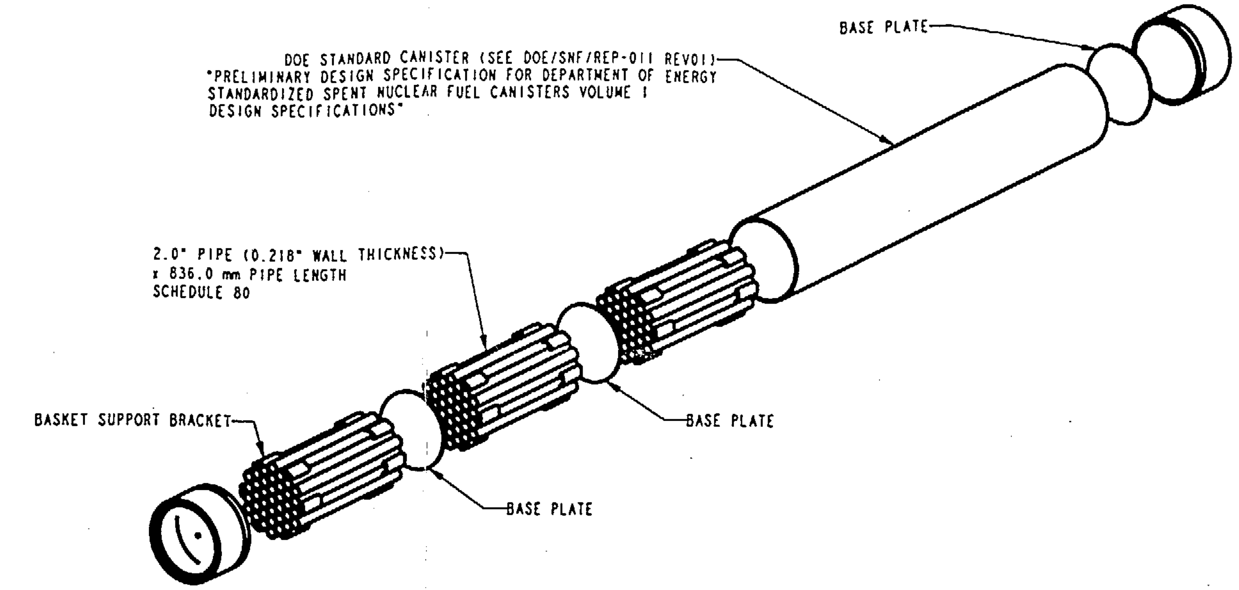

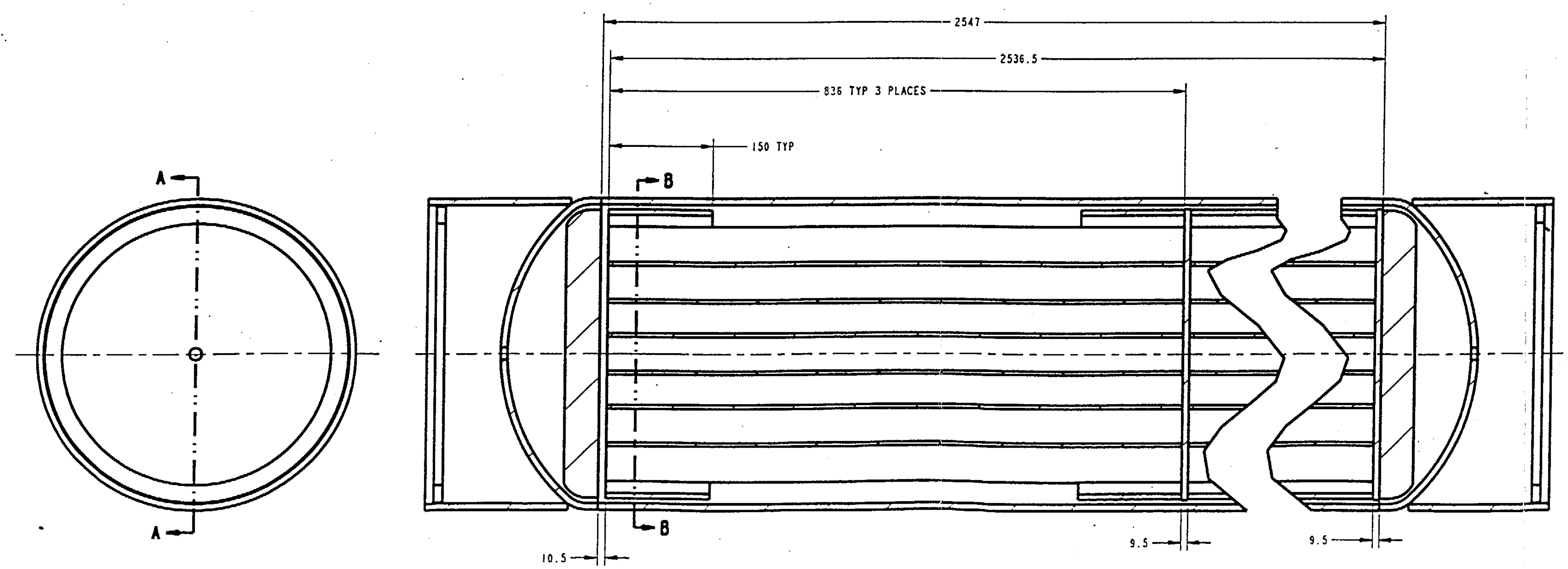

SECTION A-A

COMPONENT NAME	MATERIAL	THICKNESS	MASS (kg)	QTY REQ
BASE PLATE	SA-240 S31603	9.5	10.8	3
BASKET SUPPORT BRACKET	SA-240 S31603	7.9	0.88	36
PIPE	SA-240 S31603	5.54	6.3	111
BASKET ASSEMBLY	SA-240 S31603	----------	765	1

