INEEL/CON-99-00136

ANALYTICAL EVALUATION OF PRELIMINARY DROP TESTS PERFORMED TO DEVELOP A ROBUST DESIGN FOR THE STANDARDIZED DOE SPENT NUCLEAR FUEL CANISTER[1]

Spencer D. Snow, D. Keith Morton,
A. G. (Jack) Ware, Tom E. Rahl, Nancy L. Smith
Lockheed Martin Idaho Technologies Company
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, Idaho 83415-3760
United States of America
(208) 526-8510, (208) 526-0425, sds@inel.gov

ABSTRACT

The Department of Energy (DOE) has developed a design concept for a set of standard canisters for the handling, interim storage, transportation, and disposal in the national repository, of DOE spent nuclear fuel (SNF). The standardized DOE SNF canister has to be capable of handling virtually all of the DOE SNF in a variety of potential storage and transportation systems. It must also be acceptable to the repository, based on current and anticipated future requirements. This expected usage mandates a robust design.

The canister design has four unique geometries, with lengths of approximately 10 feet or 15 feet, and an outside nominal diameter of 18 inches or 24 inches. The canister has been developed to withstand a drop from 30 feet onto a rigid (flat) surface, sustaining only minor damage - but no rupture - to the pressure (containment) boundary. The majority of the end drop-induced damage is confined to the skirt and lifting/stiffening ring components, which can be removed if desired after an accidental drop. A canister, with its skirt and stiffening ring removed after an accidental drop, can continue to be used in service with appropriate operational steps being taken.

Features of the design concept have been proven through drop testing and finite element analyses of smaller test specimens. Finite element analyses also validated the canister design for drops onto a rigid (flat) surface for a variety of canister orientations at impact, from vertical to 45 degrees off vertical. Actual 30-foot drop testing has also been performed to verify the final design, though limited to just two full-scale test canister drops. In each case, the analytical models accurately predicted the canister response.

INTRODUCTION

This paper briefly documents the efforts to date associated with the development of the standardized DOE SNF canisters, and summarizes the analysis and testing performed in support of the design concept. The design concept will be shown to be robust (structurally sound under varying drop conditions) and drop resistant. The goals of this effort were:

- To develop a robust canister design concept that would contain DOE SNF after an accidental drop event (from a 30-ft. drop height) onto a flat surface,
- To prove the design concept by use of finite element analysis methods to predict the deformations, material strains, etc., in test specimens and representative canisters for a variety of drop orientations and drop heights onto a rigid surface,
- To validate the design concept and finite element analyses by performing limited drop testing on actual test specimens and representative canisters, and follow up with pressure testing to demonstrate the pressure boundary integrity,
- To show that the design concept maintains large factors of safety against rupture during an accidental drop event through analysis and testing.

Two additional papers (Morton, 1999, and Rahl, 1999) discuss other aspects of the standardized DOE SNF canister work.

DESIGN CONCEPT FOR DOE SNF CANISTERS

The design concept for the DOE SNF canister, shown in Fig.'s 1 and 2, includes the following:

[1]Work supported by the U. S. Department of Energy, Idaho Field Office, under DOE Contract No. DE-AC07-94ID13223.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

- Body made of seamless or longitudinally-welded pipe (18-inch diameter by 3/8-inch nominally thick, or 24-inch diameter by ½-inch thick, 316L stainless steel),
- Heads are ASME flanged and dished (3/8-inch thick for the 18-inch canister, and ½-inch thick for the 24-inch canister, 316L stainless steel),
- Skirts made of seamless or longitudinally welded pipe to match the body in diameter and thickness (316L stainless steel), 8 inches long for the 18-inch canister and 9 inches long for the 24-inch canister,
- Lifting rings made of plate (316L stainless steel), 1-inch wide by ½-inch thick, located just within the outer end of each skirt,
- Interior impact plates made of 2-inch thick plate (A36 carbon steel), flat on one side for the contents to bear on and contoured on the other side to match the inside surface of the head,
- Weight limit of 6,000 lbs on the 18-inch canister, and 10,000 lbs on the 24-inch canister.

BASIC DESIGN CONCEPT PATH

A number of considerations were made in developing the design concept for the DOE SNF canisters. Qualitative results of analytical models used to investigate design concept alternatives will be discussed. Quantitative details will be minimized.

