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NATIONAL SPENT NUCLEAR FUEL PROGRAM ENGINEERING DESIGN FILE

EDF-NSNF- 085

Revision 0

Title: Structural Analysis Results of the DOE SNF Canisters Subjected to the 23-Foot Vertical Repository Drop Event to Support Probabilistic Risk Evaluations

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5. **Purpose:**

The purpose of this effort is to perform analytical evaluations of representative configurations of the DOE SNF canisters subjected to the vertical repository drop event of 23 feet at their maximum anticipated repository operating temperatures. The containment boundary strains resulting from these drop events are to be used as input for probability risk assessments.

The NSNFP has directed that the following three DOE SNF canister analyses be performed reflecting the conditions as indicated in Table 1 below.

Table 1. DOE SNF canister analysis parameters.

Condition	18-inch Standardized DOE SNF Canister	24-inch Standardized DOE SNF Canister	MCO
Canister Length	15 feet	15 feet	Design Length
Drop Height	23-foot onto an essentially unyielding flat surface	23-foot onto an essentially unyielding flat surface	23-foot onto an essentially unyielding flat surface
Drop Orientation	3 degrees off-vertical	3 degrees off-vertical	3 degrees off-vertical
Temperature	300°F	300°F	240°F
Total Weight	6,000 lbs	10,000 lbs	20,000 lbs
Material Strength (yield & ultimate)	ASME B&PV Code minimums	ASME B&PV Code minimums	ASME B&PV Code minimums
Strain Rate Effects	20% increase	20% increase	20% increase
Containment Shell Thicknesses	12-1/2% under nominal thickness	12-1/2% under nominal thickness	nominal

Results:

Tables 2 and 3 show the resulting maximum strains in the 18-inch and 24-inch standardized canister containment boundary for the Table 1 drop conditions.

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Table 2. 18-inch standardized canister containment PEEQ strains, 3 deg. off-vertical drop, 300°F.

Component	Peak Equivalent Plastic Strains (%)		
	Outside Surface	Middle	Inside Surface
Lower Head	8	3	6
Lower Head-to-Main Shell Weld	2	2	3
Main Shell	2	2	3
Upper Head-to-Main Shell Weld	0	0	0
Upper Head	1	0.2	2

Table 3. 24-inch standardized canister containment PEEQ strains, 3 deg. off-vertical drop, 300°F.

Component	Peak Equivalent Plastic Strains (%)		
	Outside Surface	Middle	Inside Surface
Lower Head	2	0.7	1
Lower Head-to-Main Shell Weld	0.2	0.3	0.5
Main Shell	0.2	0.3	0.5
Upper Head-to-Main Shell Weld	0	0	0
Upper Head	0	0	0

The resulting strains for the MCO under the Table 1 drop conditions at 240°F were lower than those calculated for the same drop at 70°F using actual material properties as discussed in EDF-NSNF-029 (Ref. 1). Therefore, it is recommended that the Reference 1 calculated strains, shown in Table 4 below, be used for the probability risk evaluations.

Table 4. MCO containment PEEQ strains, 3 deg. off-vertical drop at 70°F.

Component	Peak Equivalent Plastic Strains (%)		
	Outside Surface	Middle	Inside Surface
Bottom	35	16	14
Bottom-to-Main Shell Weld	21	11	11
Main Shell	13	15	29
Collar	0	0	0
Cover	0	0	0

Title: Structural Analysis Results of the DOE SNF Canisters Subjected to the 23-Foot Vertical Repository Drop Event to Support Probabilistic Risk Evaluations

References:

1. S. D. Snow, *Analytical Evaluation of the MCO for Repository-Defined and Other Related Drop Events,* EDF-NSNF-029, Rev. 0, September 30, 2003.

This document was developed and is controlled in accordance with NSNFP procedures. Unless noted otherwise, information must be evaluated for adequacy relative to its specific use if relied on to support design or decisions important to safety or waste isolation.

The NSNFP procedures applied to this activity implement DOE/RW-0333P, "Quality Assurance Requirements and Description," and are part of the NSNFP QA Program. The NSNFP QA Program has been assessed and accepted by representatives of the Office of Quality Assurance within the Office of Civilian Radioactive Waste Management for the work scope of the NSNFP. The NSNFP work scope extends to the work represented in this report.

The current, principal NSNFP procedures applied to this activity include the following:

- NSNFP Procedure 6.01, *Review and Approval of NSNFP Internal Documents,*
- NSNFP Procedure 6.03, *Managing Document Control and Distribution,*
- NSNFP Procedure 3.04, *Engineering Documentation.*

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1	Report EDF-NSNF-085, Rev. 0	78	78

STRUCTURAL ANALYSIS RESULTS OF THE DOE SNF CANISTERS SUBJECTED TO THE 23-FOOT VERTICAL REPOSITORY DROP EVENT TO SUPPORT PROBABILISTIC RISK EVALUATIONS

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STRUCTURAL ANALYSIS RESULTS OF THE DOE SNF CANISTERS SUBJECTED TO THE 23-FOOT VERTICAL REPOSITORY DROP EVENT TO SUPPORT PROBABILISTIC RISK EVALUATIONS

1. INTRODUCTION

The Department of Energy (DOE) has generated or acquired a vast number and variety of spent nuclear fuels (SNF), starting back in the 1940's. With the development of the repository, DOE has been moving forward with plans to dispose of this SNF. In doing so, two different canisters designs have been developed: the Multi-Canister Overpack (MCO) and the standardized DOE SNF canister ("standardized canister"). Even though these canisters may hold different fuel types or have different diameters or lengths, all of these canisters are collectively referred to as the DOE SNF canisters.

During the late 1990s, the Hanford site developed the MCO (References 1 and 2), a SNF canister used for moving N Reactor and other Hanford SNF from older storage facilities near the Columbia River to safer, interim storage facilities away from the Columbia River at Hanford. Over 400 of these MCOs have been loaded (to date) and moved to the newer canister storage building at Hanford. The MCO's initial design purpose was to only move the Hanford SNF away from the Columbia River and place it in temporary storage. However, DOE now wants to use the MCOs to transport that SNF to the repository and be disposed at the repository, without having to reopen or repackage the MCOs.

DOE's National Spent Nuclear Fuel Program (NSNFP), working with the Office of Civilian Radioactive Waste Management (OCRWM), the Idaho National Laboratory (INL) and other DOE sites, has developed a set of standardized canisters for handling, interim storage, transportation, and disposal of other DOE SNF. Because the DOE-owned SNF has numerous geometries, the NSNFP developed a design, referred to as the standardized DOE SNF canister, with two diameters and two lengths for a total of four similar but unique geometries. The nominal sizes for the four geometries are 18-inch (3/8-inch wall) and 24-inch (1/2-inch wall) in outer diameter, and 10 and 15 feet in overall length.

The standardized canister design required a high degree of confidence against failure of the containment boundary if the canister was subjected to loads (e.g., accidental drop events) resulting in large plastic deformations and high strains. In fiscal year (FY) 1999, the NSNFP completed a test and analytical evaluation program for the 18-inch diameter standardized canister (Reference 3). A combination of analytical techniques and physical testing was used to develop and demonstrate the viability of the canister design. Nine full-scale 18-inch diameter representative (prototype) test canisters were fabricated and dropped from various heights and orientations. The nine 18-inch diameter test canisters experienced varying degrees of damage (plastic deformation) to their skirts, lifting rings and containment boundary components. However, the test results indicated that the 18-inch diameter test canister survived 30-foot drop events (with a variety of impact orientations) onto an essentially unyielding flat surface and a 40-inch drop onto a six-inch diameter bar while still maintaining a leaktight containment. Helium leak testing confirmed the post-drop leaktight containment.

In FY 2004, the NSNFP again funded a drop test and analytical evaluation effort for the MCO and 24-inch standardized canisters (References 4 and 5, respectively), with the goal of demonstrating the robust design of these canisters. Two canisters of each design were fabricated and dropped from various heights and orientations. The four test canisters experienced varying degrees of damage (plastic deformation) to their containment boundary components. However, the test results again indicated that the MCO and 24-inch standardized canisters could survive significant drop events onto an essentially unyielding flat surface and still not breach (confirmed by post-drop helium leak testing).

Hence, DOE has completed full-scale testing of its DOE SNF canisters and have demonstrated their robust design. In addition, analytical evaluations have been performed proving that an analytical methodology exists that can be used to adequately predict the structural response of these canisters for drop events not specifically tested.

2. SCOPE

The scope of this effort, defined by NSNFP, is to perform analytical evaluations of representative configurations of the DOE SNF canisters subjected to the vertical repository drop event of 23 feet at their maximum anticipated repository operating temperatures. As can be expected, due to the vast number of possible combinations of canister geometries, weights, and temperatures, it is not possible to clearly establish bounding structural results, especially since the analyses to be performed are nonlinear (fully plastic). However, it is reasonable to choose conditions that will most likely yield structural responses that challenge the containment capability of the canister being evaluated.

With that in mind, the NSNFP has directed (Reference 6) that the following three DOE SNF canister analyses be performed reflecting the conditions as indicated in Table 1 below.

Table 1. DOE SNF canister analysis parameters.

Condition	18-inch Standardized DOE SNF Canister	24-inch Standardized DOE SNF Canister	MCO
Canister Length	15 feet	15 feet	Design Length
Drop Height	23-foot onto an essentially unyielding flat surface	23-foot onto an essentially unyielding flat surface	23-foot onto an essentially unyielding flat surface
Drop Orientation	3 degrees off-vertical	3 degrees off-vertical	3 degrees off-vertical
Temperature	300°F	300°F	240°F
Total Weight	6,000 lbs	10,000 lbs	20,000 lbs
Material Strength (yield & ultimate)	ASME B&PV Code minimums	ASME B&PV Code minimums	ASME B&PV Code minimums
Strain Rate Effects	20% increase	20% increase	20% increase
Containment Shell Thicknesses	12-1/2% under nominal thickness	12-1/2% under nominal thickness	nominal

The first five lines of Table 1 list very specific requirements but the last three lines indicate conditions that require additional explanation. Regarding material strength (both yield strength and ultimate or tensile strength), the choice was to incorporate material input in to the analyses (true stress-strain curves) that reflect American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section II (Reference 7) minimum values. In this way, the canisters cannot meet their construction criteria [ASME B&PV Code (Reference 8)] without satisfying these minimum material strength values. However, most current materials used in Code fabrication have strength values above these minimums so this is generally conservative in the structural response predictions. Regarding strain rate effects, the previous drop testing efforts in FY 1999 and 2004 used a 1.2 factor increase on stress for the material input true stress-strain curves to address strain rate effects. Those drop test predictions proved accurate so the 1.2 factor increase will be used for the analyses performed herein. Finally, an effort was made to address a combination of material thickness variations present during fabrication and the potential reduction in wall thickness due to possible corrosion effects while in use. Hence, regarding the thickness entries in the last line of Table 1, the standardized canisters (that have not yet been fabricated) were identified to have a main shell thickness that was reduced by 12-1/2 percent (which is the maximum allowable underthickness for ASME SA-312 pipe). This was used to account for both thickness variations and possible corrosion effects. The heads for both the 18- and 24-inch standardized DOE SNF canisters were reduced by the same thickness value as the shell. However, since the MCOs have already been fabricated and loaded, a different approach was used. The fabrication of the MCOs reflected that the wall thickness actually was maintained very near the nominal thickness of the shell and that no reduction of wall thickness is anticipated for the MCO (Reference 4). Therefore, nominal wall thickness values were used for the MCO drop analysis prediction. Additionally, aging effects on these canisters was anticipated to be insignificant (Reference 9).

3. QUALITY ASSURANCE

This document was developed and is controlled in accordance with NSNFP procedures. Unless noted otherwise, information must be evaluated for adequacy relative to its specific use if relied on to support design or decisions important to safety or waste isolation.

The NSNFP procedures applied to this activity implement DOE/RW-0333P, "Quality Assurance Requirements and Description," (Reference 10) and are part of the NSNFP QA Program (Reference 11). The NSNFP QA Program has been assessed and accepted by representatives of the Office of Quality Assurance within the Office of Civilian Radioactive Waste Management for the work scope of the NSNFP. The NSNFP work scope extends to the work presented in this report.

The current, principal NSNFP procedures applied to this activity include the following:

- NSNFP Procedure 6.01, *Review and Approval of NSNFP Internal Documents* (Reference 12),
- NSNFP Procedure 6.03, *Managing Document Control and Distribution* (Reference 13),
- NSNFP Procedure 3.04, *Engineering Documentation* (Reference 14).

4. DOE SNF CANISTER DESIGNS

The DOE SNF canisters considered in this evaluation are: (1) the 18-inch standardized DOE SNF canister, 15-foot in length, (2) the 24-inch standardized DOE SNF canister, 15-foot in length), and (3) the MCO. Due to a short evaluation timeframe, existing models from past analysis efforts where used with modifications made as necessary.

[Note that the standardized DOE SNF canisters referred to herein have been previously identified as "ISFP canisters." The ISFP, or Idaho Spent Fuel Project, was the first intended use of the standardized canister (see Reference 15 for additional discussion).]

4.1. 18-Inch Standardized DOE SNF

Reference 15 is a report that addresses the response of an 18-inch diameter standardized canister subjected to transportation drop loads. That report provided the basis for the 18-inch canister information used herein. The basic features of the 18-inch standardized DOE SNF canister are:

- 18-inch outer diameter canister, 15 feet in overall length, with a maximum total design weight of 6000 pounds,
- Canister main shell (body) and skirts made of 18-inch nominal outer diameter, longitudinally-welded pipe, 3/8-inch nominal thickness, (SA-312 type 316L SST),
- Canister heads are ASME flanged and dished (5/8-inch nominal thickness, with a 2-inch long straight flange, later machined to 3/8-inch thickness after skirt is attached, (SA-240, type 316L SST),
- Canister skirts are 8 inches long,
- Canister lifting rings with a 17-1/4-inch outer diameter by 15-1/4-inch inner diameter made of 5/8-inch thick plate, later machined to ½-inch thickness (SA-240, 316L SST),
- Canister internal impact plates, made of 2-inch plate (SA-240 type 316L or SA-351 type CF3M), flat on one side for the contents to rest on and contoured on the other side to match the geometry of the inside surface of the head, held in place by retaining rings welded to the inside of each head.

Figure 1 shows the basic standardized canister configuration, and Figure 2 shows a close-up view of the top and bottom ends of the standardized canister.

4.2. 24-Inch Standardized DOE SNF Canister

The Reference 5 report addressed the response of a 24-inch standardized canister subjected to drop loads. That report provided the basis for the 24-inch canister information used herein. Basic features of the 24-inch standardized DOE SNF canister analyzed for this effort are as follows:

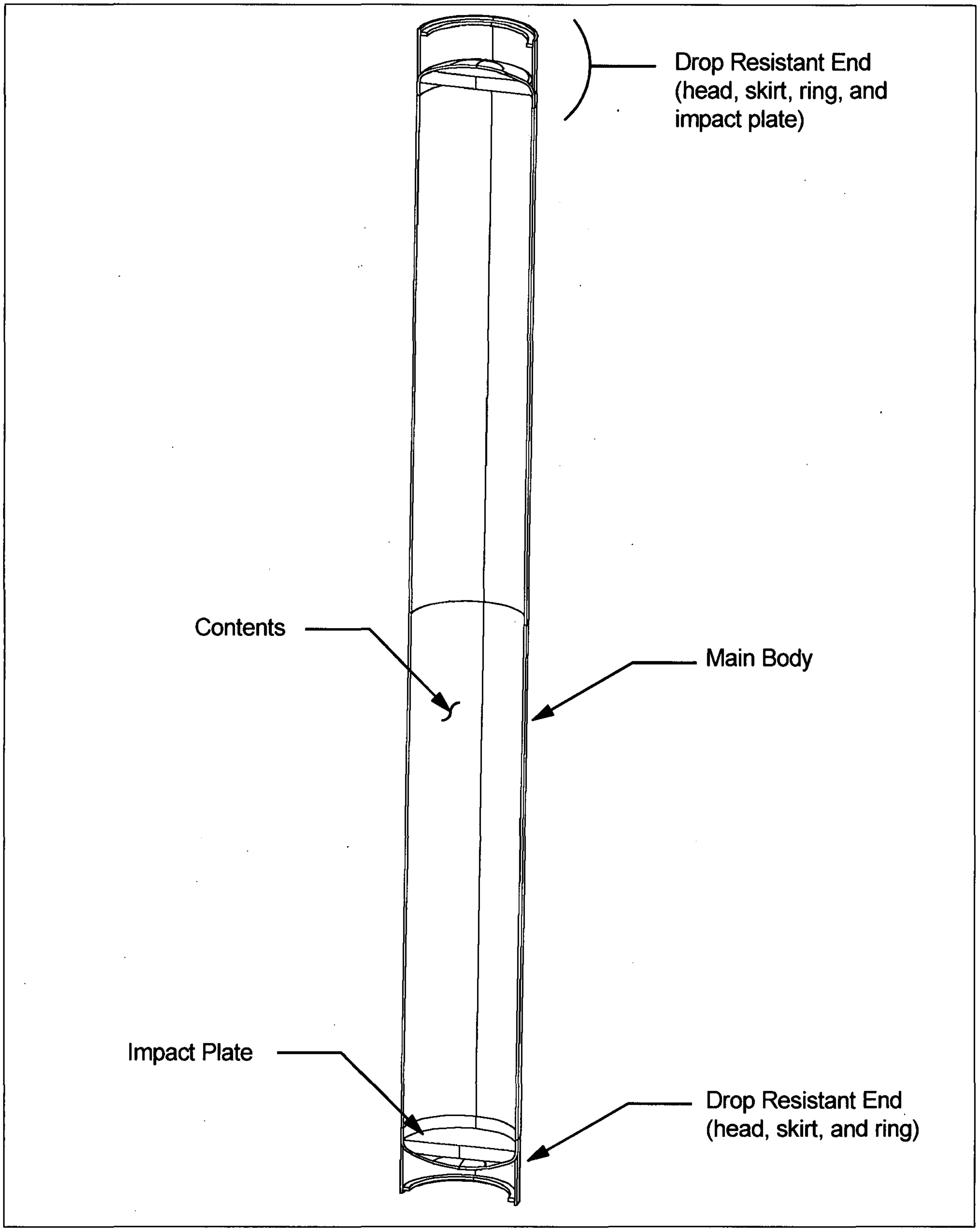
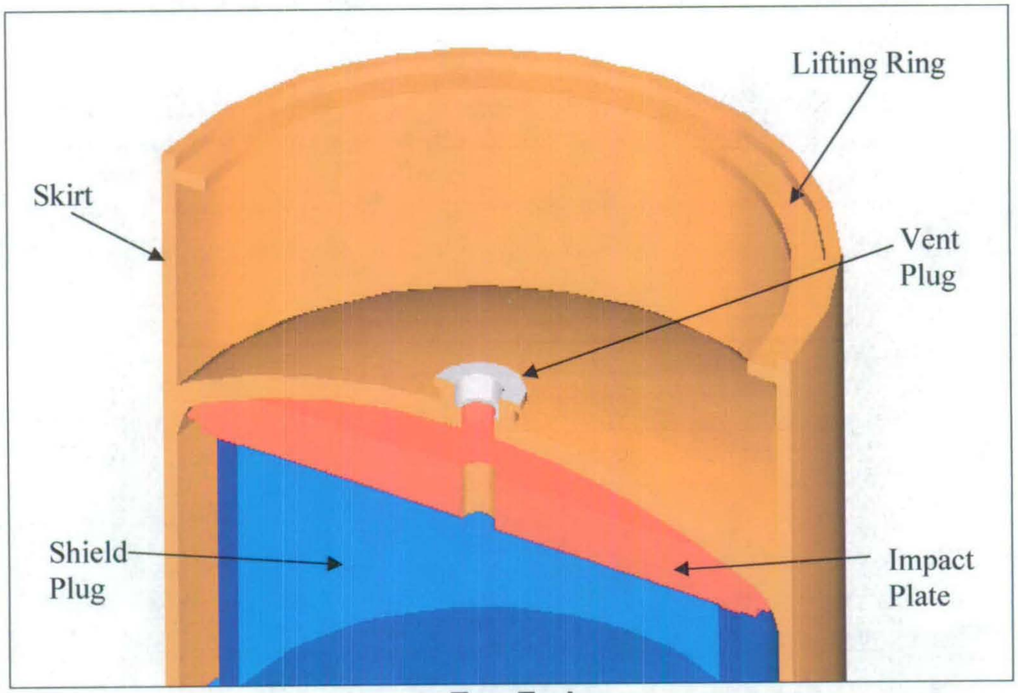
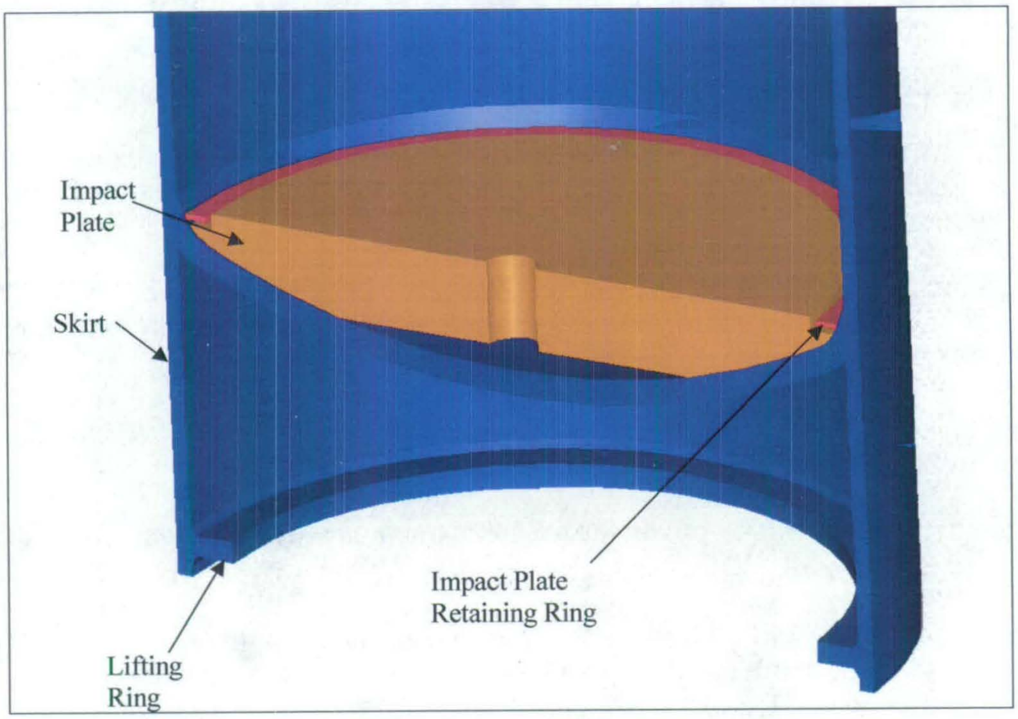


Figure 1. 18-inch and 24-inch standardized canister design.



Top End



Bottom End

Figure 2. Close-up of 18-inch and 24-inch standardized DOE SNF canister ends.

- 24-inch outer diameter canister, 15 feet in overall length, with a maximum design weight of 10,000 pounds,

- Canister main shell (body) and skirts made of 24-inch nominal outer diameter, longitudinally welded pipe, 1/2-inch nominal thickness, (SA-312 type 316L SST),

- Canister heads are ASME flanged and dished, 3/4-inch nominal thickness, with a 2-inch long straight flange, later machined to 1/2-inch thickness after skirt is attached, (SA-240 type 316L SST),

- Canister skirts are 9 inches long,

- Canister lifting rings with a 22-7/8-inch outer diameter by 20-3/4-inch inner diameter made of 5/8-inch thick plate, later machined to ½-inch thickness, (SA-240, 316L SST),

- Canister internal impact plates, made of 2-inch plate, (SA-240 type 316L, or SA-351 type CF3M), flat on one side for the contents to rest on and contoured on the other side to match the geometry of the inside surface of the head, held in place by retaining rings welded to the inside of each head.

As indicated earlier, Figure 1 shows the basic standardized canister configuration, and Figure 2 shows a close-up view of the top and bottom ends of the standardized canister.

4.3. Multi-Canister Overpack

Reference 16 is a report that addresses the response of the MCO subjected to drop loads. That report provided the basis for the MCO information used herein. The main components of the MCO were modeled as follows:

- A 24-inch nominal outer diameter canister, about 166 inches (13.8 feet) in overall length, with a maximum design weight of 20,080 pounds (with fully loaded Mark IV baskets, dry),

- The main shell was made of 24-inch nominal outer diameter pipe with a 1/2-inch nominal thickness (SA-312 TP304/304L SST),

- The shell bottom was approximately 24 inches in diameter and was about 2 inches thick (SA-182 F304/304L SST),

- The collar (SA-182 F304/304L SST), which was about 15-inches in height with an increased outer diameter of 25.3 inches, was a continuation of the main shell that was threaded to accept the locking ring,

- The closure cover was about 9 inches in height and attached to the collar to seal the container (SA-182 F304L). The cover also included a ring for lifting the sealed MCO.

Figures 3 and 4 show the MCO design, with close-up views of the top and bottom ends and certain internals (see Section 5.3 for details) shown for clarification purposes.

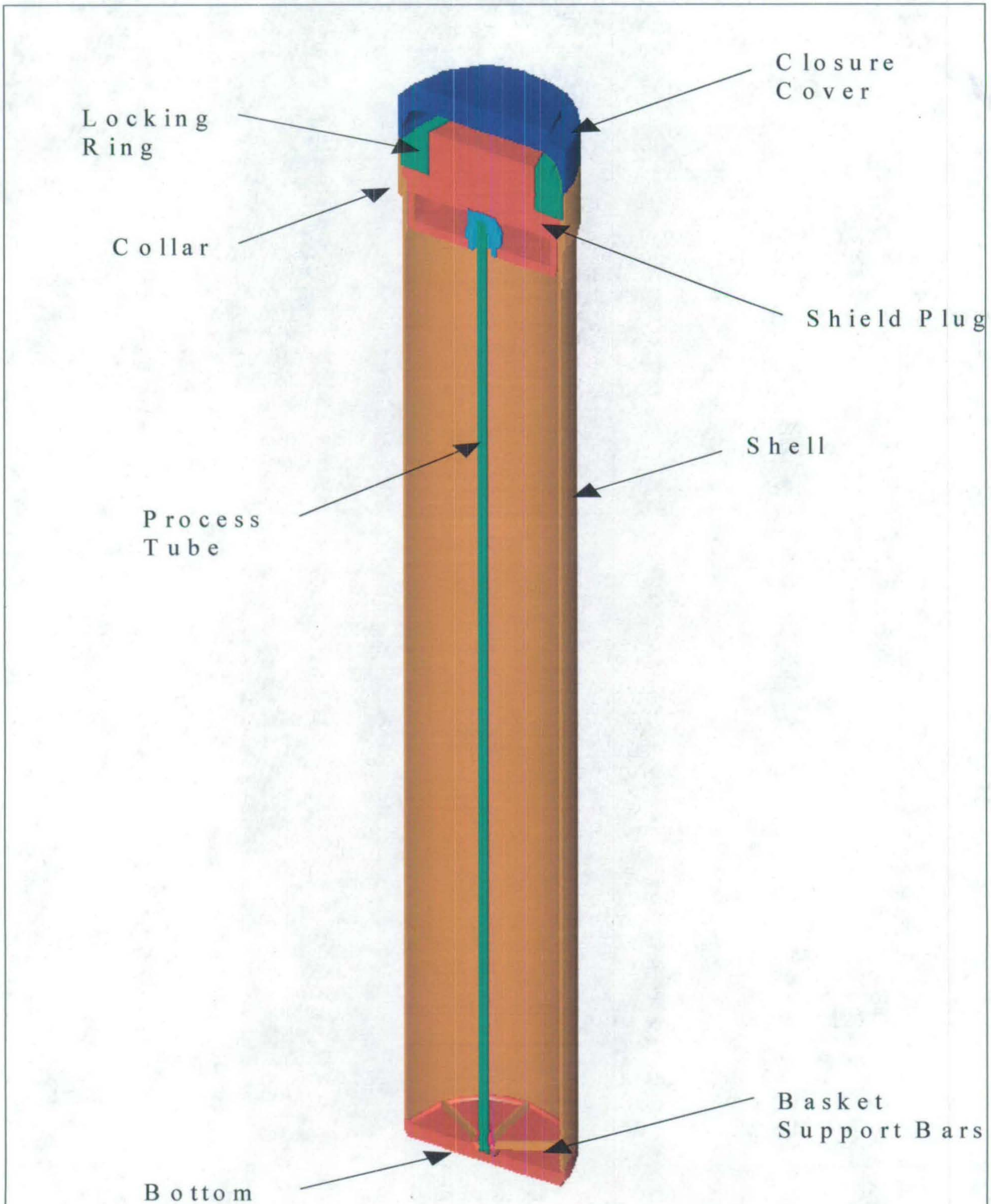
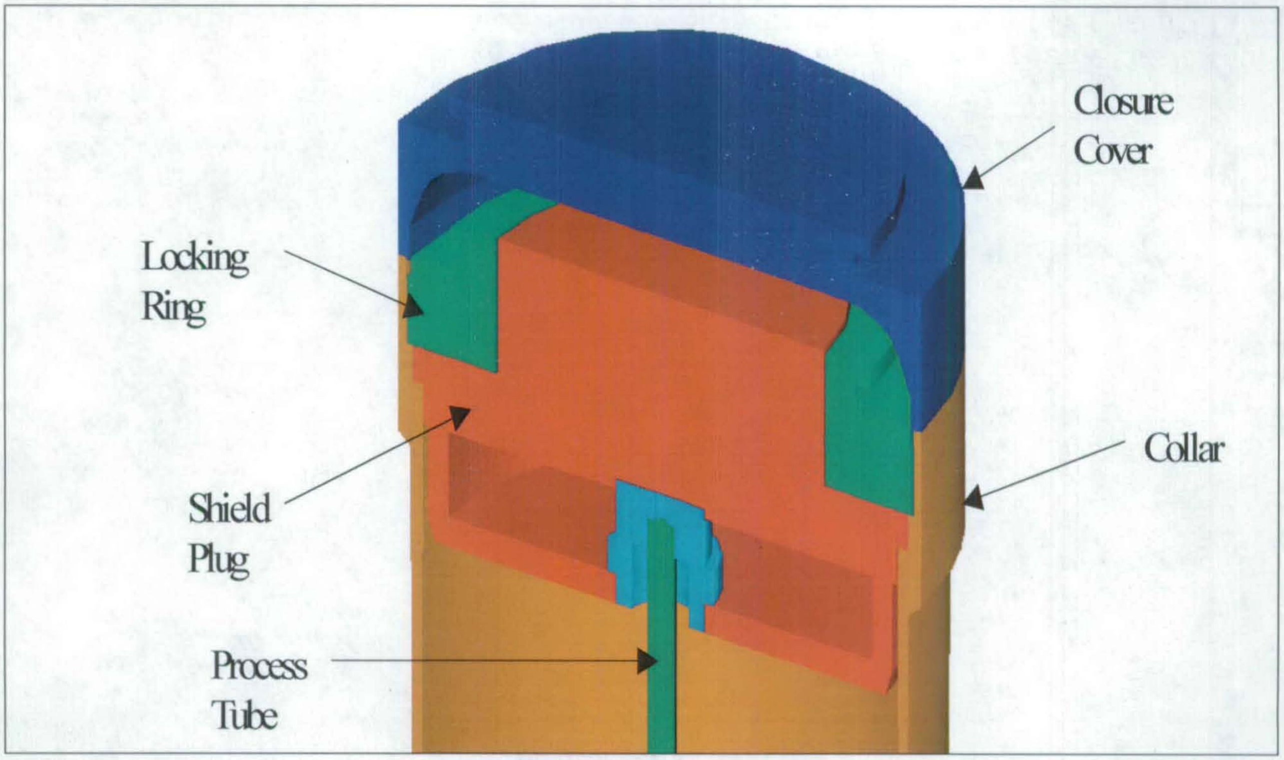
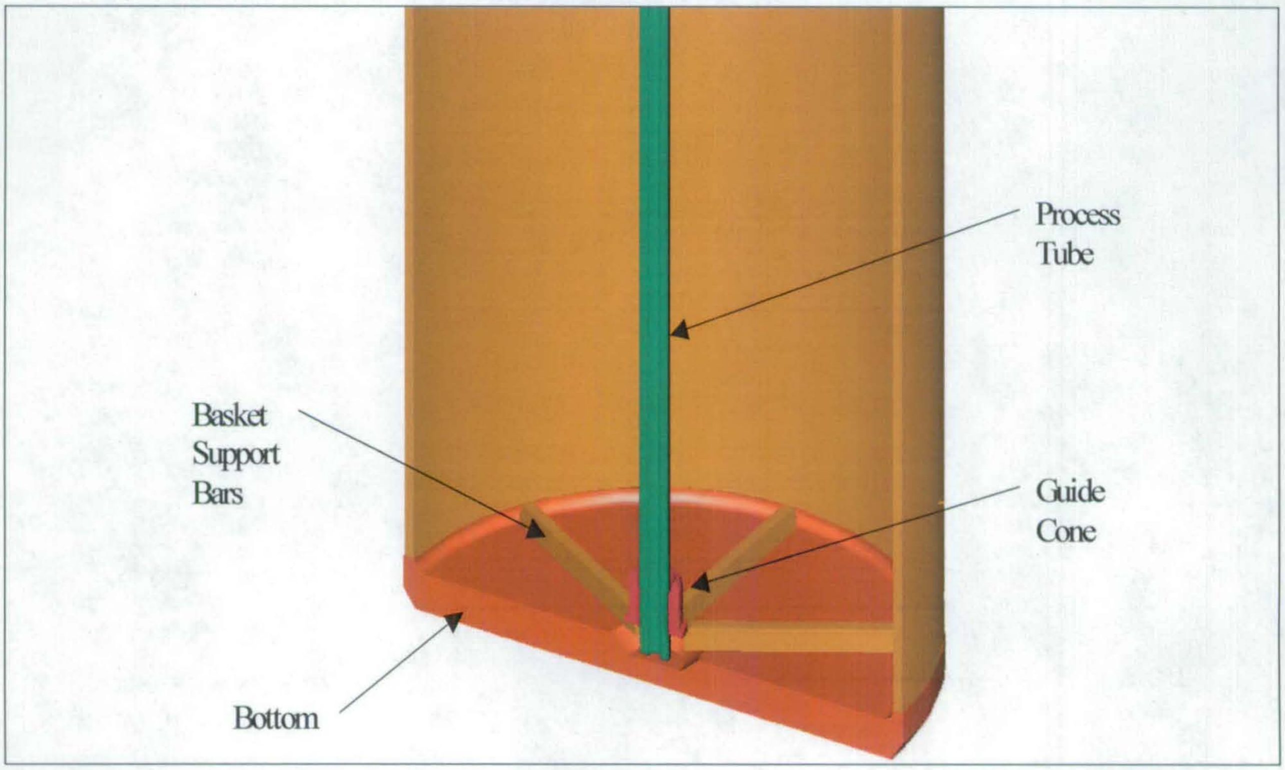


Figure 3. MCO design (cross-section view).