"FOR INFORMATION ONLY"

UNITS: mm
DO NOT SCALE FROM SKETCH

TRIGA DOE SNF BASKET ASSEMBLY	
SKETCH NUMBER:	SK-0124 REV 00
SKETCHED BY:	BRYAN HARKINS BH 19March99 JWB 03/19/99 TWD 3.19.99
DATE:	03/19/99
FILE:	/home/harkins/proe/fermi_37/SK-0124_triga.dwg

```
                    MASS PROPERTIES OF THE PART 5DHLW_DIVIDERPLATE

                           VOLUME =  8.4011719e+06 MM^3
                     SURFACE AREA =  1.4055265e+06 MM^2
                          DENSITY =  7.8500000e-06 KILOGRAM / MM^3
                             MASS =  6.5949200e+01 KILOGRAM

      CENTER OF GRAVITY with respect to _5DHLW_DIVIDERPLA coordinate frame:
X   Y   Z            6.3500000e+00  1.5150000e+03  1.0916000e+02  MM

 INERTIA with respect to _5DHLW_DIVIDERPLA coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz          2.0287213e+08 -6.3444779e+05 -4.5713743e+04
Iyx Iyy Iyz         -6.3444779e+05  1.0513382e+06 -1.0906507e+07
Izx Izy Izz         -4.5713743e+04 -1.0906507e+07  2.0182788e+08

INERTIA at CENTER OF GRAVITY with respect to _5DHLW_DIVIDERPLA coordinate frame:
                                                             (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz          5.0718032e+07  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz          0.0000000e+00  2.6283456e+05  0.0000000e+00
Izx Izy Izz          0.0000000e+00  0.0000000e+00  5.0456970e+07

                PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1  I2  I3           2.6283456e+05  5.0456970e+07  5.0718032e+07

      ROTATION MATRIX from _5DHLW_DIVIDERPLA orientation to PRINCIPAL AXES:
                        0.00000         0.00000         1.00000
                        1.00000         0.00000         0.00000
                        0.00000         1.00000         0.00000

 ROTATION ANGLES from _5DHLW_DIVIDERPLA orientation to PRINCIPAL AXES (degrees):
angles about x  y  z     0.000          90.000          90.000

                RADII OF GYRATION with respect to PRINCIPAL AXES:
R1  R2  R3           6.3130099e+01  8.7469334e+02  8.7695323e+02  MM
```

