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Analysis for Spent Nuclear Fuel Multi-Canister Overpack Drop into the Cask from the Multi-Canister Overpack-Handling Machine with Air Cushion

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ENGINEERING REPORT

ANALYSIS FOR SNF MCO DROP INTO THE CASK FROM THE MHM WITH AIR CUSHION

FLUOR DANIEL HANFORD, INC
RICHLAND, WA

SPENT NUCLEAR FUEL PROJECT

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NOVEMBER 1999

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EXECUTIVE SUMMARY

The Spent Nuclear Fuel (SNF) Canister Storage Building (CSB) is the interim storage facility for K-Basin SNF at the U.S. Department of Energy (DOE) Hanford Site. The SNF is packaged in multi-canister overpacks (MCOs). The MCO is placed inside a shipping cask at the K-Basin facilities for transportation to the CSB. At the CSB service station, the MCO is moved from the shipping cask by the MCO handling machine (MHM) to a storage tube or one of two sample/weld stations.

The purpose of this report is to investigate the potential for damage to the MCO during impact from an accidental drop from the MHM into the shipping cask. The MCO is dropped from a height of 8.2 feet above the cask, enters the cask concentrically and falls the additional 12.83 feet to the cask bottom. Because of the interface fit between the MCO and the cask and the air entrapment, the MCO fall velocity is slowed. The shipping cask is resting on an impact absorber at the time of impact. The energy absorbing properties of the impact absorber are included in the analysis. The results of this analysis are needed to show the following:

- If a breach resulting in unacceptable release of contamination could occur in the MCO
- The effect of the impact on the internals of the MCO

The MCO drop into the cask produces very large impact reactions on the MCO and internals. Plastic strains are shown to occur in the bottom of the MCO, sides of the MCO near the weld area, the basket support plates, the outside basket support posts, and the basket center support post. Large amounts of energy are absorbed during the impact by these components.

The maximum equivalent plastic strain in the bottom of MCO is 2.0%. This is below the calculated effective failure strain of 15%. The effective failure strain value is calculated based on the multi-axial stress state (triaxiality factor), temperature, and strain rate. Breaching of the MCO pressure boundary due to through-wall cracking is not expected.

Equivalent plastic strains are 2.1% in the weld area at the juncture of the MCO walls and the MCO bottom. This is below the calculated 12.5% effective failure strain. The maximum equivalent plastic strain occurs at the inside surface of the MCO in the weld area. Breaching of the MCO pressure boundary due to through-wall cracking in the weld area is also not expected.

Buckling is expected in the six support posts located near the edge of the bottom basket. The maximum equivalent plastic strain in the center support post of the bottom basket is 1.0%. The plastic strain results in shortening of the center support post of the bottom basket by about 0.13 in. Calculations show neither Euler elastic buckling or local elastic buckling in the walls of the center support post is likely. Inelastic buckling in the walls of the center support post cannot be determined from this analysis. However, calculations based on the shortening in the center support post of the bottom basket show that the crushing force has not been exceeded.

The baskets are stacked together with socket type connections between each. The top basket is engaged by a socket type connection that fits over the top of the basket.

support post. Deformations in the center support post in combination with deformation in the basket support plates and deflections of the MCO cause the gap between the MCO top and the top of the center support post to increase during the impact. The increase in the gap is not sufficient to disengage the top of the center support post from the socket in the MCO shield plug.

There is little material below the bottom basket inside the MCO to absorb the force of the impact. Due to the large inertia of the cask, the force of the impact of the MCO with the cask is not immediately transferred into the impact absorber and the MCO and its contents bounce after impact. A height of 0.9 inches is reached by the conclusion of the analysis at 0.08 seconds after impact. The impact absorber beneath the cask is not entirely effective in mitigating the effects of this impact. The impact absorber is shown to experience plastic deformation of about 0.6 in during the initial impact. The impact absorber absorbed about 1,264,000 in-lb energy (0.63 in x 2,006,000 lb) or about 1/3 of the total initial kinetic energy of 3,610,000 in-lb.

The MCO, baskets, and fuel pins decelerate from the impact velocity of 373 in/sec to zero in a time period of between 0.001 and 0.01 seconds. Study of displacement time history output indicates the MCO moves downward until approximately 0.01 seconds after impact. As a lower bound on the deceleration, the velocity is assumed to be zero at time 0.01 seconds after impact. This yields a deceleration of about 100g. Time history output of velocity from the analysis can also be used to calculate deceleration. Deceleration is determined from a velocity time history by dividing the change in velocity by the change in time for some portion of the curve. Calculation of deceleration is complicated by high frequency components in the curves, making it difficult to select an average slope of the line. Wide variations in deceleration can be calculated depending on which curve is used and where a line is drawn to determine the slope of the curve. An upper bound on the deceleration of the MCO and internals, the slope of the curve showing the maximum change in velocity divided by the minimum change in time is used. Most of the velocity curves show a very sharp spike at 0.0001 seconds. If this is ignored, a slope can be drawn on each of the curves that shows a change in velocity from -373 in/sec to 0 in/sec in a duration of between 0.001 and 0.002 seconds. This gives an average deceleration of between 1000g and 500g.

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LIST OF ACRONYMS

CSB	Canister Storage Building
DESH	Duke Engineering & Services Hanford Inc
DOE	U S Department of Energy
FDNW	Fluor Daniel Northwest
MCO	Multi-canister overpack
MHM	MCO handling machine
QA	Quality Assurance
SNF	Spent Nuclear Fuel

ENGINEERING REPORT

ANALYSIS FOR

SNF MCO DROP INTO THE CASK FROM THE MHM WITH AIR CUSHION

1 0 PURPOSE AND OBJECTIVES

The Spent Nuclear Fuel (SNF) Canister Storage Building (CSB) is the interim storage facility for K-Basin SNF at the U S Department of Energy (DOE) Hanford Site. The SNF is packaged in multi-canister overpacks (MCOs). The MCO is placed inside a shipping cask at the K-Basin facilities for transportation to the CSB. At the CSB service station the MCO is moved from the shipping cask by the MCO handling machine (MHM) to a storage tube or one of two sample/weld stations.

The purpose of this report is to investigate the potential for damage to the MCO during impact from an accidental drop from the MHM into the shipping cask. The MCO is dropped from a maximum height of 8.2 feet above the cask, enters the cask concentrically and falls the additional 12.83 feet to the cask bottom. Because of the interface fit between the MCO and the cask and the air entrapment, the MCO fall velocity is slowed. The impact velocity is taken from calculations by B. Crea (Reference 1). The shipping cask is resting on an impact absorber at the time of impact. The energy absorbing properties of the impact absorber are included in the analysis. The results of this analysis are needed to show the following:

- If a breach resulting in unacceptable release of contamination could occur in the MCO
- The effect of the impact on the internals of the MCO

2 0 SUMMARY OF FINAL RESULTS AND CONCLUSIONS

Multiple computer analyses were run to determine the worst case conditions for the MCO and internals. Variable parameters were material properties at temperatures of 50 to 270 degrees Fahrenheit and internal pressures of 0 to 450 psig. Maximum plastic strain values for the MCO and internals were found to occur at 270 degrees Fahrenheit and internal pressure of 0 psig.

The MCO drop into the cask produces very large impact reactions on the MCO and internals. Plastic deformations are shown by the analysis, occurring in the bottom of the MCO and the bottom two baskets. Plastic strains are shown to occur in the bottom of the MCO, sides of the MCO near the weld area, the basket support plates, the outside basket support posts, and the basket center support post. Large amounts of energy are absorbed during the impact by these components.

Maximum plastic strain values for the MCO and internals were found to occur at 270 degrees Fahrenheit and 0 psig. The maximum equivalent plastic strain in the bottom of MCO is 2.0%. This is below the calculated effective failure strain of 15%. The effective failure strain value is calculated based on the multi-axial stress state (triaxiality factor), temperature, and strain rate. Breaching of the MCO pressure boundary due to through-wall cracking is not expected.

Equivalent plastic strains are 2.1% in the weld area at the juncture of the MCO walls and the MCO bottom. This is below the calculated 12.5% effective failure strain. The maximum equivalent plastic strain occurs at the inside surface of the MCO in the weld area. Other locations through the thickness of the MCO wall in the weld area show effective plastic strain values of 1.0%, 0.41%, and 0.26% compared against calculated effective failure strains of 17.7%, 23.3%, and 10.9% respectively. Breaching of the MCO pressure boundary due to through-wall cracking in the weld area is also not expected.

The initial analysis (material properties at 50 degrees Fahrenheit and 0 psig) shows that the maximum stress in the outside support posts is about 62,000 psi. This is well beyond the calculated inelastic buckling stress of 30,000 psi. Buckling is expected in the six support posts located near the edge of the bottom basket. In order to determine maximum loads on the basket center support post, the cross-sectional area for the basket outside support posts is reduced to provide a reduced stiffness. This allows the basket outside support posts to yield early in the analysis, causing the basket center support post to carry the majority of the load caused by the impact. The maximum equivalent plastic strain in the center support post of the bottom basket is about 1.0%. The plastic strain results in shortening of the center support post of the bottom basket by about 0.13 in. Calculations show neither Euler elastic buckling or local elastic buckling in the walls of the center support post is likely. Inelastic buckling in the walls of the center support post cannot be determined from this analysis. However, calculations based on the shortening in the center support post of the bottom basket show that the crushing force has not been exceeded. Calculations are shown in Appendix B.

The baskets are stacked together with socket type connections between each. The top basket is engaged by another socket type connection that fits over the top of the basket support post. Deformations in the center support post in combination with deformation in the basket support plates and deflections of the MCO cause the gap between the MCO top and the top of the center support post to increase during the impact. The increase in the gap is not sufficient to disengage the top of the center support post from the socket in the MCO shield plug. The maximum gap is shown to be 0.72 inches. This includes the effects of both elastic and plastic deformations. The maximum gap is compared against the engagement length of the top of the center support post with the socket at the MCO shield plug. The initial engagement length of the MCO top with the top of the center support post of the top basket is taken from the MCO drawings (Ref 2) to be 1.625 inches. This leaves 0.905 inches of engagement length. If the center support post were assumed to bow to one side during the impact, the gap increases an additional 0.12 inches. The minimum engagement length during the impact is then 0.785 inches. Calculations are shown in Appendix B.

There is little material below the bottom basket inside the MCO to absorb the force of the impact. Due to the large inertia of the cask, the force of the impact of the MCO with the cask is not immediately transferred into the impact absorber and the MCO and its contents bounce after impact. A height of 0.9 inches is reached by the conclusion of the analysis at 0.08 seconds after impact. The impact absorber beneath the cask is not entirely effective in mitigating the effects of this impact. The impact absorber is shown to experience plastic deformation of about 0.6 in during the initial impact. The impact absorber absorbed about 1,264,000 in-lb energy (0.63 in x 2,006,000 lb) or about 1/3 of the total initial kinetic energy of 3,610,000 in-lb.

The MCO baskets and fuel pins decelerate from the impact velocity of 373 in/sec to zero in a time period of between 0.001 and 0.01 seconds. Study of displacement time history output indicates the MCO moves downward until approximately 0.01 seconds after impact. As a lower bound on the deceleration, the velocity is assumed to be zero at time 0.01 seconds after impact. This yields a deceleration of about 100g. Time history output of velocity from the analysis can also be used to calculate deceleration. Deceleration is determined from a velocity time history by dividing the change in velocity by the change in time for some portion of the curve. Calculation of deceleration is complicated by high frequency components in the curves making it difficult to select an average slope of the line. Wide variations in deceleration can be calculated depending on which curve is used and where a line is drawn to determine the slope of the curve. An upper bound on the deceleration of the MCO and internals the slope of the curve showing the maximum change in velocity divided by the minimum change in time is used. Most of the velocity curves show a very sharp spike at 0.0001 seconds. If this is ignored a slope can be drawn on each of the curves that shows a change in velocity from -373 in/sec to 0 in/sec in a duration of between 0.001 and 0.002 seconds. This gives an average deceleration of between 1000g and 500g.

