INITIAL ENTRIES

Scientific Notebook: #772E

Issued to: Roman V. Kazban

Issued Date: February 1, 2006

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Project Title: ***Three-Dimensional Models of the Drip Shield - Waste Package Mechanical Interaction***

Project Staff: Roman V. Kazban

This notebook documents the work being done to develop the three-dimensional finite element models of the drip shield - waste package mechanical interaction in support of the "Drip Shield - Waste Package Mechanical Interaction" study for the US Nuclear Regulatory Commission. Altair Hypermesh 7.0 is used as pre-processing software ("Altair Hypermesh User's Guide", Version 7.0. Altair Engineering, Inc., Troy, Michigan, 2005), and ABAQUS 6.5 finite element code is used to perform the analysis and as a post-processing software ("ABAQUS User's Manual", Version 6.5. ABAQUS, Inc., Providence, Rhode Island, 2004).

The qualifications required of the staff supporting this work are as follows:

(i) Computational Continuum Mechanics / Finite Element Analysis;
(ii) Mechanical Engineering.

Date: February 1, 2006
Entry by: Roman V. Kazban

Materials and material properties used in the three-dimensional finite element models (FEMs)

(1) Alloy 22 [data has been obtained from the Scientific Notebook (SN) #391]

Density = 8691.5 kg/m^3 = 8691.5e-9 kg/mm^3;
Modulus of elasticity = 1.97e11 *Pa* = 1.97e5 N/mm^2;
Poisson's ratio = 0.31;

At 150 ^oC:
True Yield Stress = 2.547e8 *Pa* = 2.547e2 N/mm^2;
True Stress = 9.541e8 *Pa* = 9.541e2 N/mm^2;
True Strain = 0.335.

(2) Ti-24 [data has been obtained from the Scientific Notebook #391]

Density = 4429 kg/m^3 = 4429e-9 kg/mm^3;
Modulus of elasticity = 1.072e11 *Pa* = 1.072e5 N/mm^2;
Poisson's ratio = 0.31;

At 150 ^oC:
True Yield Stress = 6.581e8 *Pa* = 6.581e2 N/mm^2;
True Stress = 8.044e8 *Pa* = 8.044e2 N/mm^2;
True Strain = 0.061.

(3) 316 S.S. (SA-240S31600 or 316NG SS, which is 316SS with tightened control on carbon and nitrogen content and has the same material properties as 316SS ["Horizontal Drop of 21-PWR Waste Package" CAL-UCD-ME-000009])

Density = 7980 kg/m^3 = 7980e-9 kg/mm^3; [CAL-UCD-ME-000009]
Modulus of elasticity = 1.8616e11 *Pa* = 1.8616e5 N/mm^2; [SN #391]
Poisson's ratio = 0.298; [CAL-UCD-ME-000009]
Elongation = 0.40; [CAL-UCD-ME-000009]
Min. Elongation = 90%*0.40 = 0.36;

At 150 ^oC:
Tensile Strength = 70.7 *ksi* = 487.46 *MPa* [SN #391]
Yield Strength = 22.9 *ksi* = 157.89 *MPa*) [SN #391]

{Note: $psi \cdot \left(\frac{1}{0.0254} \frac{in}{m} \right)^2 \cdot \left(4.44822 \, {}^{N}\!/_{lb} \right) = Pa$ }

Calculations of the True Stresses and Strains for 316 S.S.:

From SN #391: True Stress = Nominal Stress*(1 + Nominal Stress/Modulus of Elasticity);
True Strain = ln(1 + Min. Elongation) - True Stress/Modulus of Elasticity;

Then

True Yield Stress = 1.5789e8 *Pa* = 1.5789e2 N/mm^2;
True Stress = 6.6295e8 *Pa* = 6.6295e2 N/mm^2;
True Strain = 0.3039.

(4) Ti-7 [data has been obtained from the Scientific Notebook #391]

Density = 4512 kg/m^3 = 4512e-9 kg/mm^3;
Modulus of elasticity = 1.007e11 *Pa* = 1.007e5 N/mm^2;
Poisson's ratio = 0.32;

At 150 ^oC:
True Yield Stress = 1.741e8 *Pa* = 1.741e2 N/mm^2;
True Stress = 2.995e8 *Pa* = 2.995e2 N/mm^2;
True Strain = 0.1793.

Date: February 3, 2006
Entry by: Roman V. Kazban

<u>Description and Geometry of the "Partial Waste Package" FEM</u>

The finite element model is composed of the following (refer to Figure 1):

(i) Drip Shield (DS);
- (a) Titanium Grade 24 Bulkhead Web;
- (b) Titanium Grade 24 Bulkhead Flanges;
- (c) Titanium Grade 24 Longitudinal Stiffeners;
- (d) Titanium Grade 7 Shell Plate;

(ii) Waste Package (WP);
- (a) Alloy 22 Outer Shell;
- (b) 316 Stainless Steel Inner Vessel;

(iii) Emplacement Pallet is represented by the Alloy 22 Pallet Plates.

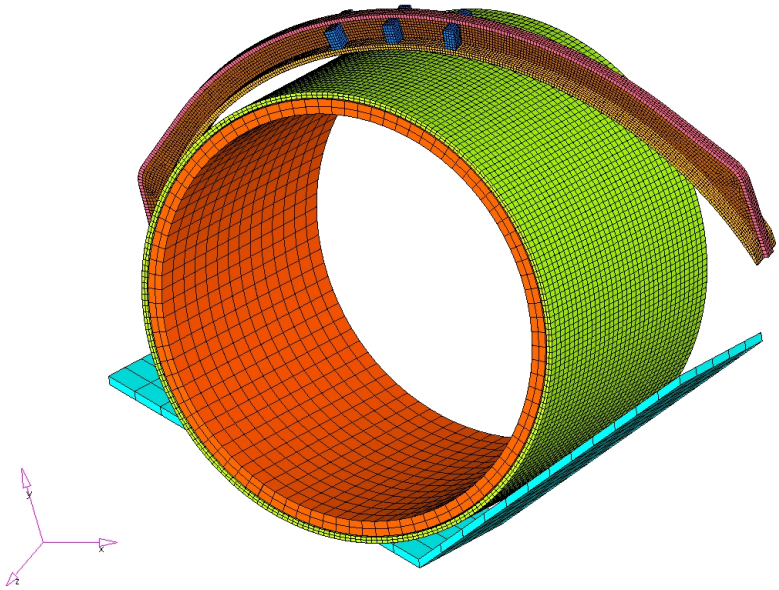


Figure 1.

The Drip Shield is inclined with 15 degree angle with respect to the Waste Package and the Emplacement Pallet to reproduce the baseline loading conditions (refer to Figure 2).

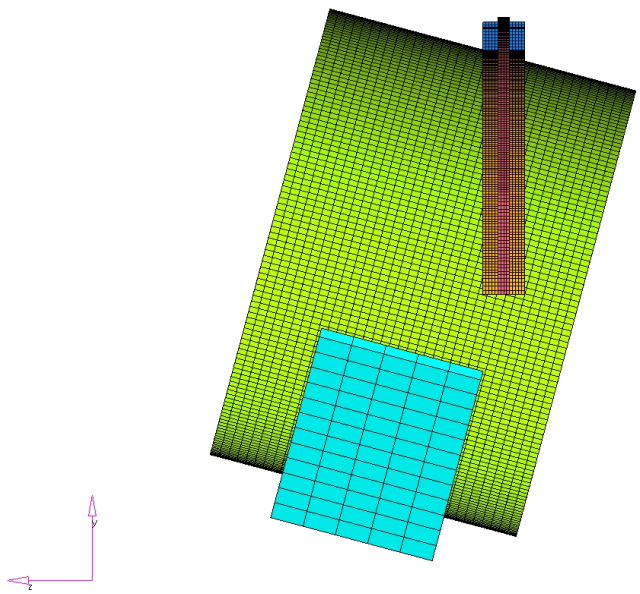


Figure 2.

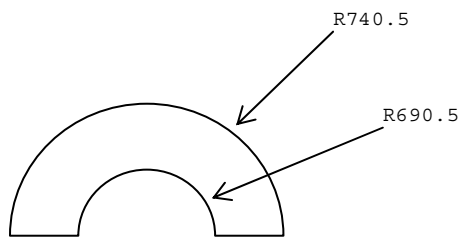
The finite element model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8) or 6-node linear tetrahedral elements (C3D6): the Bulkhead Web; the Bulkhead Flanges; the Longitudinal Stiffeners; the Outer Shell; the 316 Stainless Steel Inner Vessel. A small number of C3D6 is used in the model; and the use of such elements is limited to the Bulkhead Web component. The Shell Plate and the Pallet Plates are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Drip Shield C3D6 and C3D8 elements is 10x10x10 *mm* and 10x10x15 mm for SC8R elements of the Drip Shield Shell Plate. A typical size of the Waste Package Outer Shell C3D8 elements is 30x20x10 *mm*. A typical size of the Waste Package Inner Vessel C3D8 elements is 75x50x25 *mm*. A typical size of the Emplacement Pallet Plates SC8R elements is 110x100x30 *mm*. In addition, the common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

The width of the Waste Package is set to 1047 *mm*. To limit the number of elements in the finite element model, the width of the Shell Plate is set to 38.1 *mm*. In order to reproduce a correct stiffness of the Shell Plate due to its reduced dimension, the modulus of elasticity for the Shell Plate elements is increased by the ratio of the equivalent width to the chosen dimension (r = 230/38.1).

$$E' = \frac{230}{38.1} \cdot E_{Ti-7} = 607900.26 \, {}^{N}\!/_{mm^2}$$

Schematics of the Waste Package components used to construct the FEM

Waste Package Inner Vessel (316 S.S.)



Waste Package Outer Shell (Alloy 22)

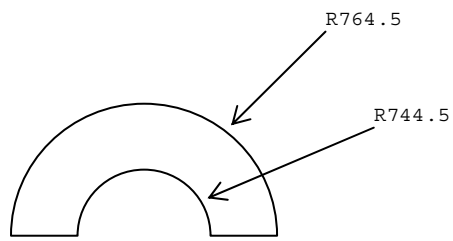


Figure 3.

{Note: All dimensions to construct the Drip Shield were taken from the sketch "Interlocking Drip Shield" SK-0230. All dimensions to construct the Emplacement Pallet were taken from the sketch "Emplacement Pallet" SK-0144.}

Boundary Conditions

Loads: Two Base loading conditions are used: (1) pressure of 300 *kPa* applied normal to the Drip Shield Shell Plate surface, and (2) vertical forces equivalent to a projected pressure of 300 *kPa*. These loads are monotonically increased up to a factor of four (1200 *kPa*).

Case 1: In order to reproduce correct loading conditions on the Shell Plate elements due to its reduced dimension, the distributed pressure is increased by the ratio of the original width to the chosen dimension (r = 1047/38.1).

$$P' = \frac{1047}{38.1} \cdot 300 = 8244.09 kPa = 8244.09 \times 10^{-3} \, N/mm^2$$

Case 2: The Shell Plate is divided into the following regions: (i) 0 - 20 degree incline angle with rotation above x-axis with a 0 degree position assigned to y-axis; (ii) 20 - 30 degree incline angle; (iii) 30 - 45 degree incline angle and (iv) 45 degree inclined flat region (refer to Figure 4).

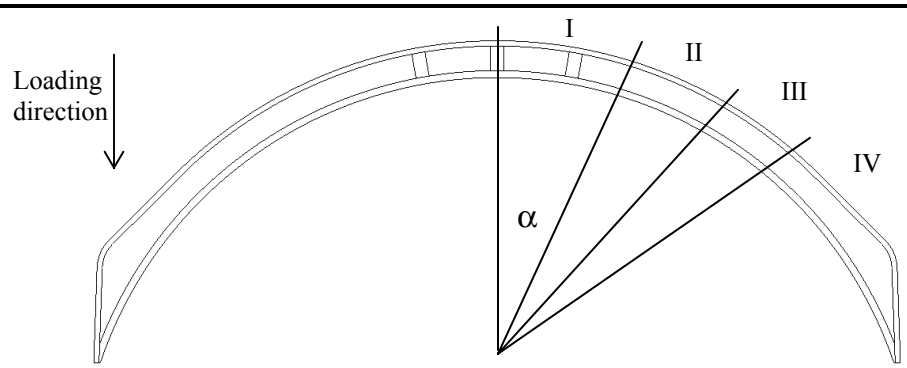


Figure 4.

Length calculations:

$$l_I = \frac{\alpha^\circ}{180}\pi R = 453.79mm \qquad l_{II} = \frac{\alpha^\circ}{180}\pi R = 226.89mm$$

$$l_{III} = \frac{\alpha^\circ}{180}\pi R = 340.34mm \qquad l_{IV} = 266.83mm$$

Average projected pressure:

$$P_I = \sum_n P \cdot \cos\alpha_n / n = 293.94kPa \qquad P_{II} = \sum_n P \cdot \cos\alpha_n / n = 271.55kPa$$

$$P_{III} = \sum_n P \cdot \cos\alpha_n / n = 237.33kPa \qquad P_{IV} = P \cdot \cos\alpha = 212.13kPa$$

Equivalent projected pressure:

$$P'_I = \frac{1047}{38.1} \cdot 293.94 = 8.0776\, {}^{N}\!/_{mm^2} \qquad P'_{II} = \frac{1047}{38.1} \cdot 271.55 = 7.4623\, {}^{N}\!/_{mm^2}$$

$$P'_{III} = \frac{1047}{38.1} \cdot 237.33 = 6.5219\, {}^{N}\!/_{mm^2} \qquad P'_I = \frac{1047}{38.1} \cdot 212.13 = 5.8294\, {}^{N}\!/_{mm^2}$$

Vertical force equivalent:

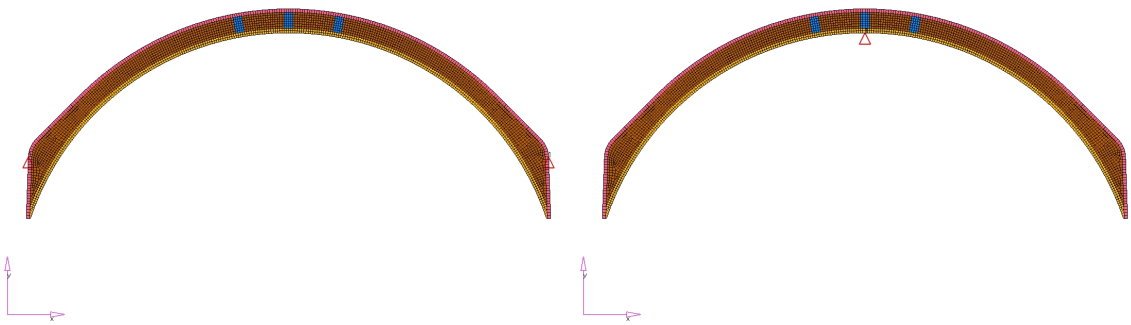
$$F_I = {}^{P'_I \cdot 38.1 \cdot l_I}\!/_{N_I} = 642.10N \qquad F_{II} = {}^{P'_{II} \cdot 38.1 \cdot l_{II}}\!/_{N_{II}} = 614.36N$$

$$F_{III} = {}^{P'_{III} \cdot 38.1 \cdot l_{III}}\!/_{N_{III}} = 528.56N \qquad F_{IV} = {}^{P'_{IV} \cdot 38.1 \cdot l_{IV}}\!/_{N_{IV}} = 474.10N$$

where N is the number of nodes in the region.

Kinematic Constraints: Two types of constraints are used for the Drip Shield. In both cases, the displacement in the vertical direction (y-axis) is constrained by 4 SPRING1 elements of a

relatively small stiffness to prevent numerical rigid body modes. The side surfaces of the Drip Shield are constrained in the transverse direction (z-axis) to simulate symmetry conditions. In some cases, however, the Drip Shield ends are constrained in the horizontal direction (x-axis), whereas in the other case the Drip Shield ends are free in all directions (refer to Figure 5).



(a) (b)

Figure 5

The Waste Package components are constrained along the line of symmetry in the vertical axial plane to prevent displacement in the horizontal direction. The displacement in the vertical direction is constrained by 4 SPRING1 elements of a relatively small stiffness on the both Waste Package Shells. Also, the side surfaces of the Waste Package are constrained from the displacement in the transverse direction to simulate symmetry conditions.

Regarding the Emplacement Pallet, each node of the bottom surface is constrained from the displacements in the horizontal and vertical directions. Also, the end nodes of the Emplacement Pallet are constrained from the displacement in the transverse direction.

There two coordinate systems are used to insure correct symmetry conditions: one for the Drip Shield and the other one for the Waste Package and the Emplacement Pallet.

A friction coefficient of 0.4 is used to model friction surface interaction between the Drip Shield and the Waste Package Outer Shell, between the Waste Package Outer Shell and Inner Vessel, and between the Waste Package Outer Shell and the Emplacement Pallet.

Date: February 6, 2006
Entry by: Roman V. Kazban
<u>Results of the "Partial Waste Package" FEM for the Waste Package Outer Shell</u>

Table 1. Normally applied pressure with the side constrained ends of the Drip Shield. (File: on Isis D:\DS\DSonWP_15FCMrev8)

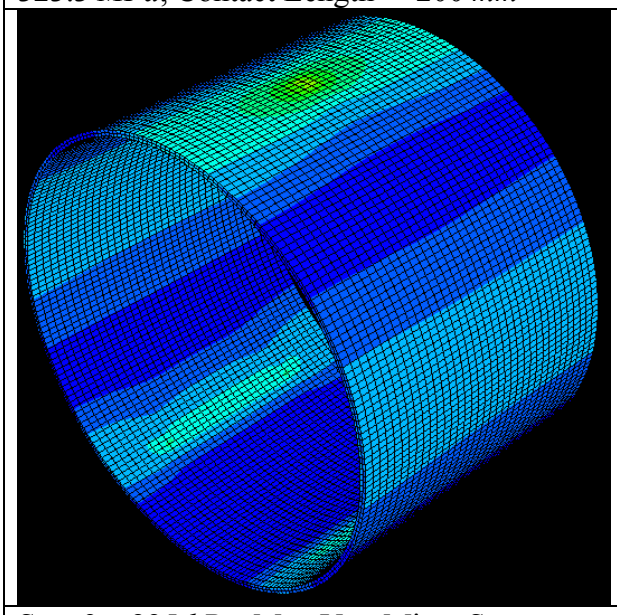
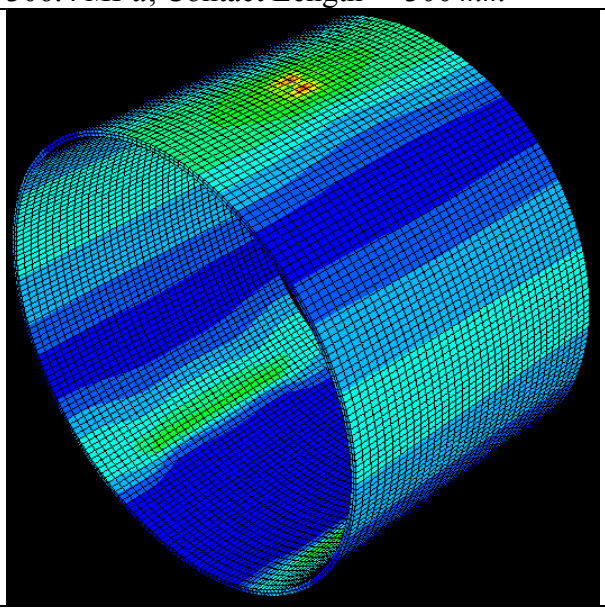
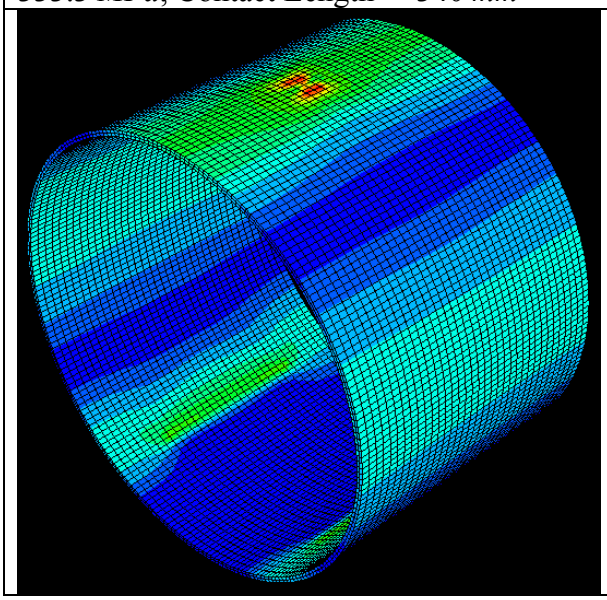
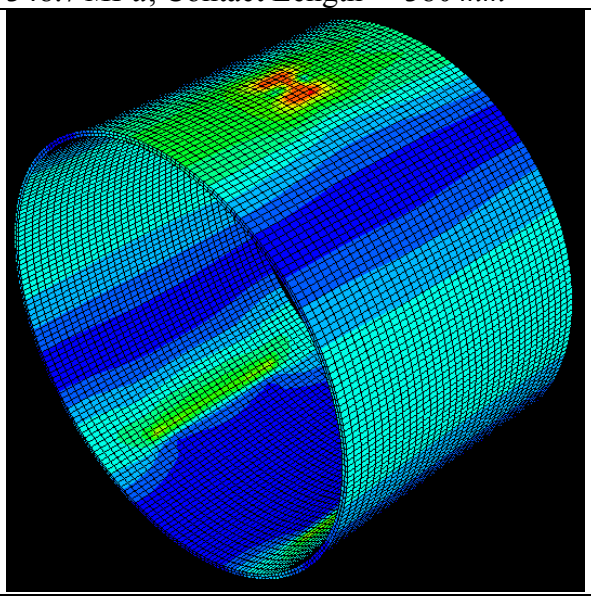
Step 1 – 75 *kPa*: Max Von Mises Stress = 323.3 *MPa*, Contact Length = 200 *mm*	Step 2 – 150 *kPa*: Max Von Mises Stress = 306.4 *MPa*, Contact Length = 300 *mm*
	
Step 3 – 225 *kPa*: Max Von Mises Stress = 333.3 *MPa*, Contact Length = 340 *mm*	Step 4 – 300 *kPa*: Max Von Mises Stress = 348.7 *MPa*, Contact Length = 380 *mm*
	

Table 2. Normally applied pressure with free ends of the Drip Shield. (File: on Isis D:\DS\DSonWP_15FCMrev7)

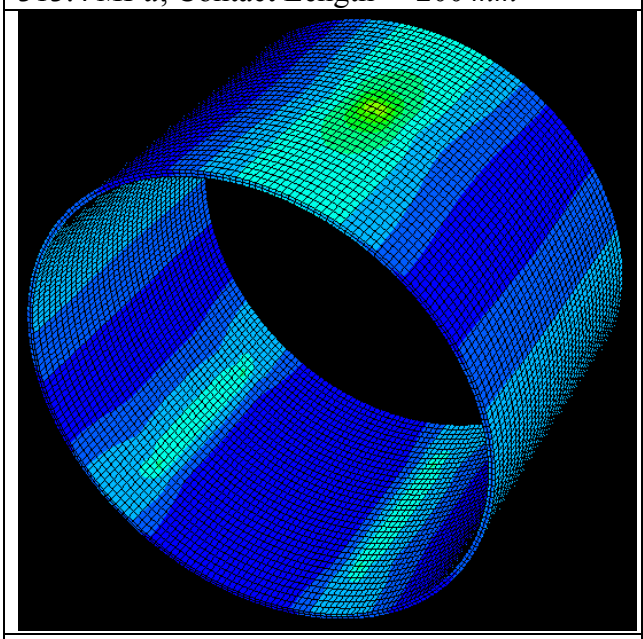
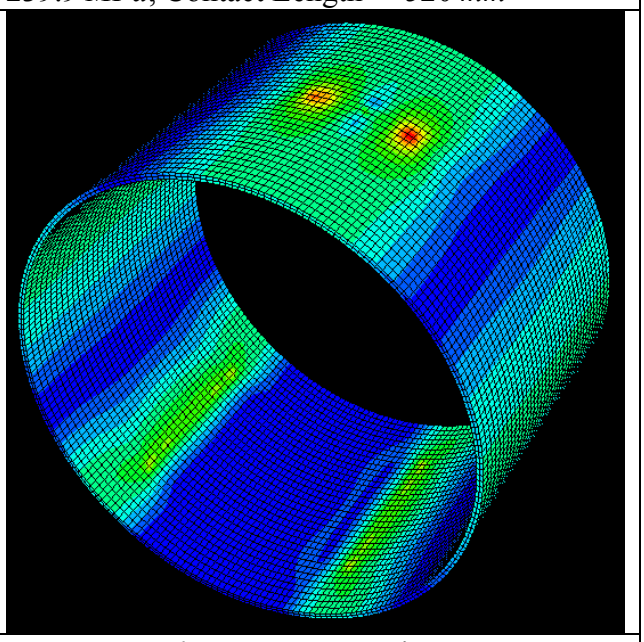
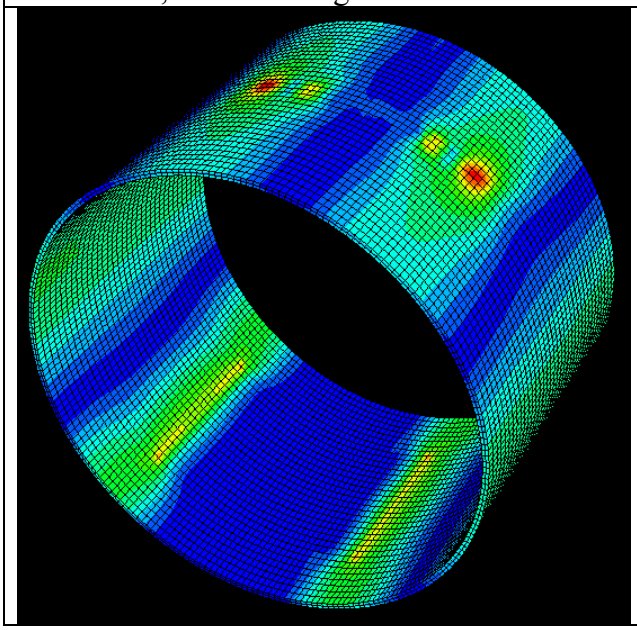
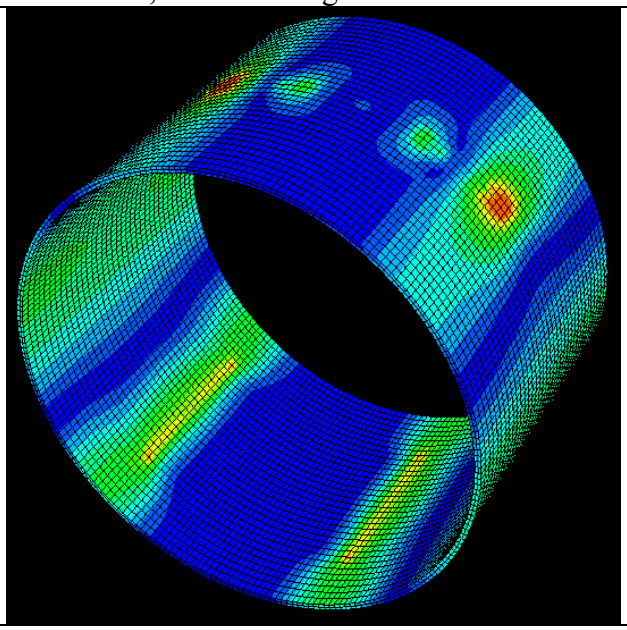
Step 1 – 75 *kPa*: Max Von Mises Stress = 313.4 *MPa*, Contact Length = 200 *mm*	Step 2 – 150 *kPa*: Max Von Mises Stress = 239.9 *MPa*, Contact Length = 520 *mm*
	
Step 3 – 225 *kPa*: Max Von Mises Stress = 281.9 *MPa*, Contact Length = 600 *mm*	Step 4 – 300 *kPa*: Max Von Mises Stress = 353.5 *MPa*, Contact Length = 640 *mm*
	

Table 3. Vertical forces perpendicular to the Drip Shield with free ends of the Drip Shield. (File: on Isis D:\DS\DSonWP_15FCMrev9)