Mass Properties of 5-DHLW/DOE Spent Fuel Disposal Container

```
                    MASS PROPERTIES OF THE PART 5DHLW_GUIDETUBE

                          VOLUME =  1.6116365e+08 MM^3
                    SURFACE AREA =  1.0258420e+07 MM^2
                         DENSITY =  7.8500000e-06 KILOGRAM / MM^3
                            MASS =  1.2651347e+03 KILOGRAM

      CENTER OF GRAVITY with respect to _5DHLW_GUIDETUBE coordinate frame:
X   Y   Z              0.0000000e+00  1.5150000e+03  0.0000000e+00  MM

  INERTIA with respect to _5DHLW_GUIDETUBE coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz            3.9168113e+09  0.0000000e+00 -2.5224778e+04
Iyx Iyy Iyz            0.0000000e+00  9.0255853e+07  0.0000000e+00
Izx Izy Izz           -2.5224778e+04  0.0000000e+00  3.9168277e+09

 INERTIA at CENTER OF GRAVITY with respect to _5DHLW_GUIDETUBE coordinate frame:
                                                          (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz            1.0130426e+09  0.0000000e+00 -2.5224778e+04
Iyx Iyy Iyz            0.0000000e+00  9.0255853e+07  0.0000000e+00
Izx Izy Izz           -2.5224778e+04  0.0000000e+00  1.0130590e+09

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3           9.0255853e+07  1.0130243e+09  1.0130773e+09

      ROTATION MATRIX from _5DHLW_GUIDETUBE orientation to PRINCIPAL AXES:
                          0.00000       -0.80902       -0.58779
                          1.00000        0.00000        0.00000
                          0.00000       -0.58779        0.80902

 ROTATION ANGLES from _5DHLW_GUIDETUBE orientation to PRINCIPAL AXES (degrees):
angles about x  y  z     0.000          -36.000          90.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3           2.6709719e+02  8.9483210e+02  8.9485553e+02  MM
```

```
                    MASS PROPERTIES OF THE PART 5DHLW_INNERBARRIER

                          VOLUME =  3.6844249e+08 MM^3
                    SURFACE AREA =  3.7127813e+07 MM^2
                         DENSITY =  8.6900000e-06 KILOGRAM / MM^3
                            MASS =  3.2017653e+03 KILOGRAM

      CENTER OF GRAVITY with respect to _5DHLW_INNERBARRI coordinate frame:
X    Y    Z          0.0000000e+00  1.5450000e+03  0.0000000e+00  MM

 INERTIA with respect to _5DHLW_INNERBARRI coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz          1.1629004e+10  0.0000000e+00 -8.0769423e+05
Iyx Iyy Iyz          0.0000000e+00  2.8899811e+09  0.0000000e+00
Izx Izy Izz         -8.0769423e+05  0.0000000e+00  1.1629529e+10

INERTIA at CENTER OF GRAVITY with respect to _5DHLW_INNERBARRI coordinate frame:
                                                          (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz          3.9863101e+09  0.0000000e+00 -8.0769423e+05
Iyx Iyy Iyz          0.0000000e+00  2.8899811e+09  0.0000000e+00
Izx Izy Izz         -8.0769423e+05  0.0000000e+00  3.9868350e+09

                PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3         2.8899811e+09  3.9857233e+09  3.9874218e+09

      ROTATION MATRIX from _5DHLW_INNERBARRI orientation to PRINCIPAL AXES:
                        0.00000       -0.80902       -0.58779
                        1.00000        0.00000        0.00000
                        0.00000       -0.58779        0.80902

 ROTATION ANGLES from _5DHLW_INNERBARRI orientation to PRINCIPAL AXES (degrees):
angles about x  y  z    0.000         -36.000         90.000

                RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3         9.5006377e+02  1.1157293e+03  1.1159670e+03  MM
```

```
                    MASS PROPERTIES OF THE PART 5DHLW_INNERBRACKET

                            VOLUME =  2.4822233e+07 MM^3
                      SURFACE AREA =  2.4709096e+06 MM^2
                           DENSITY =  7.8500000e-06 KILOGRAM / MM^3
                              MASS =  1.9485453e+02 KILOGRAM

      CENTER OF GRAVITY with respect to _5DHLW_INNERBRACK coordinate frame:
X    Y    Z          -5.3362187e+01 -5.3362530e+01  1.5150000e+03  MM

 INERTIA with respect to _5DHLW_INNERBRACK coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz           5.9744617e+08 -2.0429422e+05  1.5752764e+07
Iyx Iyy Iyz          -2.0429422e+05  5.9744628e+08  1.5752865e+07
Izx Izy Izz           1.5752764e+07  1.5752865e+07  2.2657858e+06

INERTIA at CENTER OF GRAVITY with respect to _5DHLW_INNERBRACK coordinate frame:
                                                                (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz           1.4965631e+08  3.5056211e+05  0.0000000e+00
Iyx Iyy Iyz           3.5056211e+05  1.4965644e+08  0.0000000e+00
Izx Izy Izz           0.0000000e+00  0.0000000e+00  1.1560732e+06

                PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3          1.1560732e+06  1.4930581e+08  1.5000694e+08

      ROTATION MATRIX from _5DHLW_INNERBRACK orientation to PRINCIPAL AXES:
                        0.00000         0.70717         0.70704
                        0.00000        -0.70704         0.70717
                        1.00000         0.00000         0.00000

 ROTATION ANGLES from _5DHLW_INNERBRACK orientation to PRINCIPAL AXES (degrees):
angles about x  y  z  -90.000          44.995          -90.000

                RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3          7.7026010e+01  8.7535275e+02  8.7740562e+02  MM
```

```
                    MASS PROPERTIES OF THE PART 5DHLW_INNERLID

                          VOLUME =  6.9619441e+07 MM^3
                    SURFACE AREA =  5.7174457e+06 MM^2
                         DENSITY =  8.6900000e-06 KILOGRAM / MM^3
                            MASS =  6.0499294e+02 KILOGRAM

       CENTER OF GRAVITY with respect to _5DHLW_INNERLID coordinate frame:
X    Y    Z             0.0000000e+00  0.0000000e+00  1.2500000e+01  MM

  INERTIA with respect to _5DHLW_INNERLID coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz             1.3419598e+08 -4.3609306e+02  0.0000000e+00
Iyx Iyy Iyz            -4.3609306e+02  1.3419570e+08  0.0000000e+00
Izx Izy Izz             0.0000000e+00  0.0000000e+00  2.6813960e+08

 INERTIA at CENTER OF GRAVITY with respect to _5DHLW_INNERLID coordinate frame:
                                                              (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz             1.3410145e+08 -4.3609306e+02  0.0000000e+00
Iyx Iyy Iyz            -4.3609306e+02  1.3410117e+08  0.0000000e+00
Izx Izy Izz             0.0000000e+00  0.0000000e+00  2.6813960e+08

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3            1.3410085e+08  1.3410177e+08  2.6813960e+08

       ROTATION MATRIX from _5DHLW_INNERLID orientation to PRINCIPAL AXES:
                           1.00000        0.00000        0.00000
                           0.00000        1.00000        0.00000
                           0.00000        0.00000        1.00000

  ROTATION ANGLES from _5DHLW_INNERLID orientation to PRINCIPAL AXES (degrees):
angles about x  y  z     0.000          0.000          0.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3            4.7080451e+02  4.7080612e+02  6.6574103e+02  MM
```

