INITIAL ENTRIES

Scientific Notebook: #832E

Issued to: Roman V. Kazban

Issued Date: October 31, 2006

Printing Period:

Project Title: ***Three-Dimensional Models of the Drip Shield Subjected to Static Loading***

Project Staff: Roman V. Kazban

This notebook documents the work being done to develop the three-dimensional finite element models of the drip subjected to static loading in support of the "Mechanical Disruption of Engineered Barriers" 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). MATLAB 7.0.1 code is used to create fitting curves and generate data plots ("MATLAB User's Manual", Version 7.0.1. The MathWorks, Inc., Massachusetts, 2004).

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

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

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

Materials and material properties used in the three-dimensional finite element (FE) models
[all data has been obtained from L. Ibarra, et. al. "Drip Shield-Waste Package mechanical Interaction", CNWRA, San Antonio, TX, June 2006]

(1) Alloy 22

At Room Temperature: Density = 8691.5 kg/m^3 = 8691.5e-9 kg/mm^3;
Modulus of elasticity = 1.799e11 *Pa* = 1.799e5 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 = 0.5546.

(2) Titanium Grade 24 (Ti-24)

At Room Temperature: 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 = 0.066.

(3) Titanium Grade 7 (Ti-7)

At Room Temperature: 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.

Note: Values of the density, the modulus of elasticity, and the Poisson's ratio for Alloy 22, Ti-7, and Ti-24 at 150 ^oC are not available in the literature. Therefore values of the density, the modulus of elasticity, and the Poisson's ratio at room temperature are used in the finite element models presented here.

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

<u>Description and Geometry of the "Partial Drip Shield" FE model</u> (D:\DS\DSrev0.*)**

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

(i) Titanium Grade 24 Bulkhead Web;
(ii) Titanium Grade 24 Bulkhead Flanges;
(iii) Titanium Grade 24 Longitudinal Stiffeners;
(iv) Titanium Grade 24 Support Beams;
(v) Titanium Grade 7 Shell Plate;
(vi) Titanium Grade 7 Internal Support Plates;
(vii) Titanium Grade 7 External Support Plates;
(viii) Alloy 22 Bases.

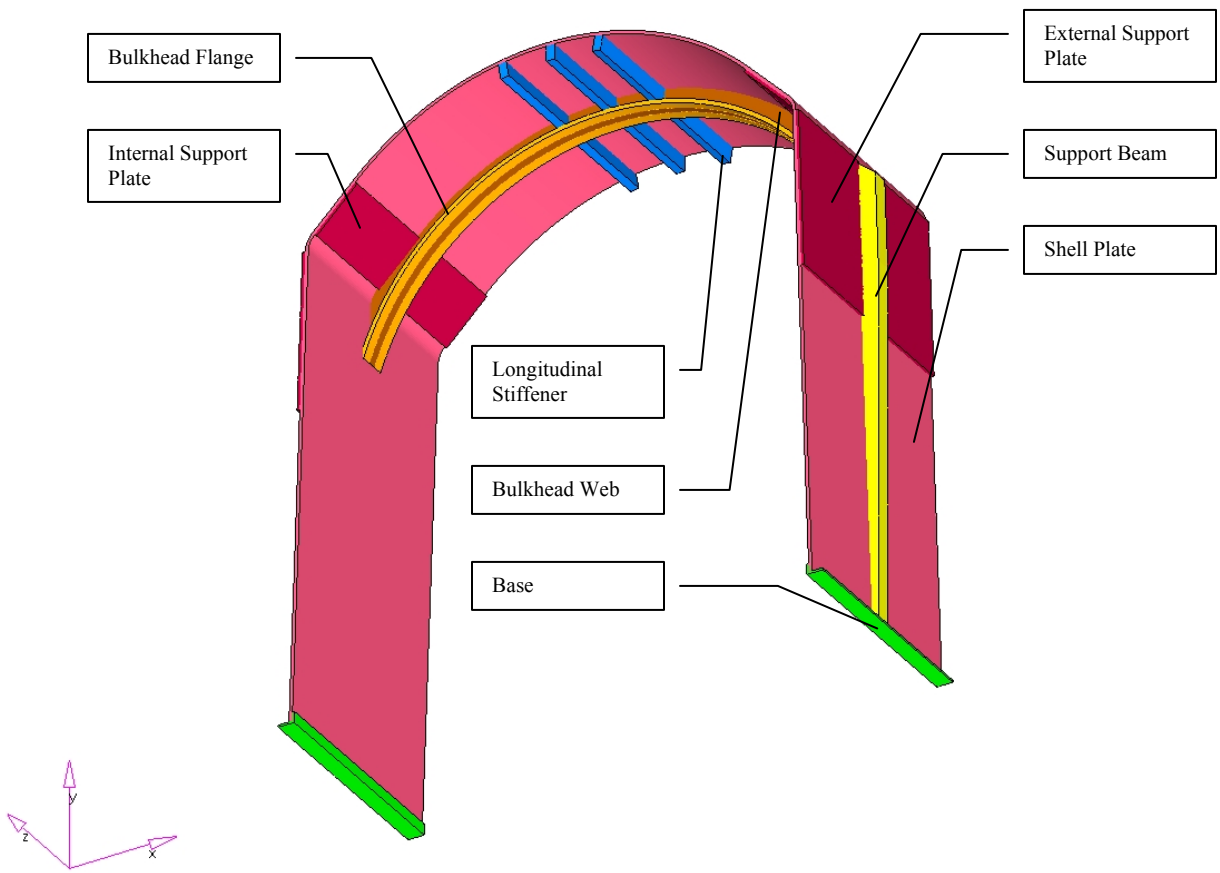


Figure 1.

All dimensions used to construct the "Partial Drip Shield" FE model were obtained from "Drip Shield Structural response to Rock Fall" (Document Identifier: 000-00C-SSE0-00300-000-00A) sketch number SK0230 Realization 00. The width of the Drip Shield (DS) is 1047.47 *mm*, which equals to the dimension between two adjoin Bulkheads or two adjoin Support Beams.

The FE model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8): the Bulkhead Web, the Bulkhead Flanges, the Longitudinal Stiffeners, the Support Beams, and the Shell Plate. Due to a sharp geometry of some components of the DS, a small number of 6-node linear tetrahedral elements (C3D6) are used to discretise the Bulkhead Web, the Bulkhead Flanges, and the Support Beams. The Internal Support Plates, the External Support Plates, and the Bases are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Bulkhead Web and the Support Beams elements is 10×10×20 *mm*. A size of the Bulkhead Flanges elements ranges between 10×10×15 *mm* and 10×10×20 *mm*. A size of the Longitudinal Stiffeners elements ranges between 10×10×15 *mm* and 10×10×30 *mm*. A size of the Shell Plate elements ranges between 7.5×10×15 *mm* and 7.5×10×30 *mm*. A size of the Internal and External Support Plates elements ranges between 10×12.7×15 *mm* and 12×12.7×30 *mm*. A size of the Base elements ranges between 7.5×10×15 *mm* and 10×10×30 *mm*. The common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

<u>Boundary Conditions</u>

Loads: The elements of the DS Shell Plate crown are loaded directly with a 700 *kPa* normal pressure and the elements that represent sides of the DS Shell Plate are loaded directly with a 315 *kPa* normal pressure. This loading case represents loading with a 0.45 lateral to vertical pressure ratio.

Kinematic Constraints: Each node in the XY-plane that belongs to the sides of the Drip Shield is constrained in the transverse direction (z-axis) to represent symmetry conditions. Only one set of nodes (along z-axis) on the bottom of each Base is constrained in the horizontal (x-axis) and vertical (y-axis) directions to represent pinned conditions (refer to Figure 2). Also, no springs are used on the sidewalls.

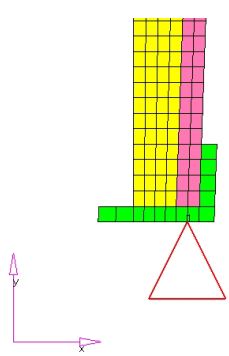


Figure 2.

Although, this type of a constraint still allows rotation around the z-axis.

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

<u>Results for the "Partial Drip Shield" FE model</u> (D:\DS\DSrev0.*)**

The computational analysis was terminated at 43.08% of the load (at 301.6 *kPa* vertical and 135.7 *kPa* horizontal pressures) due to reaching min step requirement {THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY. TIME INCREMENT REQUIRED IS LESS THAN THE MINIMUM SPECIFIED}. Figure 3 represents the Von Mises Stress distribution in the section of the Drip Shield at 301.6 *kPa* vertical and 135.7 *kPa* horizontal pressures. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 683.9 *MPa*.

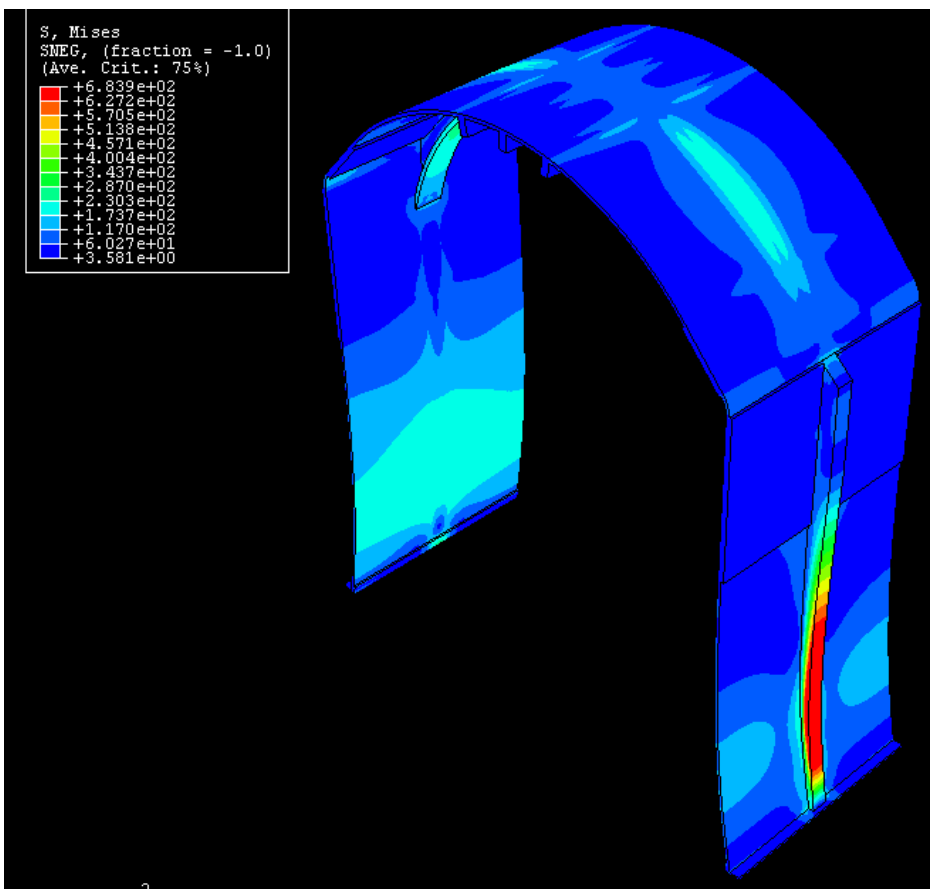


Figure 3.

Figure 4 represents the Von Mises stress distribution in the DS Shell Plate at 301.6 *kPa* vertical and 135.7 *kPa* horizontal pressures, where the gray areas represent the areas with a stress exceeding 174 *MPa*, which is the yield stress for Titanium Grade 7.

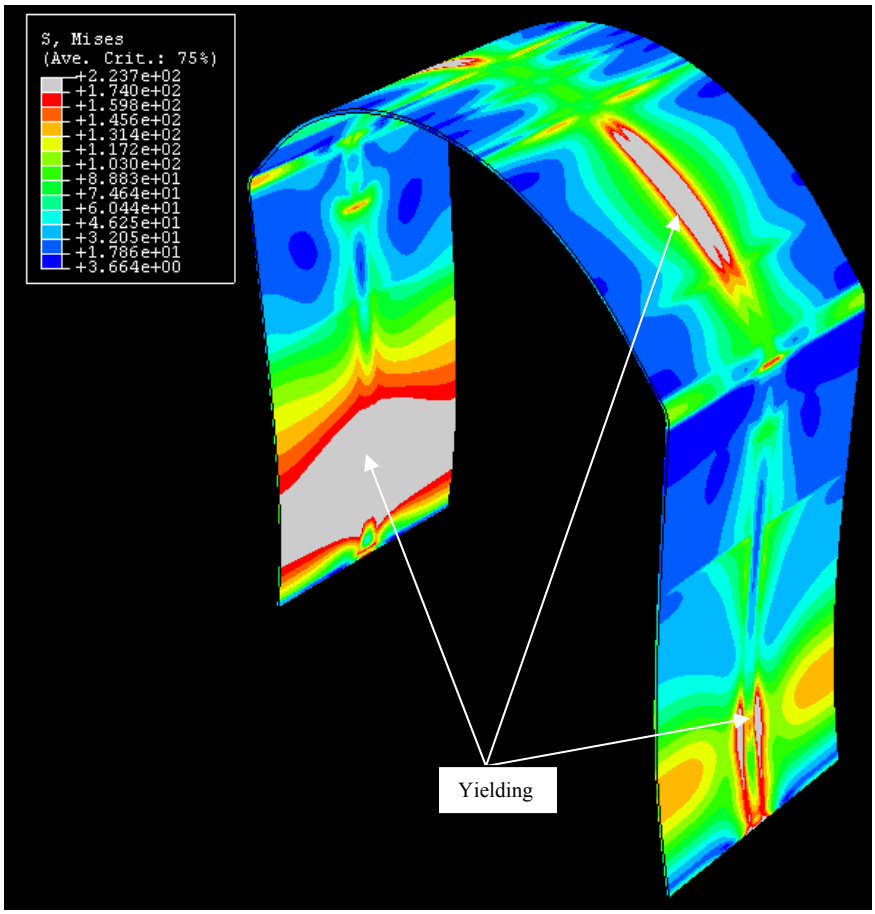


Figure 4.

Figure 5 shows the Von Mises stress in the Shell Plate of the Drip Shield crown as a function of the vertical pressure. From this plot, it can be determined that the Von Mises stress reaches the value of the yield stress of the Titanium Grade 7 at about 255 kPa vertical pressure.

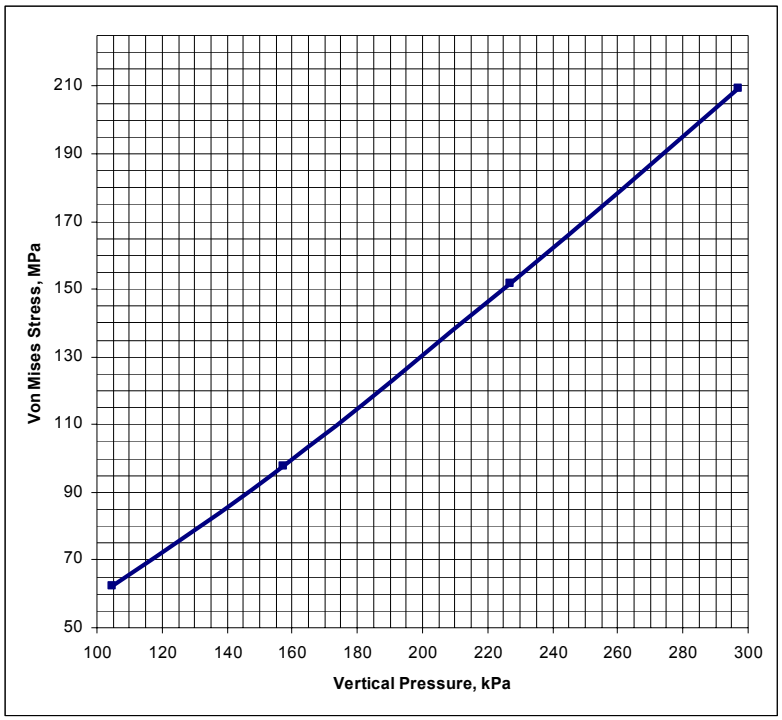


Figure 5.

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

<u>Description of the "Partial Drip Shield" FE models Realization 1 through 6</u>
(D:\DS\DSrev1.* -- D:\DS\DSrev6.***)**

Loads: The elements of the DS Shell Plate crown and the elements that represent sides of the DS Shell Plate are loaded directly with normal pressure. Each case (realization 1-6) represent unsymmetrical loading with value of vertical and horizontal pressures reported in Table 1. Values for Table 1 were obtained from Table 5-28, "Mechanical Assessment of the Drip Shield Subjected to Vibratory Motion and Dynamic and Static Rock Loading", CAL-WIS-AC-000002 REV 00A. For simplicity, it is assumed that the lateral to vertical load ratio does not change, as the magnitude of the load increases.

Table 1.

Realization	Pressure, *kPa*		
	Left Side	Crown	Right Side
1	41.54	108.92	58.76
2	19.15	147.07	19.33
3	31.35	154.80	6.69
4	57.23	129.76	128.82
5	69.69	122.73	105.43

6	32.97	113.87	52.19

*{Note: No additional changes were made to the model DSrev0.***}*

Date: November 4, 2006
Entry by: Roman V. Kazban

<u>Results for the "Partial Drip Shield" FE models Realization 1 through 6</u>
(D:\DS\DSrev1.* -- D:\DS\DSrev6.***)**

The computational analysis completion rate is reported in Table 2 as a percentage of initially intended pressure values (refer to Table 1) and represents the maximum loading applied to the DS before the computational analysis was terminated.

Table 2.

Realization	Completion rate, *%*	Max Pressure Applied, *kPa*		
		Left Side	Crown	Right Side
1	170	70.6	185.2	99.9
2	256	49.0	376.5	49.5
3	133	41.7	205.9	8.9
4	74	42.4	96.0	95.3
5	101	70.4	124.0	106.5
6	173	57.0	197.0	90.3

Values of the maximum Von Mises Stress are reported in Table 3.

Table 3.

Realization	Max Von Mises Stress, *MPa*	Von Mises Stress at 100% load, *MPa*	Location of Max Von Mises Stress
1	686.8	418.0	Right Support Beam
2	515.0	121.8	Bulkhead Flange at the Shell Plate
3	722.1	368.6	Right Support Beam
4	697.1	n/a	Right Support Beam
5	687.4	686.5	Right Support Beam
6	686.1	387.7	Right Support Beam

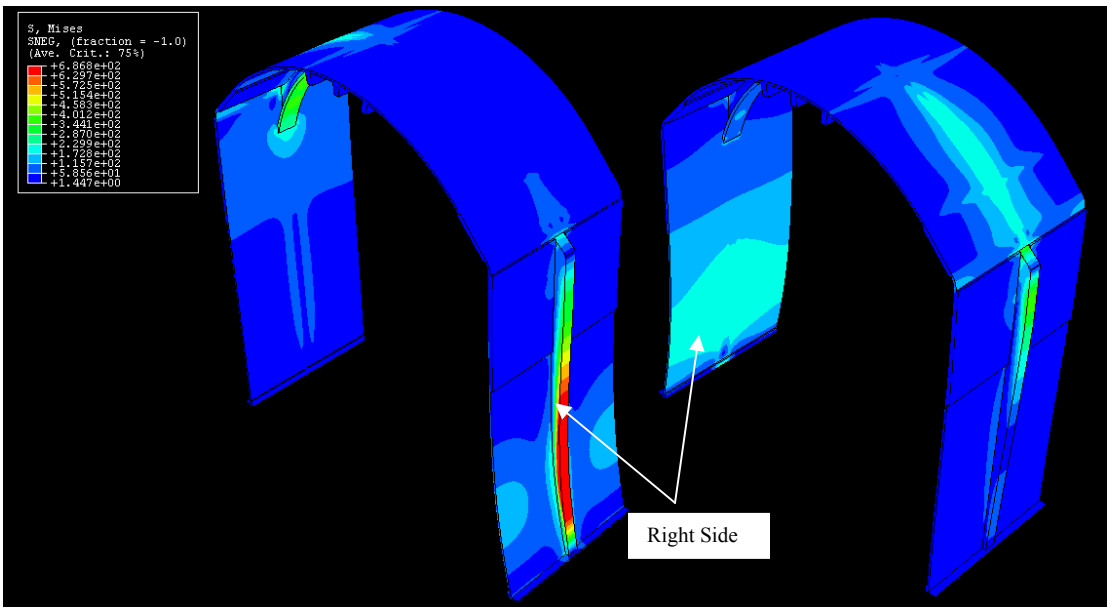


Figure 6. Von Mises stress distribution for Realization 1 at maximum loading

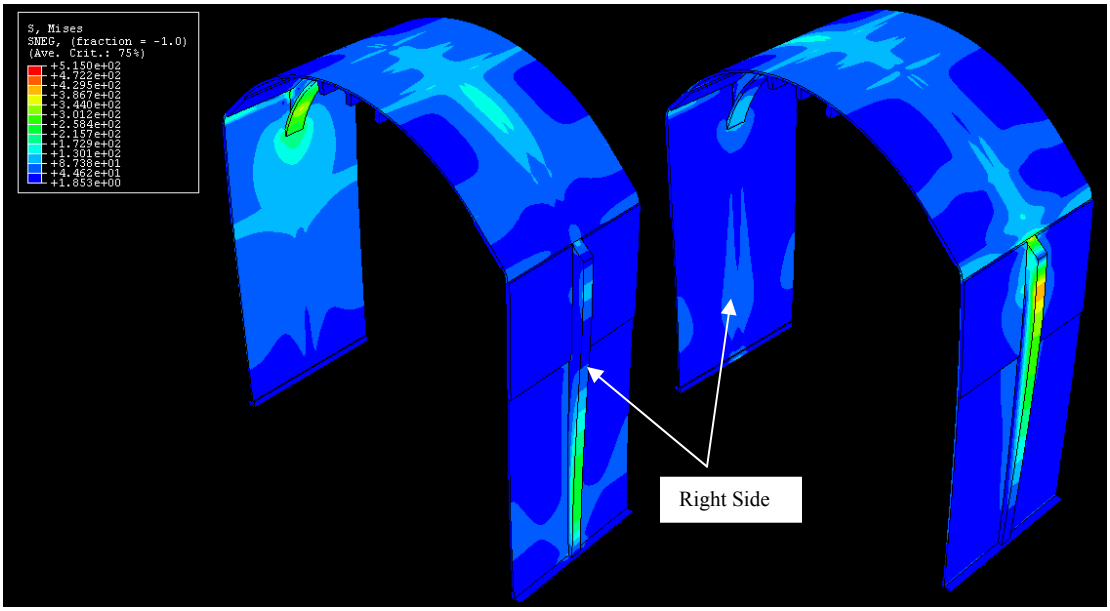


Figure 7. Von Mises stress distribution for Realization 2 at maximum loading

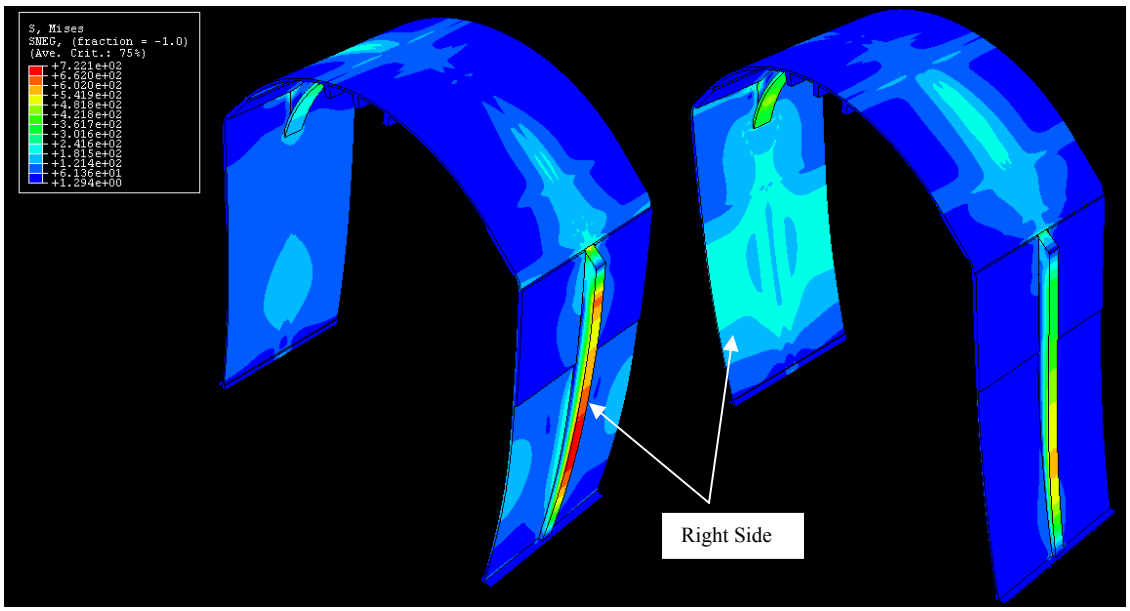


Figure 8. Von Mises stress distribution for Realization 3 at maximum loading

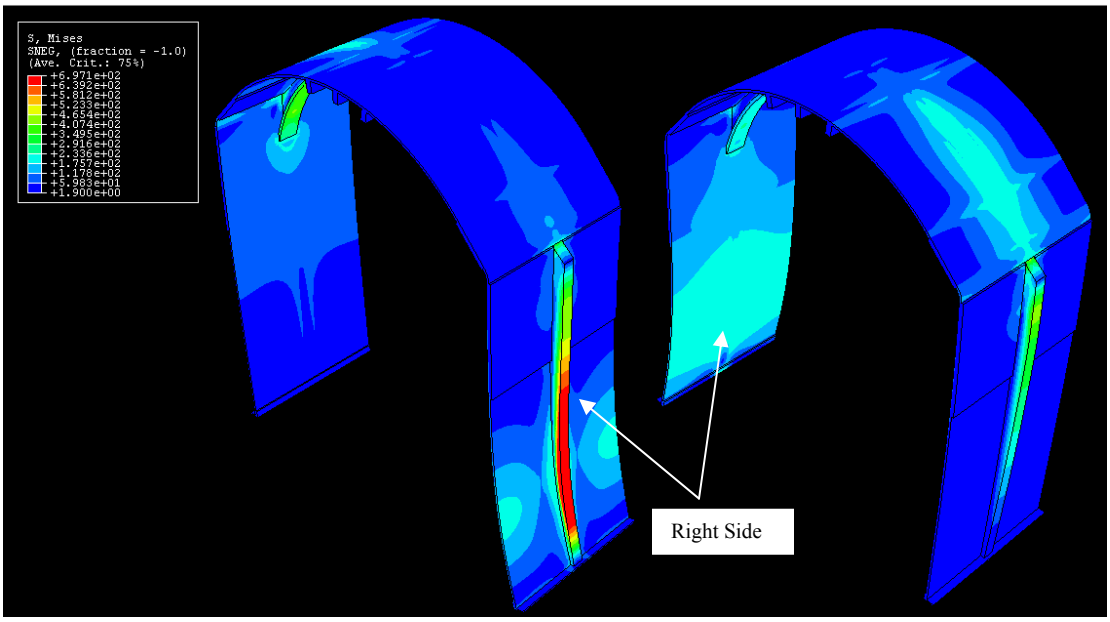


Figure 9. Von Mises stress distribution for Realization 4 at maximum loading

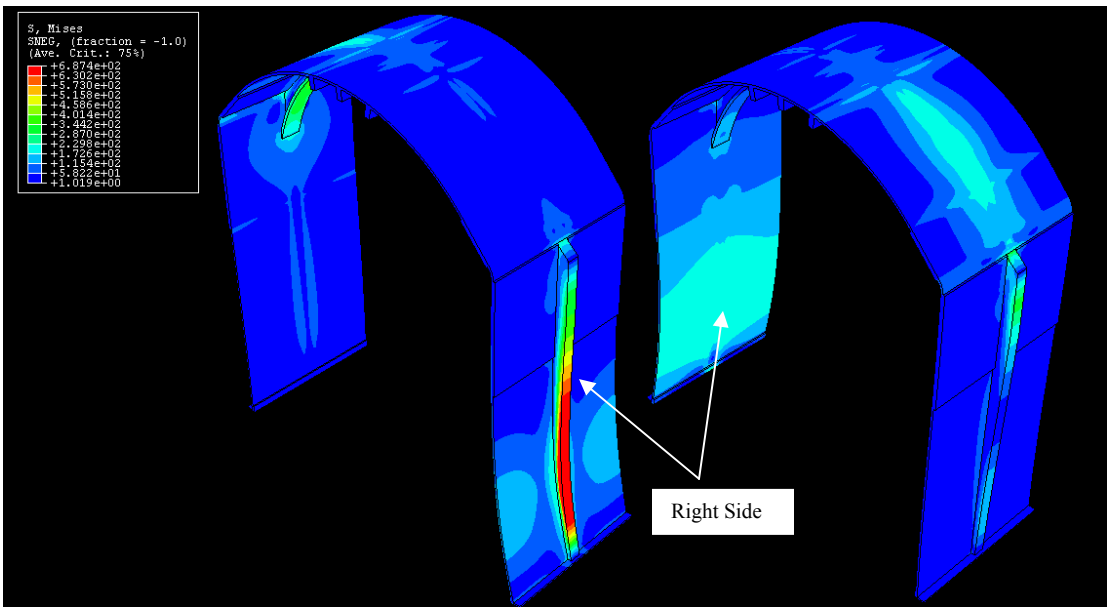


Figure 10. Von Mises stress distribution for Realization 5 at maximum loading

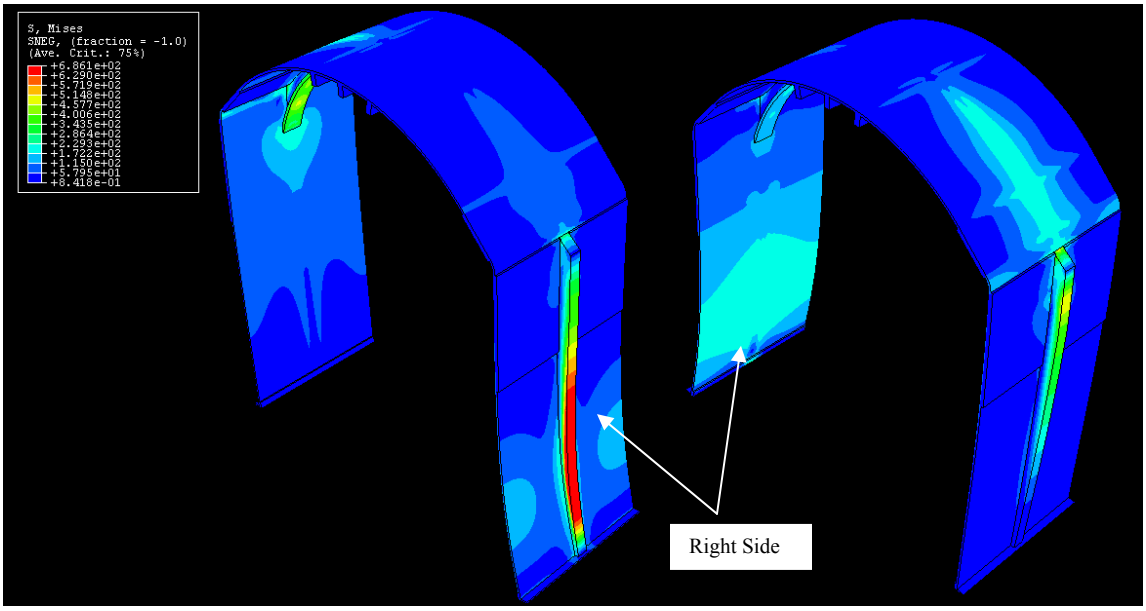


Figure 11. Von Mises stress distribution for Realization 6 at maximum loading

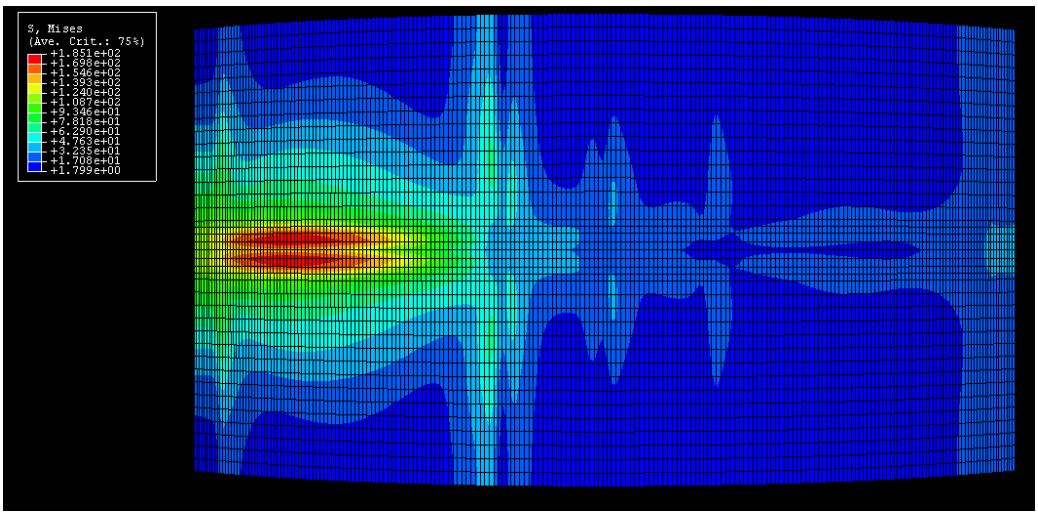


Figure 12. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 1 at first indication of yielding