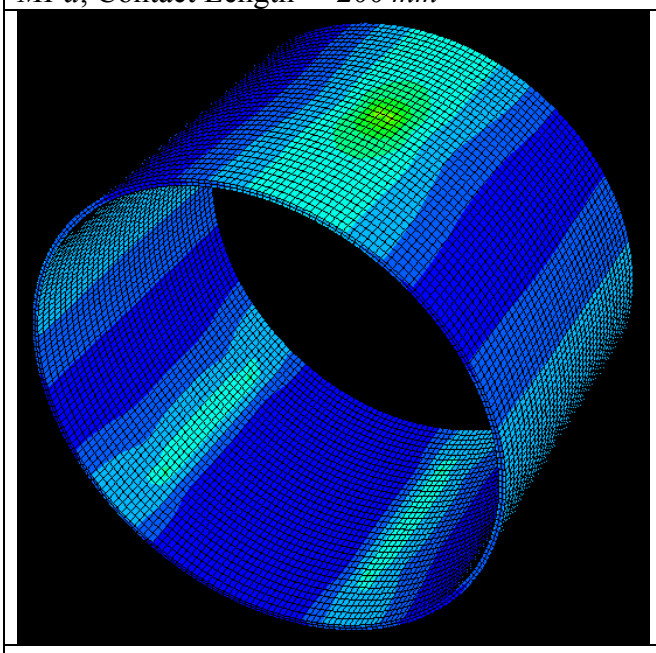
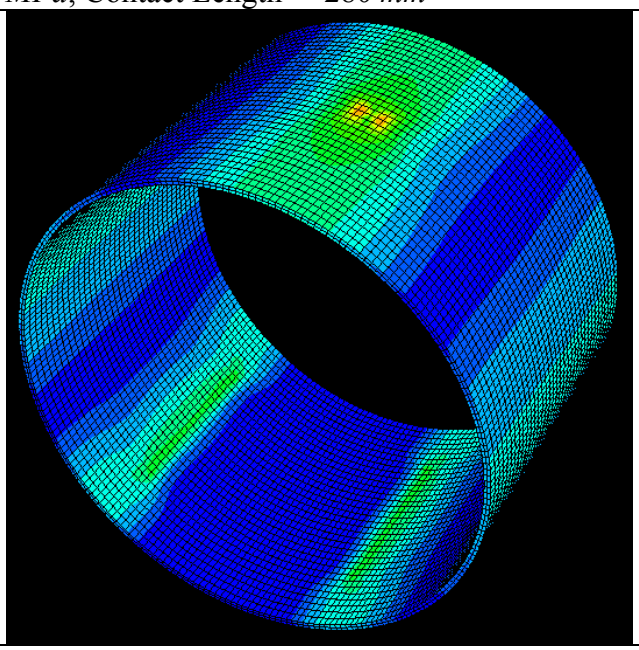
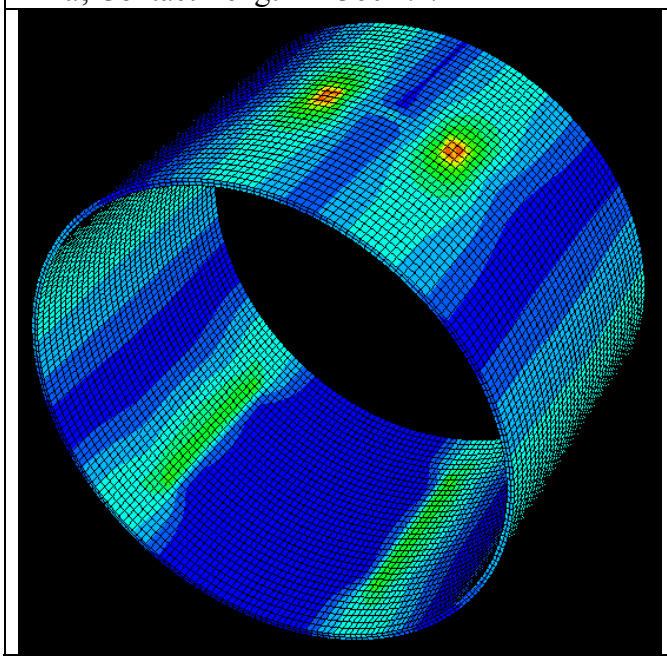
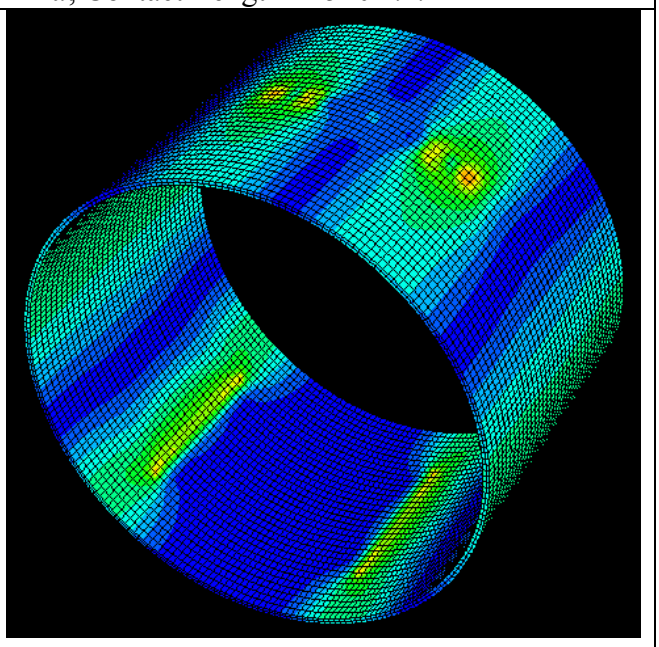
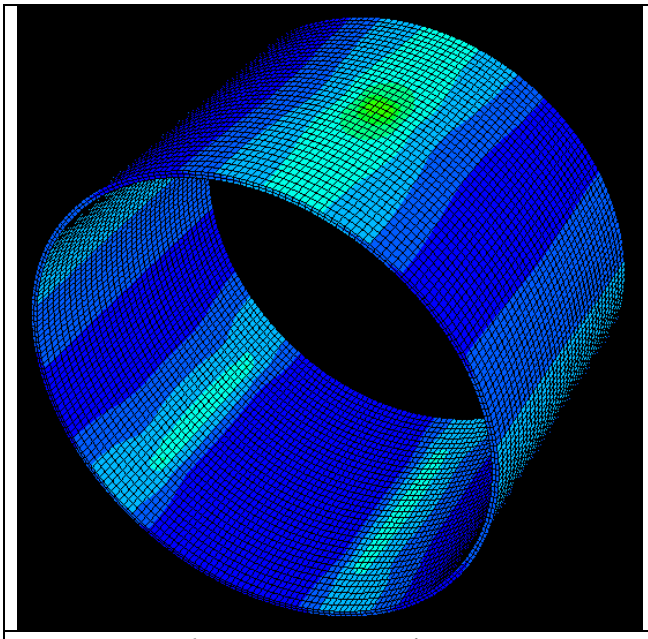
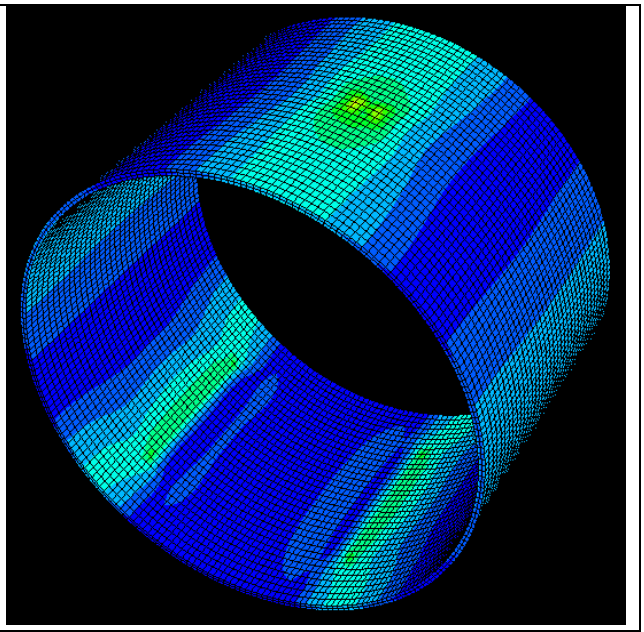
Step 1 – 75 *kPa*: Max Von Mises Stress = 333.3 *MPa*, Contact Length = 200 *mm*	Step 2 – 150 *kPa*: Max Von Mises Stress = 310.8 *MPa*, Contact Length = 280 *mm*
	
Step 3 – 225 *kPa*: Max Von Mises Stress = 376.9 *MPa*, Contact Length = 360 *mm*	Step 4 – 300 *kPa*: Max Von Mises Stress = 342.0 *MPa*, Contact Length = 520 *mm*
	

Table 4. Vertical forces perpendicular to the Drip Shield with free ends of the Drip Shield and 10x stiffness of the Inner Vessel. (File: on Isis D:\DS\DSonWP_15FCMrev10)

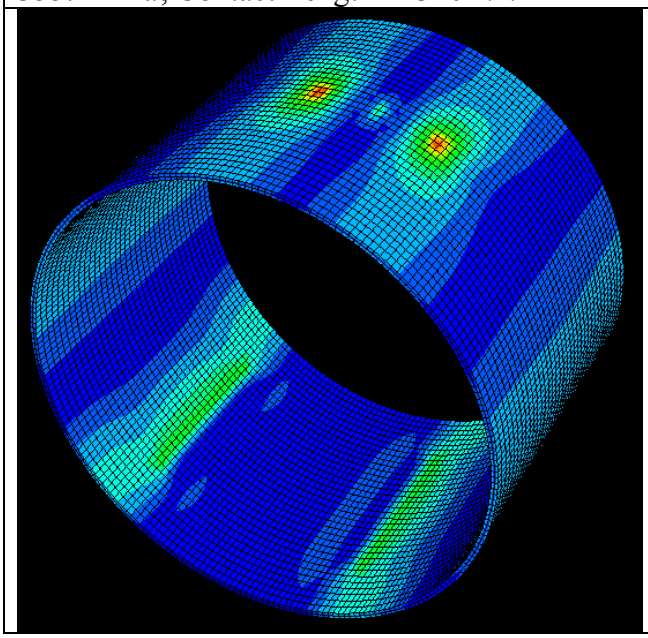
Step 1 – 75 *kPa*: Max Von Mises Stress = 310.0 *MPa*, Contact Length = 160 *mm*	Step 2 – 150 *kPa*: Max Von Mises Stress = 313.9 *MPa*, Contact Length = 200 *mm*





Step 3 – 225 *kPa*: Max Von Mises Stress = 355.1 *MPa*, Contact Length = 340 *mm*

Step 4 – 300 *kPa*: Max Von Mises Stress = 330.3 *MPa*, Contact Length = 480 *mm*



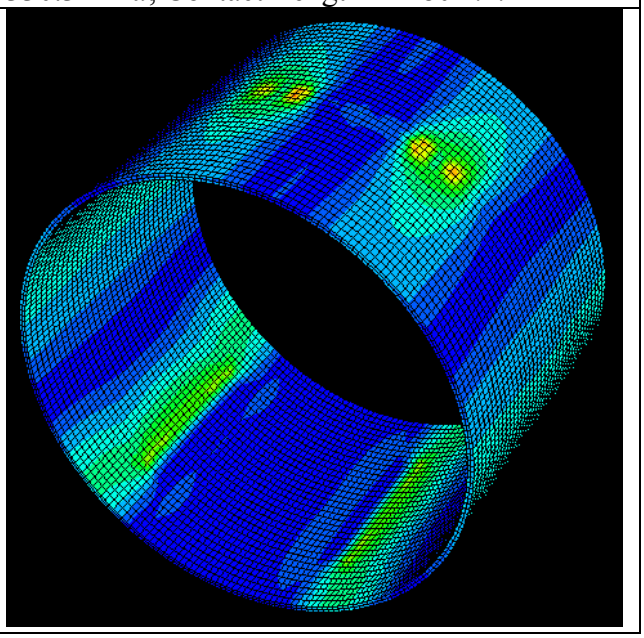
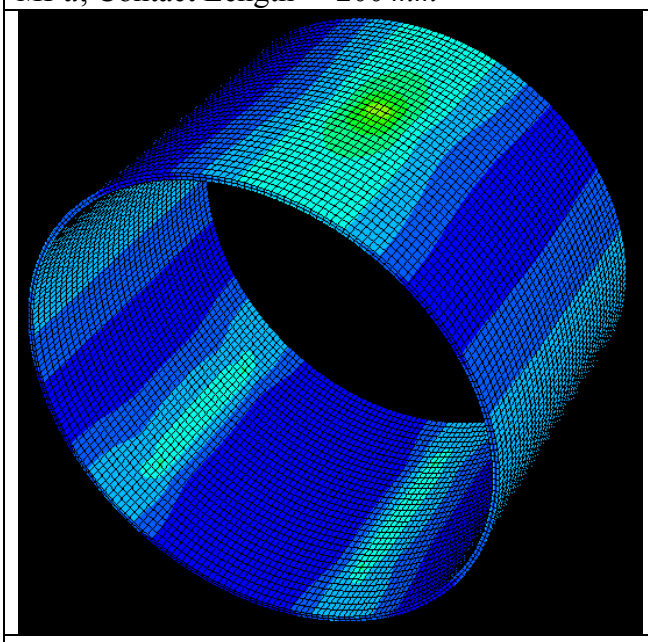
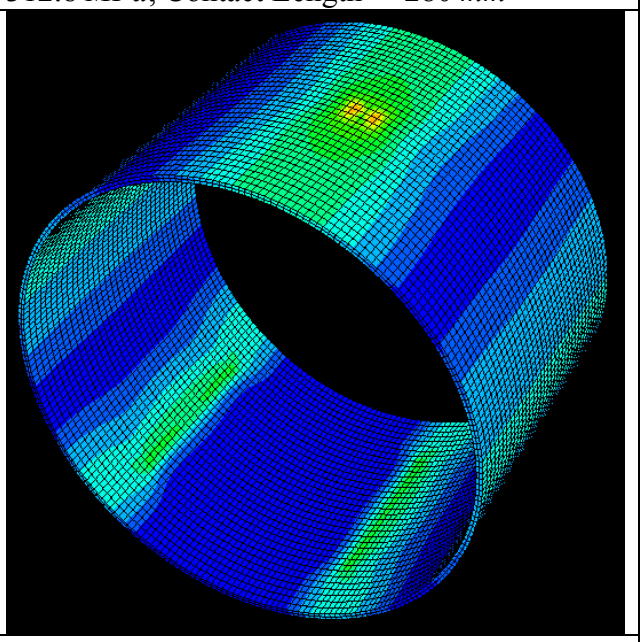
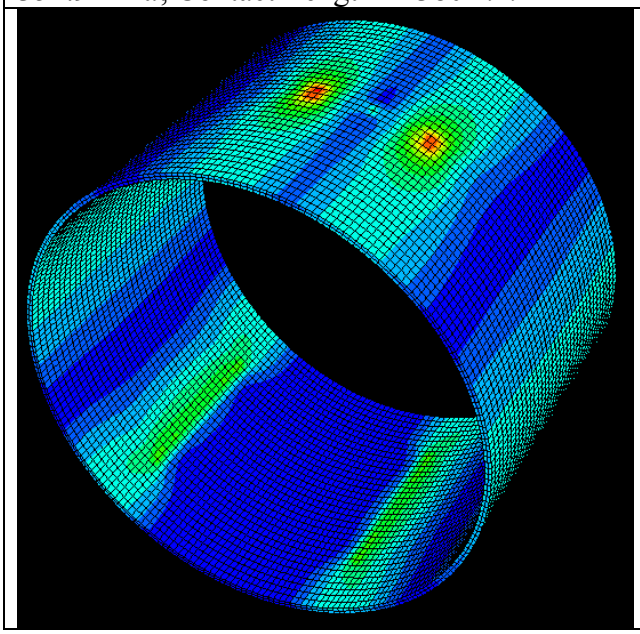
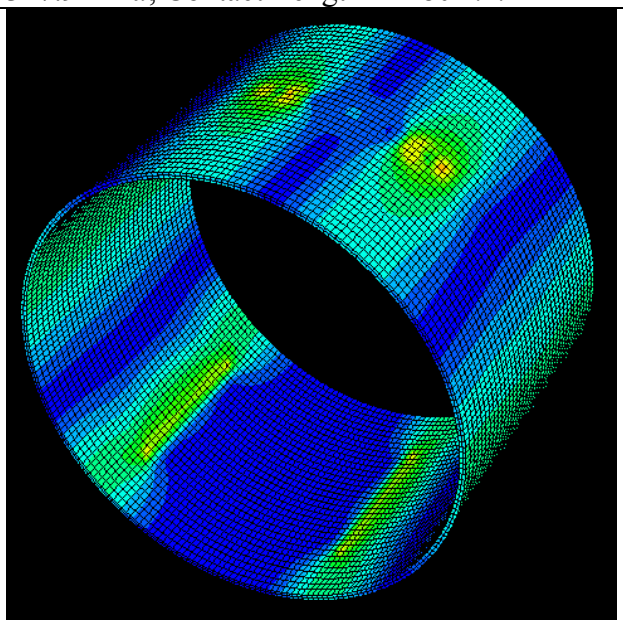


Table 5. Vertical forces perpendicular to the Waste package with free ends of the Drip Shield. (File: on Isis D:\DS\DSonWP_15FCMrev11)

Step 1 – 75 *kPa*: Max Von Mises Stress = 307.5 *MPa*, Contact Length = 200 *mm*	Step 2 – 150 *kPa*: Max Von Mises Stress = 312.8 *MPa*, Contact Length = 280 *mm*
	
Step 3 – 225 *kPa*: Max Von Mises Stress = 352.9 *MPa*, Contact Length = 380 *mm*	Step 4 – 300 *kPa*: Max Von Mises Stress = 347.9 *MPa*, Contact Length = 480 *mm*
	

{Note: The contact length was estimated by using a stress criteria, assuming that the contact is achieved if the Von Mises stress in the outer shell of the waste package exceeds a half of the yield stress of Alloy 22. Also, the estimation was performed using a contour plotting options.}

Date: February 8, 2006
Entry by: Roman V. Kazban

<u>Description and Geometry of the "Complete Waste Package" FEM</u>
The finite element model is composed of the following (refer to Figure 6):

(i) Drip Shield;
- (a) Titanium Grade 24 Bulkhead Web;
- (b) Titanium Grade 24 Bulkhead Flanges;
- (c) Titanium Grade 24 Longitudinal Stiffeners;
- (d) Titanium Grade 7 Shell Plate;

(ii) Waste Package;
- (a) Alloy 22 Outer Shell;
- (b) 316 Stainless Steel Inner Vessel;

(iii) Emplacement Pallet is represented by the Alloy 22 Pallet Plates.

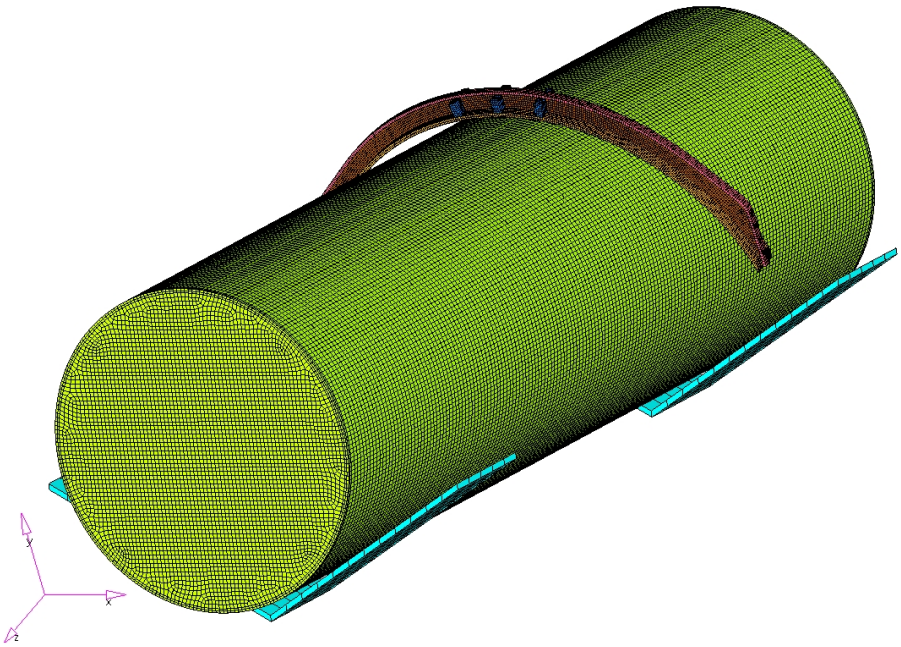


Figure 6.

The Drip Shield is inclined with 15 degree angle with respect to the Waste Package and the Emplacement Pallet to reproduce the baseline loading conditions. The finite element model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8) or 6-node linear tetrahedral elements (C3D6): the Bulkhead Web; the Bulkhead Flanges; the Longitudinal Stiffeners; the Outer Shell; the 316 Stainless Steel Inner Vessel. A small number of C3D6 is used in the model; and the use of such elements is limited to the Bulkhead Web component. The Shell Plate and the Pallet Plates are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Drip Shield C3D6 and C3D8 elements is 10x10x10 *mm* and 10x10x15 mm for SC8R elements of the Drip Shield Shell Plate. A typical size of the Waste Package Outer Shell C3D8 elements is 30x20x10 *mm*. A typical size of the Waste Package Inner Vessel C3D8 elements is 75x50x25 *mm*. A typical size of the Emplacement Pallet Plates SC8R elements is 110x100x30 *mm*. In addition, the common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

To limit the number of elements in the finite element model, the width of the Shell Plate is set to 38.1 *mm*. In order to reproduce a correct stiffness of the Shell Plate due to its reduced dimension, the modulus of elasticity for the Shell Plate elements is increased by the ratio of the equivalent width to the chosen dimension (r = 230/38.1).

$$E' = \frac{230}{38.1} \cdot E_{Ti-7} = 607900.26 \, {}^{N}\!/_{mm^2}$$

<u>Schematics of the Waste Package components used to construct the FEMs</u>

Waste Package Inner Vessel (316 S.S.)

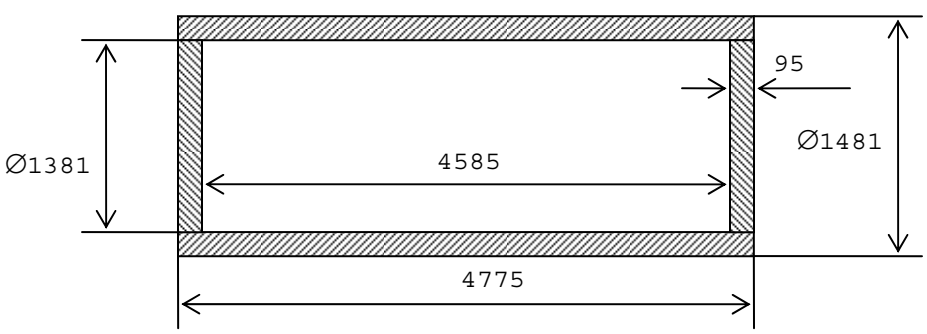


Figure 7a.

Waste Package Outer Shell (Alloy 22)

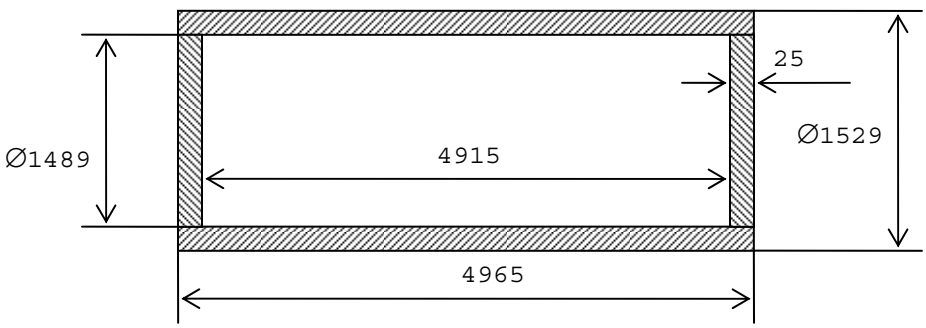


Figure 7b.

Boundary Conditions

Loads: In order to reproduce correct loading conditions on the Shell Plate elements due to its reduced dimension, the distributed pressure is increased by the ratio of the original width to the chosen dimension (r = 1047/38.1).

$$P' = \frac{1047}{38.1} \cdot 300 = 8244.09 kPa = 8244.09 \times 10^{-3} \, N/mm^2$$

Also, to reproduce additional loading from three additional Bulkheads of the Drip Shield, the Outer Shell is loaded directly in 3 places for the contact length of 800 *mm* (refer to Figure 8).

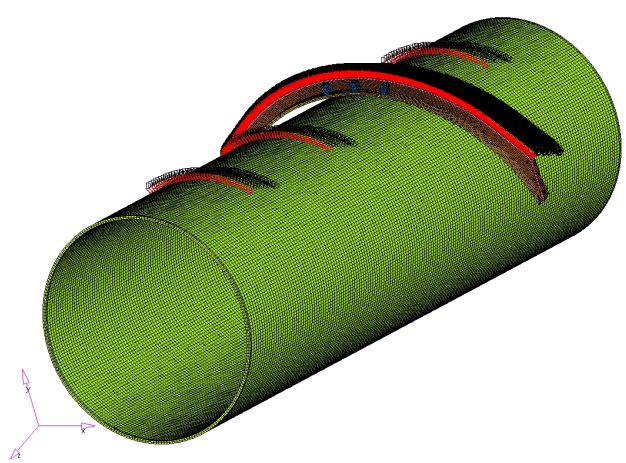


Figure 8.

Two edge pressure loadings (refer to Figure 8) represent a loading of the Drip Shield for the width of 1618.835 *mm* and the middle loading represents a loading of the Drip Shield for the width of 1047.47 *mm*.

$$P^{Edge/Middle} = P \cdot \frac{DSWidth}{ElementWidth} \cdot \frac{ShellPlateLength}{ContactLength}$$

For the WP Outer Shell the length of 1 element is 20.014 *mm* and the width of 1 element is 29.97 *mm*. 40 elements are loaded to reproduce the contact length of 800 mm, which results in a contact length of 800.56 *mm*. The length of the applied pressure area of the DS Shell Plate is 2595.023 *mm*.

For the 300 *kPa* load of the DS:

$$P^{1618} = 300 \cdot \frac{1618.835}{29.97} \cdot \frac{2595.023}{800.56} = 52527.22 kPa$$

$$P^{1047} = 300 \cdot \frac{1047.47}{29.97} \cdot \frac{2595.023}{800.56} = 33987.83 kPa$$

Kinematic Constraints: The Drip Shield displacement in the vertical direction (y-axis) is constrained by 4 SPRING1 elements of a relatively small stiffness to prevent numerical rigid body modes. The side surfaces of the Drip Shield are constrained in the transverse direction (z-axis) to represent a symmetry conditions. The Drip Shield ends are free in all directions (refer to Figure 5b) with a constraint in the horizontal direction (x-axis) in the middle of the DS.

The Waste Package components are constrained along the line of symmetry in the vertical axial plane to prevent displacement in the horizontal direction. The displacement in the vertical direction is constrained by 4 SPRING1 elements of a relatively small stiffness on the both Waste Package Shells. Also, the Waste Package is constrained from the displacement in the transverse direction in the middle of the WP on the line on symmetry.

Regarding the Emplacement Pallet, each node of the bottom surface is constrained from the displacement in the horizontal and vertical directions. Also, the end nodes of the Emplacement Pallet are constrained from the displacement in the transverse direction.

There two coordinate systems are used to insure correct symmetry conditions: one for the Drip Shield and the other one for the Waste Package and the Emplacement Pallet.

A friction coefficient of 0.4 is used to model friction surface interaction between the Drip Shield and the Waste Package Outer Shell, between the Waste Package Outer Shell and Inner Vessel, and between the Waste Package Outer Shell and the Emplacement Pallet.

Date: February 13, 2006
Entry by: Roman V. Kazban

The computational analysis of the "Complete Waste Package" FEM was terminated due to insufficient run time.