Mass Properties of 5-DHLW/DOE Spent Fuel Disposal Container

```
                 MASS PROPERTIES OF THE PART 5DHLW_OUTERBARRIER

                          VOLUME =  2.2909205e+09 MM^3
                    SURFACE AREA =  4.9520181e+07 MM^2
                         DENSITY =  7.8500000e-06 KILOGRAM / MM^3
                            MASS =  1.7983726e+04 KILOGRAM

      CENTER OF GRAVITY with respect to _5DHLW_OUTERBARRI coordinate frame:
X    Y    Z            0.0000000e+00  1.8950000e+03  0.0000000e+00  MM

 INERTIA with respect to _5DHLW_OUTERBARRI coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz            9.3557341e+10  0.0000000e+00 -5.1572641e+06
Iyx Iyy Iyz            0.0000000e+00  1.8445085e+10  0.0000000e+00
Izx Izy Izz           -5.1572641e+06  0.0000000e+00  9.3560685e+10

INERTIA at CENTER OF GRAVITY with respect to _5DHLW_OUTERBARRI coordinate frame:
                                                               (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz            2.8977330e+10  0.0000000e+00 -5.1572641e+06
Iyx Iyy Iyz            0.0000000e+00  1.8445085e+10  0.0000000e+00
Izx Izy Izz           -5.1572641e+06  0.0000000e+00  2.8980675e+10

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3           1.8445085e+10  2.8973581e+10  2.8984424e+10

     ROTATION MATRIX from _5DHLW_OUTERBARRI orientation to PRINCIPAL AXES:
                         0.00000        -0.80884         -0.58803
                         1.00000         0.00000          0.00000
                         0.00000        -0.58803          0.80884

 ROTATION ANGLES from _5DHLW_OUTERBARRI orientation to PRINCIPAL AXES (degrees):
angles about x  y  z      0.000          -36.017           90.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3           1.0127459e+03  1.2692911e+03  1.2695286e+03  MM
```

```
                    MASS PROPERTIES OF THE PART 5DHLW_OUTERBRACKET

                            VOLUME =  3.1410263e+07 MM^3
                      SURFACE AREA =  5.0567020e+06 MM^2
                           DENSITY =  7.8500000e-06 KILOGRAM / MM^3
                              MASS =  2.4657056e+02 KILOGRAM

      CENTER OF GRAVITY with respect to _5DHLW_OUTERBRACK coordinate frame:
X    Y    Z            0.0000000e+00  1.3641379e+02  1.5150000e+03  MM

 INERTIA with respect to _5DHLW_OUTERBRACK coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz            7.6088156e+08  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz            0.0000000e+00  7.6150897e+08 -5.0957970e+07
Izx Izy Izz            0.0000000e+00 -5.0957970e+07  1.3230762e+07

INERTIA at CENTER OF GRAVITY with respect to _5DHLW_OUTERBRACK coordinate frame:
                                                           (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz            1.9035828e+08  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz            0.0000000e+00  1.9557406e+08  0.0000000e+00
Izx Izy Izz            0.0000000e+00  0.0000000e+00  8.6423987e+06

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3           8.6423987e+06  1.9035828e+08  1.9557406e+08

      ROTATION MATRIX from _5DHLW_OUTERBRACK orientation to PRINCIPAL AXES:
                          0.00000        1.00000        0.00000
                          0.00000        0.00000        1.00000
                          1.00000        0.00000        0.00000

 ROTATION ANGLES from _5DHLW_OUTERBRACK orientation to PRINCIPAL AXES (degrees):
angles about x  y  z  -90.000          0.000         -90.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3           1.8721754e+02  8.7864872e+02  8.9060476e+02  MM


                    MASS PROPERTIES OF THE PART 5DHLW_OUTERLID
```