Material Selection

The material selection for the DOE SNF canisters was made with several factors in mind. First, the most demanding load on the canisters was expected to be the accidental drop, so a strong and ductile material was needed. Second, it was desirable to avoid the problems associated with intergranular stress corrosion cracking (IGSCC), making a low carbon material (base metal and welds) a requirement. Third, the canisters could be in a moist environment, and so a material with high corrosion resistance was a priority. Fourth, exotic materials would be more costly than commonly available materials. Many of these canisters might be manufactured and the use of more common materials, if they meet the structural requirements, would result in significant cost savings.

It appeared that a 304L stainless steel would satisfy the material selection requirements listed above, and was thus chosen for the DOE SNF design concept canisters. (304L material was used in the construction of the West Valley and Savannah River Site High Level Waste [HLW] canisters also.) This decision was made in October 1997.

In July 1998 the DOE SNF canisters were modified to use 316L stainless steel instead of 304L. This was because 316L has better resistance to hydrogen embrittlement than 304L.

The analyses discussed in this paper used 304L stainless steel for all canister structural components with the exception of the internal impact plates. Because the material strengths and ductility of 304L are comparable to 316L, the conclusions of this analysis and testing program are still valid for the DOE SNF canisters that now use 316L material.

Canister Body

The standardized DOE SNF canisters will be used in repository waste packages, transportation casks, and interim storage canisters and casks. A DOE SNF canister will be located within these other containers by placing one end in the package and then sliding (or lowering) the canister into position. If the canister design included anything that protruded from the canister body, then installation (and removal) within the other containers could be difficult. Therefore, it was desirable to make the canister body smooth – with no protrusions. This was easily achieved by making the canister body exterior cylindrical in shape.

A cylindrical canister body exterior was most easily produced using a standard pipe section. Using standard pipe sizes brought many advantages, including availability (does not require a special run at a mill, or the additional manufacturing efforts of rolling plates into a cylindrical shape and longitudinally seam-welding and circumferentially welding sections to obtain the required length) and, thus, cost savings.

Canister End Configurations

Canister ends could most easily and cost-effectively be produced by using standard (off-the-shelf-type) pressure vessel heads. The preliminary canister end options investigated were limited to four.

Each of these options and the advantages are briefly discussed in the next subsection. An analytical comparison of canisters with the four head configurations subject to drop events was made.

Reverse-Dished Head. The reverse-dished head option had several advantages that made it very attractive. For example, very little canister volume was taken up by the head configuration, implying that a smaller number of canisters would be needed to store a given quantity of spent fuel. The end configuration was simple - one component, one weld. The shape also provided a stable surface so that the canister would stand on its own when positioned vertically.

Hemispherical Head. The hemispherical head would provide many of the same advantages as the reverse-dished head, except that it would not be able to stand vertically on its own.

Hemispherical Head with Skirt. The hemispherical head with skirt option would add one more component and weld but would provide the stable surface for the canister to stand vertically on. Additionally, the skirt could provide space for some kind of lifting hook (or other device) without it protruding out from the cylindrical body.

Shallow Head with Skirt. The shallow head option represented a head with a dish radius that was larger than the pipe body to which it attached. This included elliptical, less than a hemispherical portion of a spherical, and other similar dished heads. This option had the advantages of the hemispherical head with skirt but allows for a larger radius on the head. Figure 3 shows the four head options considered in this evaluation.

Canister Analytical Evaluations

Analytical Models of Canister Concepts. Analytical models of the four preliminary canister concepts were created to assist in the evaluation of the head options. The following parameters were employed:

-Overall Length: 10-ft. or 15-ft.

-Contents Weight: 3,000-lb (for 10-ft.) and 4,500-lb (for 15-ft.)

-Component Thickness: ¼-in., 3/8-in., and ½-in.

-Drop Height: 15-ft. to 30-ft.

-Impact Surface: rigid and flexible

-Orientation Angles: 0°, ~6°, 15°, and 30° off of vertical

Details on the analytical models of these preliminary canister concepts will not be discussed in this paper. However, the modeling employed the I-DEAS software (SDRC, 1997), with non-linear analysis performed using ABAQUS/Explicit (HKS, 1997).

Analysis Results. Figures 4 through 7 show selected preliminary canister designs just before and after impact with a rigid surface. These selected canisters were 18 inches in outer diameter, ½-inch thick wall, 9-inch long skirt (if applicable), ½-inch thick lower head, 4,500 lbs in total weight (canister plus contents), and were dropped from 30 feet at an impact angle of 15° off vertical.