Date: February 14, 2006
Entry by: Roman V. Kazban

<u>Simulation of the Complete Inner Vessel stiffness for the "Partial Waste Package" FEM</u>

1) <u>Estimation of the Partial Inner Vessel edges stiffness</u>

The finite element model is composed of the following (refer to Figure 9):

(i) Waste Package -316 Stainless Steel Inner Vessel;
(ii) Emplacement Pallet is represented by the Alloy 22 Pallet Plates.

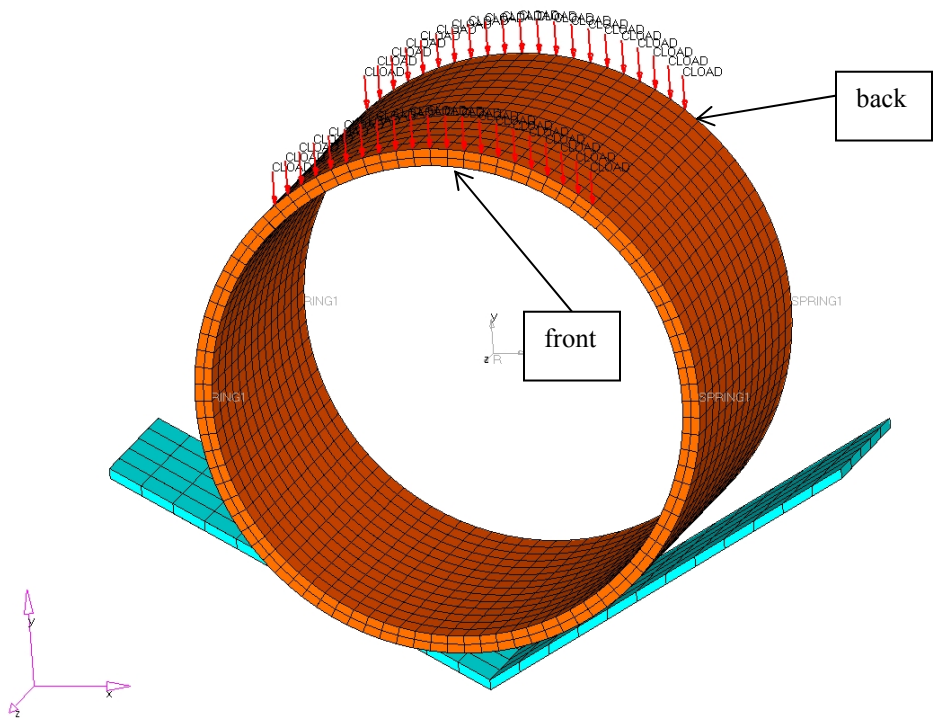


Figure 9.

The finite element model is constructed using a mixture of plate and solid elements. The 316 Stainless Steel Inner Vessel is discretized with 8-node continuum elements (C3D8). The Pallet Plates are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Waste Package Inner Vessel C3D8 elements is 75x50x25 *mm*. A typical size of the Emplacement Pallet Plates SC8R elements is 110x100x30 *mm*. The width of the Waste Package is set to 1047 *mm.*

Boundary Conditions

Loads: The Inner Vessel is loaded with the force of 30 *kN* at 21 nodes on both edges (20 elements). This reproduces the contact length of 1011.26 *mm* (the length of the Inner Vessel element is 50.563 *mm*).

Kinematic Constraints: The Inner Vessel components are constrained along the line of symmetry in the vertical axial plane to prevent displacement in the horizontal direction (x-axis). The displacement in the vertical direction (y-axis) is constrained by 4 SPRING1 elements of a relatively small stiffness. Also, the side surfaces of the Waste Package are constrained from the displacement in the transverse direction (z-axis) to simulate a symmetry conditions.

Regarding the Emplacement Pallet, each node of the bottom surface is constrained from displacement in the horizontal and vertical directions. Also, the end nodes of the Emplacement Pallet are constrained from displacement in the transverse direction.

A friction coefficient of 0.4 is used to model friction surface interaction between the Waste Package Inner Vessel and the Emplacement Pallet.

Date: February 15, 2006
Entry by: Roman V. Kazban

Results of the Partial Inner Vessel stiffness for its edges

{Note: All the front and back nodes are numbered clockwise from -10 to 10 with the 0 node located at the line of symmetry.}

Table 6. Stiffness estimation for the Partial Inner Vessel. (File: on Isis D:\ DS \ DSonWP_15InSWPrev1)

Node ##	-10	-9	-8	-7	-6	-5	-4
Displacement in y-direction	-9.48	-10.31	-11.15	-11.98	-12.78	-13.52	-14.18
Stiffness (K =F/|y|) [N/mm]	3164.26	2909.60	2689.79	2503.53	2347.42	2218.85	2114.98

Node ##	-3	-2	-1	0	1	2	3
Displacement in y-direction	-14.75	-15.19	-15.48	-15.58	-15.48	-15.21	-14.77
Stiffness (K =F/|y|) [N/mm]	2033.93	1974.94	1938.50	1925.77	1937.61	1972.91	2030.54
Node ##	4	5	6	7	8	9	10
Displacement in y-direction	-14.22	-13.56	-12.83	-12.04	-11.22	-10.39	-9.57
Stiffness (K =F/|y|) [N/mm]	2109.91	2211.83	2338.12	2491.14	2673.70	2888.34	3136.37

Date: February 16, 2006

Entry by: Roman V. Kazban

2) <u>Estimation of the Complete Inner Vessel edges stiffness</u>

The finite element model is composed of the following (refer to Figure 10):

(i) Waste Package -316 Stainless Steel Inner Vessel;

(ii) Emplacement Pallet is represented by the Alloy 22 Pallet Plates.

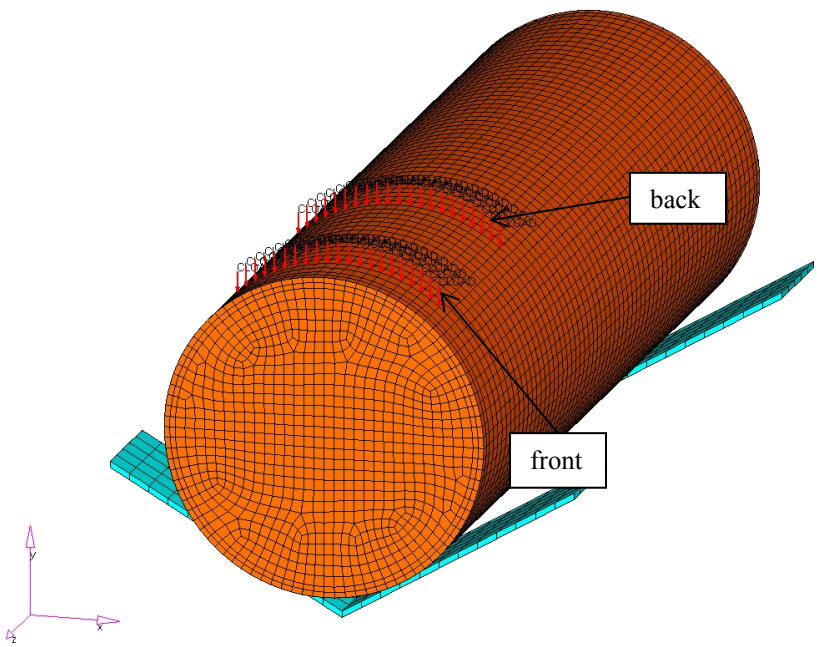


Figure 10.

The finite element model is constructed using a mixture of plate and solid elements. The 316 Stainless Steel Inner Vessel is discretized with 8-node continuum elements (C3D8). The Pallet Plates are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Waste Package Inner Vessel C3D8 elements is 75x50x25 *mm*. A typical size of the Emplacement Pallet Plates SC8R elements is 110x100x30 *mm*. In addition, the common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

{Note: Refer to Figure 7a for dimensions of the Waste package Inner Vessel}

<u>Boundary Conditions</u>

Loads: The Inner Vessel is loaded with the force of 30 *kN* at 21 nodes (20 elements) for a contact length of 1011.26 *mm* (the length of the Inner Vessel element is 50.563 *mm*). The loading is performed in two places with the line on symmetry adequate to the Bulkhead line of symmetry (in YZ plane) and a1047 *mm* spacing between two lines of loading.

Kinematic Constraints: The Inner Vessel components are constrained along the line of symmetry in the vertical axial plane to prevent displacement in the horizontal direction (x-axis). The displacement in the vertical direction (y-axis) is constrained by 4 SPRING1 elements of a relatively small stiffness. Also, the Inner Vessel Waste Package is constrained from the displacement in the transverse direction (z-axis) in the middle of the WP on the line on symmetry.

Regarding the Emplacement Pallet, each node of the bottom surface is constrained from the displacement in the horizontal and vertical directions. Also, the end nodes of the Emplacement Pallet are constrained from the displacement in the transverses direction.

A friction coefficient of 0.4 is used to model friction surface interaction between the Waste Package Inner Vessel and the Emplacement Pallet.

Date: February 17, 2006
Entry by: Roman V. Kazban

<u>Results of the Partial Inner Vessel stiffness for its edges</u>

{Note: All the front and back nodes are numbered clockwise from -10 to 10 with the 0 node located at the line of symmetry.}

Table 6. Stiffness estimation for the Complete Inner Vessel. (File: on Isis D:\ DS \ DSonWP_15InWPrev3)

Front Node ##	-10	-9	-8	-7	-6	-5	-4
Displacement in y-direction	-0.88	-0.92	-0.94	-0.97	-1.00	-1.02	-1.04
Stiffness (K =F/|y|) [N/mm]	33913.63	32776.14	31752.75	30857.85	30081.22	29423.30	28871.14

Front Node ##	-3	-2	-1	0	1	2	3
Displacement in y-direction	-1.06	-1.07	-1.08	-1.09	-1.09	-1.09	-1.08
Stiffness (K =F/|y|) [N/mm]	28419.86	28068.86	27813.83	27649.77	27576.06	27591.28	27693.16

Front Node ##	4	5	6	7	8	9	10
Displacement in y-direction	-1.08	-1.07	-1.05	-1.04	-1.02	-0.99	-0.97
Stiffness (K =F/|y|) [N/mm]	27881.04	28158.44	28522.53	28979.91	29527.56	30171.98	30889.62

Back Node ##	-10	-9	-8	-7	-6	-5	-4
Displacement in y-direction	-1.05	-1.15	-1.25	-1.35	-1.45	-1.53	-1.61
Stiffness (K =F/|y|) [N/mm]	28666.99	26121.03	23963.58	22179.51	20721.09	19551.62	18635.86

Back Node ##	-3	-2	-1	0	1	2	3
Displacement in y-direction	-1.67	-1.72	-1.75	-1.76	-1.76	-1.74	-1.70
Stiffness (K =F/|y|) [N/mm]	17942.58	17452.01	17147.76	17017.41	17057.08	17266.19	17650.17

Back Node ##	4	5	6	7	8	9	10
Displacement in y-direction	-1.65	-1.58	-1.50	-1.42	-1.32	-1.23	-1.13
Stiffness (K =F/|y|) [N/mm]	18218.25	18986.14	19970.71	21193.92	22677.45	24439.92	26478.38

Table 7. Estimation of the difference in stiffness of the Complete and Partial Inner Vessel.

Front Node ##	-10	-9	-8	-7	-6	-5	-4
Front Nodes Stiffness	30749.38	29866.54	29062.97	28354.32	27733.80	27204.45	26756.15
Back Node ##	-10	-9	-8	-7	-6	-5	-4
Back Nodes Stiffness	25502.73	23211.43	21273.79	19675.98	18373.68	17332.76	16520.87

Front Node ##	-3	-2	-1	0	1	2	3
Front Nodes Stiffness	26385.93	26093.92	25875.33	25724.00	25638.45	25618.38	25662.62
Back Node ##	-3	-2	-1	0	1	2	3
Back Nodes Stiffness	15908.66	15477.06	15209.26	15091.65	15119.48	15293.28	15619.63

Front Node ##	4	5	6	7	8	9	10
Front Nodes Stiffness	25771.13	25946.60	26184.41	26488.77	26853.86	27283.64	27753.25
Back Node ##	4	5	6	7	8	9	10
Back Nodes Stiffness	16108.34	16774.31	17632.59	18702.79	20003.75	21551.58	23342.01

Date: February 21, 2006
Entry by: Roman V. Kazban

Updated material properties used in the three-dimensional finite element models (FEMs)

Alloy 22 [data is obtained from the Scientific Notebook (SN) #764]

Density = 8691.5 kg/m^3 = 8691.5e-9 kg/mm^3;
Modulus of elasticity = 1.7996e11 *Pa* = 1.7996e5 N/mm^2;
Poisson's ratio = 0.31;

At 150 ^oC:
True Yield Stress = 2.799e8 *Pa* = 2.799e2 N/mm^2;
True Stress = 12.162e8 *Pa* = 12.162e2 N/mm^2;
True Strain = 0.553.

Date: February 22, 2006
Entry by: Roman V. Kazban

Description and Geometry of the "1/2 Waste Package" FEM
The finite element model is composed of the following (refer to Figure 11):

(i) Drip Shield;
- (a) Titanium Grade 24 Bulkhead Web;
- (b) Titanium Grade 24 Bulkhead Flanges;
- (c) Titanium Grade 24 Longitudinal Stiffeners;
- (d) Titanium Grade 7 Shell Plate;

(ii) Waste Package;
- (a) Alloy 22 Outer Shell;
- (b) 316 Stainless Steel Inner Vessel;

(iii) Emplacement Pallet is represented by the Alloy 22 Pallet Plates.

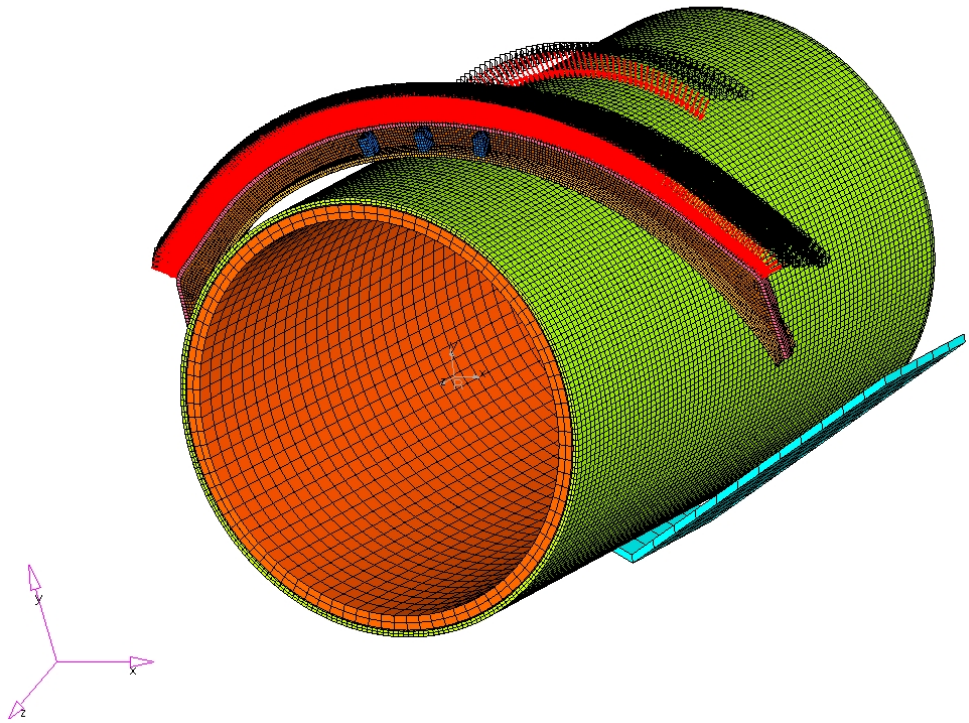


Figure 11.

The Drip Shield is inclined with 15 degree angle with respect to the Waste Package and the Emplacement Pallet to reproduce the baseline loading conditions. The finite element model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8) or 6-node linear tetrahedral elements (C3D6): the Bulkhead Web; the Bulkhead Flanges; the Longitudinal Stiffeners; the Outer Shell; the 316 Stainless Steel Inner Vessel. A small number of C3D6 is used in the model; and the use of such elements is limited to the Bulkhead Web component. The Shell Plate and the Pallet Plates are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Drip Shield C3D6 and C3D8 elements is 10x10x10 *mm* and 10x10x15 mm for SC8R elements of the Drip Shield Shell Plate. A typical size of the Waste Package Outer Shell C3D8 elements is 30x20x10 *mm*. A typical size of the Waste Package Inner Vessel C3D8 elements is 75x50x25 *mm*. A typical size of the Emplacement Pallet Plates SC8R elements is 110x100x30 *mm*. In addition, the common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

To limit the number of elements used in the finite element model, the width of the Shell Plate is set to 38.1 *mm*. In order to reproduce a correct stiffness of the Shell Plate due to its reduced

dimension, the modulus of elasticity for the Shell Plate elements is increased by the ratio of the equivalent width to the chosen dimension (r = 230/38.1).

$$E' = \frac{230}{38.1} \cdot E_{Ti-7} = 607900.26 \, {}^{N}\!/_{mm^2}$$

Only a half of the WP is used in construction of this FEM (refer to Figure 7 for WP dimensions).

Loads: In order to reproduce correct loading conditions on the Shell Plate elements due to its reduced dimension, the distributed pressure is increased by the ratio of the original width to the chosen dimension (r = 1047.47/38.1).

$$P'_{300} = \frac{1047.47}{38.1} \cdot 300kPa = 8247.80kPa = 8247.80 \times 10^{-3} \, {}^{N}\!/_{mm^2}$$

$$P'_{1200} = \frac{1047.47}{38.1} \cdot 1200kPa = 32991.18kPa = 32991.18 \times 10^{-3} \, {}^{N}\!/_{mm^2}$$

Also, to reproduce loading from an additional Bulkhead of the Drip Shield, the Outer Shell is loaded directly close to the edge of DS for the contact length of 1000 *mm* (refer to Figure 11). The edge pressure loading represents a loading of the Drip Shield for the width of 1618.835 *mm*.

$$P^{Edge/Middle} = P \cdot \frac{DSWidth}{ElementWidth} \cdot \frac{ShellPlateLength}{ContactLength}$$

For the WP Outer Shell the length of 1 element is 20.014 *mm* and the width of 1 element is 29.97 *mm*. 50 elements are loaded to reproduce the contact length of 1000 mm, which results in a contact length of 1000.7 *mm*. The length of the applied pressure area of the DS Shell Plate is 2595.023 *mm*.

For the 300 *kPa* load of the DS:

$$P_{300} = 300 \cdot \frac{1618.835}{29.97} \cdot \frac{2595.023}{1000.7} = 42021.78kPa$$

For the 1200 *kPa* load of the DS:

$$P_{1200} = 1200 \cdot \frac{1047.47}{29.97} \cdot \frac{2595.023}{1000.7} = 168087.11kPa$$

{Note: The Drip Shield and the Waste package are loaded with the load equivalent to 1200 kPa distributed load}

Kinematic Constraints: The Drip Shield displacement in the vertical direction (y-axis) is constrained by 4 SPRING1 elements of a relatively small stiffness to prevent numerical rigid

body modes. The side surfaces of the Drip Shield are constrained in transverse direction (z-axis) to represent symmetry. The Drip Shield ends are free in all directions (refer to Figure 5b) with a constraint in the horizontal direction (x-axis) in the middle of the DS.

The Waste Package components are constrained along the line of symmetry in the vertical axial plane to prevent displacement in the horizontal direction. The displacement in the vertical direction is constrained by 4 SPRING1 elements of a relatively small stiffness on the both Waste Package Shells. Also, the side surface that represents the middle of the Waste Package is constrained from the displacement in the transverse direction to simulate symmetry conditions.

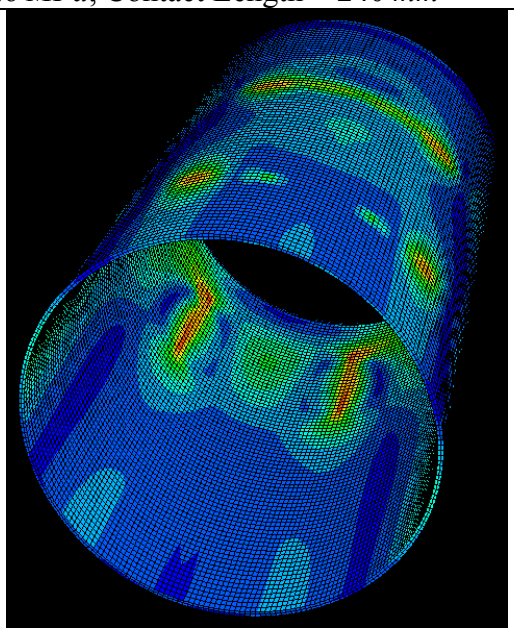
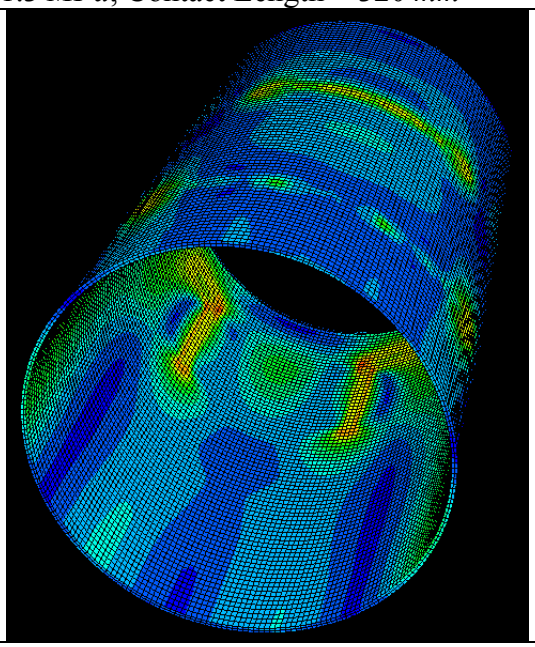
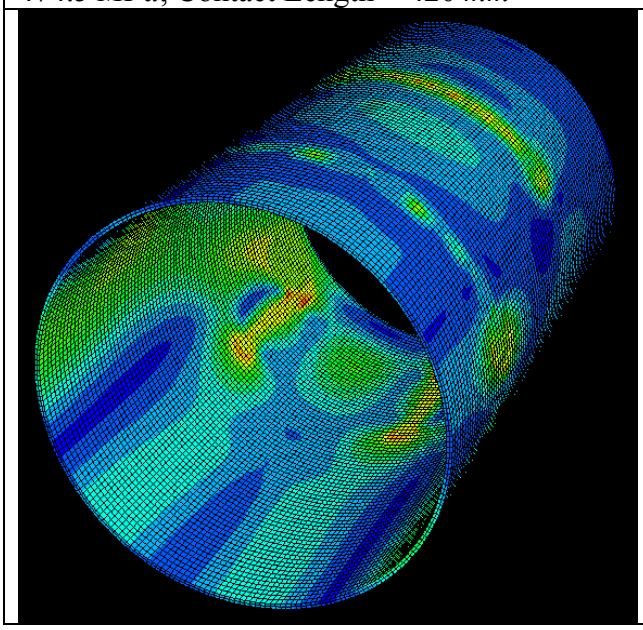
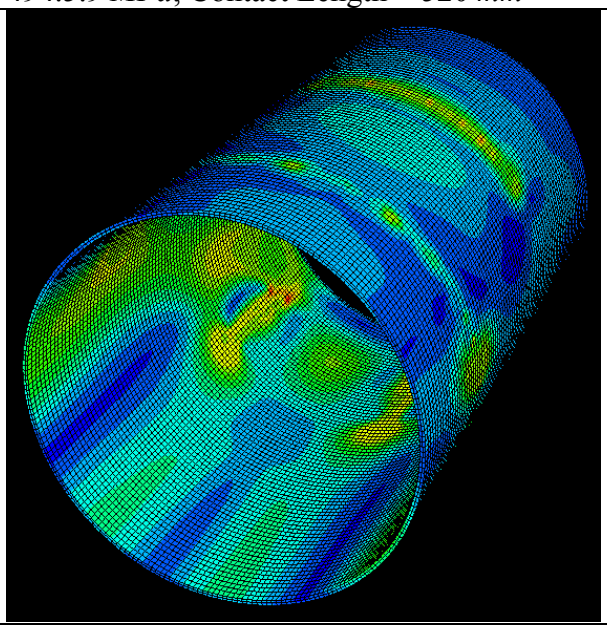
Regarding the Emplacement Pallet, each node of the bottom surface is constrained from the displacement in the horizontal and vertical directions. Also, the end nodes of the Emplacement Pallet are constrained from the displacement in the transverse direction.

There two coordinate systems are used to insure correct symmetry conditions: one for the Drip Shield and the other one for the Waste Package and the Emplacement Pallet.

A friction coefficient of 0.4 is used to model friction surface interaction between the Drip Shield and the Waste Package Outer Shell, between the Waste Package Outer Shell and Inner Vessel, and between the Waste Package Outer Shell and the Emplacement Pallet.

Date: February 28, 2006
Entry by: Roman V. Kazban
<u>Results for of the "1/2 Waste Package" FEM</u> (File: on Isis D:\DS\DSonWP_15HWP)

Table 8. Von Mises Stress distribution for the Outer Shell.

Step 1 – 300 *kPa*: Max Von Mises Stress = 428.6 *MPa*, Contact Length = 240 *mm*	Step 2 – 600 *kPa*: Max Von Mises Stress = 451.3 *MPa*, Contact Length = 320 *mm*
	
Step 3 – 900 *kPa*: Max Von Mises Stress = 474.5 *MPa*, Contact Length = 420 *mm*	Step 4 – 1200 *kPa*: Max Von Mises Stress = 494.5.9 *MPa*, Contact Length = 520 *mm*
	

{Note: The contact length was estimated by using a stress criteria, assuming that the contact is achieved if the Von Mises stress in the outer shell of the waste package exceeds the yield stress of Alloy 22. Also, the estimation was performed using contour plotting options.}

Date: February 28, 2006
Entry by: Roman V. Kazban

<u>Revision 1 to the "1/2 Waste Package" FEM</u>

Loads: The Drip Shield and the Waste package are loaded with the load equivalent to 6000 *kPa* distributed load.

In order to reproduce correct loading conditions on the Shell Plate elements due to its reduced dimension, the distributed pressure is increased by the ratio of the original width to the chosen dimension (r = 1047.47/38.1).

$$P'_{6000} = \frac{1047.47}{38.1} \cdot 6000kPa = 164955.91kPa = 164955.91 \times 10^{-3}\ N/mm^2$$

For the WP Outer Shell the length of 1 element is 20.014 *mm* and the width of 1 element is 29.97 *mm*. 50 elements are loaded to reproduce the contact length of 1000 mm, which results in a contact length of 1000.7 *mm*. The length of the applied pressure area of the DS Shell Plate is 2595.023 *mm*.

For the 6000 *kPa* load of the DS:

$$P_{6000} = 6000kPa \cdot \frac{1618.835}{29.97} \cdot \frac{2595.023}{1000.7} = 840435.53kPa$$

{Note: No additional changes were made to the model}

Date: March 6, 2006
Entry by: Roman V. Kazban

The computational analysis of the "1/2 Waste Package" Revision 1 FEM was terminated due to insufficient run time.

Date: March 6, 2006
Entry by: Roman V. Kazban

<u>Description and Geometry of the "1/4 Waste Package" FEM</u>
The finite element model is composed of the following (refer to Figure 12):

(i) Drip Shield;
- (a) Titanium Grade 24 Bulkhead Web;
- (b) Titanium Grade 24 Bulkhead Flanges;
- (c) Titanium Grade 24 Longitudinal Stiffeners;
- (d) Titanium Grade 7 Shell Plate;

(ii) Waste Package;
- (a) Alloy 22 Outer Shell;
- (b) 316 Stainless Steel Inner Vessel;

(iii) Emplacement Pallet is represented by the Alloy 22 Pallet Plates.