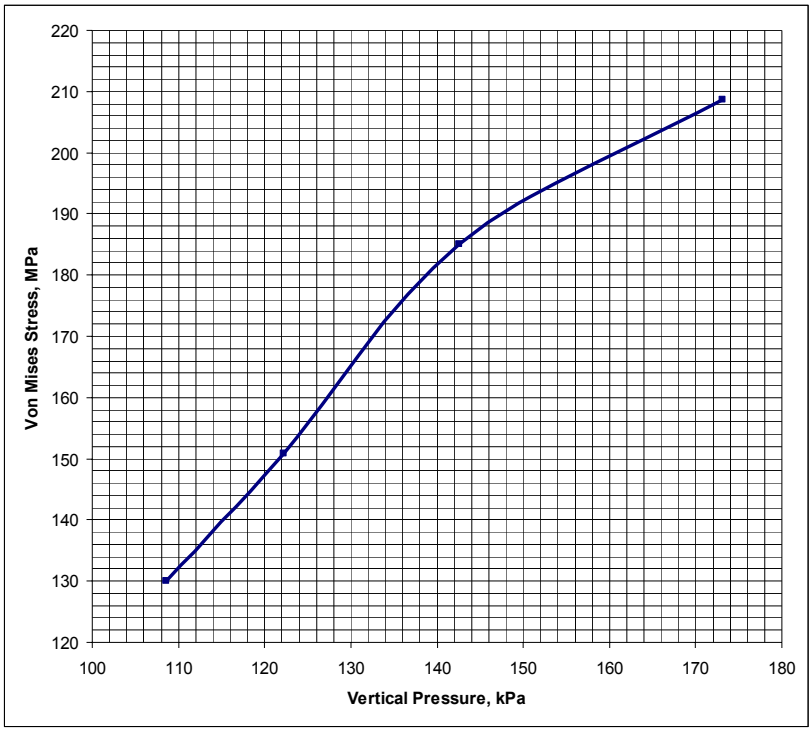


Figure 13. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 1 (135 *kPa* yielding point)

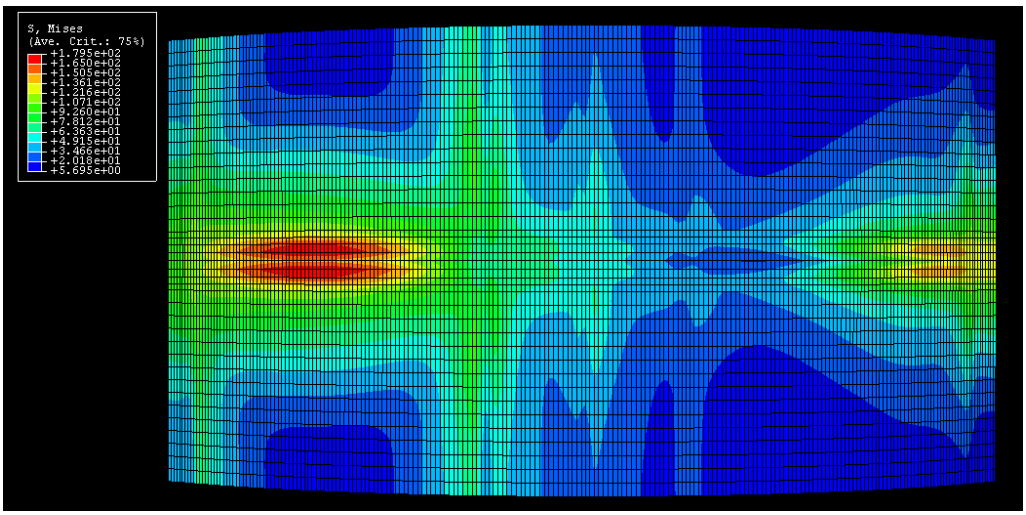


Figure 14. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 3 at first indication of yielding

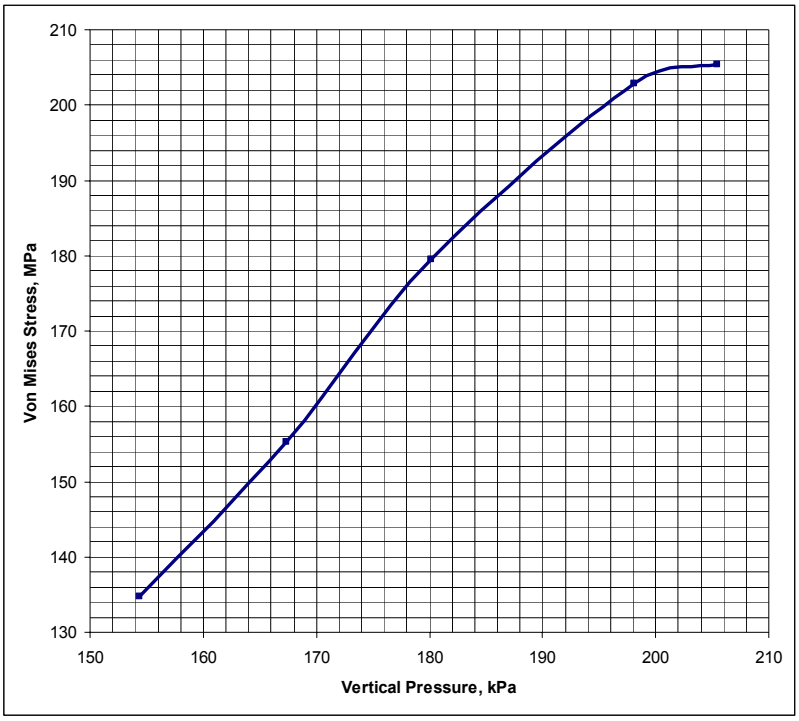


Figure 15. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 3 (177 *kPa* yielding point)

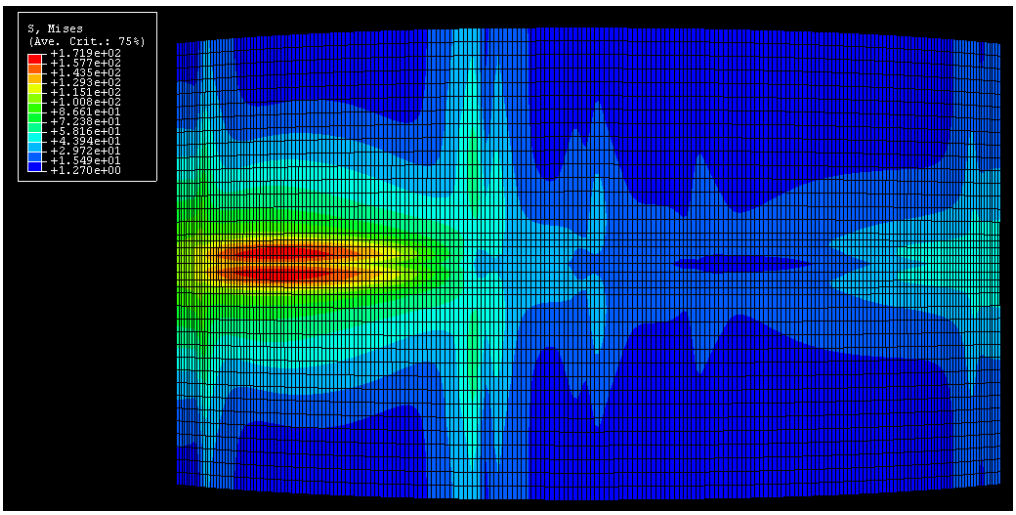


Figure 16. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 4 at first indication of yielding

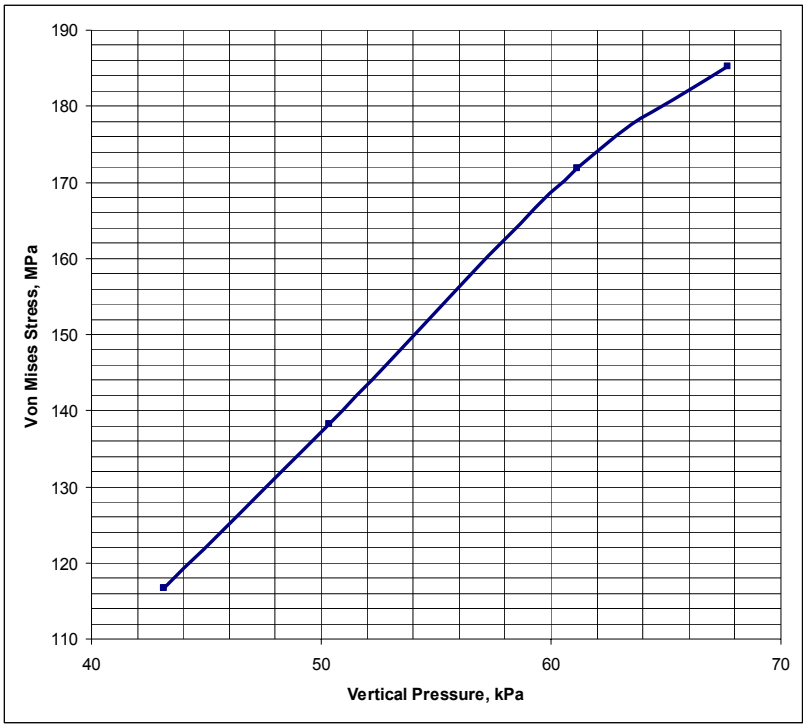


Figure 17. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 4 (62 *kPa* yielding point)

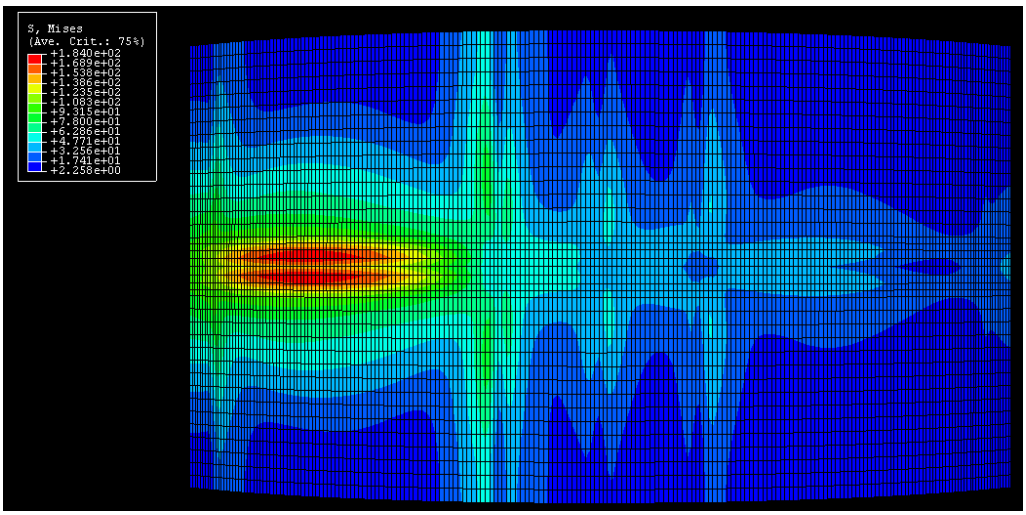


Figure 18. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 5 at first indication of yielding

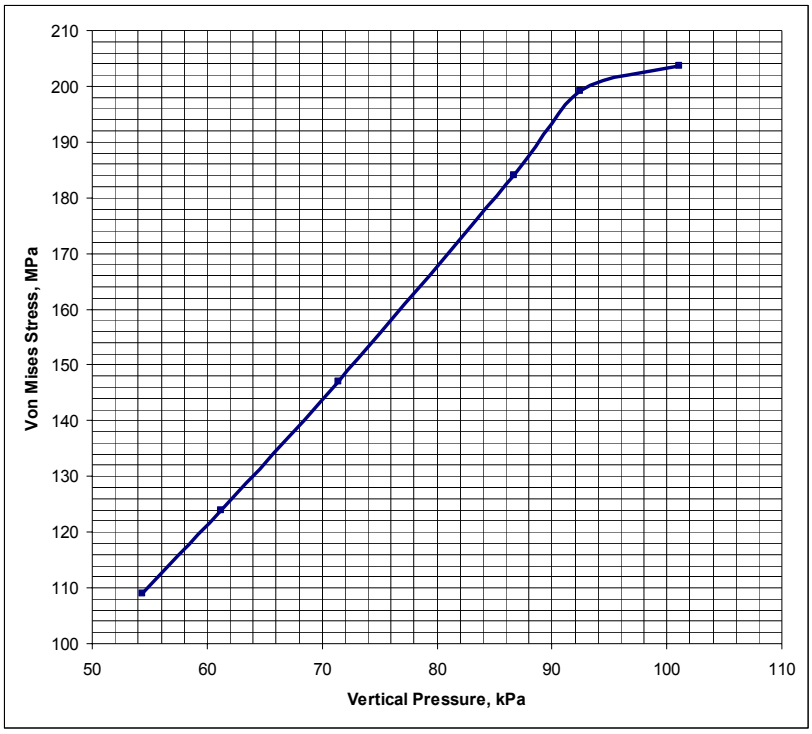


Figure 19. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 5 (82.5 *kPa* yielding point)

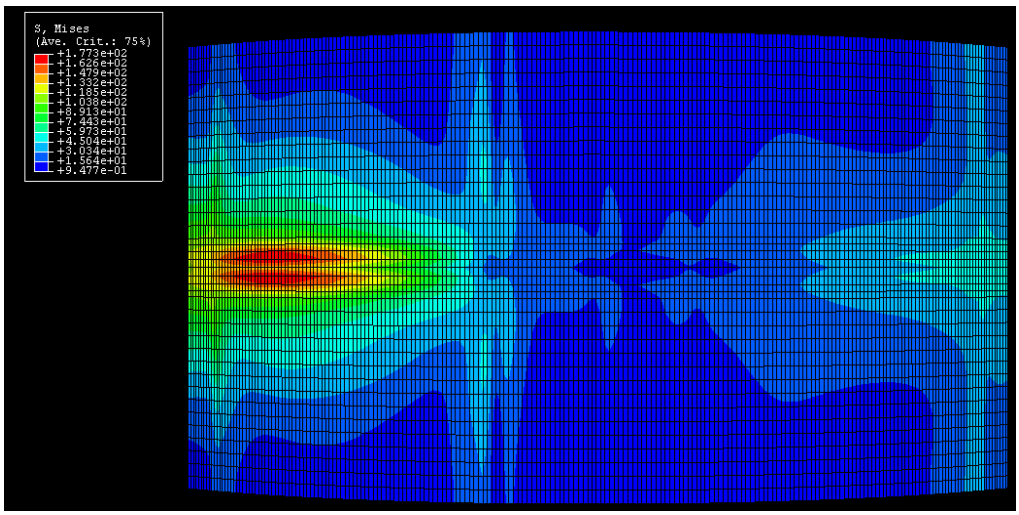


Figure 20. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 6 at first indication of yielding

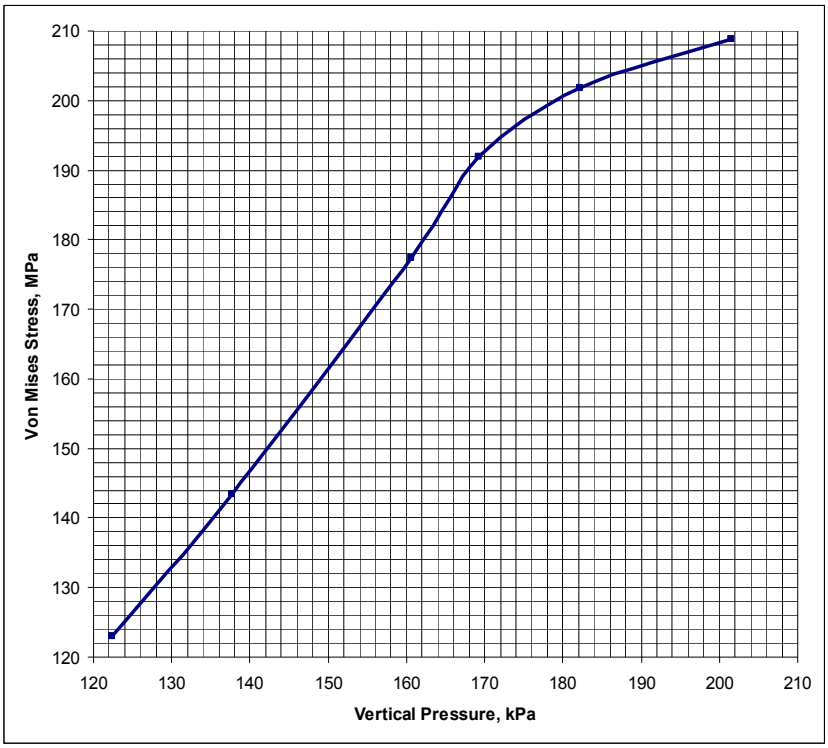
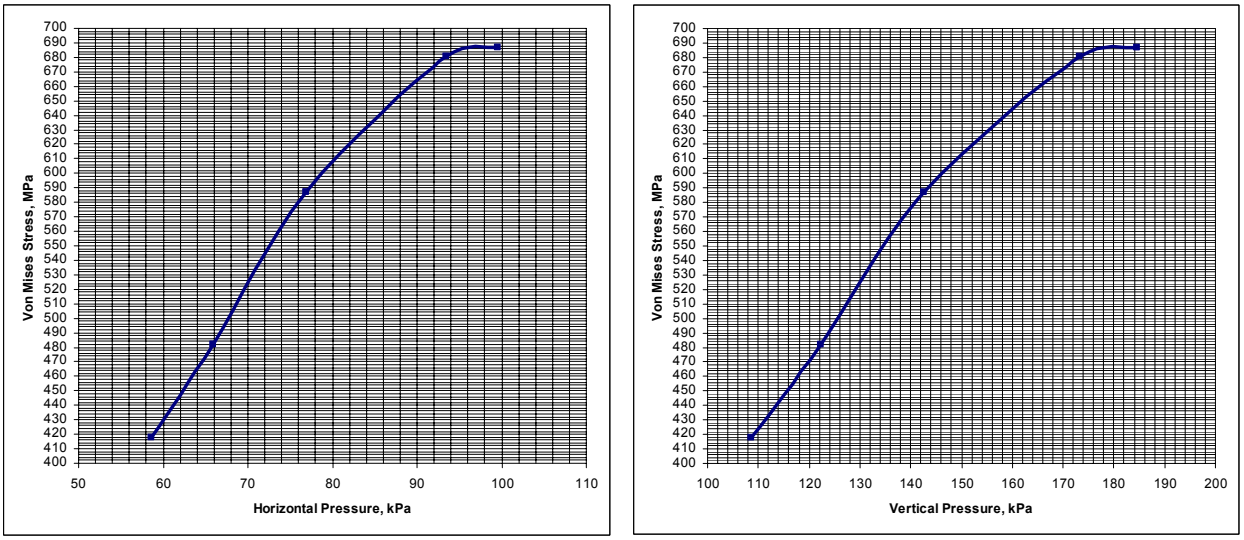
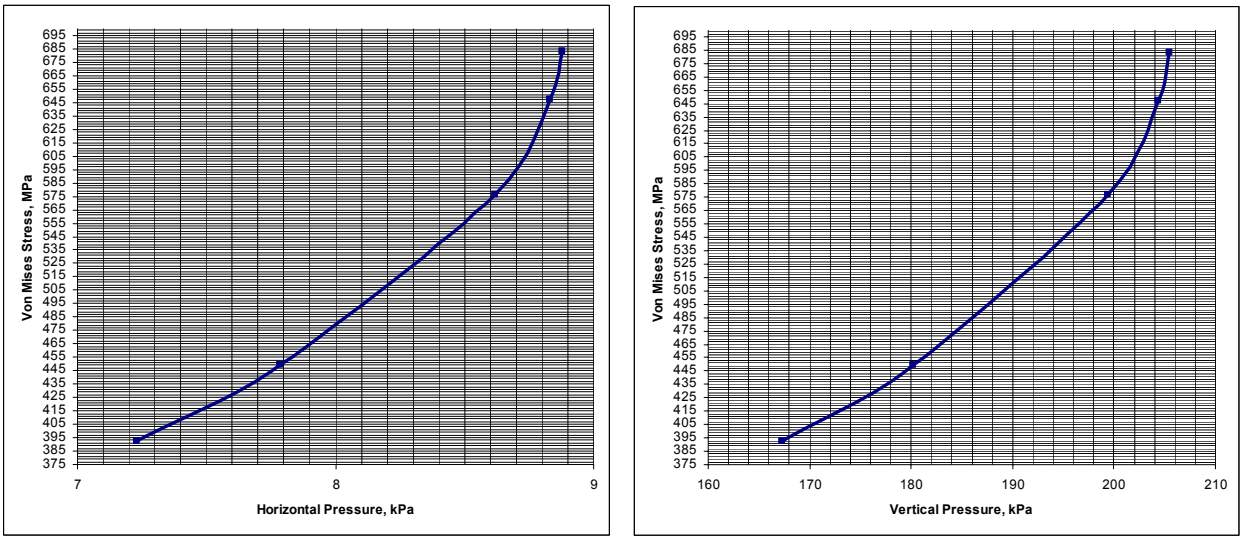


Figure 21. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 6 (158 *kPa* yielding point)



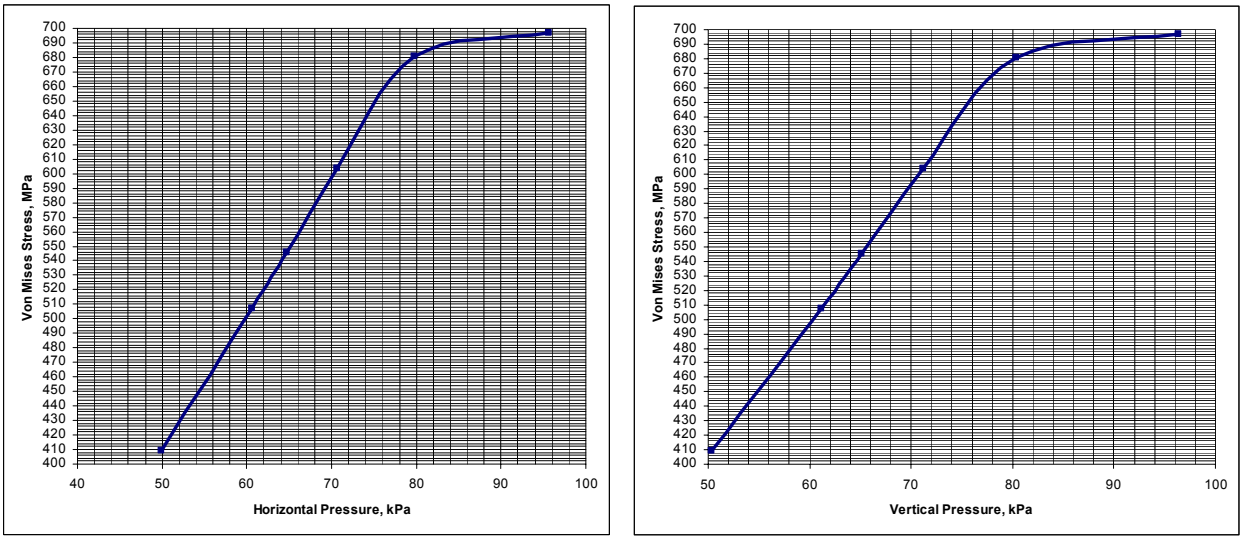
(a) (b)

Figure 22. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {89 *kPa* yielding point } and (b) vertical {165 *kPa* yielding point } pressure for Realization 1



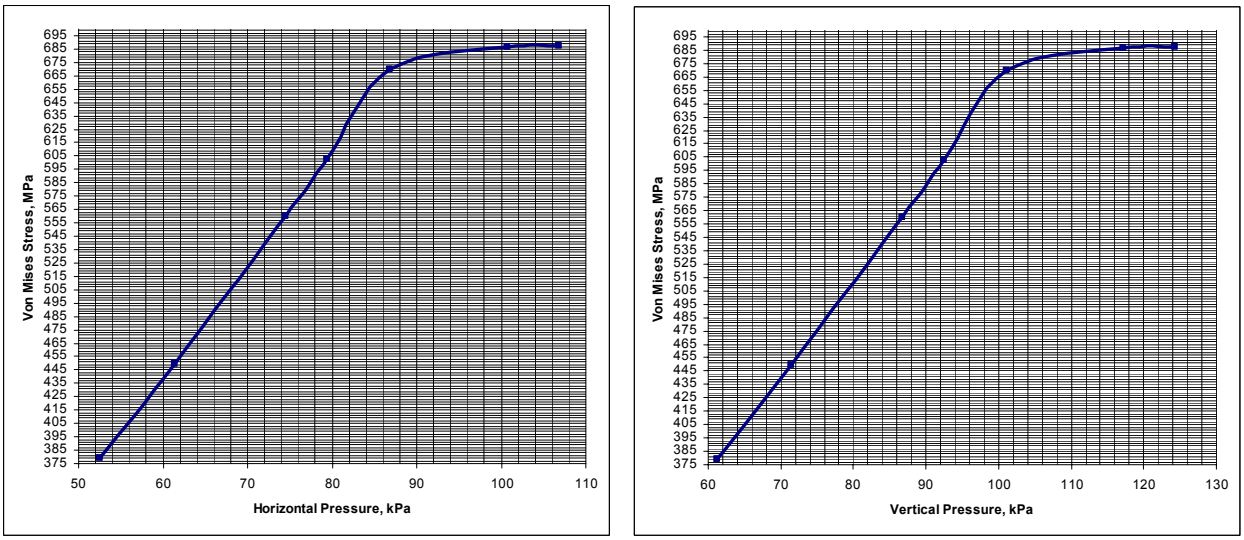
(a) (b)

Figure 23. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {8.85 *kPa* yielding point } and (b) vertical {205 *kPa* yielding point } pressure for Realization 3



(a) (b)

Figure 24. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {76 *kPa* yielding point } and (b) vertical {76.5 *kPa* yielding point } pressure for Realization 4



(a) (b)

Figure 25. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {84.5 *kPa* yielding point } and (b) vertical {101 *kPa* yielding point } pressure for Realization 5

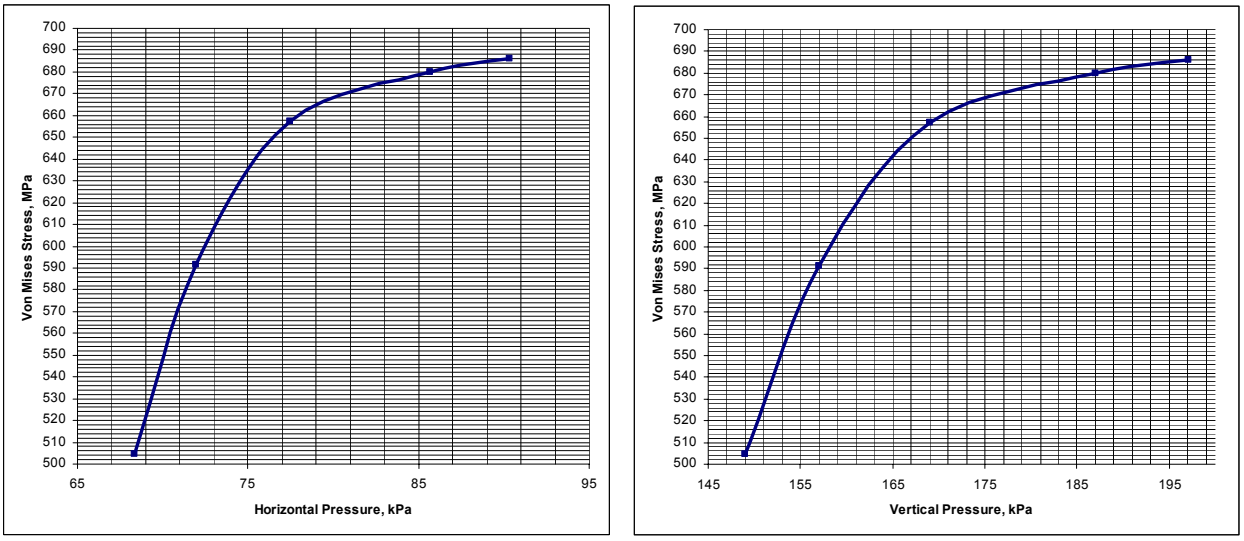


Figure 26. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {77.5 *kPa* yielding point } and (b) vertical {169 *kPa* yielding point } pressure for Realization 6

Table 4. Summary for initiation of yielding in Titanium Grade 7 Shell Plate crown

Realization	**Vertical Pressure Applied to the Crown at first indication of yielding, *kPa***	**Max Pressure Applied, *kPa***		
		Left Side	**Crown**	**Right Side**
1	135	70.6	185.2	99.9
2	no yielding	49.0	376.5	49.5
3	177	41.7	205.9	8.9
4	62	42.4	96.0	95.3
5	82.5	70.4	124.0	106.5
6	158	57.0	197.0	90.3

Table 5. Summary for initiation of yielding in Titanium Grade 24 Support Beam

Realization	**Horizontal Pressure Applied to the Support Beam at first indication of yielding, *kPa***	**Vertical Pressure Applied to the Support Beam at first indication of yielding, *kPa***	**Max Pressure Applied, *kPa***		
			Left Side	**Crown**	**Right Side**
1	89	165	70.6	185.2	99.9
2	no yielding	no yielding	49.0	376.5	49.5
3	8.85	205	41.7	205.9	8.9
4	76	76.5	42.4	96.0	95.3
5	84.5	101	70.4	124.0	106.5
6	77.5	169	57.0	197.0	90.3

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

<u>Description of the "Partial Drip Shield" FE models Realization 4 with refined mesh</u>
(D:\DS\DSrev4_fine.*)**

The finite element model was re-meshed to decrease (1.5 to 3 times reduction in the transverse direction) a typical size of elements. This resulted in the following typical element sizes:

(i) Bulkhead Web, Bulkhead Flanges, Longitudinal Stiffeners, and Support Beams – 10×10×10 *mm*.
(ii) Shell Plate – 7.5×10×10 *mm*.
(iii) Internal and External Support Plates elements ranges between 10×12.7×10 *mm* and 12×12.7×10 *mm*.
(iv) Base elements ranges between 7.5×10×10 *mm* and 10×10×10 *mm*.