Top-End



Bottom End

Figure 4. Close-up of MCO ends (cross-section view).

5. DOE SNF CANISTER INTERNAL COMPONENTS

A variety of internal component configurations are possible with the three DOE SNF canisters. The objective for this analysis effort was to select a configuration that would be representative and significantly challenge the structural integrity of the canister. Hence, a Type 1a rectangular grid basket was chosen for the 18-inch standardized canister due to the significant number of anticipated canisters using this basket (Reference 15). For the 24-inch standardized canister, actual large fuel components or "loose" rods may be loaded into the canister (Reference 17). However, specific details on these items, especially the large fuel components, are not readily available. Hence, a spoked-wheel internal and bottom spacer similar to what was actually used in full-scale drop tests was chosen due to the significant challenge these internals could provide to the structural integrity of the canister. Finally, the MCO has three specified SNF baskets (Mark 1A, Mark IV, and scrap) but for this analysis, the Mark IV basket was chosen since previous analysis work (Reference 16) indicates that this internal results in higher strains in the canister shell. All three of these canisters designs also use internal shield plugs located near the top to provide additional shielding for final closure activities.

5.1. 18-Inch Standardized DOE SNF Canister

The 18-inch standardized DOE SNF canister internals include a shield plug and three Type 1a baskets with SNF (besides the internal impact plates already discussed). These baskets are stacked vertically and rest directly upon the bottom internal impact plate. The shield plug rests directly upon the top basket when the canister is in the vertical upright position.

5.1.1. 18-Inch Canister Shield Plug

A shield plug is to be placed in the canister after the insertion of the baskets and SNF. The shield plug is very simplistic in its design, consisting of a 16.7-inch diameter 316L stainless steel solid bar that is 6-3/4 inches tall. (Height of shield plug corresponds to the remaining axial length within the canister.)

5.1.2. 18-Inch Canister Type 1a Basket

The rectangular grid basket (also referred to as the Type 1a basket) has not yet been designed. However, the design concept, as employed in this report, is discussed below.

Each canister used three rectangular grid baskets. A rectangular grid basket consists of a 1/2-inch thick base plate (16.900-inch outer diameter) and a thin sleeve (1/16-inch thick) both made of 316L stainless steel. The sleeve is attached to the base plate via a 1/16-inch all-around groove weld. A rectangular grid constructed of 3/8-inch plate made of a nickel-chromium-molybdenum-gadolinium alloy (ASTM B 932-04, Reference 18, hereafter referred to as "Ni-Gd"), rests on the basket base. The individual grid plates are welded together with continuous full-penetration groove welds. (Intermittent welding could be used between grid plates, which could result in a somewhat less stiff grid plate configuration. Continuous welds were employed herein because they would produce a stiffer basket that would be more demanding on the canister main shell integrity during off-vertical drop events.) The grid plate assembly is welded to the base plate using 3-inch long groove welds at the ends of each grid plate. Figures 5 and 6 show end and side views of the design concept of the rectangular grid basket employed in this evaluation.

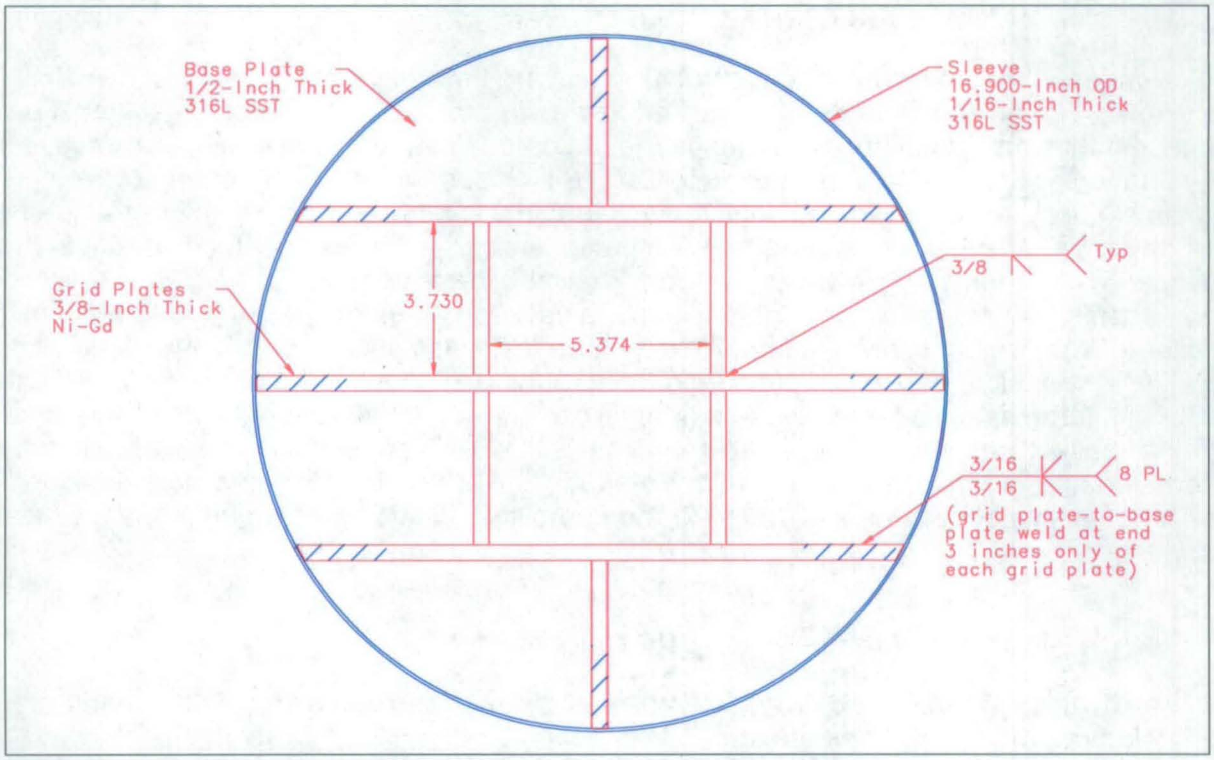


Figure 5. Type 1a rectangular grid basket design, top-end view.

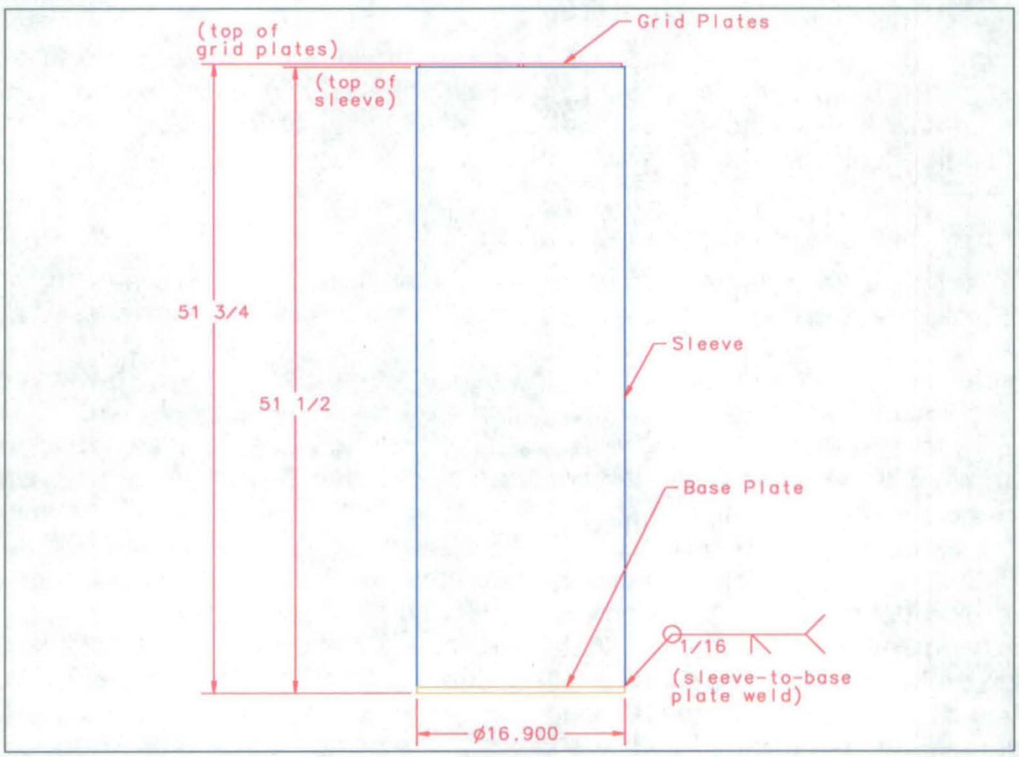


Figure 6. Type 1a rectangular grid basket design, side view.

The SNF was represented as stiff, solid bars such that the maximum allowable weight for the entire loaded canister (6,000 pounds) was achieved.

5.2. 24-Inch Standardized DOE SNF Canister

The 24-inch diameter standardized DOE SNF canister was modeled with three internals components. Starting at the top, the canister has a shield plug that is placed just below the top head impact plate. Next, the canister has a fuel basket with the SNF. For the purposes of this analysis discussed herein, a spoked-wheel was modeled with solid bars (representing the SNF) located in the center area of the pipe and in the five areas between the spokes. Finally, this basket rests directly on a 24-inch long bottom spacer that rests on the bottom head impact plate. Figure 7 shows the 24-inch canister internal component configuration (shield plug, spoked-wheel basket with SNF, and bottom spacer). Figure 8 illustrates the cross-section of the spoked-wheel basket and where the SNF is loaded.

5.2.1. 24-Inch Canister Shield Plug

This shield plug was modeled as a 10-¼ -inch length of 20-inch schedule 60 pipe (SA-312 type 316L stainless steel) welded to a 22-7/8-inch diameter, 5-¾ –inch long 316L stainless steel solid bar.

5.2.2. 24-Inch Canister Spoked-Wheel Basket

The spoked-wheel basket was modeled as an 8-inch Schedule 100 pipe (SA-312 type 316L stainless steel) with five spokes made of ½-inch by just under 7-inch plate (SA-240, type 316L stainless steel). The spokes were assumed to be skip-welded to the pipe at 72-degree intervals. The pipe and spoke overall length was 116-3/4 inches.

The SNF was represented as stiff, solid bars such that the maximum allowable weight for the entire loaded canister (10,000 pounds) was achieved.

5.2.3. 24-Inch Canister Bottom Spacer

The bottom spacer was modeled as a 20-inch schedule 60 pipe (SA-312 type 316L stainless steel) welded to two 1-inch thick end plates, 22-inches in diameter (SA-240, type 316L stainless steel). The assembled unit was 26 inches long.

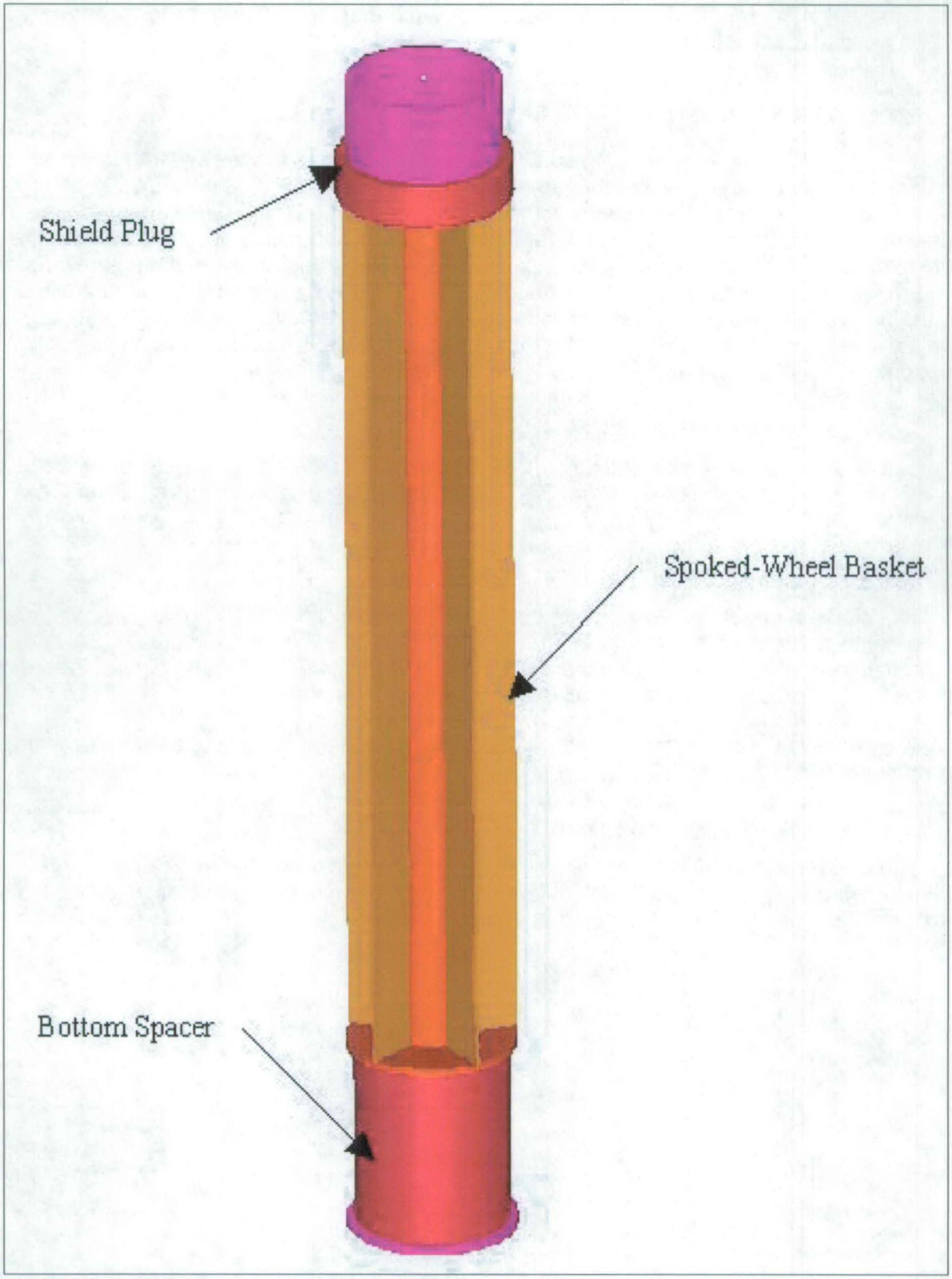


Figure 7. 24-inch standardized canister internal components.

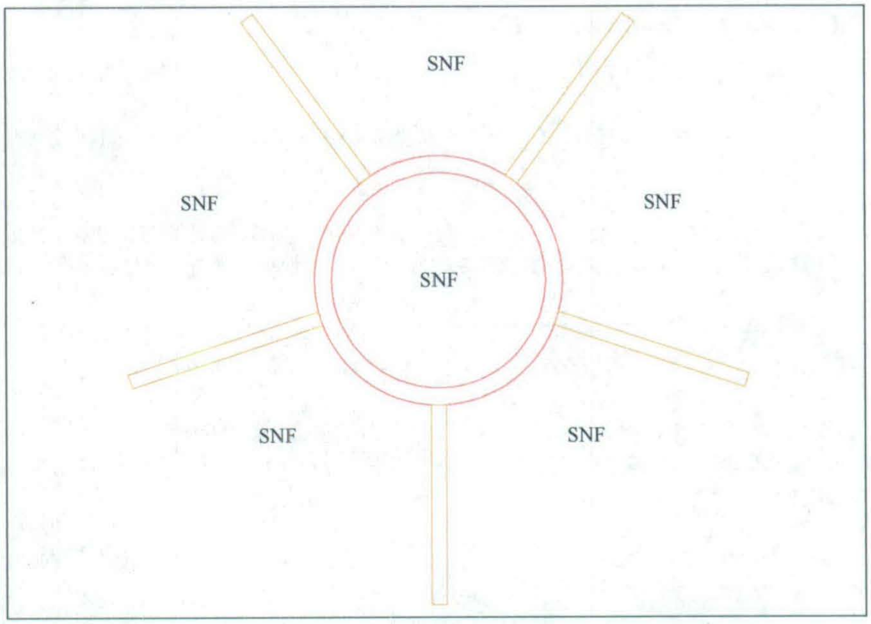


Figure 8. 24-inch standardized canister spoked-wheel cross-section.

5.3. MCO

The internals of the MCO (excluding the SNF baskets) were illustrated in Figures 3 and 4. The MCO internals include the locking ring, shield plug, process tube, basket support bars, guide cone, and five Mark IV fuel baskets and SNF.

5.3.1. MCO Locking Ring

The locking ring (SA-182 type F304N SST), which was about 6-1/2 inches in height, threaded into the collar and held the shield plug in position within the collar (the locking ring also included a ring for lifting the MCO).

5.3.2. MCO Shield Plug

The shield plug was about 16 inches in height, and housed filters, rupture disks, and process valves (SA-182 type F304L and SA-240 type 304L). For the purposes of this evaluation, when the shield plug was referred to, it included the assembly with the guard plate and ring, and the basket stabilizer extension.

5.3.3. MCO Process Tube

The process tube was made of 1-inch Schedule XXS pipe (146-1/2 inches in length), attached to the shield plug, and extended to the shell bottom (SA-312 TP304L SST).

5.3.4. MCO Basket Support Bars and Guide Cone

Six basket support bars were welded to the MCO bottom (SA-240 type 304L SST). A guide cone was attached to the basket support bars to hold the bottom-end of the process tube (SA-479 304L SST).

5.3.5. MCO Mark IV fuel Baskets

The main parts of the Mark IV fuel basket (total of five within the MCO) were as follows:

- The base plate was about 22-1/2 inches in diameter and 1-1/4-inch thick (ASTM A240 304/304L SST),
- The center post was just under 2-7/8-inch in diameter and just under 30-1/2 inches tall (ASTM A511 304/304L or 304 SST) which was threaded into the base plate,
- Six 1-5/16-inch diameter perimeter bars/posts that were just under 22-1/2 inches tall (ASTM A276 304/304L or 304 SST) which were bolted through the base plate,
- Shroud sheet metal wall (0.048 inches thick) that formed a wall 14 inches tall around the basket perimeter (ASTM A240 TP304L SST) which was welded to the base plate,
- An expanded metal spacer 0.186 inches thick (AL 5005-H34 Ryerson) that rested immediately on top of the base plate,
- A 2-1/2-inch thick fuel plate rack with holes to accept each fuel element (ASTM B26 UNS A03560-T6 or A13560-T6).

The Mark IV fuel basket is illustrated in Figure 9.

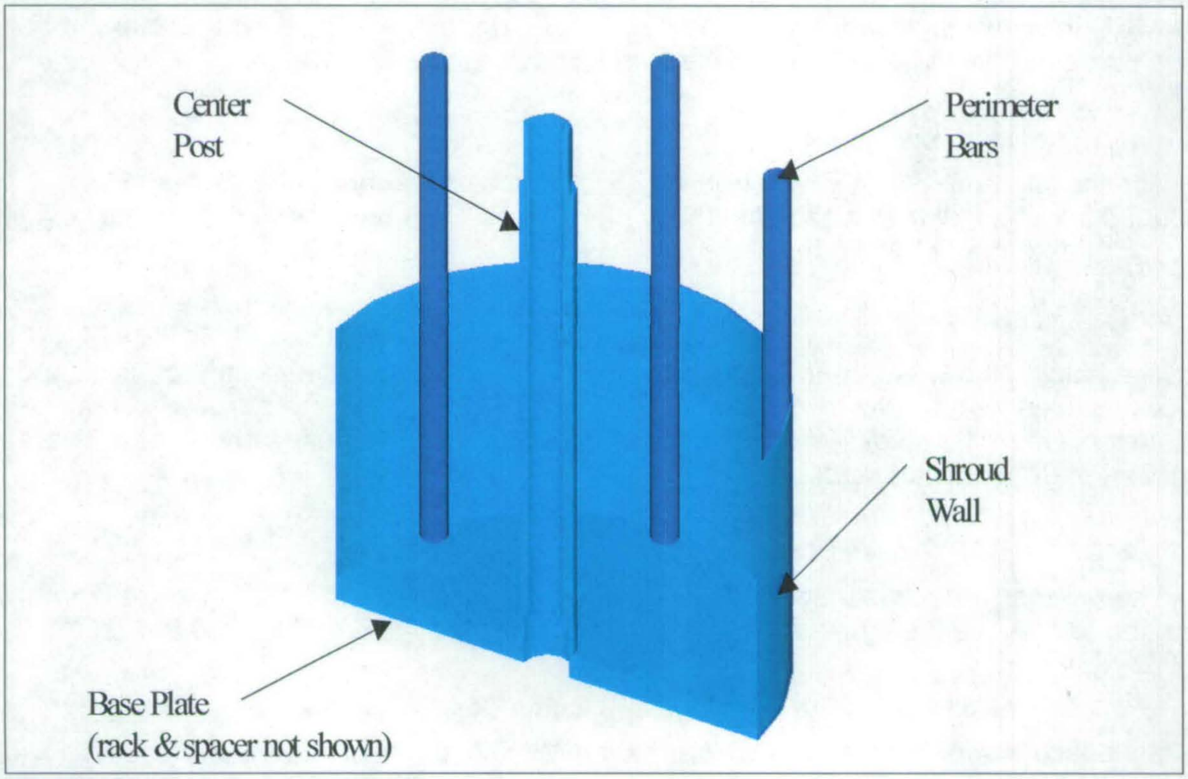


Figure 9. MCO Mark IV fuel basket.

6. DOE SNF CANISTER AND INTERNALS MATERIALS

This section provides additional details regarding the material properties used for the analyses addressed herein. Both the 18-inch and 24-inch standardized DOE SNF canisters are to be evaluated for the repository 23-foot drop response reflecting a maximum canister/internal temperature of 300°F (maximum temperature while being handled) while the MCO is to reflect a maximum canister/internal temperature of 240°F (the specified Design Temperature).

6.1. 18-Inch Standardized DOE SNF Canister Material Properties

6.1.1. Canister Materials

The 18-inch standardized DOE SNF canisters will use 316L stainless steel for all skirts, lifting rings, heads, main shell, and impact plate retaining rings. Table 2 shows the associated ASME B&PV Code material properties [References 19 (elongation) and 7 (material strengths)] for these items.

Table 2. 18-inch standardized DOE SNF canister material properties.

Component	Material	Elongation[1] At Room Temperature (%)	Engineering Yield Strength At 300°F (ksi)	Engineering Ultimate Strength At 300°F (ksi)
Main shell (body) and skirts	SA-312 TP316L pipe	35 / 25[2]	19.0	64.0
Heads, lifting rings, and retaining rings	SA-240 316L plate	40	19.0	64.0

1. This is the minimum value from the material specification.
2. Longitudinal / Transverse.

The analytical models discussed in this report required material true stress-strain curves, not engineering stress-strain curves. The Table 2 data only included engineering yield strength, ultimate strength, and elongation values. True stress-strain curves were developed for canister materials using this information as discussed below.

In order to obtain true stress-strain curves for the 18-inch standardized DOE SNF canister, the ASME B&PV Code yield and ultimate tensile strength values were used in conjunction with tensile testing performed at the Idaho National Laboratory. Specific details of how the true stress-strain curve was developed for 316L material at 300°F are presented on pages D-14 through D-19 of Reference 15. Summarizing the major steps, an engineering stress-strain curve was obtained from actual 316L material testing at 300°F. Next, this engineering curve was adjusted twice to reflect the ASME Code minimum yield strength and the minimum ultimate strength. Then, a new composite curve was developed, consisting of the first part of the minimum yield strength curve and the last part of the minimum ultimate strength curve, with a transition being made between the two curves between the yield and ultimate strength values. Finally, a true stress-strain curve was developed from the composite engineering stress-strain curve. Figure 10 illustrates the final 316L true stress-strain curve generated.

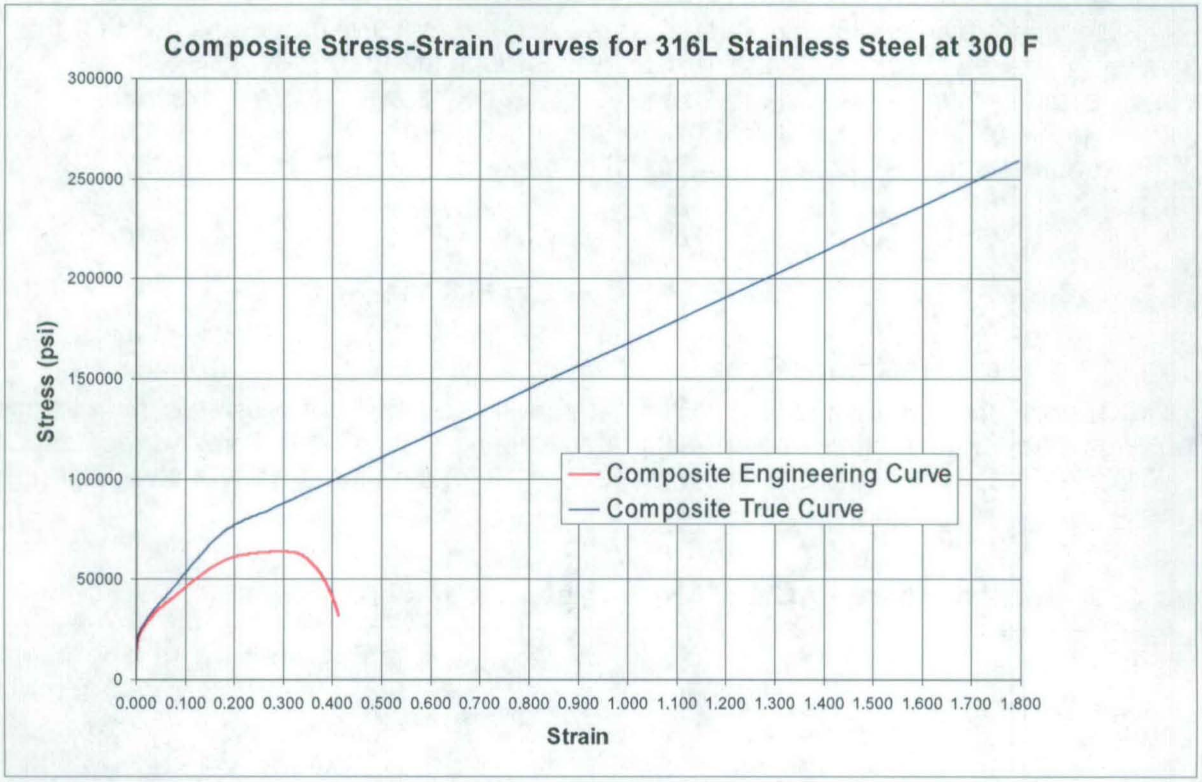


Figure 10. Composite quasi-static stress-strain curves for 316L stainless steel at 300°F.