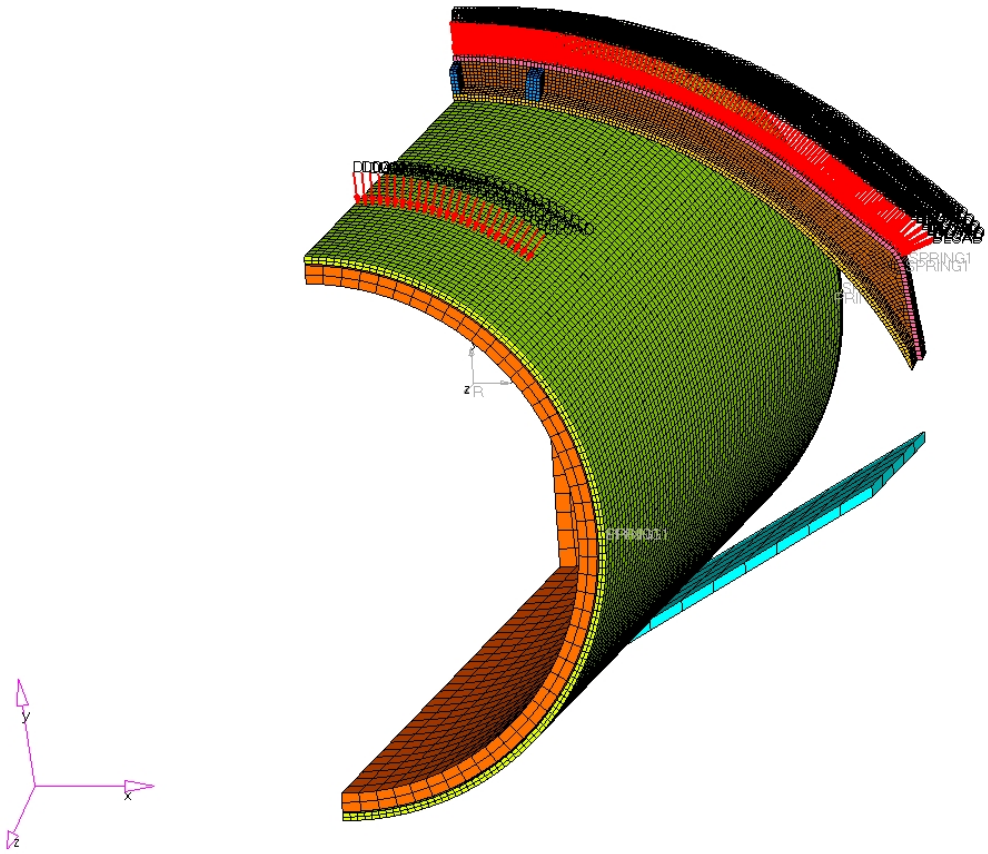


Figure 12.

The Drip Shield is inclined with 15 degree angle with respect to the Waste Package and the Emplacement Pallet to reproduce the baseline loading conditions. The finite element model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8) or 6-node linear tetrahedral elements (C3D6): the Bulkhead Web; the Bulkhead Flanges; the Longitudinal Stiffeners; the Outer Shell; the 316 Stainless Steel Inner Vessel. The Outer Shell Lid and the Inner Vessel Lid are discretized with 8-node continuum elements with reduced integration (C3D8R). A small number of C3D6 is used in the model; and the use of such elements is limited to the Bulkhead Web component. The Shell Plate and the Pallet Plates are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Drip Shield C3D6 and C3D8 elements is 10x10x10 *mm* and 10x10x15 mm for SC8R elements of the Drip Shield Shell Plate. A typical size of the Waste Package Outer Shell C3D8 elements is 30x20x10 *mm*. A typical size of the Waste Package Inner Vessel C3D8 elements is 75x50x25 *mm*. A typical size of the Emplacement Pallet Plates SC8R elements is 110x100x30 *mm*. In addition, the common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

To limit the number of elements in the finite element model, the width of the Shell Plate is set to 38.1 *mm*. In order to reproduce a correct stiffness of the Shell Plate due to its reduced dimension, the modulus of elasticity for the Shell Plate elements is increased by the ratio of the equivalent width to the chosen dimension (r = 230/38.1).

$$E' = \frac{230}{38.1} \cdot E_{Ti-7} = 607900.26 \, {}^{N}\!/_{mm^2}$$

Only a quarter of the WP is used in construction of this FEM (refer to Figure 7 for WP dimensions).

Loads: The Drip Shield and the Waste package are loaded with the load equivalent to 6000 *kPa* distributed load.

In order to reproduce correct loading conditions on the Shell Plate elements due to its reduced dimension, the distributed pressure is increased by the ratio of the original width to the chosen dimension (r = 1047.47/38.1).

$$P'_{6000} = \frac{1047.47}{38.1} \cdot 6000kPa = 164955.91kPa = 164955.91 \times 10^{-3} \, {}^{N}\!/_{mm^2}$$

For the WP Outer Shell the length of 1 element is 20.014 *mm* and the width of 1 element is 29.97 *mm*. 25 elements are loaded to reproduce the contact length of 1000 mm, which results in a contact length of 1000.7 *mm*. The length of the applied pressure area of the DS Shell Plate is 2595.023 *mm*.

For the 6000 *kPa* load of the DS:

$$P_{6000} = 6000kPa \cdot \frac{1047.47}{29.97} \cdot \frac{2595.023}{1000.7} = 543805.27kPa$$

Kinematic Constraints: The Drip Shield displacement in the vertical direction (y-axis) is constrained by 2 SPRING1 elements of a relatively small stiffness to prevent numerical rigid body modes. The side surfaces of the Drip Shield are constrained in the transverse direction (z-axis) to represent symmetry. The Drip Shield ends are free in all directions (refer to Figure 5b) with a constraints in YZ plane from the horizontal displacement (x-axis) in the middle of the DS to simulate symmetry conditions.

The displacement of the Waste Package in the vertical direction (y-axis) is constrained by 2 SPRING1 elements of a relatively small stiffness on both Waste Package Shells to prevent rigid body modes. The end nodes of the Outer Shell and Inner Vessel that are located in the middle of the Waste Package along the YZ plane are constrained from the displacement in the horizontal direction to represent symmetry conditions. Also, the side surface in the lateral plane that represents the middle of the Waste Package is constrained from displacement in the transverse direction to simulate symmetry conditions.

Regarding the Emplacement Pallet, each node of the bottom surface is constrained from the displacement in the horizontal and vertical directions. The end nodes in the XY plane of the Emplacement Pallet are constrained from the displacement in the transverse direction and the end nodes that represent the middle of the Emplacement Pallet are constrained in the horizontal direction to simulate symmetry conditions.

There two coordinate systems are used to insure correct symmetry conditions: one for the Drip Shield and the other one for the Waste Package and the Emplacement Pallet.

A friction coefficient of 0.4 is used to model friction surface interaction between the Drip Shield and the Waste Package Outer Shell, between the Waste Package Outer Shell and Inner Vessel, and between the Waste Package Outer Shell and the Emplacement Pallet.

Date: March 9, 2006
Entry by: Roman V. Kazban

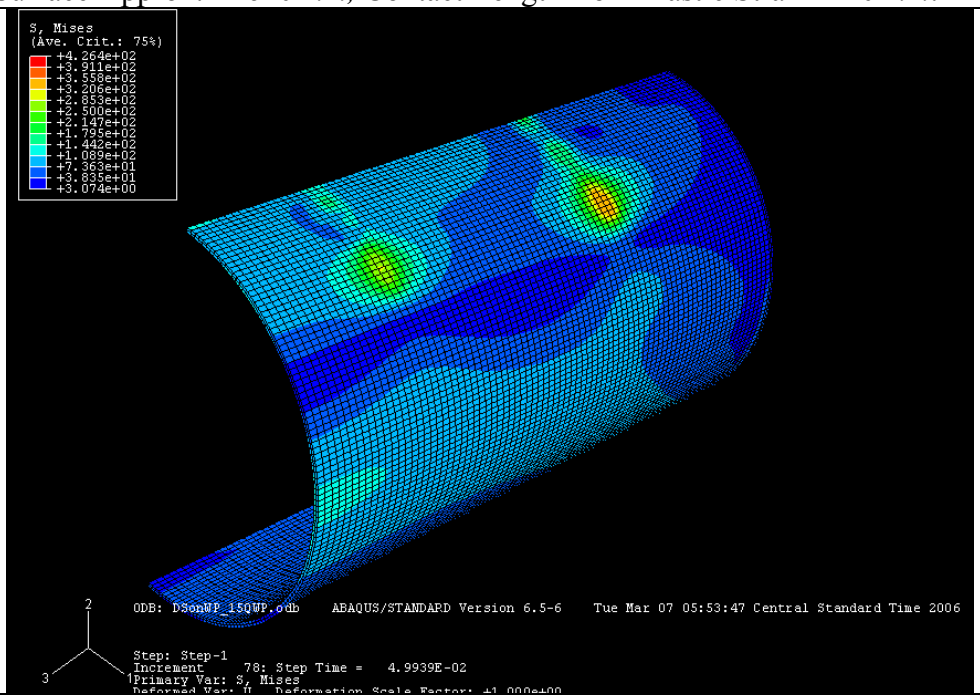
<u>Results for of the "1/4 Waste Package" FEM</u> (File: on Isis D:\DS\DSonWP_15QWP)

The computational analysis of the "1/4 Waste Package" FEM was terminated at 30% completion due to high residual forces.

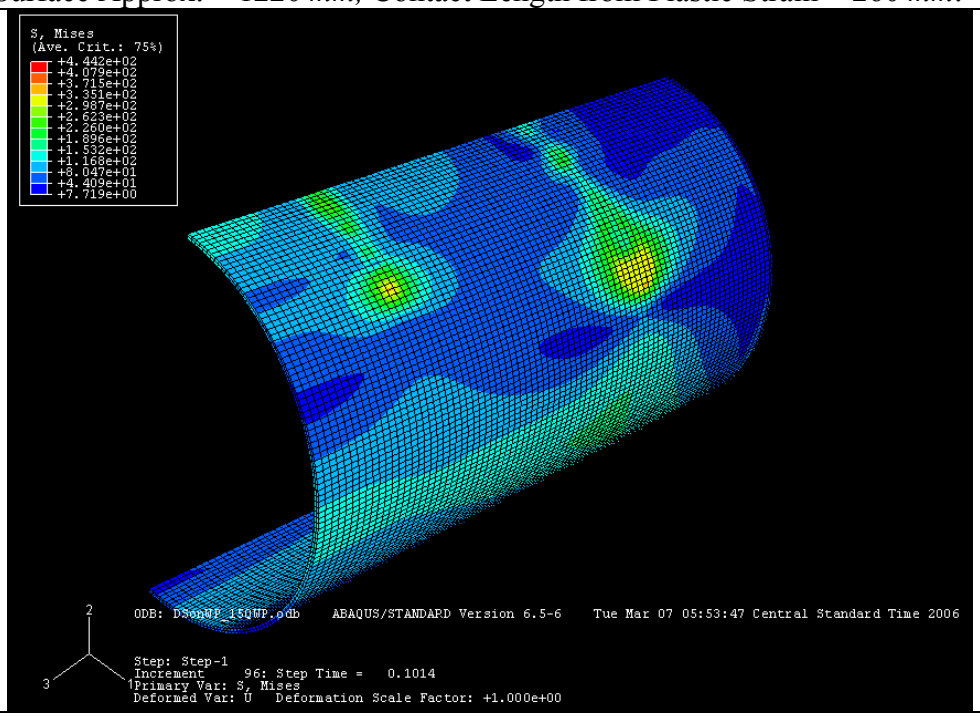
Table 9. Von Mises Stress distribution for the Outer Shell.

Step 1 – 300 *kPa*: Max Von Mises Stress = 426.4 *MPa*, Contact Length from

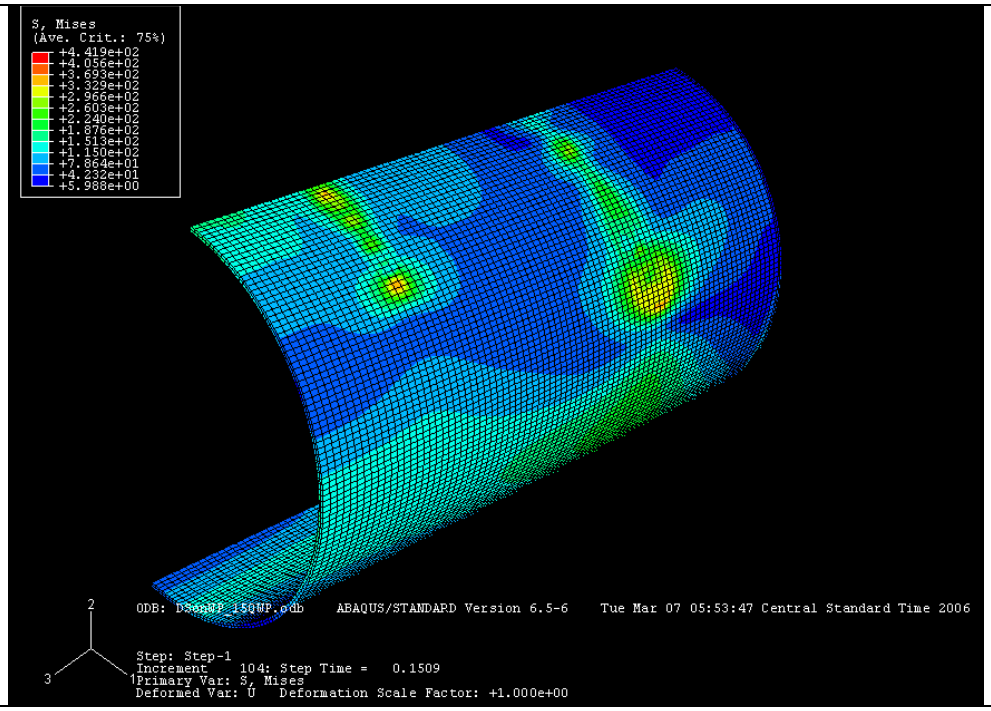
Surface Approx. = 640 *mm,* Contact Length from Plastic Strain = 40 *mm*.



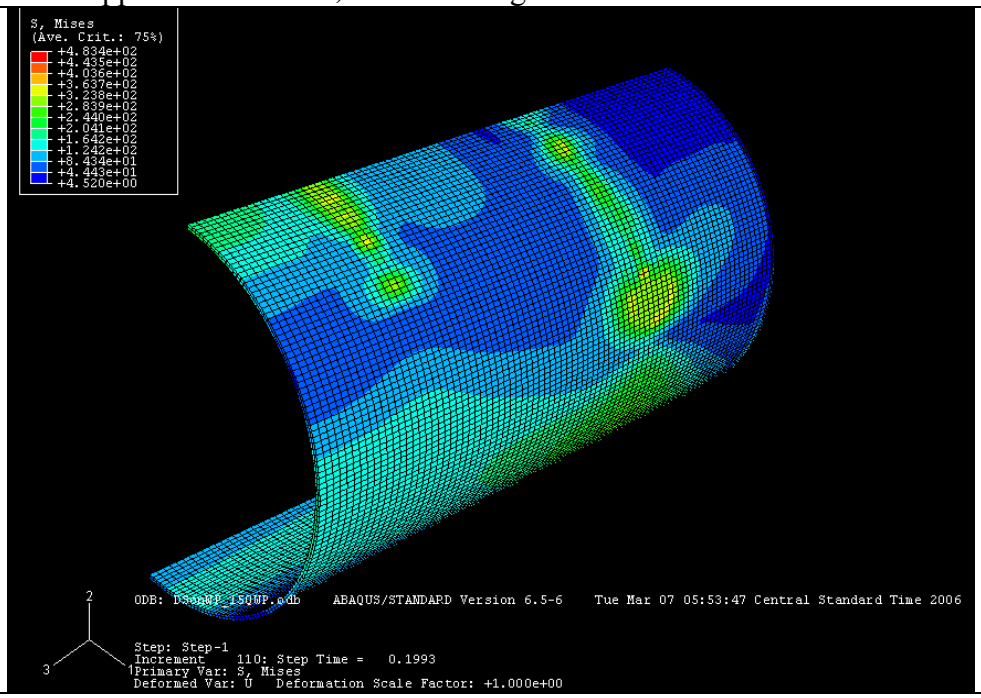
Step 2 – 600 *kPa*: Max Von Mises Stress = 444.2 *MPa*, Contact Length from Surface Approx. = 1220 *mm,* Contact Length from Plastic Strain = 260 *mm*.



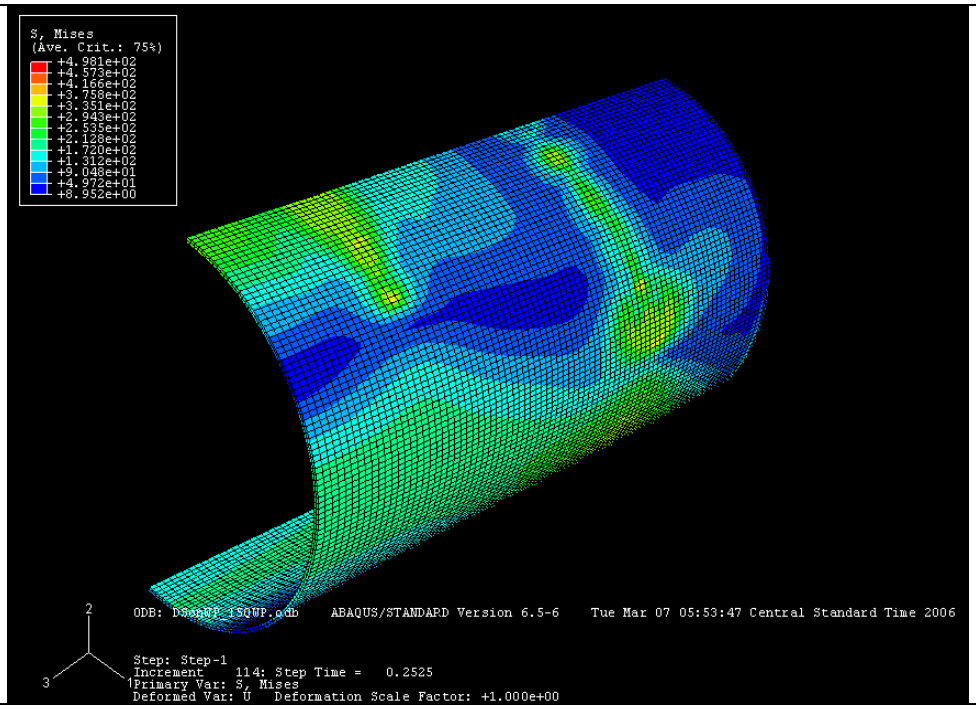
Step 3 – 900 *kPa*: Max Von Mises Stress = 441.9 *MPa*, Contact Length from Surface Approx. = 1460 *mm,* Contact Length from Plastic Strain = 380 *mm*.



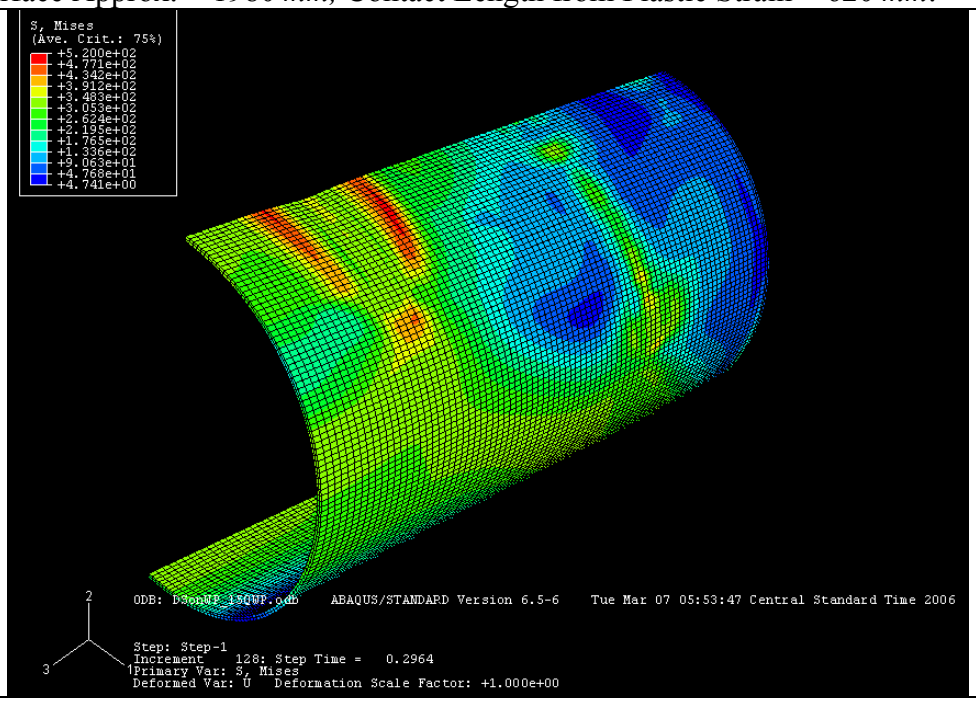
Step 4 – 1200 *kPa*: Max Von Mises Stress = 483.4 *MPa*, Contact Length from Surface Approx. = 1720 *mm,* Contact Length from Plastic Strain = 460 *mm*.



Step 5 – 1500 *kPa*: Max Von Mises Stress = 498.1 *MPa*, Contact Length from Surface Approx. = 1860 *mm,* Contact Length from Plastic Strain = 540 *mm*.



Step 6 – 1800 *kPa*: Max Von Mises Stress = 520.0 *MPa*, Contact Length from Surface Approx. = 1980 *mm,* Contact Length from Plastic Strain = 620 *mm*.

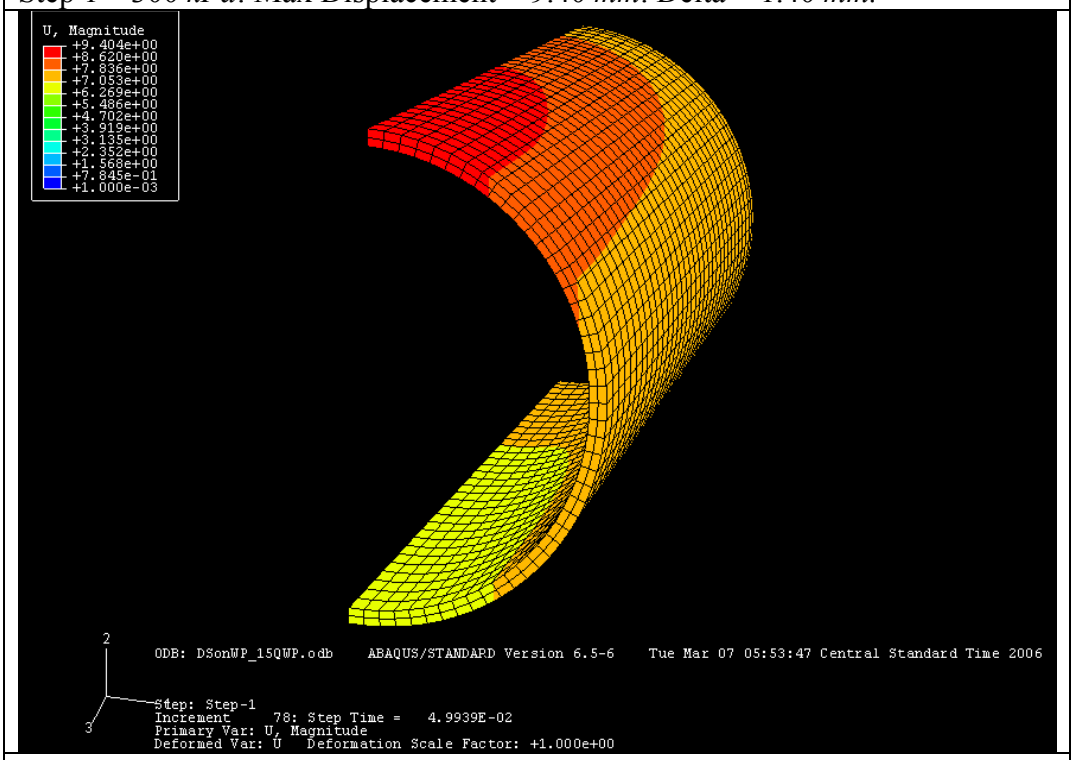


{Note: The estimation of the contact length using surface approximation criteria assumes that the contact is achieved if the surface of the DS and the outer surface of the waste package are within [-0.001 mm; 0.001mm] from each other. The estimation of the contact length using plastic

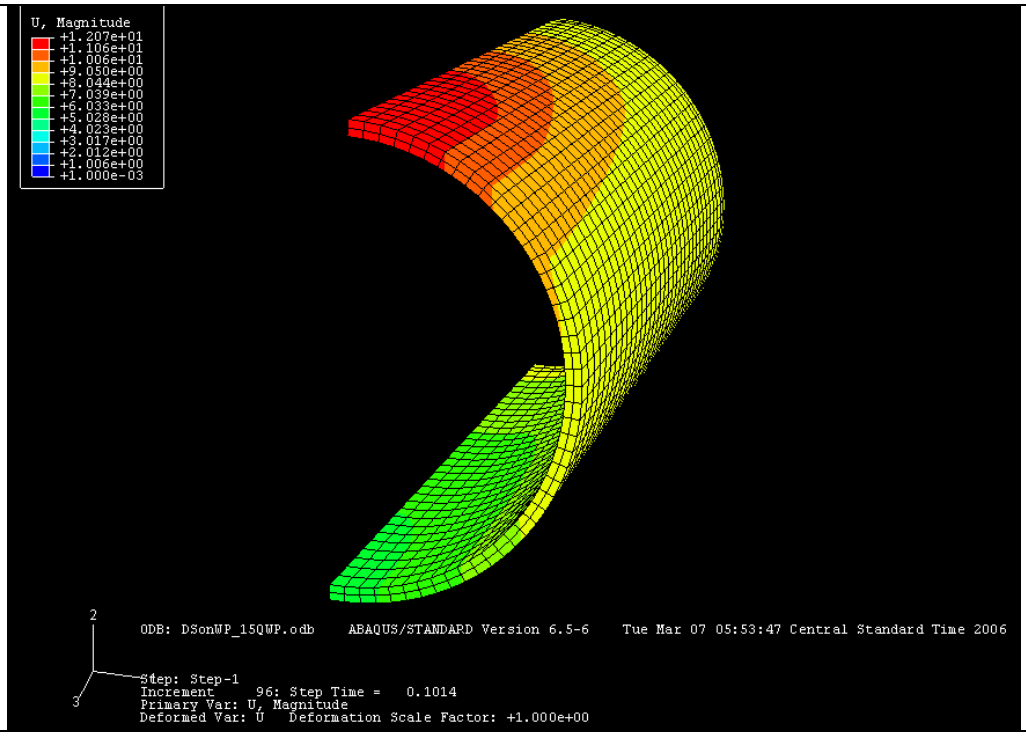
strain criteria assumes that the contact is achieved if the magnitude of the plastic strain in the outer shell of the waste package exceeds 0.1%. Also, the estimation was performed using contour plotting options.}

Table 10. Magnitude of the Displacement for the Inner Vessel.