Several comments can be made about the deformed shapes of the selected preliminary canister designs. The deformations of the reverse-dished head, hemispherical, and hemispherical with skirt canisters were significant enough that interior volume for spent fuels would be reduced. Also, the hemispherical heads exhibited instability - they easily inverted (analogous to the soft contact lens problem). Such instability was not desirable. However, while the shallow head with skirt showed extensive permanent damage to the skirt, the containment (pressure) boundary showed little deformation.

This was made clear by examining the plastic strains in the canister components resulting from the drop event. The peak equivalent plastic strains in the pressure boundary of these canisters are shown in the following table with the strains in the skirts shown in parentheses.

Table 1. Peak Plastic Strains in Preliminary Canisters, 15° Drop Orientation, 30-ft. Drop Height

Surface	Peak Equivalent Plastic Strains on Pressure Boundary (Peak Strain in Skirt where Applicable)			
	Reverse Dished Head	Hemis-pherical Head	Hemis-pherical Head with Skirt	Shallow Head with Skirt
Inside	84%	38%	21% (52%)	13% (75%)
Middle	23%	15%	8% (21%)	3% (21%)
Outside	100%	43%	20% (62%)	13% (85%)

Table 1 shows that the pressure boundary in the shallow head with skirt canister was challenged the least during the drop event. This is shown in terms of plastic strain, which was much lower for the shallow head with skirt option than the others evaluated. This shallow head concept had an advantage in that after the accidental drop event, the damaged skirt could be cut off of the canister, and the canister could still be loaded into the repository waste package (transportation and interim storage casks as well).

The results for these preliminary canisters with different component thicknesses, loaded weights, drop heights, impact surfaces, and orientation angles, all confirmed that the shallow head with skirt option pressure boundary was damaged least in the drop events.

Therefore, the shallow head with skirt design option was recommended for incorporation into the design of the DOE SNF canister. The purpose of the skirt then became to absorb as much drop energy as possible to minimize the damage to the rest of the canister.

Lifting Ring

The lifting ring idea was developed later in the design/analysis process. It was desirable that some kind of lifting bracket be provided in the skirt area of the canister. After trying out several ideas, the concept of a ring was examined. The ring (1-in. wide by ½-inch thick) would add material to the skirt to absorb drop energy and could also be used to secure to a lifting apparatus.

Recommendations

Recommendations from these preliminary canister analyses were that the DOE SNF canisters be designed with the following features:

- All exterior components of the canisters be made of a 316L stainless steel material,
- A cylindrical body with either a seamless or longitudinal seam-welded pipe of standard size,
- Canister ends of identical design, consisting of (1) a standard ASME flanged and dished pressure vessel head, (2) a skirt made from standard pipe of sufficient length, and (3) a lifting ring,

DROP-TEST ANALYSES AND TESTING PERFORMED

Seven drop tests were performed on smaller drop test specimen designs (six 5-inch diameter x 3-foot long specimens, and one 18-inch diameter x 5-foot long specimen). Design insights learned from these tests and their application to the DOE SNF canisters are listed below. A report on the drop tests performed on two full-sized DOE SNF standardized canisters also follows. A comparison to analytical calculations will be presented.

5-Inch Diameter Drop-Test Specimens

Six 5-inch diameter test specimens were constructed using 36-inch long thin wall tubes. A flat plate was welded in the top and bottom of the tube to represent heads. A relatively thick interior plate was welded 3-inches from the bottom head to support the contents, which consisted of lengths of #4 rebar. All specimen materials, excluding the interior rebar, were 304L stainless steel. The weight of the test specimens was: one at 115 lbs, and the remaining five at 111 lbs.