3.0 ASSUMPTIONS and ANALYSIS PARAMETERS

A drop of the MCO into the shipping cask is studied in this report. This accidental drop could occur at the service station.

The MCO is constructed of stainless steel and measures approximately 24 inches in diameter by about 13 feet in length as shown in Figure 3.1. Each MCO has the capacity to contain six Mark 1A baskets (see Figure 3.2) or five Mark IV baskets loaded with fuel pins (see Figure 3.3). The baskets are stacked one on top of the other. The total loaded weight of six Mark 1A baskets is heavier than the loaded weight of five Mark IV baskets. This report considers the MCO loaded only with the Mark 1A baskets. At the bottom of the MCO are six basket support plates (ribs) in a radial arrangement. These six ribs support the entire stack of baskets. The loaded baskets make up about 70% of the total weight of the MCO. The MCO and baskets are assumed to be in a temperature range of 50 to 270 degrees Fahrenheit and an internal pressure of 0 to 450 psig.

The shipping cask is constructed of SA 336 type F304 steel. It has an outside diameter of approximately 40 inches and is about 13 feet in length as shown in Figure 3.4.

The shipping cask is resting on an impact absorber (Refs. 4&5). The impact absorber is a total of 45 inches tall and composed of two layers. The top layer is designed to absorb energy by crushing when a load of between 1,200,000 lbs and 2,006,000 lbs is reached. The maximum crushing load is used in the computer simulation as this will produce higher impact loads. The top layer is constructed from 5 in. diameter steel tubes in a vertical arrangement. The bottom layer is a grid constructed of A36 steel plate. The impact absorber is shown in Figure 3.5.

The MCOs are maneuvered inside the CSB by the MCO handling machine (MHM). The MCO may accidentally be dropped from a maximum height of 8.2 feet above the shipping cask, enters the cask concentrically and falls the additional 12.83 feet to the cask bottom. (The eccentric drop has been studied in Reference 8). The impact velocity of the MCO at the bottom of the cask is slowed by the effect of air entrapped in the shipping cask, which is compressed as the MCO falls. The air escapes through the opening at the top of the cask between the MCO and the cask. The impact velocity of 31.13 ft/sec is taken from calculations by B. Crea (Appendix J of Ref. 1).

As the MCO falls into the shipping cask, it is assumed there is no contact between the MCO and the cask walls or mouth. The only impact considered is between the bottom of the MCO and the bottom inside surface of the shipping cask.

An axisymmetric model is used for this analysis to take advantage of the symmetry of the MCO, baskets, shipping cask, and impact absorber about a common centerline, and the symmetric nature of the loading imposed on the components. Use of the axisymmetric model assumes that the geometry, loading, and response of the MCO, baskets, fuel pins, shipping cask, and impact absorber is symmetric about the common centerline. The axisymmetric model represents the entire system with a 2-dimensional slice from the centerline outward. Lateral displacement of nodes on the centerline of the model is assumed not to occur.

3.1 Drop Parameters at Cask

Loaded MCO weight	20,000 lbf
Drop velocity	31 ft/sec (373 in/sec)
Kinetic energy at impact (See Appendix B for calculation)	$KE = 3.61 \times 10^6 \text{ in-lbf}$
Impact surfaces	Inside bottom surface of shipping cask and bottom of MCO

3 2 MCO Physical Properties

Wall thickness	0 5 in
Bottom thickness	2 01 in
Outside diameter	24 0 in
Outside diameter at head	25 3 in

3 3 Cask Physical Properties

Wall thickness	7 31 in
Bottom thickness	6 13 in
Outside diameter	39 81 in
Inside diameter	25 19 in
Inside diameter at top	25 5 in
Inside diameter through necked down area	24 25 in

3 4 Impact Absorber Physical Properties

Height	45 0 in
Outside Diameter	39 0 in
Crushing Load (Min - Max)	1 200,000 - 2 006,000 lbf

3 5 Material Properties

The MCO and fuel pin baskets are constructed from 304L stainless steel
Material properties at temperatures of 50 and 270 degrees Fahrenheit for type
304L stainless steel are shown below

	<u>50° F</u>	<u>270° F</u>
Elastic Modulus	28 000 000 psi	27 180,000 psi
Elongation in 2 in	36%	31%
Density	0 284 lb/in ³	0 284 lb/in ³

The shipping cask is constructed from SA 336 type F304 stainless steel
Material properties for SA 336 type F304 stainless steel are shown below

	50° F	270° F
Elastic Modulus	28 000 000 psi	27,180,000 psi
Elongation in 2 in	36%	31%
Density	0.284 lb/in ³	0.284 lb/in ³

True stress and plastic true strain values are computed using the equations shown in Table 3.1 (Ref. 6). Engineering stress-strain values and "true" stress and "true" strain values for type 304L stainless and SA 336 type F304 stainless are identical. These are shown in Table 3.1. The true stress-strain values are input into the computer model. Values for the elastic modulus and yield stress at 270 degrees Fahrenheit are interpolated from values taken from ASME section III (Ref. 9).

$$\text{True Stress} = \sigma_{\text{true}} = (1 + \epsilon_{\text{nom}}) \sigma_{\text{nom}}$$

$$\text{True Strain} = \epsilon_{\text{true}} = \ln(1 + \epsilon_{\text{nom}}) = \frac{\sigma_{\text{true}}}{E}$$

Engineering Stress at 50°F (σ_{nom})	Engineering Strain at 50°F (ϵ_{nom})	"True" Stress at 50°F (σ_{true})	"True" Strain at 50°F (ϵ_{true})
30 000 psi	0.001	30 032 psi	0
75 000 psi	0.343	100 701 psi	0.291
75,000 psi	0.353	101,451 psi	0.298
75,000 psi	0.363	102 201 psi	0.306

Engineering Stress at 270°F (σ_{nom})	Engineering Strain at 270°F (ϵ_{nom})	"True" Stress at 270°F (σ_{true})	"True" Strain at 270°F (ϵ_{true})
19 800 psi	0.001	19 814 psi	0
23 832 psi	0.006	23,972 psi	0.004988
28 184 psi	0.019	28 721 psi	0.01784
36 393 psi	0.059	38 553 psi	0.05638
42 528 psi	0.099	46 753 psi	0.093285
63 167 psi	0.599	101,025 psi	0.468136

Table 3.1 Engineering and "True" Stress-strain Values for Type 304L Stainless Steel and SA 336 type F304 Stainless Steel

The impact absorber is constructed from A36 carbon steel. Material properties for A36 steel are shown below. True stress and plastic true strain values are shown in Table 3.2.

Elastic Modulus	30 000 000 psi
Density	283 lb/in ³

Engineering Stress (σ_{nom})	Engineering Strain (ϵ_{nom})	"True" Stress (σ_{true})	"True" Strain (ϵ_{true})
36 000 psi	0.001	36 044 psi	0
37,000 psi	0.021	37 786 psi	0.02
50 000 psi	0.102	55 085 psi	0.095
55 000 psi	0.177	64 728 psi	0.161

Table 3.2 Engineering and "True" Stress-strain Values for A36 Steel

The fuel pins are manufactured from a combination of Uranium and Zircaloy cladding. Material properties for Uranium are used in the computer model. Material properties for uranium are shown below.

Elastic Modulus	24 000 000 psi
Poisson Ratio	0.27

Time dependent strain rates are enabled in the computer model using the Cowper-Symonds equation and coefficients shown in Table 3.3 (see Ref. 7).

$$\epsilon = D \left(\frac{\sigma_0}{\sigma_0} - 1 \right)^q \quad \sigma_0 \geq \sigma_0$$

where σ_0 is the dynamic flow stress at a uniaxial plastic strain rate ϵ , σ_0 is the associated static flow stress and D and q are constants for a particular material.

Material	D (s ⁻¹)	q
Stainless Steel 304	100	10

Table 3.3 Cowper-Symonds Equation and Coefficients

3.6 Failure Criteria

Failure strain is dependent on the multi-axial stress state, temperature, and strain rate. Failure strain values of 21% and 40% are used for weld metal and base metal respectively (Reference 8 provides further discussion on predicted failure).

strains) These values represent engineering strain while the computed values from the ABAQUS computer analysis will be true strain The failure strain values are reduced to account for the 270 F design temperature (Reference 10) converted to "true" strain using the Manjoine correlation as shown in Table 3 4 The resulting values are further reduced to account for dynamic strain rate effects A reduction of 20% is assumed

	Engineering Strain at 70° F (ϵ_{70})	Engineering Strain at 270°F (ϵ_{270}) ($\epsilon_{70} \cdot 31.4/36$)	True" Strain $\ln(1 + \epsilon_{270})$	Dynamic Reduction (True strain) • 8
Weld Metal	0.210	0.183	0.168	0.134
Base Metal	0.400	0.349	0.299	0.239

Table 3 4 Failure Strain Values

Note All units are in inches

Figure 3 1 Multi-canister Overpack

Figure 3 2 Mark 1A Fuel Pin Basket

Figure 3 3 Fuel Element Assembly

Note All units are in inches

Figure 3 4 Shipping Cask

Note All units are in inches

Figure 3 5 Impact Absorber

4.0 FINITE ELEMENT MODEL

A finite element computer model is used to simulate the MCO impact with the bottom of the shipping cask. The MCO fuel pin baskets, fuel pins, shipping cask, and impact absorber are all modeled. The computer model is shown in Figures 4.1 and 4.2. Multiple analyses are run to determine the worst case conditions for the MCO and internals. Variable parameters are the material properties at temperatures of 50 to 270 degrees Fahrenheit and internal pressures of 0 to 450 psig. The input files used for the analysis are listed in Appendix C.

The majority of the model is constructed from axisymmetric solid elements. Some of the components of the system cannot be represented directly using axisymmetric elements. Equivalent axisymmetric properties are calculated for these components then they are modeled using axisymmetric elements. They are the basket support plates, the basket outside support posts, the fuel pins, the pads on the inside bottom surface of the shipping cask, and the impact absorber.

The basket support plates are modeled as axisymmetric solid elements. Equivalent material properties are used for the modulus of elasticity and density. These are calculated by multiplying the ratio of actual cross-sectional area of the support plates to the cross-sectional area of a solid disk by the material property. Calculations for the equivalent material properties are shown in Appendix B.

The outside basket support posts are modeled as axisymmetric shell elements. An equivalent thickness of the shell is entered in the model in place of the actual post dimensions. The shell equivalent thickness is found by determining the thickness of continuous cylindrical shell required for the cross-sectional area of the shell to equal the cross-sectional area of the combined support posts. Calculation of the equivalent shell thickness is shown in Appendix B. In early computer runs of the model, large lateral deformations and Euler type buckling was observed in the shell elements using the computed shell thickness. In order to find the load in the outside support posts it is necessary to prevent these large lateral deformations. This was accomplished by increasing the shell thickness by a factor of 10 from 0.267 in to 2.67 in. The elastic modulus and the density were both decreased by a factor of 10 to compensate. After the maximum loads in the outside support post were determined the thickness and material properties were changed back to their original values. This allows the outside support posts to yield early in the analysis, resulting in maximum loads in the center support post.