Table 3 lists the composite quasi-static true stress-strain curve data at 300°F for Figure 10.

Table 3. Composite quasi-static true stress-strain curve data at 300°F for 316L.

True Stress (psi)	True Plastic Strain	True Stress (psi)	True Plastic Strain
0	0	51040	0.090
19055	0.002	57500	0.114
25120	0.010	63710	0.136
29253	0.020	73900	0.178
32694	0.030	77000	0.200
35903	0.040	82600	0.250
38828	0.050	83680	0.265
41573	0.060	258881	1.795
44116	0.070		

During the drop scenario, some canister components will be loaded in a dynamic manner, causing significant material straining at an elevated strain rate. Stainless steel material under elevated strain rates exhibits an increase in strength, known as dynamic strengthening. The 1999 drop test evaluations (Reference 3) accounted for that material strengthening in the canister materials by increasing the true stress of the quasi-static true stress-strain curve by 20%. Since the resulting deformations were accurately predicted, that same 1.2 increase factor will be used herein. Hence, the final step of generating the true stress-strain curve for the canister material input data was to include a 1.20 factor on the stress at a given strain to account for dynamic strengthening.

Approximately ten welds (not including seal welds) exist on the canister. Those welds are assumed to have the same properties as the base material.

6.1.2. Internal Component Materials

All internal components (i.e., internal impact plates, Type 1a rectangular grid baskets, and shield plug), excluding the SNF, in the 18-inch standardized DOE SNF canister have their ASME B&PV Code or ASTM material properties listed in Table 4. SNF was assigned a mass density property in order to achieve the design weight.

Table 4. 18-inch canister internals (ASME Code) minimum material properties.

Component	Material	Elongation[1] At Room Temperature (%)	Engineering Yield Strength[3] At 300°F (ksi)	Engineering Ultimate Strength[3] At 300°F (ksi)
Internal impact plates	SA-240 316L plate	40	19.0	64.0
	SA-351, CF3M casting	30	23.3	68.0
Type 1a Basket				
Grid plates	ASTM B-932-04 plate	20[2]	38.2[2]	100.0[2]
Base plate	SA-240 316L plate	40	19.0	64.0
Sleeve	SA-240 316L plate	40	19.0	64.0
Shield plug	SA-479 316L bar	30	19.0	64.0
	SA-351, CF3M casting	30	23.3	68.0

1. Minimum value from Reference 19 except as shown.
2. Detailed in Table 5.
3. Value listed in Reference 7 except as shown.

The 316/316L stainless steel internal components were not expected to absorb much energy in deformation during the drop events, especially the internal impact plates and the shield plug. Therefore, no dynamic increase in material strength was employed. The material true stress-strain curve identified for the canister in Figure 10 was also applicable for these stainless steel internals. (Due to the designs of the impact plates and the shield plug, equivalent canister results were expected regardless of whether minimum properties for 316L or the optional SA-351 CF3M were used.)

Welds on internal components were merely modeled using common nodes between subcomponents (to be discussed in the modeling section). Specific weld material properties were not used. (Only the overall response of the internal components was required for this evaluation – detailed component and weld deformations and strains were not of interest.)

The rectangular grids of the Type 1a basket are to be constructed using a nickel-chromium-molybdenum-gadolinium alloy (ASTM B 932-04, Reference 18). The ASME B&PV Code has permitted limited use of this material (ASME Code Case N-728, Reference 20) for "nonpressure retaining spent fuel containment internals" (not welded). Table 5 lists selected properties for this Ni-Gd material.

Table 5. Minimum specified properties for Ni-Gd.

Property	Property at Temperature (°F)				
	100	200	300	400	600
Yield Strength (x 10^3 psi)	45.0[1,2]	40.7[2]	38.2[2]	36.3[2]	33.9[2]
Ultimate Strength (x 10^3 psi)	100.0[1,2]	100.0[2]	100.0[2]	100.0[2]	100.0[2]
Modulus of Elasticity (x 10^6 psi)	(29.6[3])	29.1[4]	28.5[4]	28.0[4]	26.9[4]
Elongation (%)	20[1]	24[5]	25[5]	25[5]	28[5]

1. Reference 18 data.
2. Reference 7 data.
3. Reference 20 does not have this data at 100 °F but a value (29.8x10^6 psi) was given at 70 °F. The 100 °F value in the table was linearly interpolated between the 70 and 200 °F values.
4. Reference 20 data.
5. Reference 21, Table 5, minimum measured value at a given temperature.

Simple bi-linear engineering stress-strain curves were developed using the above tabulated modulus of elasticity, yield strength, ultimate strength, and elongation value at a given temperature. For the purposes of creating stress-strain curves, the ultimate strain was assumed to be equal to the elongation (i.e., this assumed that insignificant necking occurred). Figure 11 shows the resulting bi-linear engineering stress-strain curve 300 °F.

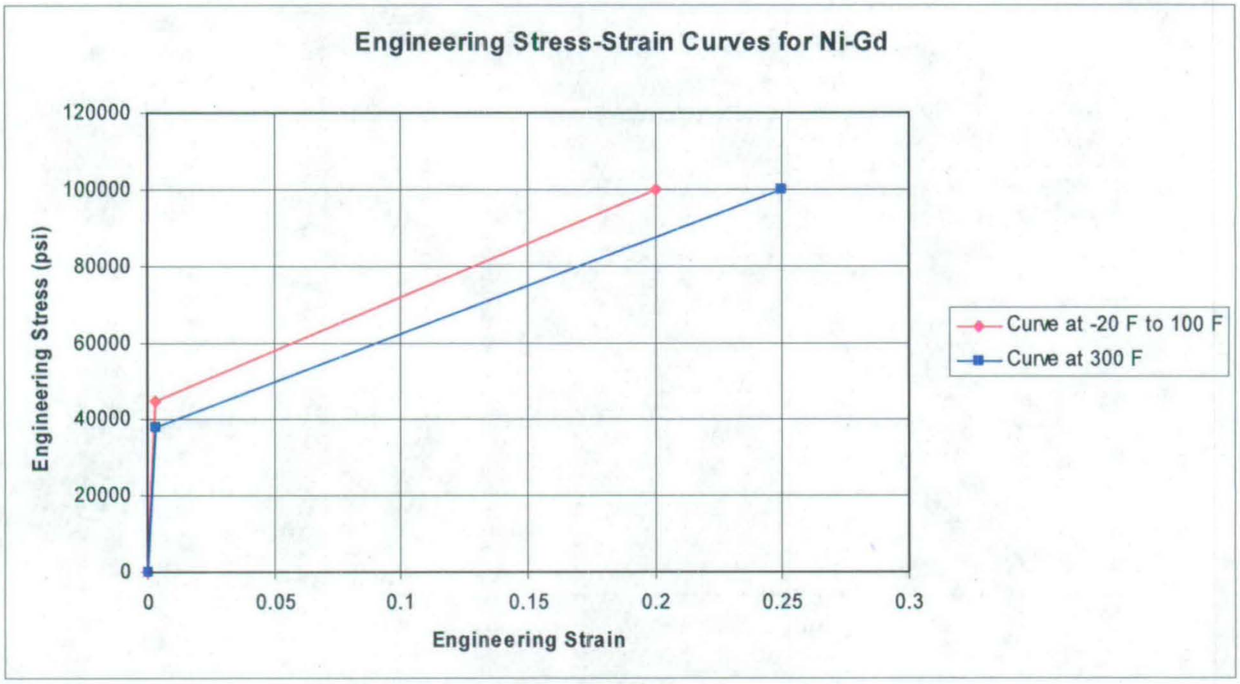


Figure 11. Ni-Gd bi-linear engineering stress-strain curve at 300°F.

The analytical evaluations performed herein required true stress-strain curves. Table 6 shows the conversion of the engineering stress-strain curve data to true stress-strain values. Figure 12 shows the resulting true stress-strain curve at 300 °F, which will be used in the analytical evaluation.

No dynamic strengthening of the Ni-Gd material was employed herein because: 1) no data was available on the dynamic properties of this material, and 2) the straining and associated strain rates occurring in the basket grid plates where this material is to be employed were expected to be relatively small. Dynamic strengthening under such conditions was considered negligible.

Table 6. Engineering-to-true stress-strain conversion for Ni-Gd.

Temperature (°F)	Engineering Stress (psi)	Engineering Strain	True Stress (psi)[2]	True Strain[3]
300	38200 (yield)	0.0033[1]	38326	0.002
	100000 (ultimate)	0.25	125000	0.219

1. Engineering strain at yield = yield strength / modulus of elasticity + 0.002 (offset)
2. True stress = engineering stress x (1 + engineering strain)
3. True strain = ln (1 + engineering strain) – true stress / modulus of elasticity

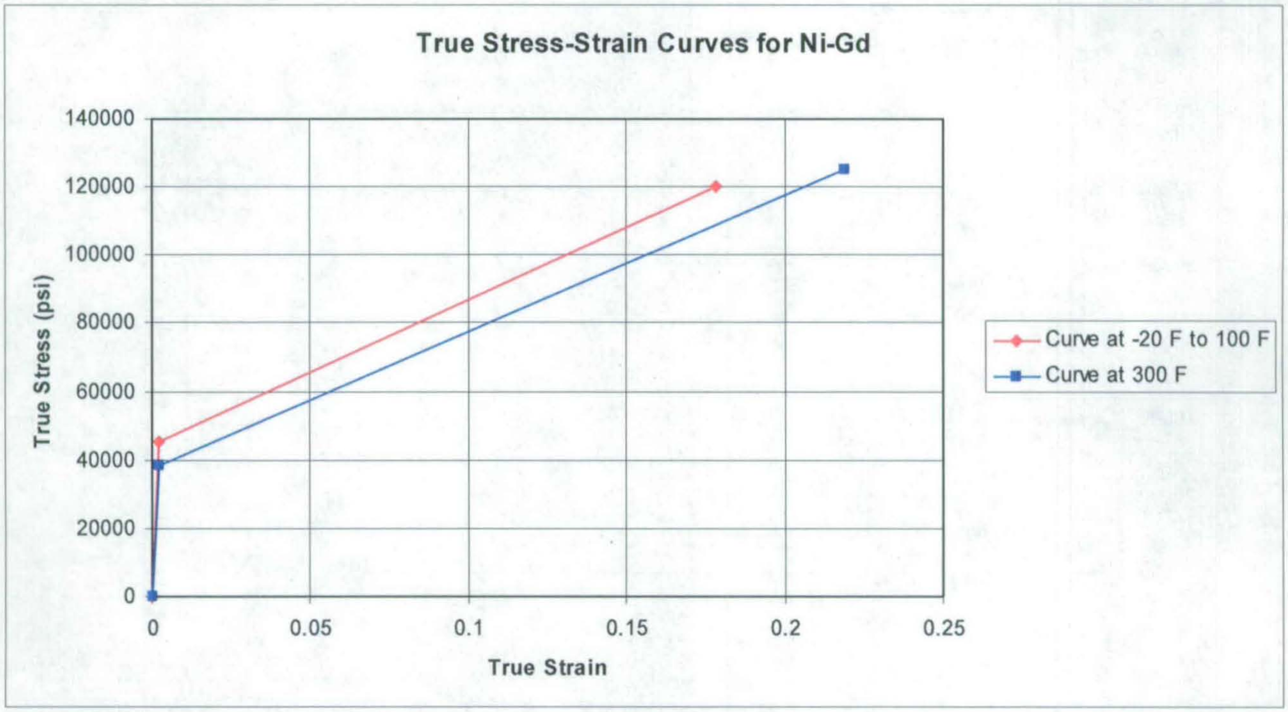


Figure 12. Ni-Gd bi-linear true stress-strain curve at 300°F

6.2. 24-Inch Standardized DOE SNF Canister Material Properties

6.2.1. Canister Materials

Like the 18-inch canisters, the 24-inch standardized DOE SNF canisters will use 316L stainless steel for all skirts, lifting rings, heads, main shell, and impact plate retaining rings. Hence, the material properties shown in Table 2 are also applicable to the 24-inch standardized DOE SNF canister. Therefore, Figure 10 will be the material definition used for the 316L stainless steel materials at 300°F and with the 1.2 strain rate factor imposed. The 24-inch canister welds are also assumed to have the same properties as the base material.

6.2.2. Internal Component Materials

All internal components (i.e., internal impact plates, bottom spacer, spoked-wheel, and shield plug), excluding the SNF, in the 24-inch standardized DOE SNF canister have their ASME B&PV Code material properties listed in Table 7. SNF was assigned a mass density property in order to achieve the design weight.

The 316/316L stainless steel internal components were not expected to absorb much energy in deformation during the drop events, especially the internal impact plates, the bottom spacer, and the shield plug. Therefore, no dynamic increase in material strength was employed. The material true stress-strain curve identified for the canister in Figure 10 was also applicable for these stainless steel internals. (Due to the designs of the impact plates and the shield plug, equivalent canister results were expected regardless of whether minimum properties for 316L or the optional SA-351 CF3M were used.)

Table 7. 24-inch canister internals (ASME Code) minimum material properties.

Component	Material	Elongation[1] At Room Temperature (%)	Engineering Yield Strength At 300°F (ksi)	Engineering Ultimate Strength At 300°F (ksi)
Internal impact plates	SA-240 316L plate	40	19.0	64.0
	SA-351, CF3M casting	30	23.3	68.0
Bottom Spacer	SA-312 TP316L pipe	35 / 25[2]	19.0	64.0
	SA-240 316L plate	40	19.0	64.0
Spoked-Wheel	SA-312 TP316L pipe	35 / 25[2]	19.0	64.0
	SA-240 316L plate	40	19.0	64.0
Shield Plug	SA-312 TP316L pipe	35 / 25[2]	19.0	64.0
	SA-479 316L bar	30	19.0	64.0
	SA-351, CF3M casting	30	23.3	68.0

1. Minimum value from Reference 19.
2. Longitudinal / Transverse.

Welds on internal components were merely modeled using common nodes between sub-components (to be discussed in the modeling section). Specific weld material properties were not used. (Only the overall response of the internal components was required for this evaluation – detailed component and weld deformations and strains were not of interest.)

6.3. MCO Material Properties

6.3.1. Canister Materials

The MCO is constructed from 304/304L stainless steel and has an ASME B&PV Code Design Temperature of 240°F. Since this analytical evaluation is at a temperature higher than room temperature, the assumption will be made herein that 304L material properties will govern. Table 8 shows the associated ASME B&PV Code minimum material properties.

Table 8. MCO (ASME Code) minimum material properties.

Component	Material	Elongation[1] At Room Temperature (%)	Engineering Yield Strength[3] At 240°F (ksi)	Engineering Ultimate Strength[3] At 240°F (ksi)
Main shell	SA-312 TP304L pipe	35 / 25[2]	20.44	64.14
Cover, collar, and bottom	SA-182 F304L forging	30	20.44	64.14

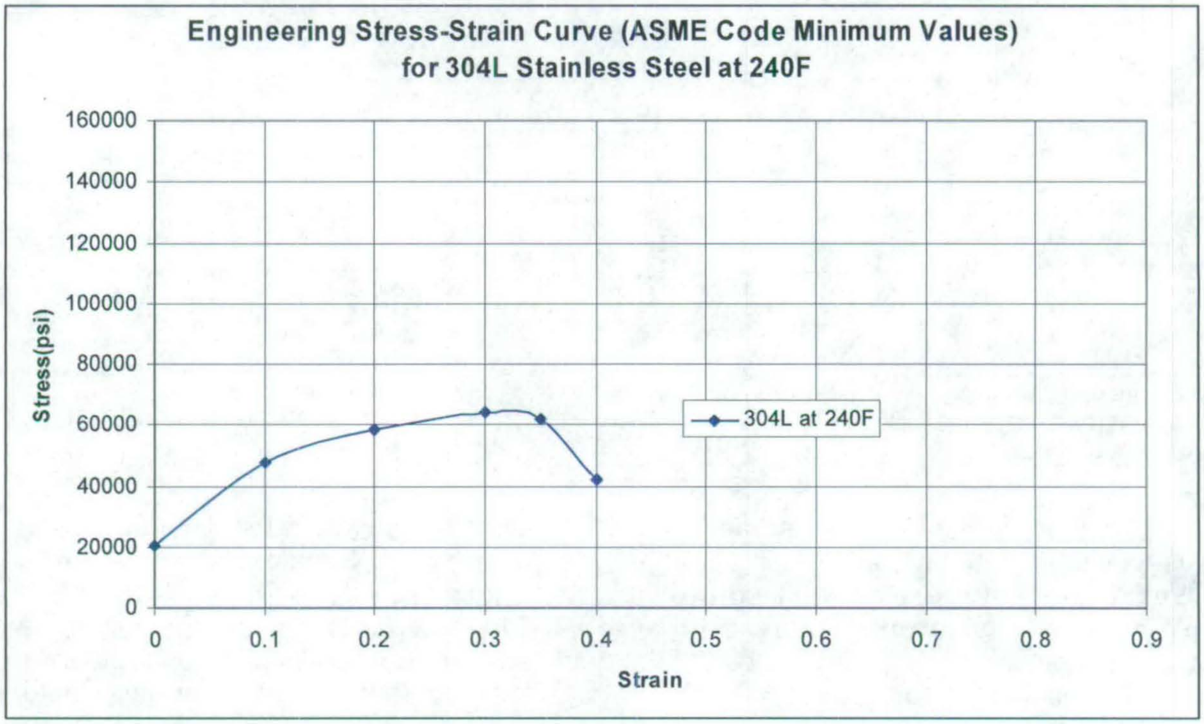
1. Minimum value from Reference 19.
2. Longitudinal / Transverse.
3. Minimum value interpolated from Reference 7.

The analytical models discussed in this report required material true stress-strain curves, not engineering stress-strain curves. The Table 8 data only included engineering yield strength, ultimate strength, and elongation values. True stress-strain curves were developed for canister materials using this information as discussed below.

In order to obtain true stress-strain curves for the MCO (not just simple bi-linear curves, but curves with a contour between the yield and ultimate strengths), the ASME B&PV Code yield and ultimate tensile strength values were used in conjunction with tensile testing performed at the Idaho National Laboratory. Specific details of how the true stress-strain curves were developed for 304L material at -20°F, 70 °F, 300 °F, and 600 °F are presented in an ASME Pressure Vessel and Piping Conference paper (Reference 22).

The conference paper recommended a process for obtaining an engineering stress-strain curve at a given temperature, based on ASME Code minimum yield and ultimate strengths. That process was as follows, using a temperature of 240 °F. First, the engineering stress-strain curve would be obtained from actual 304L material testing at 300°F (300 °F being the closest curve to the desired 240 °F). Next, this engineering curve would be adjusted twice to reflect the ASME Code minimum yield strength and the minimum ultimate strength at the new temperature of 240°F. Then, a new composite curve would be developed, consisting of the first part of the minimum yield strength curve and the last part of the minimum ultimate strength curve, with a transition being made between the two curves between the yield and ultimate strength values. Finally, a true stress-strain curve would be developed from the composite engineering stress-strain curve.

However, in this case it was noted that the 600 °F 304L engineering curve from the conference paper (Figure 4) was a good match for a 20.44 ksi yield strength and 64.14 ksi ultimate strength material (i.e., the interpolated ASME Code minimums for 304L at 240°F). Therefore, the shape of the 600 °F curve was simply used for this 304L material at 240 °F for the MCO. Figure 13 shows the resulting engineering and true stress-strain curves (quasi-static, using the same scale as in Reference 22) and Table 9 gives the defining point data.



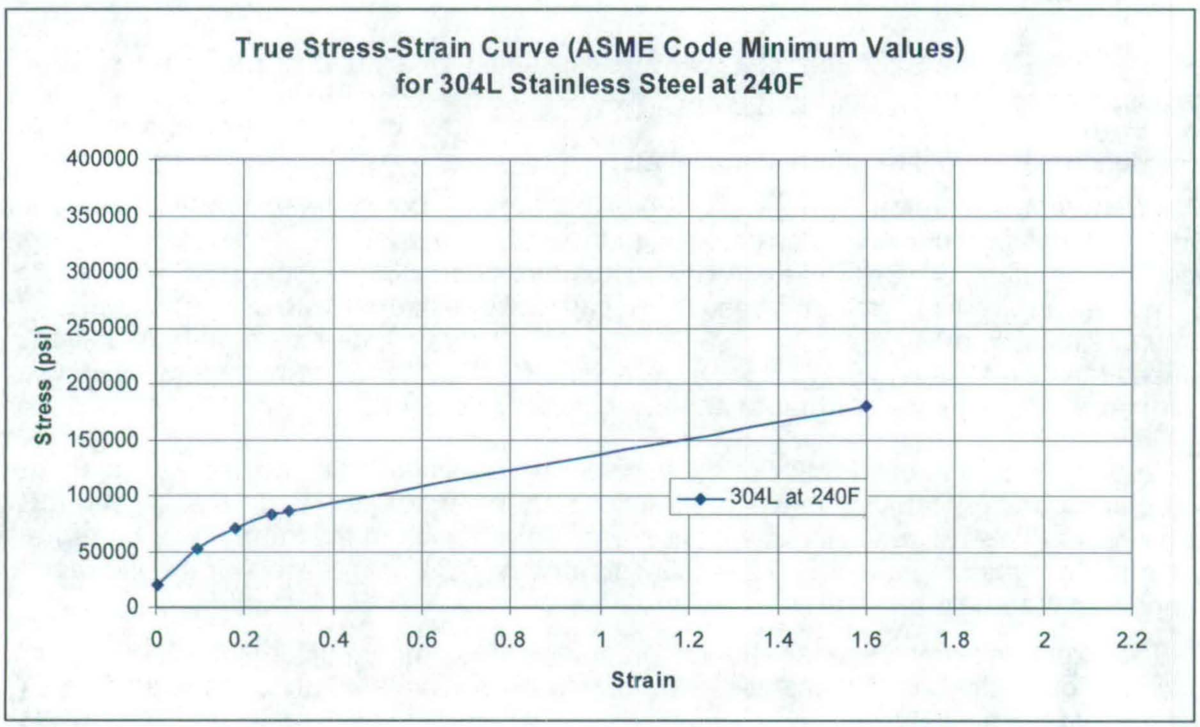


Figure 13. Quasi-static stress-strain curves for 304L stainless steel at 240°F.

Table 9. Quasi-static stress-strain curve data for 304L stainless steel at 240 °F.

Temperature (°F)	Engineering Stress (psi)	Engineering Strain	True Stress (psi)[2]	True Strain[3]
240	20440 (yield)	0.0027[1]	20500	0.002
	47500	0.1	52250	0.093
	58500	0.2	70200	0.18
	64140 (ultimate)	0.3	83382	0.26
	62000	0.35	86541	0.3
	42000	0.4	180000	1.60

1. Engineering strain at yield = yield strength / modulus of elasticity + 0.002 (offset)
2. True stress = engineering stress x (1 + engineering strain)
3. True strain = ln (1 + engineering strain) – true stress / modulus of elasticity

During the drop evaluation, some MCO components will be loaded in a dynamic manner, causing significant material straining at an elevated strain rate. Stainless steel material under elevated strain rates exhibits an increase in strength, known as dynamic strengthening. The 2004 drop test evaluations (Reference 4) accounted for that material strengthening in the MCO materials by increasing the true stress of the quasi-static true stress-strain curve by 20%. Since the resulting deformations were accurately predicted, that same 1.2 increase factor will be used herein.

The welds that exist on the MCO canister (including the longitudinal weld on the pipe body) are assumed to have the same properties as the base material.

6.3.2. Internal Component Materials

All internal components [i.e., Mark IV baskets (but excluding the expanded metal spacer and the fuel plate rack), shield plug, locking ring, basket support bars, guide cone, and process tube, but excluding the SNF] in the MCO have their ASME B&PV Code or ASTM (Reference 23) material properties listed in Table 10. Because these internal component materials are the same or similar to those used for the MCO itself, the ASME Code minimum-based stress-strain curves identified for the MCO (Table 9) were used for the internal components. SNF was assigned a mass density in order to achieve the design weight.

Due to the design of the MCO, the drop energy associated with the internal components will be absorbed primarily by those internal components during the vertical and near-vertical drop events. This will result in significant plastic deformation of the internals. Therefore, the dynamic strengthening factor of 1.2 discussed for the MCO will be used for the internal component materials.

The expanded metal spacer and fuel plate rack are components in a Mark IV fuel basket but were not included in this analysis effort due to their minimal effect on the structural response of the basket.

Welds on internal components were merely modeled using common nodes between subcomponents (to be discussed in the modeling section). Specific weld material properties were not used – weld material was assumed to respond to the loadings similar to base metal. (Only the overall response of the internal components was required for this evaluation – detailed component and weld deformations and strains were not of particular interest.)

Table 10. MCO internals material properties.

Component	Material	Elongation[1] At Room Temperature (%)	Engineering Yield Strength[3] At 240°F (ksi)	Engineering Ultimate Strength[3] At 240°F (ksi)
Locking ring	SA-182 F304N forging	30	27.08	78.44
Shield plug	SA-182 F304L forging	30	20.44	64.14
	SA-240 304L plate	40	20.44	64.14
Process tube	SA-312 TP304L pipe	35 / 25[2]	20.44	64.14
Mark IV basket				
Center post	ASTM A-511 304/304L or 304 tube	35	20.44[4]	64.14[4]
Base plate	ASTM A-240 304/304L plate	40	20.44[4]	64.14[4]
Perimeter bars	ASTM A-276 304/304L or 304 bar	30	20.44[4]	64.14[4]
Shroud wall	ASTM A-240 304L plate	40	20.44[4]	64.14[4]
Basket support bars	SA-240 304L	40	20.44	64.14
Guide cone	SA-479 304L bar	30	20.44	64.14

1. Data from Reference 19 (for SA- materials) and Reference 23 (for ASTM materials).
2. Longitudinal / Transverse.
3. Data from Reference 19 (for SA- materials) and Reference 23 (for ASTM materials)
4. Although not ASME material, value used due to similarity to SA-240.

6.4. Other Material Properties

Other relevant material properties employed in the analytical evaluations included:

Modulus of Elasticity (E) = 27.3×10^6 psi for the 304L stainless steel components at 240°F,
27.0×10^6 psi for the 316L stainless steel components at 300°F.
(Reference 7)

Poisson's Ratio (μ) = 0.29 for 304L and 316L at 70 °F (Reference 7).

7. COMPUTER PROGRAM VERIFICATION AND CONFIGURATION MANAGEMENT

7.1. Modeling Software

The I-DEAS computer program was used to create the finite element models for the three DOE SNF canisters. I-DEAS Version 11 NX Series m2 (Reference 24) was used to generate the 18-inch standardized DOE SNF canister model, I-DEAS 10 NX Series (Reference 25) was used to create the finite element model for the 24-inch standardized DOE SNF canister and I-DEAS Master Series Version 9 m2 (Reference 26) was used to create the MCO model. A solid model of each canister was created and then used to generate the finite element model. Because the I-DEAS software was used for modeling purposes only, no onsite validation and verification of this software was required. The accuracy of the models generated in I-DEAS was checked in the calculation software discussed in the next subsection.

7.2. Calculation Software

The computer program ABAQUS/Explicit Version 6.6-3, a nonlinear FE analysis software package (Reference 27) that is widely used in many industries, was employed to calculate the response of the three DOE SNF canisters to the 23-foot repository drop event. Extensive onsite validation and verification (References 28 and 29) have been performed by the NSNFP on this software, approving it for drop evaluations. This rigorous checking process eliminated the need to control or validate I-DEAS, the solid modeling software. Models were run on INL compute server "Aurora" as approved by the Reference 28 validation report.

8. ANALYTICAL MODELING OF DOE SNF CANISTERS

The element sizes for the DOE SNF canister models were chosen based on the type of event being simulated and the expected response. Because large plastic deformations were expected, the element sizes could not be too small or they would distort excessively (causing the calculation to terminate) before the event was completed. Small element size would also require many elements, resulting in excessive solution times. At the other extreme, elements that were too large would not respond properly (e.g., a bulge in a component would be shown as a sharp edge instead of a smooth curve) and the results would be in question. This was particularly important in areas where significant deformations would occur. Additionally, large elements in areas of high deformation required excessive artificial energy (model energy required to maintain solution stability). Some iteration in preliminary modeling was performed to arrive at elements sufficiently small to provide acceptable results.

8.1. 18-inch Standardized DOE SNF Canister Model Mesh Details

8.1.1. Symmetry

Plane symmetry was employed in this 18-inch diameter standardized canister model. Justification for plane symmetry is detailed in Reference 15.

8.1.2. Model Mesh Details

The 18-inch standardized DOE SNF canister model included the canister as well as the internal impact plates, baskets, simulated SNF, and the shield plug. Figure 14 shows the FE model of the standardized canister with simulated SNF and baskets. The part meshes were as follows:

Skirts: The lower and upper skirts each used 1728 shell elements (ABAQUS element type S4R), sized at about 1/4-inch x 9/16-inch (longitudinal x circumferential dimension), and placed at the skirt midplane. This mesh size was shown to accurately represent the skirt deformations of the 1999 canister drop testing effort (Reference 3). The bottom edge of the skirt just past the lifting ring was adjusted radially inward at 1/8-inch to match the actual canister skirt geometry after welding. The skirt mesh is shown in Figure 15.

Lower Head: The lower head used 2016 shell elements (ABAQUS element type S4R) to represent the head and the integral straight flange. Elements were sized at about 1/4-inch x 9/16-inch (longitudinal x circumferential) in the straight flange, and from about 3/16-inch x 3/16-inch (center of head) to about 1/4-inch x 9/16-inch (knuckle region) in the dished portion of the head. These shell elements were placed at the midplane of the head. The lower head mesh is also shown in Figure 15.

Top Head: The top canister head included a flanged access port. A total of 2064 shell elements (ABAQUS type S4R) were employed to represent this head and the integral straight flange. Elements were sized at about 1/4-inch x 9/16-inch (longitudinal x circumferential) in the straight flange, and from about 3/16-inch x 3/16-inch (center of head) to about 1/4-inch x 9/16-inch (knuckle region) in the dished portion of the head. These shell elements were placed at the midplane of the head. The top head mesh is shown in Figure 16.