Mass Properties of 5-DHLW/DOE Spent Fuel Disposal Container

```
                         VOLUME =  3.1947813e+08 MM^3
                   SURFACE AREA =  6.4732344e+06 MM^2
                        DENSITY =  7.8500000e-06 KILOGRAM / MM^3
                           MASS =  2.5079033e+03 KILOGRAM

       CENTER OF GRAVITY with respect to _5DHLW_OUTERLID coordinate frame:
X    Y    Z            0.0000000e+00  0.0000000e+00  5.5000000e+01  MM

  INERTIA with respect to _5DHLW_OUTERLID coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz            5.8975092e+08 -2.3656393e+04  0.0000000e+00
Iyx Iyy Iyz           -2.3656393e+04  5.8973555e+08  0.0000000e+00
Izx Izy Izz            0.0000000e+00  0.0000000e+00  1.1592561e+09

 INERTIA at CENTER OF GRAVITY with respect to _5DHLW_OUTERLID coordinate frame:
                                                             (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz            5.8216452e+08 -2.3656393e+04  0.0000000e+00
Iyx Iyy Iyz           -2.3656393e+04  5.8214914e+08  0.0000000e+00
Izx Izy Izz            0.0000000e+00  0.0000000e+00  1.1592561e+09

                  PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3           5.8213196e+08  5.8218170e+08  1.1592561e+09

       ROTATION MATRIX from _5DHLW_OUTERLID orientation to PRINCIPAL AXES:
                          0.58778       -0.80902         0.00000
                          0.80902        0.58778         0.00000
                          0.00000        0.00000         1.00000

  ROTATION ANGLES from _5DHLW_OUTERLID orientation to PRINCIPAL AXES (degrees):
angles about x  y  z    0.000          0.000          54.000

                  RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3           4.8178727e+02  4.8180786e+02  6.7988317e+02  MM
```

```
                    MASS PROPERTIES OF THE PART BASE-PLATE_TRIGA

                              VOLUME =  1.3540437e+06 MM^3
                        SURFACE AREA =  2.9777586e+05 MM^2
                             DENSITY =  7.9800000e-06 KILOGRAM / MM^3
                                MASS =  1.0805269e+01 KILOGRAM

      CENTER OF GRAVITY with respect to _BASE-PLATE_TRIGA coordinate frame:
X    Y    Z              0.0000000e+00  0.0000000e+00  4.7500000e+00  MM

 INERTIA with respect to _BASE-PLATE_TRIGA coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz              1.2288125e+05 -3.9864195e-01  0.0000000e+00
Iyx Iyy Iyz             -3.9864195e-01  1.2288099e+05  0.0000000e+00
Izx Izy Izz              0.0000000e+00  0.0000000e+00  2.4511212e+05

INERTIA at CENTER OF GRAVITY with respect to _BASE-PLATE_TRIGA coordinate frame:
                                                               (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz              1.2263745e+05 -3.9864195e-01  0.0000000e+00
Iyx Iyy Iyz             -3.9864195e-01  1.2263720e+05  0.0000000e+00
Izx Izy Izz              0.0000000e+00  0.0000000e+00  2.4511212e+05

                    PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3             1.2263691e+05  1.2263774e+05  2.4511212e+05

     ROTATION MATRIX from _BASE-PLATE_TRIGA orientation to PRINCIPAL AXES:
                          1.00000         0.00000         0.00000
                          0.00000         1.00000         0.00000
                          0.00000         0.00000         1.00000

 ROTATION ANGLES from _BASE-PLATE_TRIGA orientation to PRINCIPAL AXES (degrees):
angles about x  y  z       0.000           0.000           0.000

                    RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3             1.0653512e+02  1.0653549e+02  1.5061374e+02  MM
```

Mass Properties of TRIGA DOE SNF Basket Assembly

```
                    MASS PROPERTIES OF THE PART BASKET_SUPPORT_BRACKET

                              VOLUME =  1.0994257e+05 MM^3
                        SURFACE AREA =  3.1653244e+04 MM^2
                             DENSITY =  7.9800000e-06 KILOGRAM / MM^3
                                MASS =  8.7734170e-01 KILOGRAM

       CENTER OF GRAVITY with respect to _BASKET_SUPPORT_B coordinate frame:
X    Y    Z            0.0000000e+00  7.5000000e+01 -8.9047240e+00  MM

 INERTIA with respect to _BASKET_SUPPORT_B coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz            6.6909170e+03  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz            0.0000000e+00  5.5766401e+02  5.8593643e+02
Izx Izy Izz            0.0000000e+00  5.8593643e+02  7.0268723e+03

INERTIA at CENTER OF GRAVITY with respect to _BASKET_SUPPORT_B coordinate frame:
                                                             (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz            1.6863019e+03  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz            0.0000000e+00  4.8809598e+02  0.0000000e+00
Izx Izy Izz            0.0000000e+00  0.0000000e+00  2.0918252e+03

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3           4.8809598e+02  1.6863019e+03  2.0918252e+03

      ROTATION MATRIX from _BASKET_SUPPORT_B orientation to PRINCIPAL AXES:
                          0.00000        -1.00000          0.00000
                          1.00000         0.00000          0.00000
                          0.00000         0.00000          1.00000

 ROTATION ANGLES from _BASKET_SUPPORT_B orientation to PRINCIPAL AXES (degrees):
angles about x  y  z     0.000           0.000           90.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3           2.3586757e+01  4.3841286e+01  4.8829054e+01  MM
```

Mass Properties of TRIGA DOE SNF Basket Assembly

```
                    MASS PROPERTIES OF THE ASSEMBLY FUEL_TRIGA

                        VOLUME =  9.5886371e+07 MM^3
                  SURFACE AREA =  3.4194435e+07 MM^2
               AVERAGE DENSITY =  7.9800000e-06 KILOGRAM / MM^3
                          MASS =  7.6517324e+02 KILOGRAM

         CENTER OF GRAVITY with respect to _FUEL_TRIGA coordinate frame:
X    Y    Z          0.0000000e+00  1.2550906e+03  0.0000000e+00  MM

     INERTIA with respect to _FUEL_TRIGA coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz          1.6278683e+09  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz          0.0000000e+00  1.5401219e+07  0.0000000e+00
Izx Izy Izz          0.0000000e+00  0.0000000e+00  1.6278686e+09

   INERTIA at CENTER OF GRAVITY with respect to _FUEL_TRIGA coordinate frame:
                                                         (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz          4.2252731e+08  0.0000000e+00  0.0000000e+00
Iyx Iyy Iyz          0.0000000e+00  1.5401219e+07  0.0000000e+00
Izx Izy Izz          0.0000000e+00  0.0000000e+00  4.2252756e+08

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3         1.5401219e+07  4.2252731e+08  4.2252756e+08

        ROTATION MATRIX from _FUEL_TRIGA orientation to PRINCIPAL AXES:
                          0.00000        0.00000        1.00000
                          1.00000        0.00000        0.00000
                          0.00000        1.00000        0.00000

    ROTATION ANGLES from _FUEL_TRIGA orientation to PRINCIPAL AXES (degrees):
angles about x  y  z     0.000          90.000         90.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3         1.4187232e+02  7.4310041e+02  7.4310064e+02  MM
```

```
                 MASS PROPERTIES OF COMPONENTS OF THE ASSEMBLY
              (in assembly units and the _FUEL_TRIGA coordinate frame)

                                     MATERIAL
        DENSITY         MASS         C.G.:  X           Y            Z

    BASE-PLATE_TRIGA                 UNKNOWN
        7.98000e-06  1.08053e+01  1.84261e-14  4.75000e+00  2.03756e-15
    CAN-PATTERN_TRIGA                UNKNOWN
        7.98000e-06  2.44252e+02  2.95572e-15  4.27500e+02 -6.86148e-15
    BASE-PLATE_TRIGA                 UNKNOWN
        7.98000e-06  1.08053e+01 -1.84261e-14  8.50250e+02  2.03756e-15
    CAN-PATTERN_TRIGA                UNKNOWN
```