The fuel pins are modeled with three axisymmetric solid elements. The total cross-sectional area of the axisymmetric elements is equal to the total cross-sectional area of the fuel pins loaded in each basket. Calculations are shown in Appendix B.

The cask pads are modeled as axisymmetric solid elements. An equivalent width of the solid element is entered in the model in place of the actual pad dimensions. The equivalent width is found by determining the width of a continuous cylindrical shaped solid required for the cross-sectional area of the

cylinder to equal the cross-sectional area of the combined pads. Calculation of the equivalent width of the solid element is shown in Appendix B.

The bottom of the impact absorber is constructed from plate material. Equivalent properties are calculated for an axisymmetric solid based on the ratio of actual material to that of a solid disk. The yield stress for the top crushing layer of the impact absorber is based on the maximum crushing load of 2 006 000 lbs rather than actual material properties. Other material properties are based on the ratio of actual cross-sectional area to a solid section. Calculations are shown in Appendix B.

Contact surfaces are modeled between the following components in the computer model:

- The top inside surface of the MCO and the top fuel pin basket post
- Individual fuel pin baskets
- Fuel pins between the basket plates
- The bottom fuel pin basket and the basket support plate
- The basket support plate and the bottom inside surface of the MCO
- The bottom outside surface of the MCO and the bottom inside surface of the shipping cask
- The bottom outside surface of the shipping cask and the top surface of the impact absorber

Adjustments to the material properties are made for the outside basket support posts as described above in this section. The material density for the fuel pin elements is adjusted so that the total weight of the MCO, baskets and fuel pins is 20 000 lb.

Boundary conditions are applied to the model to prevent displacement at certain locations. Lateral restraints are applied to nodes on the centerline of the model. Both lateral and vertical restraints are applied to the nodes at the bottom of the impact absorber.

Figure 4 1 Axisymmetric Computer Model

Figure 4 2 Close-up View of Axisymmetric Computer Model

4 1 Computer Program

Industry-accepted quality assurance (QA) approved and efficient computer analysis codes are required to perform sophisticated nonlinear dynamic finite-element analyses. The ABAQUS/Explicit computer program was used in this analysis. ABAQUS/Explicit is a well-documented and proven finite-element program. It is a general-purpose finite-element analysis program, which has been used in the nuclear industry for decades. The program has an extensive element library. Nonlinear geometry (including contact surfaces and sliding surfaces), nonlinear material properties (plasticity, strain hardening, and strain rate) and explicit time integration are specific options that make the program ideal for evaluation of nonlinear dynamic impact evaluations. Contact surfaces allow free movement of two adjacent nontouching surfaces but preclude penetration of one contact surface to another. Sliding surfaces allow free movement of two adjacent nontouching surfaces but resist movement if the two surfaces are in contact. Friction forces that are determined by normal forces and prescribed friction coefficients model the resistance. The program comes with a well-documented theoretical manual and verification manual. The program has an error reporting system available through the Internet. ABAQUS/Explicit has extensive preprocessing, post-processing, and graphics capabilities.

ABAQUS/Explicit has been verified and validated through the FDNW QA program. ABAQUS/Explicit is currently maintained in accordance with these requirements. Use of the program at FDNW is restricted to authorized users administered by the FDNW software administrator. ABAQUS/EXPLICIT version 5.8-10 is used in the analysis.

5 0 RESULTS

Multiple analyses are run to determine the worst case conditions for the MCO and internals. Variable parameters are the material properties at temperatures of 50 to 270 degrees Fahrenheit and internal pressures of 0 to 450 psig. Maximum plastic strain values for the MCO and internals were found to occur at 270 degrees Fahrenheit and internal pressure of 0 psig. Only results from this analysis are reported. Results from the analysis show that as the MCO strikes the bottom of the shipping cask, the MCO and its contents will bounce up from the bottom of the cask. Although the shipping cask rests on the impact absorber, the inertia of the shipping cask is large enough that the force of the drop is not immediately transferred into the impact absorber. The MCO and contents decelerate to zero velocity and begin to bounce upward during the first 0.01 seconds of the analysis. Figure 5.1 shows the vertical deflection of the MCO shipping cask, and the impact absorber. The maximum permanent deformation in the impact absorber is about 0.6 in.

During the initial 0.01 seconds of the impact, plastic strains are experienced in the basket support plates, in the bottom of the MCO, in the walls of the MCO near the bottom, the center post of the bottom basket, and in the pads at the bottom of the cask.

Contour plots showing the areas of maximum equivalent plastic strain in the basket support plates and the MCO bottom and walls are shown in Figures 5.3 – 5.5. Figure 5.2 shows the computer model with labels on the various parts. The maximum equivalent plastic strain in the bottom plate of the MCO is 2.0%. The maximum equivalent plastic strain in the MCO wall near the weld area is 2.1%. The basket support plates show very large plastic deformations during the impact. The analysis shows equivalent plastic strain of 33% in the area of the basket support plates directly below the center support post.

The effective failure strain value is calculated based on the multi-axial stress state (triaxiality factor), temperature and strain rate at any point in time. Triaxiality factors can then be used to compute the effective failure strain at any point in time.

The effective failure strain (ϵ_f) and triaxiality factor (TF) are computed from the following equations:

$$\epsilon_f = \epsilon_t * 2^{1/TF} \quad \text{for } TF \geq 0$$

$$\epsilon_f = \epsilon_t * 2 \quad \text{for } TF < 0$$

where

ϵ_f is the effective failure strain

ϵ_t is the uniaxial failure strain

TF is the stress state triaxiality factor

$$TF = \frac{\sqrt{2}(\sigma_1 + \sigma_2 + \sigma_3)}{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_1)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}}$$

where σ_1 , σ_2 , and σ_3 are principal stresses

The computed effective failure strain is compared against the equivalent plastic strain at that point in time to determine if failure of the material is likely. Figure 5.6 shows element locations where triaxiality factors and equivalent plastic strain are provided. The two areas included are locations of maximum equivalent plastic strain on the bottom of the MCO and in the weld area of the MCO. Figures 5.7 – 5.11 show time history plots of equivalent plastic strain (in percent) and triaxiality factors. The maximum equivalent plastic strain in the bottom of MCO is 2.0%. This is below the calculated effective failure strain of 15%. Equivalent plastic strains are 2.1% in the weld area at the juncture of the MCO walls and the MCO bottom. This is below the calculated 12.5% effective failure strain. The maximum equivalent plastic strain occurs at the inside surface of the MCO in the weld area. Other locations through the thickness of the MCO wall in the weld area show effective plastic strain values of 1.0%, 0.41%, and 0.26% compared against calculated effective failure strains of 17.7%, 23.3%, and 10.9% respectively. Calculations of effective failure strain and comparison with the equivalent plastic strain are shown in Appendix B.

Deformations in the center support post in combination with deformation in the basket support plates and deflections of the MCO cause the gap between the MCO top and the top of the center support post to increase during the impact. Figure 5 12 shows the gap change between the MCO top and the top of the center support post. The maximum gap is shown to be 0 72 inches. This includes the effects of both elastic and plastic deformations. The maximum gap is compared against the engagement length of the top of the center support post with the socket at the MCO shield plug. The initial engagement length of the MCO top with the top of the center support post of the top basket is taken from the MCO drawings (Ref 2) to be 1 625 inches. This leaves 0 905 inches of engagement length. If the center support post were assumed to bow to one side during the impact, the gap increases an additional 0 12 inches. The minimum engagement length during the impact is then 0 785 inches. Calculations are shown in Appendix B.

The maximum equivalent plastic strain in the center support post is 1 0% and is shown in Figure 5 13. Figure 5 14 shows node and element locations in the center support post of the bottom basket where displacement and Mises stresses are reported. The plastic strain results in shortening of the center support post of the bottom basket by about 0 13 in and is shown in Figure 5 15. Figure 5 16 shows the Mises stress time history in the center support post. Calculations show neither Euler elastic buckling or local elastic buckling in the walls of the center support post is likely. Inelastic buckling in the walls of the center support post cannot be determined from this analysis. However, calculations based on the shortening in the center support post of the bottom basket show that the crushing force has not been exceeded. Calculations of the crushing force is based on equations and experimental data provided in Reference 5. Calculations are shown in Appendix B.

Figure 5 17 shows the time history of the total kinetic energy in the system. The plot shows that the majority of the kinetic energy is gone 0 01 seconds after the impact.

The MCO baskets and fuel pins decelerate from the impact velocity of 373 in/sec to zero in a time period of between 0 001 and 0 01 seconds. Study of displacement time history output indicates the MCO moves downward until approximately 0 01 seconds after impact (Figure 5 1). As a lower bound on the deceleration, the velocity is assumed to be zero at time 0 01 seconds after impact. This yields a deceleration of about 100g. Time history output of velocity from the analysis can also be used to calculate deceleration. Deceleration is determined from a velocity time history by dividing the change in velocity by the change in time for some portion of the curve. Calculation of deceleration is complicated by high frequency components in the curves, making it difficult to select an average slope of the line. Figure 5 18 shows node locations for which velocity time histories have been plotted. Figures 5 19 – 5 23 show the velocity time history at each node location. Nodes 60001 and 60031 are at the bottom of the MCO. Node 31010 is located on the center support post of the bottom basket. Node 31063 is located at the top of a fuel element in the bottom basket. Node 70340 is located on the MCO wall near the top of the MCO. Wide variations in deceleration can be calculated depending on which curve is used.

and where a line is drawn to determine the slope of the curve. An upper bound on the deceleration of the MCO and internals, the slope of the curve showing the maximum change in velocity divided by the minimum change in time is used. Most of the velocity curves show a very sharp spike at 0.0001 seconds. If this is ignored, a slope can be drawn on each of the curves that shows a change in velocity from -373 in/sec to 0 in/sec in a duration of between 0.001 and 0.002 seconds. This gives an average deceleration of between 1000g and 500g.

Additional results from the analysis are included in Appendix A. This appendix provides time history output of the plastic equivalent strain in the MCO bottom, the MCO weld area, the basket support plates, and the bottom basket support post. X-Y plots of displacement time history and velocity time history are included for the baskets. An x-y plot of principle components of plastic strain are shown for the MCO weld area.

Figure 5 1 Vertical Deflection of MCO, Shipping Cask, and Impact Absorber

Figure 5 2 Plastic Strain Output Locations

Figure 5.3 Equivalent Plastic Strain in Basket Support Plate

Figure 5.4 Equivalent Plastic Strain in MCO Bottom

Figure 5.5 Equivalent Plastic Strain in Weld Area of MCO

Figure 5 6 Equivalent Plastic Strain and Triaxiality Factor Element Locations

Figure 5 7 Equivalent Plastic Strain and Triaxiality Factor for Element 60270

Figure 5.8 Equivalent Plastic Strain and Triaxiality Factor for Element 60428

Figure 5 9 Equivalent Plastic Strain and Triaxiality Factor for Element 60429

Figure 5 10 Equivalent Plastic Strain and Triaxiality Factor for Element 60430

Figure 5 11 Equivalent Plastic Strain and Triaxiality Factor for Element 60431

Figure 5 12 Gap Change from MCO Top to Center Support Post

Figure 5 13 Equivalent Plastic Strain in Center Support Post

Figure 5 14 Node and Element Locations in Center Support Post

Figure 5 15 Shortening in Center Support Post of Bottom Basket

Figure 5 16 Mises Stress in Center Support Post of Bottom Basket

Figure 5 17 Total Kinetic Energy

Figure 5 18 Node Locations for Velocity Output

Figure 5 19 Vertical Velocity at Node 60001

Figure 5 20 Vertical Velocity at Node 60031

Figure 5 21 Vertical Velocity at Node 31010

Figure 5 22 Vertical Velocity at Node 31063

Figure 5 23 Vertical Velocity at Node 70340

6 0 CONCLUSIONS AND DISCUSSION

Maximum plastic strain values for the MCO and internals were found to occur at 270 degrees Fahrenheit and 0 psig. The maximum equivalent plastic strain in the bottom of MCO is 2.0%. This is below the calculated effective failure strain of 15%. The effective failure strain value is calculated based on the multi-axial stress state (triaxiality factor), temperature, and strain rate. Breaching of the MCO pressure boundary due to through-wall cracking is not expected. Calculations are shown in Appendix B.