The 5-inch diameter test specimens were initially oriented at 15° off vertical, and were dropped at heights of 10 feet, 15 feet, 20 feet, 25 feet, and 30 feet onto a "rigid" surface (2-inch steel plate on a thick concrete pad.) The test results and design insights gained are summarized as follows:

- The specimen damage was confined to the volume between the bottom head and the contents support plate. The bulk of the deformation occurred in the tube wall as a single outward bulge.
- Finite element models (using ABAQUS/Explicit) predicted the general deformed shape of the dropped specimens very well.
- Plastic straining of the drop-test specimens was calculated in the finite element models. The peak equivalent plastic strain levels increased with drop height, reaching a maximum of 86% (on a surface, 26% at mid-thickness) on the highest drop. However, pressure testing of all specimens after drop testing indicated that the pressure boundary had been maintained (25 psig pressure was held steady for 1 hour without loss).
- The drop-test specimens were oriented such that the impact point included the longitudinal seam in the tube wall. In all drop events, the tube longitudinal weld appeared to deform just as the surrounding base metal.
- Two design ideas/features were suggested for incorporation into the standardized DOE SNF canister. First, that an interior contents support (or impact) plate be included that was thick enough to minimize variations in deformation due to contents loading (local vs. distributed). Second, that the DOE SNF canisters include some material (e.g., a skirt) supported off the pressure boundary whose purpose was to absorb drop energy.

18-Inch Diameter Short Drop-Test Specimen

One 18-inch diameter test specimen was constructed using a 5-foot long thin wall tube (0.188-inch thick). A flat plate was welded to the tube top to form the top head. An 18-inch radius shallow head was inserted 7 inches into the bottom of the tube and welded in place. Two 3/8-inch thick stainless steel plates (impact plates) were placed inside the specimen on the lower head. The contents, consisting of #4 rebar and a lightweight interior structure, rested on the impact plates. All specimen materials, excluding the contents, were 304L stainless steel. The total weight of the specimen was about 1,000 lbs.

This test specimen included the two design recommendations of the previous section: the interior (impact) plate and the skirt (7-inch long tube past the lower head). The 18-inch diameter short specimen was oriented at 32° off vertical at impact and was dropped from a height of 30 feet onto a "rigid" surface (again, a 2-inch steel plate on a thick concrete pad). The test results, and design insights learned, are summarized as follows:

- The specimen damage was confined to the 7-inch long skirt. The skirt folded inward toward the lower head, buckling the skirt walls. However, the skirt did not impact the lower head and no damage was visible.
- It was determined, during the pre-test and post-test analytical (finite element) evaluations, that the value of the coefficient of friction on the rigid surface affected the calculated deformed shape of the specimen. A coefficient of 0.5 caused the skirt to fold up under the specimen in an accordion manner, while a coefficient of 0.1 caused the skirt to flatten out in the shape that actually resulted from the drop test.
- The peak equivalent plastic strain in the pressure boundary was calculated in the finite element model at 13% (on a surface, 3% at mid-thickness), while the peak strain in the skirt was 48% (on a surface, 13% at mid-thickness). Clearly, the skirt protected the test specimen pressure boundary by absorbing a significant amount of drop energy.
- After the drop testing was completed, the test specimen was pressurized to 25 psig and held steady for one hour. This confirmed that the test specimen maintained its pressure boundary during and after the drop event.
- The drop-test specimen was oriented such that the impact point included the longitudinal weld seam in the tube wall. In the drop event, the tube longitudinal weld appeared to deform just as the surrounding base metal.

Representative Drop-Test Canisters

Two full-scale representative drop-test canisters, whose designs included the features recommended and confirmed in the previous analyses and testing, were constructed. The first was the 18-inch diameter DOE SNF canister design concept described earlier, 15-foot long, but with two differences: the lower head was a ½-inch thick 2-to-1 elliptical head, and the upper head consisted of a flat plate only (no impact plate, skirt, and lifting ring). The second was the 24-inch diameter DOE SNF canister design concept described earlier, 15-foot long, but with one change: the upper head consisted of a flat plate only (no skirt and lifting ring).

Test Canister Contents. The contents of the 18-inch canister consisted of a 10-foot long 16-inch diameter pipe filled with miscellaneous steel sections, rebar, and concrete. Rebar was also placed around the outside of the pipe to maximize the weight. The total loaded weight of the 18-inch test canister was 5,690 lbs. This same contents load was placed into the 24-inch canister, along with a 41-inch long 20-inch diameter pipe that was similarly loaded. The total loaded weight of the 24-inch test canister was 9,790 lbs.