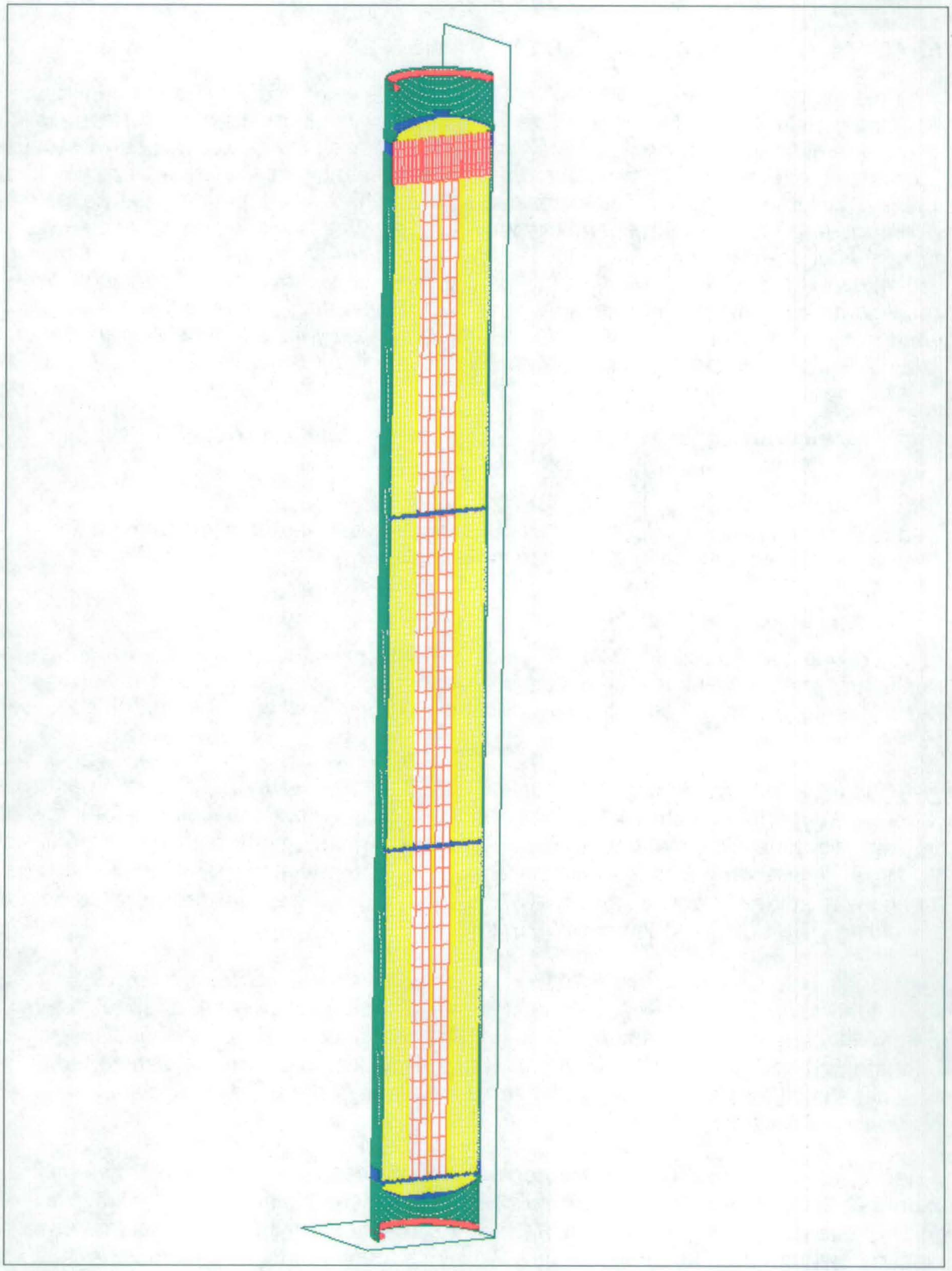


Figure 14. FE model of 18-inch standardized canister with SNF and three Type 1a baskets.

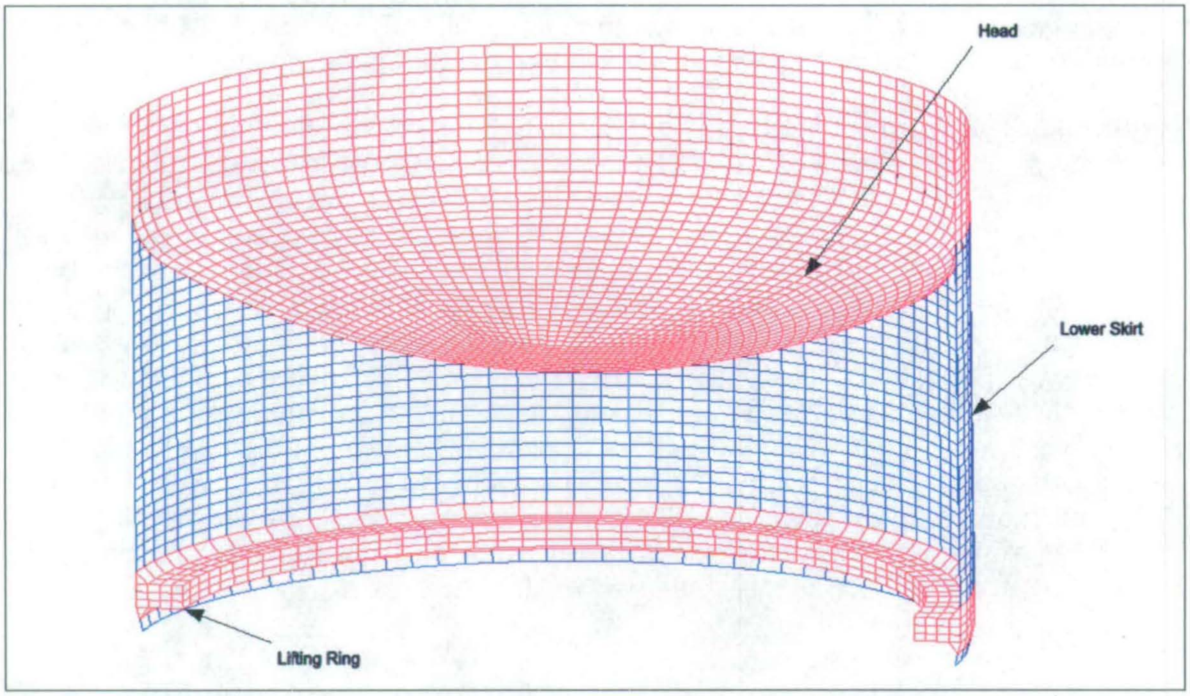


Figure 15. 18-inch standardized canister lower head, skirt, and lifting ring FE mesh.

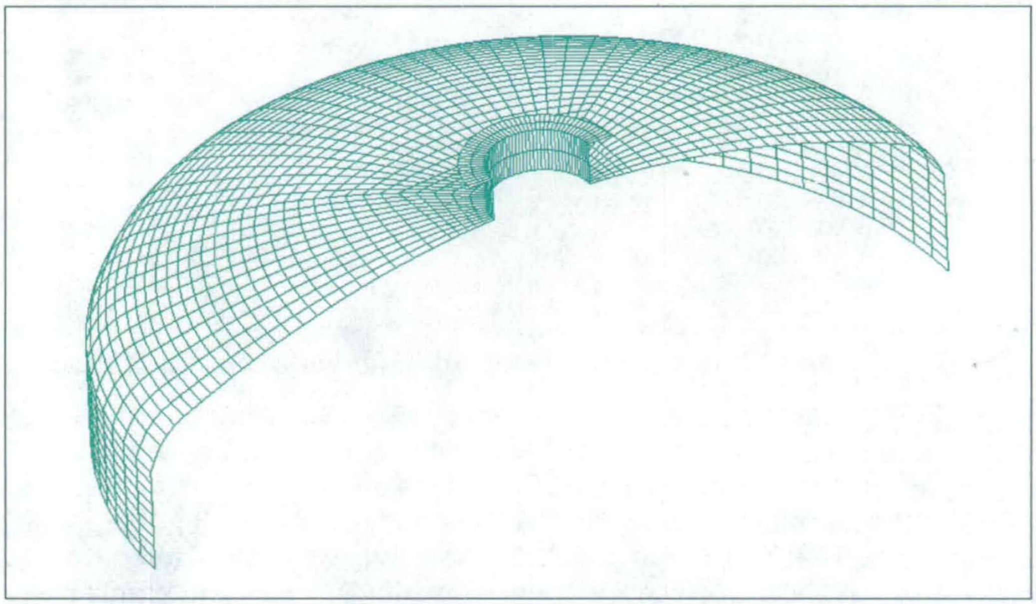


Figure 16. 18-inch standardized canister top head with flanged access port FE mesh.

Lifting Rings and Attaching Welds: The lifting rings and attaching welds (full-penetration groove welds) used the same circumferential spacing as the skirts. The mesh used 4 solid brick elements (ABAQUS element type C3D8R) through the radial width and 3 brick elements through the thickness, with wedge elements (ABAQUS element type C3D6) to represent the remaining cap on the groove welds. A total of 672 elements were used to represent each lifting ring and attachment weld. The weld was connected to the skirt using common nodes. The lifting ring and attachment weld mesh are also shown in Figure 15. Solid elements were used instead of shell elements on the lifting rings to more accurately represent their behavior during these drop events, as prescribed and justified in the 1999 drop testing evaluations.

Skirt-to-Head Weld: The skirt-to-head weld consisted of a full penetration groove weld between the skirt and knuckle area of the head. If the modeling of the skirt and head used continuum (solid) elements, then the exact geometry of this weld could be precisely represented using solid elements as well. However, because the skirt and head were both modeled using shell elements (discussed previously), the shells being placed at the part midplanes, the geometry of this weld could not be exactly duplicated. An exact duplication of the weld was not required, only the weld stiffness and the correct transfer of load from the skirt to the head were necessary. Therefore, this weld was simulated with a combination of: 1) placing shell elements to extend from the end of the skirt to the intersection with the head shell elements, and 2) constraining all of the degrees of freedom of these 'weld' element nodes to the adjacent head nodes using ABAQUS multipoint constraints (ABAQUS option MPC BEAM). This method of simulating this weld was employed in the 1999 drop testing and associated evaluations discussed previously (Reference 3). Figure 17 shows a close-up of the skirt and head at the location of this simulated weld.

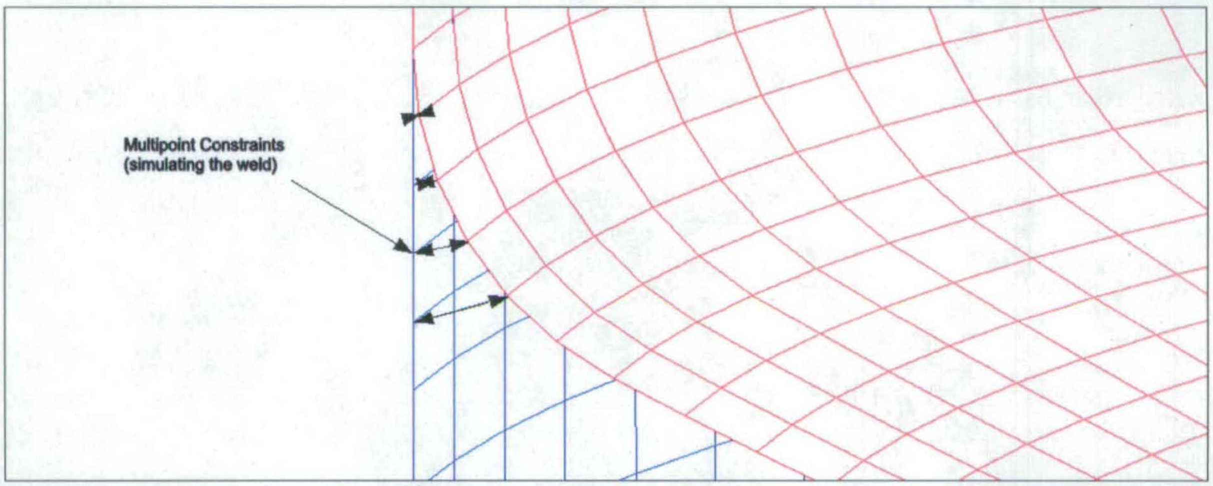


Figure 17. 18-inch standardized canister skirt-to-head weld representation.

Canister Main Shell: The deformations in the standardized canister main shell, under the 3 degrees off-vertical drop event specified for this evaluation, were expected to be small – possibly consisting of some bending and gentle bulges due to internal part impacts. (This was consistent with the results of the 1999 drop testing effort, Reference 3.) Therefore, element sizes that were somewhat larger than the skirts and heads were considered justified. The element size began at about 1/2-inch x 9/16-inch (longitudinal x circumferential) at the main shell ends (first 21 inches of shell) adjacent to the head straight flanges, and then grew to about 3/4-inch x 9/16-inch for the remainder of the main shell. A total of 11424 shell elements (ABAQUS element type S4R) were employed. Figures 18 and 19 show the main shell FE mesh.

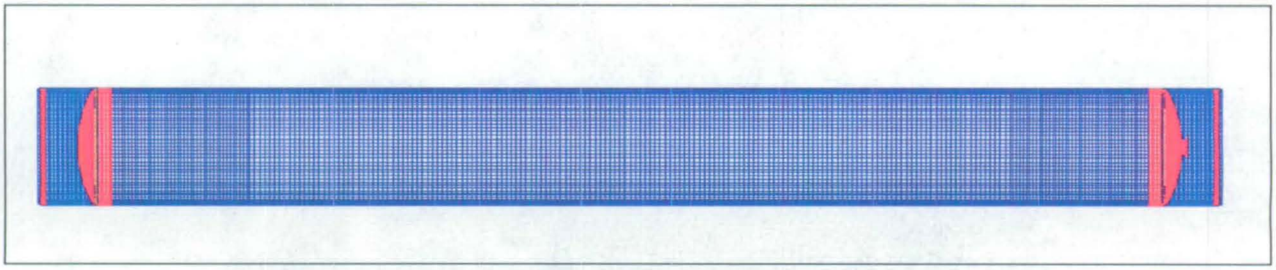


Figure 18. 18-inch standardized canister main shell FE mesh.

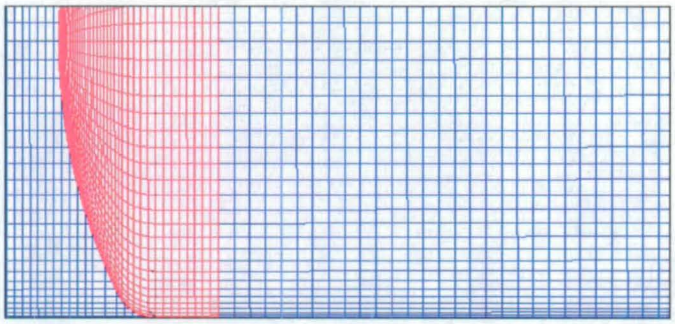


Figure 19. 18-inch standardized canister main shell FE mesh – close-up at head.

Head-to-Main Shell Weld: The full penetration circumferential weld that attached each head to the main shell was represented by the last row of elements on the head straight flange and the first row of elements on the canister main shell. These elements were joined using common nodes.

Internal Impact Plates: The top and bottom internal impact plates have a notched edge to allow for placement of the retaining ring. A total of 4048 brick elements (ABAQUS type C3D8R) represented each impact plate, with 5 elements through the thickness. This mesh size will adequately transfer any internals loadings from a drop event to the head. The impact plate mesh is shown in Figure 20, installed in the end assembly. A single impact plate FE model is illustrated in Figure 21. The impact plate was held in place with a retaining ring. This is shown in Figure 22. A total of 192 shell elements (ABAQUS type S4R) simulated the retaining ring and attaching weld. The weld was represented by the last row of shells, attached to the head using common nodes.

Simulated SNF: The exact condition of the simulated SNF was not of interest in this evaluation, only its effects on the baskets and canister. Therefore, the SNF was simulated in the standardized canister FE model with a coarse mesh, specifically with 68 brick elements (ABAQUS element type C3D8R) per fuel element. The SNF FE mesh is shown in Figure 23.

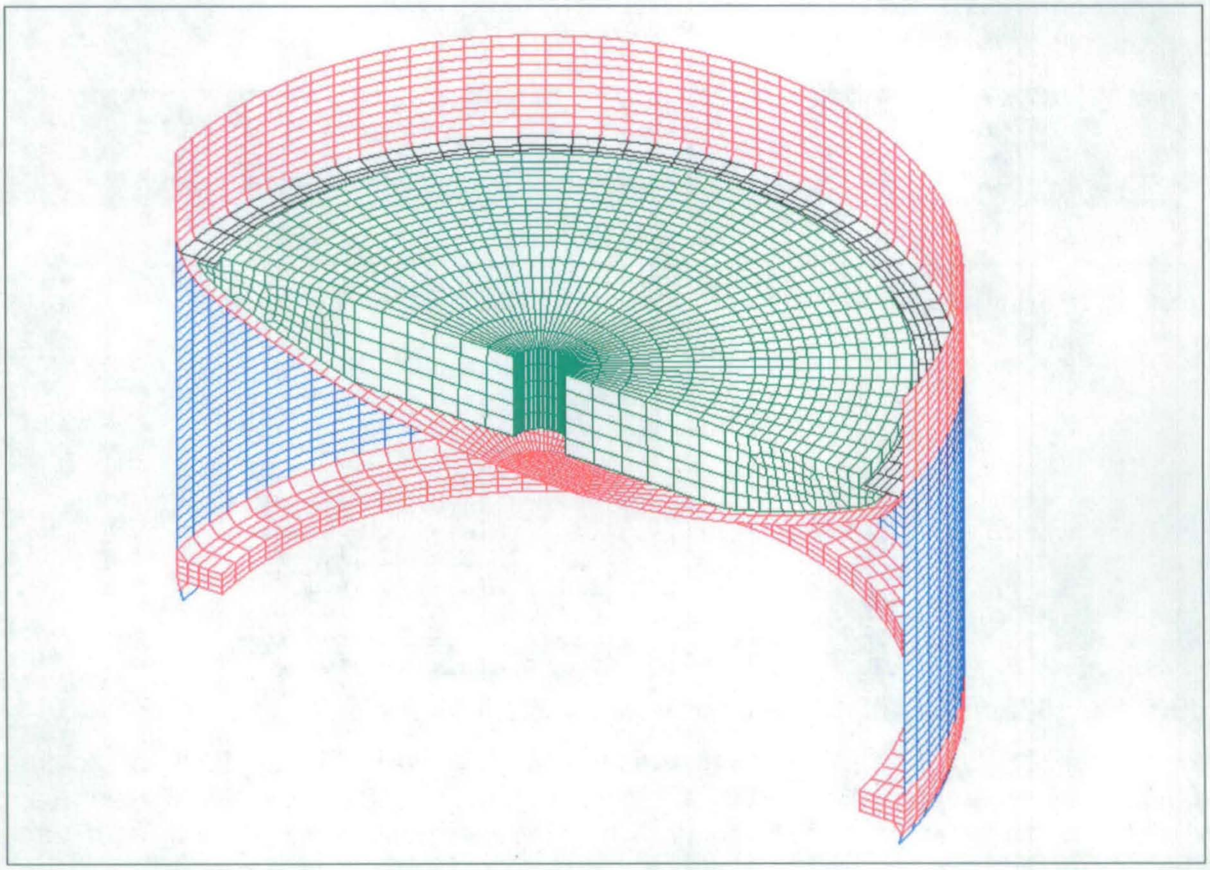


Figure 20. 18-inch standardized canister end assembly with impact plate FE mesh.

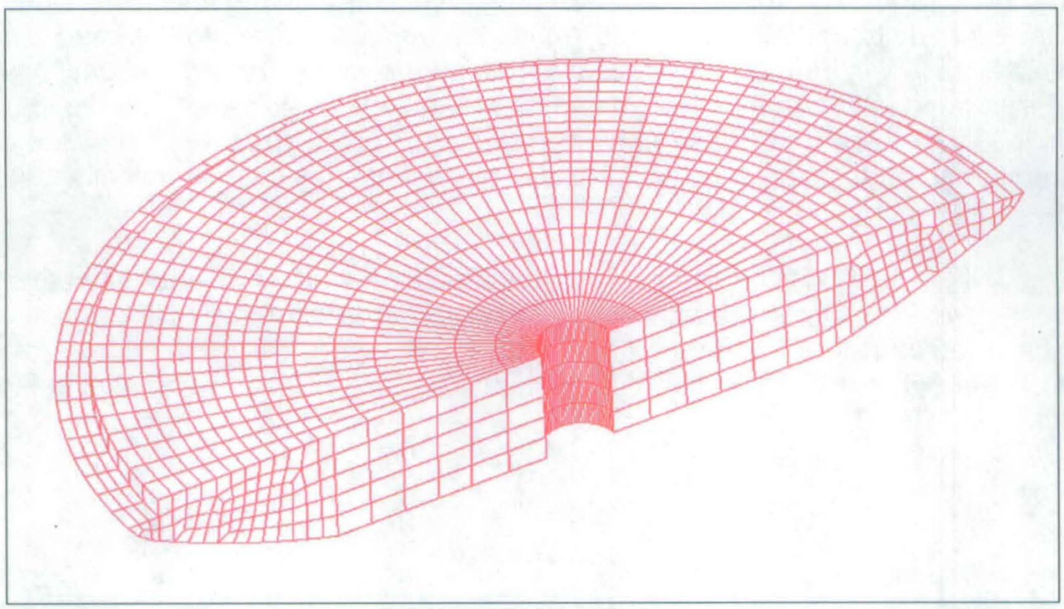


Figure 21. 18-inch standardized canister top and bottom internal impact plate FE mesh.

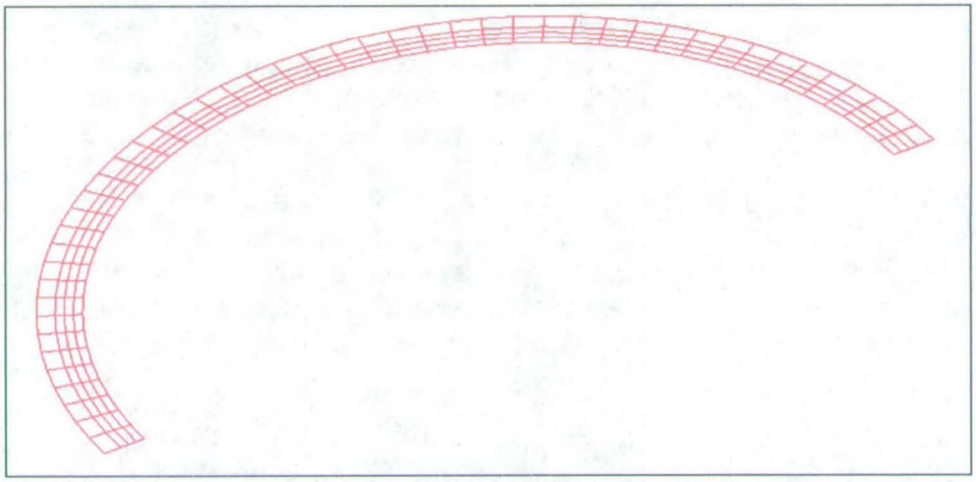


Figure 22. 18-inch standardized canister internal impact plate retaining ring FE mesh.

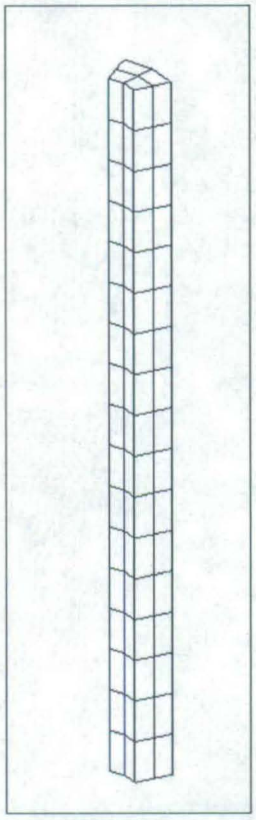


Figure 23. 18-inch standardized canister SNF element FE mesh.

Type 1a Rectangular Grid Basket: The rectangular grid basket consisted of a ½-inch thick base plate, 3/8-inch grid plates, and an integral sleeve of 0.062-inch wall thickness. The rectangular grid basket was modeled with 3036 brick and wedge elements (ABAQUS element types C3D8R and C3D6) to represent each base plate, 6292 shell elements (ABAQUS element type S4R) for each basket grid plates assembly, and 2176 shell elements to represent each basket sleeve wall. The sleeve wall-to-base plate weld was represented by the lowest row of shell elements on the sleeve and was connected to the base plate using common nodes. The grid plates-to-base plate welds were simulated by the last row of sleeve shell elements, which were also connected to the base plate using common nodes. The grid plate-to-adjacent grid plate welds were represented in the same manner. The rectangular grid basket mesh is shown in Figure 24. Figure 25 shows the basket with SNF elements.

Shield Plug: The shield plug was a solid piece of stainless steel, 16.7 inches in diameter and 6-3/4 inches thick. It was not expected to deform significantly during the defined drop events. The shield plug was only modeled to simulate its impact on the adjacent parts (upper impact plate, canister wall, basket, etc.) during the drop event. The shield plug employed 5060 bricks (ABAQUS element type C3D8R). The shield plug mesh is shown in Figure 26.

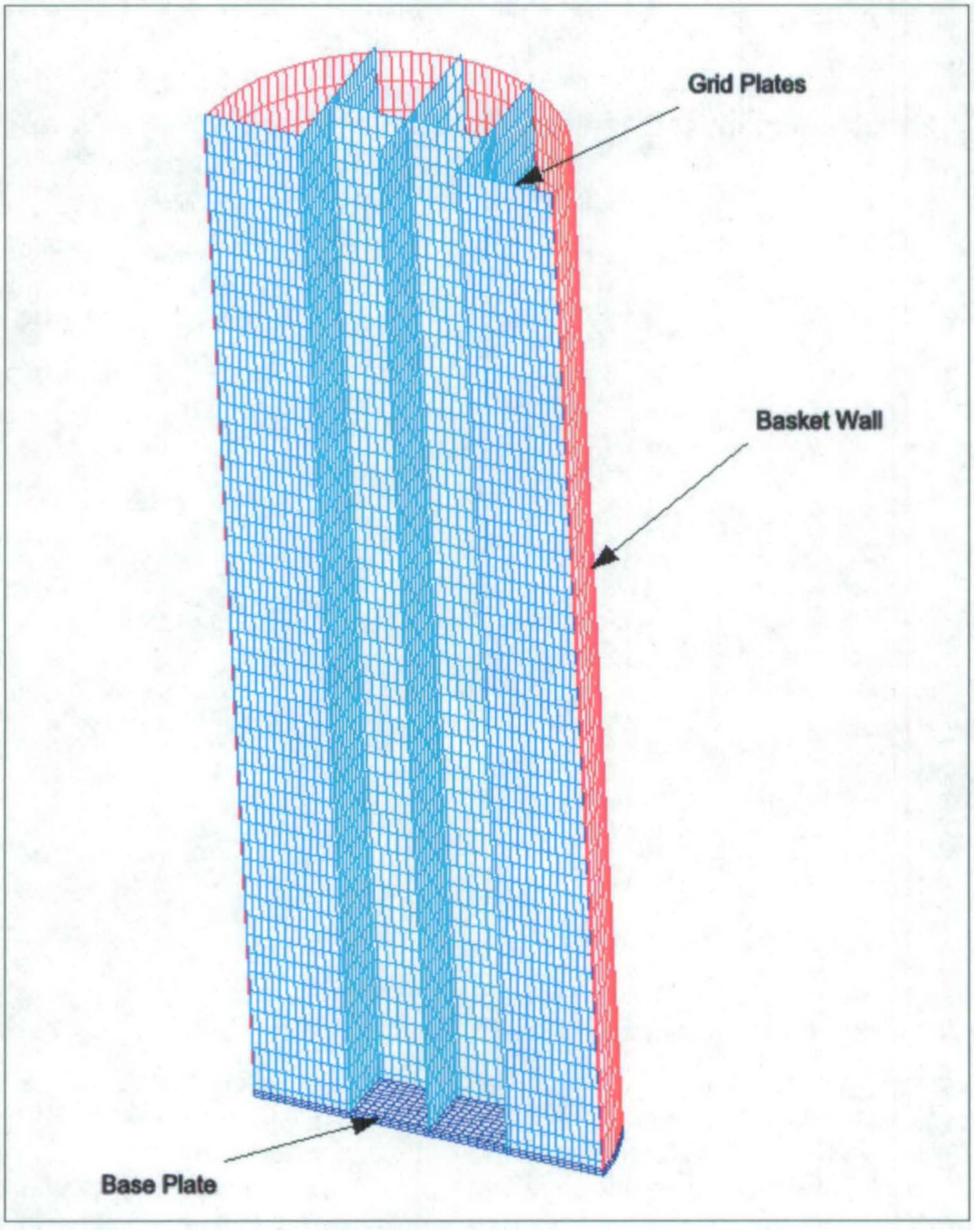


Figure 24. 18-inch standardized canister Type 1a basket FE mesh.