The same boundary conditions (loads and kinematic constraints), as in the finite element model Realization 4, were applied (see pages4 and 7-8 for more details).

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

<u>Results for the "Partial Drip Shield" FE models Realization 4 with refined mesh</u>
(D:\DS\DSrev4_fine.*)**

The computational analysis completion rate for the Rev. 4 refined model is 72.4*%,* which is equal to the following maximum pressures applied: left side – 41.4 *kPa*, crown – 93.95 kPa, and right side – 93.27 *kPa* (74*%* completion rate for the original model). The maximum Von Mises stress is estimated at 691.5 *MPa* (697.1 *MPa* for the original model) and is located at the Right Support Beam.

From comparison of Figures 9 and 27, it can be concluded that both models (with initial and refined meshes) result in similar Von Mises stress distributions with a difference less than 1% for the maximum stress. From comparison of Figures 16 and 28, and Figures 17 and 28, it can be concluded that both models (with initial and refined meshes) result in similar Von Mises stress distributions for the Titanium Grade 7 Shell Plate crown. However, for the case with initial mesh, initiation of yielding occurs at 62 *kPa* vertical load, where as in the case with refined mesh, initiation of yielding occurs at 56 *kPa*. This difference accounts for about 10*%*. No differences between models are observed in the initiation of yielding in the Titanium Grade 24 Support Beam, in both cases it occurs at 76 *kPa* horizontal and 76.5 *kPa* vertical loading pressures (refer to Figures 24 and 30).

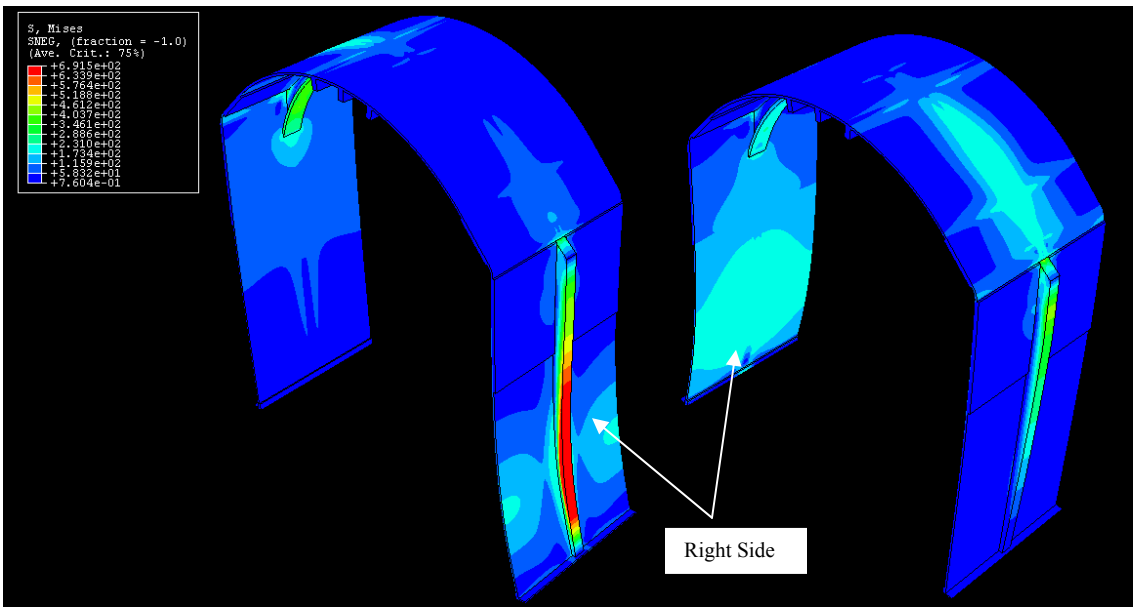


Figure 27. Von Mises stress distribution for Realization 4 with refined mesh at maximum loading

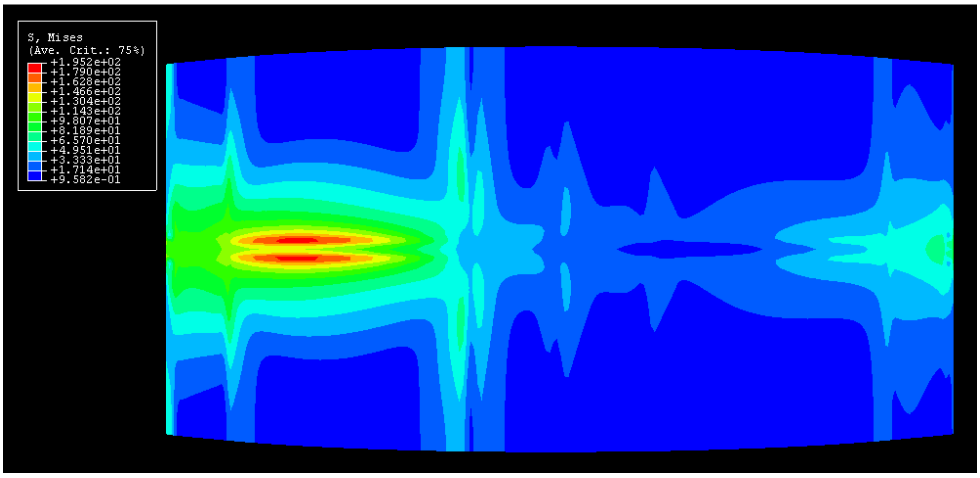


Figure 28. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 4 with refined mesh at first indication of yielding

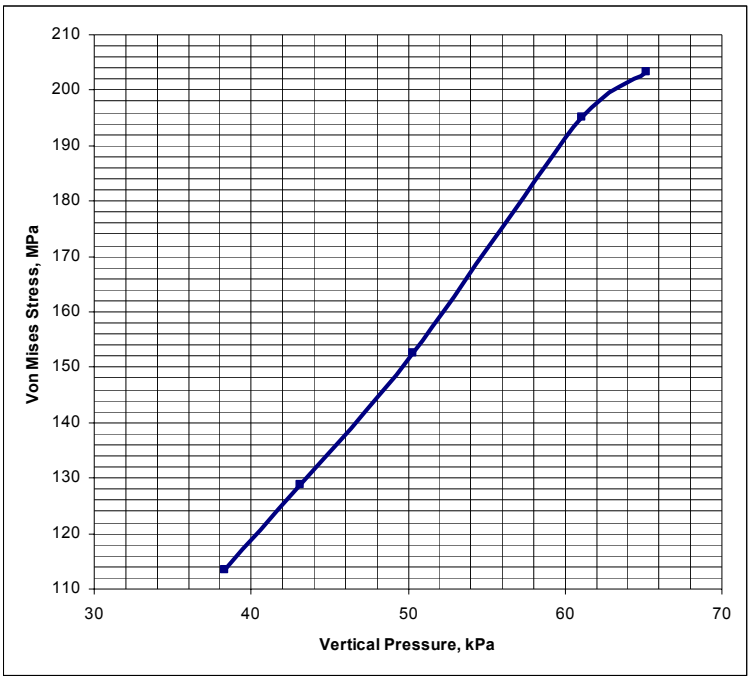


Figure 29. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 4 with refined mesh (56 *kPa* yielding point)

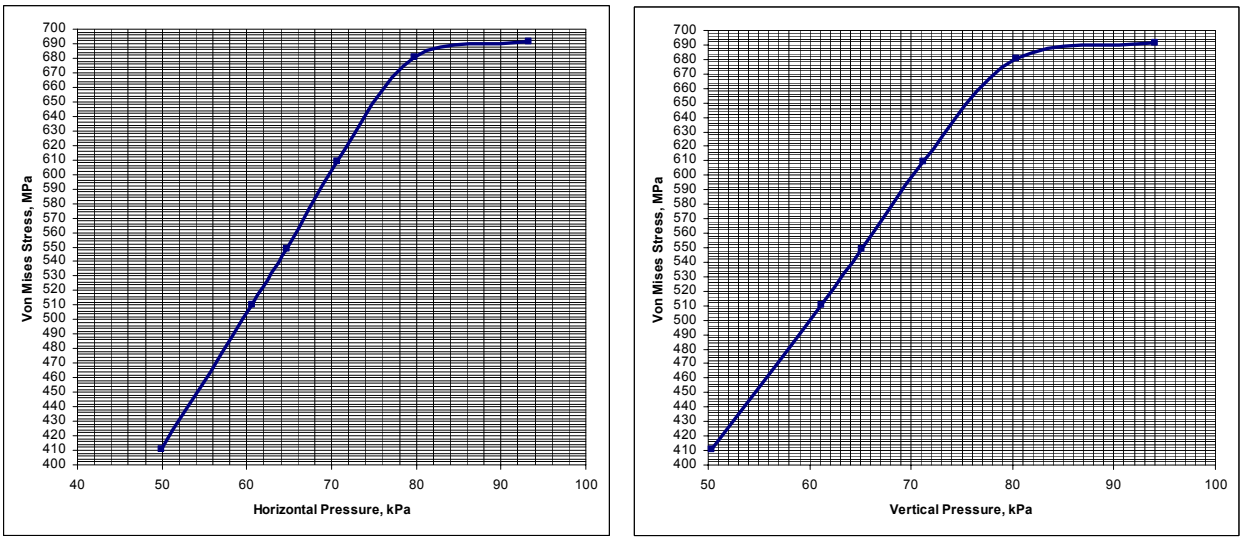


Figure 30. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {76 *kPa* yielding point } and (b) vertical {76.5 *kPa* yielding point }pressure for Realization 4 with refined mesh

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

<u>Description of the "Partial Drip Shield" FE models Realization 4 with shell elements</u>
(D:\DS\DSrev4_shell.*)**

The finite element model has been re-meshed (see Figure 31) to replace 8-node continuum elements with 4-node doubly curved general-purpose shell elements (S4). The following typical element sizes are used:

(i) Bulkhead Web, and Support Beams –10×10×20 *mm* (C3D8).
(ii) Bulkhead Flanges – from 10×10×15 *mm* to10×10×20 *mm* (C3D8).
(iii) Longitudinal Stiffeners – from 10×10×15 *mm* to10×10×30 *mm* (C3D8).
(iv) Shell Plate – from 15×10×15 *mm* to 15×10×30 *mm* (S4).
(v) Internal and External Support Plates elements ranges between 10×12.7×15 *mm* and 12×12.7×30 *mm* (SC8R).
(vi) Base elements ranges between 7.5×10×15 *mm* and 10×10×30 *mm* (SC8R).

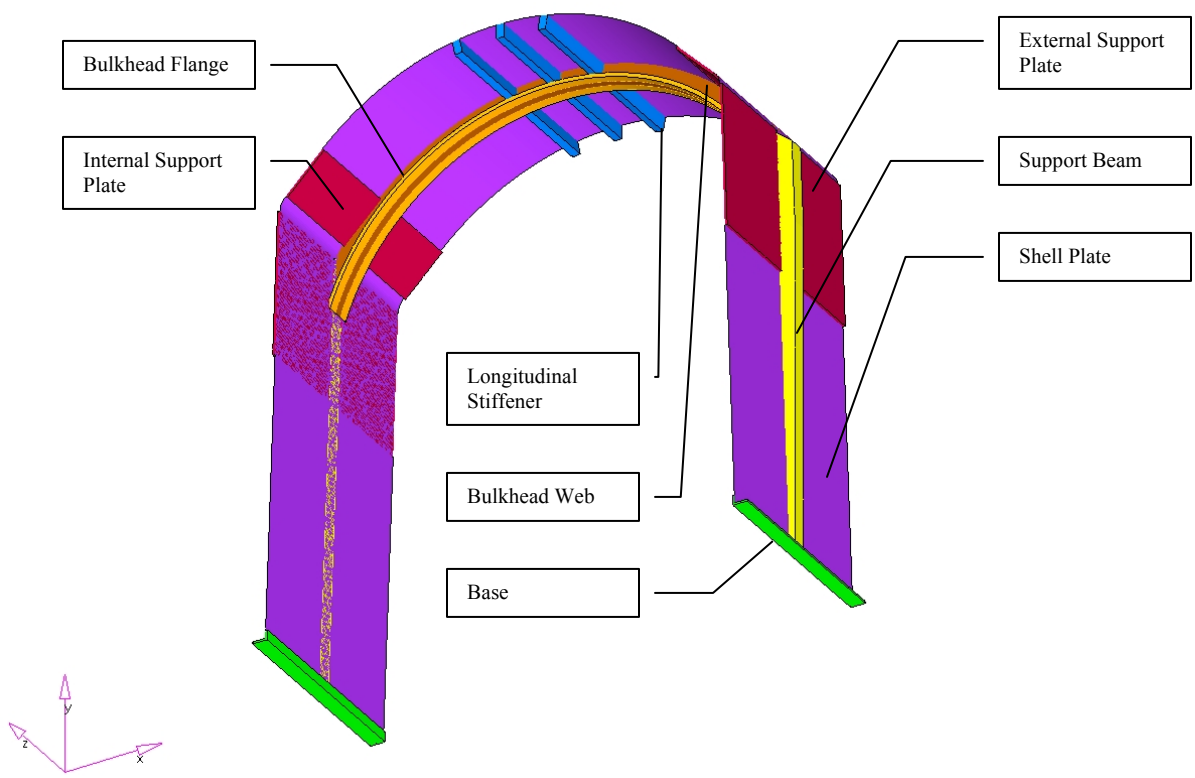


Figure 31.

The same boundary conditions (loads and kinematic constraints), as in the finite element model Realization 4, were applied (see pages4 and 7-8 for more details).

Date: November 10, 2006
Entry by: Roman V. Kazban

<u>Results for the "Partial Drip Shield" FE models Realization 4 with refined mesh</u>
(D:\DS\DSrev4_shell.*)**

The first indication of reaching ultimate tensile strength (UTS) in Titanium Grade 24 Support Beams occurs at about 60.5% of completion, which is equal to the following maximum pressures applied: left side – 34.62 *kPa*, crown – 78.50 *kPa*, and right side – 77.94 *kPa* (74% completion rate for the original, and 72.4% completion rate for the refined models with C3D8 elements representing the Shell Plate). The maximum Von Mises stress is located at the Right Support Beam.

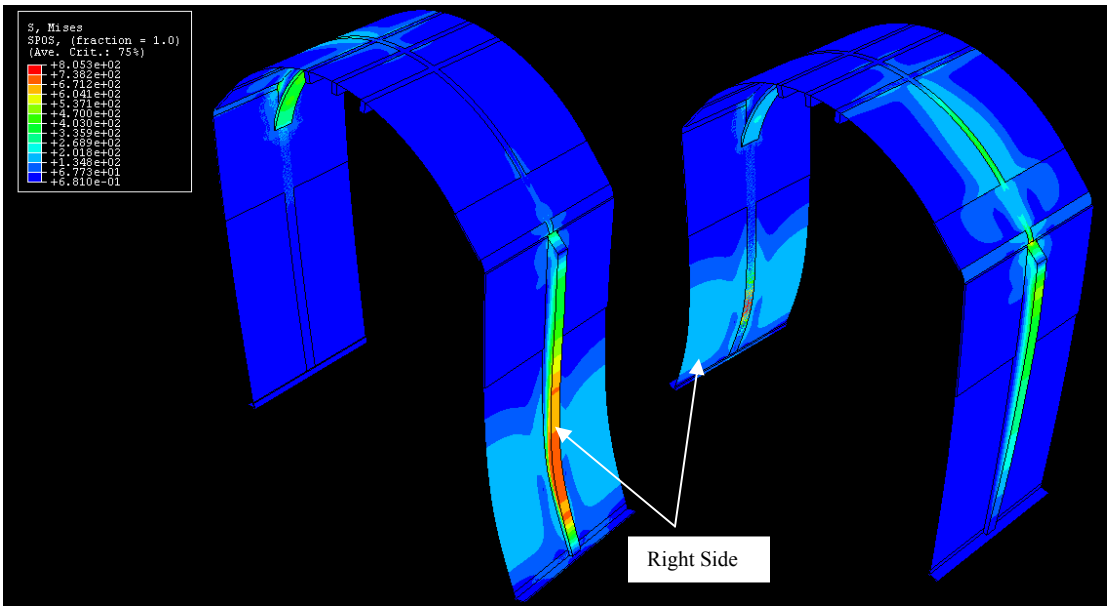


Figure 32. Von Mises stress distribution for Realization 4 with shell elements at first indication of reaching UTS in Ti-24 Support Beam

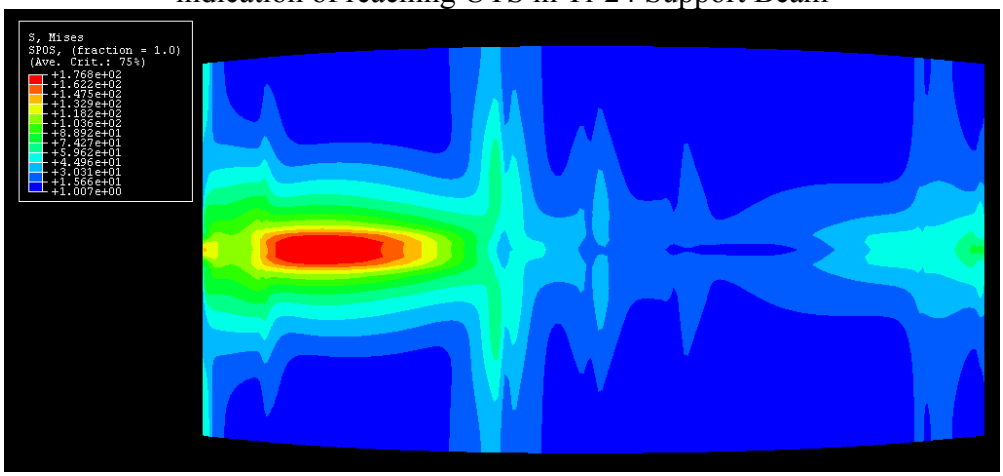


Figure 33. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 4 with shell elements at first indication of yielding in Ti-7

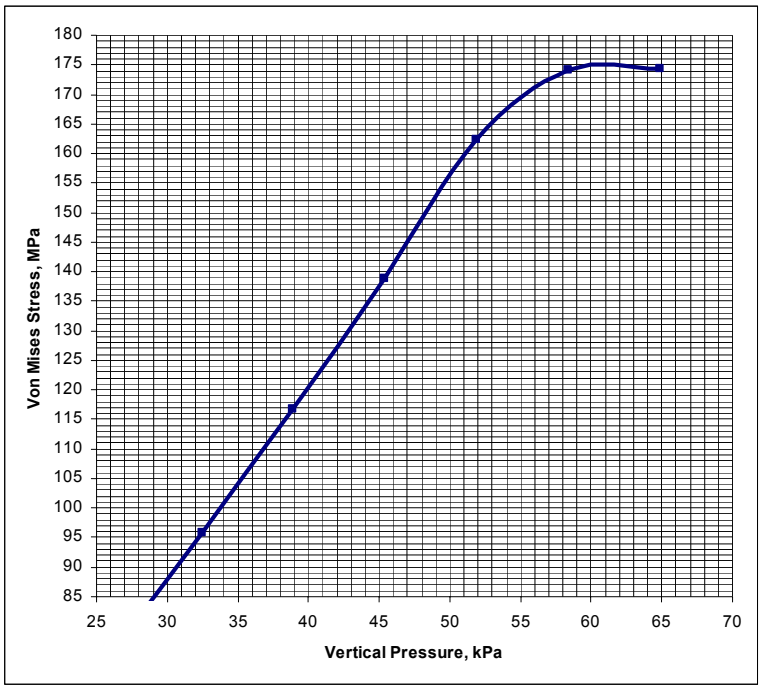


Figure 34. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 4 with shell elements (58 *kPa* yielding point)

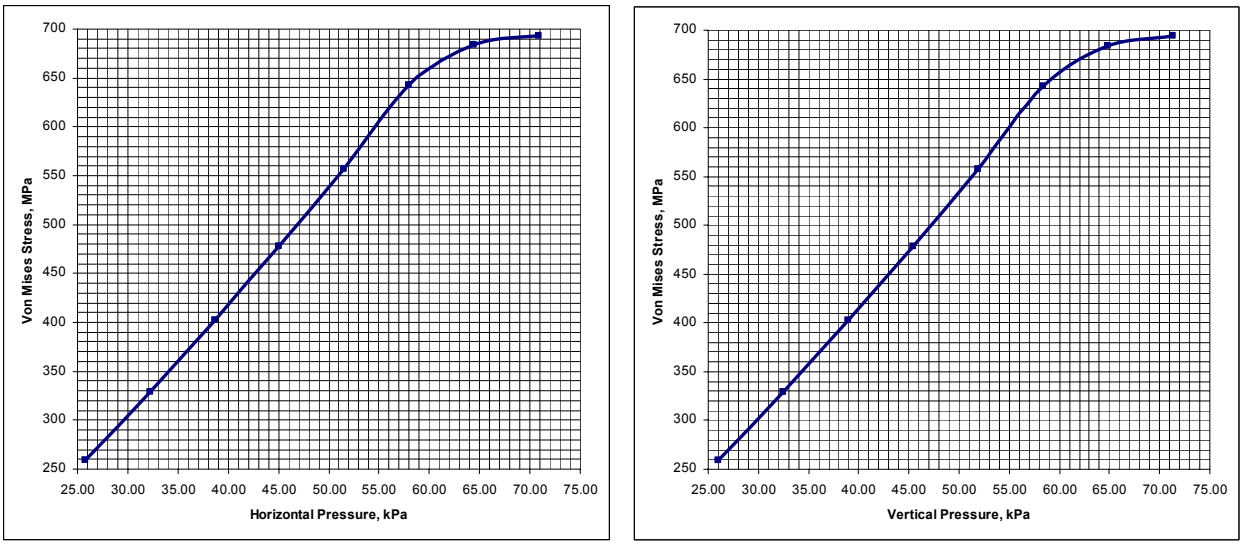


Figure 35. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {60 *kPa* yielding point} and (b) vertical {61 *kPa* yielding point}pressure for Realization 4 with shell elements

Date: November 11, 2006
Entry by: Roman V. Kazban

<u>Description of the "Partial Drip Shield" FE models Realization 4 with refined shell elements</u> (D:\DS\DSrev4_shell_fine.*)**

The finite element model was re-meshed to decrease (1.5 to 3 times reduction in the transverse direction) a typical size of elements. This resulted in the following typical element sizes:

(i) Bulkhead Web, Bulkhead Flanges, Longitudinal Stiffeners, and Support Beams – 10×10×10 *mm* (C3D8).
(ii) Shell Plate – 15×10×10 *mm* (S4).
(iii) Internal and External Support Plates elements ranges between 10×12.7×10 *mm* and 12×12.7×10 *mm* (SC8R).
(iv) Base elements ranges between 7.5×10×10 *mm* and 10×10×10 *mm* (SC8R).

The same boundary conditions (loads and kinematic constraints), as in the finite element model Realization 4, were applied (see pages4 and 7-8 for more details).

Date: November 12, 2006
Entry by: Roman V. Kazban

<u>Results for the "Partial Drip Shield" FE models Realization 4 with refined mesh</u> (D:\DS\DSrev4_shell_fine.*)**

The first indication of reaching ultimate tensile strength (UTS) in Titanium Grade 24 Support Beams occurs at about 60.7% of completion, which is equal to the following maximum pressures applied: left side – 34.62 *kPa*, crown – 78.50 *kPa*, and right side – 77.94 *kPa* (74% completion rate for the original, and 72.4% completion rate for the refined models with C3D8 elements representing the Shell Plate). The maximum Von Mises stress is located at the Right Support Beam.

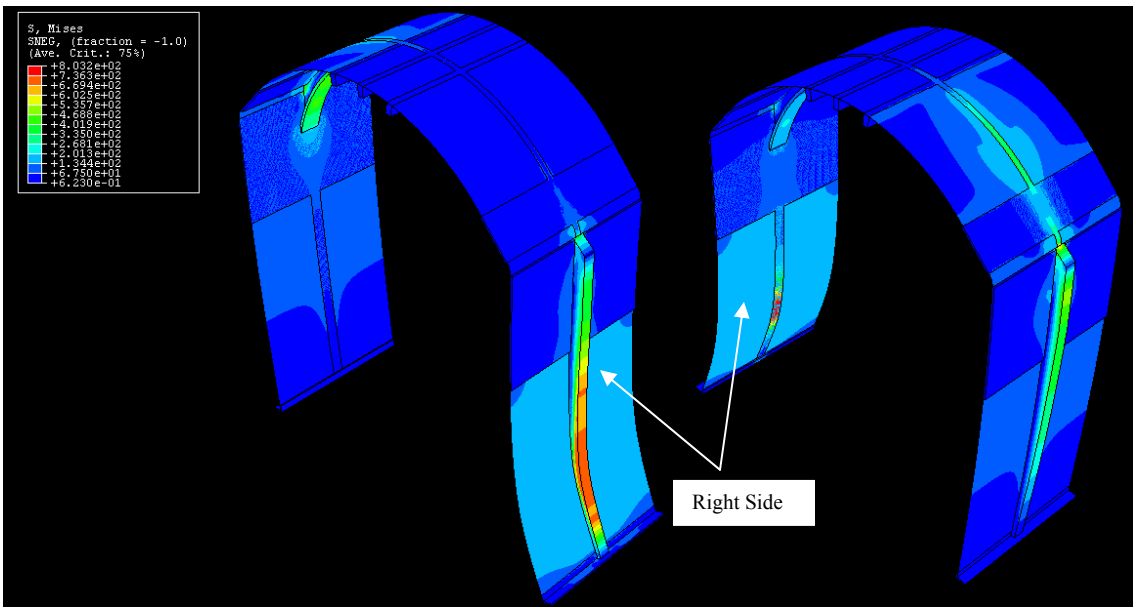


Figure 36. Von Mises stress distribution for Realization 4 with refined shell elements at first indication of reaching UTS in Ti-24 Support Beam

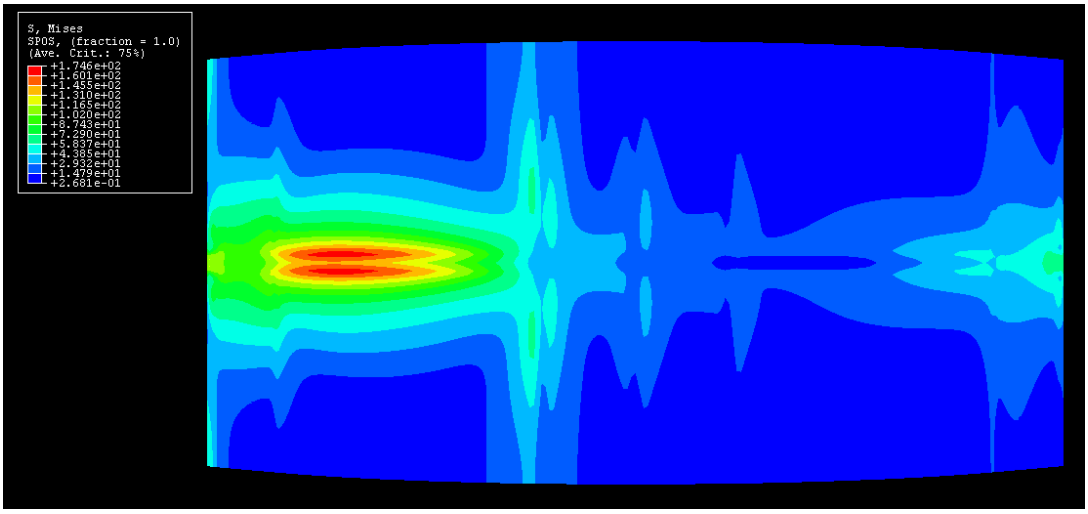


Figure 37. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 4 with refined shell elements at first indication of yielding in Ti-7

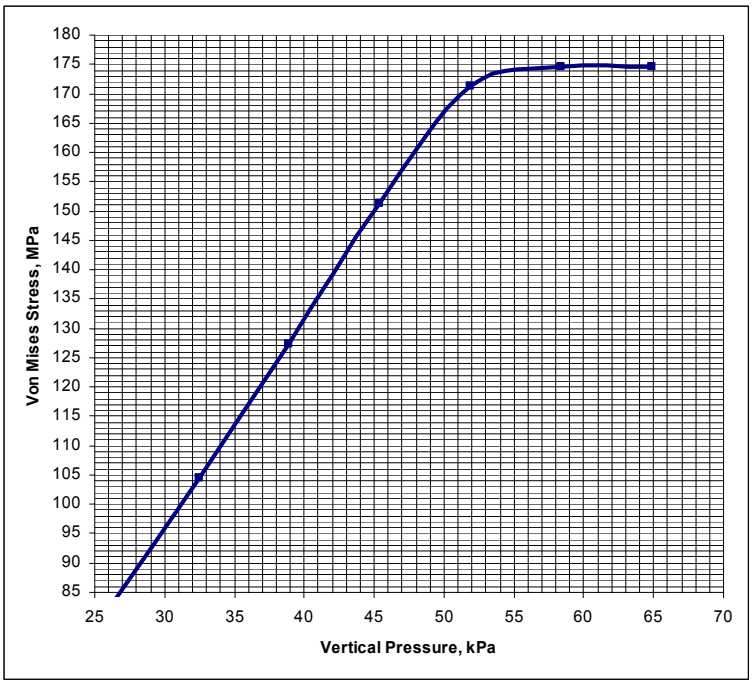


Figure 38. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 4 with refined shell elements (54 *kPa* yielding point)

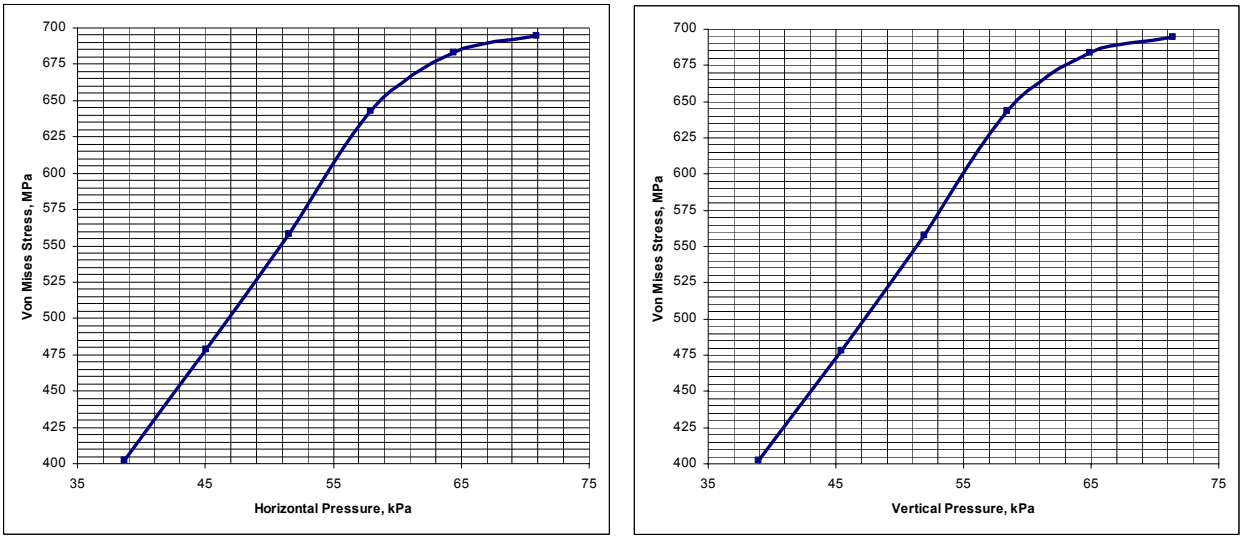


Figure 39. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {60 *kPa* yielding point} and (b) vertical {60.5 *kPa* yielding point}pressure for Realization 4 with shell elements

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

<u>Description of the "Partial Drip Shield" FE models Realization 4 with refined shell elements</u> (D:\DS\DSrev4_shell_fine_plus.*)**

The finite element model has been re-meshed (see Figure 40) to replace Internal and External Support Plate quadrilateral continuum shell elements with reduced integration (SC8R) with 4-node doubly curved general-purpose shell elements (S4). To reduce the number of elements in the model, the elements of the Internal and External Support Plates represent the combination through the thickness of the Shell Plate and Support Plates elements. Therefore, the thickness of these elements is set to 27.7 *mm*, which includes a 15 *mm* thick Shell Plate and a 12.7 *mm* thick Support Plates. The following typical element sizes are used:

(i) Bulkhead Web, Bulkhead Flanges, Longitudinal Stiffeners, and Support Beams – 10×10×10 *mm* (C3D8).
(ii) Shell Plate – 10×10×15 *mm* (S4).
(iii) Internal and External Support Plates elements ranges between 10×10×27.7 *mm* and 10×12×27.7 *mm* (S4).
(iv) Base elements ranges between 7.5×10×10 *mm* and 10×10×10 *mm* (SC8R).