Mass Properties of TRIGA DOE SNF Basket Assembly

```
        7.98000e-06  2.44252e+02  2.95572e-15  1.27300e+03 -6.86148e-15
   BASE-PLATE_TRIGA                   UNKNOWN
        7.98000e-06  1.08053e+01  1.84261e-14  1.69575e+03  2.03756e-15
   CAN-PATTERN_TRIGA                  UNKNOWN
        7.98000e-06  2.44252e+02  2.95572e-15  2.11850e+03 -6.86148e-15
```

Mass Properties of TRIGA DOE SNF Basket Assembly

```
                    MASS PROPERTIES OF THE PART FUEL-PIPE_TRIGA

                          VOLUME =  7.9158836e+05 MM^3
                    SURFACE AREA =  2.8974406e+05 MM^2
                         DENSITY =  7.9800000e-06 KILOGRAM / MM^3
                            MASS =  6.3168751e+00 KILOGRAM

      CENTER OF GRAVITY with respect to _FUEL-PIPE_TRIGA coordinate frame:
X   Y   Z              0.0000000e+00  4.1800000e+02  0.0000000e+00  MM

  INERTIA with respect to _FUEL-PIPE_TRIGA coordinate frame:  (KILOGRAM * MM^2)

INERTIA TENSOR:
Ixx Ixy Ixz            1.4740076e+06  0.0000000e+00  1.3387769e+00
Iyx Iyy Iyz            0.0000000e+00  4.7902279e+03  0.0000000e+00
Izx Izy Izz            1.3387769e+00  0.0000000e+00  1.4740085e+06

 INERTIA at CENTER OF GRAVITY with respect to _FUEL-PIPE_TRIGA coordinate frame:
                                                          (KILOGRAM * MM^2)
INERTIA TENSOR:
Ixx Ixy Ixz            3.7029791e+05  0.0000000e+00  1.3387769e+00
Iyx Iyy Iyz            0.0000000e+00  4.7902279e+03  0.0000000e+00
Izx Izy Izz            1.3387769e+00  0.0000000e+00  3.7029878e+05

                 PRINCIPAL MOMENTS OF INERTIA:  (KILOGRAM * MM^2)
I1   I2   I3           4.7902279e+03  3.7029693e+05  3.7029975e+05

     ROTATION MATRIX from _FUEL-PIPE_TRIGA orientation to PRINCIPAL AXES:
                          0.00000        0.00000        1.00000
                          1.00000        0.00000        0.00000
                          0.00000        1.00000        0.00000

 ROTATION ANGLES from _FUEL-PIPE_TRIGA orientation to PRINCIPAL AXES (degrees):
angles about x  y  z      0.000          90.000         90.000

                 RADII OF GYRATION with respect to PRINCIPAL AXES:
R1   R2   R3           2.7537654e+01  2.4211624e+02  2.4211716e+02  MM
```