Impacted Surface. The representative canister drop tests were performed at an old test facility at the Idaho National Engineering and Environmental Laboratory (INEEL) that was not clearly defined by available drawings. However, a general description of the structure is as follows. Steel rails were anchored to what appeared to be short (about 3-ft. tall) foundation walls on footings. A concrete pad about 8 inches in thickness was poured against the steel rails and under-structure, and on the soil. The top of the pad was level with the top of the rails. A 2-inch thick carbon steel plate (6-ft. by 8-ft.) was placed on the concrete pad so as to span two steel rails. This arrangement would surely not be "rigid" as far as the impacting canisters were concerned, especially since these two test canisters were so heavy. However, in the analytical models the impacted surface was defined as rigid for the purpose of predicting the maximum deformations in the test canisters. The coefficient of friction applied at this impacted surface was 0.30 in the models. (In this paper a "rigid" surface is defined as one that is flat, fixed in space, and has no flexibility or energy-absorption capabilities.)

Test Canister Drop Height and Orientation at Impact. The 18-inch canister was oriented at 6° off vertical at impact, while the 24-inch canister was positioned at 9° off vertical. These impact angles put the center-of-gravity of the canisters approximately above the impact point on the canister skirts. The drop height was 30 feet.

Analytical (Finite Element) Modeling. The test canisters were modeled using linear quadrilateral finite elements (FE, ABAQUS/Explicit element S4R) for the pipe shell, upper and lower heads, skirts, and lifting rings. The internal impact plate was simulated using solid brick and wedge elements (ABAQUS elements C3D8R and C3D6). Full penetration welds between members were modeled using common nodes. The contents were simulated with solid elements only. This was considered acceptable because the contents were expected to act as a whole unit. A constraint (ABAQUS/Explicit "contact pair" option) was added to the model to keep the contents from penetrating the canister walls and internal impact plates.

The impact surface (steel plate on concrete and rail structure) was placed in the FE models as a rigid surface (ABAQUS/Explicit element R3D4).

Figure 8 shows a hidden line plot of the FE models. Only half of the test canister geometry was necessary due to symmetry in geometry and loading during the drop event.

Material Modeling. Pressure boundary, skirt, and lifting ring components of these test canisters were made of 304L stainless steel. The American Society of Testing and Materials (ASTM, 1993) specified minimum engineering strengths for this material at 25 ksi for yield strength (0.2% offset) and 70 ksi for ultimate strength, at 70 °F (e.g., ASTM A-312 pipe). It was expected that the actual material would have strengths somewhat higher than the specified minimums. However, these strengths were based on slow load rates when compared to those occurring during a drop event. Typically, dynamic yield strength (yield strength at a very high load rate) would be 10–20% higher than the near static strength value. If it were assumed that the actual yield strength of this 304L stainless steel was 37 ksi, then that value under dynamic conditions could be near 45 ksi (20% increase).

It was assumed, for the pre-drop test FE analyses, that the dynamic yield strength was 45 ksi, and the ultimate strength was 105 ksi (at 50% nominal plastic strain). The stress-strain curve between these two points was assumed linear.

After the drop testing, unused canister body pipe was tensile tested (at 0.1 inches per minute displacement rate). The results showed slightly higher yield strengths (39 ksi average) and somewhat lower ultimate strengths (83 ksi average) than were used in the pre-drop test FE models. However, the average total elongation value at the ultimate strength was 71%. This would indicate an ultimate plastic strain value of greater than 71%, which was much higher than used in the pre-test models. Post-drop test models used an average stress-strain curve from the tensile testing, with a 20% increase on the yield strength to account for dynamic strengthening.

18-Inch Diameter Test Canister Results and Conclusions. A visual examination of the canister after the drop-test indicated that the damage was confined (as intended) to the skirt and lifting ring, with no damage noted in the lower head or canister body. Figure 9 shows a photograph of the impacted end of the canister. After the drop event the canister was pressurized to 25 psig and held steady for 1 hour. No drop in pressure occurred during the pressure test, which indicated that the canister pressure boundary had been maintained (no local tearing or rupture).

Pre- and post-drop test FE models showed a good match in overall deformation shape to the actual dropped canister. This is seen in the Figure 10 post-drop deformation plot. The FE models did not predict any visible damage to the lower head or body of the canister, and all damage was limited to the skirt and lifting ring. The main difference between the FE model predictions and the actual dropped canister was that the models predicted more crush depth than actually occurred. This was expected due to the conservative modeling of the impacted surface (i.e., steel plate, concrete base, and soil) and the contents. For example, the actual impacted steel plate rebounded with the canister off the concrete base. This clearly showed that some of the drop energy was converted into elastic energy in the steel plate. Not visible was the portion of drop energy that would have been converted into elastic and non-elastic energy in the concrete base and the soil beneath it. This energy absorbed into the actual impacted surface was not available to deform the dropped canister. In other words, the FE model calculations enveloped the response of the actual canister for the drop event.