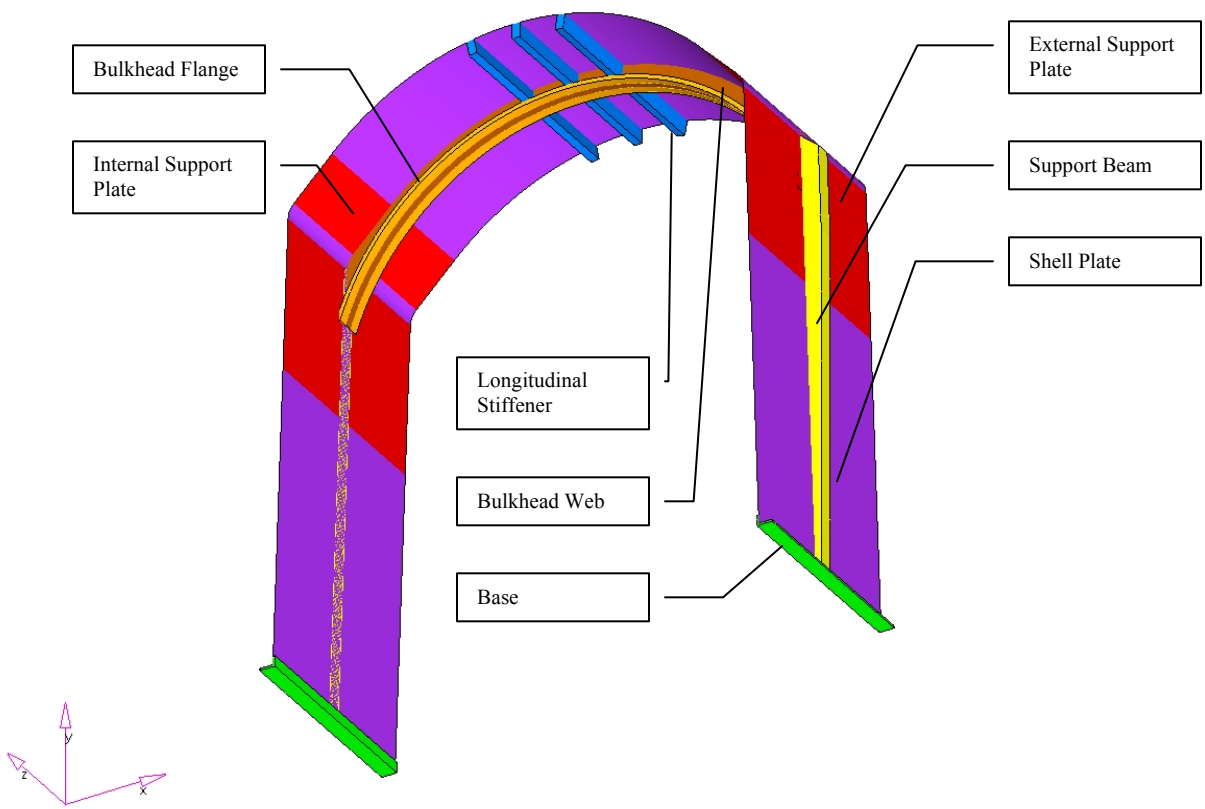


Figure 40.

The same boundary conditions (loads and kinematic constraints), as in the finite element model Realization 4, were applied (see pages 4 and 7-8 for more details).

Date: November 27, 2006
Entry by: Roman V. Kazban

<u>Results for the "Partial Drip Shield" FE models Realization 4 with refined mesh</u>
(D:\DS\DSrev4_shell_fine_plus.*)**

The first indication of reaching ultimate tensile strength (UTS) in Titanium Grade 24 Support Beams occurs at about 60.5% of completion, which is equal to the following maximum pressures applied: left side – 34.62 *kPa*, crown – 78.50 *kPa*, and right side – 77.94 *kPa* (74% completion rate for the original, and 72.4% completion rate for the refined models with C3D8 elements representing the Shell Plate). The maximum Von Mises stress is located at the Right Support Beam.

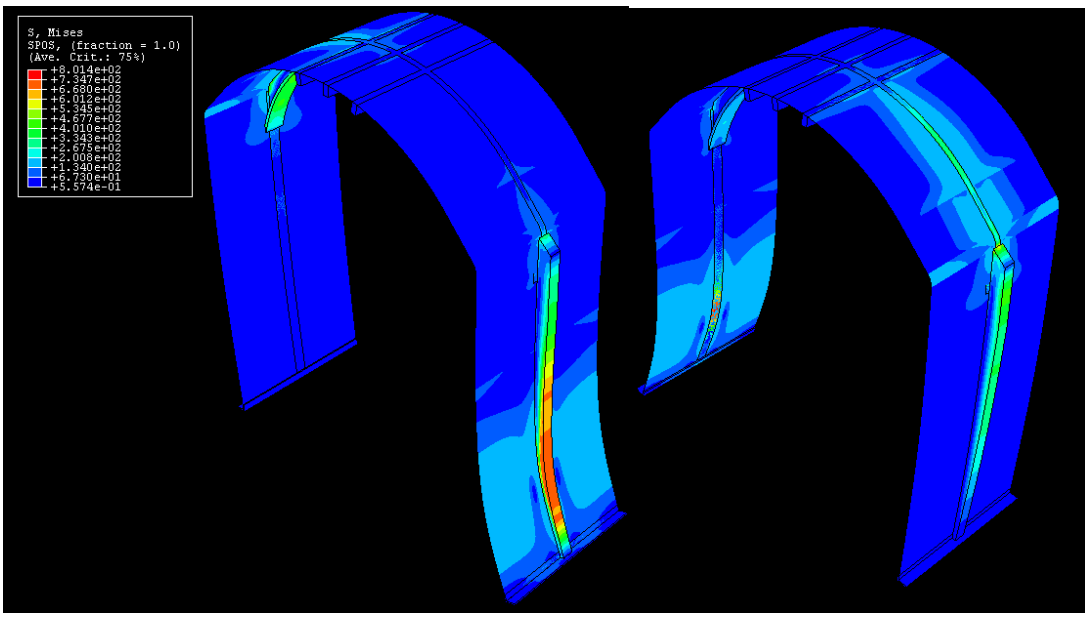


Figure 41. Von Mises stress distribution for Realization 4 with refined shell elements at first indication of reaching UTS in Ti-24 Support Beam

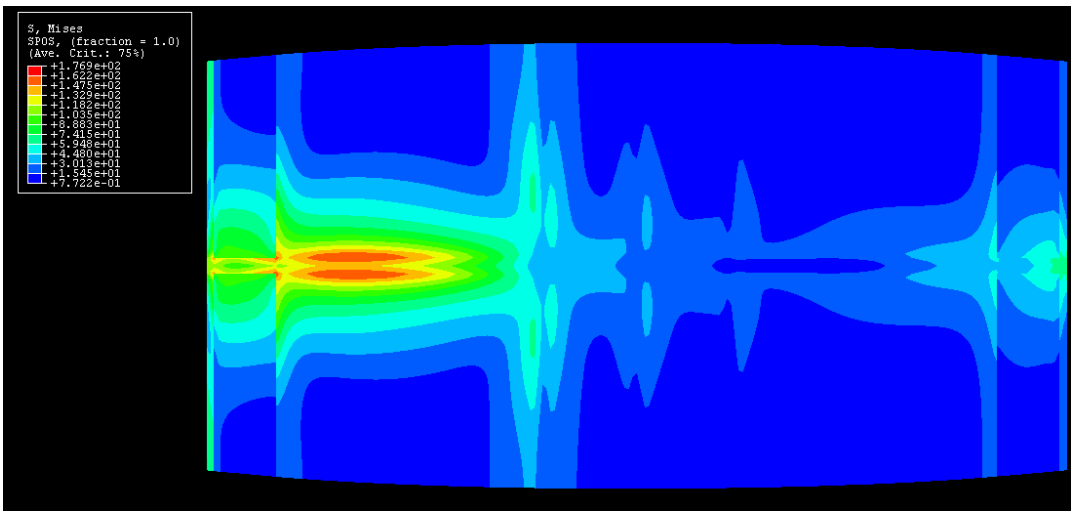


Figure 42. Von Mises stress distribution in the Shell Plate crown (top view) for Realization 4 with refined shell elements at first indication of yielding in Ti-7

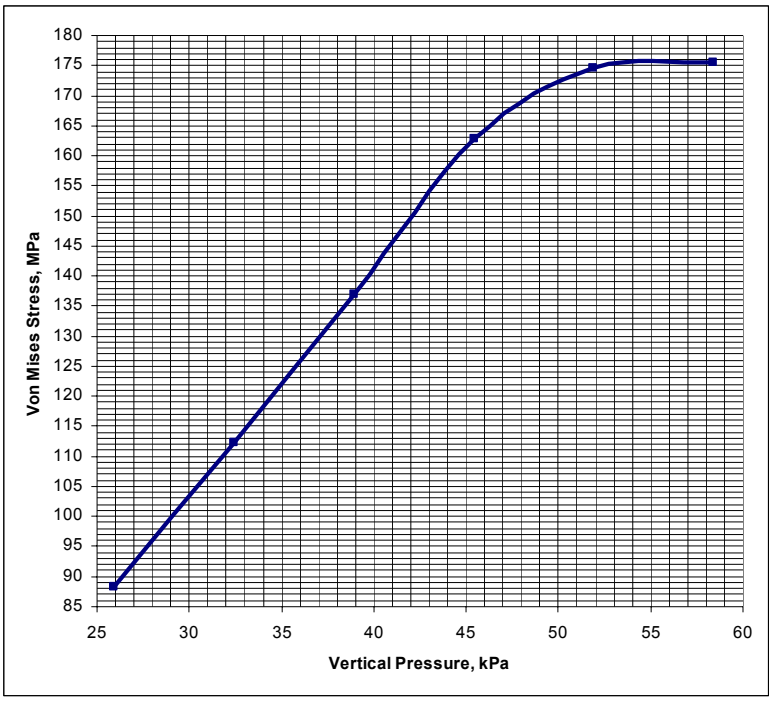


Figure 43. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure for Realization 4 with refined shell elements (52 *kPa* yielding point)

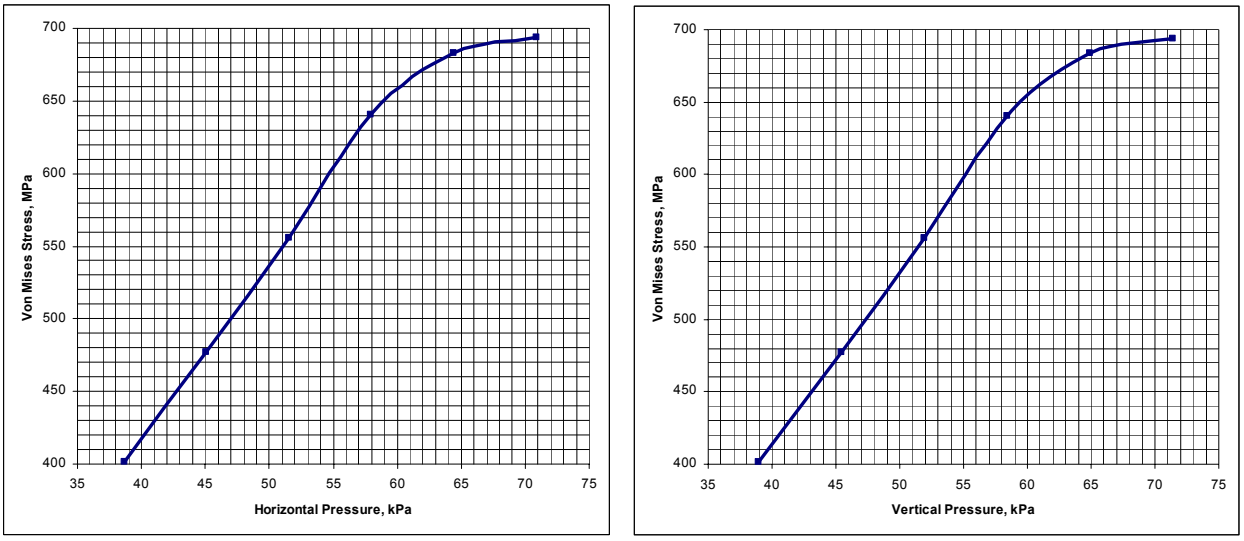


Figure 44. Von Mises stress in the Support Beam of the Drip Shield as a function of (a) horizontal {60 *kPa* yielding point} and (b) vertical {60.5 *kPa* yielding point}pressure for Realization 4 with shell elements

-----end of part 1-----

Date: May 29, 2007
Entry by: Roman V. Kazban

<u>Description of the "Base Line No Non-Linear Springs" FE model</u> (D:\DS\DS Models \Base_Line_No_NLS.*)**

The finite element model is presented on Figure 40. All dimensions used to construct the "Base Line No Non-Linear Springs" FE model were obtained from "Drip Shield Structural response to Rock Fall" (Document Identifier: 000-00C-SSE0-00300-000-00A) sketch number SK0230 Realization 00. The width of the Drip Shield (DS) is 1071.60 *mm*, which equals to the dimension between two adjoin Bulkheads or two adjoin Support Beams. Material properties for all materials used in this FE model correspond to material properties at 150°*C* (refer to page 2).

The FE model is constructed using a mixture of plate and solid elements. The following components are discretized with 8-node continuum elements (C3D8): the Titanium Grade 24 Bulkhead Web, the Bulkhead Flanges, the Longitudinal Stiffeners, and the Support Beams. Due to a sharp geometry of some components of the DS, a small number of 6-node linear tetrahedral elements (C3D6) are used to discretise the Bulkhead Web, the Bulkhead Flanges, and the Support Beams. The Titanium Grade 7 Shell Plate, Internal Support Plates, and External Support Plates are discretized with 4-node general-purpose shell elements (S4). The Alloy 22 Bases are constructed of the quadrilateral continuum shell elements with reduced integration (SC8R). A typical size of the Bulkhead Web, Bulkhead Flanges, Longitudinal Stiffeners, and Support Beams elements is 10×10×10 *mm*. A typical size of the Shell Plate elements is 10×10×15 *mm*. To reduce the number of elements in the model, the elements of the Internal and External Support Plates represent the combination through the thickness of the Shell Plate and Support Plates elements. Therefore, the thickness of these elements is set to 27.7 *mm*, which includes a 15 *mm* thick Shell Plate and a 12.7 *mm* thick Support Plates. A typical size of the Internal and External Support Plates combined with the Shell Plate elements ranges between 10×10×27.7 *mm* and 10×12×27.7 *mm*. A typical size of the Base elements ranges between 7.5×10×10 *mm* and 10×10×10 *mm*. The common surfaces between components are modeled as idealized tied surfaces by equivalencing the common nodes.

<u>Boundary Conditions</u>

Loads: The elements of the Shell and Internal Support Plates at the top of the DS, the elements at the top of the Support Beams, and the elements of the Base external side are loaded directly with 3000 *kPa* vertical pressure normally applied to each element (refer to Figure 45). Furthermore, (i) the elements that represent the Shell and External Plates on the left side of the DS are loaded directly with 1260 *kPa* normal pressure; and (ii) the elements that represent the Shell and the External Plates on the right side of the DS are loaded directly with 840 *kPa* normal pressure. This loading case corresponds to a 0.35 lateral to vertical pressure ratio and 0.50 lateral asymmetry ratio.

Kinematic Constraints: All nodes in the XY-plane that belongs to the sides of the Drip Shield are constrained in the transverse direction (z-axis) to represent symmetry conditions, and are constrained from rotation around x- and y-axis. The DS displacements in x- and y-directions are constrained by four SPRING1 elements (two in each direction) of a relatively small stiffness to prevent rigid body modes.

The Drip Shield is model as a free standing structure. Therefore, a friction condition is modeled between the Rigid Surface that represents the Invert and the Base bottom surfaces. The coefficient of friction is set to 0.4.

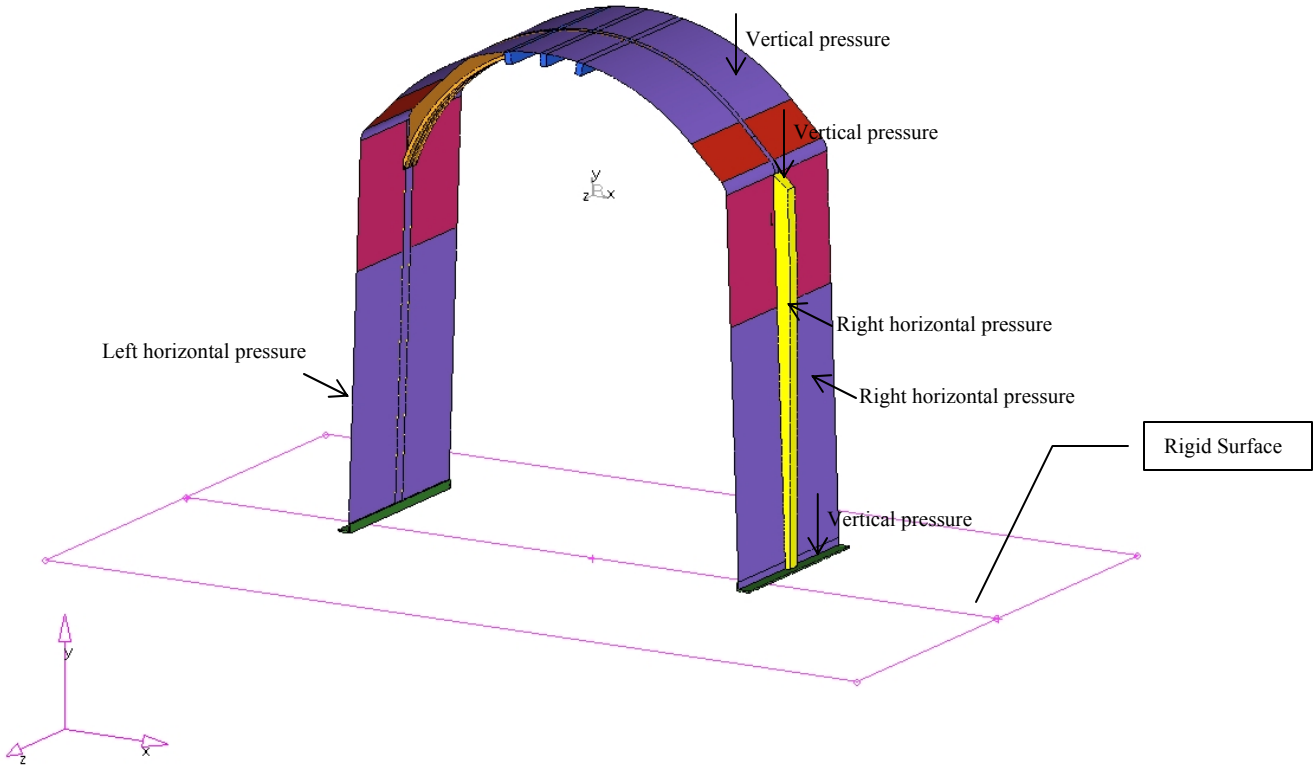


Figure 45. Loading of the Drip Shield

Date: May 30, 2007
Entry by: Roman V. Kazban

<u>Results for the "Base Line No Non-Linear Springs" FE model</u> (D:\DS\\DS Models Base_Line_No_NLS.*)"**

The first indication of reaching UTS in Titanium Grade 24 Support Beams occurs at about 5.93% of completion, which is equal to the following maximum pressures applied: left side – 74.72 *kPa*, crown – 177.90 *kPa*, and right side – 49.81 *kPa*. The maximum Von Mises stress is located in the Support Beam end at the Right Base. The maximum deformation occurs in the Left Support Beam some distance from the Base. The maximum Von Mises stress at this location is 694 *MPa*.

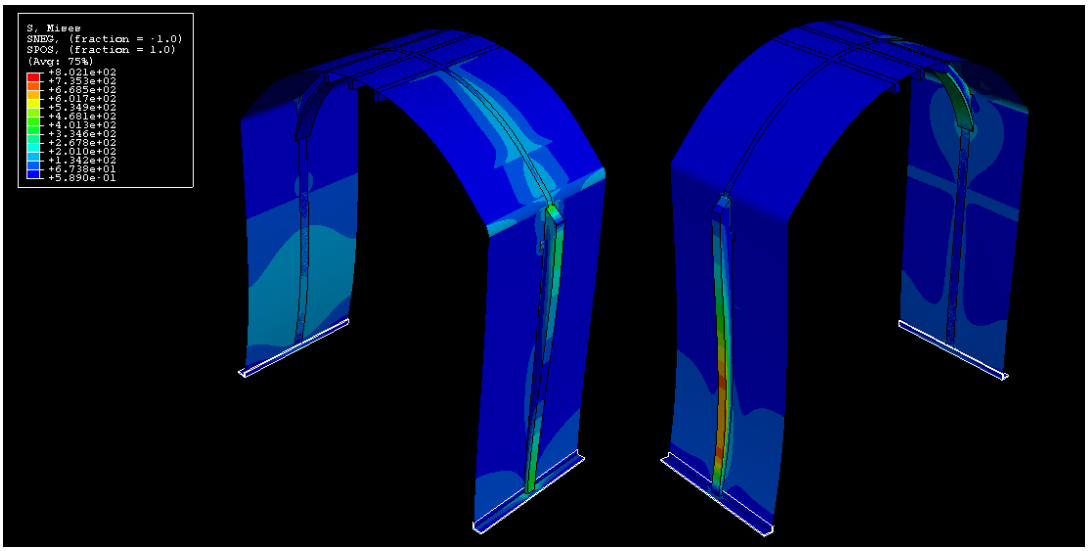


Figure 46. Von Mises stress distribution at first indication of reaching UTS in Ti-24 Support Beam

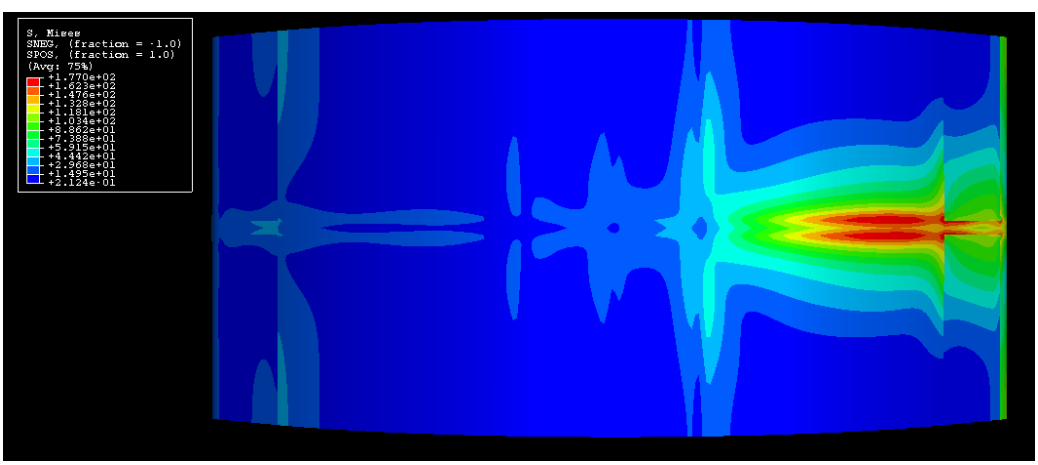


Figure 47. Von Mises stress distribution in the Shell Plate crown (top view) at first indication of yielding in Ti-7

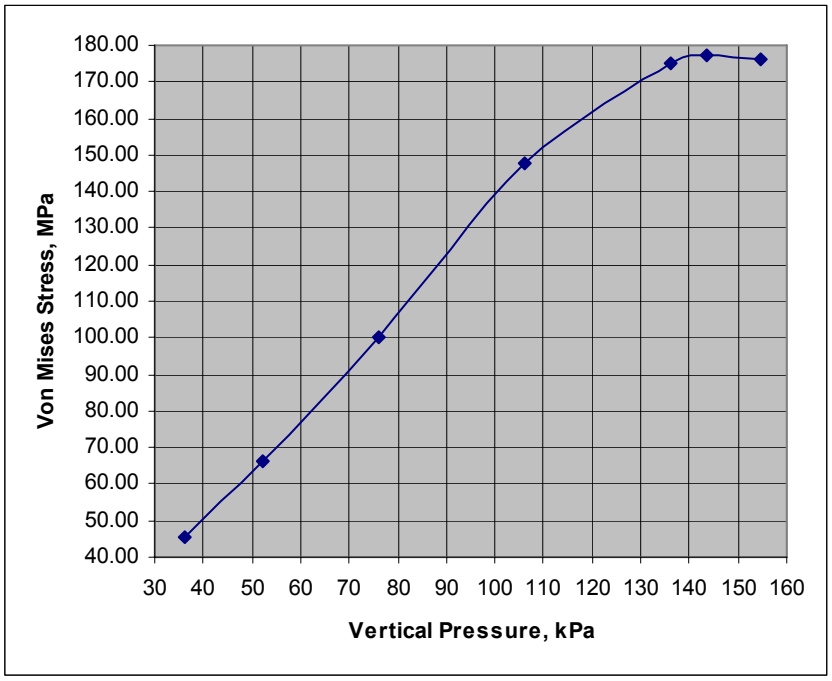
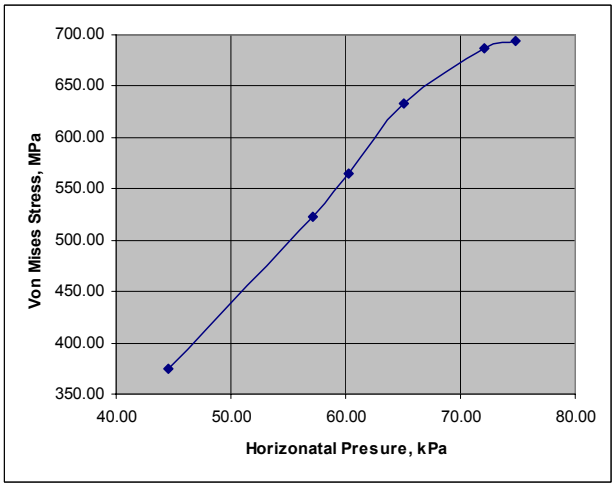


Figure 48. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure (yielding @ 134 *kPa*)



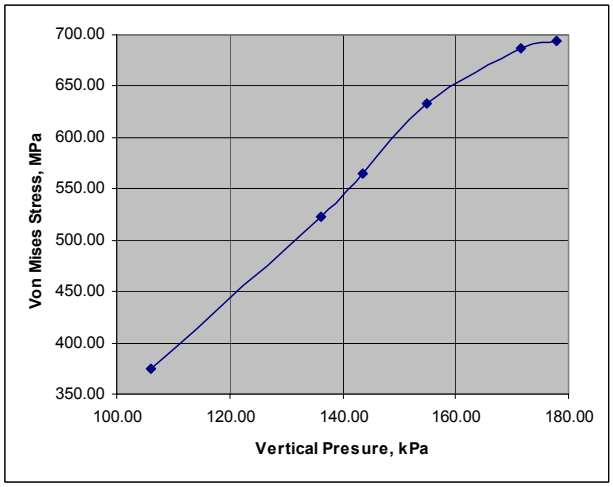


Figure 49. Von Mises stress in the Left Support Beam of the Drip Shield as a function of (a) horizontal {yielding @ 68 *kPa*} and (b) vertical {yielding @ 162 *kPa*} pressure

The displacement of the Left Base in x-direction (horizontal) as a function of the applied pressure to the DS is presented on Figure 50. It can be concluded that after the initial contact between the DS Base and the Rigid Surface achieved the DS Base does not move in the horizontal direction. The same type of behavior is observed for the Right Base as well.

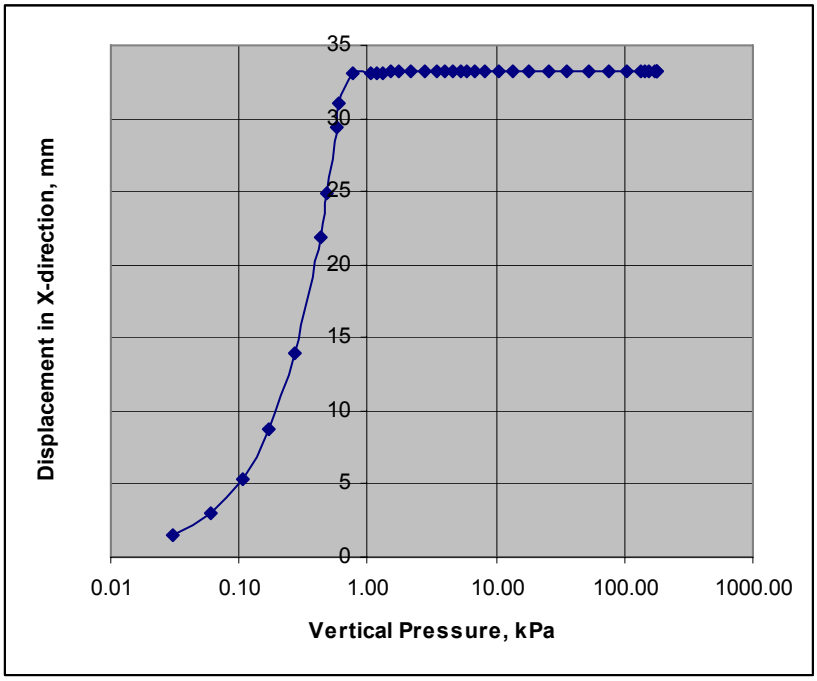


Figure 50. Left Base displacement in horizontal direction as a function of the Vertical Pressure applied to the DS

Date: May 30, 2007
Entry by: Roman V. Kazban

Description of the "Base Line No Non-Linear Springs with Fixed Boundary Conditions" FE model (D:\DS\DS Models \Base_Line_No_NLS_fixed.*)**

The "Base Line No Non-Linear Springs" FE model was modified to include a fixed boundary condition for DS Bases. To achieve this type of boundary conditions, one set of nodes along z-axis (refer to Figure 2 of this scientific notebook) on the bottom of each Base is constrained from displacement in the horizontal (x-axis) and vertical (y-axis) directions.

No additional changes were made to the model.

Date: May 31, 2007
Entry by: Roman V. Kazban

<u>Results for the "Base Line No Non-Linear Springs with Fixed Boundary Conditions" FE model</u> (D:\DS\DS Models\Base_Line_No_NLS_fixed.*)"**

The computational analysis completion rate for the "Base Line No Non-Linear Springs with Fixed Boundary Conditions" model is 5.39*%,* which is equal to the following maximum pressures applied: left side – 67.91 *kPa*, crown – 161.70 kPa, and right side – 45.28 *kPa*. The maximum Von Mises stress is estimated at 694.7 *MPa* and is located in the Left Support Beam.