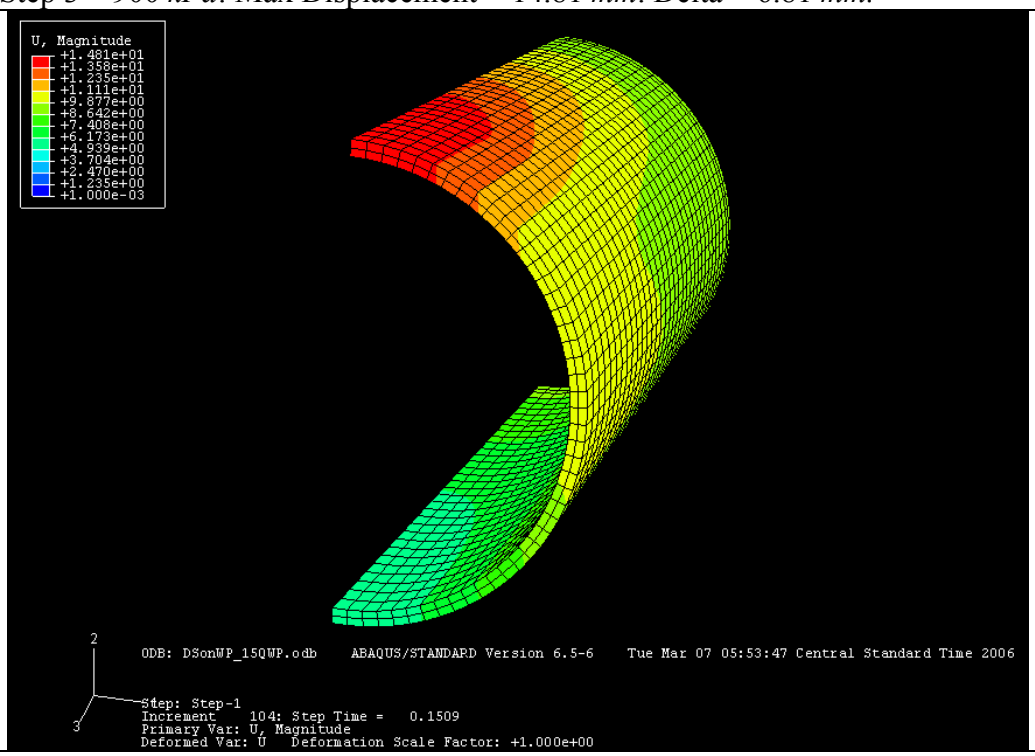
Step 1 – 300 *kPa*: Max Displacement = 9.40 *mm*. Delta = 1.40 *mm.*



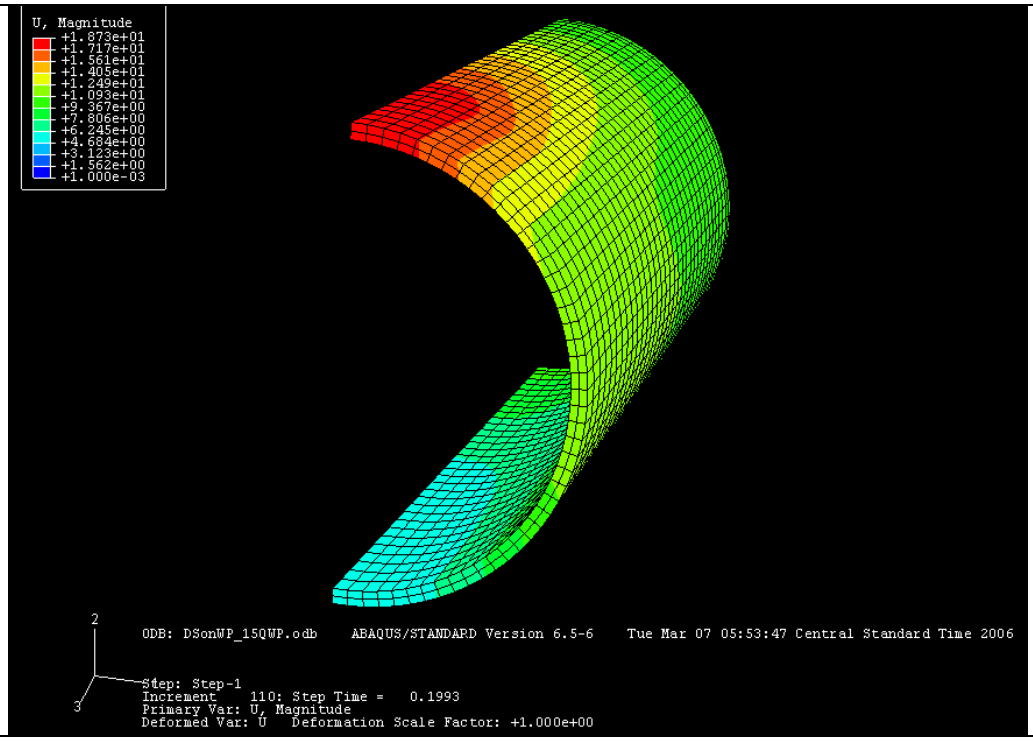
Step 2 – 600 *kPa*: Max Displacement = 12.07 *mm*. Delta = 4.07 *mm.*



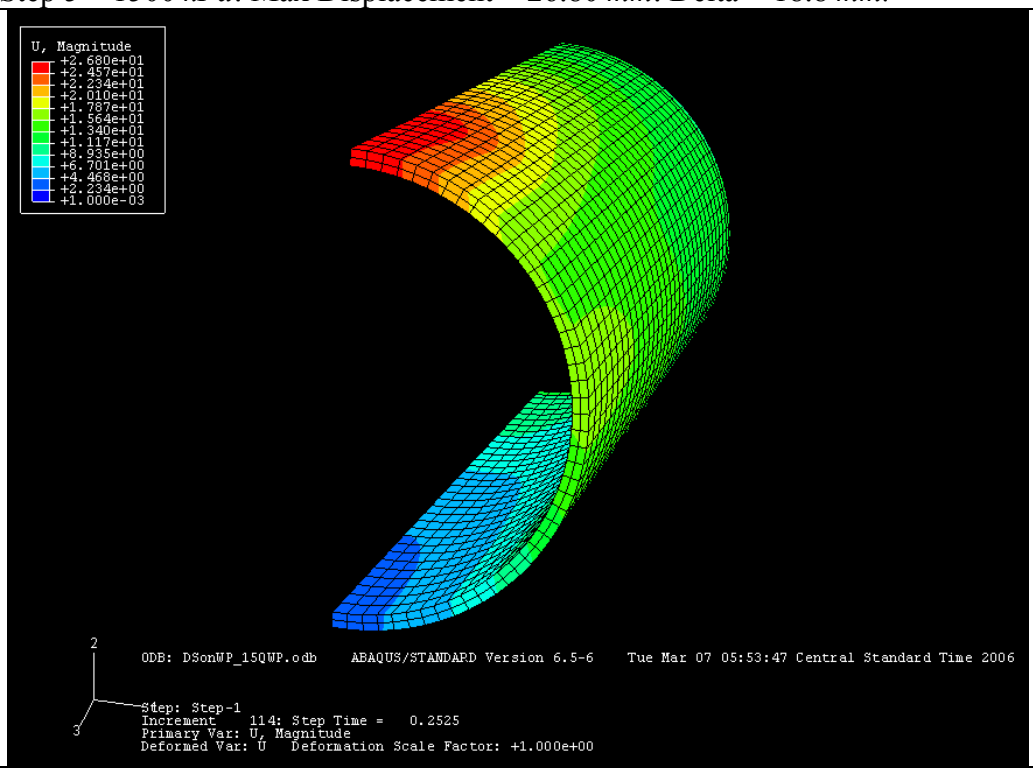
Step 3 – 900 *kPa*: Max Displacement = 14.81 *mm*. Delta = 6.81 *mm.*



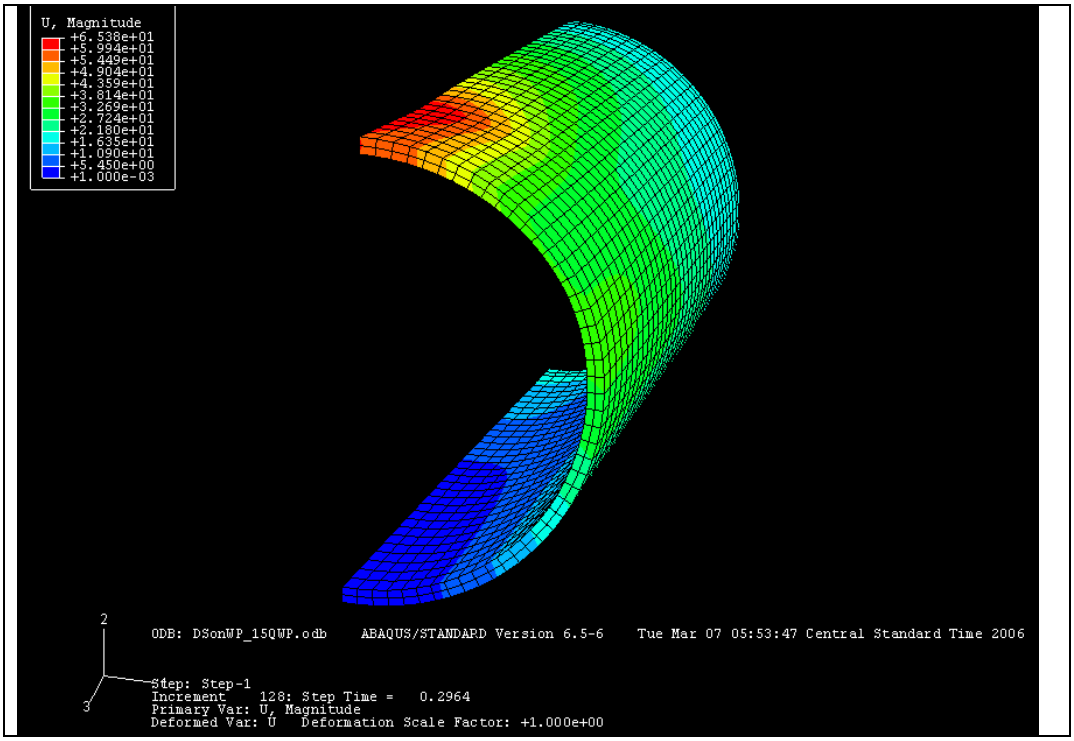
Step 4 – 1200 *kPa*: Max Displacement = 18.73 *mm*. Delta = 10.73 *mm.*



Step 5 – 1500 *kPa*: Max Displacement = 26.80 *mm*. Delta = 18.8 *mm*.



Step 6 – 1800 *kPa*: Max Displacement = 65.38 *mm*. Delta = 57.38 *mm*.



{Note: The maximum displacement occurs approximately in the middle of the waste package inner vessel.}

Date: March 9, 2006
Entry by: Roman V. Kazban

<u>Revision 1 to the "1/4 Waste Package" FEM</u>

Loads: The Drip Shield and the Waste package are loaded with the load equivalent to 6000 *kPa* distributed load.

In order to reproduce correct loading conditions on the Shell Plate elements due to its reduced dimension, the distributed pressure is increased by the ratio of the original width to the chosen dimension (r = 1047.47/38.1).

$$P'_{6000} = \frac{1047.47}{38.1} \cdot 6000kPa = 164955.91kPa = 164955.91 \times 10^{-3}\ N/mm^2$$

For the WP Outer Shell the length of 1 element is 20.014 *mm* and the width of 1 element is 29.97 *mm*. 250 elements are loaded (25 elements long in circumferential direction and 5 elements think in longitudinal direction, refer to Figure 13) to reproduce the contact length of 1000 mm and the 138.1 *mm* width of the DS, which results in a contact length of 1000.7 *mm* and a width of 149.85 *mm*. The length of the applied pressure area of the DS Shell Plate is 2595.023 *mm*.

For the 6000 *kPa* load of the DS:

$$P_{6000} = 6000kPa \cdot \frac{1047.47}{149.85} \cdot \frac{2595.023}{1000.7} = 108761.05kPa$$

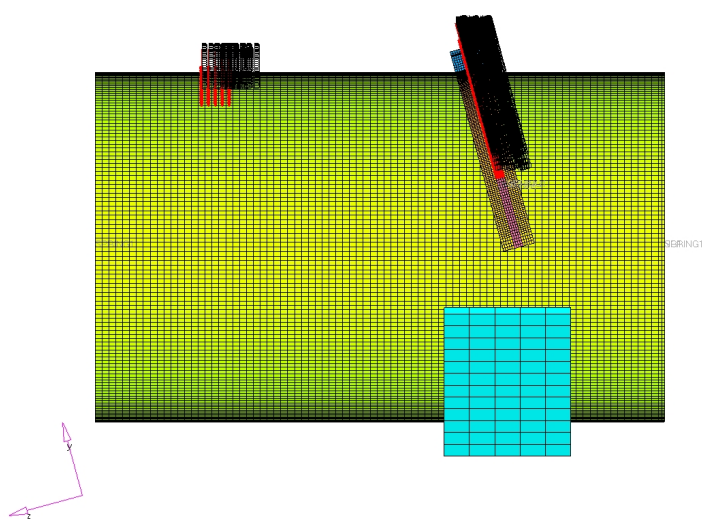


Figure 13.

{Note: No additional changes were made to the model}

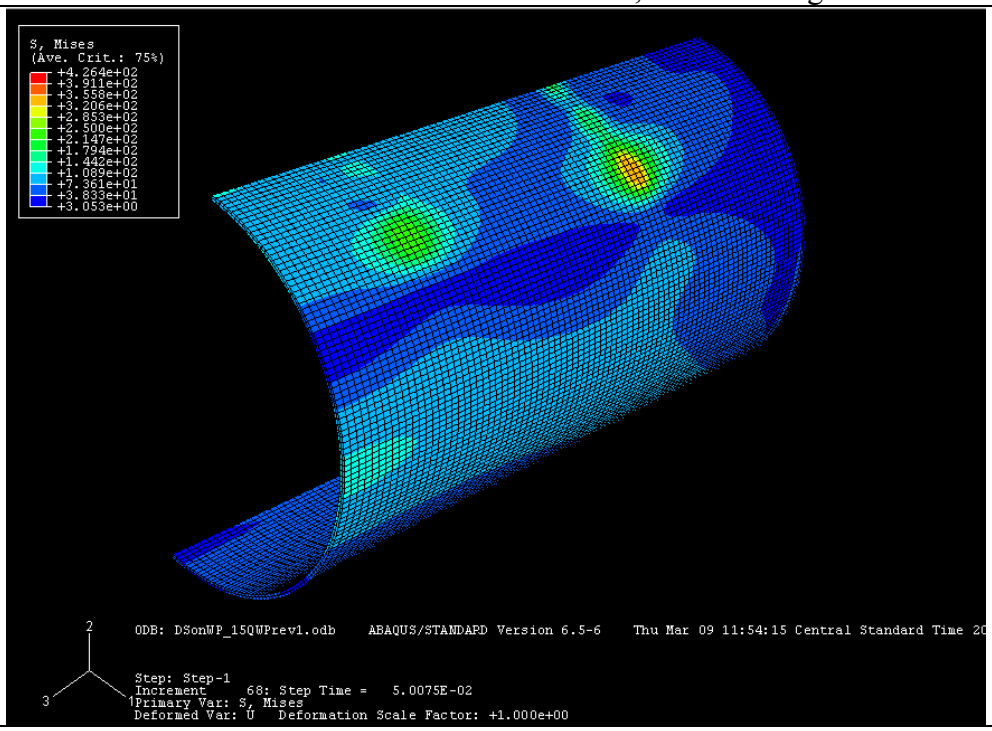
Date: March 13, 2006
Entry by: Roman V. Kazban

<u>Results for of the "1/4 Waste Package Rev. 1" FEM</u> (File: D:\DS\DSonWP_15QWPrev1)

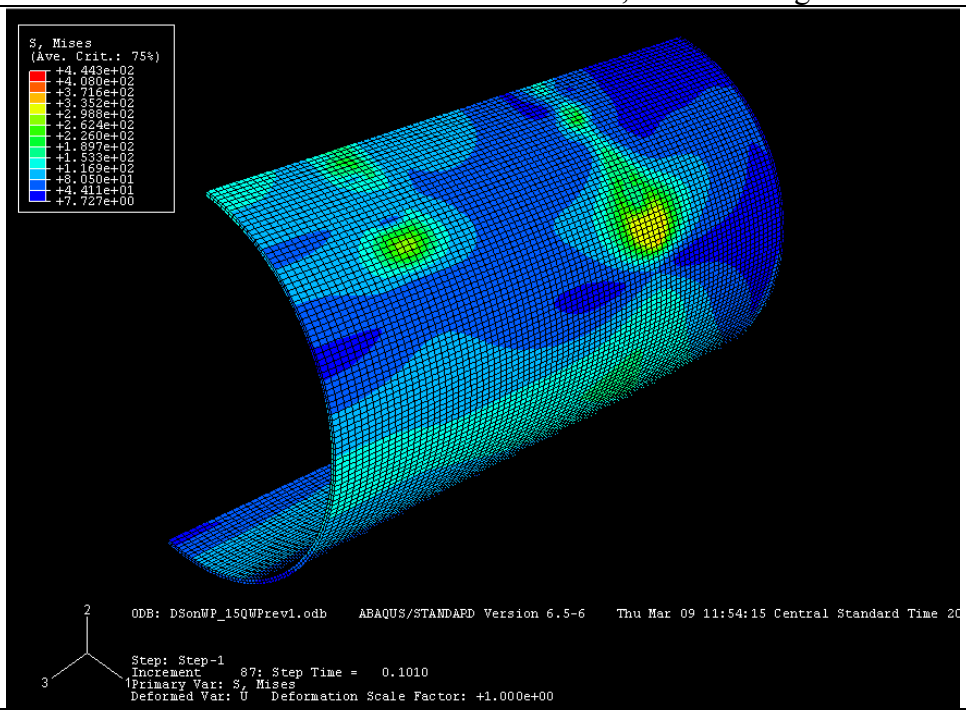
The computational analysis of the "1/4 Waste Package" FEM was terminated at 30% completion due to high residual forces.

{Note: The contact length was estimated by using a stress criteria, assuming that the contact is achieved if the Von Mises stress in the outer shell of the waste package exceeds the yield stress of Alloy 22. Also, the estimation was performed using contour plotting options.}

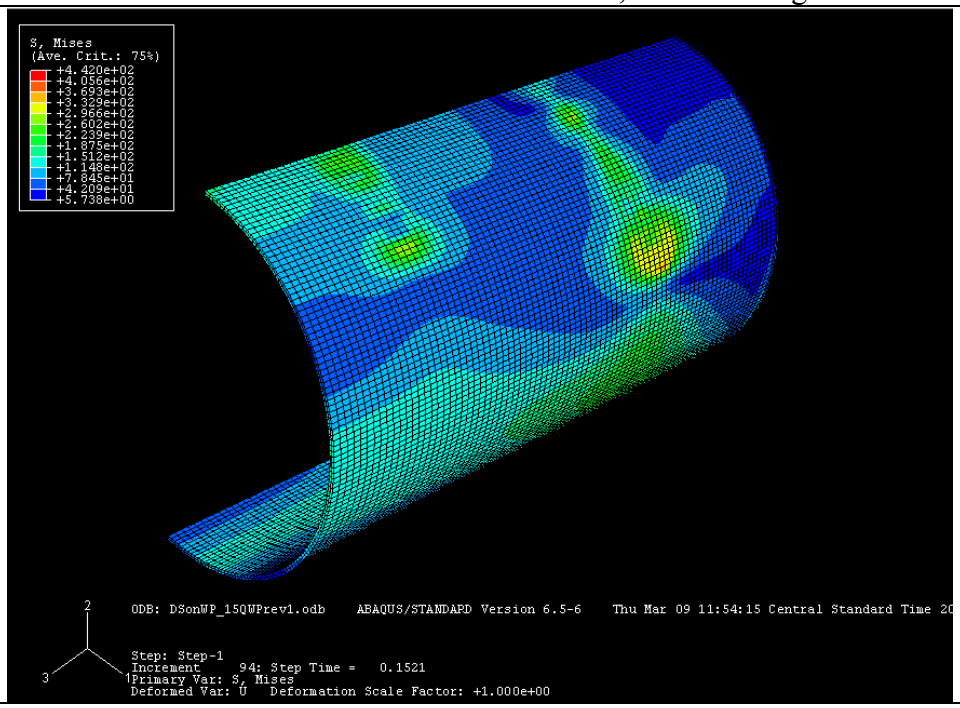
Table 11. Von Mises Stress distribution for the Outer Shell.

Step 1 – 300 *kPa*: Max Von Mises Stress = 426.4 *MPa*, Contact Length = 280 *mm*


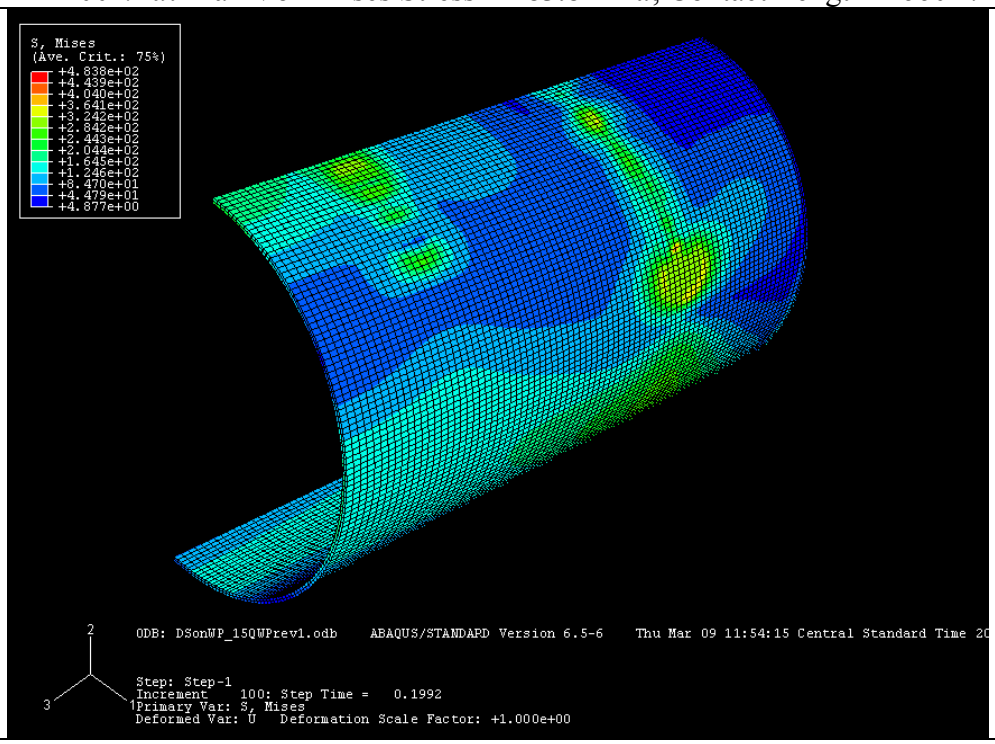
Step 2 – 600 *kPa*: Max Von Mises Stress = 444.3 *MPa*, Contact Length = 340 *mm*.



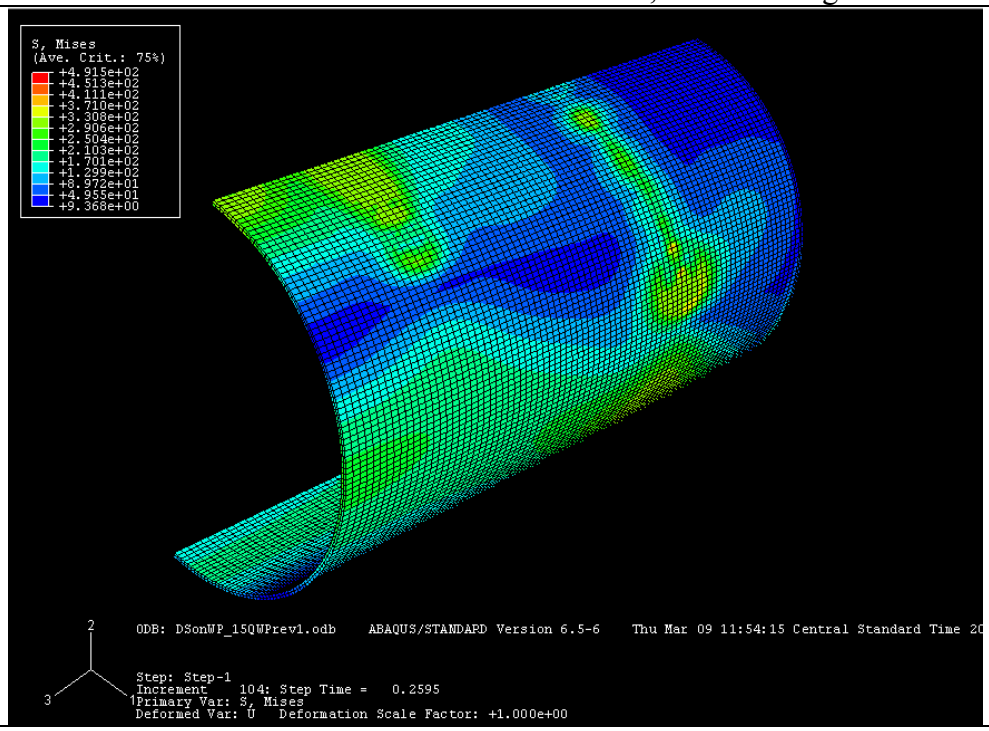
Step 3 – 900 *kPa*: Max Von Mises Stress = 442.0 *MPa*, Contact Length = 380 *mm*.



Step 4 – 1200 *kPa*: Max Von Mises Stress = 483.8 *MPa*, Contact Length = 660 *mm*.



Step 5 – 1500 *kPa*: Max Von Mises Stress = 491.5 *MPa*, Contact Length = 740 *mm*.



Step 6 – 1800 *kPa*: Max Von Mises Stress = 517.4 *MPa*, Contact Length = 1120 *mm*.

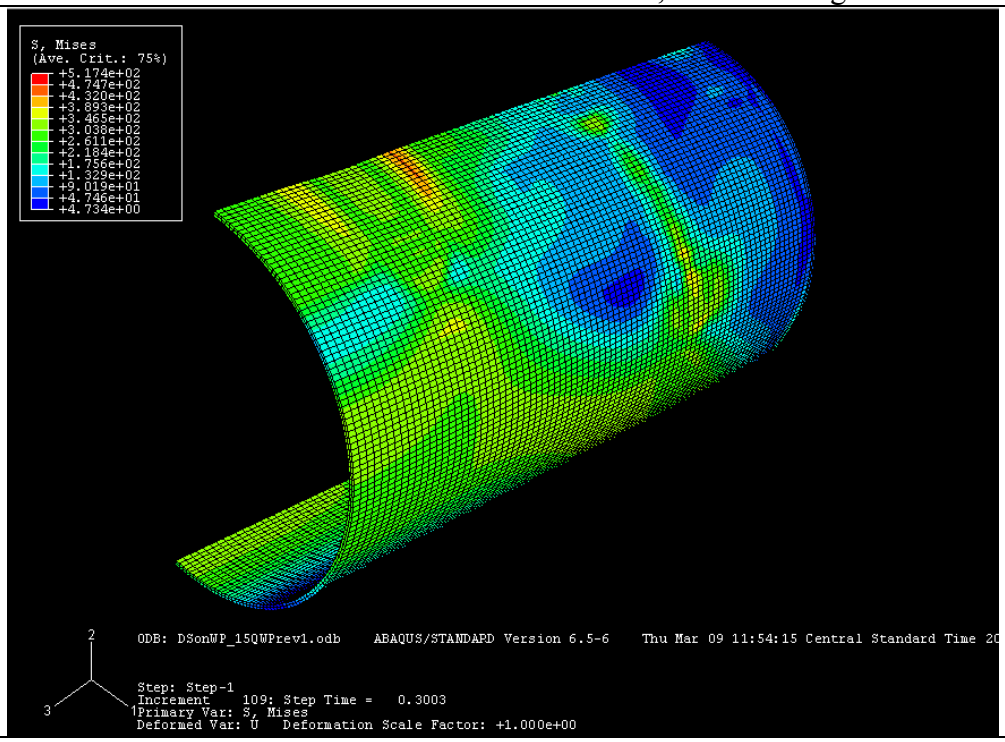
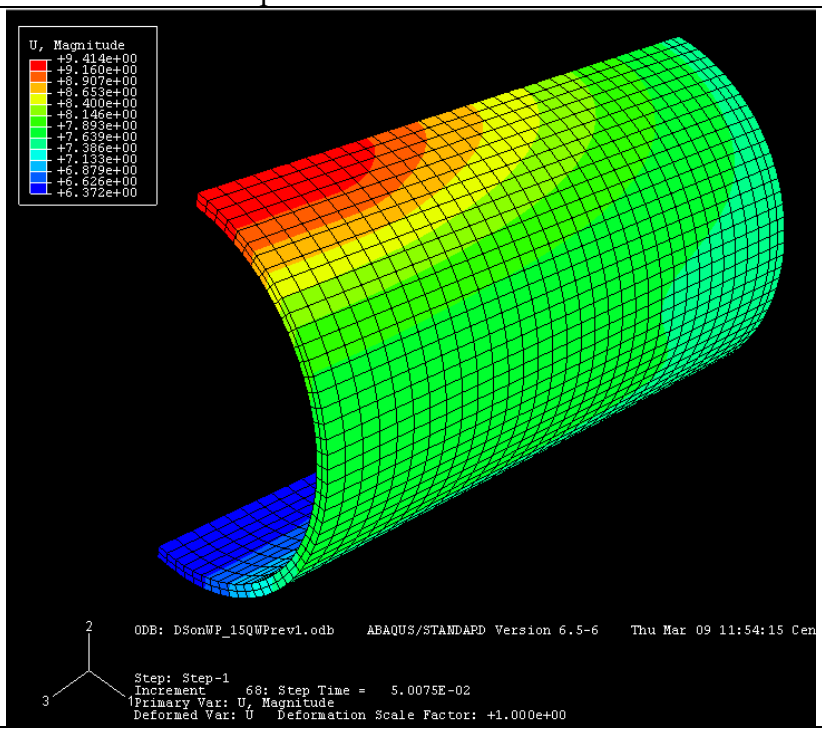
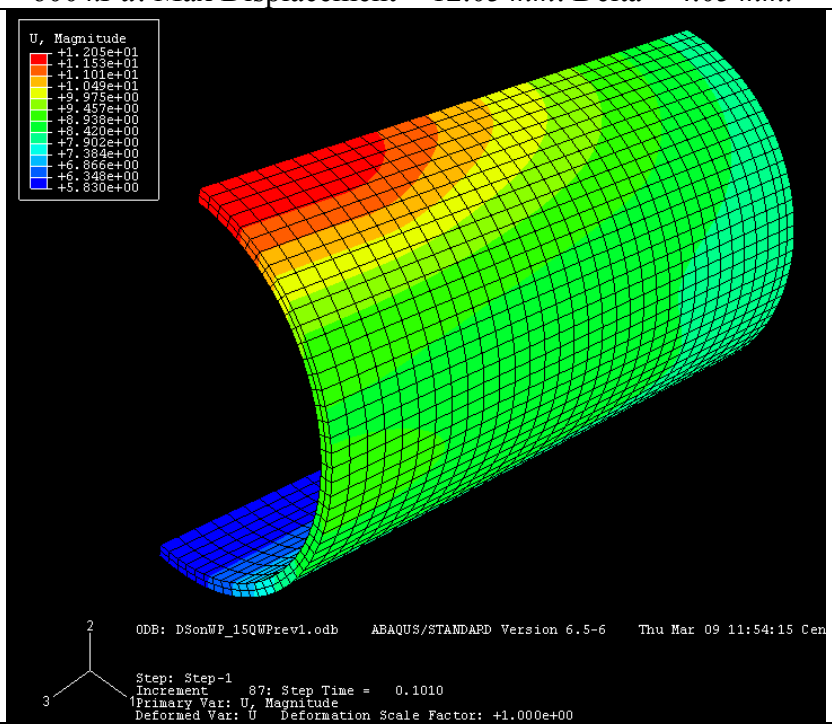


Table 12. Magnitude of the Displacement for the Inner Vessel.