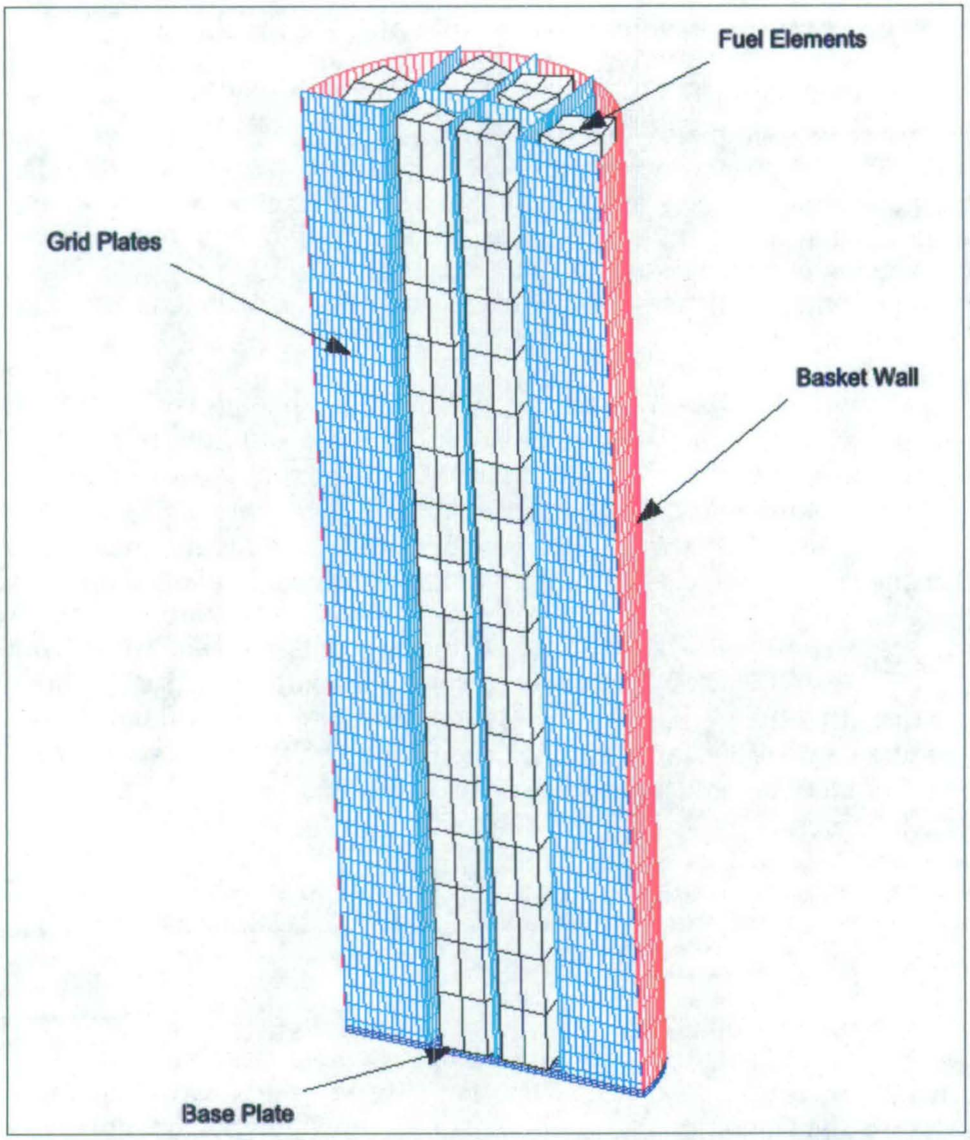


Figure 25. 18-inch standardized canister Type 1a basket with SNF FE mesh.

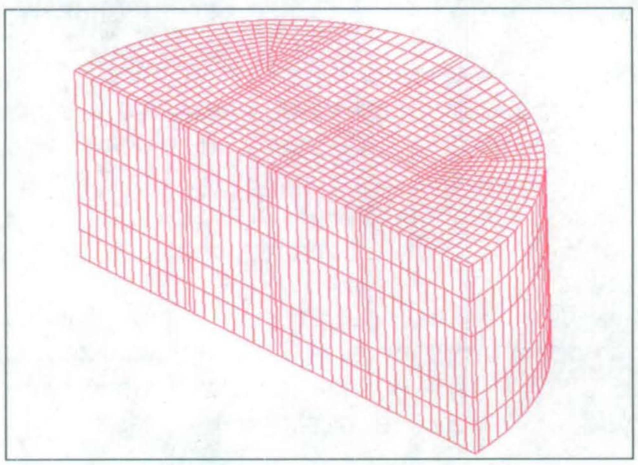


Figure 26. 18-inch standardized canister shield plug FE mesh.

8.1.3. 18-Inch Standardized Canister Part Thickness

The parts that made up the 18-inch standardized DOE SNF canister and their internals were specified to ASME (Reference 19) or ASTM standards (Reference 23). Those standards give nominal values for thickness and sometimes allow for some under thickness. Corrosion may also reduce the thickness of a part. It was not the intent of this report to evaluate every possible combination of part thicknesses under the specified drop condition, but instead to evaluate expected part thicknesses that would result in a significant challenge to the containment boundary.

<u>Main Shell Thickness:</u> The SA-312 pipe which is used to fabricate the main shell of the 18-inch standardized canister has an allowable underthickness of 12.5% of nominal. The NSNFP has specified that this underthickness be employed in this current evaluation (Reference 6). Therefore, the main shell wall thickness used herein was 3/8-inch x (1 – 12.5%), or **0.328 inches**. (This was 0.047 inches thinner than the nominal thickness.) This value of main shell thickness is consistent with the Reference 15 evaluation.

<u>Head Thickness:</u> The 18-inch standardized DOE SNF canister heads were formed from 5/8-inch thick plate material (SA-240). No under thickness was specified for this plate material, though some minor thinning is possible due to the forming process. In order to ensure conservatism, the same reduction in wall thickness used on the main shell, or 0.047 inches, was deducted from the nominal head nominal thickness (5/8-inch), giving a head dish thickness of **0.578 inches** for this current evaluation.

The head straight flange was machined after forming to match the main shell inside and outside diameter. Therefore, the main shell thickness of **0.328 inches** was applied to the head straight flange.

<u>Skirt and Lifting Ring Thicknesses:</u> During a 3 degree off-vertical drop event, a stiff skirt and lifting ring would be less likely to deform and would therefore transfer more load to the head and main shell than a less stiff skirt and lifting ring. Thicker skirts and lifting rings are stiffer than thinner skirts and lifting rings. Therefore, this evaluation used nominal thickness for all skirts (SA-312 pipe, **3/8-inch** nominal thickness) and lifting rings (SA-240, **1/2-inch** nominal or machined thickness), conservatively ignoring corrosion and fabrication under thicknesses.

<u>Impact Plate and Shield Plug Thicknesses:</u> The internal impact plates were made of 2-inch thick SA-240 (316L) plate and the shield plug was made of 6-3/4-inch thick SA-351, CF3M or SA-479 (316L) bar. Fabrication under thicknesses and corrosion would not appreciably reduce these part thicknesses. Additionally, thicker impact plates and the shield plug would be stiffer, and thus transfer more load to the containment boundary. Therefore, this evaluation used **nominal thicknesses** for the impact plates and shield plug.

<u>Basket Part Thicknesses:</u> The basket base plate was made of ½-inch thick SA-240 (316L) plate, and the basket grid plates were made of 3/8-inch thick Ni-Gd plate. The basket sleeve walls were made of 0.062-inch thick sheet metal. As with the impact plates and shield plug, thicker basket parts would provide a stiffer basket, thus transferring more load to the

containment boundary. Therefore, this evaluation used **nominal thicknesses** for basket parts, conservatively neglecting fabrication under thicknesses and corrosion.

Table 11 shows the part thicknesses employed in the 18-inch standardized canister FE model of this report.

Table 11. 18-inch standardized canister part thicknesses used in FE model.

Part		Nominal Thickness (in.)	Modeled Thickness (in.)
Main Shell		3/8	0.328
Canister Heads:	straight flange	3/8	0.328
	dished portion	5/8	0.578
Skirts		3/8	0.375
Lifting Ring		1/2	0.500
Impact Plates		2	2.000
Shield Plug		6-3/4	6.750
Basket Base Plates		1/2	0.500
Basket Grid Plates		3/8	0.375
Basket Sleeve Wall		0.062	0.062

8.2. 24-inch Standardized DOE SNF Canister Model Mesh Details

8.2.1. Symmetry

Plane symmetry was employed in this 24-inch diameter standardized canister model. Justification for plane symmetry is detailed in Reference 5.

8.2.2. 24-Inch Standardized Canister Model Mesh Details

The 24-inch standardized DOE SNF canister model includes the canister as well as the internals (a bottom spacer, spoked-wheel basket, shield plug, and simulated SNF). Figure 27 shows the FE model of the canister.

Skirts: The skirts are anticipated to be the most deformed of all the canister components for the defined drop event. A sufficient number of elements were required to reflect the actual deformed shape of these skirts (too few elements would result in deformed skirts with "flat" sections and large angles between adjacent elements). Therefore, the lower and upper skirts each used 2,624 shell elements (ABAQUS element type S4R), sized at about 1/4-inch x 6/10-inch (longitudinal x circumferential dimension). This gave a skirt mesh that resulted in smooth deformations for the drop event. The bottom edge of the skirt just past the lifting ring was adjusted radially inward approximately 1/8-inch to match the actual canister skirt geometry after welding (lifting ring-to-skirt weld). The skirt mesh is shown in Figure 28.

Skirt-to-Head Weld: The groove weld that attached each skirt to a head used 64 wedges (ABAQUS element type C3D6) and 192 bricks (ABAQUS element type C3D8R). Previous canister analytical models (Reference 3) employed multipoint constraints to represent these welds. However, additional modeling efforts indicated that modeling the skirt-to-head welds with solid elements resulted in comparable general deformations and strains. The skirt-to-head weld mesh is also shown in Figure 28.

Lifting Rings and Attaching Welds: The lifting rings and attaching groove welds used the same circumferential spacing as the skirts. The brick mesh used 4 elements (ABAQUS element type C3D8R) through the width and 3 brick elements through the thickness, with wedge elements (ABAQUS element type C3D6) to represent the fillet cap on the groove welds. A total of 896 elements were used to represent each lifting ring. The lifting ring and attachment weld mesh is also shown in Figure 28.

Heads: Each head used 2,326 shell elements (ABAQUS element type S4R) to represent the head and the integral straight flange. Elements were sized at about 1/4-inch x 6/10-inch (longitudinal x circumferential) in the straight flange, and from about 0.2-inch x 0.2-inch to about 6/10-inch x 6/10-inch in the dished portion of the head. The head mesh is also shown in Figure 28. No vent ports in the top head were included in this model since any structural effects due to the presence of a vent port were considered insignificant for this evaluation.

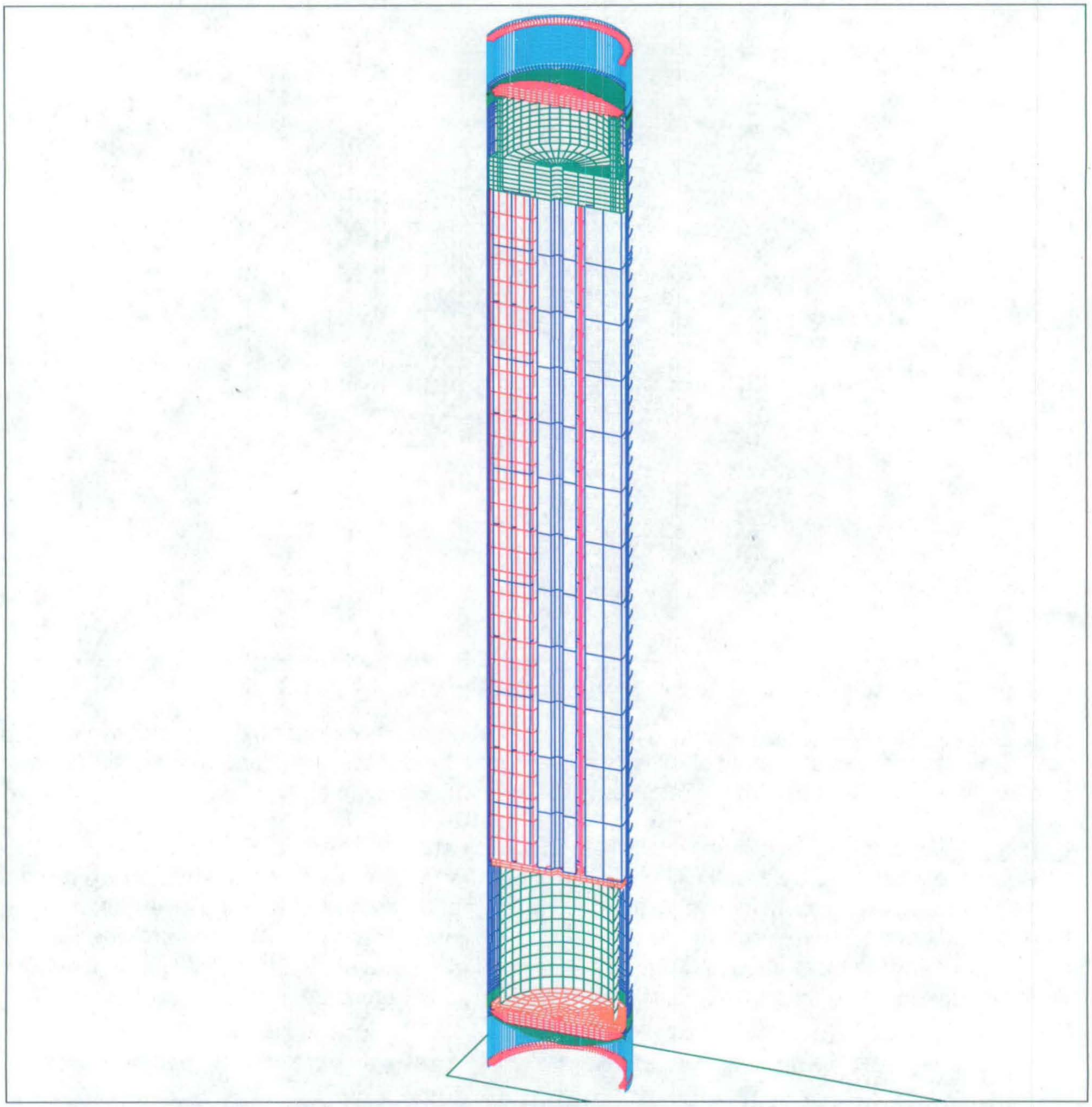


Figure 27. 24-inch standardized DOE SNF canister FE mesh.

The component meshes were as follows:

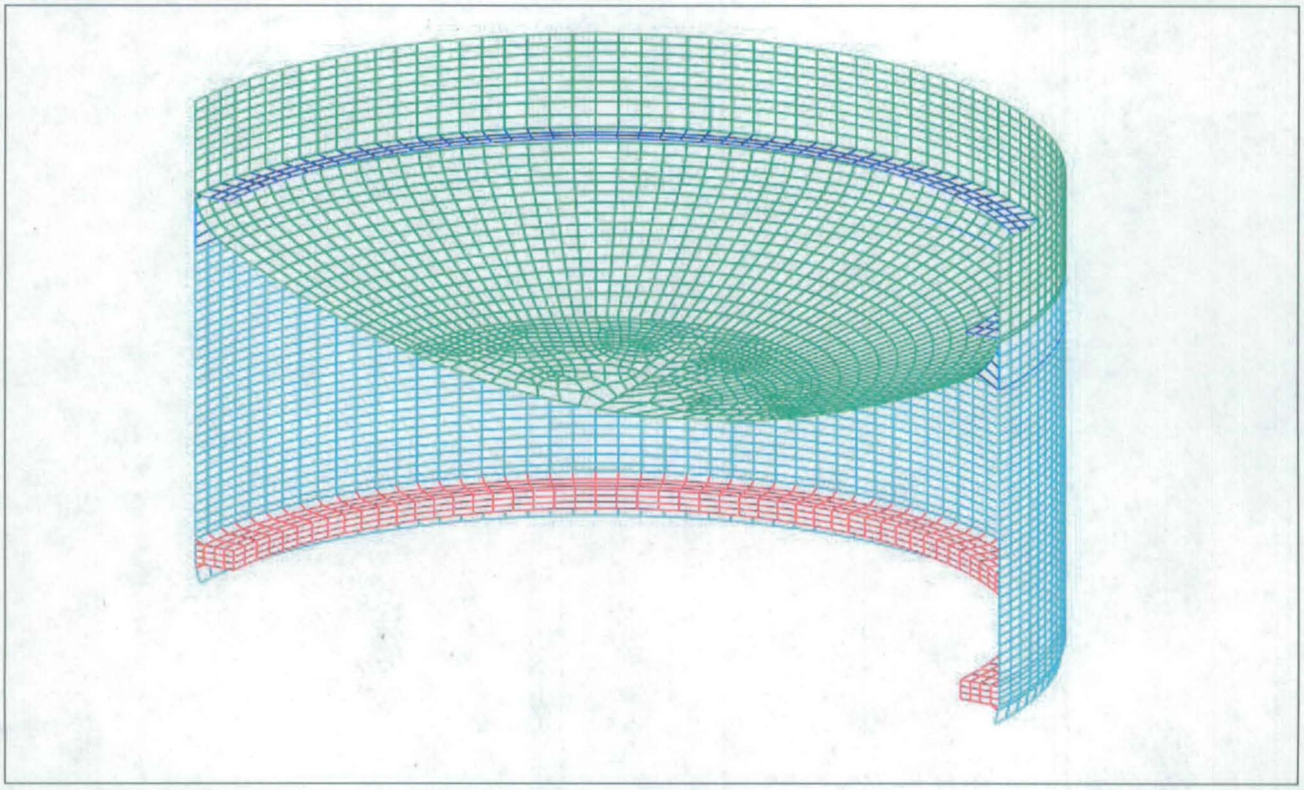


Figure 28. 24-inch standardized canister end FE mesh.

Head-to-Canister Main Shell Weld: The full penetration circumferential weld that attached each head to the canister main shell was represented by the last row of elements on the head straight flange and the first row of elements on the canister main shell.

Canister Main Shell: The deformations in the 24-inch standardized DOE SNF canister main shell were expected to be small. Therefore, element sizes that were somewhat larger than the skirts and heads were considered justified. The element size began at about 1/4-inch x 6/10-inch (longitudinal x circumferential) at the heads and then grew to a maximum of 3-inch x 6/10-inch in the canister main shell. A total of 4,480 shell elements (ABAQUS element type S4R) were employed. The main shell FE model is illustrated in Figure 29.

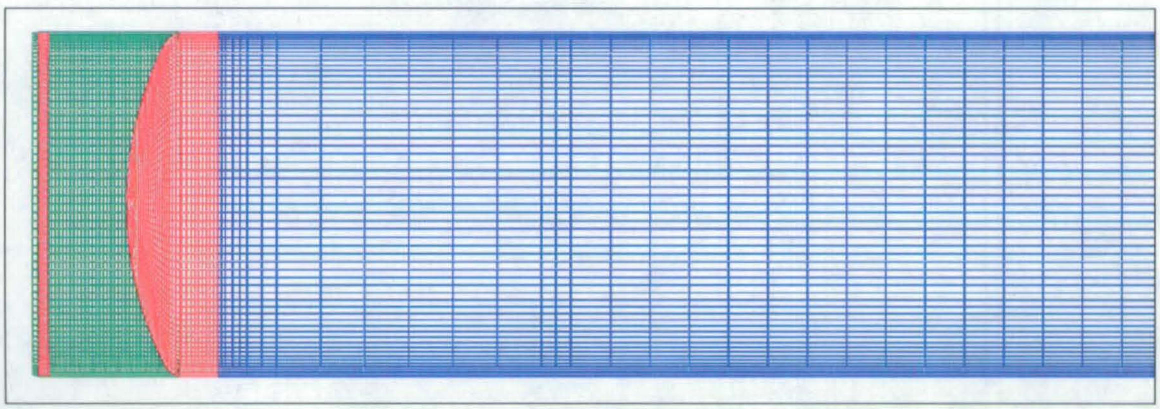


Figure 29. 24-inch standardized canister main shell FE mesh (close-up of end).

Internal Impact Plates: Each internal impact plate used a total of 3,712 brick elements (ABAQUS element type C3D8R), with 4 elements through the thickness. The 4 elements through the thickness allowed the impact plate to bend correctly due to the internal load from above and the impact load from below. The impact plate mesh is shown in Figure 30.

Impact Plate Retaining Ring: The impact plate retaining rings were modeled with 3 shell elements through the width, with a circumferential mesh that matched the heads (6/10-inch). A total of 192 shell elements (ABAQUS element type S4R) were used. The actual rings were welded to the head knuckle (dish-to-straight flange transition) at about 30-degree segments (30 degrees of weld, 30 degrees no weld, and so on). The rings were more simply modeled as continuously welded (modeled using common nodes between the retaining ring and the head, with the one row of ring elements representing the weld). The impact plate retaining ring mesh is shown previously in Figure 28.

Bottom Spacer: The bottom spacer consisted of a pipe with two end plates. The exact condition of the bottom spacer was not of interest in this evaluation, only its effects on the canister. Therefore, a simplified representation of the bottom spacer was used that included: 392 bricks (ABAQUS element type C3D8R) on each end plate, and 324 shells (ABAQUS element type S4R) for the pipe. The welded connection between an end plate and the pipe was modeled using common nodes that represented a full-penetration weld. This was stronger than the actual weld, a fillet, but was considered acceptable because the fillet weld was not expected to be damaged during the drop event. The bottom spacer mesh is shown in Figure 31.

Spoked-Wheel Basket: The spoked-wheel basket consisted of a center pipe with six spokes. The exact condition of the spoked-wheel basket was not of interest in this calculation, only the effects that it had on the canister. Therefore, the spoked-wheel basket was modeled with 270 shells (ABAQUS element type S4R) to represent the center pipe and 450 shells (ABAQUS element type S4R) for the spokes. The actual spokes were skip-welded (double fillet welds) to the center pipe, but were represented in the model as continuously welded (modeled using common nodes). The actual welds were not expected to experience significant damage; therefore, the modeling technique used was considered acceptable. The spoked-wheel mesh is shown in Figure 32.

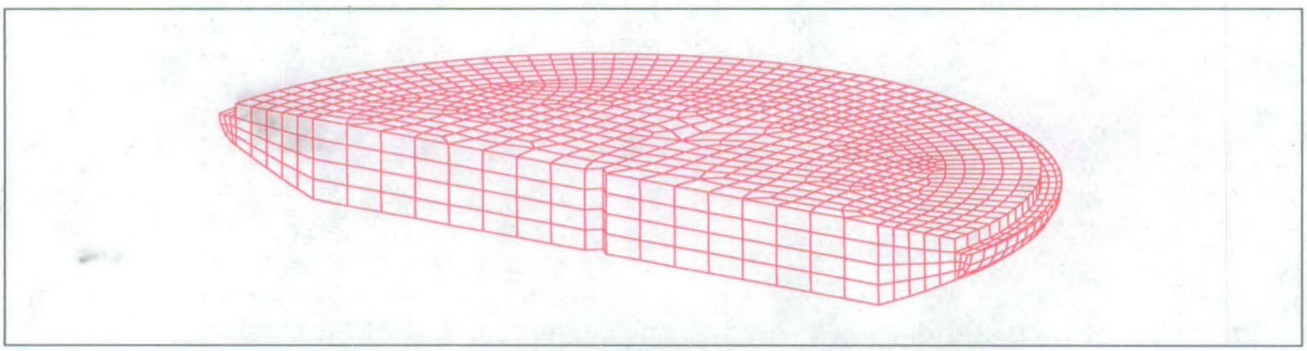


Figure 30. 24-inch standardized canister impact plate FE mesh.

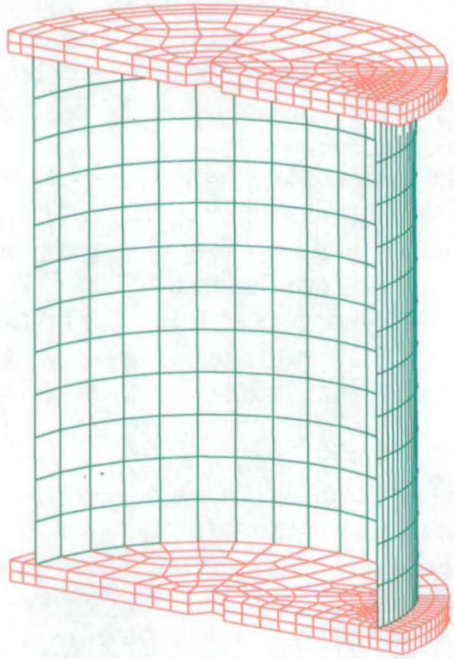


Figure 31. 24-inch standardized canister bottom spacer FE mesh.

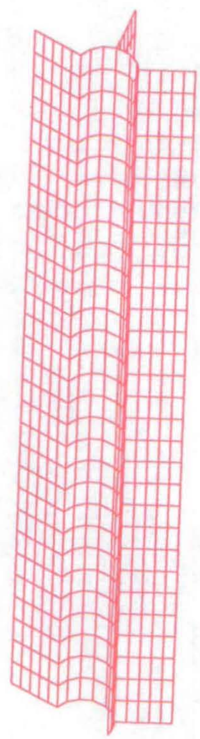


Figure 32. 24-inch standardized canister spoked-wheel basket FE mesh.

Shield Plug: The shield plug was basically a large mass of steel. It was not expected to deform significantly during the defined drop event. The shield plug was only modeled to simulate its impact on the adjacent components (upper impact plate, canister wall, spoked wheel basket, etc.) during the drop event. The shield plug employed 1,656 bricks (ABAQUS element type C3D8R). The shield plug mesh is shown in Figure 33.

Simulated SNF: The exact condition of the simulated SNF was not of interest in this evaluation, only its effects on the canister. Therefore, the SNF was modeled as a full-length solid section within each spoke section and within the center pipe of the basket. Sufficient gaps were provided between this simplified SNF and the basket and canister so that it would not stiffen the canister main shell. A total of 336 bricks (ABAQUS element type C3D8R) were used to simulate the SNF. The simulated SNF mesh is shown in Figure 34.

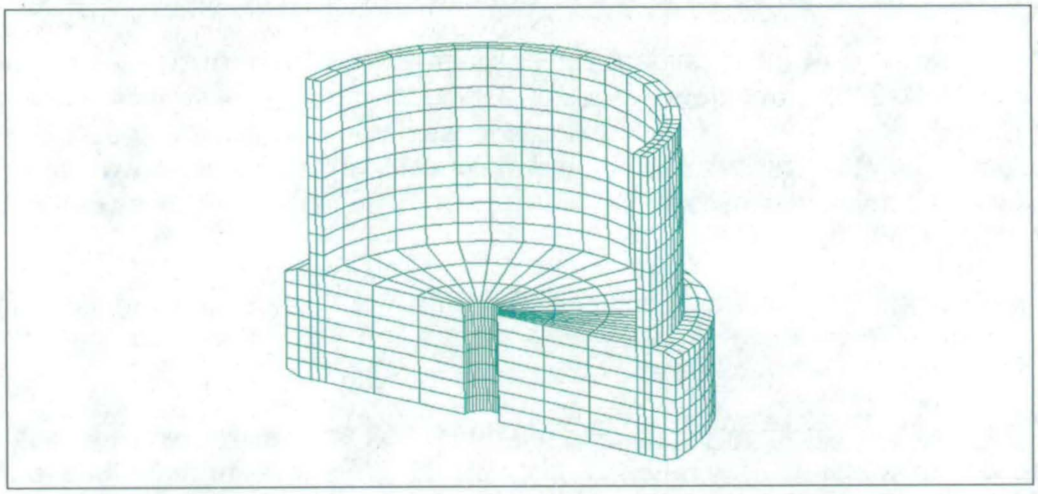


Figure 33. 24-inch standardized canister shield plug FE mesh.

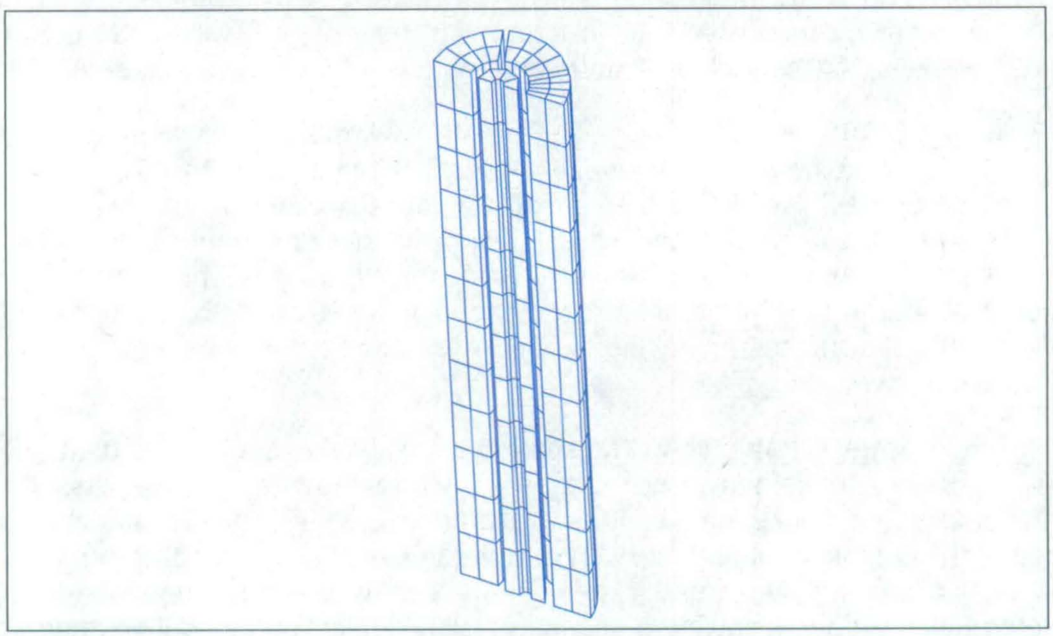


Figure 34. 24-inch standardized canister simulated SNF FE mesh.

8.2.3. 24-Inch Standardized Canister Part Thickness

The parts that made up the 24-inch standardized DOE SNF canister and their internals were specified to ASME (Reference 19) standards. Those standards give nominal values for thickness and sometimes allow for some under thickness. Corrosion may also reduce the thickness of a part. It was not the intent of this report to evaluate every possible combination of part thicknesses under the specified cask drop conditions, but instead to evaluate expected part thicknesses that would result in a significant challenge to the containment boundary.

Main Shell Thickness: The SA-312 pipe which is used to fabricate the main shell of the 24-inch canister has an allowable underthickness of 12.5% of nominal. The NSNFP has specified that this underthickness be employed in this current evaluation (Reference 6). Therefore, the main shell wall thickness used herein was 1/2-inch x (1 – 12.5%), or **0.438 inches**. (This was 0.062 inches thinner than the nominal thickness.)

Head Thickness: The 24-inch standardized canister heads were formed from 7/8-inch thick plate material (SA-240). No under thickness was specified for this plate material, though some minor thinning is possible due to the forming process. In order to ensure conservatism, the same reduction in wall thickness used on the main shell, or 0.062 inches, was deducted from the nominal head nominal thickness (7/8-inch), giving a head dish thickness of **0.813 inches** for this current evaluation.

The head straight flange was machined after forming to match the main shell inside and outside diameter. Therefore, the main shell thickness of **0.438 inches** was applied to the head straight flange.

Skirt and Lifting Ring Thicknesses: During a 3 degree off-vertical drop event, a stiff skirt and lifting ring would be less likely to deform and would therefore transfer more load to the head and main shell than a less stiff skirt and lifting ring. Thicker skirts and lifting rings are stiffer than thinner skirts and lifting rings. Therefore, this evaluation used nominal thickness for all skirts (SA-312 pipe, **1/2-inch** nominal thickness) and lifting rings (SA-240, **1/2-inch** nominal or machined thickness), conservatively ignoring corrosion and fabrication under thicknesses.

Impact Plate and Shield Plug Thicknesses: The internal impact plates were made of 2-inch thick SA-240 plate and the shield plug was made of 5-3/4-inch thick SA-351, CF3M or SA-479 bar and 20-inch Sch. 60 SA-312 pipe. Fabrication under thicknesses and corrosion would not appreciably reduce these part thicknesses. Additionally, thicker impact plates and the shield plug would be stiffer, and thus transfer more load to the containment boundary. Therefore, this evaluation used **nominal thickness** for the impact plates and shield plug bar, and slightly larger than nominal thickness (matching the thickness used in the Reference 5 drop test canisters) for the shield plug pipe.