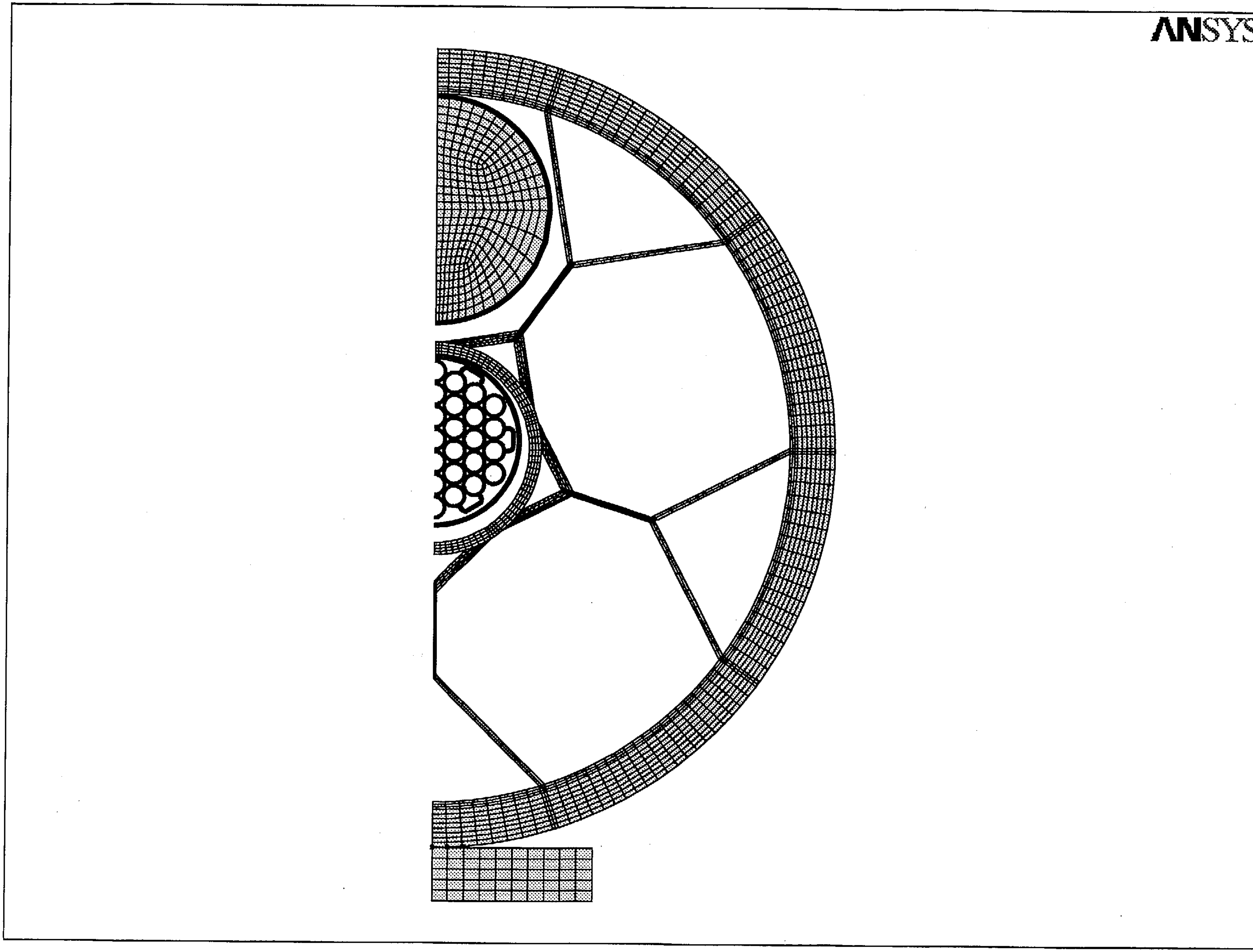

Figure II-1. Finite Element Representation for 5-DHLW/DOE SNF WP

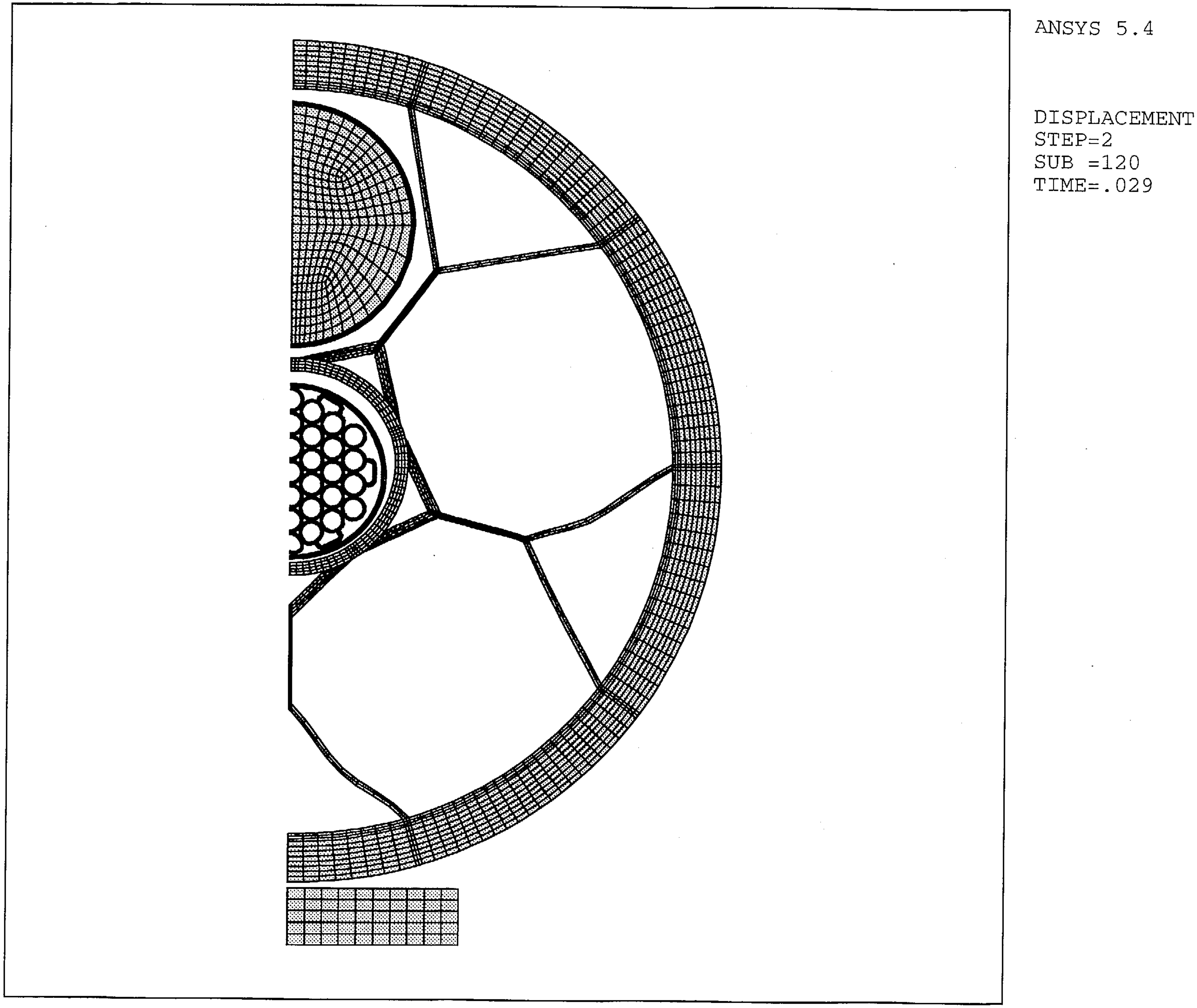