Equivalent plastic strains are 2.1% in the weld area at the juncture of the MCO walls and the MCO bottom. This is below the calculated 12.5% effective failure strain. The maximum equivalent plastic strain occurs at the inside surface of the MCO in the weld area. Other locations through the thickness of the MCO wall in the weld area show effective plastic strain values of 1.0%, 0.41%, and 0.26% compared against calculated effective failure strains of 17.7%, 23.3%, and 10.9% respectively. Breaching of the MCO pressure boundary due to through-wall cracking in the weld area is also not expected. Calculations are shown in Appendix B.

The initial analysis (material properties at 50 degrees Fahrenheit and 0 psig) shows that the maximum stress in the outside support posts is about 62,000 psi. This is well beyond the calculated inelastic buckling stress of 30,000 psi. Buckling is expected in the six support posts located near the edge of the bottom basket. In order to determine maximum loads on the basket center support post, the cross-sectional area for the basket outside support posts is reduced to provide a reduced stiffness. This allows the basket outside support posts to yield early in the analysis, causing the basket center support post to carry the majority of the load caused by the impact. The maximum equivalent plastic strain in the center support post of the bottom basket is about 1.0%. The plastic strain results in shortening of the center support post of the bottom basket by about 0.13 in. Calculations show neither Euler elastic buckling or local elastic buckling in the walls of the center support post is likely. Inelastic buckling in the walls of the center support post cannot be determined from this analysis. However, calculations based on the shortening in the center support post of the bottom basket show that the crushing force has not been exceeded. Calculations are shown in Appendix B.

The baskets are stacked together with socket type connections between each. The top basket is engaged by another socket type connection that fits over the top of the basket support post. Deformations in the center support post in combination with deformation in the basket support plates and deflections of the MCO cause the gap between the MCO top and the top of the center support post to increase during the impact. The increase in the gap is not sufficient to disengage the top of the center support post from the socket in the MCO shield plug. The maximum gap is shown to be 0.72 inches. This includes the effects of both elastic and plastic deformations. The maximum gap is compared against the engagement length of the top of the center support post with the socket at the

MCO shield plug The initial engagement length of the MCO top with the top of the center support post of the top basket is taken from the MCO drawings (Ref 2) to be 1.625 inches. This leaves 0.905 inches of engagement length. If the center support post were assumed to bow to one side during the impact the gap increases an additional 0.12 inches. The minimum engagement length during the impact is then 0.785 inches.

There is little material below the bottom basket inside the MCO to absorb the force of the impact. Due to the large moment of inertia of the cask, the force of the impact of the MCO with the cask is not immediately transferred into the impact absorber and the MCO and its contents bounce after impact. A height of 0.9 inches is reached by the conclusion of the analysis at 0.08 seconds after impact. The impact absorber beneath the cask is not entirely effective in mitigating the effects of this impact. The impact absorber is shown to experience plastic deformation of about 0.6 in during the initial impact. The impact absorber absorbed about 1,264,000 in-lb energy (0.63 in x 2,006,000 lb) or about 1/3 of the total initial kinetic energy of 3,610,000 in-lb.

The MCO baskets, and fuel pins decelerate from the impact velocity of 373 in/sec to zero in a time period of between 0.001 and 0.01 seconds. Study of displacement time history output indicates the MCO moves downward until approximately 0.01 seconds after impact. As a lower bound on the deceleration, the velocity is assumed to be zero at time 0.01 seconds after impact. This yields a deceleration of about 100g. Time history output of velocity from the analysis can also be used to calculate deceleration. Deceleration is determined from a velocity time history by dividing the change in velocity by the change in time for some portion of the curve. Calculation of deceleration is complicated by high frequency components in the curves making it difficult to select an average slope of the line. Wide variations in deceleration can be calculated depending on which curve is used and where a line is drawn to determine the slope of the curve. An upper bound on the deceleration of the MCO and internals the slope of the curve showing the maximum change in velocity divided by the minimum change in time is used. Most of the velocity curves show a very sharp spike at 0.0001 seconds. If this is ignored a slope can be drawn on each of the curves that shows a change in velocity from -373 in/sec to 0 in/sec in a duration of between 0.001 and 0.002 seconds. This gives an average deceleration of between 1000g and 500g.

7.0 REFERENCES

- 1 "Design Calculations HNF-SD-SNF-DP-007 Rev 0 Appendix J by B. Crea January 1997
- 2 Multi-Canister Overpack Shell Hanford drawing No. H-2-828043, Rev. 3
- 3 TN - WHC Cask Transportation System Transnuclear drawing No. 3035-3, Rev. 7

- 4 "MCO Service Station Impact Absorber IMP-4,' PacTec drawing No 99006-102 Rev 0
- 5 CSB Impact Absorber Analysis Report PacTec Document ED-037 Rev 0 June 21 1999
- 6 ABAQUS/EXPLICIT User's Manual Volume I, Version 5.8 Hibbitt, Karlsson & Sorensen Inc 1998
- 7 'Structural Impact Cambridge University Press Jones Norman 1989
- 8 Analysis for Eccentric Multi-Canister Overpack Drops at the Canister Storage Building SNF-5204 Rev 0 September 1999
- 9 1998 ASME Boiler & Pressure Vessel Code Part D – Properties American Society of Mechanical Engineers New York New York
- 10 "Nuclear Systems Material Handbook TID-2-6666 Oakridge

Appendix A

Additional Analysis Results

Appendix A

This appendix provides additional details regarding the sequencing and response of various parts of the MCO and its contents during the impact

Plastic strain occurs in the bottom of the MCO and the bottom basket during the impact. Figure A 1 shows the computer model and labels the areas where equivalent plastic strain output is provided. The cask pad and the basket support plates show the highest levels of plastic strain. Figures A 2 through A 6 show the sequence of deformation and accumulation of equivalent plastic strain from time 0.0008 through 0.0040 seconds in time steps of 0.0008 seconds. The equivalent plastic strain contours are overlaid on the deformed shape of the computer model for each time step. The maximum equivalent plastic strains for these two areas are reached 0.0040 seconds after the impact.

Figure A 7 shows a close-up of the computer model in the weld area of the MCO. Figures A 8 through A 21 show the sequence of deformation and accumulation of equivalent plastic strain from time 0.0008 through 0.0112 seconds in time steps of 0.0008 seconds. The equivalent plastic strain contours are overlaid on the deformed shape of the computer model for each time step. Figures A 22 and A 23 show the plastic strain components in element 60428, which is in the weld area and shows the highest plastic strain values. These two plots show two cycles during which equivalent plastic strain is accumulated.

Figures A 24 through A 27 show the center support post of the bottom basket sequence of deformation and accumulation of equivalent plastic strain from time 0.0016 through 0.0040 seconds in time steps of 0.0008 seconds. The equivalent plastic strain contours are overlaid on the deformed shape of the computer model for each time step.

Figure A 28 shows the computer model at the bottom of the MCO with nodes labeled for displacement and velocity time history output. Locations are selected at the center of the MCO (node 60001), above the cask pad (node 60020), and at the outer edge of the bottom surface (node 60031). Figure A 29 shows the displacement time history for all three nodes from time 0 to 0.08 seconds. Figure A 30 shows the displacement time history for all three nodes from time 0 to 0.015 seconds.

Figures A 31 through A 36 show velocity time histories for the same three nodes. Two plots are shown for each node. The first from time 0 to 0.08 seconds, the second from time 0 to 0.01 seconds.

MCO wall node locations and element locations for displacement time history and stress time history output are shown in figures A 37 through A 40. Figures A 41 and A 42 show displacement time history for the three node locations from time 0 to 0.08 seconds and from time 0 to 0.015 seconds. Figures A 43 and A 44 show the vertical stress component in three elements in the MCO wall at top, middle, and bottom locations.

Figures A 45 and A 46 show node locations on the baskets for displacement time history output. Each node location is at the bottom of the center support post for each basket. Figures A 47 and A 48 show the displacement time history for each node location from time 0 to 0.08 seconds and from time 0 to 0.03 seconds.

Figure A 1 Plastic Strain Output Locations

**Figure A 2 Equivalent Plastic Strain Cask Pad and Basket Support Plates,
Time = 0.0008 seconds**

**Figure A 3 Equivalent Plastic Strain Cask Pad and Basket Support Plates,
Time = 0.0016 seconds**

**Figure A 4 Equivalent Plastic Strain Cask Pad and Basket Support Plates,
Time = 0.0024 seconds**

**Figure A 5 Equivalent Plastic Strain Cask Pad and Basket Support Plates,
Time = 0.0032 seconds**

**Figure A 6 Equivalent Plastic Strain Cask Pad and Basket Support Plates,
Time = 0.0040 seconds**

Figure A 7 MCO Weld Area, Plastic Strain Output Location

Figure A 8 Equivalent Plastic Strain MCO Weld Area, Time = 0.0008 Seconds

Figure A 9 Equivalent Plastic Strain MCO Weld Area, Time = 0.0016 Seconds

Figure A 10 Equivalent Plastic Strain MCO Weld Area, Time = 0.0024 Seconds

Figure A 11 Equivalent Plastic Strain MCO Weld Area, Time = 0.0032 Seconds

Figure A 12 Equivalent Plastic Strain MCO Weld Area, Time = 0.0040 Seconds

Figure A 13 Equivalent Plastic Strain MCO Weld Area, Time = 0.0048 Seconds

Figure A 14 Equivalent Plastic Strain MCO Weld Area, Time = 0.0056 Seconds

Figure A 15 Equivalent Plastic Strain MCO Weld Area, Time = 0.0064 Seconds

Figure A 16 Equivalent Plastic Strain MCO Weld Area, Time = 0.0072 Seconds

Figure A 17 Equivalent Plastic Strain MCO Weld Area, Time = 0.0080 Seconds

Figure A 18 Equivalent Plastic Strain MCO Weld Area, Time = 0.0088 Seconds

Figure A 19 Equivalent Plastic Strain MCO Weld Area, Time = 0.0096 Seconds

Figure A 20 Equivalent Plastic Strain MCO Weld Area, Time = 0.0104 Seconds

Figure A 21 Equivalent Plastic Strain MCO Weld Area, Time = 0.0112 Seconds

Figure A 22 Plastic Strain Time History MCO Weld Area

Figure A 23 Plastic Strain Time History MCO Weld Area

Figure A 24 Equivalent Plastic Strain Center Support Post, Time = 0.0016 Seconds

Figure A 25 Equivalent Plastic Strain Center Support Post, Time = 0.0024 Seconds

Figure A 26 Equivalent Plastic Strain Center Support Post, Time = 0.0032 Seconds

Figure A 27 Equivalent Plastic Strain Center Support Post, Time = 0.0040 Seconds

Figure A 28 MCO Bottom Node Locations for Displacement and Velocity Output

Figure A 29 MCO Bottom Displacement Time History

Figure A 30 MCO Bottom Displacement Time History

Figure A 31 MCO Bottom Velocity Time History, Node 60001

Figure A 32 MCO Bottom Velocity Time History, Node 60001

Figure A 33 MCO Bottom Velocity Time History, Node 60020

Figure A 34 MCO Bottom Velocity Time History, Node 60020

Figure A 35 MCO Bottom Velocity Time History, Node 60031

Figure A 36 MCO Bottom Velocity Time History, Node 60031

Figure A 37 MCO Wall Node Locations for Displacement Output

Figure A 38 MCO Wall Element and Node Locations for Displacement and Stress Output