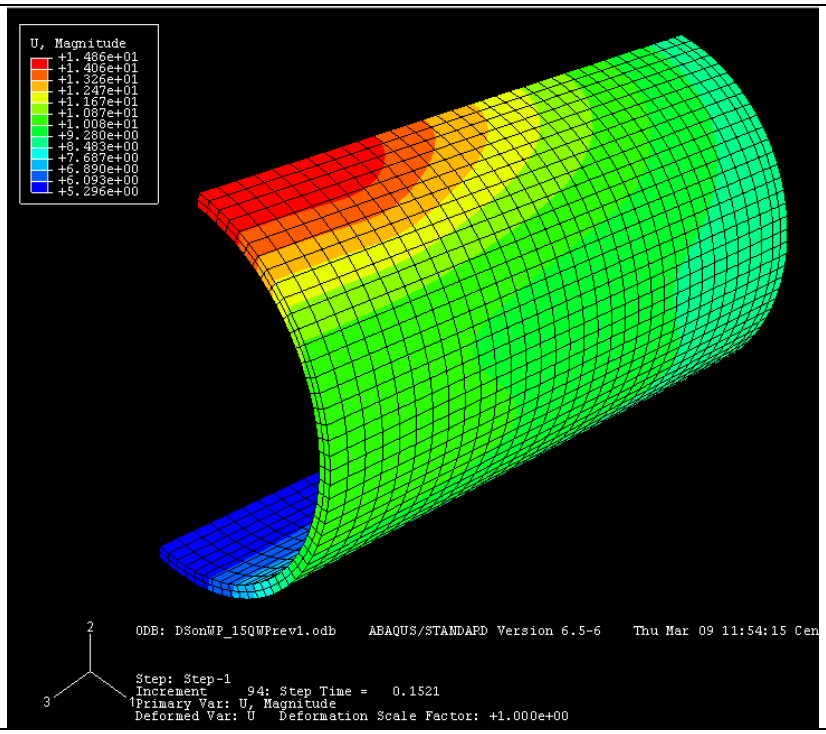
Step 1 – 300 *kPa*: Max Displacement = 9.41 *mm*. Delta = 1.41 *mm.*



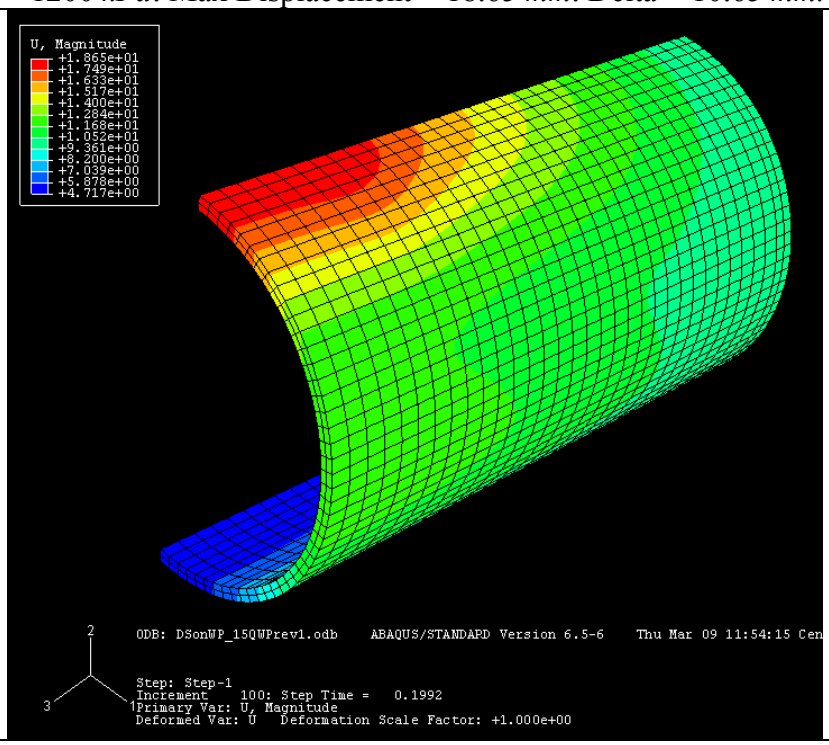
Step 2 – 600 *kPa*: Max Displacement = 12.05 *mm*. Delta = 4.05 *mm.*



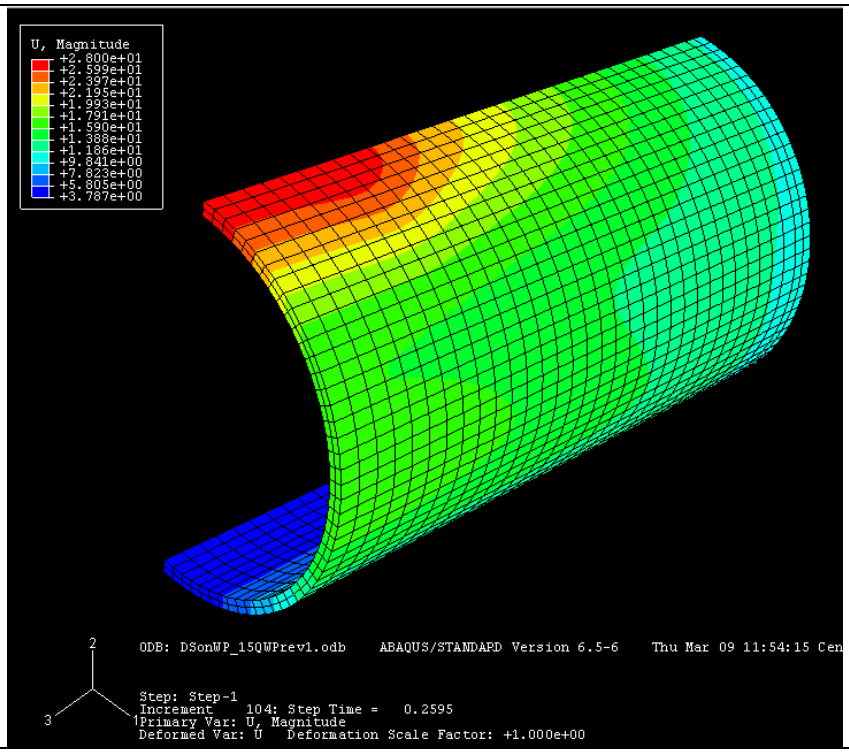
Step 3 – 900 *kPa*: Max Displacement = 14.86 *mm*. Delta = 6.86 *mm.*



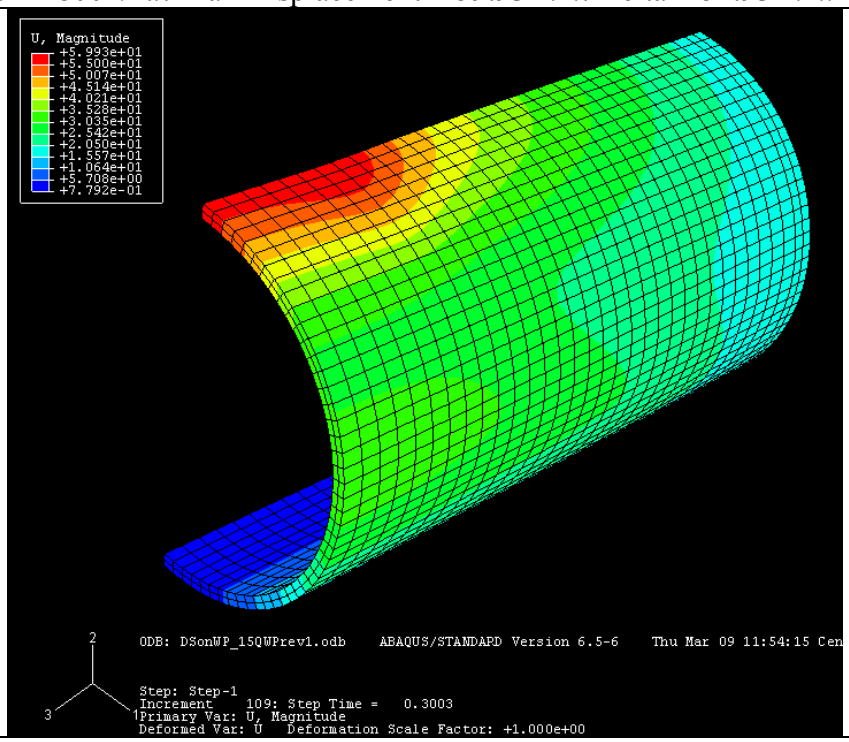
Step 4 – 1200 *kPa*: Max Displacement = 18.65 *mm*. Delta = 10.65 *mm.*



Step 5 – 1500 *kPa*: Max Displacement = 28.0 *mm*. Delta = 20.0 *mm.*



Step 6 – 1800 *kPa*: Max Displacement = 59.93 *mm*. Delta = 51.93 *mm.*



{Note: The maximum displacement occurs approximately in the middle of the waste package inner vessel.}

Date: March 14, 2006
Entry by: Roman V. Kazban

Revision 2 to the "1/4 Waste Package" FEM

Kinematic Constraints: The Drip Shield displacement in the vertical direction (y-axis) is constrained by 2 SPRING1 elements of a relatively small stiffness to prevent numerical rigid body modes. The side surfaces of the Drip Shield are constrained in the transverse direction (z-axis) to represent symmetry. The Drip Shield end are constrained from the displacement in the horizontal direction (refer to Figure 5a). Also, the Drip Shield is constrained in YZ plane from the horizontal displacement in the middle of the DS to simulate symmetry conditions.

{Note: No additional changes were made to the model}

Date: March 16, 2006
Entry by: Roman V. Kazban

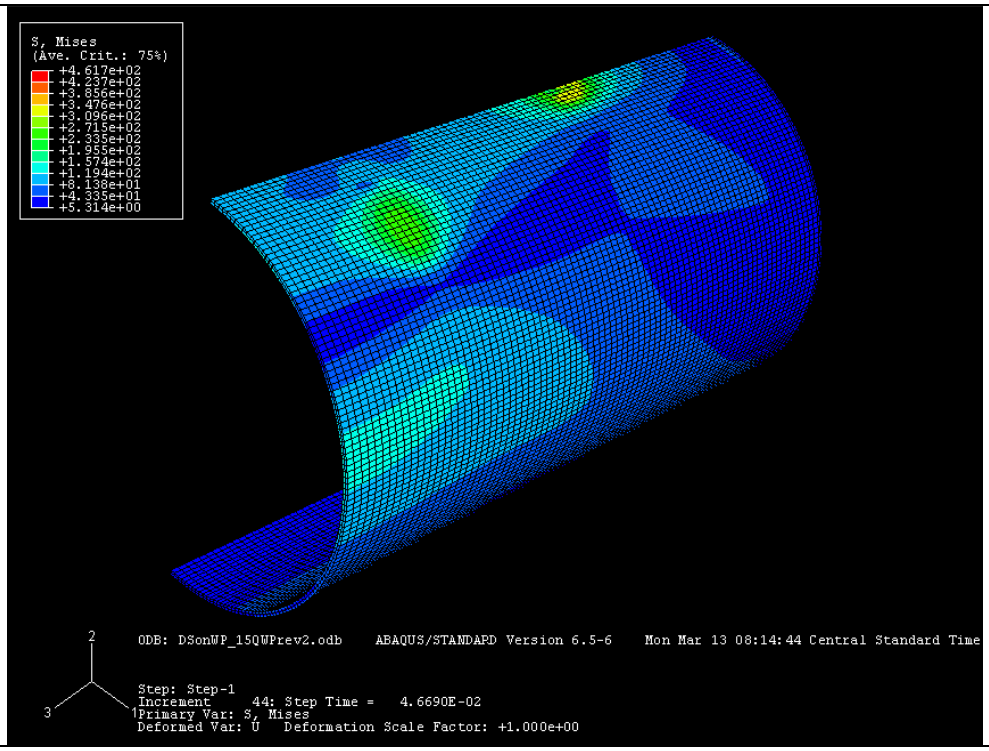
Results for of the "1/4 Waste Package Rev. 2" FEM (File: D:\DS\DSonWP_15QWPrev2)

The computational analysis of the "1/4 Waste Package" FEM was terminated at 25% completion due to high residual forces.

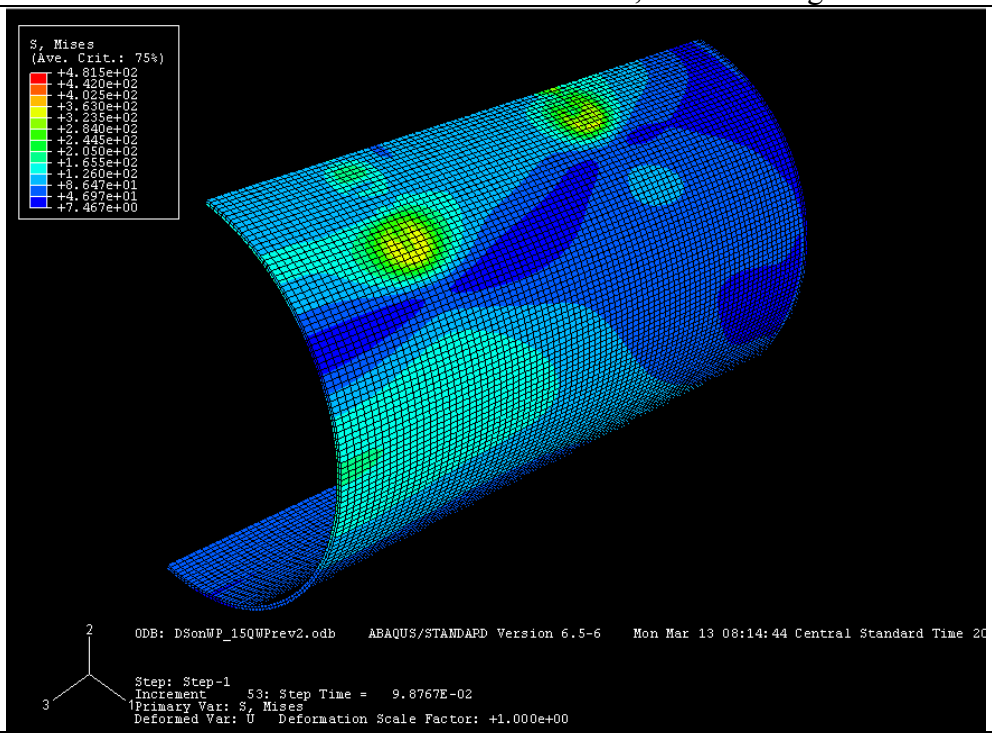
{Note: The contact length was estimated by using a stress criteria, assuming that the contact is achieved if the Von Mises stress in the outer shell of the waste package exceeds the yield stress of Alloy 22. Also, the estimation was performed using contour plotting options.}

Table 13. Von Mises Stress distribution for the Outer Shell.

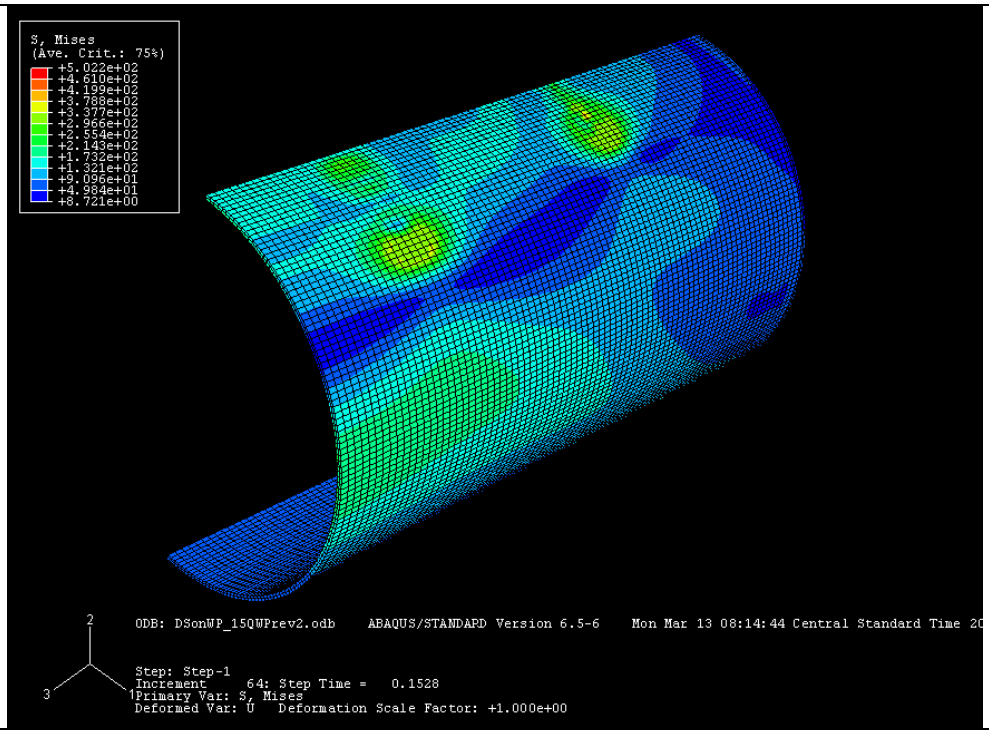
Step 1 – 300 *kPa*: Max Von Mises Stress = 461.7 *MPa*, Contact Length = 200 *mm*



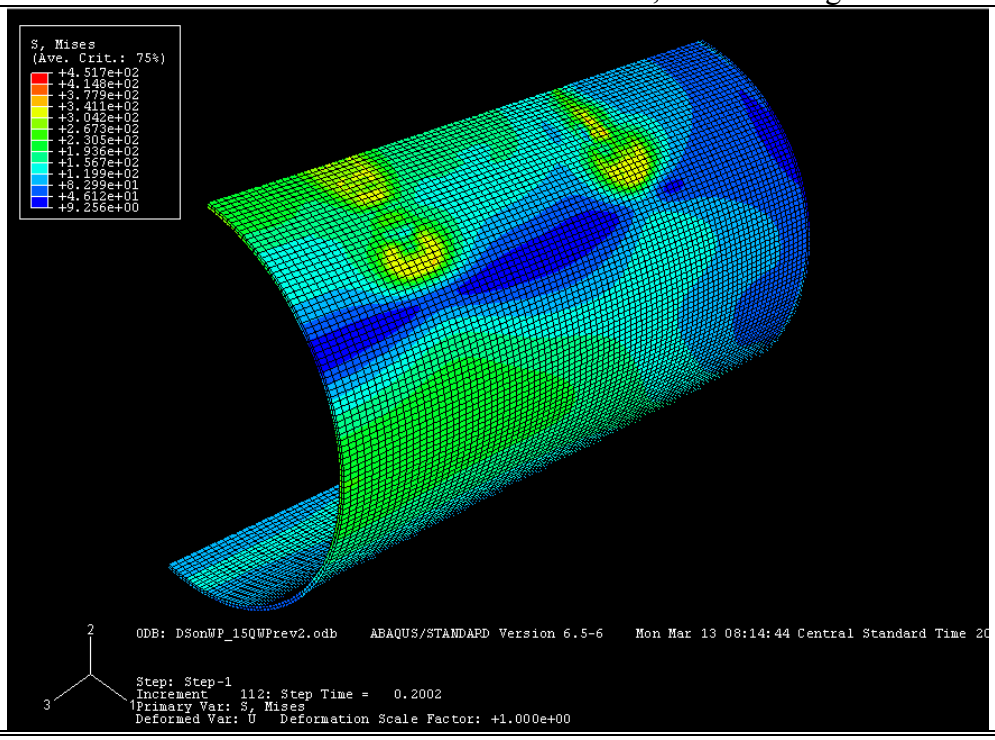
Step 2 – 600 *kPa*: Max Von Mises Stress = 481.5 *MPa*, Contact Length = 340 *mm*.



Step 3 – 900 *kPa*: Max Von Mises Stress = 502.2 *MPa*, Contact Length = 500 *mm*.



Step 4 – 1200 *kPa*: Max Von Mises Stress = 451.7 *MPa*, Contact Length = 680 *mm*.



Step 5 – 1500 *kPa*: Max Von Mises Stress = 505.7 *MPa*, Contact Length = 840 *mm*.

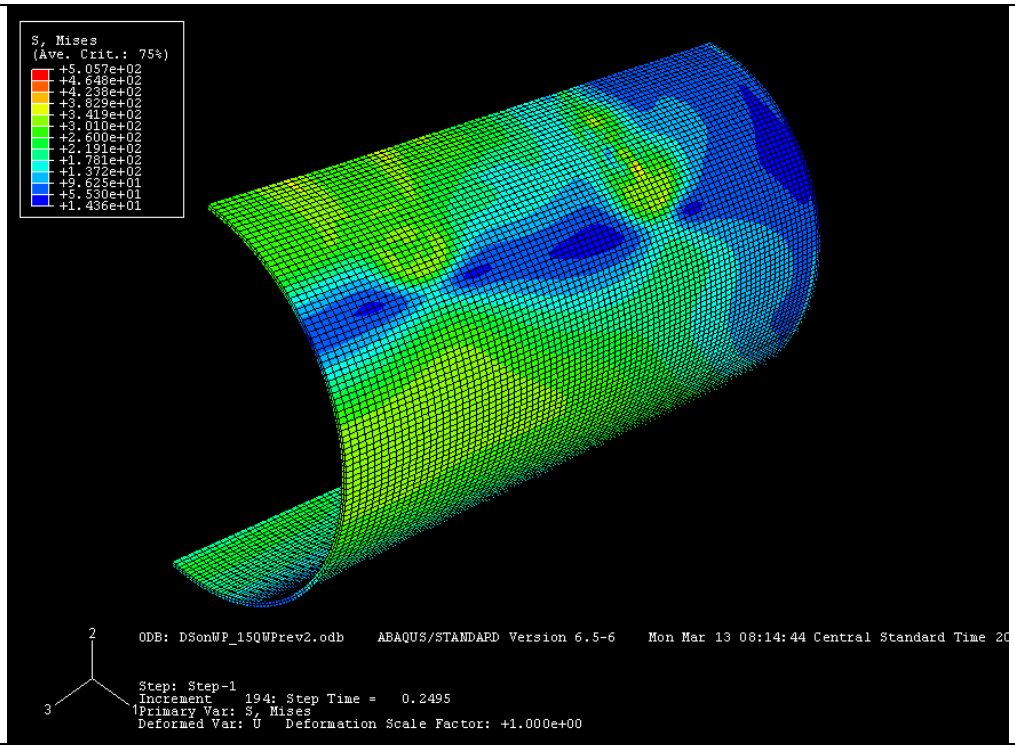
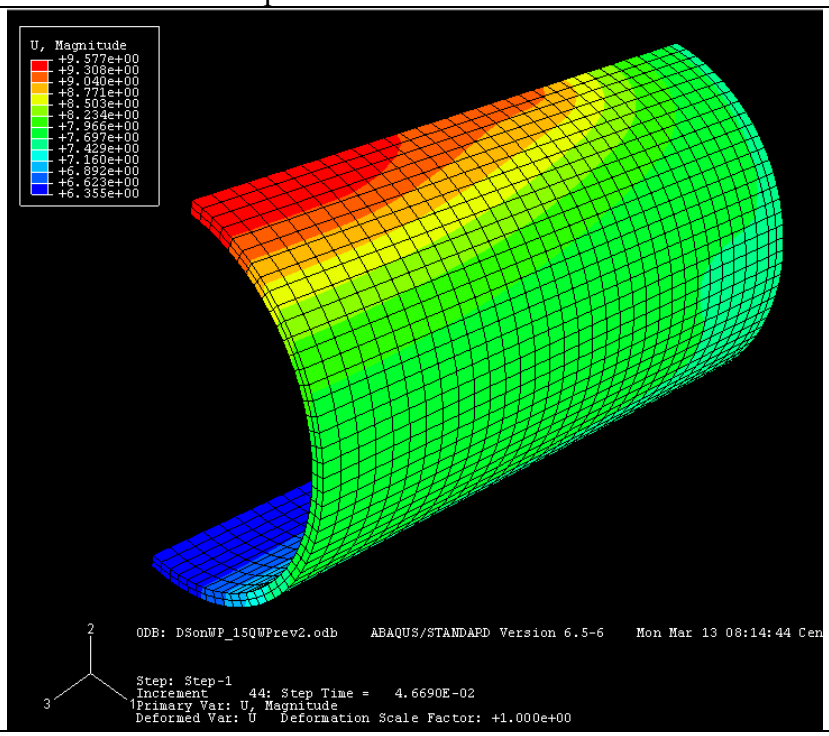
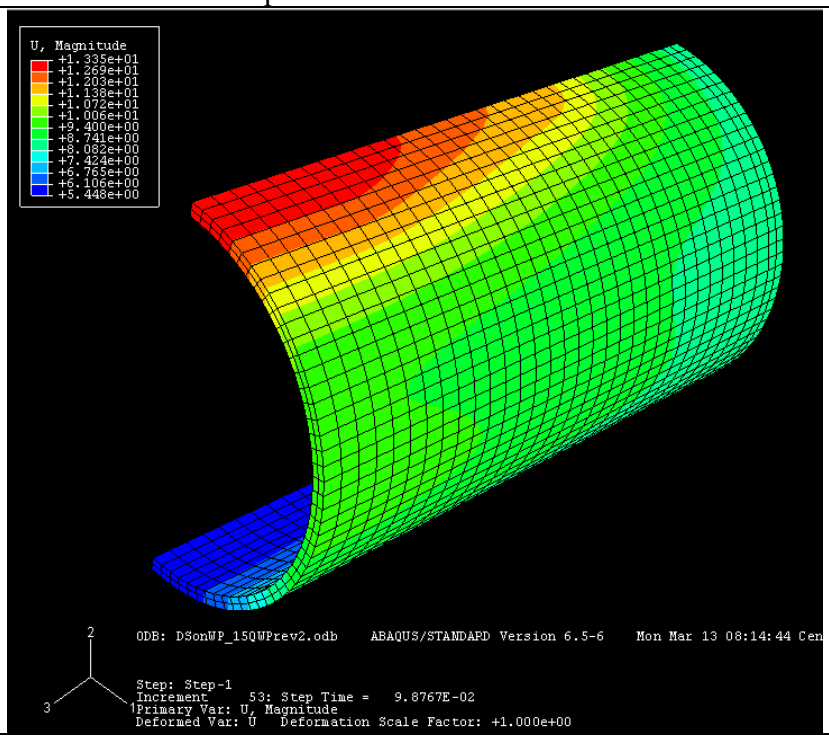

S, Mises
(Ave. Crit.: 75%)
+5.057e+02
+4.648e+02
+4.238e+02
+3.829e+02
+3.419e+02
+3.010e+02
+2.600e+02
+2.191e+02
+1.781e+02
+1.372e+02
+9.625e+01
+5.530e+01
+1.436e+01
ODB: DSonWP_15QWPrev2.odb ABAQUS/STANDARD Version 6.5-6 Mon Mar 13 08:14:44 Central Standard Time 20
2
3
1
Step: Step-1
Increment 194: Step Time = 0.2495
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00

Table 14. Magnitude of the Displacement for the Inner Vessel.