Spoked-Wheel Basket Thicknesses: The spoked-wheel basket spokes are made of ½-inch thick SA-240 plate, and the basket center pipe is 8-inch Schedule 100 pipe. As with the impact plates and shield plug, thicker basket parts would provide a stiffer basket, thus transferring more load to the containment boundary. Therefore, this evaluation used **nominal thickness** for the spokes and a slightly larger thickness on the center pipe (matching the thickness used in the Reference 5 drop test canisters), conservatively neglecting fabrication under thicknesses and corrosion.

<u>Bottom Spacer Thicknesses:</u> The bottom spacer was made of 20-inch Sch. 60 SA-312 center pipe and two 1-inch thick SA-240 plate. As with the impact plates and shield plug, thicker spacer parts would provide a stiffer spacer, thus transferring more load to the containment boundary. Therefore, this evaluation used **nominal thickness** for the spacer plates and a slightly larger thickness on the center pipe (matching the thickness used in the Reference 5 drop test canisters), conservatively neglecting fabrication under thicknesses and corrosion.

Table 12 shows the part thicknesses employed in the FE model for the 24-inch standardized DOE SNF canister.

Table 12. 24-inch canister component thicknesses used in analytical models.

Part		Nominal Thickness (in.)	Modeled Thickness (in.)
Main Shell		1/2	0.438
Heads	straight flange	1/2	0.438
	dished portion	7/8	0.813
Skirts, Lifting Rings		1/2	0.500
Impact Plates		2	2.000
Shield Plug	bar	5-3/4	5.750
	pipe	0.812	0.839[1]
Spoked-Wheel	spokes	1/2	0.500
	center pipe	0.593	0.612[1]
Bottom Spacer	pipe	0.812	0.843[1]
	plates	1	1.000
1. Modeled thickness matched that used in the Reference 5 drop test canisters (thicker than nominal).			

All other components used nominal thicknesses.

8.3. MCO Model Mesh Details

8.3.1. Symmetry

Plane symmetry was employed in this MCO model. Justification for plane symmetry is detailed in Reference 16.

8.3.2. MCO Model

The MCO was modeled (Figure 35) using solid linear brick elements (element type C3D8R), wedge elements (element type C3D6), and linear quadrilateral shell elements (element type S4R) as follows:

Bottom: The bottom used 2,944 solid (brick and wedge) elements, with four elements through the thickness of the base and four in the connection to the wall. This was done to ensure adequate modeling of bending responses. See Figure 36.

Main Shell: The cylindrical shell employed 14,720 solid (brick only) elements, with four elements through the thickness. The connection between the shell and the bottom consisted of a full-penetration groove weld. This weld was modeled using nodes common to the shell and bottom elements. See Figure 35.

Collar: The collar was modeled with 4,992 solid (brick only) elements, with a minimum of four elements through the thickness. The connection between the collar and the main shell, consisting of a full-penetration groove weld, was modeled using nodes common to the collar and main shell elements. See Figure 37.

Cover: The cover used 2,144 solid (brick only) elements, with four elements through the thickness in the cylindrical portion and three elements through the flat top. The groove weld connection between the cover and the collar was also represented with common nodes. See Figure 37.

Shield Plug: The shield plug utilized a total of 762 solid (brick only) elements. The mesh size in this component was quite coarse in order to simplify the model. The coarse mesh size was considered acceptable since the plug consisted of very thick members that were unlikely to deform significantly during any drop event – a coarse mesh would adequately simulate such a response. Valves, ports, filters, etc. that were part of the shield plug were not explicitly modeled because their influence on the adjacent components was considered negligible. See Figure 38.

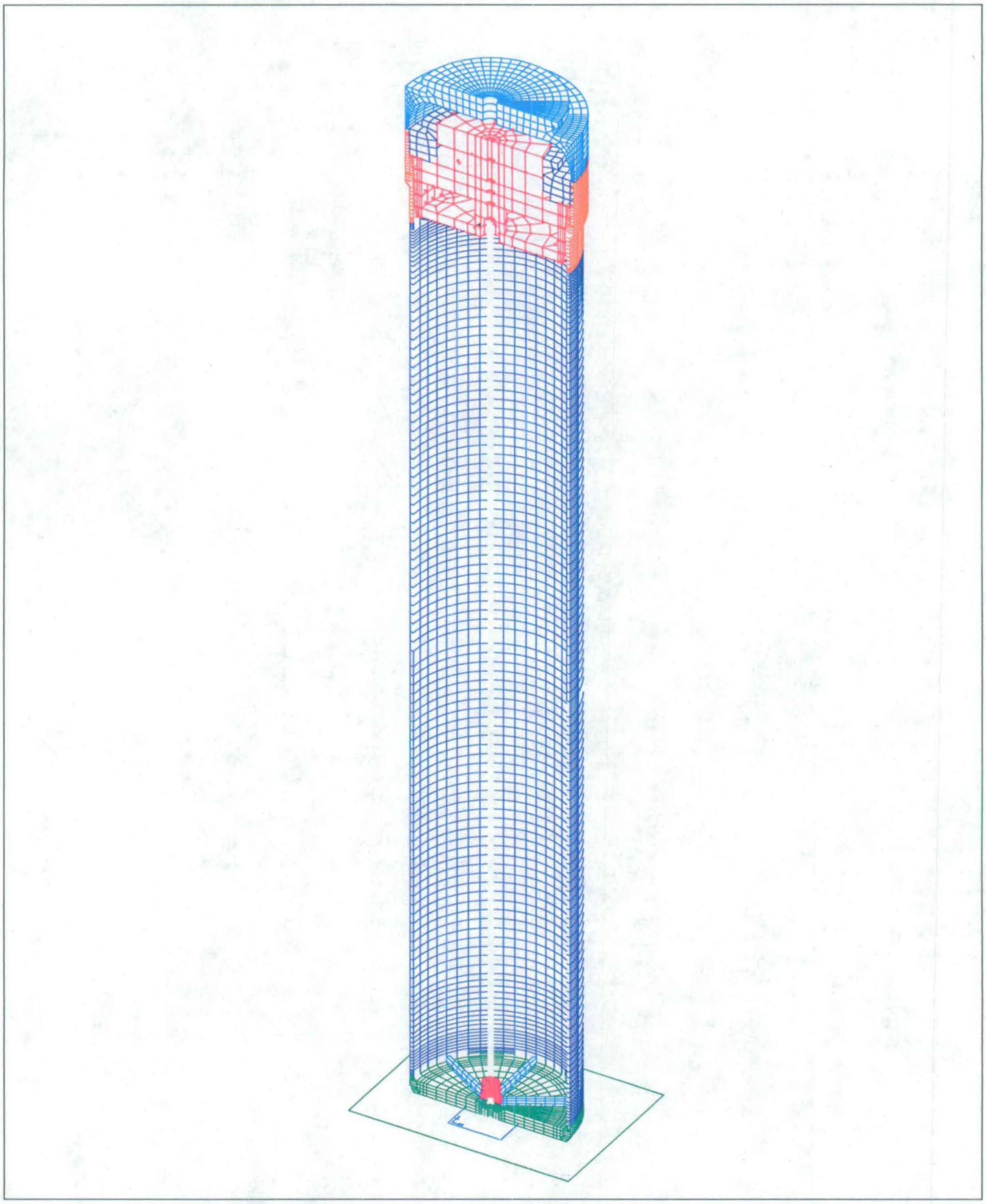


Figure 35. FE mesh of MCO (minus baskets and SNF).

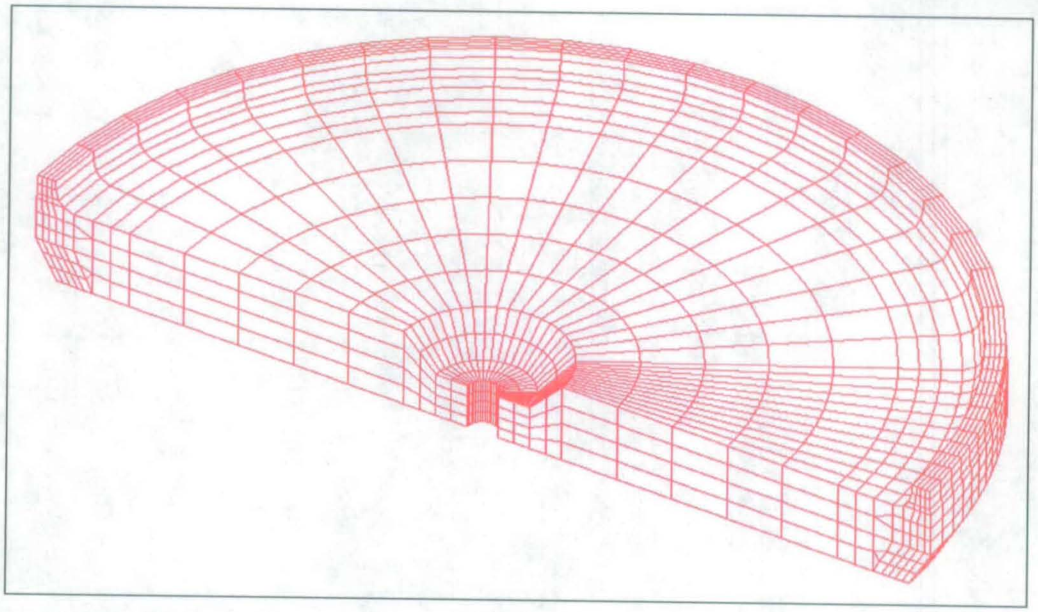


Figure 36. MCO bottom FE mesh.

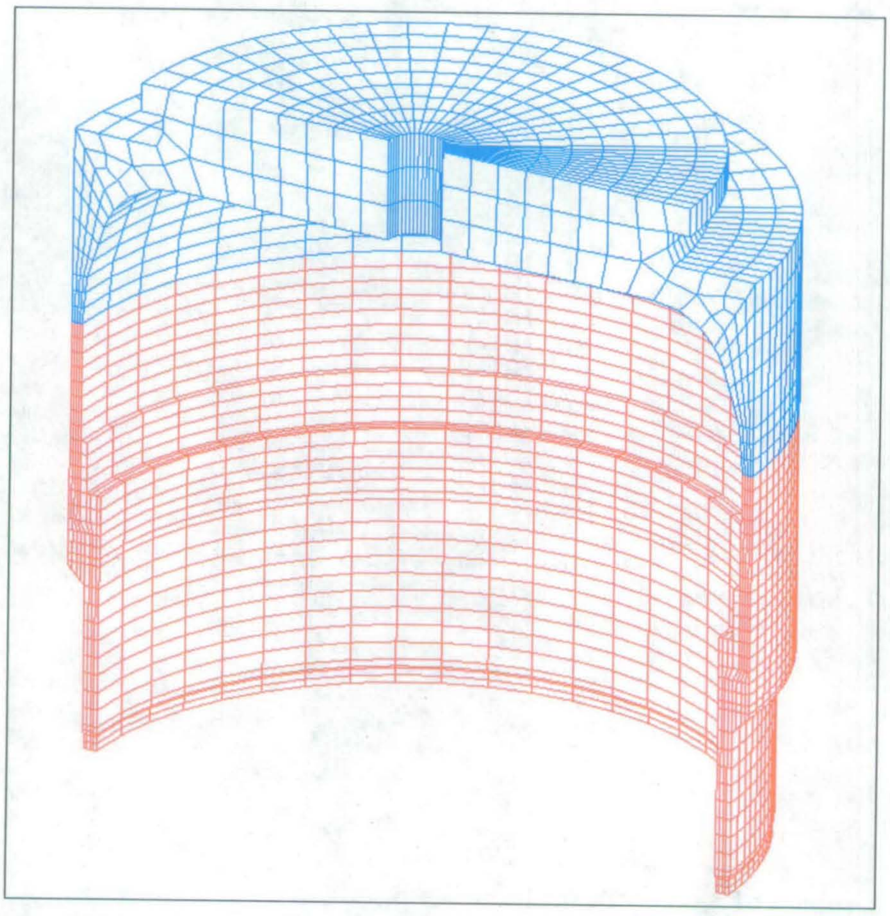


Figure 37. MCO collar and cover FE mesh.

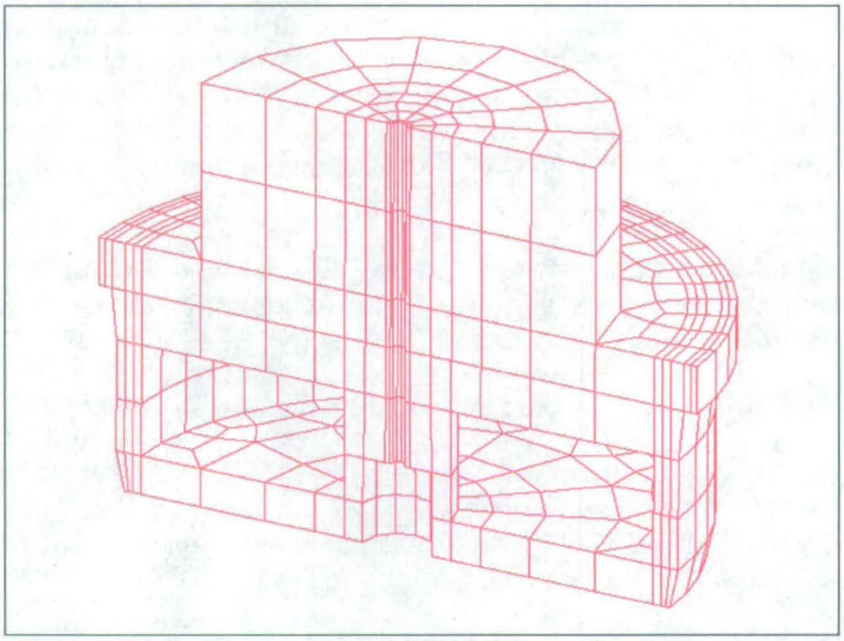


Figure 38. MCO shield plug FE mesh.

Locking Ring: The locking ring employed 432 solid (brick only) elements. This mesh was also coarse for the same reasons given for the shield plug. The threaded connection between the locking ring and the collar was represented by fixing the locking ring nodes (in the threaded portion) to the inside wall of the collar (*TIED option). This assumed that the threaded connection between the ring and collar would not fail during any bottom-impact drop event. (This assumption was considered valid because of the more than 3 inches of thread engagement length was far in excess of that required to resist the worst-case loading during any bottom-impact drop event without failure.) The set-screws on the locking ring were ignored in this evaluation since they had no significant effect on the MCO response during any drop event. Their purpose was to ensure a seal between the shield plug and the collar – which was not needed after the cover was welded onto the collar. See Figure 39.

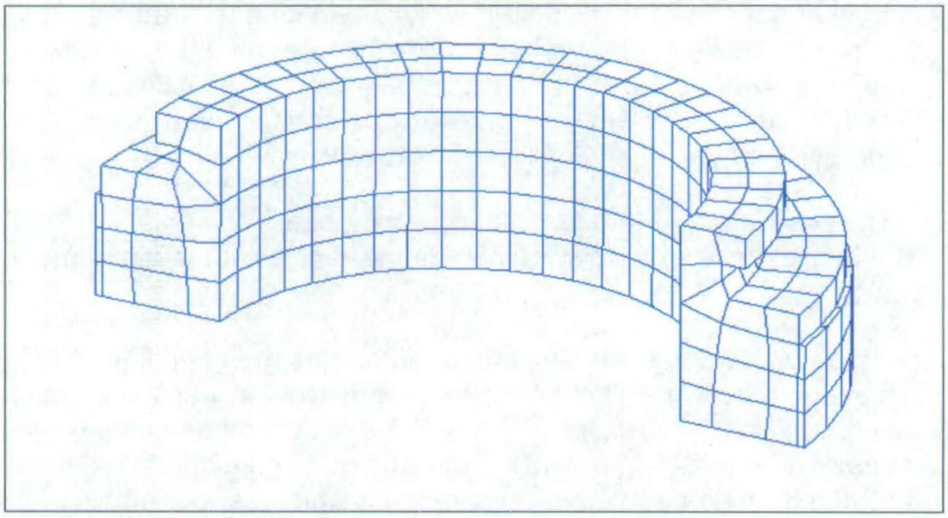


Figure 39. MCO locking ring FE mesh.

Basket Support Bars: The six basket support bars were each represented using 29 solid (brick only) elements. The fillet weld that attached each bar to the MCO bottom was represented by fixing the bar edge nodes to the top surface of the bottom (*Tied option). This was considered adequate since the exact condition of these welds was not of interest, only their affect on adjacent components during any drop event. This assumed that these welds would not fail during any drop event. See Figure 35.

Guide Cone: The guide cone was modeled using 108 solid (brick only) elements. The welded connection between the guide cone and the six basket support bars was conservatively modeled using common nodes (as described previously). See Figure 35.

Process Tube: The process tube employed 462 quadrilateral shell elements.

Mark IV Baskets: This MCO model was used with five Mark IV basket models placed within to simulate the fully loaded package. Each Mark IV basket was modeled using solid linear brick elements (element type C3D8R), wedge elements (element type C3D6), and linear quadrilateral shell elements (element type S4R) as follows:

Basket Base: The basket base was represented with 324 solid (brick only) elements, with three elements through the thickness. See Figure 40.

Center Post: The center post was modeled using 1032 solid (brick only) elements, with three elements through the wall. The threaded connection between the center post and the basket base employed nodes common to both components. This assumed that the post would remain firmly attached to the base during all drop events. The design of this connection prevents the post from separating from the base during any of the specified drop events, though the vertical and near vertical drops do cause significant bending in the post just above this connection. The modeling of this connection was considered valid. See Figure 40.

Perimeter Bars: The round perimeter bars were each represented using 312 solid (brick only) elements. The actual connection was made using one bolt through the base and into the bar end. The model simulated this connection by fixing the bar nodes to the base (*TIED option). This made a connection that was more rigid than was provided by the bolt. This was acceptable since the objective of this evaluation was to determine the condition of the MCO containment boundary – not determine the exact condition of the baskets and fuels during a drop event. This method of modeling the perimeter bar connection was conservative as far as the MCO containment boundary was concerned. See Figure 40.

Basket Walls: The basket walls were simulated with 84 shell elements. The walls were connected to the basket base using common nodes to represent the attachment weld. See Figure 40.

SNF: It was not the purpose of this evaluation to determine the condition of the fuels during and after a drop event. Therefore, the modeling of fuels was only sufficient to represent their effect on the basket and MCO structure. The fuel was simply modeled as 62 mass elements on each basket base (element type MASS). This was quite conservative because it prevented the fuel from absorbing any drop energy – all energy was forced to the basket and MCO structures.

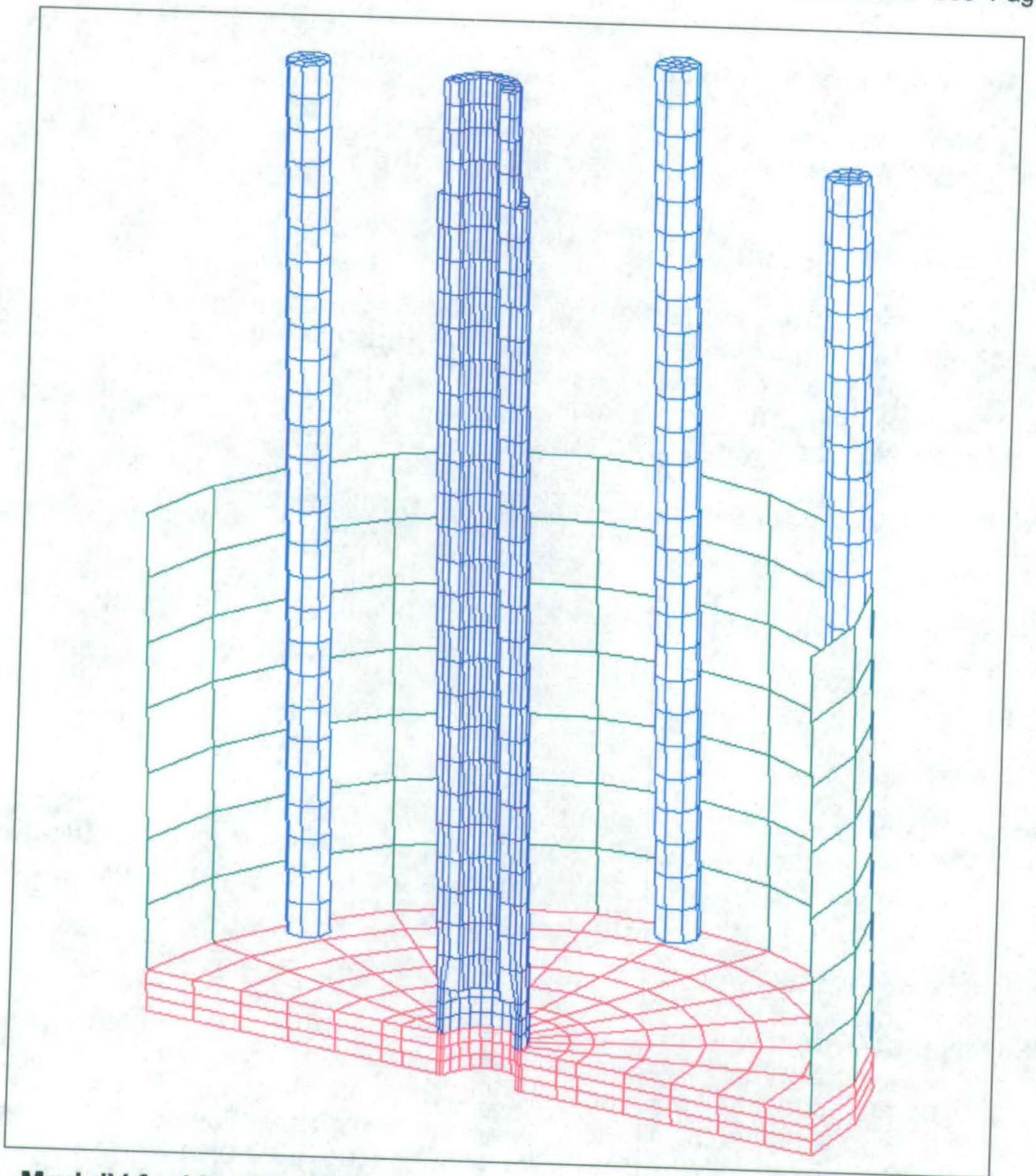


Figure 40. Mark IV fuel basket FE mesh.

8.3.3. MCO Component Thickness

All components were modeled using nominal dimensions. The MCOs have already been constructed and loaded. Detailed wall thickness measurements for specific canisters indicate that the Hanford project went to extreme lengths to achieve a full nominal ½-inch wall thickness for the main shell. This is readily understood when one considers that the machining of the bottom plate and collars required a tight tolerance on the main shell in order to achieve good weld match up.

8.4. Flat, Rigid Impact Surface

The flat, rigid impact surface was modeled using one large rigid quadrilateral element (element type R3D4) that was fixed in space.

8.5. Initial Drop Conditions

The analysis models began the drop event by locating the canister or MCO just above the rigid surface and applying a gravitational acceleration and an initial velocity, both directed vertically downward. The initial velocity was calculated by equating the potential energy of the canister at the beginning of the drop to the kinetic energy just before impact. Therefore, at a drop height of 23 feet, the velocity at impact of the canister was:

- Potential energy at 23-ft drop height = mass x gravity x height
- Kinetic energy at impact = ½ x mass x velocity^2
- Solve for velocity = [2 x gravity (386.4 in./sec.^{2}) x height (276 in.)]$^{1/2}$

  = 461.84 in./sec.

8.6. Material Density

The basic density of 316/316L stainless steel is 0.283 pounds per cubic inch and the basic density of 304/304L stainless steel is 0.285 pounds per cubic inch. However, density values were modified as necessary in the analytical models in order to obtain the desired weights.

8.7. Contact Modeling

Contact between components was simulated using the ABAQUS General Contact option supplemented by the Contact Pairs option in areas of interest (impact locations). This was one of the approved methods detailed in the ABAQUS Software Report (Reference 29). These contact options employed penalty contact stiffness. Preliminary evaluations increased the default stiffness calculated within ABAQUS/Explicit Version 6.3-3 by a factor of 10. The results were the same as those obtained using the default stiffness values. This indicated that the default penalty stiffness calculated within ABAQUS was adequately stiff to simulate a "hard impact" for these evaluations.

8.8. Friction

The coefficient of friction between two steel surfaces during an impact event can vary widely. In 2001, the NSNFP performed an investigation into how the coefficient of friction (representing static and sliding conditions) value used in analytical canister drop test simulations affected the resulting canister deformations (Reference 30). Actual drop testing accompanied the investigation to determine the valid canister response. The results gave a recommended coefficient of friction, or a range of valid coefficients of friction, for use in analytical simulations for canister impact orientations from vertical to horizontal (impact surface was always horizontal). For a 3 degree off-vertical impact orientation, a range of coefficients of friction, including a value of 0.3, was recommended. Therefore, for these canister drop evaluations, a coefficient of friction of 0.3 was used.

8.9. Plastic Strain Hardening

ABAQUS/Explicit gave two options for defining the hardening law for plasticity: isotropic hardening, and Johnson-Cook hardening. Because specific data on these canister materials were not available to justify using the Johnson-Cook hardening law, isotropic hardening was used in the analyses reported herein. This was consistent with the previous analyses (References 3, 4, and 5) which produced accurate matches between predicted and actual canister deformations.

8.10. Model Solution Termination

Unless otherwise noted, model solution was terminated when the canister had progressed through the first impact for the 3 degree off-vertical drop events.

9. ANALYSIS RESULTS

9.1. 18-Inch Standardized DOE SNF Canister

9.1.1. Analytical Model Energy History

Several types of model energy were tracked within the ABAQUS/Explicit software. Figure 41 shows a plot of the energy history for this 3 degrees off-vertical drop event. The plot shows model artificial energy history (ALLAE), frictional dissipation history (ALLFD), kinetic energy history (ALLKE), plastic dissipation history (ALLPD), and elastic energy history (ALLSE). At the beginning of the event the model showed a high kinetic energy (ALLKE curve) with all other energies at zero. As the canister impacted the rigid surface kinetic energy was then expended primarily by way of plastic deformation (ALLPD curve). At 15 milliseconds after impact the kinetic energy was all expended and the canister started to rebound off the surface due to the small amount of elastic energy (ALLSE curve). Note that a small fraction of the kinetic energy was also expended in frictional dissipation (ALLFD curve).

Artificial energy was the amount of drop energy used (taken away from the total model energy) to prevent finite element numerical instabilities. An artificial energy total of 3% - 6% for a drop evaluation is typical – results are considered valid. Figure 41 shows the artificial energy (ALLAE curve) at about (0.04/0.8 =) 5% at the end of the evaluation. Therefore, this artificial energy was acceptable – results from the model were considered valid.

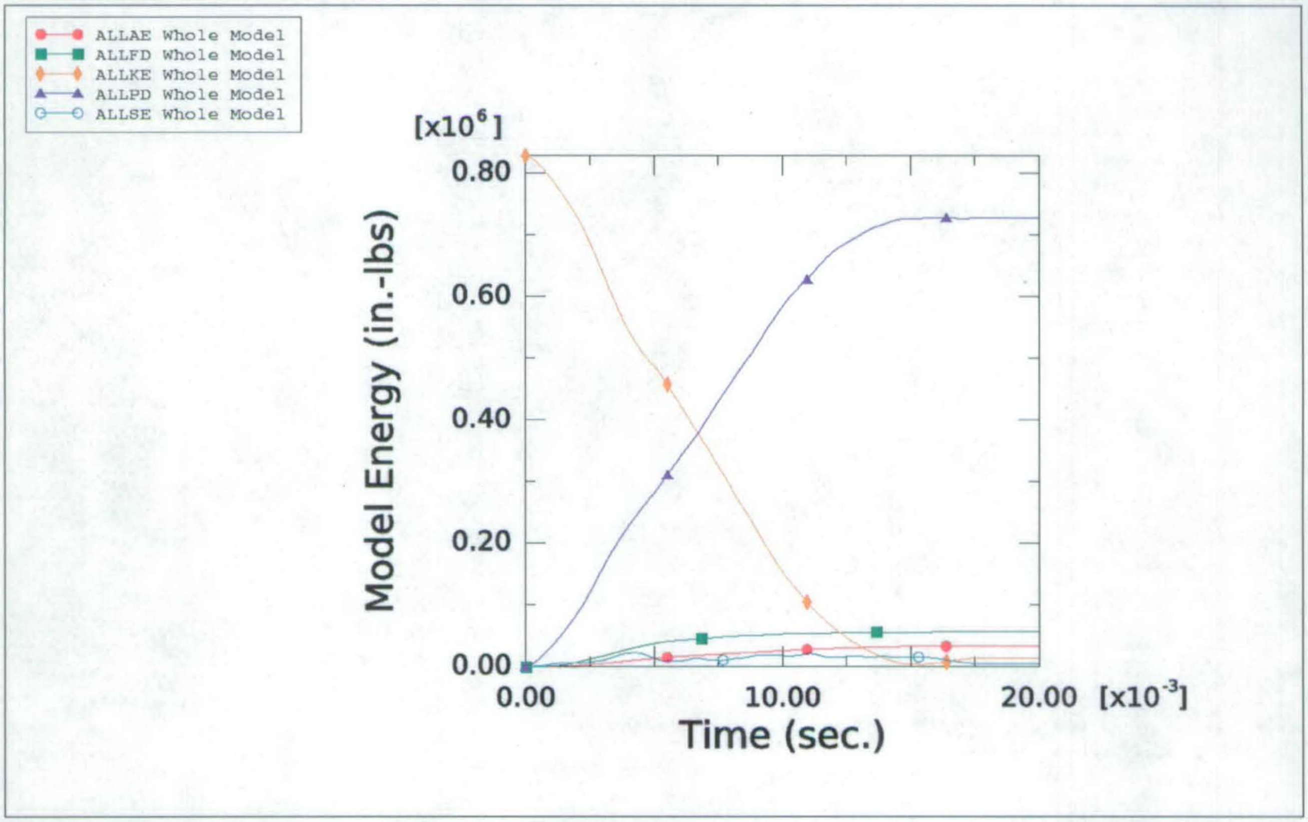


Figure 41. 18-inch standardized canister model energies, 3 deg. off-vertical drop, 300°F.

9.1.2. Analytical Predictions of Deformations

Figure 42 shows the bottom of the 18-inch standardized canister as it is just rebounding off the rigid surface. The impacting skirt shows the expected buckling pattern, consistent with previous analyses and actual drop testing.