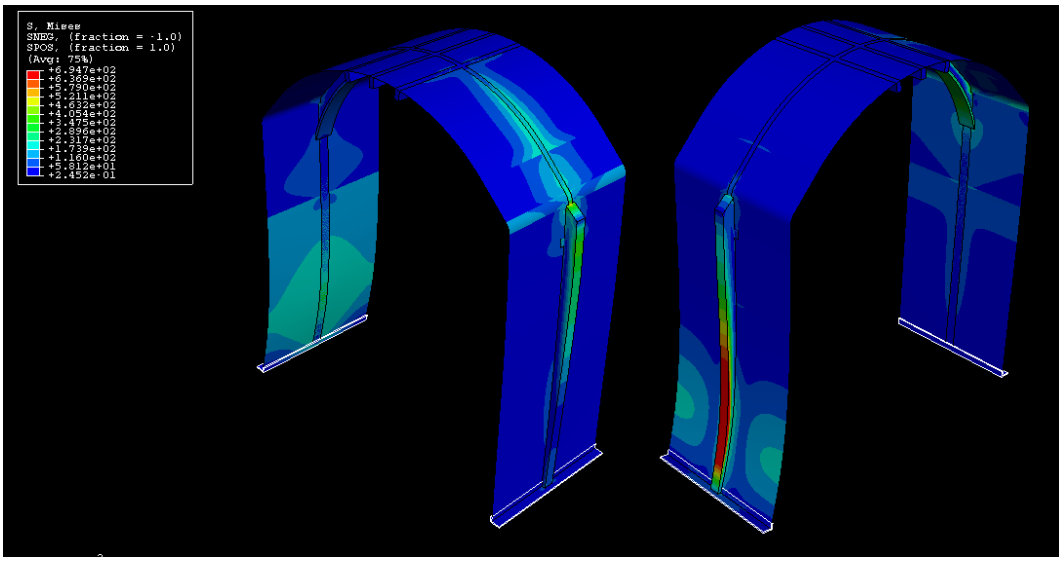


Figure 51. Von Mises stress distribution at maximum loading

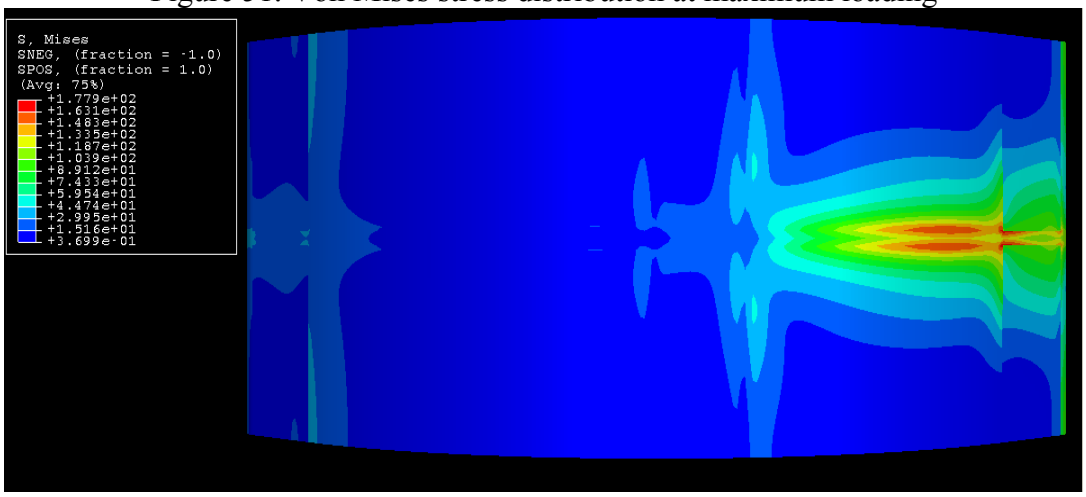


Figure 52. Von Mises stress distribution in the Shell Plate crown (top view) at first indication of yielding in Ti-7

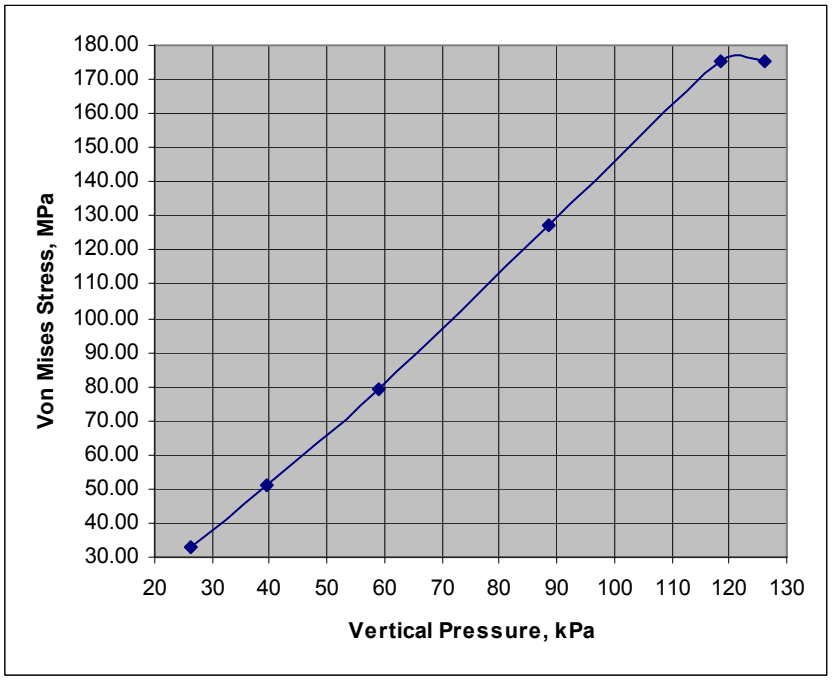
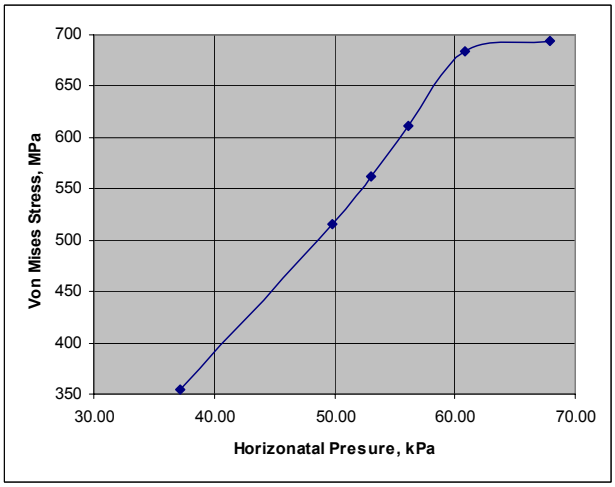


Figure 53. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure (yielding @ 118 *kPa*)



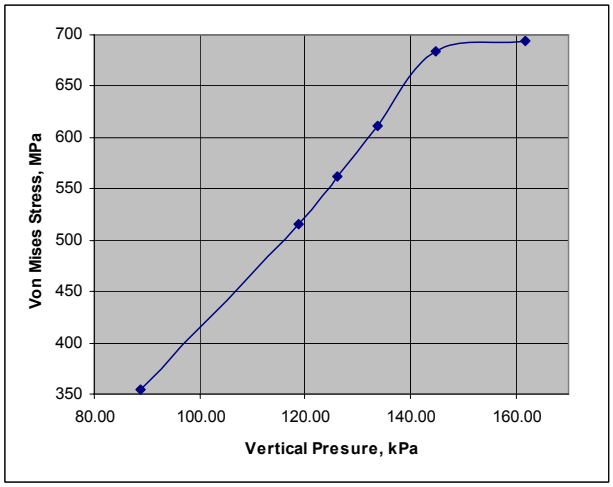


Figure 54. Von Mises stress in the Left Support Beam of the Drip Shield as a function of (a) horizontal {yielding @ 59 *kPa*} and (b) vertical {yielding @ 139.5 *kPa*} pressure

Date: June 6, 2007
Entry by: Roman V. Kazban

Description of the "Base Line" FE model (D:\DS\DS Models \Base_Line.*)**

If the Drift degradation occurs, the Drip Shield will be subjected to static loads due the accumulated rockfall rubble. Also, the rubble surrounding the Drip Shield sides may contribute to the structural resistance of the Drip Shield when the outward deformations of the DS compress the rubble, thereby developing passive resistance. To account for the rubble resistance in this FE model, the accumulated rubble on the side of the DS is represented by non-linear springs. The non-linear behavior of a spring is approximated by three linear regions as shown on Figure 55.

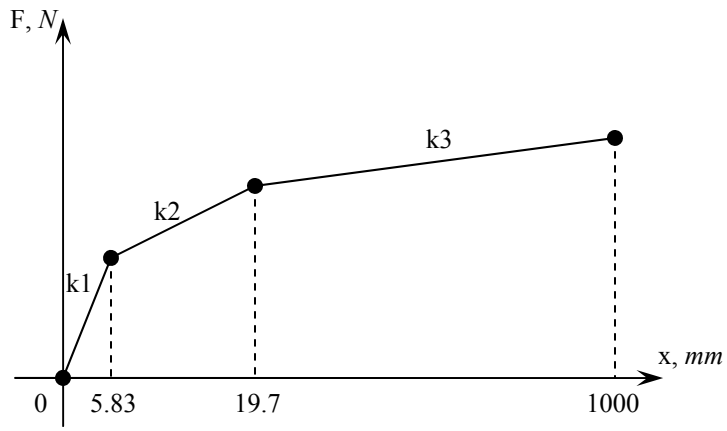


Figure 55. Approximation of the non-linear spring behavior.

Table 6 presents the data from a FE model that was developed to calculate the equivalent spring constants for the rock rubble with Young's modulus E=30 *MPa* and Poisson's ration υ=0.17 {SN 391]. The FE model to produce this data has the following parameters: (i) 400 *kPa* applied vertical pressure to the rubble, and (ii) 0.4 coefficient of friction between the DS Base and the invert. In Table 6 the y-coordinate refers to the distance from the DS Base (or Invert) to the point on the side of the DS.

Table 6. Initial Spring Constants Data obtained from preceding FE model [SN 391].

N/N	y_{max}	k_1 (N/m)	k_2 (N/m)	k_3 (N/m)
1	2.1698	1764774.68	869615.04	802804.70
2	2.1156	2035694.57	985094.00	878552.57
3	2.0647	1534611.40	756563.89	711240.63
4	2.0198	1470853.97	742654.64	730886.44
5	1.9780	1511202.11	765491.56	742318.51
6	1.9363	1539969.81	785201.00	755586.86

7	1.8948	1543434.27	793254.09	766965.78
8	1.8535	1558734.25	807835.01	788685.86
9	1.8123	1570896.55	821149.55	807951.12
10	1.7712	1580693.07	833463.58	824568.27
11	1.7300	1588620.65	844959.00	842638.75
12	1.6888	1595327.84	855936.67	861814.61
13	1.6477	1601113.05	866515.54	876942.20
14	1.6065	1606221.38	876786.56	890099.41
15	1.5653	1610766.20	886840.68	903626.29
16	1.5242	1614904.21	896761.86	917102.43
17	1.4830	1618635.43	906585.10	930433.60
18	1.4419	1622129.90	916296.38	943630.67
19	1.4011	1566133.33	892200.08	922207.78
20	1.3611	1568704.17	901218.70	934712.62
21	1.3214	1570619.79	909992.44	947215.05
22	1.2817	1571460.07	918353.39	959781.50
23	1.2421	1570296.35	925706.82	972292.39
24	1.2024	1565626.50	931157.17	984219.77
25	1.1628	1556416.83	934263.67	1000794.64
26	1.1229	1611092.97	977208.83	1017303.06
27	1.0833	1667212.91	1021735.22	1031541.50
28	1.0439	1659505.40	1028039.16	1047294.87
29	1.0043	1652991.62	1034825.87	1061959.77
30	0.9646	1653215.02	1046265.32	1077667.23
31	0.9249	1657313.02	1060636.35	1094266.26
32	0.8852	1663841.82	1077071.37	1111634.84
33	0.8455	1672282.90	1095199.58	1129718.60
34	0.8058	1682476.22	1114916.01	1148441.44
35	0.7661	1694436.78	1136122.72	1167672.87
36	0.7264	1708282.95	1158735.75	1187234.12
37	0.6867	1723602.94	1182258.33	1206035.48
38	0.6471	1734724.90	1201799.85	1220208.68
39	0.6072	1787643.80	1254645.21	1267496.59
40	0.5676	1815009.37	1284352.79	1287913.15
41	0.5280	1818483.84	1291335.40	1281591.27
42	0.4881	1867151.35	1331593.87	1307752.25
43	0.4484	1917287.68	1367535.43	1327526.12
44	0.4086	1977618.99	1403840.81	1344306.36
45	0.3689	2052173.27	1440635.96	1358501.31
46	0.3291	2145590.36	1477424.11	1369742.50
47	0.2893	2264142.30	1513463.62	1377657.85
48	0.2495	2416721.98	1547656.03	1381875.26
49	0.2097	2616558.73	1578685.97	1382184.53

50	0.1698	2887838.73	1604671.36	1378281.22
51	0.1299	3251587.18	1624030.97	1370600.24
52	0.0896	3951846.88	1629439.35	1355675.61
53	0.0462	6375070.98	2018065.77	1670891.67
54	0.0000	6375070.98	2018065.77	1670891.67

To limit the number of spring constants, the DS was divided into 12 regions as shown on Figure 56. Regions one through four have 100 *mm* height, regions four through eleven have 200 *mm* height, and region twelve has 350 *mm* height.

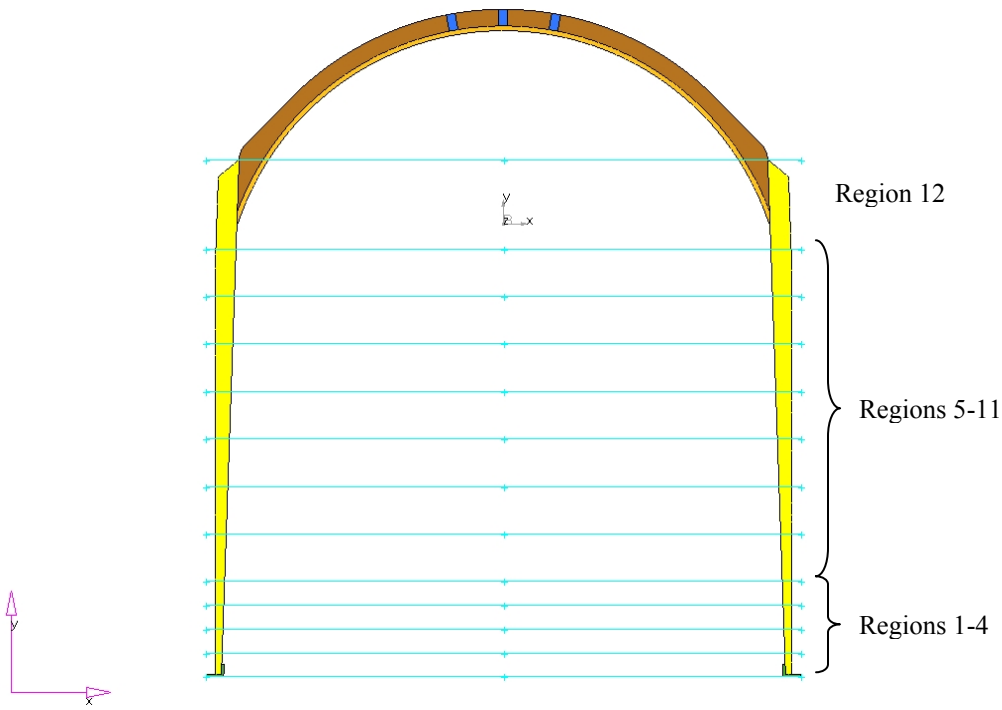


Figure 56.

The following MATLAB® Code was used to estimate spring constants for each DS region. The fitting curves are presented on Figures 57-59, and estimated springs constants for each region are presented in Tables 7 and 8 as a force—displacement data. On these figures, the data points obtained form the preceding FE model is presented as "blue star" points, the "red" curves presents polynomial fitting curves (7th-order polynomial for k1 and k2, and 5th-orderpolynomial for k3), and the "black" step function represents accepted spring constants for each DS region.