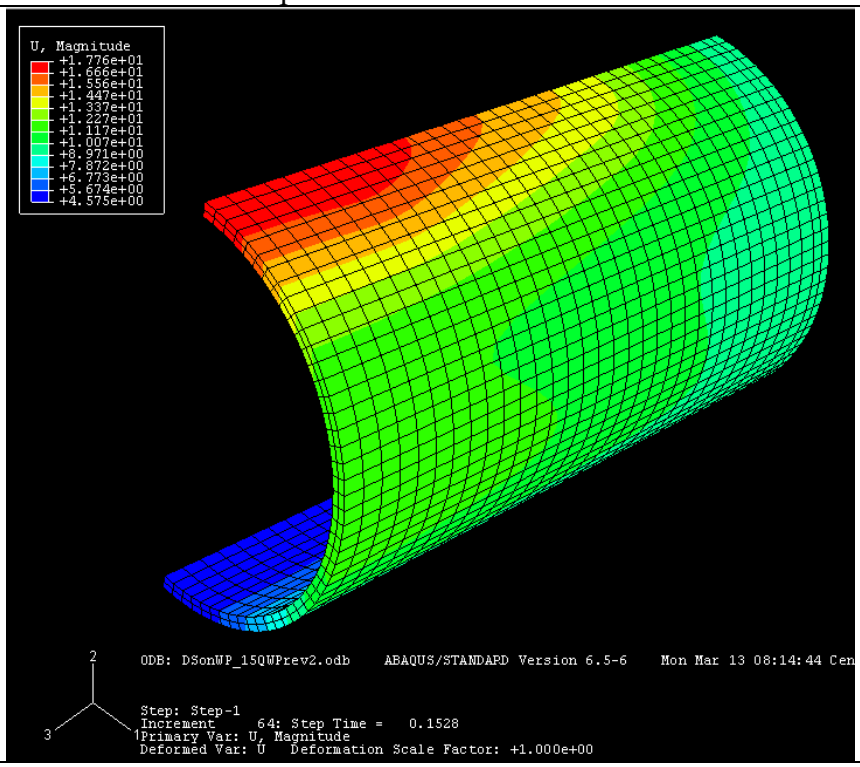
Step 1 – 300 *kPa*: Max Displacement = 9.58 *mm*. Delta = 1.58 *mm.*



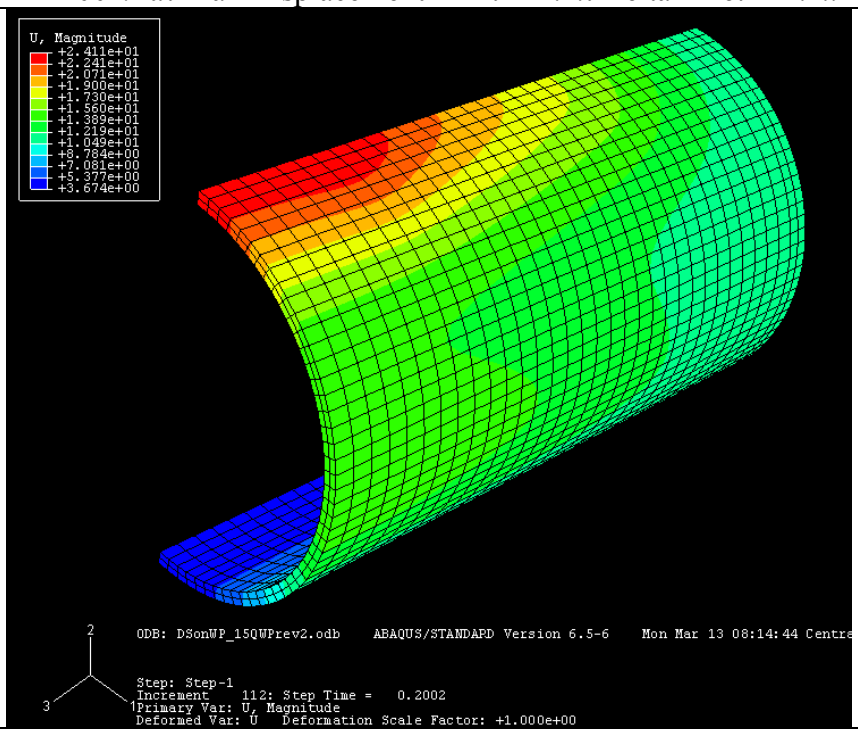
Step 2 – 600 *kPa*: Max Displacement = 13.35 *mm*. Delta = 5.35 *mm.*



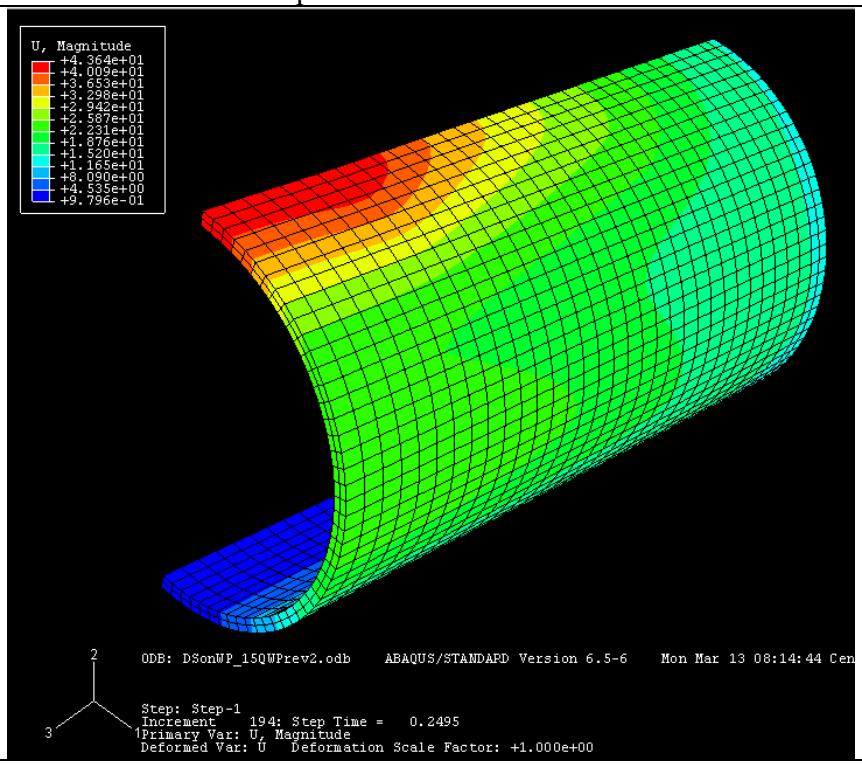
Step 3 – 900 *kPa*: Max Displacement = 17.76 *mm*. Delta = 9.76 *mm*.



Step 4 – 1200 *kPa*: Max Displacement = 24.11 *mm*. Delta = 16.11 *mm*.



Step 5 – 1500 *kPa*: Max Displacement = 43.64 *mm*. Delta = 35.64 *mm*.



{Note: The maximum displacement occurs approximately in the middle of the waste package inner vessel.}

Date: March 21, 2006
Entry by: Roman V. Kazban

Table 15. Results for the "1/4 Waste Package Rev. 1" FEM, using quilt plotting options.

Load, kPa	300	600	900	1200	1500
Max Stress DS side, MPa	275	290	308	312	306
Max Stress Pallet side, MPa	308	314	326	323	346
Contact Length from Stress Criteria, mm	0	200	200	360	280

Table 16. Results for the "1/4 Waste Package Rev. 2" FEM, using quilt plotting options.

Load, kPa	300	600	900	1200	1500
Max Stress DS side, MPa	293	294	311	311	309
Max Stress Pallet side, MPa	295	312	313	323	342
Contact Length from Stress Criteria, mm	80	160	200	200	280

{Note: The contact length was estimated by using a stress criteria, assuming that the contact is achieved if the Von Mises stress in the outer shell of the waste package exceeds the yield stress of Alloy 22. Also, the estimation was performed using quilt plotting options.}

Date: March 29, 2006
Entry by: Roman V. Kazban

Table 17. Results for the "1/4 Waste Package Rev. 1" FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
Max Stress DS side, MPa	368	399	389	396	414
Max Stress Pallet side, MPa	402	441	441	483	491
Contact Length from Stress Criteria, mm	280	340	380	660	740

Table 18. Results for the "1/4 Waste Package Rev. 2" FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
Max Stress DS side, MPa	460	481	482	421	460
Max Stress Pallet side, MPa	393	397	437	447	480
Contact Length from Stress Criteria, mm	200	340	500	680	840

{Note: The contact length was estimated by a using stress criteria, assuming that the contact is achieved if the Von Mises stress in the outer shell of the waste package exceeds the yield stress of Alloy 22. Also, the estimation was performed using contour plotting options.}

Date: March 30, 2006
Entry by: Roman V. Kazban

Table 19. Results for the "1/4 Waste Package Rev. 1" FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
IS Max Displacement at DS, mm	8.33	9.80	11.33	13.17	17.80
IS Displacement Delta at DS, mm	0.33	1.80	3.33	5.17	9.80
IS Max Displacement at Simulated DS, mm	9.36	11.97	14.78	18.57	27.87
IS Displacement Delta at Simulated DS, mm	1.36	3.97	6.78	10.57	19.87

Table 20. Results for the "1/4 Waste Package Rev. 2" FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
IS Max Displacement at DS, mm	9.15	11.83	14.27	17.42	27.17
IS Displacement Delta at DS, mm	1.15	3.83	6.27	9.42	19.17
IS Max Displacement at Simulated DS, mm	9.56	13.32	17.71	24.03	43.37
IS Displacement Delta at Simulated DS, mm	1.56	5.32	9.71	16.03	35.37

Date: March 31, 2006
Entry by: Roman V. Kazban

Table 21. Results for the "1/4 Waste Package Rev. 1" FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
IS Max Horizontal Displacement at DS, mm	0.69	1.53	2.44	3.49	5.85
IS Max Horizontal Displacement at Simulated DS, mm	1.28	2.75	4.30	6.16	10.65

Table 22. Results for the "1/4 Waste Package Rev. 2" FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
IS Max Horizontal Displacement at DS, mm	0.81	2.07	3.44	5.18	10.52
IS Max Horizontal Displacement at Simulated DS, mm	1.41	3.58	5.90	9.07	18.65

Table 23. Results for the "1/4 Waste Package" Rev.1 & 2 FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
Max Von Mises Stress in DS bulkhead with an unconstrained end (Rev. 1), MPa	857.4	838.2	865.7	906.8	912.7
Max Von Mises Stress in DS bulkhead with a constrained end (Rev. 2), MPa	892.7	877.3	938.3	903.3	926.2

Date: July 28, 2006
Entry by: Roman V. Kazban

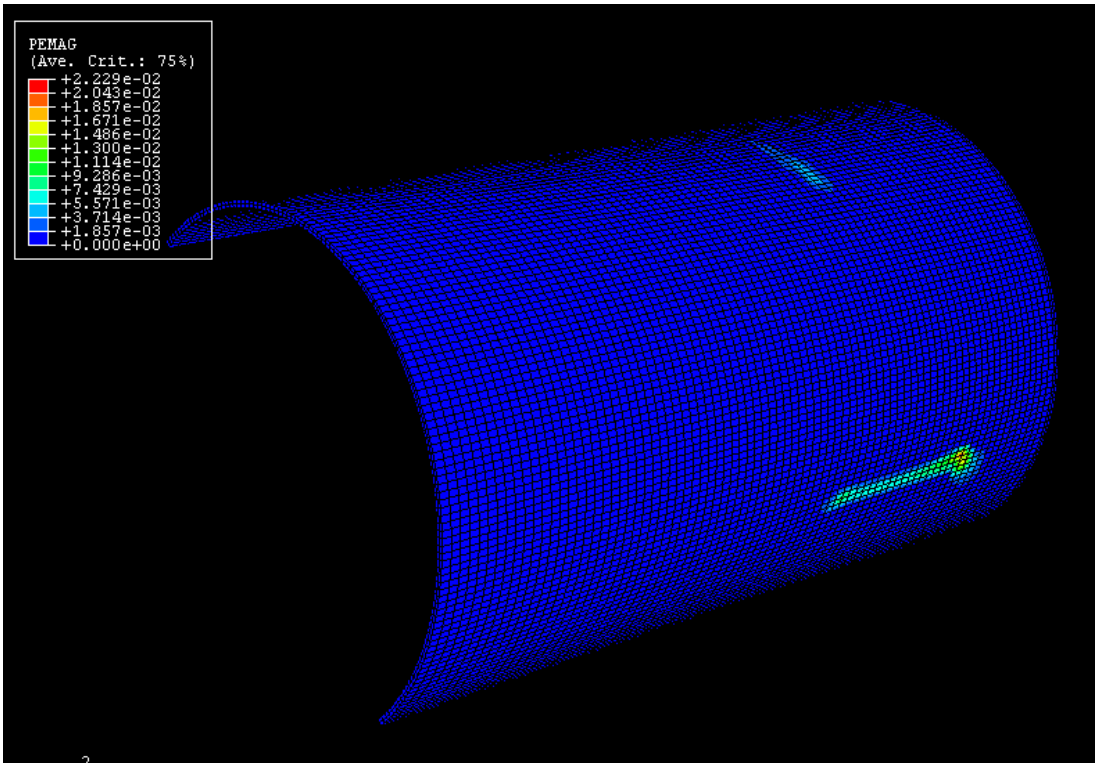


Figure 14. Maximum Principal Plastic Strain Distribution of the Waste Package Outer Shell, Unconstrained Drip Shield End at 1500 kPa
{from results of the "1/4 Waste Package Rev. 1" FEM}

Table 24. Results for the "1/4 Waste Package" Rev.1 FEM, using contour plotting opt.

Load, kPa	300	600	900	1200	1500
Max Principal Plastic Strain at DS, %	0.0036	0.0036	0.0036	0.0054	0.0057
Max Principal Plastic Strain at Pallet, %	0.0064	0.0098	0.0120	0.0131	0.0208

Date: August 1, 2006
Entry by: Roman V. Kazban

<u>Revision 3 to the "1/4 Waste Package" FEM</u>

The Emplacement Pallet has been redefined and is represented by plates #2, 4 and 6 [ref to ANL-XCS-ME_000001 REV 00, Sketch Number SK-0144 REV 01] Every plate is discretized using the quadrilateral continuum shell elements with reduced integration (SC8R)

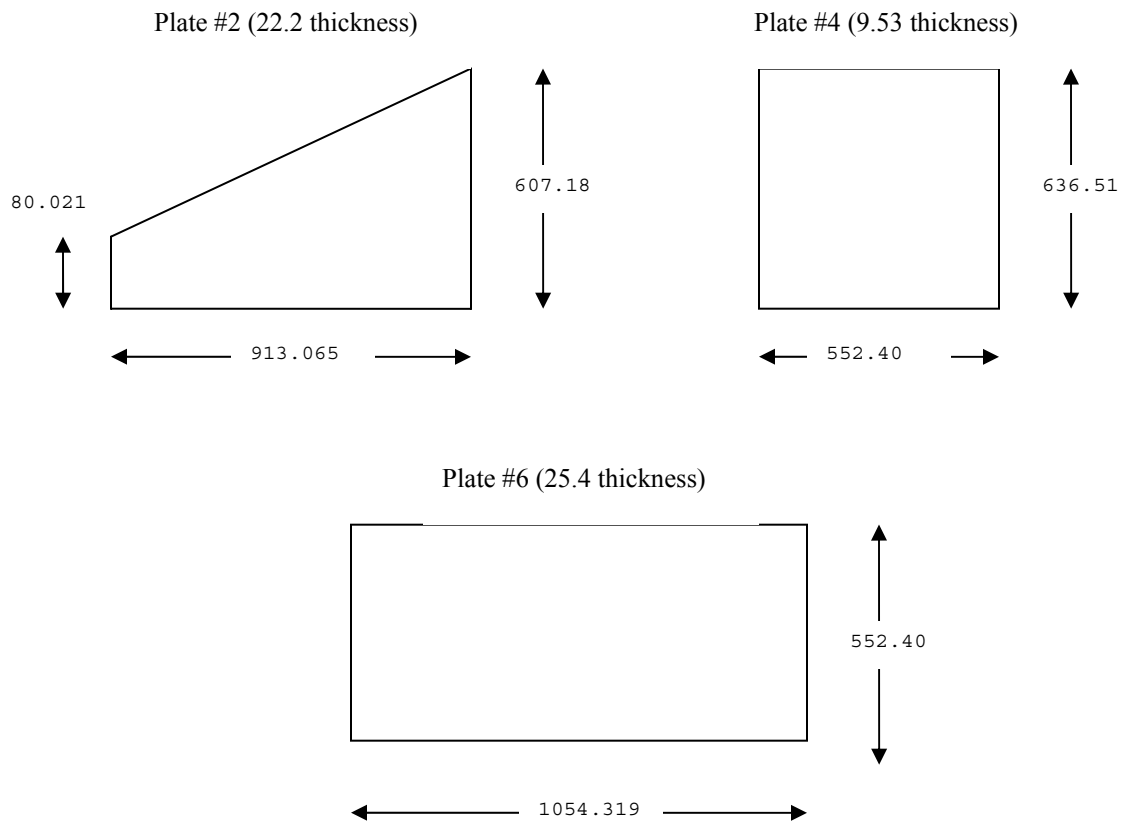


Figure 15.

Kinematic Constraints: The same constraints are applied to the Drip Shield and the Waste Package as in Revision 2 of the "1/4 Waste Package" FEM. Also it should be noted that the Drip Shield ends are free in all directions (refer to Figure 5b).

Each node of the bottom surface of the Emplacement Pallet is constrained from the vertical displacement. All nodes on the symmetry plane are constrained from the displacement in the x-directions. Nodes of the Plate #4 that belong to the area of the contact with the Stainless Steel

Tubes [Sketch Number SK-0144 REV 01] are constrained from the displacement in z-direction (see Figure 16).

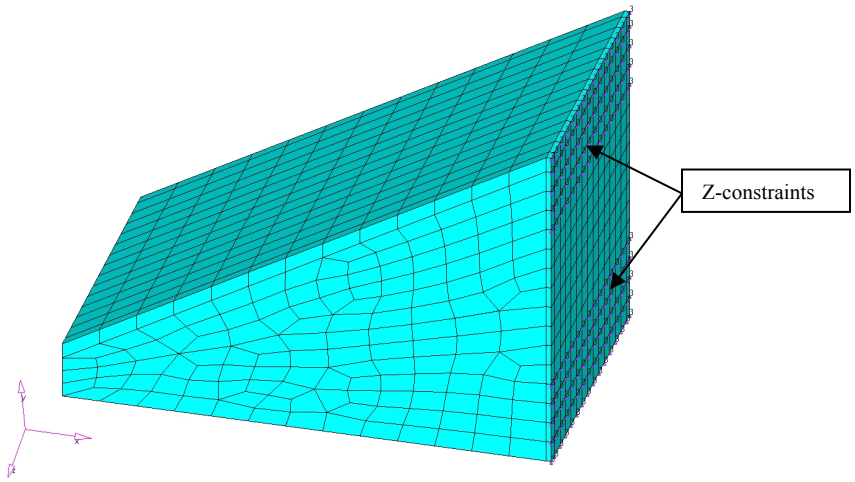


Figure 16.

{Note: No additional changes were made to the model}

Date: August 7, 2006
Entry by: Roman V. Kazban

<u>Results for the "1/4 Waste Package Rev. 3" FEM</u> (File: D:\DS\DSonWP_15QWPrev3)

The computational analysis of the Rev. 3 "1/4 Waste Package" FEM was terminated at 20% completion due to convergence.

Table 25. Results for the "1/4 Waste Package Rev. 3" FEM, using quilt plotting options.

Load, kPa	300	600	900	1200
Max Von Mises Stress in Outer Shell, MPa	441.2	457.2	473.8	499
Max Von Mises Stress in Outer Shell on DS side, MPa	371	397	390	389
Max Von Mises Stress in Outer Shell on Pallet side, MPa	418	423	456	499

Date: August 23, 2006
Entry by: Roman V. Kazban

<u>Description and Geometry of the "1/4 WP with a complete DS" FEM</u>
The finite element model is composed of the following (refer to Figure 17):

(i) Drip Shield (refer to Figure 18);
- (a) Titanium Grade 24 Bulkhead Web;
- (b) Titanium Grade 24 Bulkhead Flanges;
- (c) Titanium Grade 24 Longitudinal Stiffeners;
- (d) Titanium Grade 7 Shell Plate;
- (e) Titanium Grade 7 Internal Support Plate;

(ii) Waste Package;
- (a) Alloy 22 Outer Shell;
- (b) 316 Stainless Steel Inner Vessel;

(iii) Alloy 22 Emplacement Pallet (for details see Figures 15 and 16).

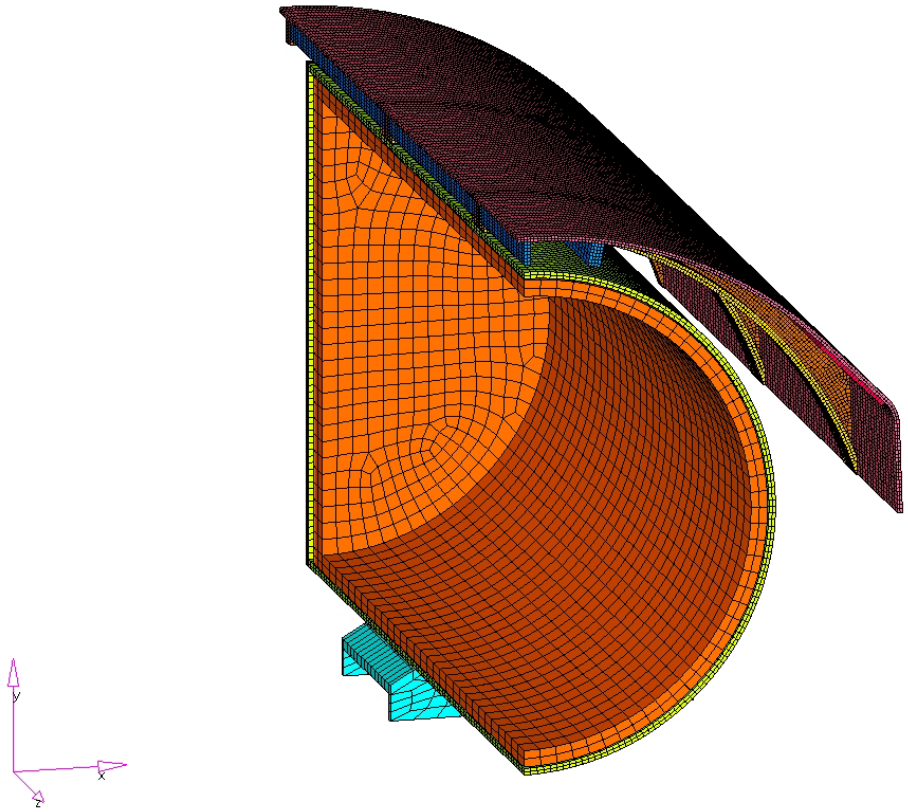


Figure 17.

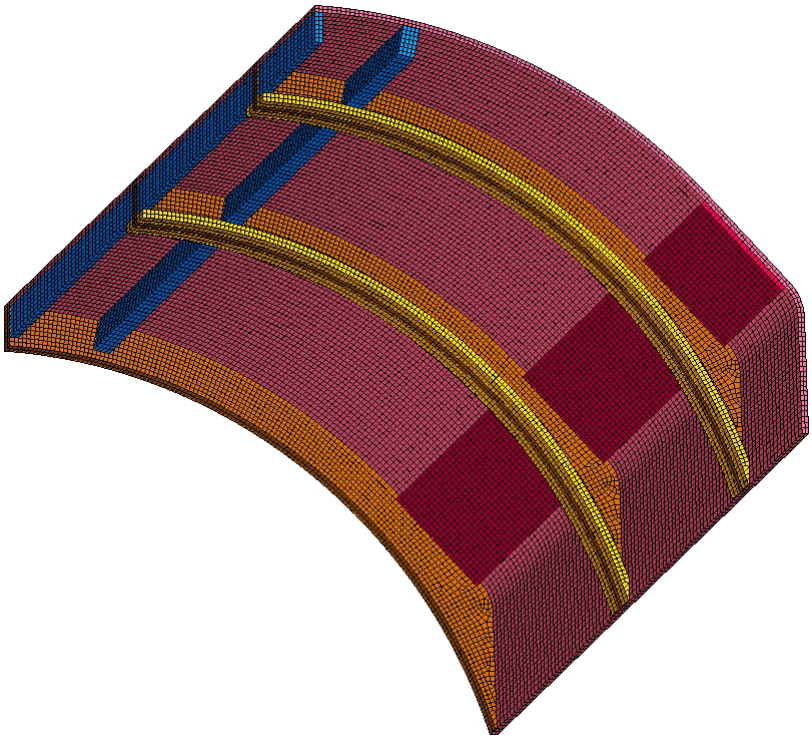


Figure 18.

The Drip Shield is positioned at 0 degree angle with respect to the Waste Package and the Emplacement Pallet to reproduce the loading conditions that result in the maximum contact area between the DS and WP. The finite element model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8) or 6-node linear tetrahedral elements (C3D6): the Bulkhead Web; the Bulkhead Flanges; the Longitudinal Stiffeners; the Shell Plate; the Outer Shell; the 316 Stainless Steel Inner Vessel. The Outer Shell Lid and the Inner Vessel Lid are discretized with 8-node continuum elements with reduced integration (C3D8R). A small number of C3D6 is used in the model; and the use of such elements is limited to the Bulkhead Web component. The Internal Support Plate and the Pallet Plates #2, 4 and 6 are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). The common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

Loads: The Drip Shield Shell Plate is loaded with 6000 *kPa* distributed load.

Kinematic Constraints: The Drip Shield displacement in the vertical direction (y-axis) is constrained by 2 SPRING1 elements of a relatively small stiffness to prevent numerical rigid body modes. The side surfaces of the Drip Shield are constrained in the transverse direction (z-axis) to represent symmetry. The Drip Shield ends are free in all directions (refer to Figure 5b)

with a constraints in YZ plane from the horizontal displacement (x-axis) in the middle of the DS to simulate symmetry conditions.

The displacement of the Waste Package in the vertical direction (y-axis) is constrained by 2 SPRING1 elements of a relatively small stiffness on both Waste Package Shells to prevent rigid body modes. The end nodes of the Outer and Inner Vessel that are located in the middle of the Waste Package along the YZ plane are constrained from the displacement in the horizontal direction to represent symmetry conditions. Also, the side surface in the lateral plane that represents the middle of the Waste Package is constrained from displacement in the transverse direction to simulate symmetry conditions.

Each node of the bottom surface of the Emplacement Pallet is constrained from the vertical displacement. All nodes on the symmetry plane are constrained from the displacement in the x-directions. Nodes of the Plate #4 that belong to the area of the contact with the Stainless Steel Tubes [Sketch Number SK-0144 REV 01] are constrained from the displacement in z-direction (see Figure 16).

A friction coefficient of 0.4 is used to model friction surface interaction between the Drip Shield and the Waste Package Outer Shell, between the Waste Package Outer Shell and Inner Vessel, and between the Waste Package Outer Shell and the Emplacement Pallet.