Figure A 39 MCO Wall Element and Node Locations for Displacement and Stress Output

Figure A 40 MCO Wall Element and Node Locations for Displacement and Stress Output

Figure A 41 MCO Wall Displacement Time History

Figure A 42 MCO Wall Displacement Time History

Figure A 43 MCO Wall Vertical Stress Time History

Figure A 44 MCO Wall Vertical Stress Time History

Figure A 45 Basket Node Locations for Displacement Output

Figure A 46 Basket Node Locations for Displacement Output

Figure A 47 Basket Displacements

Figure A 48 Basket Displacements

Appendix B

Calculations

IMP-004 IMPACT ABSORBER**TOP CRUSHING PART**

$$OD_{\text{pipe}} = 5 \text{ m}$$

$$t_{\text{pipe}} = 0.188 \text{ m}$$

$$A_{\text{pipe}} = \pi \left[\left(\frac{OD_{\text{pipe}}}{2} \right)^2 - \left(\frac{OD_{\text{pipe}}}{2} - t_{\text{pipe}} \right)^2 \right] \quad A_{\text{pipe}} = 2.842 \text{ m}^2$$

$$A_{\text{assembly}} = \pi \left(\frac{39 \text{ in}}{2} \right)^2 \quad A_{\text{assembly}} = 1.195 \cdot 10^3 \text{ in}^2$$

$$E_{\text{top}} = 30 \cdot 10^6 \text{ psi} \left(\frac{12 A_{\text{pipe}}}{A_{\text{assembly}}} \right) \quad E_{\text{top}} = 8.565 \cdot 10^5 \text{ psi}$$

$$\text{Crush_Force} = 2006000 \text{ lbf}$$

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$$F_{y \text{ top}} = \frac{\text{Crush_Force}}{A_{\text{assembly}}} \quad F_{y \text{ top}} = 1.679 \cdot 10^3 \text{ psi}$$

Assume crushed up to 75%

$$\text{Density}_{\text{top}} = 0.0007339 \frac{12 A_{\text{pipe}}}{A_{\text{assembly}}} \quad \text{Density}_{\text{top}} = 2.095 \cdot 10^{-5}$$

BASE

$$A(\text{OD } t) = \pi \left[\left(\frac{OD \text{ in}}{2} \right)^2 - \left(\frac{OD \text{ in}}{2} - t \text{ in} \right)^2 \right]$$

$$A_{\text{base}} = A(37.1) + A(24.0968) + A(10.751) + 4 \left(\frac{37}{2} - 1 - \frac{10.75}{2} - 0.968 \right) 1 \text{ in}^2$$

$$A_{\text{base}} = 258.398 \text{ in}^2$$

$$E_{\text{base}} = 30 \cdot 10^6 \text{ psi} \left(\frac{A_{\text{base}}}{A_{\text{assembly}}} \right)$$

$$E_{\text{base}} = 6 \cdot 489 \cdot 10^6 \text{ psi}$$

$$Fy_{\text{base}} = 36000 \text{ psi} \frac{A_{\text{base}}}{A_{\text{assembly}}}$$

$$Fy_{\text{base}} = 7 \cdot 787 \cdot 10^3 \text{ psi}$$

$$\text{Density}_{\text{base}} = 0 \cdot 0007339 \frac{A_{\text{base}}}{A_{\text{assembly}}}$$

$$\text{Density}_{\text{base}} = 1 \cdot 587 \cdot 10^{-4}$$

EQUIVALENT MATERIAL PROPERTIES FOR BASKET SUPPORT PLATES

$$w = 0 \cdot 5 \text{ in}$$

$$r = 11 \cdot 01 \text{ in}$$

$$\text{ratio}_{\text{bsp}} = \frac{6 \cdot w \cdot r}{\pi \cdot r^2}$$

$$\text{ratio}_{\text{bsp}} = 0 \cdot 087$$

$$\text{Density}_{\text{bsp}} = \text{ratio}_{\text{bsp}} \cdot 0 \cdot 000735$$

$$\text{Density}_{\text{bsp}} = 6 \cdot 375 \cdot 10^{-5}$$

$$E_{\text{bsp}} = \text{ratio}_{\text{bsp}} \cdot 28000000 \text{ psi}$$

$$E_{\text{bsp}} = 2 \cdot 429 \cdot 10^6 \text{ psi}$$

$$Fy_{\text{bsp}} = \text{ratio}_{\text{bsp}} \cdot 36161$$

$$Fy_{\text{bsp}} = 3 \cdot 136 \cdot 10^3$$

$$Fu_{\text{bsp}} = \text{ratio}_{\text{bsp}} \cdot 127236$$

$$Fu_{\text{bsp}} = 1 \cdot 104 \cdot 10^4$$

EQUIVALENT SHELL ELEMENT THICKNESS FOR POST

$$A_{\text{post}} = \frac{1 \cdot 23 + 3 \cdot 14}{2} \cdot 1 \cdot 45$$

$$t = \frac{6 \cdot A_{\text{post}}}{2 \cdot \pi \cdot 11 \cdot 3125}$$

$$t = 0 \cdot 267$$

EQUIVALENT RING THICKNESS FOR 2 DIAMETER PAD

$$A_{\text{pad}} = \pi l^2$$

$$r_{\text{ring}} = 7.5$$

$$t_{\text{ring}} = 0.272$$

$$4 A_{\text{pad}} = 12.566$$

$$A_{\text{ring}} = \pi \left[(r_{\text{ring}})^2 - (r_{\text{ring}} - t_{\text{ring}})^2 \right]$$

$$A_{\text{ring}} = 12.585$$

TOTAL KINETIC ENERGY

$$\frac{1}{2} 20000 \text{ lb} \left(31.13 \frac{\text{ft}}{\text{sec}} \right)^2 = 3.614 \cdot 10^6 \text{ lbf} \cdot \text{ft}$$

FUEL ELEMENTS

$$A_{\text{fuel}} = \frac{48}{4} \pi (6.10^2 - 4.50^2 + 3.18^2 - 1.11^2) \text{ cm}^2$$

$$A_{\text{fuel}} = 150.995 \text{ in}^2$$

$$A_{\text{model}} = \pi (10.5^2 - 9.40^2 + 7.8^2 - 6.7^2 + 5.20^2 - 4.10^2) \text{ in}^2$$

$$A_{\text{model}} = 151.016 \text{ in}^2$$

$$50 \text{ cm} = 19.685 \text{ in}$$

$$M = 60000 \text{ lb}$$

$$k = \frac{2006000 \text{ lbf}}{0.6 \text{ in}}$$

$$k = 3.343 \cdot 10^6 \frac{\text{lbf}}{\text{in}}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{M}}$$

$$f = 23.344 \text{ Hz}$$

$$M = 10 \text{ lb}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{M}}$$

$$f = 1.808 \cdot 10^3 \text{ Hz}$$

Center Suppor Post, Euler Buckling

$$\delta = 2\,0595\text{ m} + 0\,187\text{ m}$$

$$\text{arc} = (143\,38 - 0\,25)\text{ m}$$

$$\text{arc} = 143\,13\text{ m}$$

guess

$$r = 1000\text{ m}$$

Given

$$\cos\left(\frac{\text{arc}}{2r}\right) = \frac{r - \delta}{r}$$

$$a = \text{Find}(r)$$

$$a = 1\,859\,10^3\text{ m}$$

$$l = 2 \sin\left(\frac{\text{arc}}{2r}\right) r$$

$$l = 143\,008\text{ m}$$

$$\text{arc} - l + 0\,25\text{ m} = 0\,372\text{ m}$$

CENTER POST

Material type 304L

Modulus of elasticity $E = 27.18 \times 10^6 \text{ psi}$

Yield stress $F_y = 19.8 \text{ ksi}$

Effective length factor $K = 0.8$ Post is considered fixed at the bottom and pinned at the top

Outside diameter $OD = 6.625 \text{ in}$

Inside diameter $ID = 1.75 \text{ in}$

Length of the post $L = 21.682 \text{ in}$

Moment of inertia $I = \frac{\pi (OD^4 - ID^4)}{64} \quad I = 94.101 \text{ in}^4$

Cross sectional area $A = \pi \frac{OD^2 - ID^2}{4} \quad A = 32.066 \text{ in}^2$

Radius of gyration $r = \sqrt{I/A} \quad r = 1.713 \text{ in}$

Post wall thickness $t = \frac{OD - ID}{2} \quad t = 2.438 \text{ in}$

The strength of the post can be controlled by either inelastic buckling (short columns) or elastic (Euler) buckling. The proper behavior of the column is determined by comparison of slenderness ratio to the C_c .

$$C_c = \sqrt{\frac{2 \pi^2 E}{F_y}} \quad C_c = 164.61$$

Slenderness ratio of the Center Post is

$$\frac{KL}{r} = 10.126 \quad \text{which clearly indicates inelastic buckling}$$

Critical stress (no factor of safety) is

$$F_{cr} = \left[1 - \left(\frac{KL}{r} \right)^2 (2 C_c^2)^{-1} \right] F_y \quad F_{cr} = 19.763 \text{ ksi}$$

Critical load (no factor of safety) is

$$P_{cr} = F_{cr} A \quad P_{cr} = 633.71 \text{ kips}$$

Allowable load (AISC 9th Ed)

$$\frac{OD}{t} = 2.718 \quad \frac{3300 \text{ ksi}}{(F_y)} = 166.667$$

$D/t < 3300/F_y$ So provisions of Table B5.1 are met (local buckling is prevented)

$KL/r < C_c$ Therefore use formula E2.1

$$F_a = \frac{\left[1 - \left(\frac{KL}{r} \right)^2 (2 C_c^2)^{-1} \right] F_y}{\frac{5}{3} + 3 \frac{KL}{r} (8 C_c)^{-1} - \left(\frac{KL}{r} \right)^3 (8 C_c^3)^{-1}}$$

$$F_a = 11.696 \text{ ksi}$$

$$P = F_a A \quad P = 375.04 \text{ kips}$$

OUTSIDE POST

Material SA-479 type 304 or 304L

Modulus of elasticity $E = 28 \cdot 10^6 \text{ psi}$

Yield stress $F_y = 30 \text{ ksi}$

Effective length factor $K = 2.0$ Post is considered fixed at the bottom and free at the top

Length of the post $L = 21.682 \text{ m}$

Moments of inertia $I_x = 0.4968 \text{ in}^4$ $I_y = 1.3689 \text{ in}^4$

Cross sectional area $A = 3.1316 \text{ in}^2$ $A = 3.132 \text{ in}^2$

Radius of gyration $r_x = \sqrt{I_x / A} = 0.398 \text{ in}$ $r_y = \sqrt{I_y / A} = 0.661 \text{ in}$

The strength of the post can be controlled by either inelastic buckling (short columns) or elastic (Euler) buckling. The proper behavior of the column is determined by comparison of slenderness ratio to the C_c .