Plastic straining of the 18-inch test canister was not measured during the testing due to limitations in the scope of work. However, equivalent plastic strains were calculated in the FE models. Those strain levels were very low on the pressure boundary components (i.e., lower head, body, and upper head), at a maximum of 3% (post-drop model on a surface, 1% at mid-thickness). However, peak plastic straining in the skirt was 67% at the surface (peak mid-thickness strain of 18%). This showed that the skirt did protect the canister pressure boundary by absorbing most of the drop energy. Tensile testing of the 18-inch canister material indicated that a minimum ultimate plastic strain of 66% was required for rupture to occur. Therefore, rupture (including local tearing) of the canister pressure boundary components was not predicted.

For additional insights, the damaged 18-inch test canister was dropped for a second time on the steel plate from a drop height of 30 feet. This second drop oriented the canister horizontally, which caused the cylindrical body of the canister to flatten on impact over the 8-ft. length of the steel plate, with a flat width of about 6 inches. The transition from the flat section back to the cylindrical body was fairly gentle with no sharp change apparent (other than a faint line at the plate edge). The deformed skirt also contacted the concrete next to the steel floor plate. This was evident because of a gouge left in the concrete. The only visible change to the skirt deformation was to make it slightly non-symmetric about the impact point of the first drop test. After this horizontal drop, the canister was again pressurized to 25 psig and held steady for 1 hour. Again, the canister held the pressure for the specified time, indicating that even after the second drop event, the canister pressure boundary was still intact. (No analytical calculations were done on the canister for this additional drop.)

24-Inch Diameter Test Canister. A visual examination of the 24-inch canister after the drop test indicated that the damage was confined (as intended) to the skirt and lifting ring, with no damage noted in the lower head or canister body. Figure 11 shows a photograph of the impacted end of the canister. After the drop event the canister was pressurized to 25 psig and held there for 1 hour. A drop of ½ psig pressure was noted at the end of the hour. A drop in temperature of the canister components caused this small drop in pressure. The canister had been in the sun for several hours, but cooled in the shade while the pressure test was being performed. Schedule constraints prohibited a second pressure test under constant temperature conditions. Because the slight drop in pressure was attributed to the temperature variation, the canister pressure boundary was considered maintained (no local tearing or rupture).

Pre- and post-drop test analytical models showed a good match in overall deformation shape to the actual dropped 24-inch canister. This is seen in the Fig. 12 post-drop deformation plot. The FE models did not predict any damage to the lower head or body of the canister. However, considerable damage to the skirt and lifting ring was shown (as intended). The main difference between the FE model predictions and the actual canister was that the models predicted more crush depth than actually occurred (as expected due to the conservative modeling of the impacted surface and contents). In other words, the FE model calculations enveloped the response of the actual canister for the drop event. (This was consistent with the results for the 18-inch canister test.)

Plastic straining of the 24-inch canister was not measured during the testing due to limitations in the scope of work. However, equivalent plastic strains were calculated in the FE models. Those strain levels were low on the pressure boundary components (i.e., lower head, body, and upper head), at a maximum of 4% (post-drop model on a surface, 1% at mid-thickness). However, peak plastic straining in the skirt was 80% at the surface (peak mid-thickness strain of 16%). This showed that the skirt did protect the canister pressure boundary by absorbing most of the drop energy. Tensile testing of the 24-inch canister material indicated that a minimum ultimate plastic strain of 76% was required for rupture to occur. Therefore, rupture (including local tearing) of the canister pressure boundary components was not predicted. As with the 18-inch canister, the bulk of the material straining in the 24-inch canister occurred in the skirt and lifting ring (as intended).

Rigid Impacted Surface vs. Flexible Surface. The use of a rigid impact surface in the 18-inch and 24-inch canister FE modeling has been discussed in this paper. Because the actual impact surface was not rigid and absorbed some of the drop energy, the FE models over-predicted the actual dropped canister deformations. To illustrate that a non-rigid surface would reduce the deformations of the canisters, the two canister models were reevaluated with the impact surface movement in the vertical direction restrained only by a grounded spring of stiffness $1.0x10^5$ lbs per inch. Additionally, the surface was given a weight of 9,000 lbs (approximate weight of the steel plate plus the concrete slab below it). This was a simple way of representing a surface with some flexibility, but was not intended to exactly match the actual impact surface. The results of these evaluations showed that the canister deformations were almost identical to those of the actual canisters.