Date: August 31, 2006
Entry by: Roman V. Kazban

<u>Results for the "1/4 WP with a complete DS" FEM</u> (File: D:\DS\DSonWP_00QWPrev3)

The computational analysis of the Rev. 3 "1/4 Waste Package" FEM was terminated at 26% completion due to unlikely convergence {THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY}.

Table 26. Results for the "1/4 WP with a complete DS" FEM, using quilt plotting options.

Load, kPa	300	600	900	1200	1500
Max Von Mises Stress in Outer Shell, MPa	444.2	470.2	495.2	501.0	495.8
Max Von Mises Stress in Outer Shell on DS side, MPa	444	433	418	422	423
Max Von Mises Stress in Outer Shell on Pallet side, MPa	416	470	495	501	495

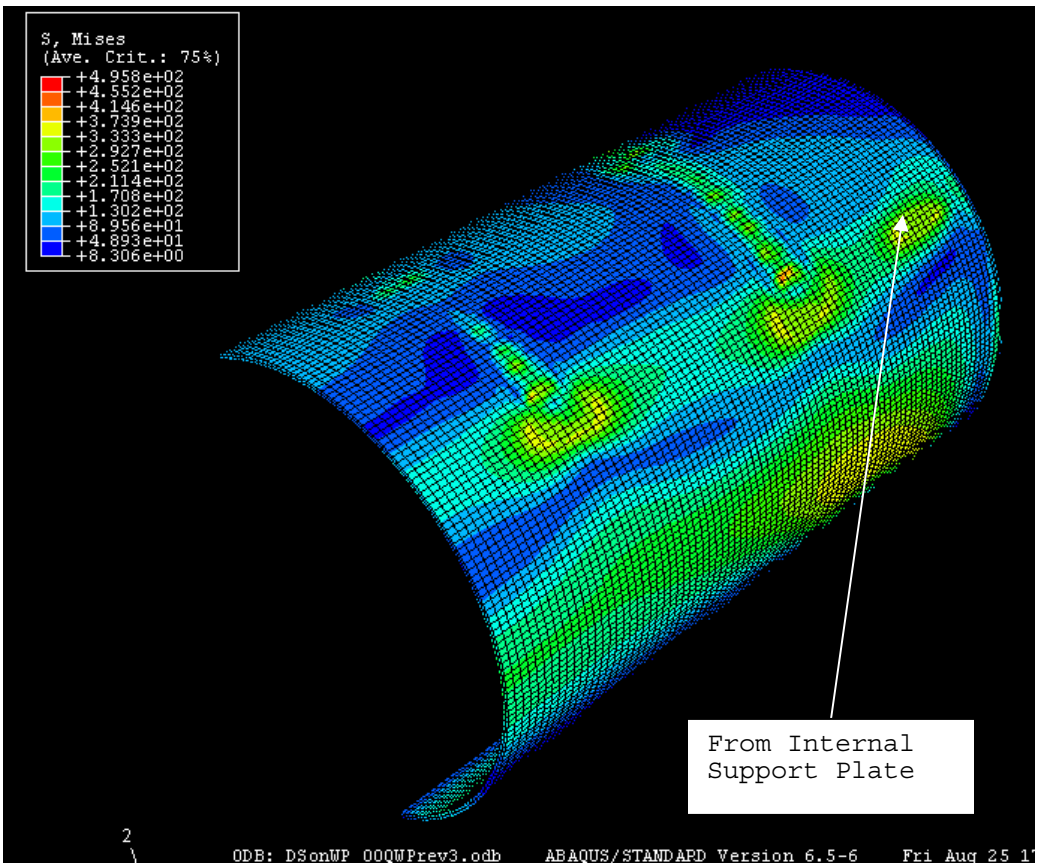


Figure 19. Von Mises Stress distribution for the Outter Shell at 1500 kPa load

Date: September 18, 2006
Entry by: Roman V. Kazban

<u>Results for the "1/4 WP with a complete DS" FEM</u> (File: D:\DS\DSonWP_00QWPrev3)

Table 27. Results for the "1/4 WP with a complete DS" FEM, using quilt plotting options.

Load, kPa	300	600	900	1200	1500
Max Von Mises Stress in Drip Shield Shell Plate, MPa	290.6	291.5	317.5	331.0	334.3

Titanium 7 Drip Shield Shell Plate elements reach yielding (174.1 MPa) at about 65 kPa distributed load.

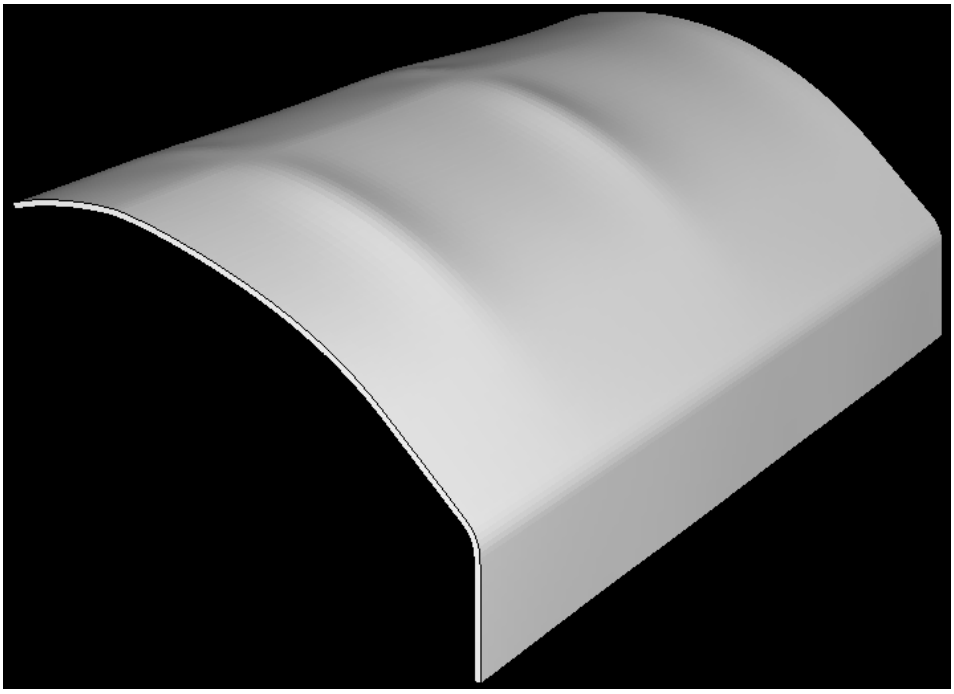


Figure 20. Deformation of the Drip Shield Shell Plate at 300 kPa load (2X Scale)

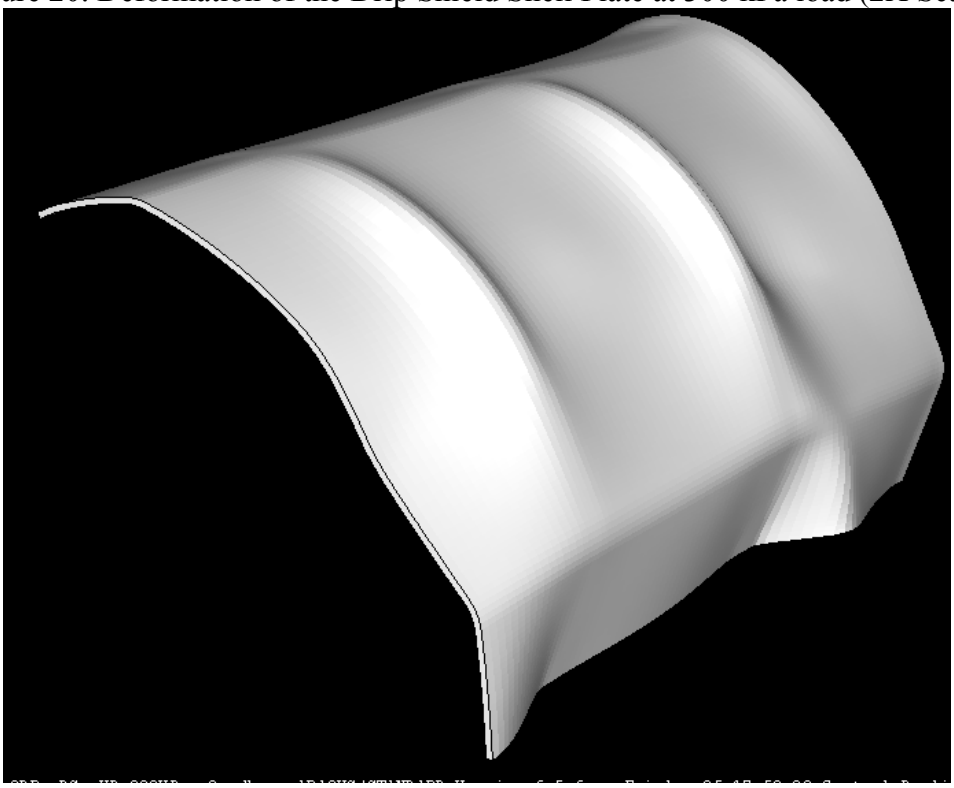


Figure 21. Deformation of the Drip Shield Shell Plate at 1500 kPa load (2X Scale)

Date: February 1, 2006
Entry by: Roman V. Kazban

<u>Description and Geometry of the "1/4 WP with inner vessel" FEM</u>

The finite element model represents a quarter of the WP and is composed of the following (refer to Figure 22):

(a) Alloy 22 Outer Shell (refer to Figure 7b for dimensions);
(b) 316 Stainless Steel Inner Vessel (refer to Figure 7a for dimensions).

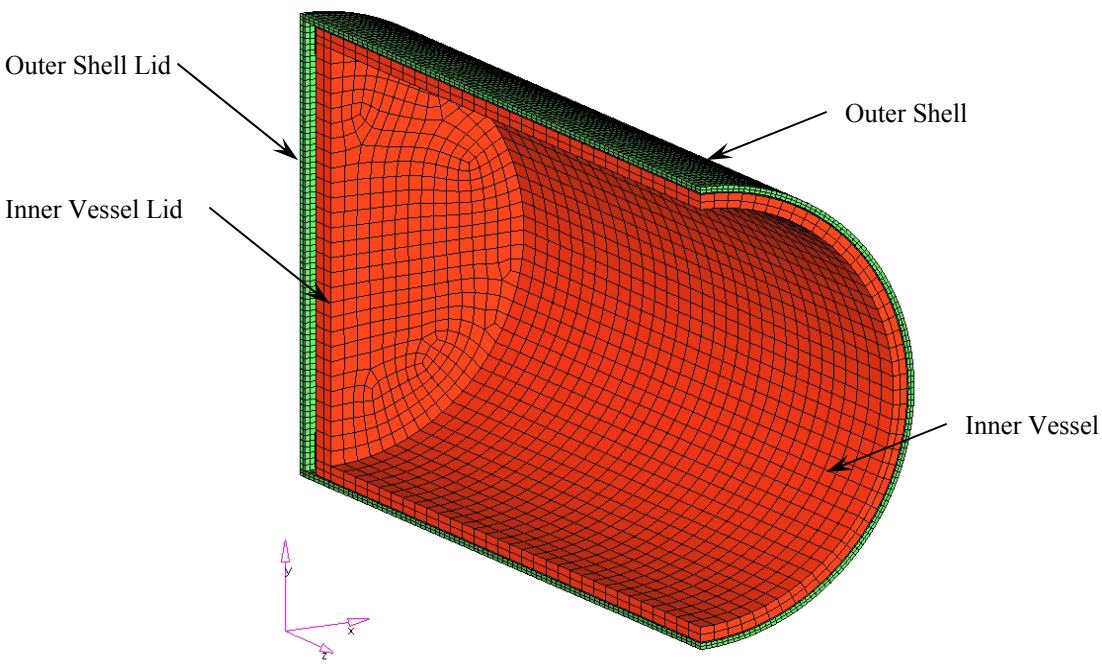


Figure 22.

The finite element model is constructed using 8-node solid elements: the Outer Shell and the Inner Vessel are discretized with 8-node continuum elements (C3D8), and the Outer Shell Lid and the Inner Vessel Lid are discretized with 8-node continuum elements with reduced integration (C3D8R). The common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

Loads: The Outer Shell is loaded with a projected pressure P_{proj} acting normal to the Outer Shell surface.

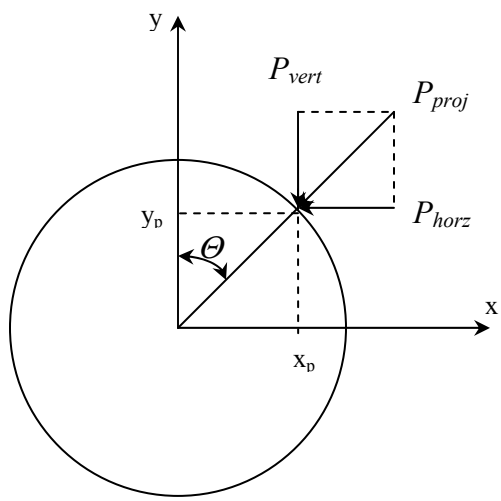


Figure 23.

Projected pressure P_{proj} can be derived as $P_{proj} = \sqrt{P_{vert}^2 + P_{horz}^2}$ (refer to Figure 23). It can be shown that $P_{vert} = P_{vert}^0 \cos\Theta$ and

$P_{horz} = P_{horz}^0 \sin\Theta$, where $\cos\Theta = \dfrac{y_p}{\sqrt{x_p^2 + y_p^2}}$ and

$\sin\Theta = \dfrac{x_p}{\sqrt{x_p^2 + y_p^2}}$. Assuming that

$P_{horz}^0 / P_{vert}^0 = 0.35$ and $P_{vert}^0 = P^0$,

$$P_{proj} = \left(P^{02} \frac{y_p^2}{x_p^2 + y_p^2} + (0.35)^2 P^{02} \frac{x_p^2}{x_p^2 + y_p^2} \right)^{1/2}$$

$$P_{proj} = P^{02} \left(\frac{y_p^2 + 0.1225 x_p^2}{x_p^2 + y_p^2} \right)^{1/2} .$$

In the finite element model, the Outer Shell is loaded with projected pressure P_{proj} corresponding to the value of P^0=10.0 *MPa*. The Outer Shell Lid is loaded with 3.5 *MPa* pressure acting in the z-direction.

Kinematic Constraints: The end nodes of the Outer Shell and Inner Vessel that are located in the middle of the Waste Package along the YZ plane are constrained from the displacement in the x-direction to represent symmetry conditions. Also, the nodes of the side surface in the lateral XY plane that represents the middle of the Waste Package are constrained from displacement in the z-direction to simulate symmetry conditions. The displacement of the Waste Package Inner Vessel in the y-direction is constrained by 2 SPRING1 elements of a relatively small stiffness to prevent rigid body modes. The displacement of the Waste Package Outer Shell in the y-direction is constrained by applying 0 displacement to 85 nodes on its side (refer to Figure 24).

A friction coefficient of 0.4 is used to model friction surface interaction between the Waste Package Outer Shell and Inner Vessel.

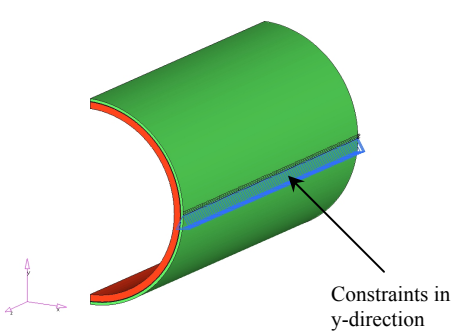


Figure 24.

Date: February 2, 2006
Entry by: Roman V. Kazban

<u>Results for the "1/4 WP with inner vessel" FEM</u> (File: D:\WP\WP Models\WP_with_inner)

The computational analysis of the "1/4 WP with inner vessel" FEM was terminated at 46.4% completion due to unlikely convergence {THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY}. Therefore, the maximum applied pressure in the vertical and horizontal directions before structural instabilities occurred was 4640 and 1624 *kPa* respectively. Typical Von Mises Stress distributions in the Waste Package Outer Shell and Inner Vessel at 46.4% completion are presented on Figures 25 and 26, respectively.

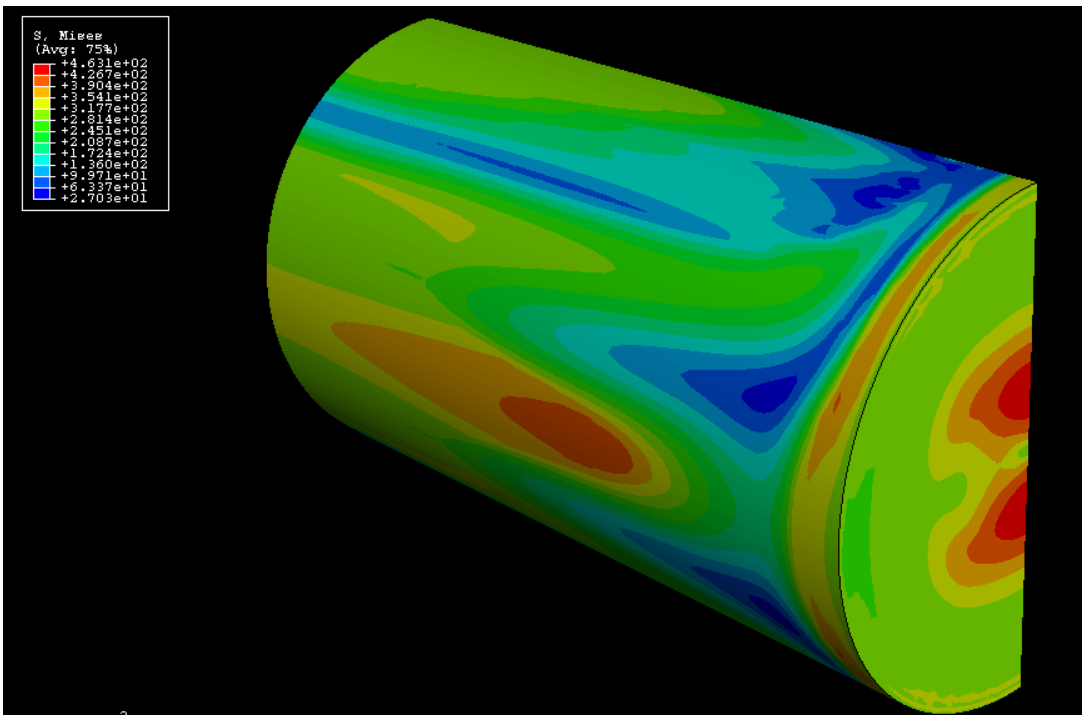


Figure 25. Von Mises Stress for the Outer Shell at 46.4% of loading applied (the maximum stress is 463.1 *MPa*)

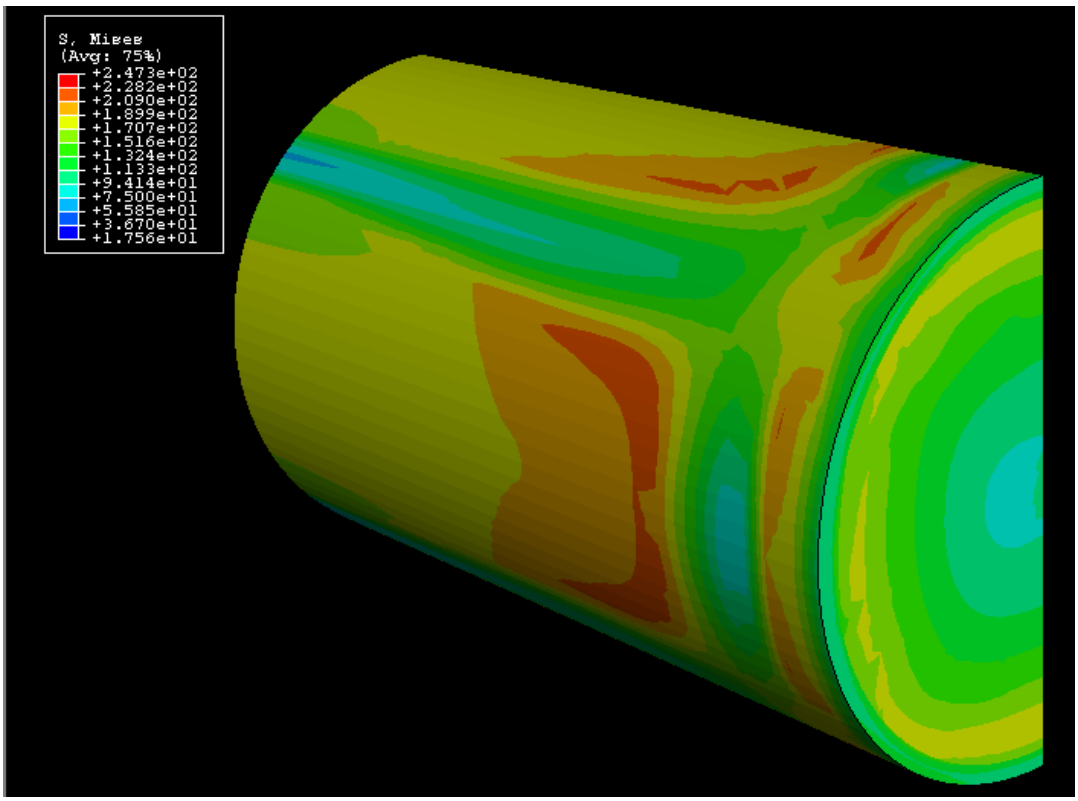


Figure 26. Von Mises Stress for the Inner Vessel at 46.4% of loading applied (the maximum stress is 247.3 *MPa*)

Date: February 2, 2006
Entry by: Roman V. Kazban

<u>Description and Geometry of the "1/4 WP without inner vessel" FEM</u>

The finite element model "1/4 WP with inner vessel" was modified to remove the Inner Vessel (refer to Figure 27) and a new model "1/4 WP without inner vessel" was created.

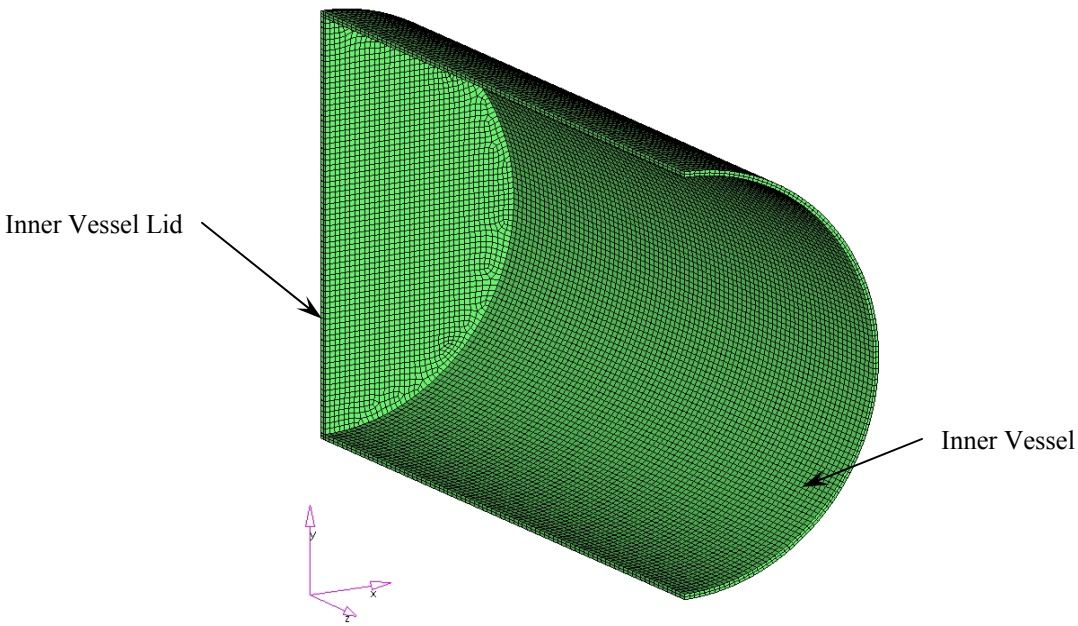


Figure 27.

The finite element model is constructed using 8-node solid elements: the Outer Shell is discretized with 8-node continuum elements (C3D8), and the Outer Shell Lid is discretized with 8-node continuum elements with reduced integration (C3D8R). The common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

Loads: The Outer Shell is loaded with projected pressure P_{proj} corresponding to the value of P^0=10.0 *MPa* (refer to "1/4 WP with inner vessel" FEM). The Outer Shell Lid is loaded with 3.5 *MPa* pressure acting in the z-direction.

Kinematic Constraints: The end nodes of the Outer Shell that are located in the middle of the Waste Package along the YZ plane are constrained from the displacement in the x-direction to represent symmetry conditions. Also, the nodes of the side surface in the lateral XY plane that represents the middle of the Waste Package are constrained from displacement in the z-direction

to simulate symmetry conditions. The displacement of the Waste Package Outer Shell in the y-direction is constrained by applying 0 displacement to 85 nodes on its side (refer to Figure 24).

Date: February 2, 2006
Entry by: Roman V. Kazban

<u>Results for the "1/4 WP without inner vessel" FEM</u>

(File: D:\WP\WP Models\WP_without_inner)

The computational analysis of the "1/4 WP without inner vessel" FEM was terminated at 12.4% completion due to unlikely convergence {THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY}. Therefore, the maximum applied pressure in the vertical and horizontal directions before structural instabilities occurred was 1240 and 434 *kPa* respectively. A typical Von Mises Stress distribution in the Waste Package Outer Shell at 12.4% completion is presented on Figures 28.

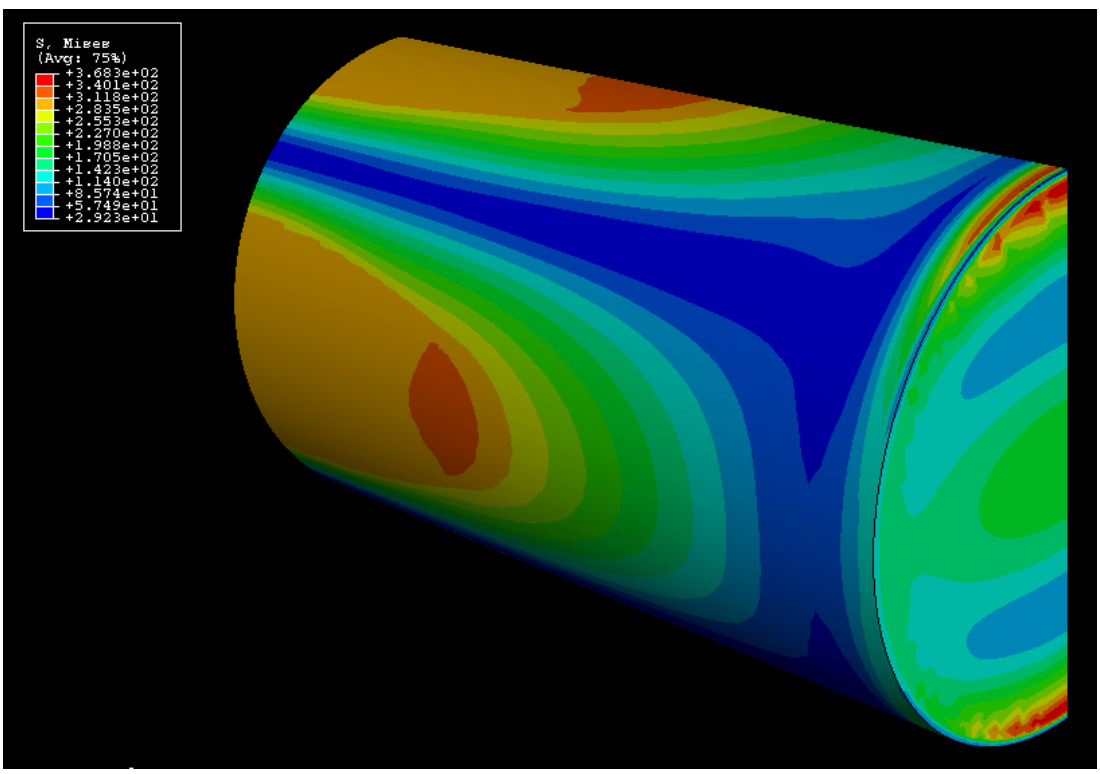


Figure 28. Von Mises Stress for the Outer Shell at 12.4% of loading applied (the maximum stress is 368.3 *MPa*)