$$C_c = \sqrt{\frac{2 \pi^2 E}{F_y}} \quad C_c = 135.73$$

Slenderness ratios of the Outside Post are

$$\frac{KL}{r_x} = 108.873 \quad \frac{KL}{r_y} = 65.588$$

which clearly indicates inelastic buckling (buckling about x axis controls)

Critical stress (no factor of safety) is

$$F_{cr} = \left[1 - \left(\frac{KL}{r_x} \right)^2 (2 C_c^2)^{-1} \right] F_y \quad F_{cr} = 20.35 \text{ ksi}$$

Critical load (no factor of safety) is

$$P_{cr} = F_{cr} A \quad P_{cr} = 63.73 \text{ kips}$$

Allowable load (AISC 9th Ed)

$KL/r < C_c$ Therefore use formula E2.1

$$F_a = \frac{\left[1 - \left(\frac{KL}{r} \right)^2 (2 C_c)^{-1} \right] F_y}{\frac{5}{3} + 3 \frac{KL}{r} (8 C_c)^{-1} - \left(\frac{KL}{r} \right)^3 (8 C_c)^{-1}}$$

$$F_a = 16.98 \text{ ksi}$$

$$P = F_a A$$

$$P = 53.18 \text{ kips}$$

Calculation of Effective Failure Strain

The effective failure strain (ϵ_f) is computed from the following equations

$$\epsilon_f = \epsilon_t * 2^{1/TF} \quad \text{for } TF \geq 0$$

$$\epsilon_f = \epsilon_t * 2 \quad \text{for } TF < 0$$

where

ϵ_f is the effective failure strain

ϵ_t is the uniaxial failure strain

TF is the stress state triaxiality factor

$$TF = \frac{\sqrt{2}(\sigma_1 + \sigma_2 + \sigma_3)}{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_1)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}}$$

where σ_1 , σ_2 , and σ_3 are principal stresses

Check Equivalent Plastic Strain at MCO Bottom, Element 60270

The equivalent plastic strain and triaxiality factor are taken from Figure 5.7 at approximately time 0.002 seconds

$$PEEQ = 0.02$$

$$TF = 1.7$$

From Table 3.4

$$\epsilon_t \text{ for the base metal} = 0.239$$

$$\epsilon_f = 0.239 * 2^{(1/1.7)} = 0.147$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

Check Equivalent Plastic Strain at MCO Weld Area, Element 60428

At approximately time 0.005 seconds the equivalent plastic strain and triaxiality factor taken from Figure 5.8 are

$$\begin{aligned} PEEQ &= 0.015 \\ TF &= 1.6 \end{aligned}$$

From Table 3.3

$$\epsilon_t \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1.6)} = 0.088$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

At approximately time 0.012 seconds the equivalent plastic strain and triaxiality factor taken from Figure 5.8 are

$$\begin{aligned} PEEQ &= 0.021 \\ TF &= 1.1 \end{aligned}$$

From Table 3.3

$$\epsilon_t \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1.1)} = 0.125$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

Check Equivalent Plastic Strain at MCO Weld Area, Element 60429

At approximately time 0.006 seconds the equivalent plastic strain and triaxiality factor taken from Figure 5.9 are

$$\begin{aligned} PEEQ &= 0.008 \\ TF &= 1.5 \end{aligned}$$

From Table 3.3

$$\epsilon_t \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1.5)} = 0.0948$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

At approximately time 0.011 seconds the equivalent plastic strain and triaxiality factor taken from Figure 5.9 are

$$\begin{aligned} PEEQ &= 0.01 \\ TF &= 0.6 \end{aligned}$$

From Table 3.3

$$\epsilon_t \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1-0.6)} = 0.177$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

Check Equivalent Plastic Strain at MCO Weld Area, Element 60430

At approximately time 0.001 seconds the equivalent plastic strain and triaxiality factor taken from Figure 5.10 are

$$\begin{aligned} PEEQ &= 0.004 \\ TF &= 0.55 \end{aligned}$$

From Table 3.3

$$\epsilon_t \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1-0.55)} = 0.183$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

At approximately time 0.006 seconds, the equivalent plastic strain and triaxiality factor taken from Figure 5.10 are

$$\begin{aligned} PEEQ &= 0.0041 \\ TF &= 0.2 \end{aligned}$$

From Table 3.3

$$\epsilon_t \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1-0.2)} = 0.233$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

Check Equivalent Plastic Strain at MCO Weld Area, Element 60431

At approximately time 0.001 seconds the equivalent plastic strain and triaxiality factor taken from Figure 5.11 are

$$\begin{aligned} PEEQ &= 0.0025 \\ TF &= 1.3 \end{aligned}$$

From Table 3.3

$$\epsilon_f \text{ for the weld material} = 0.134$$

$$\epsilon_f = 0.134 * 2^{(1.3)} = 0.109$$

$$PEEQ < \epsilon_f \quad \text{OK}$$

Check Center Support Post of Bottom Basket for Crushing

The maximum load in the center support post of the bottom basket can be estimated by the equation

$$P_{\max} = \sigma_{\max} A$$

where $P_{\max}$ is the maximum load in the center support post

$\sigma_{\max}$ is the maximum stress in the center support post

A is the cross-sectional area of the center support post

$$\sigma_{\max} = 51\,000 \text{ psi} \quad (\text{from Figure 5-16})$$

$$A = 32\,066 \text{ in}^2 \quad (\text{see page B-6})$$

$$P_{\max} = 1.6 \times 10^6 \text{ lbf}$$

From Reference 5 the crushing force can be estimated by the equation

$$P_{\text{crush}} = 21.1(R)(H) \frac{\left(1 + 0.41\sqrt{\frac{H}{R}}\right)}{\left(2.14\sqrt{\frac{R}{H}} - 1\right)} (\sigma_e) f(\epsilon, T)$$

where

P_{crush} = the average crushing force over the entire length of the tube lbs

R = the mean tube radius, inch

H = the wall thickness inch

σ_e = the effective strength psi

$f(\epsilon, T)$ = a factor that is a function of the strain rate and temperature

$$\sigma_e = \text{average flow strength} = (25000 + 75000)/2 = 50\,000 \text{ psi}$$

$$R = 1.75 + (2.438/2) = 2.969 \text{ in} \quad (\text{see page B-6 for dimensions})$$

$$H = 2.438 \text{ in}$$

$$F(\epsilon, T) = 1.09 \quad (\text{see Reference 5})$$

$$P_{\text{crush}} = 8.4 \times 10^6 \text{ lbf}$$

$$P_{\max} < P_{\text{crush}}$$

Appendix C

Abaqus/Explicit Input Files

Input File a7.inp

```

** file "a7.inp"
*HEADING
MCO DROP INTO SHIPPING CASK - Axisymmetric model
** 270 deg, 0 psig Thin shell ( 267) for outer support posts
*INCLUDE, INPUT=mco4a.txt
*INCLUDE, INPUT=bskl3a.txt
*include, input=ca_ial.txt
*SYSTEM
,,
**
** Boundary conditions, line of symmetry restraints
**
*nset,nset=xsym,generate
11,81,10
100,160,20
60006,60066,20
50000,50006,1
31000,31040,10
31100,31140,10
31200,31240,10
31300,31340,10
31400,31440,10
31500,31540,10
31051,31551,100
31061,31561,100
31053,31553,100
31063,31563,100
31055,31555,100
31065,31565,100
*boundary
xsym,1
**
** Material Properties
**
** 304L Stainless Steel material properties at 270 deg F
*solid section,elset=bskp,material=ss304
*shell section elset=bsks, material=ss304
0 267
*MATERIAL,NAME=SS304
*DENSITY
000735
*ELASTIC
27 18E+06, 30
*PLASTIC
19814 ,0 0
23972 0 004988
28721 ,0 01784
38553 ,0 05638
46753 ,0 093285
101025 ,0 468136
*rate dependent,type=power law
100,10
*solid section, elset=bskd, material=ss304
** Material for fuel
*solid section, elset=fuel, material=fuel
*MATERIAL,NAME=fuel
*DENSITY

```

Input File a7 inp

```

004256
*ELASTIC
24 E+06, 30
*solid section, elset=cask material=F304
*solid section, elset=pad, material=F304
** cask material SA336 type F304
*MATERIAL,NAME=F304
*DENSITY
000735
*ELASTIC
27 18E+06, 30
*PLASTIC
19814 ,0 0
23972 ,0 004988
28721 ,0 01784
38553 ,0 05638
46753 ,0 093285
101025 ,0 468136
*rate dependent,type=power law
100,10
** equivalent material for basket support plate
*MATERIAL,NAME=bsp
*DENSITY
6 375E-5
*ELASTIC
2 429E+06, 30
*PLASTIC
3136,0
11040,0 466
*rate dependent,type=power law
100,10
** IMP-004 impact absorber
*SOLID SECTION ELSET=impt, MATERIAL=impt
*SOLID SECTION, ELSET=impb, MATERIAL=impb
*MATERIAL,NAME=impt
*DENSITY
2 095E-5
*ELASTIC
8 565E+05, 30
*PLASTIC
1679,0
1680 0 75
10000,0 76
100000,0 77
*MATERIAL,NAME=impb
*DENSITY
1 587E-4
*ELASTIC
6 489E6,0 30
*PLASTIC
7787,0
8000,0 02
9000,0 09
10000,0 15
**
**
** Pressure loading

```

Input File a7 inp

```

**
***dload
**mco1,p1,450
**mco3,p3,450
**mco4,p4,450
**
*INITIAL CONDITIONS, TYPE=VELOCITY
MCO, 2, -373 56
BSK, 2, -373 56
*RESTART WRITE, NUMBER INTERVAL=1
*STEP
*DYNAMIC, EXPLICIT
,0 08
**
** Gravity
**
*elset,elset=ttt
bsk,mco,cask,pad,impb,impt,fuel
*dload
ttt,grav,386 4,0,-1,0
**
** Surface definitions
**
**
**                                     basket
*surface definition,name=bsk0b
bsk0b,s1
*surface definition,name=bskt0
31001,s3
31002,s3
31003,s3
31004,s3
31005 s3
31006,s3
*surface definition,name=bskt1
31101,s3
31102,s3
31103,s3
31104 s3
31105,s3
31106,s3
*surface definition,name=bskt2
31201,s3
31202,s3
31203,s3
31204,s3
31205 s3
31206,s3
*surface definition,name=bskt3
31301,s3
31302,s3
31303,s3
31304,s3
31305,s3
31306,s3
*surface definition,name=bskt4
31401,s3
31402,s3

```

Input File - a7 inp

```

31403,s3
31404,s3
31405,s3
31406,s3
*surface definition,name=bskt5
31501,s3
31502,s3
31503,s3
31504,s3
31505,s3
31506,s3
**
*surface definition,name=mcosl
mcosl,s4
*surface definition,name=mcobt
mcobt,s3
*surface definition,name=mcobb
mcobb,s1
*surface definition,name=bspt
bspt,s3
*surface definition,name=bspb
bspb,s1
**
*surface definition,name=cabt
cabt,s3
165,s2
165,s3
165,s4
*surface definition,name=cabb
cabb,s1
*surface definition,name=imptt
imptt,s3
**
**
*surface definition,name=cask
cask,s3
165,s2
165,s3
165,s4
*surface definition,name=cabb
cabb,s1
*surface definition,name=imptt
imptt,s3
**
**
*surface definition,name=fuel
fuel,s3
165,s2
165,s3
165,s4
*surface definition,name=cabb
cabb,s1
*surface definition,name=imptt
imptt,s3
**
**
*nset,nset=fuel0,generate
31051,31056,1
*nset,nset=fuel1,generate
31151,31156,1
*nset,nset=fuel2,generate
31251,31256,1
*nset,nset=fuel3,generate
31351,31356,1
*nset,nset=fuel4,generate
31451,31456,1
*nset,nset=fuel5,generate
31551,31556,1
*nset,nset=fult0,generate
31061,31066,1
*nset,nset=fult1,generate
31161,31166,1
*nset,nset=fult2,generate
31261,31266,1
*nset,nset=fult3,generate
31361,31366,1
*nset,nset=fult4,generate
31461,31466,1
*nset,nset=fult5,generate