This showed that when some of the drop energy of the canisters was absorbed into the impact surface, as actually occurred in the canister drop tests, the calculated canister deformations were much closer to those of the actual canisters. Again, the choice of spring stiffness on the impact surface was somewhat arbitrary and was only intended to illustrate this point. (It is recognized that the energy absorption mechanisms in the impact surface are much more complicated than can be represented by a simple spring.)

Representative Canisters at Various Impact Orientations

The FE models for the 18-inch and 24-inch test canisters were also evaluated for drop angles between 0° and 45° at a drop height of 30 feet, while varying the coefficient of friction at the impacted surface from 0.05 to 0.30. These analyses showed that the design concept for the DOE SNF canisters, as represented by these two test canisters, is robust and drop resistant.

Conclusions. Generally, the lower coefficient of friction on the impacted surface caused more deformation (crushed skirt) for the steeper oriented canisters than the higher coefficient of friction. On the more shallow impact orientations (30° and 45° drops), the lower coefficient of friction caused the skirt to fold over the lower head in a more flat central shape, where the higher coefficient of friction caused the skirt to fold up more under the impact point. Based on the results reported earlier for the 18-inch diameter 5-foot drop-test specimen, it would appear that the lower coefficient of friction resulted in a more accurate prediction of the deformed shape for the shallower drop orientations. Based on the results reported for the 18-inch and

24-inch test canisters, the higher coefficient of friction appears more applicable to the steeper drop orientations.

However, the above comments are merely observations and should not be construed as facts. Sufficient testing has not been performed to determine if the friction varies as supposed. It is possible that some other, as yet unidentified, factors are simply being mimicked by this variation in coefficient of friction.

The variation in coefficient of friction from 0.05 to 0.30 produced peak strains that were comparable (in some cases identical). This is interesting in that the deformed shapes vary, but the peak plastic strains match well.

In all cases evaluated, the mid-thickness peak strain never exceeded 5% and 15% on the 18-inch and 24-inch canisters, respectively. Additionally, the peak surface strain was below 23% and 27% for the 18-inch and 24-inch canisters, respectively. As discussed previously, the canisters were not expected to rupture unless the mid-thickness strains exceeded a minimum value of 66% for the 18-inch canisters and 76% for the 24-inch canisters.

OTHER FACTORS AFFECTING THE CANISTER PERFORMANCE

Temperature Variations

The drop testing of the test specimens and representative canisters were performed under temperature conditions between 70°F and 85°F. The FE models also assumed that temperature range when defining material properties. The question of how the representative canisters would respond to the drop event if the ambient temperature were much higher or lower is briefly addressed.

Low Temperature Accidental Drops. Low temperatures on stainless steels reduce their ductility. The scope of this effort prohibited a detailed investigation of the impact of low temperatures on a drop event of a canister. However, it is expected that temperatures above freezing (32°F) would not adversely change the canister response to an accidental drop event.

High Temperature Accidental Drops. High temperatures on stainless steels increase the ductility but decrease the stiffness of the components. This means that, in an accidental drop event, the skirt and lifting rings would deform more than predicted in this report. This could lead to higher straining of the pressure boundary components (heads and canister body). But, the magnitude of plastic straining in pressure boundary components could potentially be much greater than the ultimate strain at 70°F before rupture would occur. Again, the scope of this effort prohibited a detailed investigation of the impact of high temperatures on a drop event of a canister. However, it is expected that material temperatures up to 300°F would not significantly change the canister response to an accidental drop event. The actual canister drop tests (at 70°F) showed that the skirts could experience more deformation before the lower head would be damaged. This deformation margin could be used to counter the effects of higher temperatures.

Varying Material Properties

Stainless steels are manufactured to national standards (e.g., ASTM) that require, among other properties, minimum yield and ultimate strengths, and a minimum elongation value. Actual materials usually exhibit higher than required minimum values for these properties. This has been shown in the material testing performed in support of the development of the canister design. (A detailed discussion of the material tensile testing done as part of this effort was not included in this paper.) The question of how the representative canisters would respond to the drop event if these minimum required values were much higher or lower was not evaluated. The scope of this effort prohibited a detailed investigation of the impact of varying material properties on a drop event of a canister. However, some general observations/expectations can be made.