++
BEGINNING OF THE CODE
++

```
clear all
close all
clc

% new values for the position
height_new = .005:.005:2.2;

% reading the data file
[height, k_1, k_2, k_3]=textread('SpringConst.dat');

% creating regions for averaging the values
regions_x = [0:100:300 400:200:1800 2150].*1e-3;

% devide each region into 5 intervals (6 points)
for i=1:1:length(regions_x)-1
   delta_pos(i,:) = [regions_x(i):(regions_x(i+1)-regions_x(i))./5:regions_x(i+1)];
end

% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
% k_1 fitting and estimation
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
[f_1, s_1] = polyfit(height, k_1, 7);
[k_1_fit, delta_1] = polyval(f_1, height_new, s_1);

for i=1:1:length(regions_x)-1
   k_1_est(i)=mean(polyval(f_1, delta_pos(i,:)));
end

figure(1)
hold on
plot(height_new, k_1_fit, 'r', height, k_1, '*');
axis([0 2.3 1e6 5.5e6])
xlabel('Position, \it{m}');
ylabel('k_1, \it{N/m}');
title('k_1 as a funcion of a position')
for i=2:1:length(regions_x)
   line([regions_x(i) regions_x(i)], [0 1e10], 'Color','g','LineWidth',1, 'LineStyle', '--')
end
for i=1:1:length(k_1_est)
   line([regions_x(i) regions_x(i+1)], [k_1_est(i) k_1_est(i)],'Color','k','LineWidth',2)
end
for i=1:1:length(k_1_est)-1
```

```
   line([regions_x(i+1) regions_x(i+1)], [k_1_est(i) k_1_est(i+1)],'Color','k','LineWidth',2)
end

% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
% k_2 fitting and estimation
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
[f_2, s_2] = polyfit(height, k_2, 7);
[k_2_fit, delta_2] = polyval(f_2, height_new, s_2);

for i=1:1:length(regions_x)-1
   k_2_est(i)=mean(polyval(f_2, delta_pos(i,:)));
end

figure(2)
hold on
plot(height_new, k_2_fit, 'r', height, k_2, '*');
axis([0 2.3 0.5e6 1.8e6])
xlabel('Position, \it{m}');
ylabel('k_2, \it{N/m}');
title('k_2 as a funcion of a position')
for i=2:1:length(regions_x)
   line([regions_x(i) regions_x(i)], [0 1e10], 'Color','g','LineWidth',1, 'LineStyle', '--')
end
for i=1:1:length(k_2_est)
   line([regions_x(i) regions_x(i+1)], [k_2_est(i) k_2_est(i)],'Color','k','LineWidth',2)
end
for i=1:1:length(k_2_est)-1
   line([regions_x(i+1) regions_x(i+1)], [k_2_est(i) k_2_est(i+1)],'Color','k','LineWidth',2)
end

% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
% k_3 fitting and estimation
% ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
[f_3, s_3] = polyfit(height, k_3, 5);
[k_3_fit, delta_3] = polyval(f_3, height_new, s_3);

for i=1:1:length(regions_x)-1
   k_3_est(i)=mean(polyval(f_3, delta_pos(i,:)));
end

figure(3)
hold on
plot(height_new, k_3_fit, 'r', height, k_3, '*');
axis([0 2.3 0.6e6 1.4e6])
xlabel('Position, \it{m}');
```

```
ylabel('k_3, \it{N/m}');
title('k_3 as a funcion of a position')
for i=2:1:length(regions_x)
   line([regions_x(i) regions_x(i)], [0 1e10], 'Color','g','LineWidth',1, 'LineStyle', '--')
end
for i=1:1:length(k_3_est)
   line([regions_x(i) regions_x(i+1)], [k_3_est(i) k_3_est(i)],'Color','k','LineWidth',2)
end
for i=1:1:length(k_3_est)-1
   line([regions_x(i+1) regions_x(i+1)], [k_3_est(i) k_3_est(i+1)],'Color','k','LineWidth',2)
end


Spring_Matrix = [k_1_est; k_2_est; k_3_est]./1e3
Displacement_Matrix = [0.005829; 0.019695; 1.000000].*1e3
Force_Matrix = [Spring_Matrix(1,:).*Displacement_Matrix(1,1);...
            Spring_Matrix(2,:).*Displacement_Matrix(2,1);...
            Spring_Matrix(3,:).*Displacement_Matrix(3,1)]
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
END
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

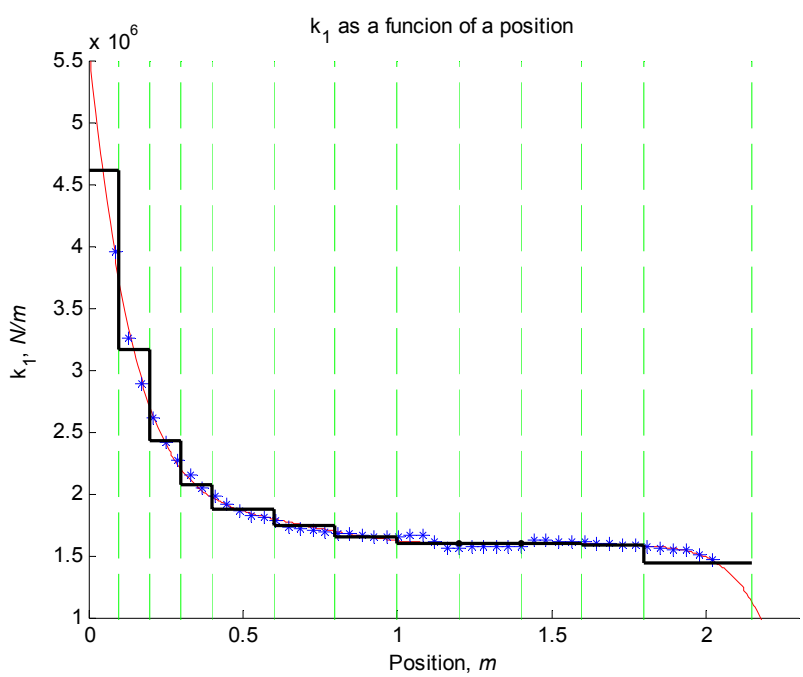


Figure 57.

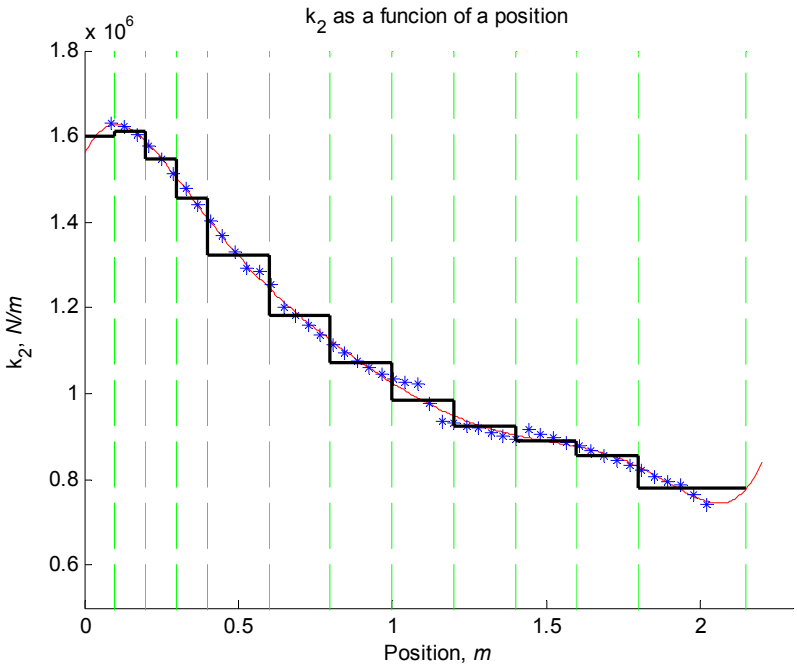


Figure 58.

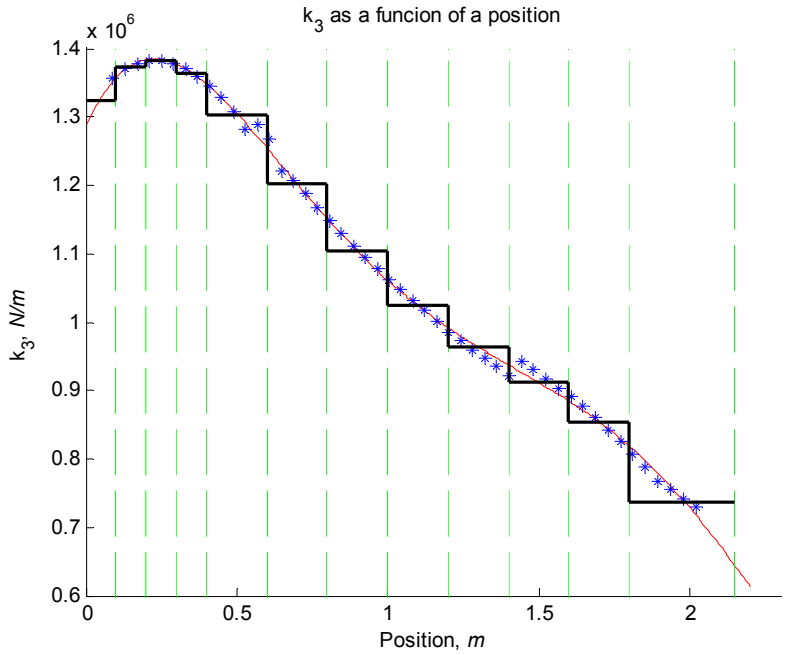


Figure 59.

Table 7. Force-displacement data for each DS region

Δu, *mm*						0.00E+00	5.83E+00	1.97E+01	1.00E+03
Region	1	(0-100 mm)	**Node Numbers**	0-10	**Force, *N***	0.00E+00	2.69E+04	3.15E+04	1.32E+06
	2	(100-200 mm)		11-20		0.00E+00	1.84E+04	3.18E+04	1.37E+06
	3	(200-300 mm)		21-30		0.00E+00	1.41E+04	3.05E+04	1.38E+06
	4	(300-400 mm)		31-40		0.00E+00	1.21E+04	2.87E+04	1.36E+06
	5	(400-600 mm)		41-60		0.00E+00	1.09E+04	2.61E+04	1.30E+06
	6	(600-800 mm)		61-80		0.00E+00	1.02E+04	2.33E+04	1.20E+06
	7	(800-1000 mm)		81-100		0.00E+00	9.64E+03	2.11E+04	1.10E+06
	8	(1000-1200 mm)		101-120		0.00E+00	9.36E+03	1.94E+04	1.03E+06
	9	(1200-1400 mm)		121-140		0.00E+00	9.30E+03	1.82E+04	9.64E+05
	10	(1400-1600 mm)		141-160		0.00E+00	9.31E+03	1.75E+04	9.11E+05
	11	(1600-1800 mm)		161-180		0.00E+00	9.26E+03	1.69E+04	8.53E+05
	12	(1800-2150 mm)		181-215		0.00E+00	8.39E+03	1.54E+04	7.37E+05

Table 8. Force-displacement data for each node of DS regions

Δu, *mm*						0.00E+00	5.83E+00	1.97E+01	1.00E+03
Region	1	(0-100 mm)	**Number of Nodes**	1199	**Force per node, *N***	0.00E+00	2.24E+01	2.63E+01	1.10E+03
	2	(100-200 mm)		1090		0.00E+00	1.69E+01	2.91E+01	1.26E+03
	3	(200-300 mm)		1090		0.00E+00	1.30E+01	2.80E+01	1.27E+03
	4	(300-400 mm)		1090		0.00E+00	1.11E+01	2.63E+01	1.25E+03
	5	(400-600 mm)		2180		0.00E+00	5.00E+00	1.20E+01	5.98E+02
	6	(600-800 mm)		2180		0.00E+00	4.66E+00	1.07E+01	5.52E+02
	7	(800-1000 mm)		2180		0.00E+00	4.42E+00	9.70E+00	5.07E+02
	8	(1000-1200 mm)		2180		0.00E+00	4.29E+00	8.90E+00	4.70E+02
	9	(1200-1400 mm)		2180		0.00E+00	4.27E+00	8.34E+00	4.42E+02
	10	(1400-1600 mm)		2180		0.00E+00	4.27E+00	8.04E+00	4.18E+02
	11	(1600-1800 mm)		2180		0.00E+00	4.25E+00	7.73E+00	3.91E+02
	12	(1800-2150 mm)		3769		0.00E+00	2.23E+00	4.08E+00	1.96E+02

The "Base Line No Non-Linear Springs" FE model was modified to include non-linear springs SPRING1 elements to each side of the drip shield to represent accumulated rockfall rubble. Non-linear springs provide a resistance to loading only in outward direction, i.e. in the negative x-direction for the left side of the DS, and in the x-direction for the right side of the DS.

No additional changes were made to the model.

Date: June 7, 2007
Entry by: Roman V. Kazban

<u>Results for the "Base Line" FE model</u> (D:\DS\DS Models\Base_Line.*)"**

The computational analysis completion rate for the "Base Line" model is 7.56*%,* which is equal to the following maximum pressures applied: left side – 95.26 *kPa*, crown – 226.80 kPa, and right side – 63.50 *kPa*. The maximum Von Mises stress is estimated at 691.9 *MPa* and is located in the Left Support Beam.

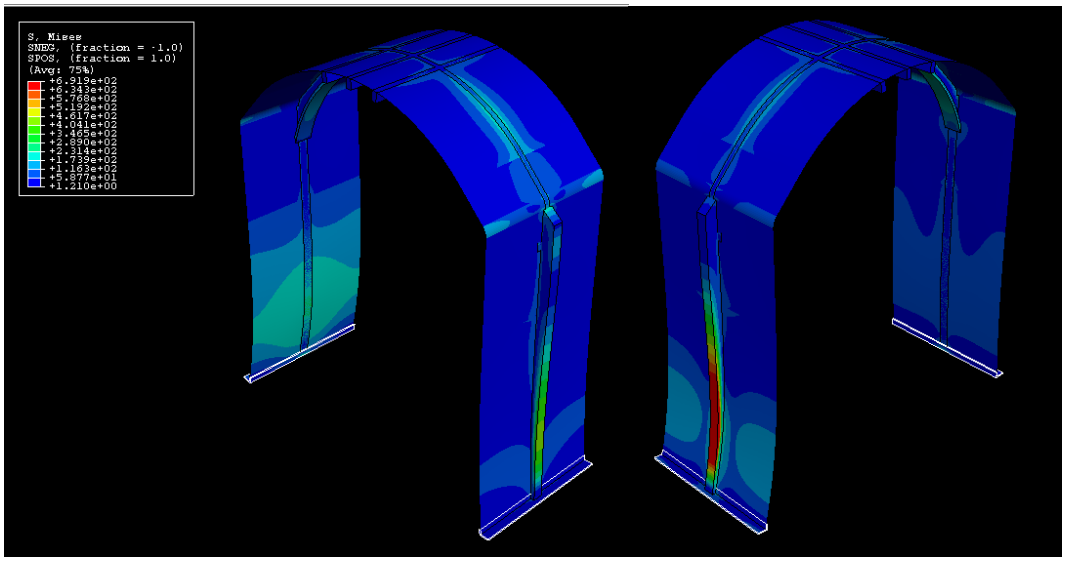


Figure 60. Von Mises stress distribution at maximum loading

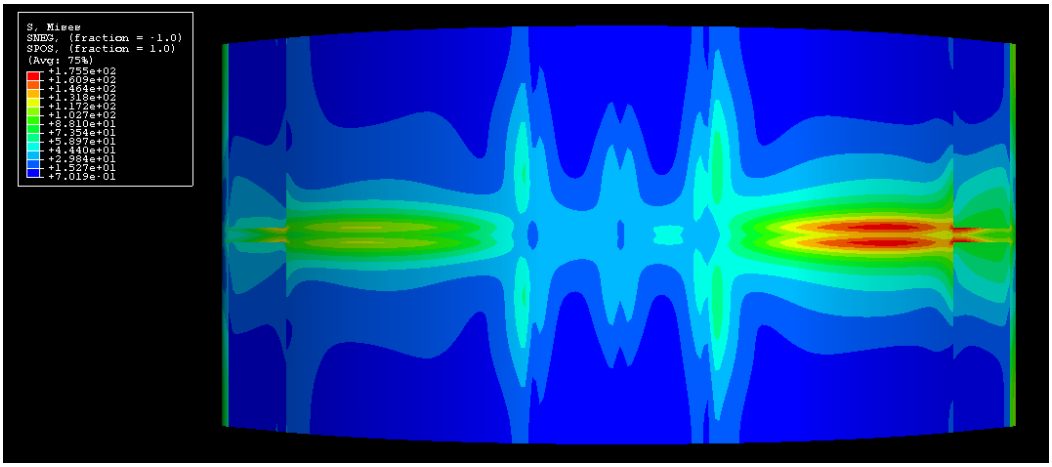


Figure 61. Von Mises stress distribution in the Shell Plate crown (top view) at first indication of yielding in Ti-7

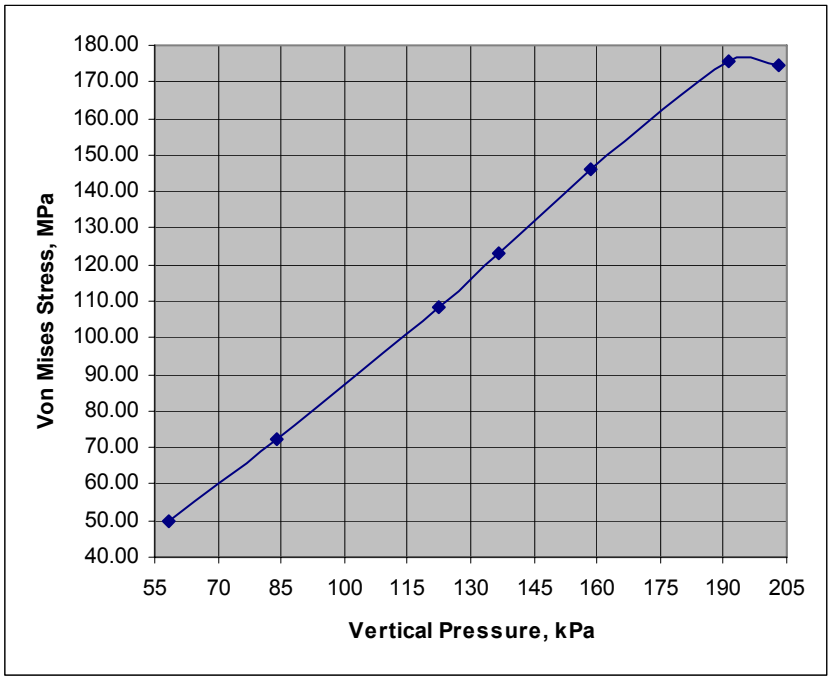
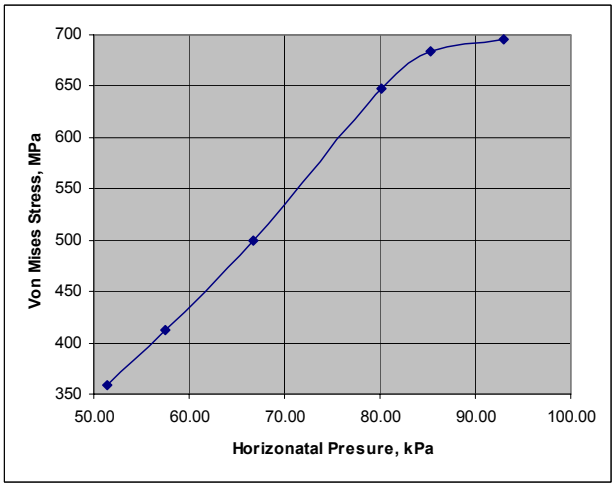


Figure 62. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure (yielding @ 188 *kPa*)



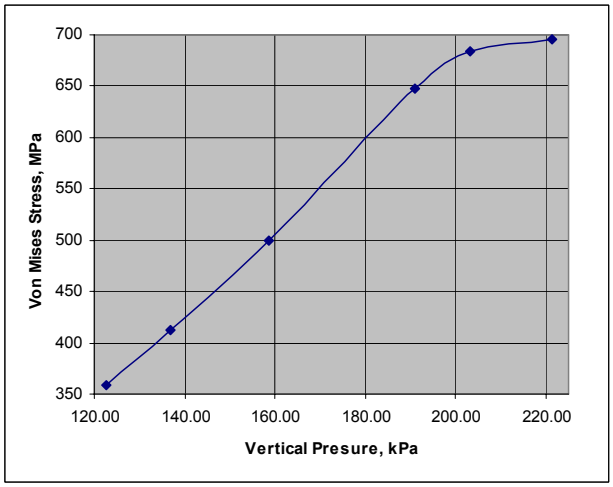


Figure 63. Von Mises stress in the Left Support Beam of the Drip Shield as a function of (a) horizontal {yielding @ 81 *kPa*} and (b) vertical {yielding @ 193 *kPa*} pressure

The displacement of the Left Base in x-direction (horizontal) as a function of the applied pressure to the DS is presented on Figure 64. It can be concluded that after the initial contact between the DS Base and the Rigid Surface achieved the DS Base does not move in the horizontal direction. The same type of behavior is observed for the Right Base as well.

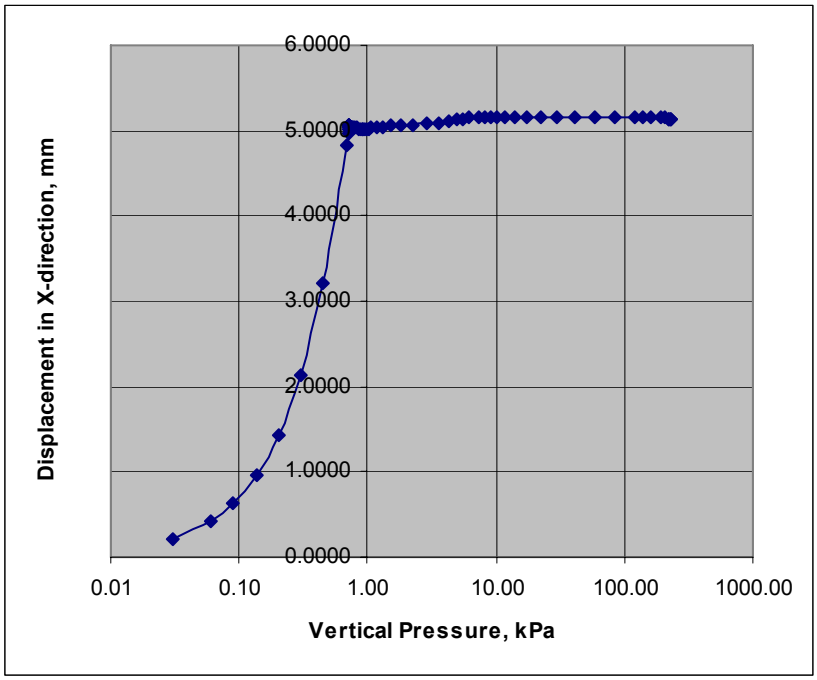


Figure 64. Left Base displacement in horizontal direction as a function of the Vertical Pressure applied to the DS

Date: June 11, 2007
Entry by: Roman V. Kazban

<u>Description of the "Base Line with Fixed Boundary Conditions" FE model</u> (D:\DS\DS Models \Base_Line_fixed.*)**

The "Base Line" FE model was modified to include a fixed boundary condition for DS Bases. To achieve this type of boundary conditions, one set of nodes along z-axis (refer to Figure 2 of this scientific notebook) on the bottom of each Base is constrained from displacement in the horizontal (x-axis) and vertical (y-axis) directions.

No additional changes were made to the model.

Date: June 12, 2007
Entry by: Roman V. Kazban

<u>Results for the "Base Line with Fixed Boundary Conditions" FE model</u> (D:\DS\DS Models\Base_Line_fixed.*)"**

The computational analysis completion rate for the "Base Line with Fixed Boundary Conditions" model is 6.73*%,* which is equal to the following maximum pressures applied: left side – 84.80 *kPa*, crown – 201.90 kPa, and right side – 56.53 *kPa*. The maximum Von Mises stress is estimated at 693.4 *MPa* and is located in the Left Support Beam.

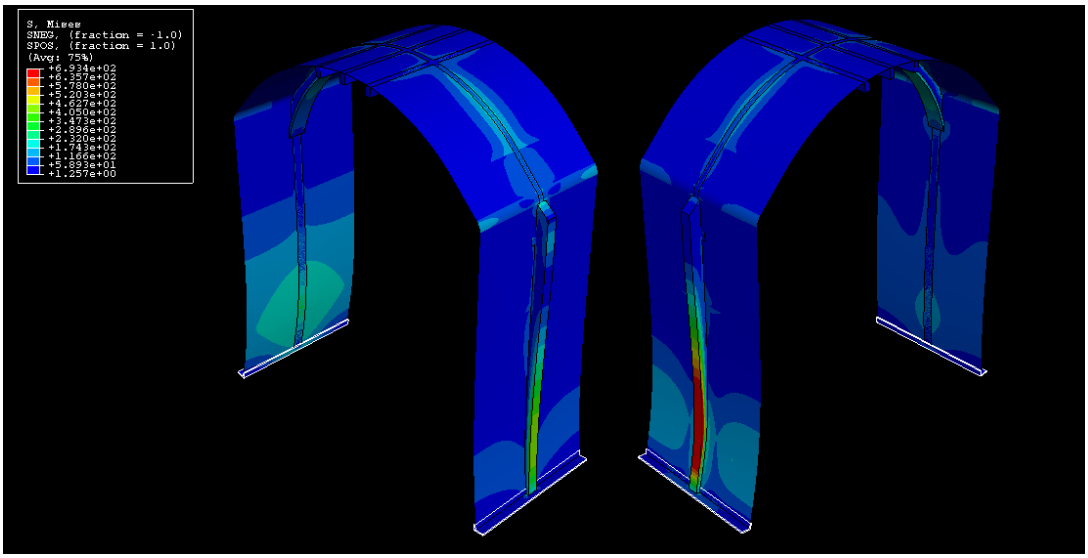


Figure 65. Von Mises stress distribution at maximum loading

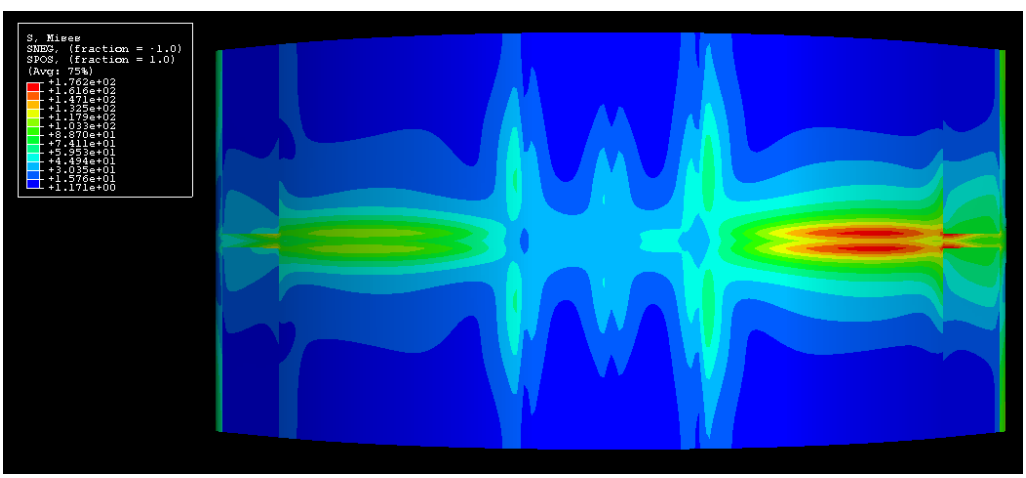


Figure 66. Von Mises stress distribution in the Shell Plate crown (top view) at first indication of yielding in Ti-7

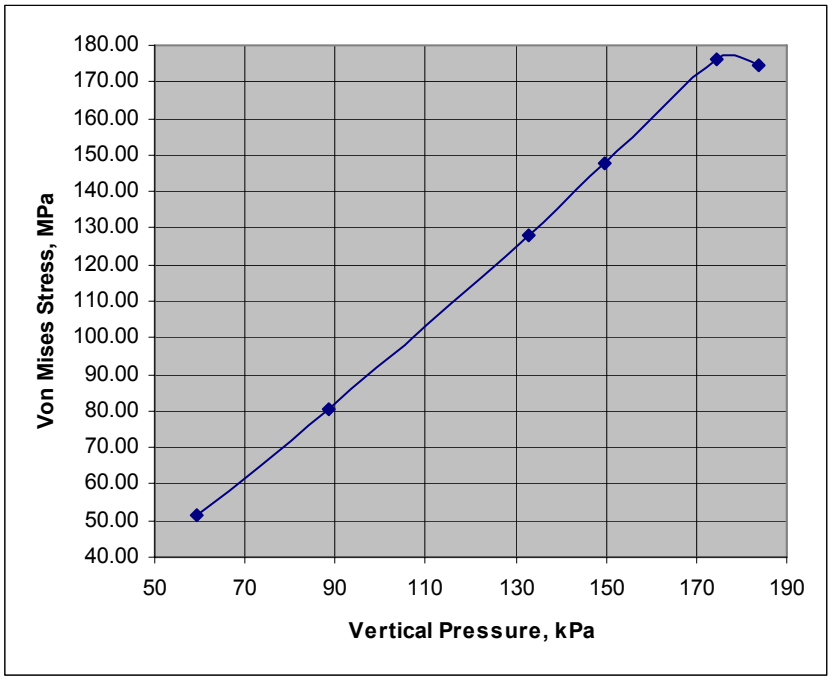
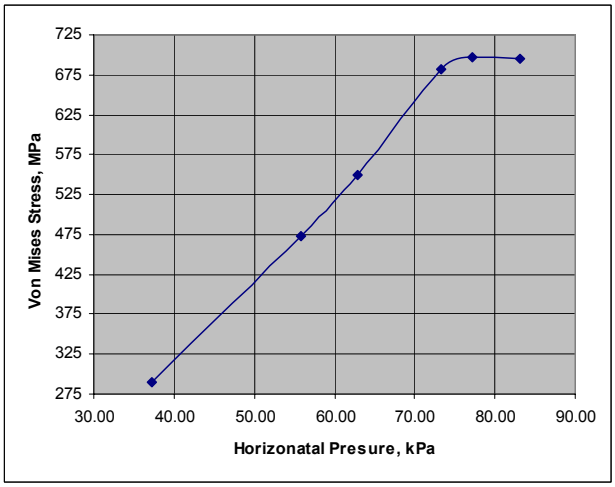


Figure 67. Von Mises stress in the Shell Plate of the Drip Shield crown as a function of vertical pressure (yielding @ 172 *kPa*)



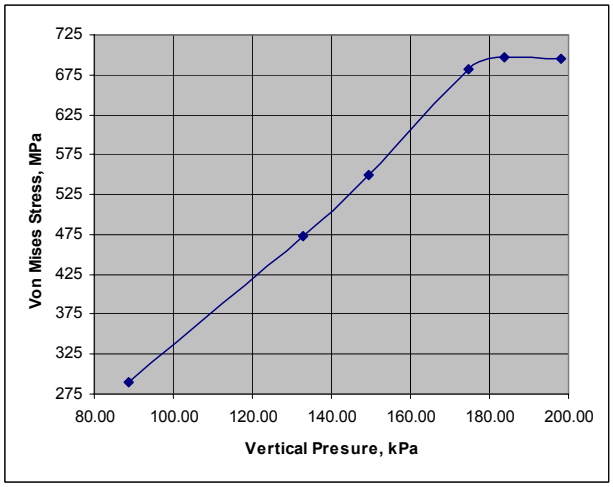


Figure 68. Von Mises stress in the Left Support Beam of the Drip Shield as a function of (a) horizontal {yielding @ 71 *kPa*} and (b) vertical {yielding @ 170 *kPa*} pressure

Date: June 12, 2007
Entry by: Roman V. Kazban

All Finite Element models created starting January, 2007 were generated using Altair HyperMesh 8.0 ("Altair HyperMesh User's Guide", Version 8.0. Altair Engineering, Inc., Troy, Michigan, 2006). See NCR 2007-20 for more details.

Date: June 13, 2007
Entry by: Roman V. Kazban

<u>Description of the "Base Line with Projected Loading Conditions" FE model</u> (D:\DS\DS Models \Base_Line_project.*)**

The pressure produced by accumulated rockfall rubble surrounding the DS is acting in vertical and horizontal directions. This type of loading in both directions can be approximated as uniformly distributed [Ibarra, L., T. Wilt, G. Ofoegbu, and A. Chowdhury. "Structural Performance of Drip Shield Subjected to Static and Dynamic Loading." San Antonio, Texas: CNWRA. January 2007.]

In all preceding FE models, the DS Crown was loaded directly with 3000 *kPa* vertical pressure components normally applied to each element; also, the horizontal pressure component acting on the DS Crown was disregarded. The loading conditions for the DS Crown of "Base Line" FE model were modified to include the loading produced by the horizontal pressure component: 3000 *kPa* vertical pressure, 1260 *kPa* horizontal pressure on the left side of the DS, and 840 *kPa* horizontal pressure on the right side of the DS were projected to the DS Crown surface (refer to Figure 69).

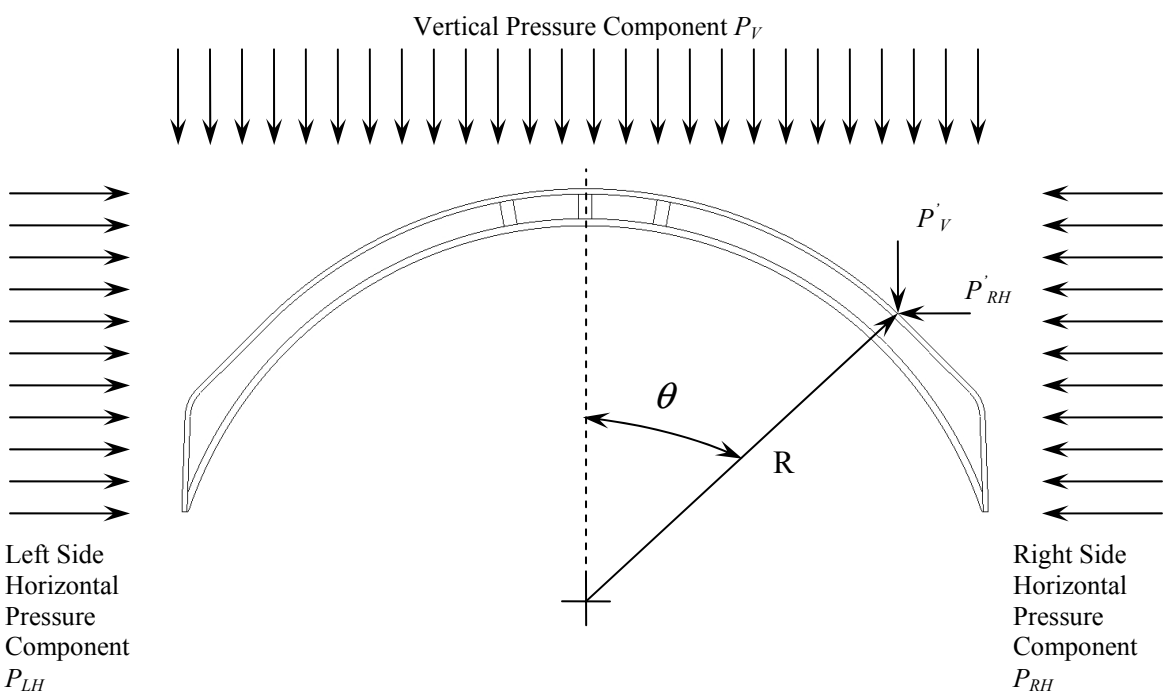


Figure 69.

The concept of a projected pressure loading is shown on Figure 70. Distributed Load q is applied to AB that has length l. When distributed load q is projected onto $A'B'$ it's equal to distributed load q'. It can be shown that for the pressure load to be equivalent on both surfaces, $q' = q\cos\theta$.

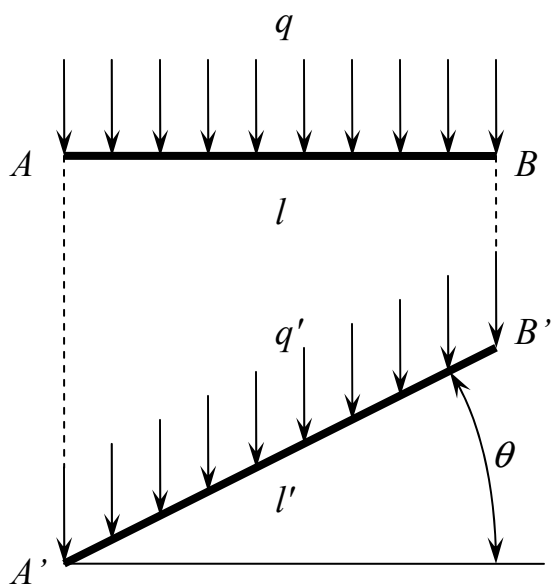


Figure 70.

Since, the DS Crown has a curvature (refer to Figure 69), it can be represented as an arc. Therefore, the total projected pressure P_{proj} for the DS Crown can be derived as $P_{proj} = \sqrt{P_V'^{\,2} + P_{LH(RH)}'^{\,2}}$ (refer to Figure 71). It can be shown that $P_V' = P_V \cos\theta$ and $P_{LH(RH)}' = P_{LH(RH)} \sin\theta$, where $\cos\theta = \dfrac{y_p}{\sqrt{x_p^2 + y_p^2}}$ and $\sin\theta = \dfrac{x_p}{\sqrt{x_p^2 + y_p^2}}$. As a result

$$P_{proj} = \left(P_V^2 \frac{y_p^2}{x_p^2 + y_p^2} + P_{LH(RH)}^2 \frac{x_p^2}{x_p^2 + y_p^2} \right)^{1/2}$$

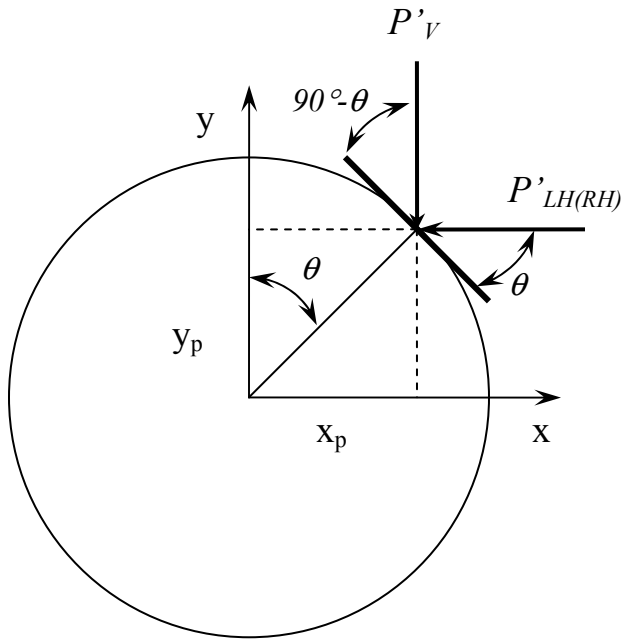


Figure 71.

However, because in the FE model the center for the DS curvature is offset from the origin by 382.23 *mm* in y-direction, the projected pressure at a given point can be calculated as follows:

$$P_{proj} = \left(\frac{P_V^2 \left(y_p + 382.23 \right)^2 + P_{LH(RH)}^2 x_p^2}{x_p^2 + \left(y_p + 382.23 \right)^2} \right)^{1/2}$$

No additional changes were made to the model.

Date: June 15, 2007
Entry by: Roman V. Kazban

<u>Results for "Base Line with Projected Loading Conditions" FE model</u> (D:\DS\DS Models \Base_Line_project.*)**

The computational analysis completion rate for the "Base Line with Projected Loading Conditions" model is 7.74*%,* which is equal to the following maximum pressures applied: left side – 97.52 *kPa*, crown – 232.20 kPa, and right side – 65.02 *kPa*. The maximum Von Mises stress is estimated at 693.5 *MPa* and is located in the Left Support Beam.

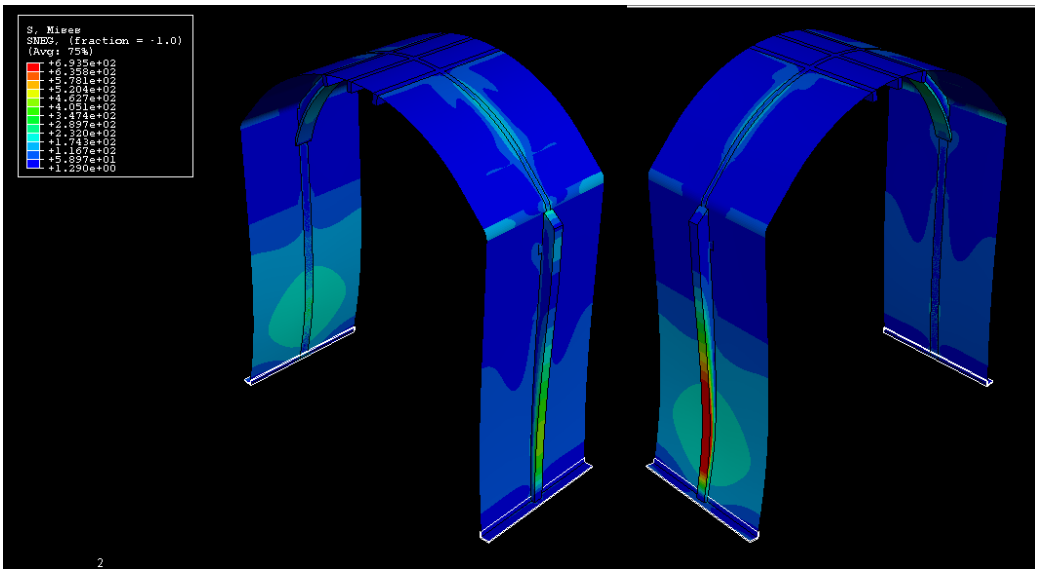


Figure 72. Von Mises stress distribution at maximum loading

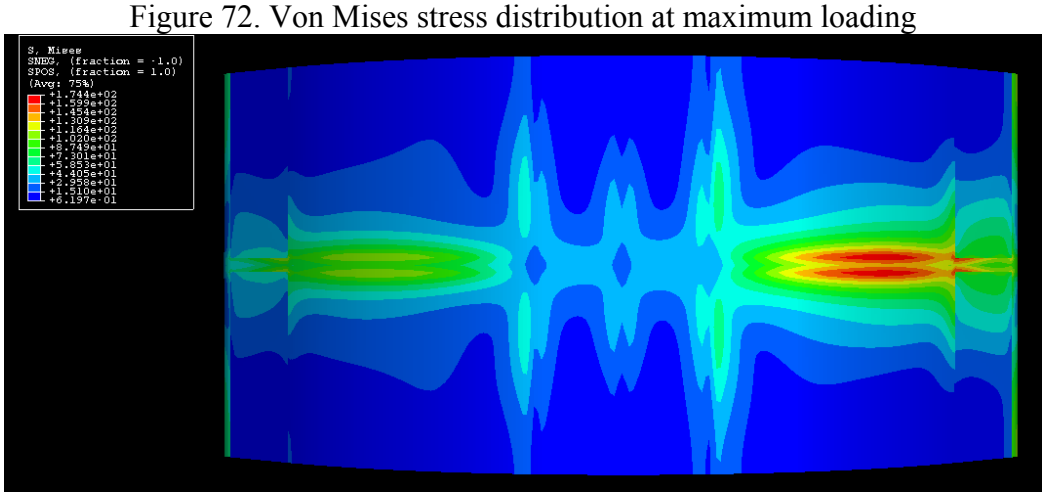


Figure 73. Von Mises stress distribution in the Shell Plate crown (top view) at first indication of yielding in Ti-7

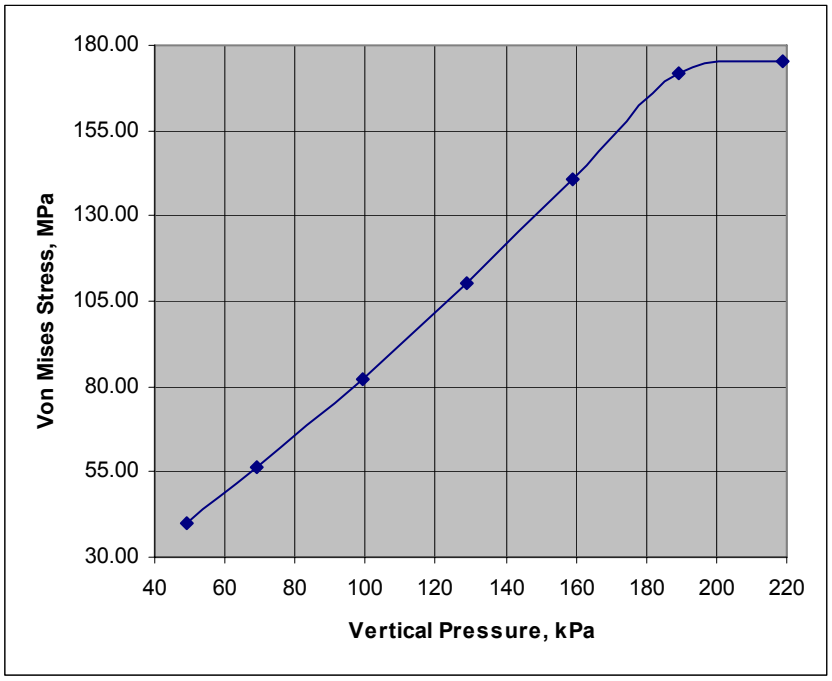


Figure 74: Von Mises stress in the Drip Shield crown due to vertical pressure (yielding @ 196 kPa).

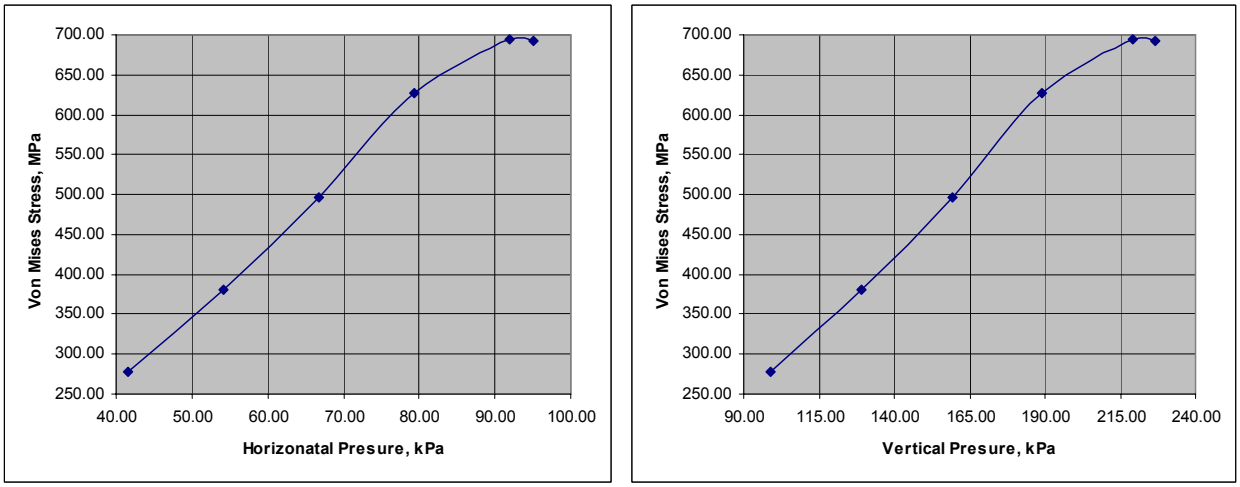


Figure 75. Von Mises stress in the Left Support Beam of the Drip Shield as a function of (a) horizontal {yielding @ 84 *kPa*} and (b) vertical (yielding @ 200 kPa) pressure