```

Input File a7 inp

```

31561,31566,1
*CONTACT NODE SET, NAME=fuel0
fuel0
*CONTACT NODE SET, NAME=fuel1
fuel1
*CONTACT NODE SET NAME=fuel2
fuel2
*CONTACT NODE SET, NAME=fuel3
fuel3
*CONTACT NODE SET, NAME=fuel4
fuel4
*CONTACT NODE SET, NAME=fuel5
fuel5
*CONTACT NODE SET, NAME=fult0
fult0
*CONTACT NODE SET, NAME=fult1
fult1
*CONTACT NODE SET, NAME=fult2
fult2
*CONTACT NODE SET, NAME=fult3
fult3
*CONTACT NODE SET, NAME=fult4
fult4
*CONTACT NODE SET, NAME=fult5
fult5
**
** Contact pairs
**
*CONTACT PAIR
fuel0,BSKt0
*CONTACT PAIR
fuel1,BSKt1
*CONTACT PAIR
fuel2,BSKt2
*CONTACT PAIR
fuel3,BSKt3
*CONTACT PAIR
fuel4,BSKt4
*CONTACT PAIR
fuel5,BSKt5
*CONTACT PAIR
fult0,BSK1b
*CONTACT PAIR
fult1,BSK2b
*CONTACT PAIR
fult2,BSK3b
*CONTACT PAIR
fult3,BSK4b
*CONTACT PAIR
fult4,BSK5b
*CONTACT PAIR
fult5,mcotb
** mco bottom to basket support plate
*contact pair,cpset=mcosp
mcobt,bspb
** basket support plate to basket
*contact pair cpset=spbsk

```

Input File a7.inp

```

bspt,bsk0b
** cask to mco
*contact pair,cpset=camco
cabt,mcobb
** cask to impact absorber
*contact pair,cpset=caimp
cabb,imptt
**
** Define surfaces between baskets
**
** basket 0-1
*surface definition,name=bsk0t
31009,s3
*contact node set,name=bsk0n
31046
*elset,elset=bsk1b generate
31100,31106,1
*surface definition,name=bsk1b
bsk1b,s1
*contact pair,cpset=bsk01,interaction=fr01
bsk0n,bsk1b
bsk0t,bsk1b
*surface interaction, name=fr01
*friction
0 3
** basket 1-2
*surface definition,name=bsk1t
31109,s3
*contact node set,name=bsk1n
31146
*elset,elset=bsk2b,generate
31200,31206,1
*surface definition,name=bsk2b
bsk2b s1
*contact pair,cpset=bsk12,interaction=fr12
bsk1n,bsk2b
bsk1t,bsk2b
*surface interaction name=fr12
*friction
0 3
** basket 2-3
*surface definition name=bsk2t
31209,s3
*contact node set,name=bsk2n
31246
*elset,elset=bsk3b,generate
31300,31306,1
*surface definition,name=bsk3b
bsk3b,s1
*contact pair cpset=bsk23,interaction=fr23
bsk2n bsk3b
bsk2t,bsk3b
*surface interaction, name=fr23
*friction
0 3
** basket 3-4
*surface definition,name=bsk3t

```


Input File a7.inp

```

31309,s3
*contact node set,name=bsk3n
31346
*elset,elset=bsk4b,generate
31400,31406,1
*surface definition,name=bsk4b
bsk4b,s1
*contact pair,cpset=bsk34,interaction=fr34
bsk3n,bsk4b
bsk3t,bsk4b
*surface interaction name=fr34
*friction
0 3
** basket 4-5
*surface definition,name=bsk4t
31409,s3
*contact node set,name=bsk4n
31446
*elset,elset=bsk5b,generate
31500,31506,1
*surface definition,name=bsk5b
bsk5b,s1
*contact pair,cpset=bsk45,interaction=fr45
bsk4n,bsk5b
bsk4t,bsk5b
*surface interaction, name=fr45
*friction
0 3
** basket 5 - MCO top
*surface definition,name=bsk5t
31520,s3
*contact node set,name=bsk5n
31546
*elset,elset=mcotb,generate
50030,50034 1
*elset,elset=mcotb
50024
*surface definition,name=mcotb
mcotb,s1
*contact pair,cpset=bsk5m,interaction=b5mco
bsk5n,mcotb
bsk5t,mcotb
*surface interaction name=b5mco
*friction
0 3
**
**
*NSET,NSET=UVOUT,generate
31000,31500,100
31040,31540,100
31010,31016 3
31110,31116,3
31210,31216,3
31310,31316,3
31410,31416,3
31510,31516,3
31542,31543,1

```

Input File - a7.inp

```

50000,50040,20
70200,70340,10
40200,40210,10
40140,40150,10
60311,60321,10
60001,60031,10
160,170 5
185,186,1
100,112,6
113,493,20
51 56,5
91,96,5
31051,31065,2
31151,31165,2
31251,31265,2
31351,31365,2
31451,31465,2
31551,31565,2
*nset,nset=uvout
50000,50030,50003 50033,50006,50036
70343,70643,70943
70270,70570,70870
70200,70500,70800
60031,60182,60332,60181,60331
60025,60125,60325
60020,60170,60320
60015,60165 60315
60001,60151,60301
*NSET,NSET=RFOUT,generate
1,6,1
*elset,elset=eout
mco,cask,impt,impb,pad,bsk
*output, field, number interval=100
*element output, elset=eout
s,le,ne,pe,peeq
*node output
u,rf,v
*contact output variable=preselect
*OUTPUT,HISTORY TIME INTERVAL=1 E-4
*node output,nset=uvout
u2,v2
*node output,nset=rfout
rf2
*elset elset=Sout generate
31008,31508,100
31012,31512,100
60428,60431 1
60378 60381 1
70305,70308,1
*elset,elset=Sout
60001,60101,60251,60015,60115,60265,60020,60120,60270,60025 60125,60275
,60030,60130,60280
70305,70306,70307,70308
70585,70586,70587,70588
70873,70874,70875,70876
50030,50033,50040,50043,50055,50058
*ELEMENT OUTPUT ELSET=SOUT

```

Input File a7.inp

```
s,sp,mises,pe,peeq
*elset,elset=eout2
165
*elset,elset=eout2,generate
100,152,1
1,85,1
60251,60277,1
60001,60032,1
60328,60331,1
60378,60381,1
70301,70320,1
31000,31013,1
31100,31113,1
31200,31213,1
31300,31313,1
31400,31413,1
31500,31513,1
*ELEMENT OUTPUT,ELSET=EOUT2,position=nodes,v=preselect
*ENERGY output, variable=all, elset=ttt
*monitor,dof=2,node=31000
**DIAGNOSTICS,PLASTICITY=DETAIL
*END STEP
** end of file
```

Input File - mco4a.txt

```

**      "MCO4a TXT"
**      4 elements through thickness
**      with basket support plates off symm plane
**      MCO model drop in shipping cask
**      MCO bottom
*NODE
60028,10 3,0,0
60328,11 0125,2 01,0
*NGEN,NSET=N3
60028,60328 50
*NODE,NSET=N3
60378,11 366,2 1564,0
60428,11 50,2 51,0
*NODE
60032,11 423 0 0
60182,11 93076,1 13,0
*NGEN,NSET=N4
60032,60182,50
*NODE,NSET=N4
60232,12,1 423333,0
60332,12,2 01,0
60432,12,2 51,0
*NGEN NSET=N4
60232,60332,50
60332,60432,50
*NFill,NSET=N34
N3,N4,4,1
*NODE,NSET=N34
60032,11 394,0 0502,0
*nset,nset=mco
n34
** side(solid)
*NODE
70200,11 5,2 8,0
70343,11 5,148 0,0
70349,11 5,160 0,0
70800,12 0,2 8,0
70943,12 0 148 0 0
70949,12 0,160 0,0
*ngen,NSET=ssb
70200,70800,150
*ngen,NSET=sst1
70343,70943,150
*NGEN NSET=SST2
70349,70949,150
*nfill,nset=n34
ssb,sst1,143,1
*NFill,NSET=N34
SST1,SST2,6,1
*nset nset=mco
n34
** bottom
*NODE
60001,0,0
*NGEN,NSET=N1
60001 60028,1
** adjust nodes for pad location

```

Input File mco4a.txt

```

**
*node,nset=n1
60020,7 3667,0,0
60021,7 6333,0,0
**
*node,nset=n2
60301,0, 88,0
60306 1 08, 88,0
60307,1 25,1 13,0
60311,2 13,2 01 0
*ngen nset=n2
60301,60306,1
60307,60311,1
60311,60328,1
*nfill,nset=n12
n1,n2,6,50
*nset,nset=mco
n12
**
*ELEMENT TYPE=CAX4R,ELSET=MCOB
60001,60001,60002,60052,60051
*ELGEN,ELSET=MCOB
60001 31 1 1 6 50 50
60278,2,50,50
60328,4,1,1,2,50,50
*ELEMENT,TYPE=CAX4R,ELSET=MCOPS
60428,60428,60429,70350,70200
60429,60429,60430,70500,70350
60430,60430,60431,70650,70500
60431,60431,60432,70800,70650
70305,70200,70350,70351,70201
*ELGEN,ELSET=MCOPS
70305,4,150,1,149,1,4
**
** MCO Top
**
*NODE
50000 0 148 0 0
50050,9 5,148 0 0
50006,0,160 0,0
50056,9 5,160 0,0
*NGEN,NSET=NT1
50000 50050,10
*NGEN,NSET=NT2
50006 50056,10
*NFILL
NT1,NT2,6,1
*nset,nset=mco
nt1,nt2
*ELEMENT TYPE=CAX4R,ELSET=MCOTS
50024,50050,70343,70344,50051
*ELGEN ELSET=MCOTS
50024,6,1,1
*ELEMENT,TYPE=CAX4R,ELSET=MCOTS
50030,50000,50010,50011,50001
*ELGEN ELSET=MCOTS
50030,5,10 1,6,1,5

```

Input File mco4a.txt

```

** add basket support plates
*node
40140,1 25,2 01,0
40200,1 25,3 25,0
40154,11 01,2 01,0
40214,11 01,3 25,0
*ngen,nset=bsp1
40140,40200,20
*ngen,nset=bsp2
40154,40214,20
*nfill,nset=mco
bsp1,bsp2,14,1
*ELEMENT,TYPE=CAX4R,ELSET=bsp
97001,40140,40141,40161,40160
*ELGEN,ELSET=bsp
97001,14,1,1,3 20 14
*ELSET, ELSET=MCOSL
MCOTS, MCOB, MCOPS
*SOLID SECTION, ELSET=MCOSL, MATERIAL=SS304
*SOLID SECTION, ELSET=bsp, MATERIAL=bsp
*elset,elset=bspb,generate
97001,97014,1
*elset,elset=bspt,generate
97029,97042,1
*ELSET, ELSET=MCO
MCOSL, mcops, bsp
*elset,elset=mcobt,generate
60251,60277,1
*elset,elset=mcobb,generate
60001,60031,1
*elset,elset=mcosi
60328
60378
60428
*elset,elset=mcosi,generate
70301,70873,4
** Element set for pressure loading
*elset,elset=mcop1 generate
50030 50034 1
*elset,elset=mcop1
50024
*elset,elset=mcop4,generate
60328,60428,50
70305 70873 4
*elset,elset=mcop3 generate
60251,60277,1
** end of file