9.1.3. Analytical Predictions of Material Strains

During this canister drop event, the majority of the kinetic energy at impact was transformed into plastic work in the material. The best measure of that plastic work was the equivalent plastic strain, which was a cumulative strain measure that takes into account the entire deformation history. The equivalent plastic strain is defined as:

$$\varepsilon^{pl} = \int_0^t \left(\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl} \right)^{1/2} dt$$

The equivalent plastic strain is, therefore, never decreasing and always positive (straining occurred, whether caused by tension, compression, or shear).

Table 13 shows the peak equivalent plastic strains (PEEQ) in the containment boundary of the 18-inch standardized canister. The strain was calculated at three positions through the thickness of a component: at the outside surface, middle, and inside surface. (Strains discussed in this report, unless specifically referred to as another type of strain, are always equivalent plastic strains.)

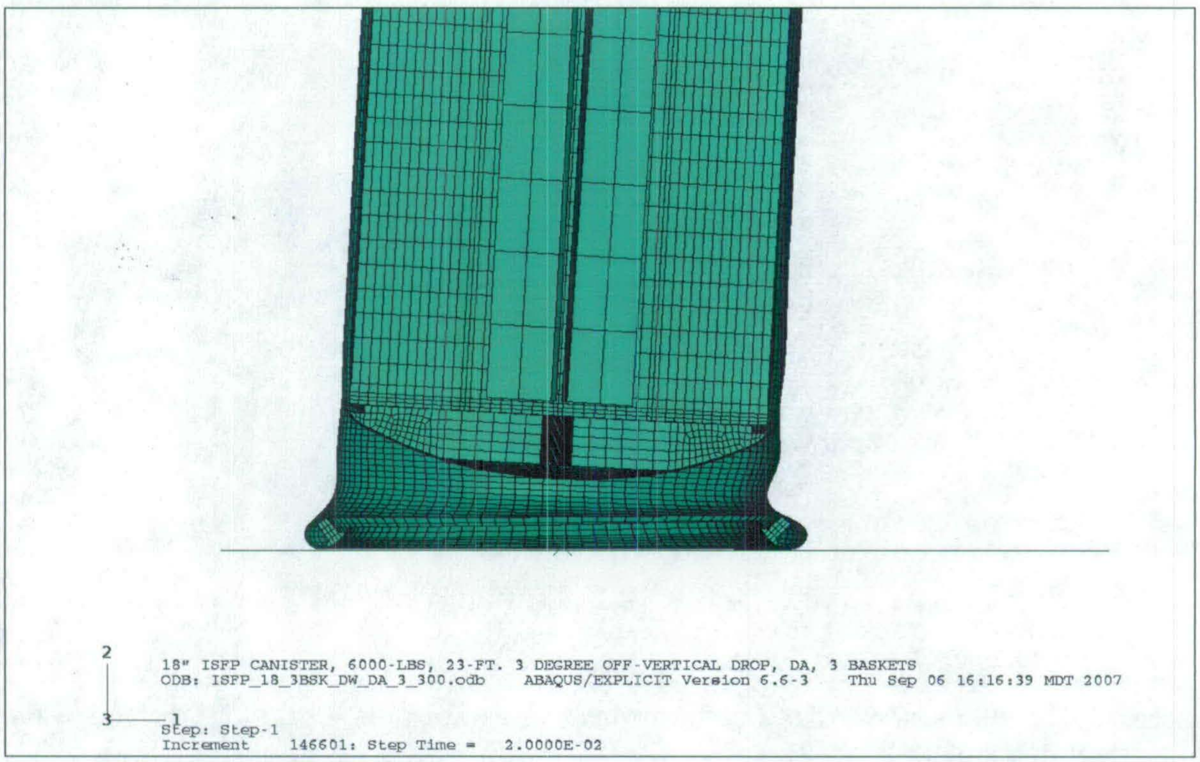


Figure 42. 18-inch standardized canister deformed shape, 3 deg. off-vertical drop, 300°F.

Table 13. 18-inch standardized canister containment PEEQ strains, 3 deg. off-vertical drop, 300°F.

Component	Peak Equivalent Plastic Strains (PEEQ, %)[1,2]		
	Outside Surface	Middle	Inside Surface
Lower Head	8	3	6
Lower Head-to-Main Shell Weld	2	2	3
Main Shell	2	2	3
Upper Head-to-Main Shell Weld	0	0	0
Upper Head	1[3]	0.2[3]	2[3]

1. Peak strains did not necessarily occur at the same location through the thickness.
2. Note that all strains in this report were post-processed using integration point data extrapolated to the nodes and then averaged at the nodes using 100% weighting factor.
3. Strains in upper head due to the upper impact plate bearing on the retaining ring welded to the inside of the upper head.

Figures 43 through 46 showed these PEEQ strains on the surface with the largest strain for the Table 13 components.

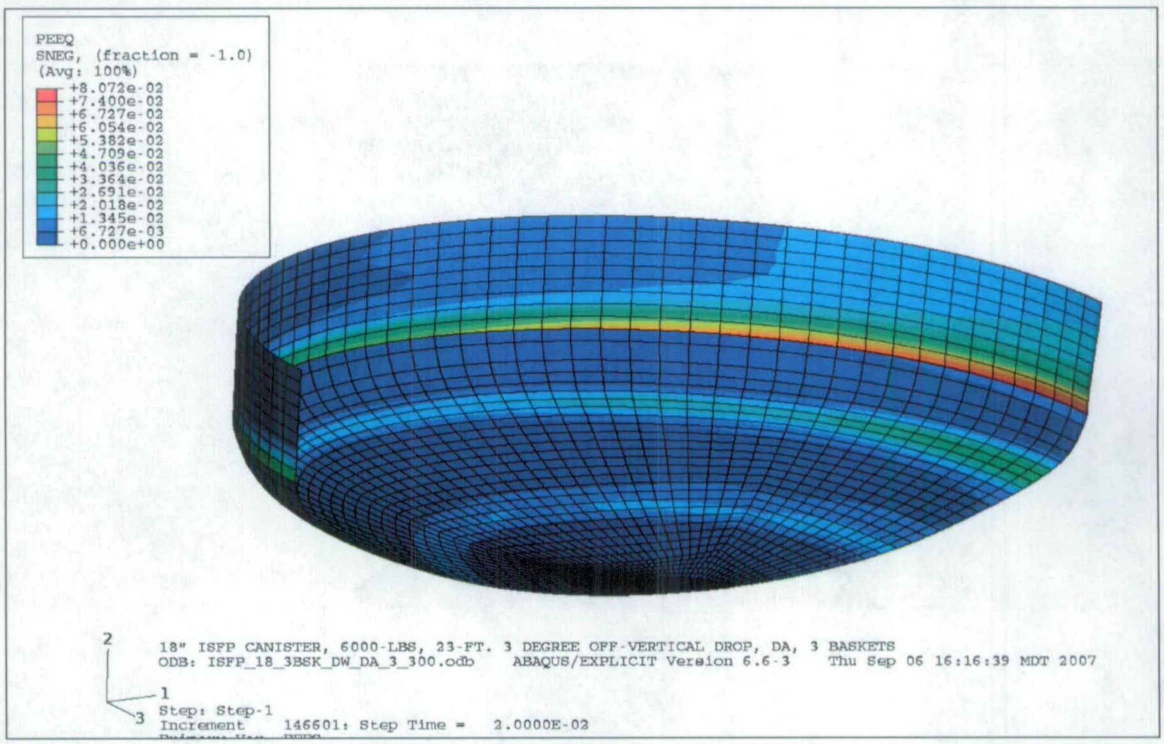


Figure 43. 18-inch standardized canister lower head strains – outside surface, 3 deg. off-vertical drop, 300°F.

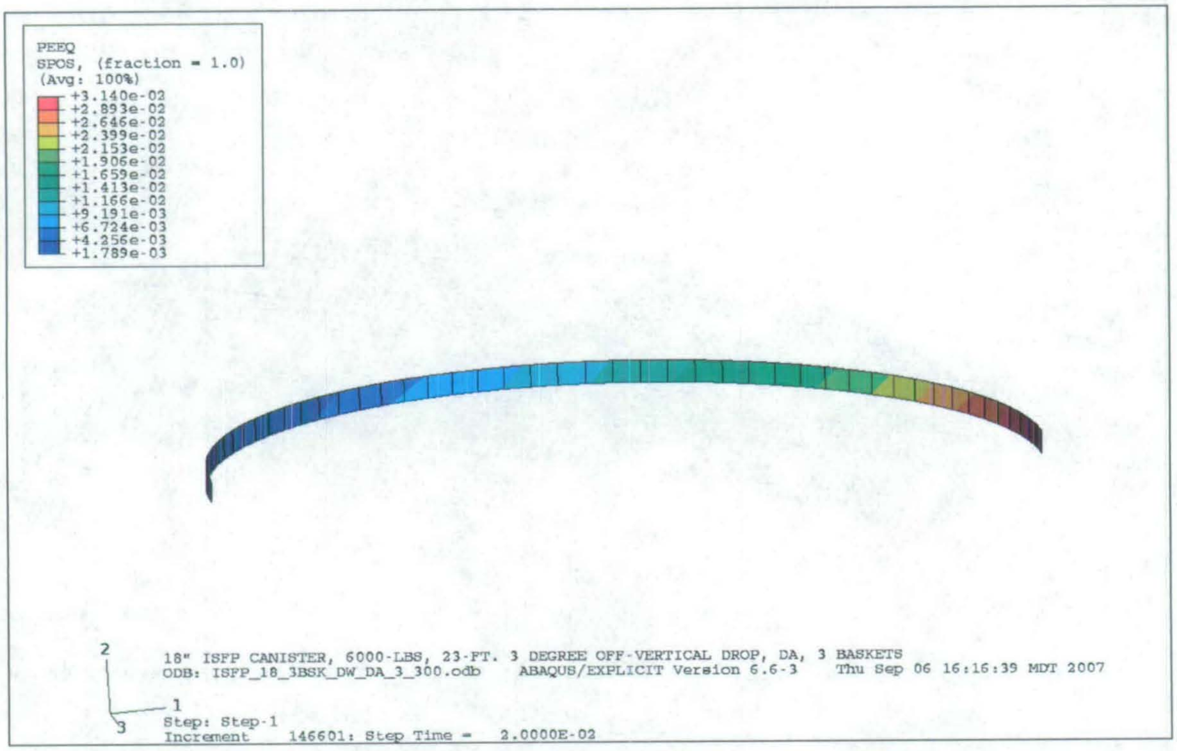


Figure 44. 18-inch standardized canister lower head-to-main shell weld strains – inside surface, 3 deg. off-vertical drop, 300°F.

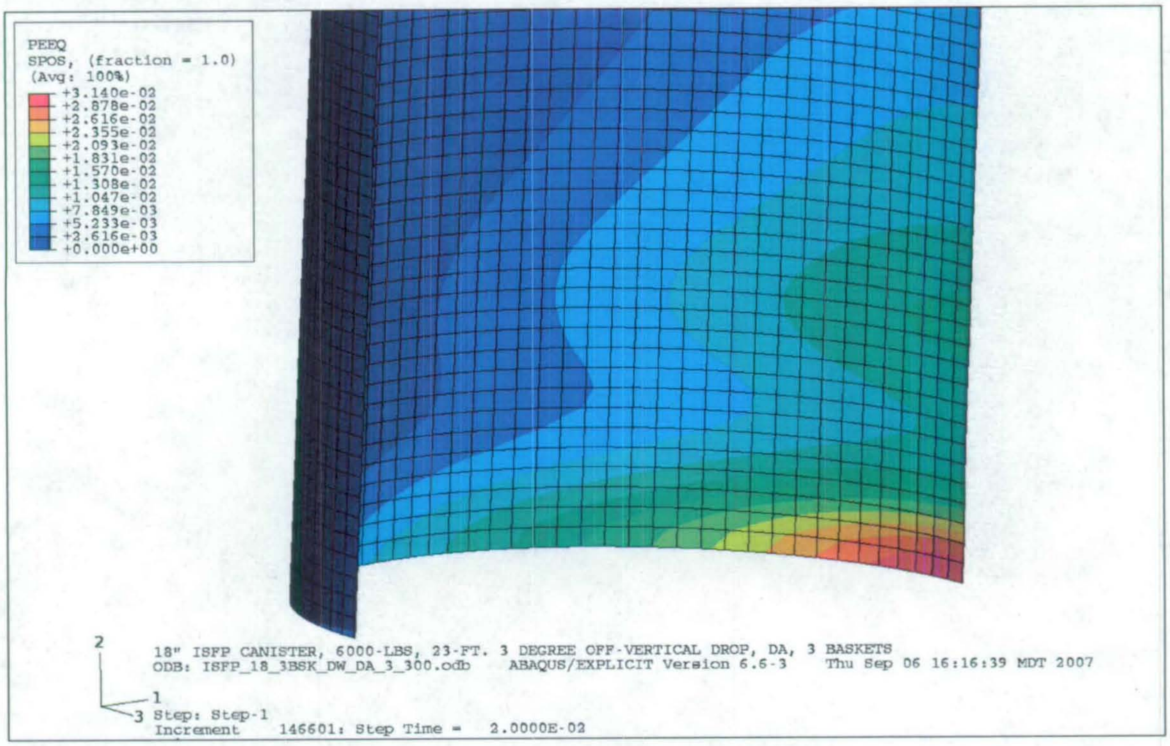


Figure 45. 18-inch standardized canister main shell strains – inside surface, 3 deg. off-vertical drop, 300°F.

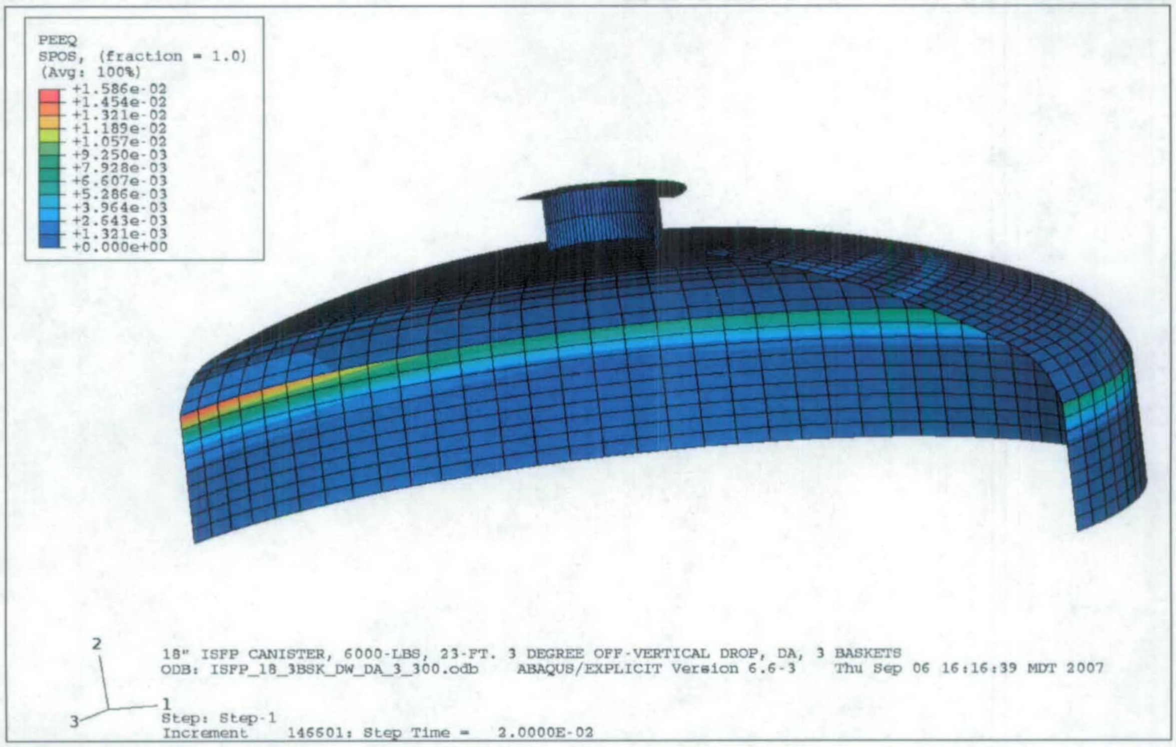


Figure 46. 18-inch standardized canister upper head strains – inside surface, 3 deg. off-vertical drop, 300°F.

9.2. 24-Inch Standardized DOE SNF Canister

9.2.1. Analytical Model Energy History

Figure 47 shows a plot of the energy history for this 3 degrees off-vertical drop event. The plot shows model artificial energy history (ALLAE), frictional dissipation history (ALLFD), kinetic energy history (ALLKE), plastic dissipation history (ALLPD), and elastic energy history (ALLSE). At the beginning of the event the model showed a high kinetic energy (ALLKE curve) with all other energies at zero. As the canister impacted the rigid surface kinetic energy was then expended primarily by way of plastic deformation (ALLPD curve). At 15 milliseconds after impact the kinetic energy was all expended and the canister started to rebound off the surface due to the small amount of elastic energy (ALLSE curve). Note that a small fraction of the kinetic energy was also expended in frictional dissipation (ALLFD curve).

Artificial energy was the amount of drop energy used (taken away from the total model energy) to prevent finite element numerical instabilities. An artificial energy total of 3% - 6% for a drop evaluation is typical – results are considered valid. Figure 47 shows the artificial energy (ALLAE curve) at about (0.032/1.38 =) 2% at the end of the evaluation. Therefore, this artificial energy was acceptable – results from the model were considered valid.

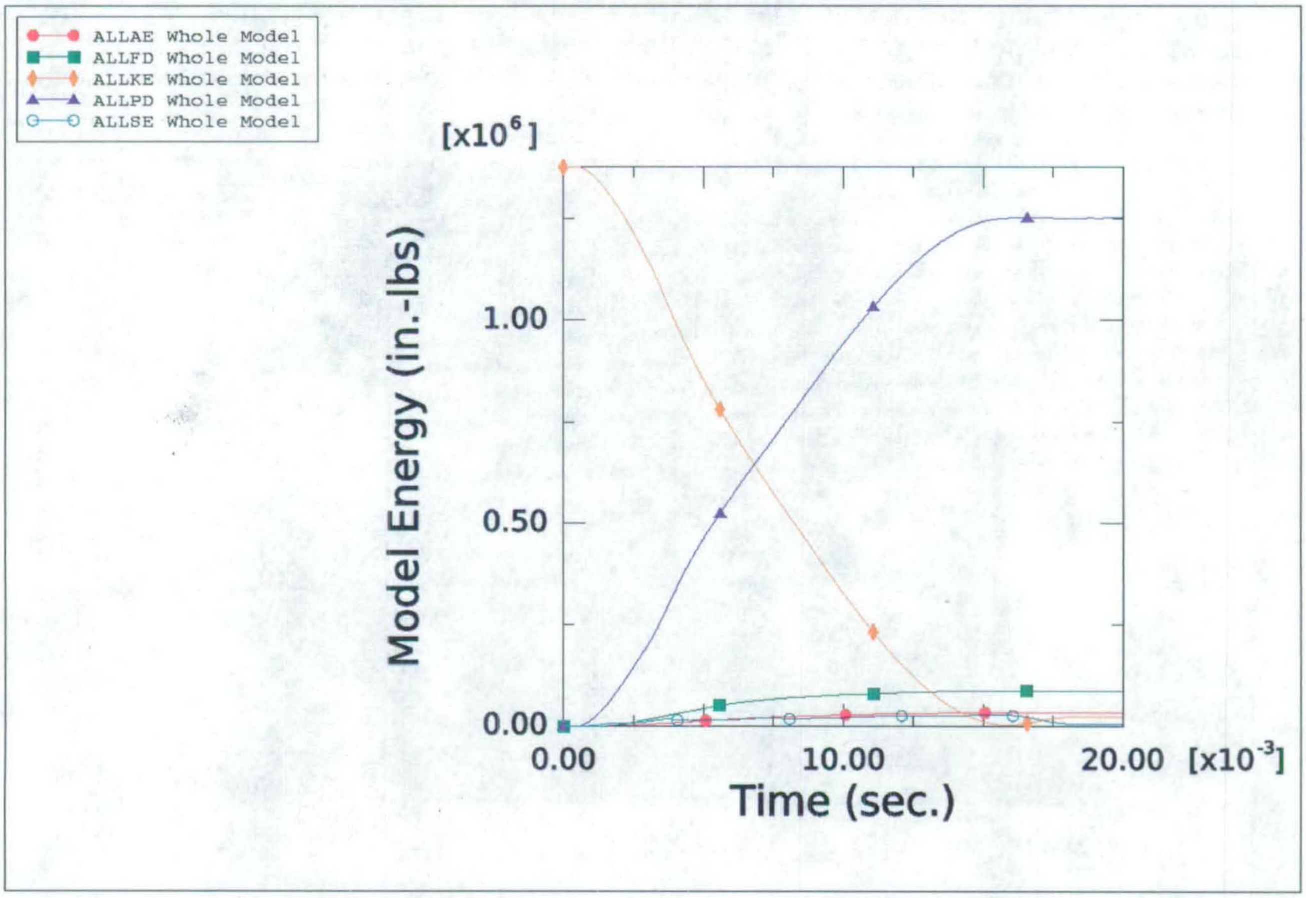


Figure 47. 24-inch standardized canister model energies, 3 deg. off-vertical drop, 300°F.

9.2.2. Analytical Predictions of Deformations

Figure 48 shows the bottom of the 24-inch standardized canister as it is just rebounding off the rigid surface. The impacting skirt shows the expected buckling pattern, consistent with previous analyses.

9.2.3. Analytical Predictions of Material Strains

During this canister drop event, the majority of the kinetic energy at impact was transformed into plastic work in the material. The best measure of that plastic work was the equivalent plastic strain, which was a cumulative strain measure that takes into account the entire deformation history. The equivalent plastic strain is defined as:

$$\varepsilon^{pl} = \int_0^t \left(\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl} \right)^{1/2} dt$$

The equivalent plastic strain is, therefore, never decreasing and always positive (straining occurred, whether caused by tension, compression, or shear).

Table 14 shows the peak equivalent plastic strains (PEEQ) in the containment boundary of the 24-inch standardized canister. The strain was calculated at three positions through the thickness of a component: at the outside surface, middle, and inside surface. (Strains discussed in this report, unless specifically referred to as another type of strain, are always equivalent plastic strains.)

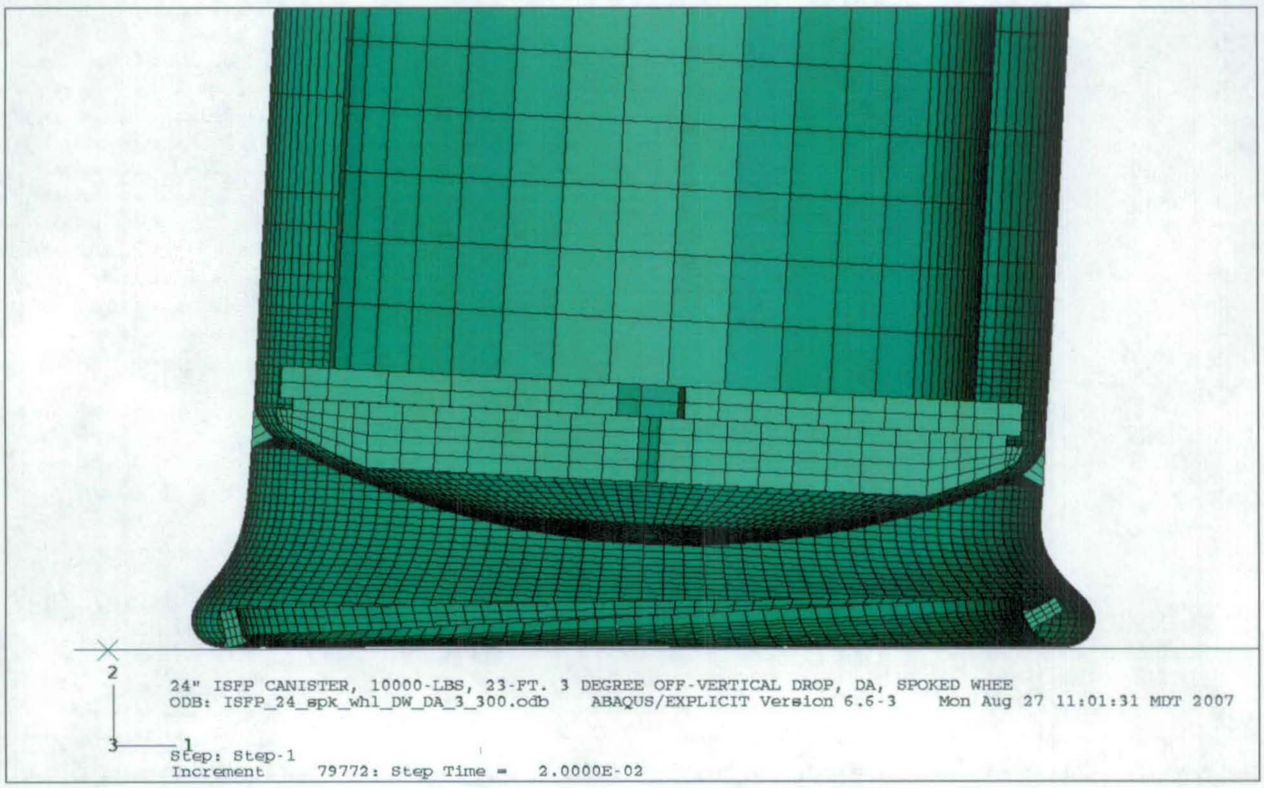


Figure 48. 24-inch standardized canister deformed shape, 3 deg. off-vertical drop, 300°F.

Table 14. 24-inch standardized canister containment PEEQ strains, 3 deg. off-vertical drop, 300°F.

Component	Peak Equivalent Plastic Strains (PEEQ, %)[1,2]		
	Outside Surface	Middle	Inside Surface
Lower Head	2	0.7	1
Lower Head-to-Main Shell Weld	0.2	0.3	0.5
Main Shell	0.2	0.3	0.5
Upper Head-to-Main Shell Weld	0	0	0
Upper Head	0	0	0

1. Peak strains did not necessarily occur at the same location through the thickness.
2. Note that all strains in this report were post-processed using integration point data extrapolated to the nodes and then averaged at the nodes using 100% weighting factor.

Figures 49 through 51 showed these PEEQ strains on the surface with the largest strain for the Table 14 components.

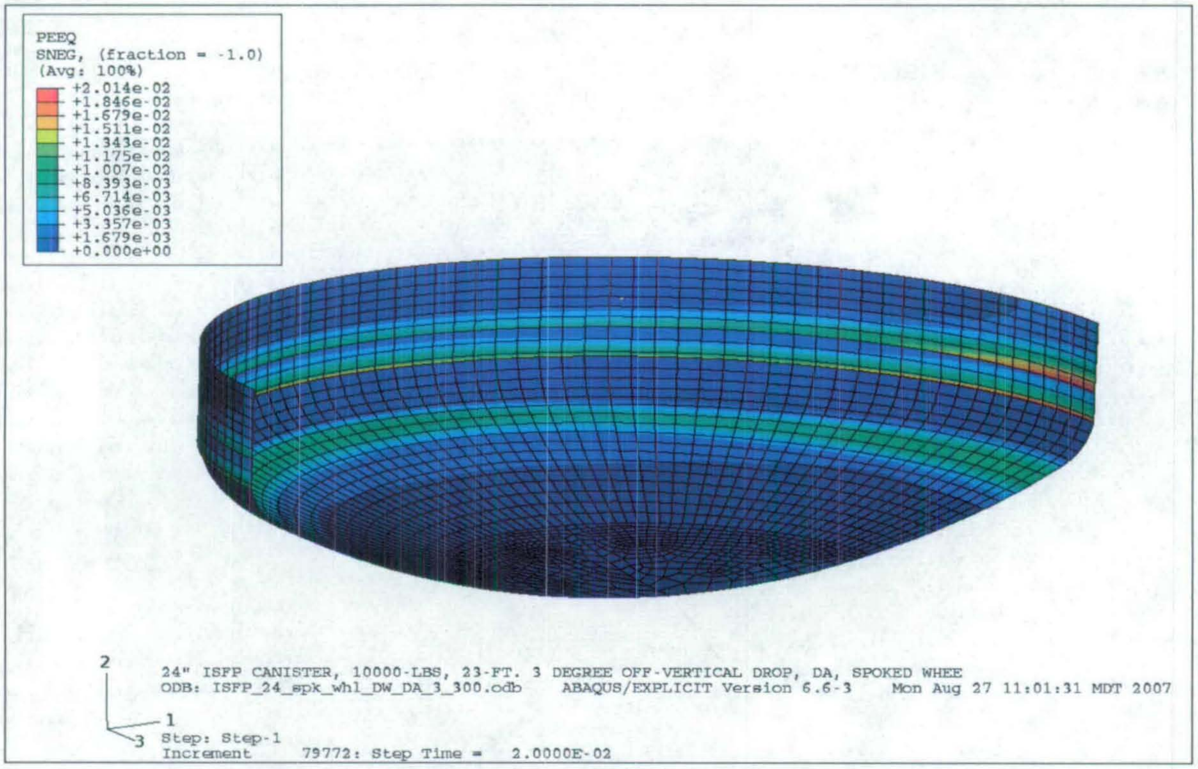


Figure 49. 24-inch standardized canister lower head strains – outside surface, 3 deg. off-vertical drop, 300°F.