The displacement of the Left Base in x-direction (horizontal) as a function of the applied pressure to the DS is presented on Figure 76. It can be concluded that after the initial contact between the DS Base and the Rigid Surface achieved the DS Base does not move in the horizontal direction. The same type of behavior is observed for the Right Base as well.

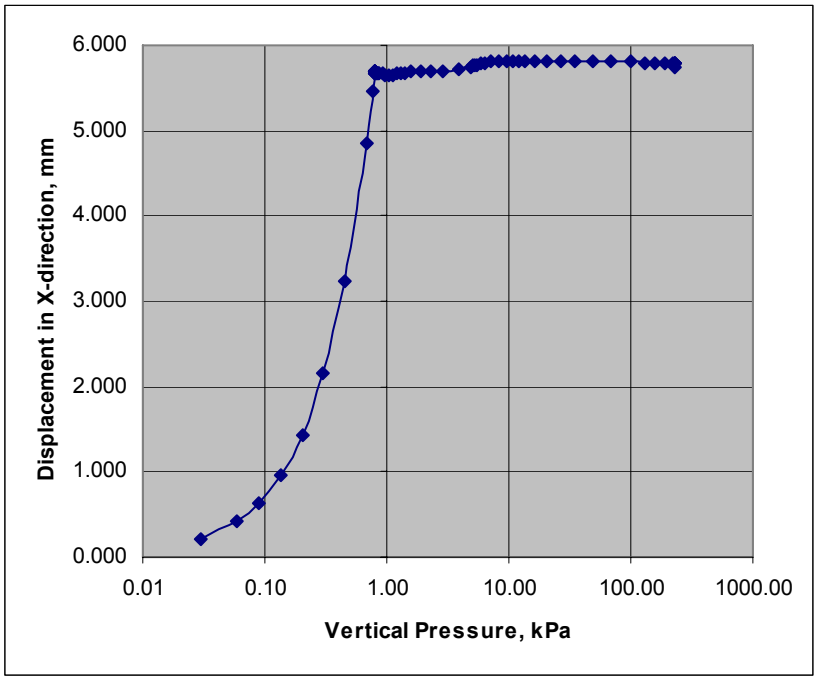


Figure 76. Left Base displacement in horizontal direction as a function of the Vertical Pressure applied to the DS

Date: June 18, 2007
Entry by: Roman V. Kazban

<u>Description of the "Base Line with Projected Loading and Fixed Boundary Conditions" FE model</u> (D:\DS\DS Models\Base_Line_Project_fixed.*)"**

The "Base Line with Projected Loading" FE model was modified to include a fixed boundary condition for DS Bases. To achieve this type of boundary conditions, one set of nodes along z-axis (refer to Figure 2 of this scientific notebook) on the bottom of each Base is constrained from displacement in the horizontal (x-axis) and vertical (y-axis) directions.

No additional changes were made to the model.

Date: June 18, 2007
Entry by: Roman V. Kazban

<u>Results for the "Base Line with Projected Loading and Fixed Boundary Conditions" FE model</u> (D:\DS\DS Models\Base_Line_Project_fixed.*)"**

The computational analysis completion rate for the "Base Line with Projected Loading and Fixed Boundary Conditions" model is 6.95*%,* which is equal to the following maximum pressures applied: left side – 87.57 *kPa*, crown – 208.50 kPa, and right side – 58.38 *kPa*. The maximum Von Mises stress is estimated at 693.8 *MPa* and is located in the Left Support Beam.

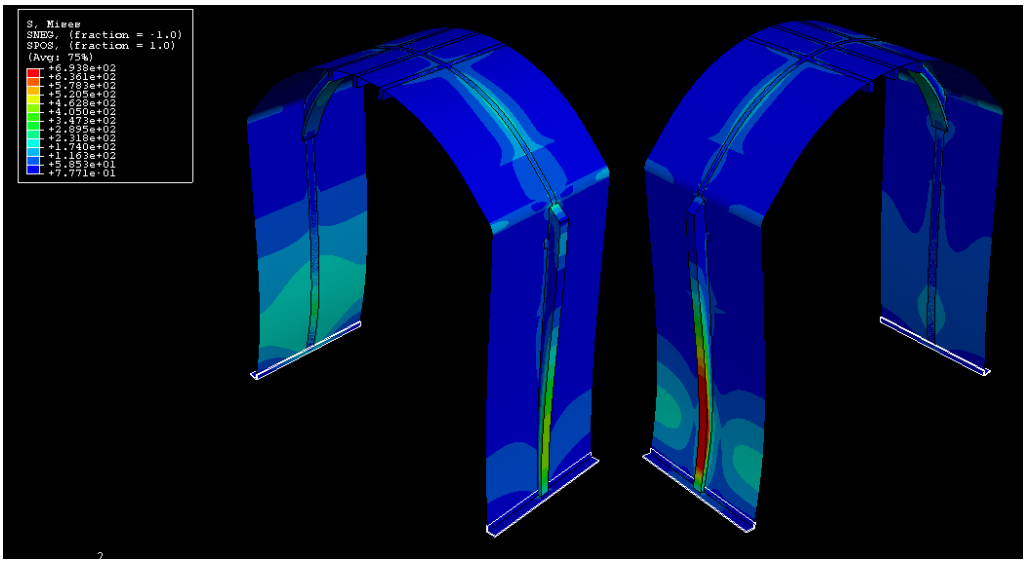


Figure 77. Von Mises stress distribution at maximum loading

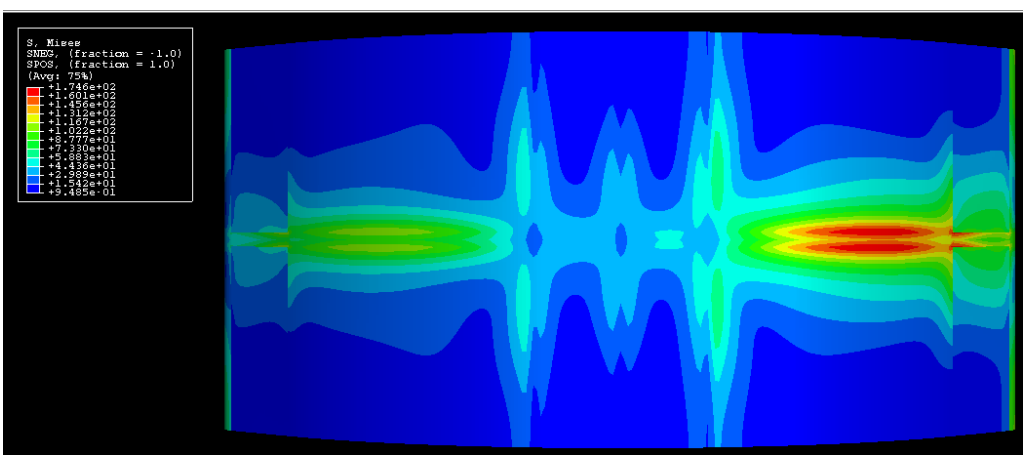


Figure 78. Von Mises stress distribution in the Shell Plate crown (top view) at first indication of yielding in Ti-7

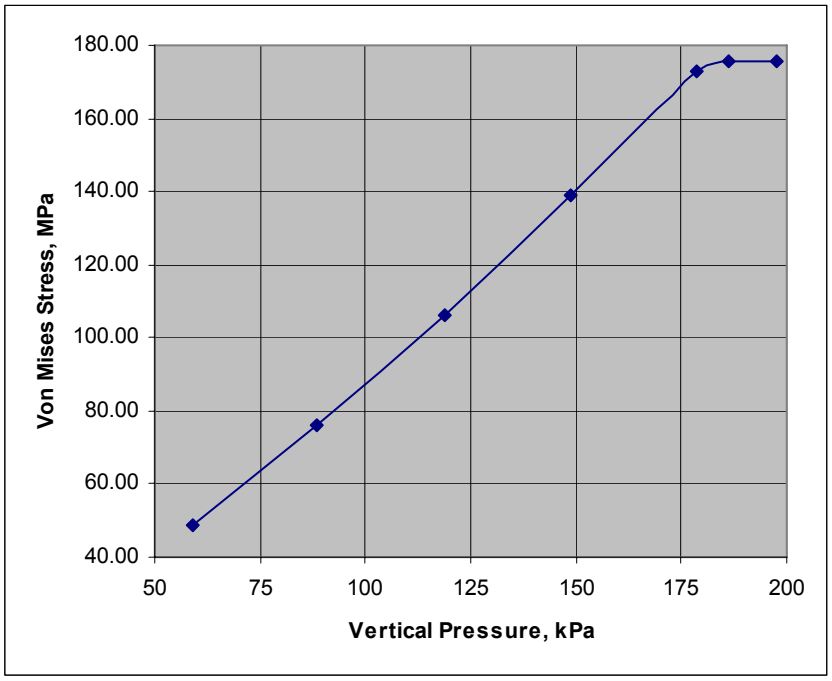
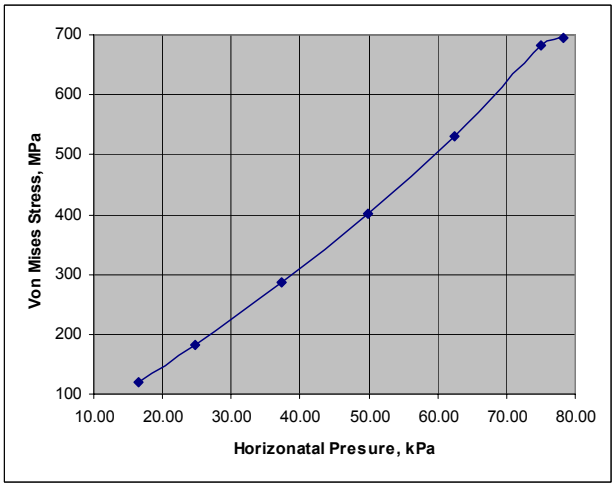


Figure 79: Von Mises stress in the Drip Shield crown due to vertical pressure (yielding @ 180 kPa).



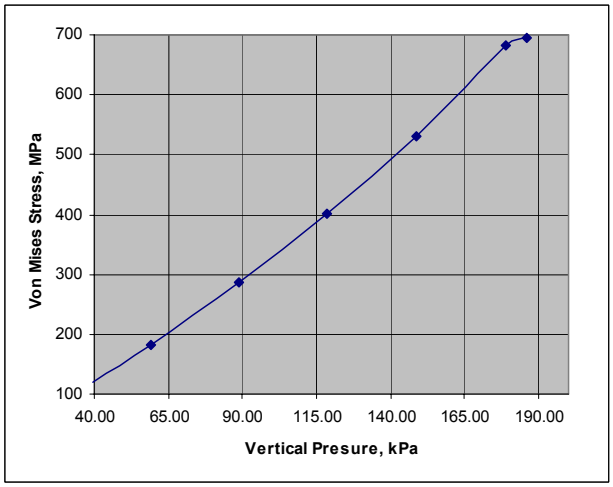


Figure 80. Von Mises stress in the Left Support Beam of the Drip Shield as a function of (a) horizontal {yielding @ 73 *kPa*} and (b) vertical (yielding @ 173 kPa) pressure

Date: August 17, 2007
Entry by: Roman V. Kazban

Summary of models used for "Modeling Techniques for Structural Performance Assessment of Drip Shield Systems—an Engineered Barrier of a Potential Geologic Repository" conference paper for IMAC-XXVI: Conference & Exposition on Structural Dynamics.

Two finite element models were used and identified as "Solid" and "Shell". The "Solid" finite element model correspond to "Partial Drip Shield" model (see pages 3-4 of this scientific notebook), and "Shell" finite element model corresponds to "Base Line No Non-Linear Springs with Fixed Boundary Conditions" model (see page 38 of this scientific notebook). Only loading conditions were changes for these models, and identified in Table 9. Finite element calculations were performed for each loading condition using both models, and Model identified as "IMAC_Solid_RunXX" and "IMAC_Shell_RunXX". Moreover, "Partial Drip Shield" model was re-mashed to represent the Drip Shield Shell Plate as 4 C3D8 solid elements through the thickness; this model is identified as "IMAC_Solid_RunXX_4elem" and is referred as "Solid4".

Table 9. Summary of Loading Conditions for both Drip Shield Models

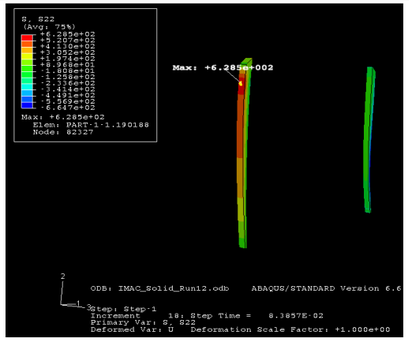
	Asymmetrical (Lateral to Vertical Ratio)				Asymmetrical (Lateral Asymmetry Ratio)				
	25	35	50	75	0	25	50	100	125
Run 1, kPa				225/300				150/300	
Run 2, kPa				225/300			180/270		
Run 3, kPa				225/300					138/312
Run 4, kPa				225/300		200/250			
Run 5, kPa				225/300	225/225				
Run 6, kPa			150/300				120/180		
Run 7, kPa			150/300			133/167			
Run 8, kPa			150/300		150/150				
Run 9, kPa		105/300					84/126		
Run 10, kPa		105/300				93/117			
Run 11, kPa		105/300			105/105				
Run 12, kPa	75/300						60/90		
Run 13, kPa	75/300					67/83			
Run 14, kPa	75/300				75/75				

Table 10 present the results of the finite element calculations.

Table 10	Max Load, %	Max Press applied, kPa			Max Stress, MPa	Location	Max Stress, MPa			1st Yielding - Von Mises			UTS Reached	Location	Max Load, %	Diff in Elem.	Yield vs Max	1st Yielding - S11			1st Yielding - S22		
		Vertical	Left Side	Right Side			Crown	Sides	Beam	Crown	Sides	Beam						Crown	Sides	Beam	Crown	Sides	Beam
Run 3 - Solid	30.07%	90.2	60.1	75.2	697.0	Supp. Beam	211.5	219.6	697.0	18.9%	22.9%	26.4%	No		30.07%	4.29%	62.87%	29.76%	160.5	255.4	107.5	26.42%	414.5
Run 3 - Shell	30.31%	90.9	60.6	75.8	965.9	Supp. Beam	184.0	211.1	804.7	16.2%	16.2%	18.8%	26.5%	Supp. Beam	25.78%		62.88%	15.16%	15.16%	27.74%	16.21%	23.45%	24.78%
Run 1 - Solid	32.05%	96.1	72.1	96.1	689.2	Supp. Beam	211.4	216.0	689.2	20.4%	26.4%	26.4%	No		32.05%	4.85%	63.81%	31.6%	154.4	241.3	107.7	26.42%	383.3
Run 1 - Shell	33.54%	100.6	75.5	100.6	966.4	Supp. Beam	212.0	273.5	966.4	16.7%	19.1%	22.7%	27.7%	Supp. Beam	27.20%		61.54%	16.7%	16.7%	29.2%	19.1%	24.5%	26.3%
Run 2 - Solid	38.54%	115.6	69.4	104.1	685.1	Supp. Beam	210.6	212.7	685.1	29.4%	29.4%	31.5%	No		38.54%	7.94%	76.21%	37.62%	130.1	196.5	104.9	29.38%	284.6
Run 2 - Shell	60.07%	180.2	108.1	162.2	1340.0	Bulkhead Fl.	182.0	198.1	806.7	20.5%	22.9%	26.4%	31.0%	Supp. Beam	30.60%		66.95%	20.49%	20.49%	32.20%	22.86%	29.76%	30.62%
Run 4 - Solid	44.94%	134.8	101.1	101.1	684.6	Supp. Beam	209.8	212.1	684.6	30.0%	39.4%	39.4%	No		44.94%	10.43%	66.76%	44.65%	101.7	154.7	100.6	39.38%	193.7
Run 4 - Shell	34.51%	103.5	77.6	77.6	690.5	Supp. Beam	179.0	182.6	690.5	29.4%	29.4%	29.4%	No		34.51%		85.12%	29.38%	23.75%	294.3	29.38%	33.91%	343.1
Run 5 - Solid	60.25%	180.7	135.6	135.6	691.2	Supp. Beam	209.9	211.4	691.2	47.5%	47.5%	57.5%	No		60.25%	15.50%	78.84%	57.50%	85.95	100.9	97.75	57.50%	79.02
Run 5 - Shell	44.75%	134.2	100.7	100.7	690.7	Supp. Beam	176.2	178.1	690.7	37.5%	37.5%	37.5%	No		44.75%		83.80%	37.50%	37.50%	143.5	37.50%	44.75%	218.6
Run 6 - Solid	54.07%	162.2	64.9	97.3	685.0	Supp. Beam	209.6	213.2	685.0	37.5%	43.8%	49.4%	No		54.07%	12.50%	69.36%	54.07%	151.9	235.3	102.6	49.38%	371.9
Run 6 - Shell	41.57%	124.7	49.9	74.8	691.6	Supp. Beam	178.7	181.3	691.6	31.5%	31.5%	39.4%	No		41.57%		75.74%	31.48%	29.38%	393.8	29.38%	41.17%	288.9
Run 7 - Solid	62.96%	188.9	83.7	105.1	685.0	Supp. Beam	208.2	211.7	685.0	47.5%	57.5%	57.5%	No		62.96%	15.09%	75.44%	172	131.5	197.6	97.62	57.50%	288.9
Run 7 - Shell	47.87%	143.6	63.7	79.9	692.6	Supp. Beam	179.6	179.3	692.6	39.4%	39.4%	41.5%	No		47.87%		82.26%	39.38%	39.38%	335.1	39.38%	47.73%	259.6
Run 8 - Solid	87.70%	263.1	131.5	131.5	684.0	Supp. Beam	208.9	205.0	684.0	67.5%	77.5%	77.5%	No		87.70%	23.03%	76.97%	157.9	87.7	102.2	77.31	77.50%	108.5
Run 8 - Shell	64.67%	194.0	97.0	97.0	692.3	Supp. Beam	176.0	176.5	692.3	57.5%	57.5%	57.5%	No		64.67%		88.92%	57.50%	47.50%	173.1	57.50%	60%	158.9
Run 9 - Solid	70.04%	210.1	58.8	74.2	685.3	Supp. Beam	208.1	212.9	685.3	57.5%	57.5%	63.8%	No		70.04%	16.36%	82.10%	165	70.05%	287.2	101.8	63.75%	488.9
Run 9 - Solid4	70.36%	211.1	59.1	74.6	686.2	Supp. Beam	200.1	231.1	686.2	57.5%	62.5%	62.5%	No		70.36%		81.72%	167.1	182.2	289.7	104.4	60%	329.6
Run 9 - Shell	53.68%	161.0	45.1	56.9	692.6	Supp. Beam	179.0	180.4	692.6	40.0%	43.8%	49.4%	No		53.68%		74.51%	40%	40%	431.9	37.50%	53.54%	385.8
Run 10 - Solid	81.26%	243.8	75.6	95.1	685.4	Supp. Beam	208.6	208.5	685.4	67.5%	77.5%	77.5%	No		81.26%	19.39%	83.07%	160.5	162	256.1	98.6	77.50%	421.4
Run 10 - Shell	61.88%	185.6	57.5	72.4	692.9	Supp. Beam	179.8	180.0	692.9	47.5%	53.8%	59.4%	No		61.88%		76.77%	50%	50%	391.2	47.50%	61.88%	332.2
Run 11 - Solid	127.30%	381.9	133.7	133.7	682.6	Supp. Beam	211.8	208.1	682.6	117.5%	107.5%	107.5%	No		127.30%	34.12%	84.45%	124.6	94.24	125.1	71.13	117.50%	148
Run 11 - Shell	93.18%	279.5	97.8	97.8	691.1	Supp. Beam	176.5	178.4	691.1	77.5%	77.5%	80.0%	No		93.18%		83.17%	89.38%	77.50%	217.9	67.50%	195.70	173.5
Run 12 - Solid	83.86%	251.6	50.3	75.5	831.4	Bulkhead Fl.	207.5	219.1	685.2	67.5%	77.5%	80.0%	83.8%	Bulkhead Fl.	83.86%	19.18%	80.49%	156.3	224	351.6	99.58	80%	628.5
Run 12 - Shell	64.68%	194.0	38.8	58.2	694.1	Supp. Beam	179.3	182.6	694.1	47.5%	59.4%	61.5%	No		64.68%		73.44%	53.75%	53.75%	477.3	47.50%	196.3	472.2
Run 13 - Solid	97.54%	292.6	65.4	81.0	768.9	Bulkhead Fl.	208.7	216.5	687.0	87.5%	97.5%	97.5%	No		97.54%	22.28%	89.71%	149.8	97.50%	328.4	99.13	97.50%	584.2
Run 13 - Shell	75.26%	225.8	50.4	62.5	693.3	Supp. Beam	179.8	182.3	693.3	57.5%	67.5%	72.5%	No		75.26%		76.40%	67.50%	67.50%	449.8	57.50%	196.3	434.7
Run 14 - Solid	180.00%	540.0	135.0	135.0	683.1	Supp. Beam	210.5	223.1	683.1	167.8%	167.8%	167.8%	No		180.00%	50.30%	93.22%	89.53	129.8	183	63.26	177.80%	281.4
Run 14 - Shell	129.70%	389.1	97.3	97.3	690.3	Supp. Beam	179.7	177.4	690.3	97.5%	111.1%	116.4%	No		129.70%		75.17%	128.2%	107.5%	271.7	87.50%	197.2	228.5

***Notes**

Solids ran longer than shells except for Run 1, 2, and 3
Most models stopped due to stresses in the support beam, except for Run 12- Solid and 13- Solid, which stopped w/ high stresses in the bulkhead fl.
Crown always yields first (Von Mises) except for Run 11 – Solid
Larger difference in the max load of solids vs. shells as loading becomes more symmetrical
Max S22 stress in the support beam usually occurred on the outside of the left beam rather than the inside of the right beam (see picture)



Blue Stress - Max stress in the expected area; did not reach yielding
Red Stress - Max stress not in the expected area; did not reach yielding
Red % - % at which yielding was reached, but expected area did not yield
Black % - % at which yielding was reached in the expected area

For the pinned restraints sensitivity analysis, the results of the "Base Line No Non-Linear Springs" model were used (see pages 33-37 of this scientific notebook).

For the projected loads sensitivity analysis, the "Base Line with Projected Loading and Fixed Boundary Conditions" (see page 61 of this scientific notebook) was modified to remove non-linear spring, and is identified as "Base_Line_Project_No_NLS_fixed". For this model the maximum load that the structure can withstand was estimated at 163.8 kPa of vertical load (for base case loading conditions) and the Drip Shield Crown yielding initiation was at 120.0 kPa of vertical load.

Date: January 18, 2007
Entry by: Roman V. Kazban

Additional models used for "Effect of Parameter Variations on the Structural Response of Drip Shield—an Engineered Barrier of a Potential Geologic Repository" conference presentation for IMAC-XXVI: Conference & Exposition on Structural Dynamics.

Additional loading configurations are highlighted in the Table 11.

Table 11. Complete Loading Conditions Matrix for Drip Shield Models

	Asymmetrical (Lateral to Vertical Ratio)				Asymmetrical (Lateral Asymmetry Ratio)				
	25	35	50	75	0	25	50	100	125
Run 3, kPa				225/300					138/312
Run 1, kPa				225/300				150/300	
Run 2, kPa				225/300			180/270		
Run 4, kPa				225/300		200/250			
Run 5, kPa				225/300	225/225				
Run 15, kPa			150/300						92/208
Run 16, kPa			150/300					100/200	
Run 6, kPa			150/300				120/180		
Run 7, kPa			150/300			133/167			
Run 8, kPa			150/300		150/150				
Run 17, kPa		105/300							65/145
Run 18, kPa		105/300						70/140	
Run 9, kPa		105/300					84/126		
Run 10, kPa		105/300				93/117			
Run 11, kPa		105/300			105/105				
Run 19, kPa	75/300								46/104
Run 20, kPa	75/300							50/100	
Run 12, kPa	75/300						60/90		
Run 13, kPa	75/300					67/83			
Run 14, kPa	75/300				75/75				

Table 12. Results of the Additional Finite Element Calculations

Loading Case	Model Used	Maximum Vertical Pressure Applied, kPa	Difference between models, %	Vertical Pressure at Yielding Initiation, kPa			Pv at Yield / Pv Max
				Drip Shield Crown	Drip shield Sides	Support Beam	
15	Solid	126.5	17.4%	79.1	68.0	108.5	53.7%
	Shell	104.5		68.0	68.3	80.8	65.0%
16	Solid	134.8	20.5%	86.0	74.0	114.5	54.9%
	Shell	107.2		71.4	81.4	86.6	66.6%
17	Solid	165.9	22.5%	111.8	86.8	144.4	52.3%
	Shell	128.6		87.6	87.8	113.7	68.1%
18	Solid	175.4	22.8%	120.0	95.6	152.2	54.5%
	Shell	135.5		93.2	94.2	116.6	68.8%
19	Solid	200.6	22.3%	146.7	107.3	183.1	53.5%
	Shell	155.9		117.8	115.5	143.9	74.1%
20	Solid	212.6	22.5%	157.5	116.4	195.1	54.7%
	Shell	164.7		117.8	116.3	150.4	70.6%

-----end of part 2-----

Date: April 6, 2009
Entry by: Roman V. Kazban

Note: Starting with the entry to follow and until further note, ABAQUS 6.8 finite element code is used to perform the analysis and as post-processing software ("ABAQUS User's Manual", Version 6.8. ABAQUS, Inc., Providence, Rhode Island, 2008).

Description of the "DOE Average Loading Case with Linear Springs and Constant Lateral Load at 60 °C" FE model (D:\LA Review\Conform Analyses\DS Conform Analyses\ DOE_Clone_20xAveLoad_EqlSpring_ConstLateral.*)**

To obtain "DOE Average Loading Case with Linear Springs and Constant lateral Load at 60 °C" FE Model (refer to Figure 81), the finite element model presented on Figure 1 (page 3 of this scientific notebook) was modified to include

1) Pallet Constraints constructed of the quadrilateral continuum shell elements with reduced integration (SC8R) with 26.8×27.6×25.4 *mm* typical size (refer to Figure 81);
2) Rigid Surface (refer to "Base_Line_No_Non-Linear_Springs" FE Model on page 33)
3) Linear Springs to account for rubble resistance (refer to "Base_Line" FE Model on page 41).