```

Input File bsk1a3.txt

```

** bsk1a2.txt w/ fuel elements
*SYSTEM
0,3 25,0
**
** Node definition for basket 0
**
*node,nset=nbsk0
31000,0 875,0,0
31001,3 3125,0 0
31006,10 8125,0,0
31007,11 3125 0 0
*ngen,nset=nbsk0
31001,31006,1
*ncopy,change number=10,old set=nbsk0,shift,new set=nbsk0
0,1 0,0

*nset nset=ntmp
31010,31011,31016
*ncopy,change number=10,old set=ntmp,shift,new set=nbsk0
0,7 7222,0

*ncopy,change number=20,old set=ntmp,shift,new set=nbsk0
0,15 4444,0

*ncopy,change number=30 old set=ntmp,shift,new set=nbsk0
0,22 166,0

** fuel element
*node,nset=fuelb
31051,4 10,1 0,0
31052,5 20,1 0,0
31053,6 70,1 0,0
31054,7 80,1 0,0
31055,9 40,1 0 0
31056,10 5,1 0,0
*ncopy,change number=10,old set=fuelb,shift,new set=fuelb
0,10 0,0

*nset,nset=nbsk0
fuelb,fuelb
**
** Generate nodes for baskets 1-5
**
*ncopy,change number=100,old set=nbsk0,shift,new set=nbsk1
0,23 166,0

*ncopy,change number=200,old set=nbsk0,shift,new set=nbsk2
0,46 332 0

*ncopy,change number=300,old set=nbsk0,shift,new set=nbsk3
0,69 498,0

*ncopy,change number=400,old set=nbsk0,shift,new set=nbsk4
0,92 664,0

*ncopy,change number=500,old set=nbsk0,shift,new set=nbsk5
0,115 83,0

```

Input File bsk1a3.txt

```

** Define extra length for center post
** Gap=1 37" between post top to MCO head
*node,nset=nbsk5
31542,0 875,143 38,0
31543,3 3125,143 38,0
*nset,nset=bsk
nbsk0,nbsk1,nbsk2,nbsk3,nbsk4,nbsk5
**
** Define elements for basket 0
**
*element,type=cax4r,elset=bsk0
31000,31000,31001,31011,31010
31007,31010,31011,31021,31020
*elgen,elset=bsk0
31000,7,1,1
31007,3,10,1
*element,type=sax1,elset=bsks0
31010,31006,31016
31011,31016 31026
31012,31026,31036
31013,31036,31046
**
** Generate elements for baskets 1-5
** 1
*elcopy, element shift=100, old set=bsk0, shift nodes=100, new set=bsk1
*elcopy, element shift=100, old set=bsks0, shift nodes=100, new
set=bsks1
** 2
*elcopy element shift=200 old set=bsk0 shift nodes=200, new set=bsk2
*elcopy, element shift=200, old set=bsks0, shift nodes=200, new
set=bsks2
** 3
*elcopy, element shift=300, old set=bsk0, shift nodes=300, new set=bsk3
*elcopy, element shift=300, old set=bsks0, shift nodes=300, new
set=bsks3
** 4
*elcopy element shift=400 old set=bsk0, shift nodes=400, new set=bsk4
*elcopy, element shift=400, old set=bsks0, shift nodes=400, new
set=bsks4
** 5
*elcopy element shift=500 old set=bsk0, shift nodes=500, new set=bsk5
*elcopy, element shift=500 old set=bsks0, shift nodes=500, new
set=bsks5
*element,type=cax4r,elset=bsk5
31520 31540 31541,31543,31542
** fuel elements
*element,type=cax4r,elset=fuel
31051,31051,31052,31062,31061
*elgen,elset=fuel
31051,3,2,1,6,100,100
**
** Define element sets
**
** element sets for material properties
*elset,elset=bskp
31520

```


Input File - bsk1a3.txt

```
*elset,elset=bskp,generate
31000,31500,100
31007,31507,100
31008,31508,100
31009,31509,100
*elset,elset=bskd,generate
31001,31006,1
31101,31106,1
31201,31206,1
31301,31306,1
31401,31406,1
31501,31506,1
*elset,elset=bsks
bsks0,bsks1,bsks2,bsks3,bsks4,bsks5
** end material property element sets
*elset,elset=bsk
bsk0,bsks0,bsk1,bsks1,bsk2,bsks2,bsk3,bsks3,bsk4,bsks4,bsk5,bsks5
**
** Define element sets for surfaces
**
*elset,elset=bsk0b,generate
31000,31006,1
*elset,elset=bskf0,generate
31006,31506 100
** end of file
```

Input File - ca_ia1.txt

```

**   ca_ia.txt
**
**   Cask and Impact absorber   2D axisymmetric model
**
*system
0,-6 25,0
**
** Impact Absorber
**
*node,nset=nimp1
1,0,-45 0,0
6,19 5,-45 0,0
*ngen,nset=nimp1
1,6,1
*node,nset=nimp2
91,0,0,0
96,19 5,0,0
*ngen,nset=nimp2
91,96,1
*nfill,nset=nimp
nimp1,nimp2,9,10
*element,type=cax4r,elset=impb
1,1,2,12,11
*elgen,elset=impb
1,5,1,1,5,10,10
*element,type=cax4r,elset=impt
51,51,52,62,61
*elgen,elset=impt
51,5,1,1,4,10,10
*boundary
nimp1,1,2
** elset for surface
*elset,elset=imptt,generate
81,85,1
**
** Cask
**
*node,nset=nca1
100 0 0,0
113,19 905,0,0
*ngen,nset=nca1
100,113,1
*node,nset=nca2
160,0,6 13,0
163,5 875,6 13,0
164,6 875 6 13,0
165,7 3667,6 13,0
166,7 6333,6 13,0
167,8 125,6 13,0
168,9 125 6 13 0
170,12 595,6 13,0
173,19 905,6 13,0
*ngen,nset=nca2
160,163,1
168,170,1
170,173,1
*nfill,nset=nca

```

Input File ca_ia1.txt

```

nca1,nca2,3,20
*node,nset=nca
185,7 3667,6 25,0
186,7 6333,6 25,0
*nset,nset=nca3,generate
170,173,1
*node,nset=nca4
490,12 595,159 25,0
493,19 905,159 25,0
*ngen,nset=nca4
490,493 1
*nfill,nset=nca
nca3,nca4,16,20
*element,type=cax4r elset=pad
165,165,166,186,185
*element,type=cax4r,elset=cask
100,100,101,121,120
170,170,171,191,190
*elgen,elset=cask
100,13,1,1,3 20 20
170,3,1,1,16,20,20
**
** elsets for surfaces
**
*elset,elset=cabb,generate
100,113,1
*elset,elset=cabt,generate
140,144,1
146,149,1
** end of file

```

Appendix D

Statement of Work

**STATEMENT OF WORK
for
“ SNF MCO Drop into the Cask from the MHM with Air Cushion”
Revision 0, 8/3/1999**

1 INTRODUCTION

This Statement of Work describes the continuation and expansion of the FDNW contract (TBD) as noted herein for the SNF MCO Drop into the Cask from the MHM with Air Cushion. The additional scope involves the assessment of the MCO dropping from the MHM (approximately 8.2 feet before entering the cask) entering the Cask concentrically and falling the additional 12.83 feet to the cask bottom while considering the effect of the air cushion. Because of the interface fit of the Cask/MCO and the air entrapment, the MCO fall velocity is slowed. This effect was studied by B. Crea in January 1997 as listed in the references. The overall task is to calculate the impact forces on the MCO and its internals and to determine the resulting strains on the MCO pressure boundary and see if the resulting strains are of significant magnitude to result in a breach of the MCO pressure boundary. This work needs to be completed as soon as possible in order to support the SNF MCO Topical Report schedule.

2 WORK SCOPE

Subtask 1—Determine Impact Velocity of the MCO falling into the Cask

Assess the MCO falling height from the MHM onto and into the Cask while the Cask is positioned in the Canister Storage Receiving Pit. This fall height from the MHM must correlate with the MCO bounding drop height currently being investigated by the seller. Working with this height, an initial velocity at entrance to the Cask can be determined. Using this initial velocity plus one to be determined through use of B. Crea's analysis (Ref. 1), determine the velocity at impact of the MCO bottom and Cask lower end. Through use of this velocity, determine the impact acceleration and forces through use of a finite element model non-linear solution. In addition, determine the MCO strains, which can be determined through the use of a finite element model of the MCO and its internals. The internals must be modeled with care such that the proper energy dissipation is achieved in the packaged fuel rods and baskets.

Subtask 2---Determination of Resulting Strains

Determine the maximum surface and through wall strains which occur in the MCO pressure boundary body. Assess whether these strains are of significant magnitude to possibly cause breach of the MCO. The strains are to be categorized with type as well as direction and will be depicted with contour plots and charts. The strains are to be compared to material ultimate elongation values at temperatures of 50 to 270 degrees Fahrenheit. The strain solution shall consider the effects of internal pressures from 0 to 450 psig, whichever is worse.

Subtask 3---Drop Condition

Report the drop condition at the worst case with either a maximum or minimum load weighted MCO as shown in the Design Analysis Report, Ref. 2.

Subtask 4---Report on Findings

The evaluation report is to be submitted, reviewed and approved by the investigating engineer, the engineer's management, an independent reviewer, and the MCO subproject Design Authority. The buyer is to approve the report upon receipt.

The format for the report is to include but not limited to the following:

Title Page
 Purpose and Objectives
 Summary of Final Results and Conclusions
 Assumptions
 Finite Element Model
 Input Data
 Calculation
 Results
 Conclusions
 References

3 DELIVERABLES

Documents as noted in the above listed items under Work Scope above. The format if different than that noted under deliverables must be agreed upon by the design authority or his designee.

4 SCHEDULE

The assessment and related documents are due no later than one month from the Notice to Proceed or contract extension approval notification. The Design Authority, Buyer, and/or SNF Project management reserves the right to renegotiate the delivery dates if necessary.

5 PROCUREMENT

This contract statement of work authorizes no procurement.

6 PERMITS & SAFETY

Permits – not applicable
 Does not require safety review or signature

7 REPORTING

As noted in Subtask 4 above.

8 QUALITY ASSURANCE

All work performed in accordance with this statement of work shall be performed in accordance with the Seller's approved Quality Assurance Plan. The QA Program shall also comply with the sections 71.103, 71.105, 71.107, 71.109, 71.111, 71.113, 71.115, 71.133, and 71.135 of 10 CFR 71 subpart H, Quality Assurance.

9 INTERFACE POINTS

The Buyers Technical Representative (BTR) will be D M Chenault (376 6230)

10 REFERENCES

HNF SD SNF DP 007 Rev 0 Multi Canister Overpack/Cask Drop Analysis File
Documentation D M Chenault 6/17/97 Appendices J

HNF SD SNF DR 003 Rev 2 Multi Canister Overpack Design Report January 1999

11 OTHER/ADDITIONAL REQUIREMENTS

Coordinate solution input with the BTR or MCO Design Authority before making the significant
analysis finite element runs