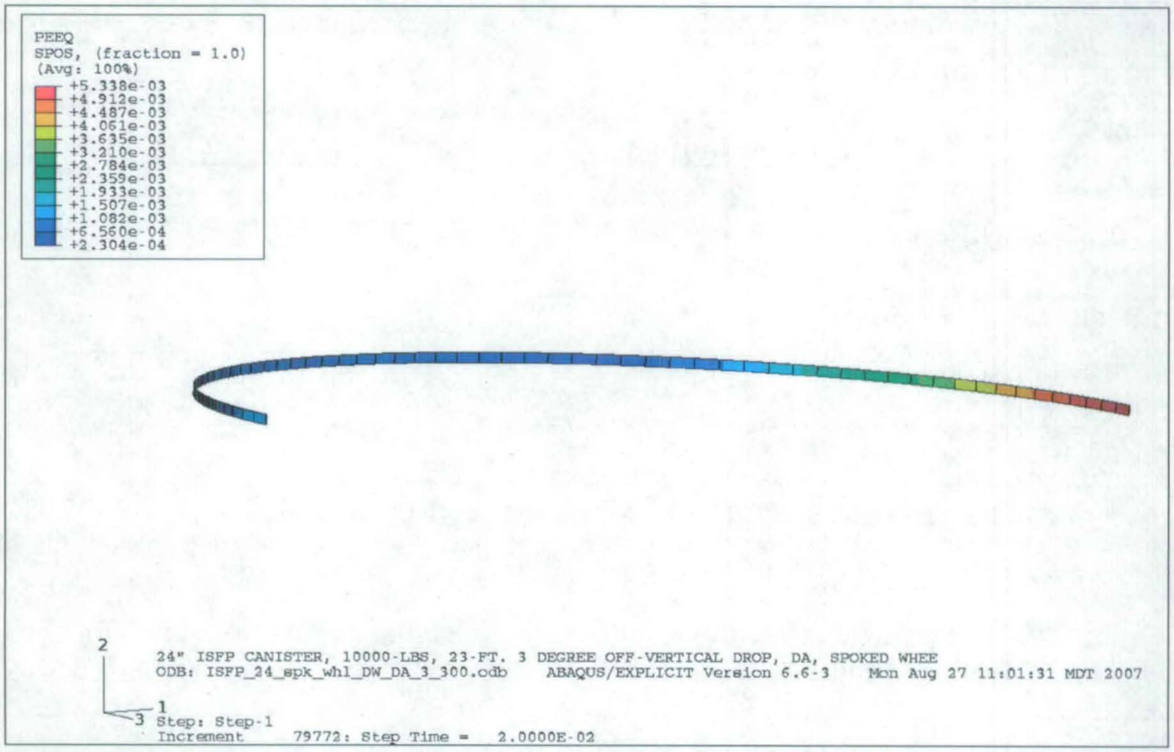


Figure 50. 24-inch standardized canister lower head-to-main shell weld strains – inside surface, 3 deg. off-vertical drop, 300°F.

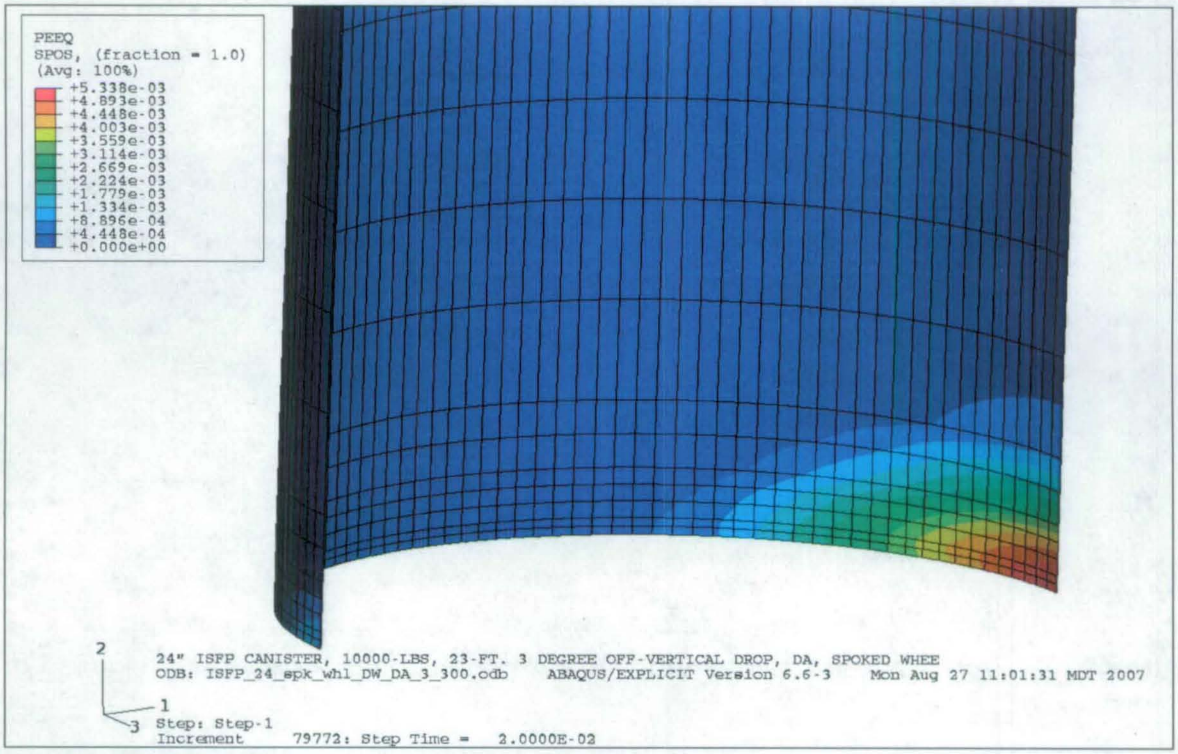


Figure 51. 24-inch standardized canister main shell strains – inside surface, 3 deg. off-vertical drop, 300°F.

9.3. MCO

9.3.1. Analytical Model Energy Histories

Figure 52 shows a plot of the energy history for the MCO in the 3 degrees off-vertical drop event. The plot shows model artificial energy history (ALLAE), frictional dissipation history (ALLFD), kinetic energy history (ALLKE), plastic dissipation history (ALLPD), and elastic energy history (ALLSE). At the beginning of the event the model showed a high kinetic energy (ALLKE curve) with all other energies at zero. As the MCO impacted the rigid surface kinetic energy was then expended primarily by way of plastic deformation (ALLPD curve) of the MCO main shell and bottom. However, at about 5 milliseconds the MCO structure itself had come to rest while the internal baskets and fuels continued to decelerate, causing significant plastic deformation of the bottom basket. At 60 milliseconds after impact the kinetic energy was all expended and the MCO started to rebound off the surface due to the small amount of elastic energy (ALLSE curve). Note that a small fraction of the kinetic energy was also expended in frictional dissipation (ALLFD curve).

Artificial energy was the amount of drop energy used (taken away from the total model energy) to prevent finite element numerical instabilities. An artificial energy total of 3% - 6% for a drop evaluation is typical – results are considered valid. Figure 52 shows the artificial energy (ALLAE curve) at about (0.050/2.80 =) 2% at 5 milliseconds when the MCO structure came to rest. The artificial energy increased to (0.263/2.80 =) 9% by 60 milliseconds, which represented the energy required to prevent numerical instabilities while the bottom basket was undergoing large plastic deformations. Because the artificial energy was only 2% during the MCO structure deformations, which were of primary interest in this evaluation, the results for the MCO structure are considered valid.

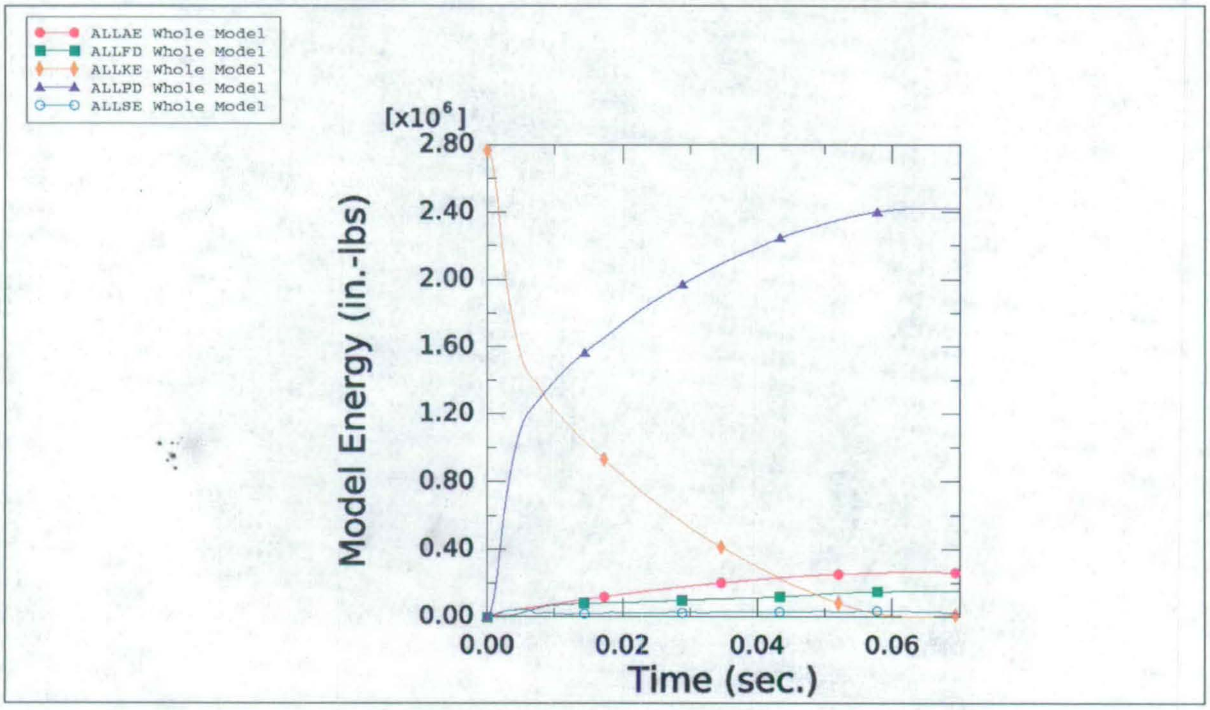


Figure 52. MCO model energies, 3 deg. off-vertical drop, 240°F.

9.3.2. Analytical Predictions of Deformations

Figure 53 shows the bottom of the MCO as it is just rebounding off the rigid surface. The main shell near the impacting bottom shows the expected bending pattern, consistent with previous analyses, though not as pronounced as for the 70°F, 3 degrees off-vertical drop event (see Reference 16).

9.3.3. Analytical Predictions of Material Strains

During this MCO drop event, the majority of the kinetic energy at impact was transformed into plastic work in the material. The best measure of that plastic work was the equivalent plastic strain, which was a cumulative strain measure that takes into account the entire deformation history. The equivalent plastic strain is defined as:

$$\varepsilon^{pl} = \int_0^t \left(\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl} \right)^{1/2} dt$$

The equivalent plastic strain is, therefore, never decreasing and always positive (straining occurred, whether caused by tension, compression, or shear).

Table 15 shows the peak equivalent plastic strains (PEEQ) in the containment boundary of the MCO. The strain was calculated at three positions through the thickness of a component: at the outside surface, middle, and inside surface.

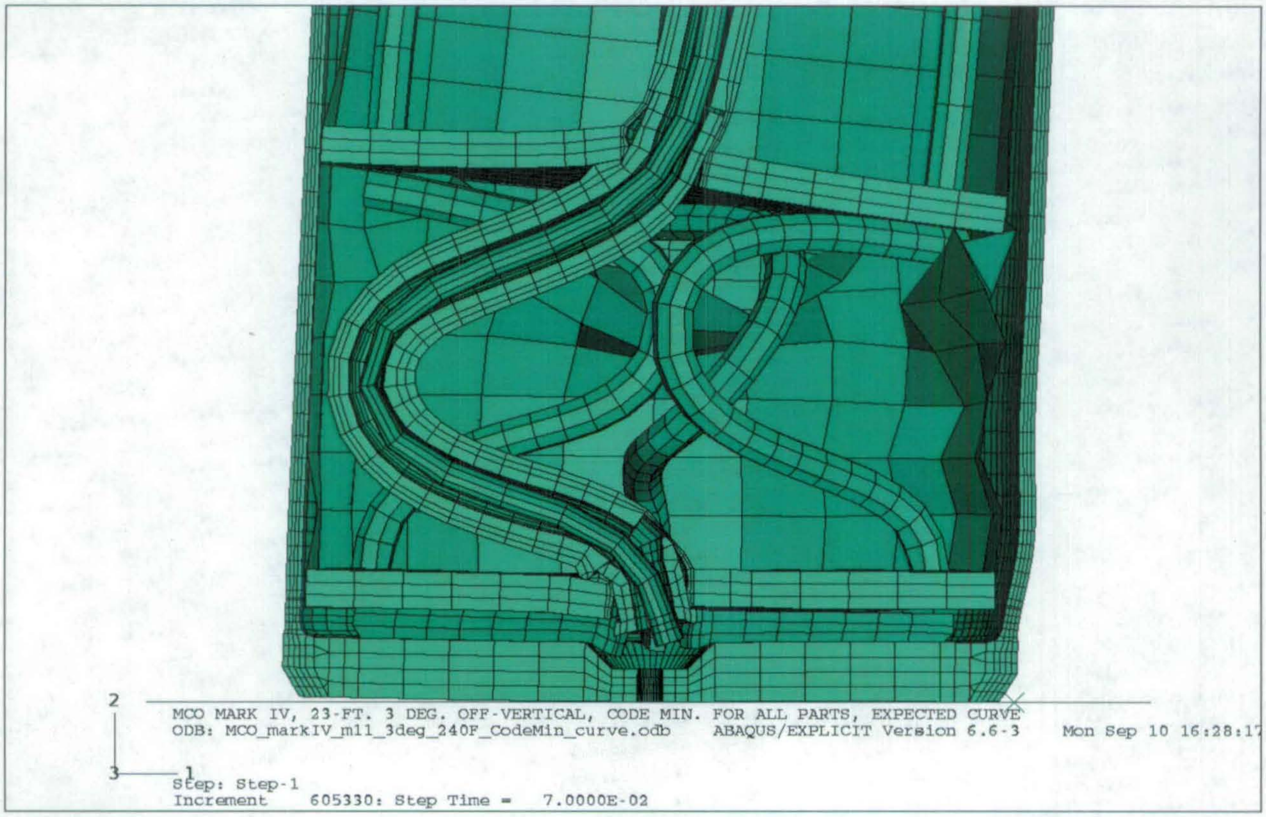


Figure 53. MCO deformed shape, 3 deg. off-vertical drop, 240°F.

Table 15. MCO containment PEEQ strains, 3 deg. off-vertical drop, 240°F.

Component	Peak Equivalent Plastic Strains (PEEQ, %)[1]		
	Outside Surface	Middle	Inside Surface
Bottom	8	6	3
Bottom-to-Main Shell Weld	8	6	3
Main Shell	5	6	8
Collar	0	0	0
Cover	0	0	0

1. All strains in this report were post-processed using integration point data extrapolated to the nodes and then averaged at the nodes using 100% weighting factor.

Figures 54 through 56 showed these PEEQ strains.

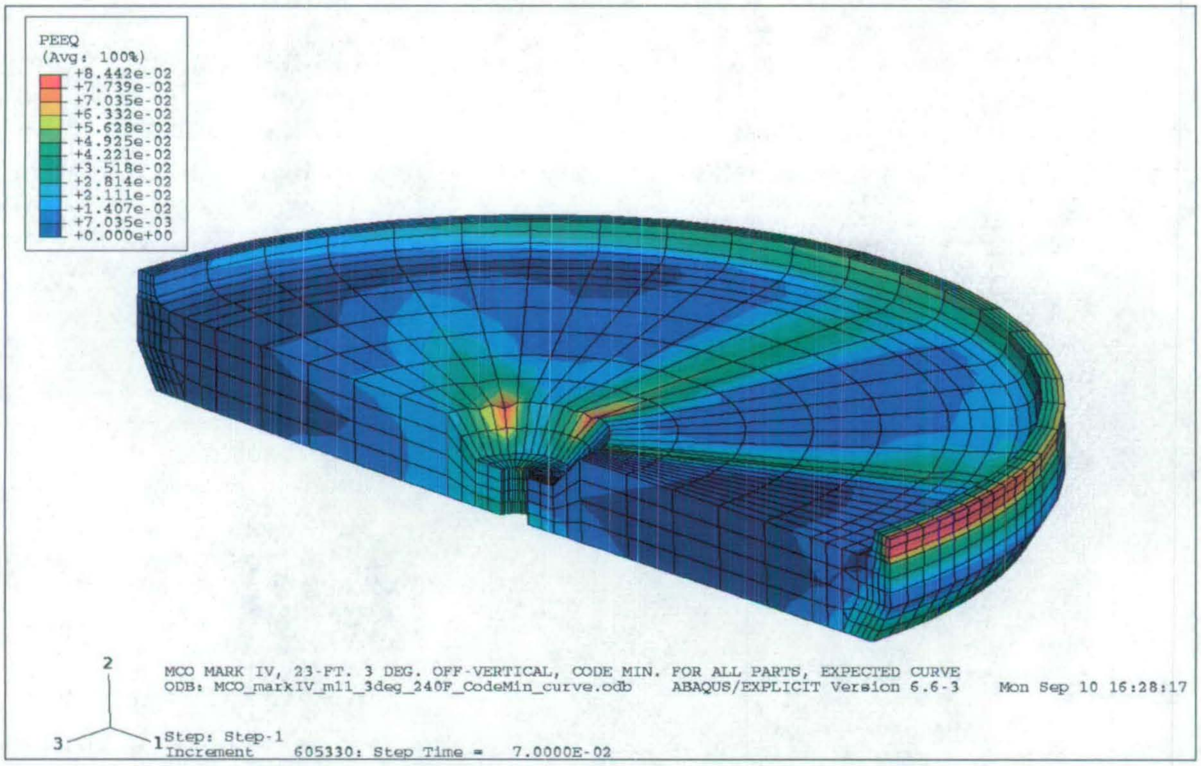


Figure 54. MCO bottom strains – outside surface, 3 deg. off-vertical drop, 240°F.

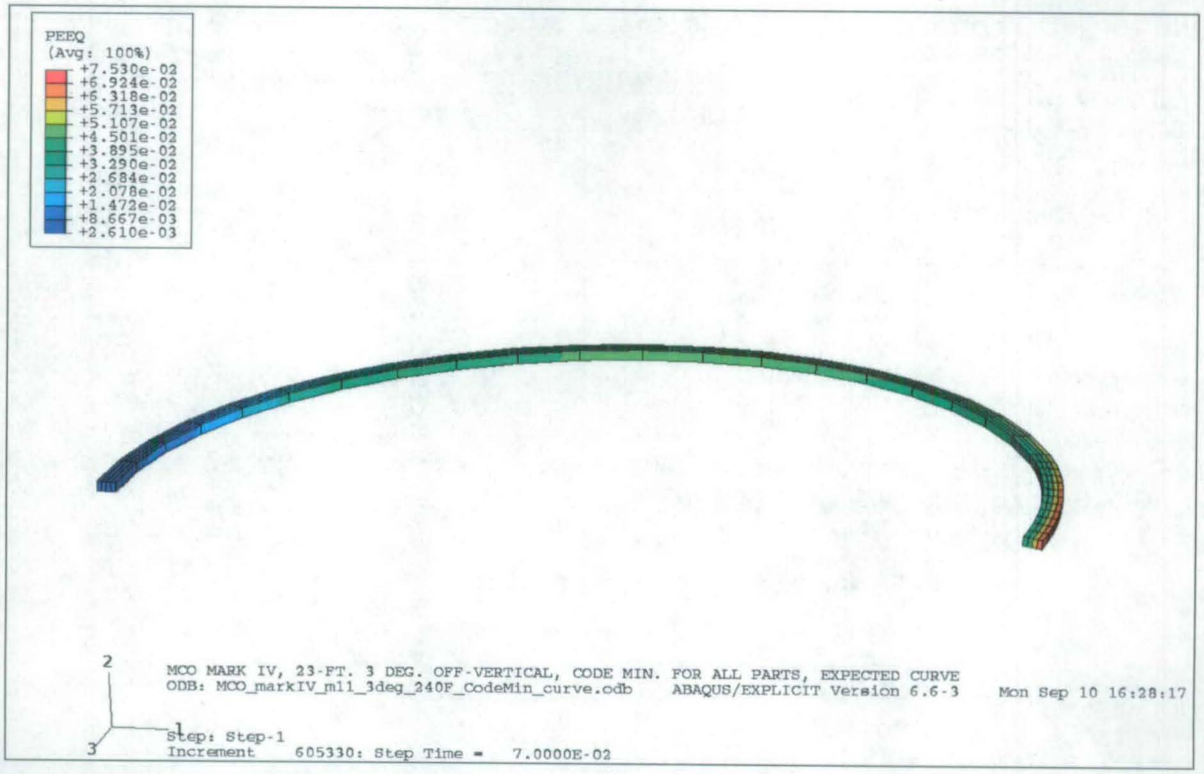


Figure 55. MCO bottom-to-main shell weld strains – inside surface, 3 deg. off-vertical drop, 240°F.

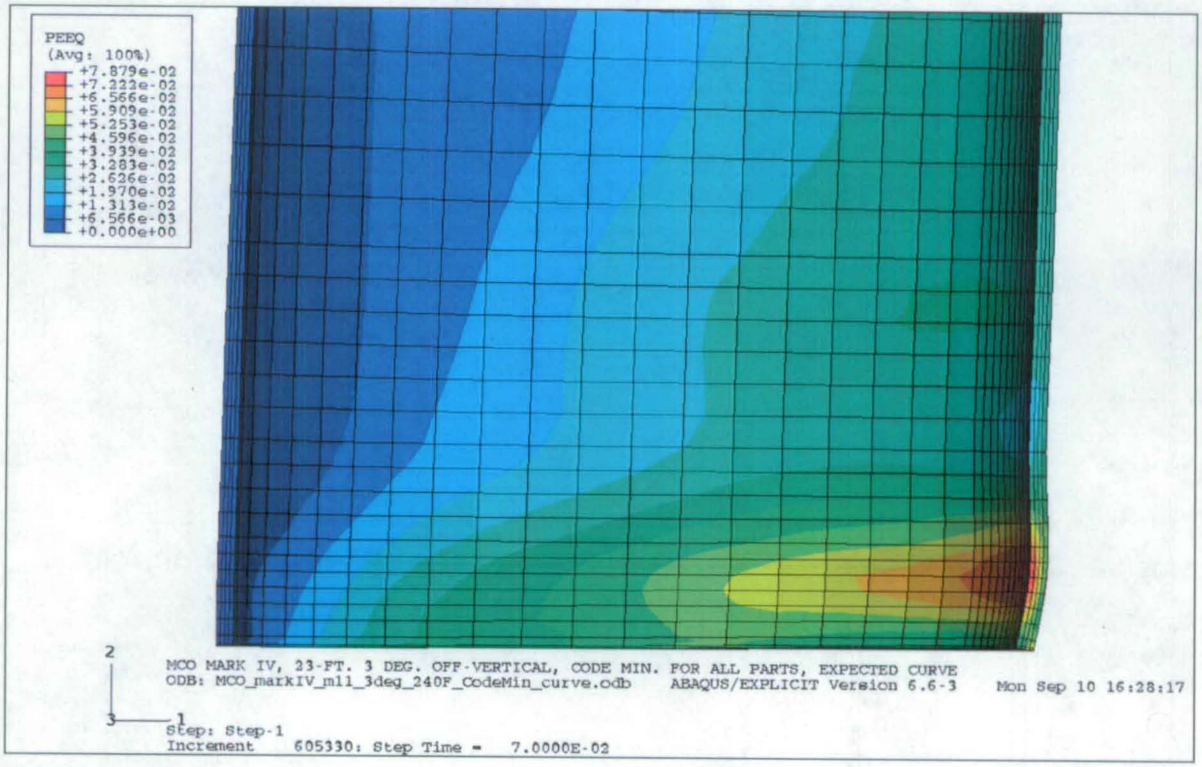


Figure 56. MCO main shell strains – inside surface, 3 deg. off-vertical drop, 240°F.

It is noted that the strains resulting in the MCO for this 3 degrees off-vertical drop event at 240°F were smaller that those reported previously for the same drop event at 70°F (Reference 16). The 70°F drop evaluation resulted in a buckling of the MCO main shell near the bottom that caused higher local strains. This current 240°F drop evaluation resulted in a bending of the MCO main shell near the bottom with local straining in addition to significant general straining above that location involving a large volume of shell material (as seen in Figure 56).

Why did the MCO main shell buckle in the 70°F event and not in the 240°F event? Buckling is dependent on component stiffness and a critical buckling stress. Considering stiffness, the geometry of the MCO did not change but the modulus of elasticity did because of the temperature change (28.3E6 psi at 70°F and a lower 27.3E6 psi at 240°F). Considering stress, the actual stress-strain curve at 70°F (employed in the Reference 16 evaluation) was much higher (stronger) than the 240°F curve based on ASME Code minimum strengths used herein. Therefore, the MCO at 240°F was less stiff and less strong compared to the 70°F MCO - and therefore less likely to buckle.

9.3.4. Recommendation for Probability Risk Evaluations

Because the 70°F MCO evaluation of Reference 16 resulted in higher material straining in the containment boundary, it is recommended that the probability risk evaluations employ the 70°F material strains. Table 16, below lists those strains from Reference 16, with supplemental data obtained from rerunning that FE model.

Table 16. MCO containment PEEQ strains, 3 deg. off-vertical drop at 70°F (Ref. 16).

Component	Peak Equivalent Plastic Strains (PEEQ, %)[1]		
	Outside Surface	Middle	Inside Surface
Bottom	35	16[2]	14
Bottom-to-Main Shell Weld	21	11	11
Main Shell	13	15[2]	29
Collar	0	0[2]	0
Cover	0[2]	0[2]	0[2]

1. Strains reported in this table were from Reference 16, Table 5, last row, for the MCO with Mark IV baskets under a 23-foot drop at 3 deg. off-vertical, 70°F, unless otherwise noted.
2. Strain values obtained from a rerun of the Reference 16 FE model.

10. CONCLUSIONS

The 18-inch standardized DOE SNF canister, the 24-inch standardized DOE SNF canister, and the MCO have been evaluated for a 23-foot drop, oriented at 3 degrees off-vertical, onto a flat, rigid surface. The canister temperatures employed were the maximum expected during handling at the repository: 300°F for the 18-inch and 24-inch standardized canisters and 240°F for the MCO. The total canister weights were the maximum design weights: 6,000 pounds for the 18-inch standardized canister; 10,000 pounds for the 24-inch standardized canister; 20,000 pounds for the MCO.

The containment boundary strains resulting from these drop events are to be used as input for probability risk assessments. It is recommended that the results shown in Tables 13 and 14 be employed for the standardized canisters and that the results from Table 16 be used for the MCO, as discussed herein.

11. ANALYTICAL MODEL FILES

The following table lists the names and dates for the analytical models employed in this report, as written out to a DVD. This data is being provided in accordance with NSNFP 19.03 (Reference 31). Mr. D. K. Morton checked the DVD for readability.

Table 17. Analytical model files.

ISFP_18_3BSK_DW_DA_3_300.inp	8,346 KB	INP File	9/6/2007 9:59 PM
ISFP_18_3BSK_DW_DA_3_300.odb	410,431 KB	ABAQUS ODB File	9/7/2007 8:48 AM
ISFP_24_spk_whl_DW_DA_3_300.inp	3,743 KB	INP File	8/27/2007 6:00 PM
ISFP_24_spk_whl_DW_DA_3_300.odb	201,198 KB	ABAQUS ODB File	8/27/2007 10:38 PM
MCO_markIV_m11_3deg_240F_CodeMin_curve.inp	5,205 KB	INP File	9/10/2007 11:27 PM
MCO_markIV_m11_3deg_240F_CodeMin_curve.odb	124,278 KB	ABAQUS ODB File	9/11/2007 6:27 PM
MCO_markIV_m11_3deg_mass.inp	5,206 KB	INP File	8/29/2003 10:11 PM
MCO_markIV_m11_3deg_mass.odb	92,937 KB	ABAQUS ODB File	8/30/2007 11:13 AM

12. REFERENCES NOT READILY AVAILABLE

Reference 6:

Brett W Carlsen/BCARLSEN/CC01/INEEL/US
08/01/2007 04:23 PM

To: michael_frank@notes.ymp.gov
cc: Thomas J Hill/TJH/CC01/INEEL/US@INEL, Dana K Morton/DXM/CC01/INEEL/US@INEL, Spencer D Snow/SDS/CC01/INEEL/US@INEL,
bcc:
Subject: Fw: Canister calcs

History: This message has been replied to.

By 8/31 we'll provide results for an end drop for an 18" diameter by 15' long standardized canister, a 24" diameter by 15' long standardized canister, and an MCO using the following inputs.

1) Drop height = 23 ft onto an unyielding surface (from bottom of canister to impact surface)
2) Drop orientation is 3 degrees off-vertical
3) Temperature = 300F for standardized canisters and 240F for MCOs.

Based on the calcs, only two of the ~600 fuels exceeded will exceed 300F in your handling environment (assumed at 120F). And both these were based on very conservative bounding source term assumptions. The overwhelming majority of the fuels were at 150F or less. We conservatively selected the 300F temperature for the analyses because it is the design temperature for canister operations. In other words, if any of the canisters are above this temperature when the transportation cask is opened. Handling procedures will prohibit lifting them until they have cooled to below 300F.

Similarly, the 240F temperature was selected because it is specified as the maximum operating temperature for the MCOs.

4) Total Weight =	6,000lbs	18" x 15' standardized canister (maximum expected load)
	10,000 lbs	24" x 15' standardized canister (maximum expected load)
	20,000 lbs	MCO (design load -- but actual loads are reasonably close to this limit)

Although the majority of the 18" x 15' canisters have a payload of 1000 lbs or less (i.e. total weight of ~4000lbs or less), some may approach the 6000 lb canister limit. There are only a handful (~20 canisters) of fuels slated for the 24" x 15' canisters but they approach the 10,000 lb design limit.

5) Material Strength = ASME minimums for canister materials
6) Strain Rate Effects = 1.2 factor to account for strain-rate hardening (supported by drop test resutls and by material impact testing)
7) Thicknesses = 12.5% underthickness (maximum fabrication allowance for pipe per ASME Code, which is conservative for plate material used in the heads)

By 9/30, we'll provide a referenceable Engineering Design File that will document the results and also will provide a qualitative discussion of the basis for concluding that it is reasonable to assume that these results are conservative relative to the canister on canister drop (case CN-4) from the scenarios provided to us by BSC.

INL
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Phone: (208) 526-3347 Fax: (208) 526-5337 Email: brett.carlsen@inl.gov

13. REFERENCES

1. B. D. Lorenz, et. al., *Multi-Canister Overpack Topical Report*, HNF-SD-SARR-005, Rev. 1, November 1999.

2. L. H. Goldman, et. al., *Multi-Canister Overpack Design Report*, HNF-SD-SNF-DR-003, Rev. 3, February 2000, with Rev. 3A (July 2000) and Rev. 3B (April 2002).

3. D. K. Morton, S. D. Snow, T. E. Rahl, *FY1999 Drop Testing Report for the 18-inch Standardized DOE SNF Canisters*, EDF-NSNF-007, Rev. 2, September 5, 2002.

4. D. K. Morton, S. D. Snow, *Drop Testing Representative Multi-Canister Overpacks*, EDF-NSNF-047, Rev. 0, January 28, 2005.

5. D. K. Morton, S. D. Snow, *Drop Testing Representative 24-inch Diameter Idaho Spent Fuel Project Canisters*, EDF-NSNF-045, Rev. 0, January 28, 2005.

6. Brett W. Carlsen email to Michael Frank, *Canister calcs*, 8/1/2007. (Included in Section 12.)

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