Figure II-2. Deformed Configuration of 5-DHLW/DOE SNF WP at the Last Substep

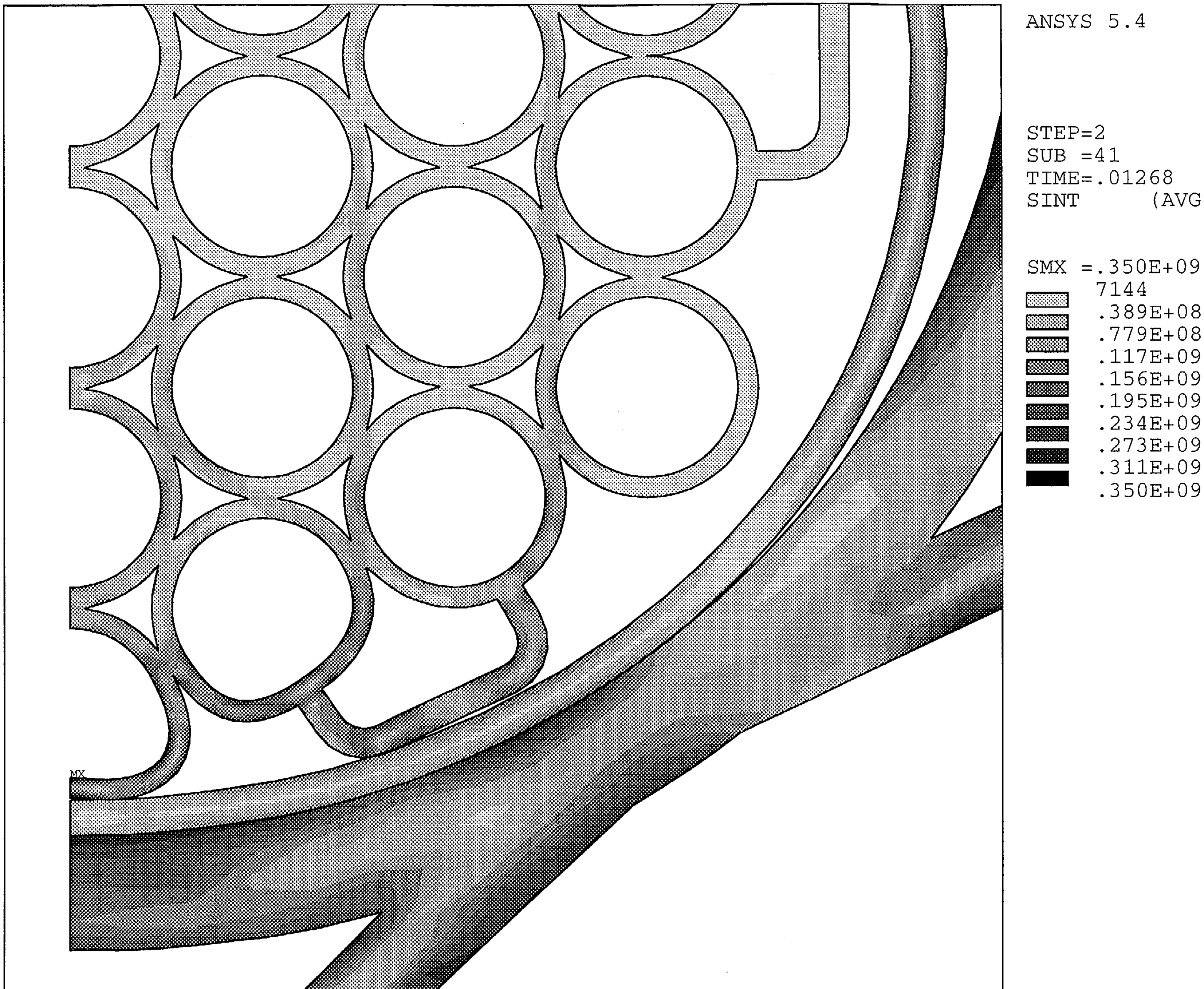

Figure II-3. Stress Intensity Plot for 5-DHLW/DOE SNF WP