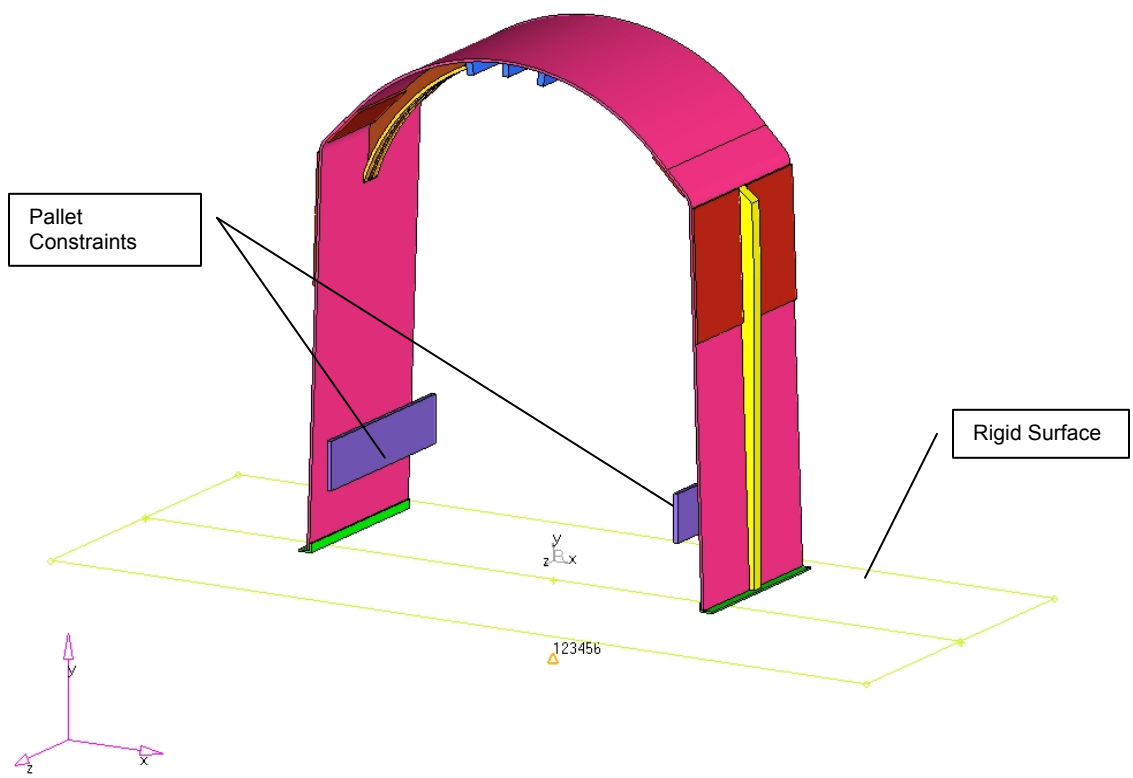


Figure 81. "DOE Average Loading Case with Linear Springs and Constant Lateral Load at 60 °C" FE model

The following material properties were assumed for Ti-7 and Ti-24 at 60 °C:

(1) Titanium Grade 24 (Ti-24)

At Room Temperature: Density = 4429 kg/m^3 = 4429e-9 kg/mm^3;
Poisson's ratio = 0.31;

At 60 ^oC: Modulus of elasticity = 1.140e11 *Pa* = 1.140e5 N/mm^2;
True Yield Stress = 7.770e8 *Pa* = 7.770e2 N/mm^2;
True Stress = 8.530e8 *Pa* = 8.530e2 N/mm^2;
True Strain = 0.070.

(2) Titanium Grade 7 (Ti-7)

At Room Temperature: Density = 4512 kg/m^3 = 4512e-9 kg/mm^3;
Poisson's ratio = 0.32;

At 60 ^oC: Modulus of elasticity = 1.050e11 *Pa* = 1.050e5 N/mm^2;
True Yield Stress = 2.430e8 *Pa* = 2.430e2 N/mm^2;
True Stress = 3.210e8 *Pa* = 3.210e2 N/mm^2;
True Strain = 0.130.

Boundary Conditions:

Loads: The loading is performed in two steps:

Step 1: The elements of the DS Shell Plate crown, the elements at the top of the Support Beams, and the elements of the Base external side are loaded directly with 127.86 *kPa* vertical pressure normally applied to each element (refer to Figure 45). Furthermore, (i) the elements that represent the Shell, the External Plates, and the Support Beam on the left side of the DS are loaded directly with 41.99 *kPa* normal pressure; and (ii) the elements that represent the Shell, the External Plates, and the Support Beam on the right side of the DS are loaded directly with 61.87 *kPa* normal pressure.

Step 2: Vertical pressure of 127.86 *kPa* normally applied to the elements of the DS Shell Plate crown, the elements at the top of the Support Beams, and the elements of the Base external side is monotonically increased until failure in any part of the structure is observed. Normal pressures of 41.99 *kPa* on the left side and 61.87 *kPa* on the right side of the DS applied to the elements that represent the Shell, the External Plates, and the Support Beam are kept constant.

Kinematic Constraints: The Drip Shield is model as a free standing structure. Therefore, a friction condition is modeled between the Rigid Surface that represents the Invert and the Base bottom surfaces. The coefficient of friction is set to 0.4.

All nodes in the XY-plane that belongs to the sides of the Drip Shield are constrained in the transverse direction (z-axis) to represent symmetry conditions. The DS displacement in y-direction is constrained by two SPRING1 elements of a relatively small stiffness to prevent rigid body modes. The DS displacement in x-direction is prevented by linear SPRING1 elements that represent rubble interaction with the DS. For these springs, the spring constant was derived as follows [refer to: "Creep Deformation of the Drip Shield (BSC 2005)"]:

$$k = \frac{E \cdot A}{w}$$

where E is the rubble modulus of elasticity, A is DS contact area with the rubble on the DS side, and w is an average distance from the DS to the drift wall. The DS contact area can be calculated from the FE model by multiplying DS Segment width of 1071.60 *mm* by DS Segment height of 2176.40 *mm*, as a results $A = 2332.2\ mm^2$. Therefore, for $E = 50\ MPa$ and $w = 2.5\ m$ [refer to: "Creep Deformation of the Drip Shield (BSC 2005)"], the total spring stiffness is

$$k^{TOTAL} = \frac{50 \times 10^6 \cdot 2.3322}{2.5} = 46.654 \times 10^6\ N/m$$

The total number of nodes in this model on the DS contact area is $N = 23{,}179$. Thus, the spring stiffness per node is

$$k^N = \frac{46.654 \times 10^6}{23.498 \times 10^3} = 1.99 \times 10^3\ N/m \cong 2\ N/mm.$$

<u>FEA Results:</u>

The computational analysis was terminated at the load of ***1,590.58 kPa*** vertical and left and right horizontal pressures of 41.99 *kPa* and 61.87 *kPa* due to reaching numerical instability {`THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY. TIME INCREMENT REQUIRED IS LESS THAN THE MINIMUM SPECIFIED`}.

Figure 82 represents the Von Mises Stress distribution in the section of the Drip Shield after completion of <u>*Step 1*</u> loading. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 285.25 *MPa* (based on the quilt plot without extrapolation).

Figure 83 represents the Von Mises Stress distribution in the section of the Drip Shield maximum loading achieved in <u>*Step 2*</u>. It was determined, that the maximum Von Mises stress occurred in the DS Bulkhead at the Crown on the DS side and was estimated at 864.5 MPa (based on the quilt plot without extrapolation).

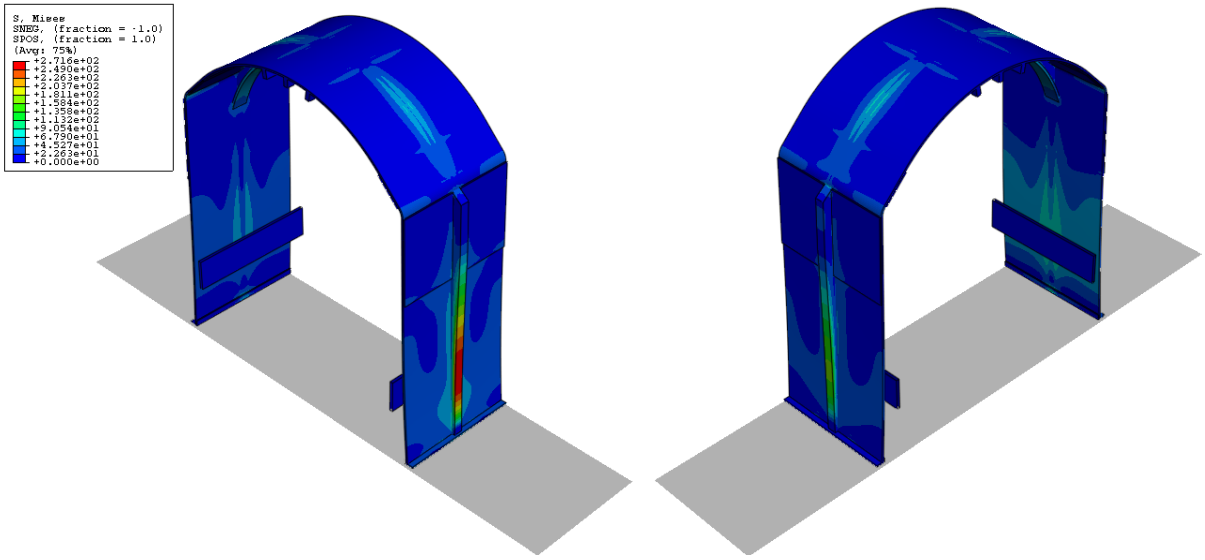


Figure 82. Von Mises stress distribution after completion of *Step 1* loading.

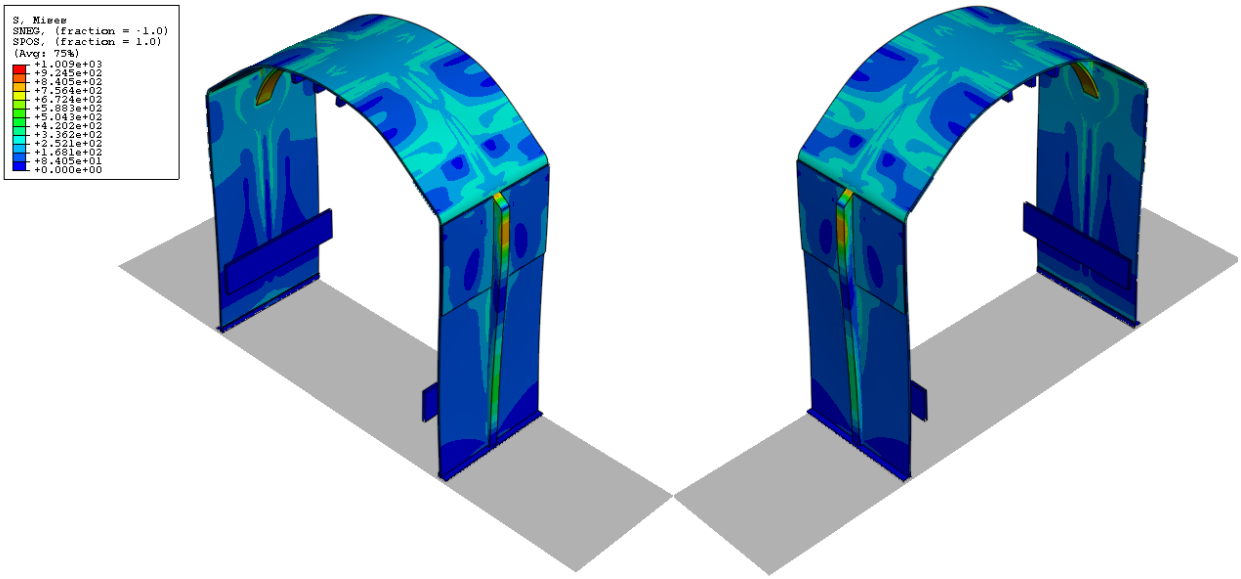


Figure 83. Von Mises stress distribution at maximum loading during *Step 2*.

Date: April 7, 2009
Entry by: Roman V. Kazban

<u>Description of the "DOE Average Loading Case with Linear Springs and Loads as a function of the Safety Factor at 60 °C" FE model</u> (D:\LA Review\Conform Analyses\DS Conform Analyses\ DOE_Clone_20xAveLoad_EqlSpring_LoadFunOfSF.*)**

The "DOE Average Loading Case with Linear Springs and Constant Lateral Load at 60 °C" FE model was modified to incorporate loads as a function of the safety factor. Based on information provided in "Structural Stability of a Drip Shield Under Quasi-Static Pressure" [BCS, 2004], vertical-to-lateral and lateral asymmetry ratios as a function of the safety factor (i.e., density multiplier) were estimated from the Average Case and the Six UDEC realizations as follows:

Table 13. Vertical-to-Lateral and Lateral Asymmetry ratios as a function of the Safety Factor.

Safety Factor	Vertical-to-Lateral Ratio	Lateral Asymmetry Ratio
0-1	0.406	1.47
2.5	0.30	1.36
3	0.28	1.324
4-20	0.27	1.25

Based on the values provided in Table 13, vertical and horizontal pressure loads as a function of safety factor were estimated as follows:

Table 14. Vertical and Horizontal Pressure Loads as a function of Safety Factor

Safety Factor	Left Horizontal Pressure, *kPa*	Vertical Pressure, *kPa*	Right Horizontal Pressure, *kPa*	Average Lateral Pressure, *kPa*
1	41.99	127.86	61.87	51.93
2.5	67.05	263.73	91.19	79.12
3	75.86	314.81	100.44	88.15
4	99.83	415.97	124.79	112.31
20	489.42	2039.26	611.78	550.6

No additional changes were made to the model.

<u>FEA Results:</u>

The computational analysis was terminated at the load of ***548.56 kPa*** vertical and left and right horizontal pressures of 131.65 *kPa* and 164.57 *kPa* due to reaching numerical instability {`THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY. TIME INCREMENT REQUIRED IS LESS THAN THE MINIMUM SPECIFIED`}.

Figure 84 represents the Von Mises Stress distribution in the section of the Drip Shield at loads corresponding to safety factor of 1. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 295.48 *MPa* (based on the quilt plot without extrapolation).

Figure 85 represents the Von Mises Stress distribution in the section of the Drip Shield at maximum loading achieved. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 813.6 *MPa* (based on the quilt plot without extrapolation).

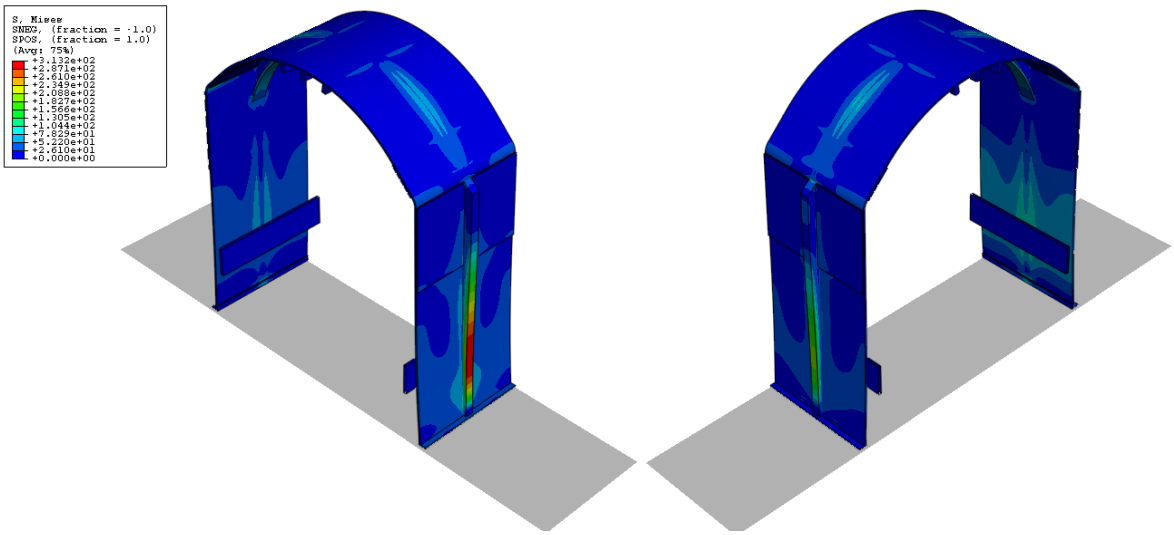


Figure 84. Von Mises stress distribution at loads corresponding to safety factor of 1.

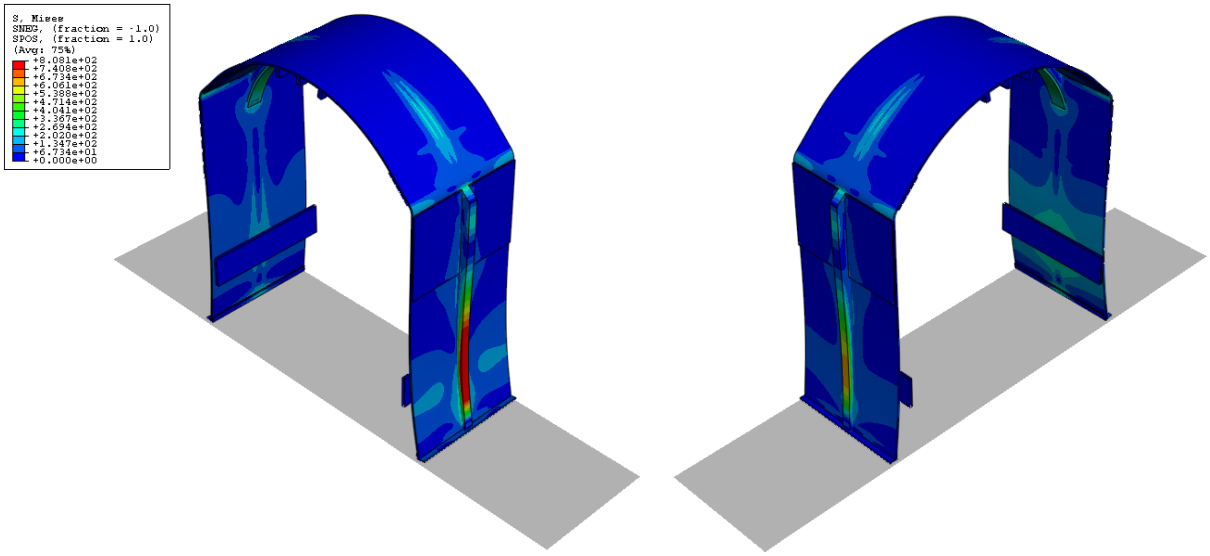


Figure 85. Von Mises stress distribution at maximum loading achieved.

Date: April 8, 2009
Entry by: Roman V. Kazban

<u>Description of the "DOE Average Loading Case with Linear Springs and Loads as a function of the Safety Factor at 150 °C" FE model</u> (D:\LA Review\Conform Analyses\DS Conform Analyses\ DOE_Clone_20xAveLoad_EqlSpring_LoadFunOfSF_150C.*)**

The "DOE Average Loading Case with Linear Springs and Loads as a function of the Safety Factor at 60 °C" FE model was modified to incorporate material properties at 150 °C (refer to page 2). No additional changes were made to the model.

<u>FEA Results:</u>

The computational analysis was terminated at the load of ***493.50 kPa*** vertical and left and right horizontal pressures of 118.44 *kPa* and 148.05 *kPa* due to reaching numerical instability {`THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY. TIME INCREMENT REQUIRED IS LESS THAN THE MINIMUM SPECIFIED`}.

Figure 86 represents the Von Mises Stress distribution in the section of the Drip Shield at loads corresponding to safety factor of 1. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 291.50 *MPa* (based on the quilt plot without extrapolation).

Figure 87 represents the Von Mises Stress distribution in the section of the Drip Shield at maximum loading achieved. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 690.0 *MPa* (based on the quilt plot without extrapolation).

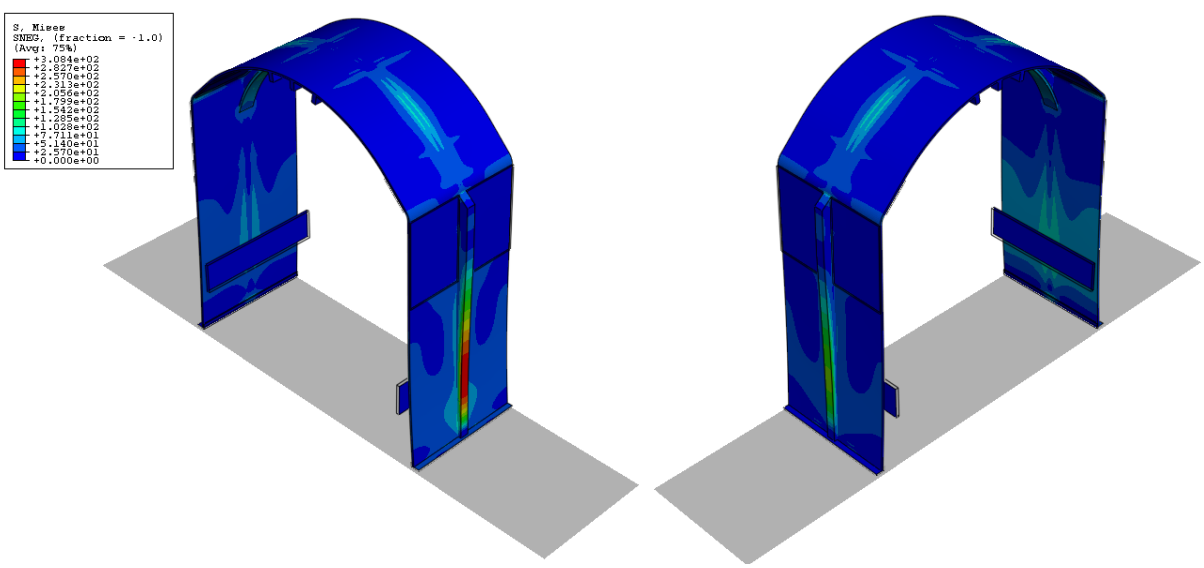


Figure 86. Von Mises stress distribution at loads corresponding to safety factor of 1.

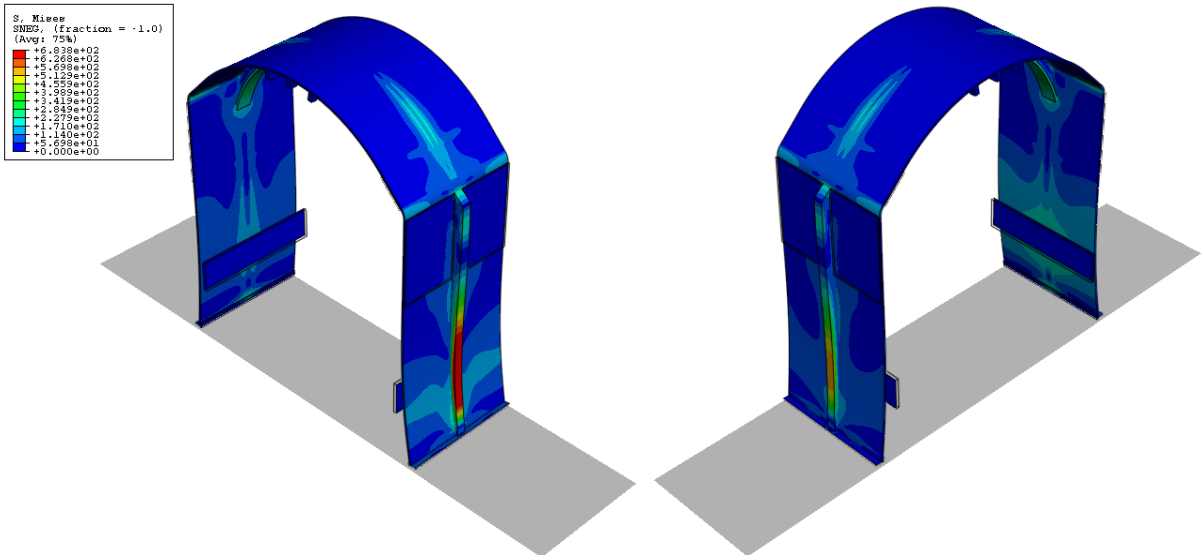


Figure 87. Von Mises stress distribution at maximum loading achieved.

Date: April 9, 2009
Entry by: Roman V. Kazban

<u>Description of the "DOE Average Loading Case with Non-Linear Springs and Loads as a function of the Safety Factor at 150 °C" FE model</u> (D:\LA Review\Conform Analyses\DS Conform Analyses\ DOE_Case_20xAveLoad_NonLinSpring_LoadFunOfSF.*)**

The "Base Line" FE Model (refer to page 41) was modified to incorporate loads as a function of the safety factor (refer to page 72). No additional changes were made to the model.

<u>FEA Results:</u>

The computational analysis was terminated at the load of ***329.86 kPa*** vertical and left and right horizontal pressures of 79.17 *kPa* and 98.96 *kPa* due to reaching numerical instability {THE SOLUTION APPEARS TO BE DIVERGING. CONVERGENCE IS JUDGED UNLIKELY. TIME INCREMENT REQUIRED IS LESS THAN THE MINIMUM SPECIFIED}.

Figure 88 represents the Von Mises Stress distribution in the section of the Drip Shield at loads corresponding to safety factor of 1. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 102.90 *MPa* (based on the quilt plot without extrapolation).

Figure 89 represents the Von Mises Stress distribution in the section of the Drip Shield at maximum loading achieved. It was determined, that the maximum Von Mises stress occurred in the Support Beam and was estimated at 698.50 *MPa* (based on the quilt plot without extrapolation).

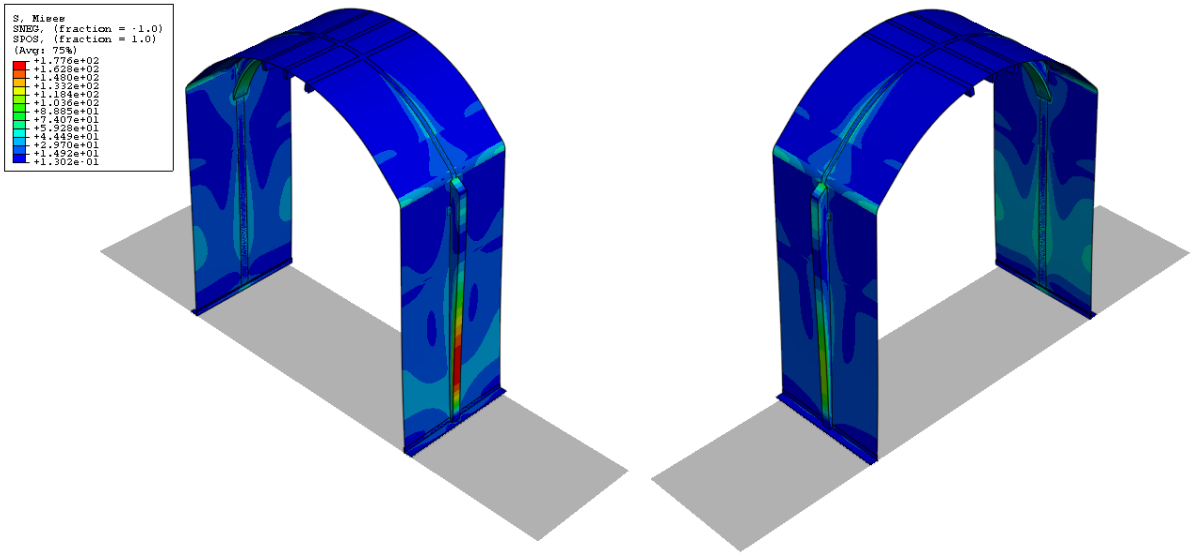


Figure 88. Von Mises stress distribution at loads corresponding to safety factor of 1.

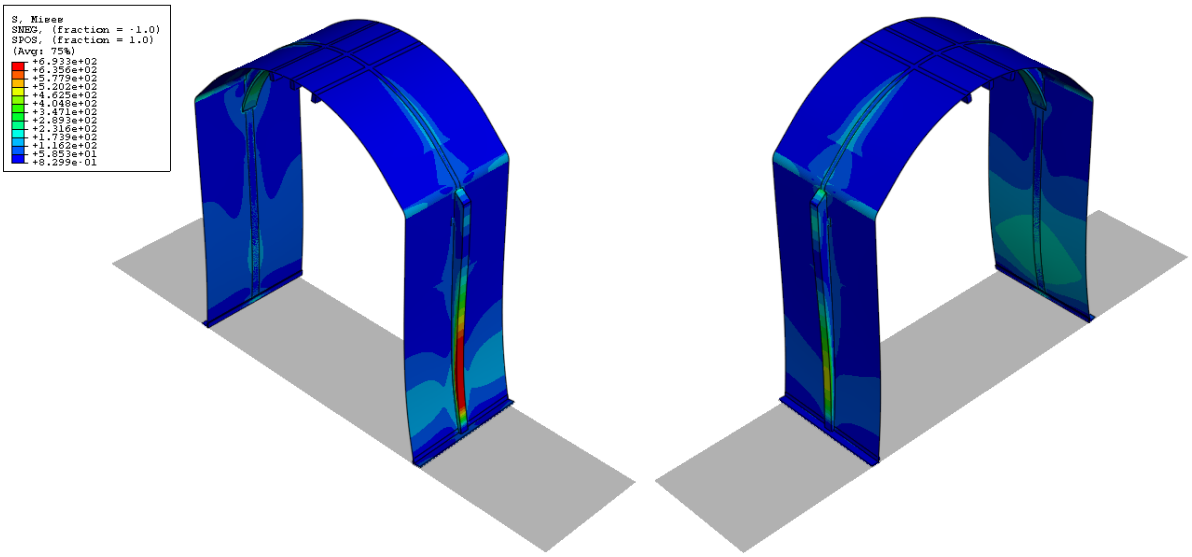


Figure 89. Von Mises stress distribution at maximum loading achieved.

Date: April 13, 2009
Entry by: Roman V. Kazban

The "Base Line" FE Model (refer to page 41) was used to perform sensitivity analysis on the DS capacity as a function of the spring stiffness. For this purpose, the "Base Line" FE Model was modified to incorporate linear SPRING1 elements that represent rubble interaction with the DS. The spring constant k^N was derived using the methodology presented on page 70 for the rubble modulus of elasticity in the range of $E = 0 - 50\,MPa$, and the total number of nodes in this model on the DS contact area of $N = 23{,}498$. Thus, the spring stiffness per node is

FE Model	Rubble Modulus E, MPa	Spring Constant k^N, N/mm
Case_Ave_Equal_Spring_Const_E50MPa.***	50	2
Case_Ave_Equal_Spring_Const_E40MPa.***	40	1.6
Case_Ave_Equal_Spring_Const_E30MPa.***	30	1.2
Case_Ave_Equal_Spring_Const_E20MPa.***	20	0.8
Case_Ave_Equal_Spring_Const_E10MPa.***	10	0.4
Case_Ave_Equal_Spring_Const_E05MPa.***	5	0.2
Case_Ave_Equal_Spring_Const_E03MPa.***	3	0.12
Case_Ave_Equal_Spring_Const_E01MPa.***	1	0.04
Case_Ave_No_Springs.***	0	0

Loads: 127.86 *kPa* vertical pressure, 41.99 *kPa* left side normal pressure, and 61.87 *kPa* right side normal pressure. All pressures were monotonically increased until failure.

Kinematic constraints: In "Case_Ave_No_Springs.***" FE Model, the DS displacement in x- and y-directions are constrained by four SPRING1 elements (two in each direction) of a relatively small stiffness to prevent rigid body modes.

FEA Results: The computational analysis was terminated as presented in Table 15.

Table 15.

FE Model	Right Side Pressure, *kPa*	Vertical Pressure, *kPa*	Left Side Pressure, *kPa*
Case_Ave_Equal_Spring_Const_E50MPa.***	68.44	208.41	100.85
Case_Ave_Equal_Spring_Const_E40MPa.***	68.02	207.13	100.23
Case_Ave_Equal_Spring_Const_E30MPa.***	67.60	205.85	99.61
Case_Ave_Equal_Spring_Const_E20MPa.***	67.18	204.58	98.99
Case_Ave_Equal_Spring_Const_E10MPa.***	65.92	200.74	97.14
Case_Ave_Equal_Spring_Const_E05MPa.***	64.24	195.63	94.66
Case_Ave_Equal_Spring_Const_E03MPa.***	62.57	190.51	92.19
Case_Ave_Equal_Spring_Const_E01MPa.***	58.37	177.73	86.00
Case_Ave_No_Springs.***	42.41	129.14	62.49

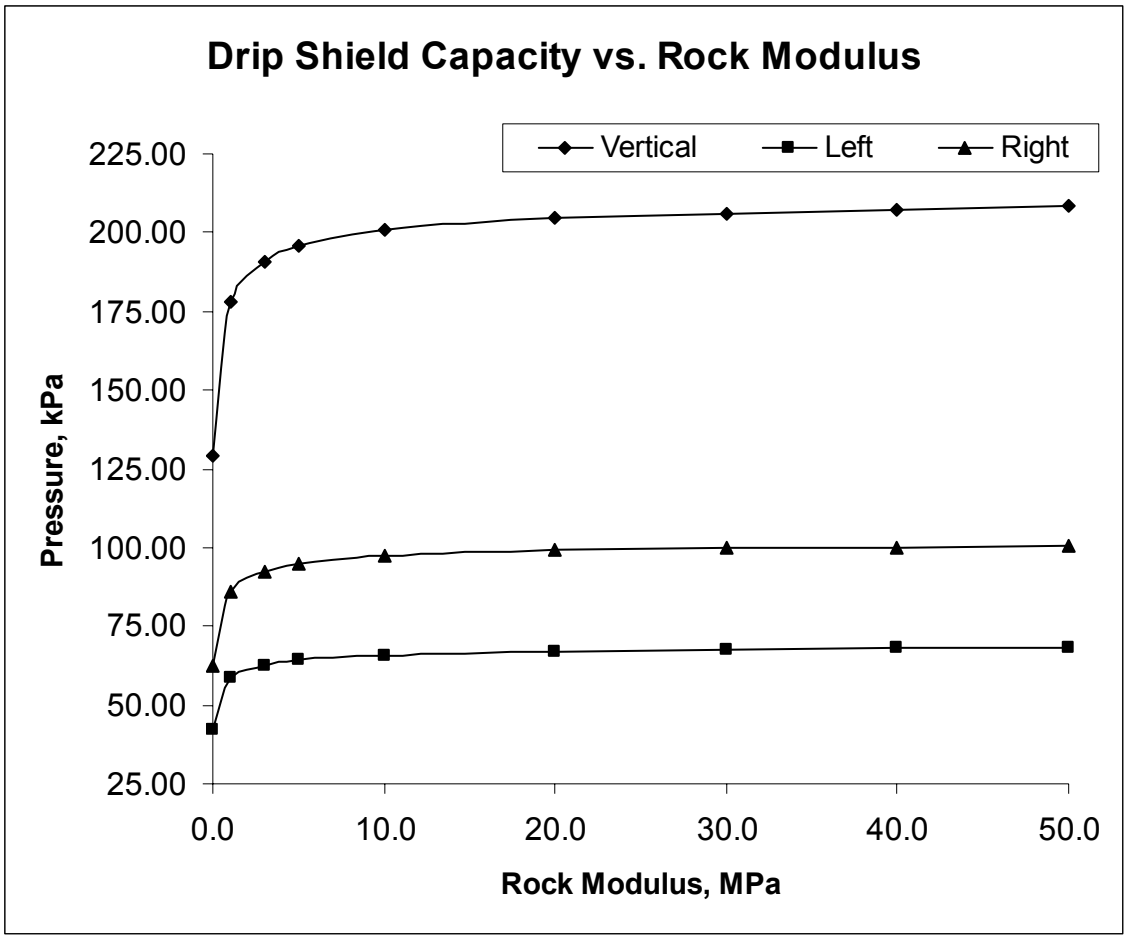

Drip Shield Capacity vs. Rock Modulus
Vertical
Left
Right
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
Pressure, kPa
0.0
10.0
20.0
30.0
40.0
50.0
Rock Modulus, MPa

Figure 90.

Date: June 18, 2009
Entry by: Roman V. Kazban

Installation Testing for HyperMesh 9.0 Software Release Notice

Auto_job2_rev1.hm model, auto_job2_rev1_hm.inp input file for ABAQUS and auto_job2_rev1_hm.res analysis results (see HyperMesh 8.0 validation package for files and description) were used to perform installation testing for HyperMesh 9.0. The models and analysis results displayed were consistent with those of similar utilities available in ABAQUS/CAE.