Material Strengths. The analysis and testing of this report used material yield and ultimate strengths that were somewhat higher than the minimum required values (probably typical values). Higher or lower strength values would change the deformations of the canister components, but integrity of the canister pressure boundary would still be expected. The only area of concern would be if the yield strength were to approach the ultimate strength value, say at 80% of the value. This would surely reduce the ductility of the material.

Elongation Value. The peak strain values reported for the representative canisters for the specified accidental drop events were very low in the pressure boundary material. The minimum required elongation value, as specified by ASTM, for 300 series stainless steel materials would be sufficient to prohibit rupture of the canister pressure boundary.

Keep in mind the relationship between elongation and plastic strain. A ductile tensile test specimen will stretch uniformly throughout its gauge length at the beginning of the tensile load application. This is uniform elongation. Later, the tensile specimen will "neck down", which means that a small portion of the gauge length will reduce in area more rapidly than the remaining portion. As the tensile specimen is on the verge of breaking at the necked-down region, the length is measured and then used to calculate the total elongation value (based on the original gauge length).

The plastic strain is equal to the elongation value while the deformation is uniform. When necking-down begins, the plastic strain value no longer equals elongation. That is because the plastic strain is not just a function of the load and displacement, but also the area in the necked-down region. Therefore, the ultimate plastic strain is greater than the total elongation value in a ductile material.

Variations in Nominal versus Actual Thickness

The pipe wall (canister body) thickness is allowed to be under the nominal dimension by 12.5% (per ASTM A312). The representative test canisters had actual wall thicknesses that were about 7% less than the nominal dimensions. The affect of the thinner actual wall dimension was to cause slightly more damage to the skirt and lifting ring, as evidenced by the pre-drop and post-drop test analytical predictions. (Post-drop models used the actual thicknesses, where pre-drop models used nominal values). However, peak material strains in the canister pressure boundary components were still low when compared to the expected ultimate strain at rupture.

The basic pipe wall allowable thickness variation is considered small enough to not significantly affect the capability of the canister to maintain its containment after an accidental drop event (as evaluated herein).

PROPOSED 1999 TASKS

It has been proposed for 1999 that a number (estimated at 9) of drop tests be performed on the representative canisters. This testing would be done at a qualified facility prepared for such drop tests. The impact surface will be a thick steel plate anchored to a very thick (several feet) concrete block. This will better simulate a non-yielding surface than was used in the drop tests reported herein. Deformations, accelerations, and strains will be measured during the tests. This will give an opportunity to better match the actual test data to analytical model calculations (which used the rigid surface assumption). This may also give insights into the friction occurring between the impacted surface and the canister.

CONCLUSIONS

This effort has resulted in a design concept for the standardized DOE SNF canister that is robust and drop resistant. The canister withstands a drop from 30 feet onto a rigid surface, sustaining only minor damage - but no rupture - to the pressure (containment) boundary. The majority of the damage is confined to the skirt and lifting ring components, which can be removed if desired after an accidental drop. A canister, with its skirt and lifting ring removed after an accidental drop, can continue to be used in service with appropriate operational steps being taken.

The analysis reported herein validates the design concept for a 30-ft. drop onto a rigid surface in a variety of canister orientations at impact, from vertical to 45° off vertical. The actual drop testing performed verifies the design, though it was limited to just two representative test canister drops. In each case, the analytical models conservatively predicted the canister response.

REFERENCES

ABAQUS/Explicit, Version 5.7, Hibbitt, Karlsson, and Sorenson (HKS), Inc., 1997.

I-DEAS Master Series, Version 5.0, Structural Dynamics Research Corporation (SDRC), 1997.

Annual Book of ASTM Standards, American Society of Testing and Materials, 1993.

Morton, D. K., et. al., Development of the Standardized DOE Spent Nuclear Fuel Canister Design and Preliminary Design Specification, 1999 ASME PVP Conference Paper, Boston, Massachusetts., August 1-5, 1999.

Rahl, T. E., et. al., Lessons Learned From Drop Testing, 1999 ASME PVP Conference Paper, Boston, Massachusetts., August 1-5, 1999.

NOTICE

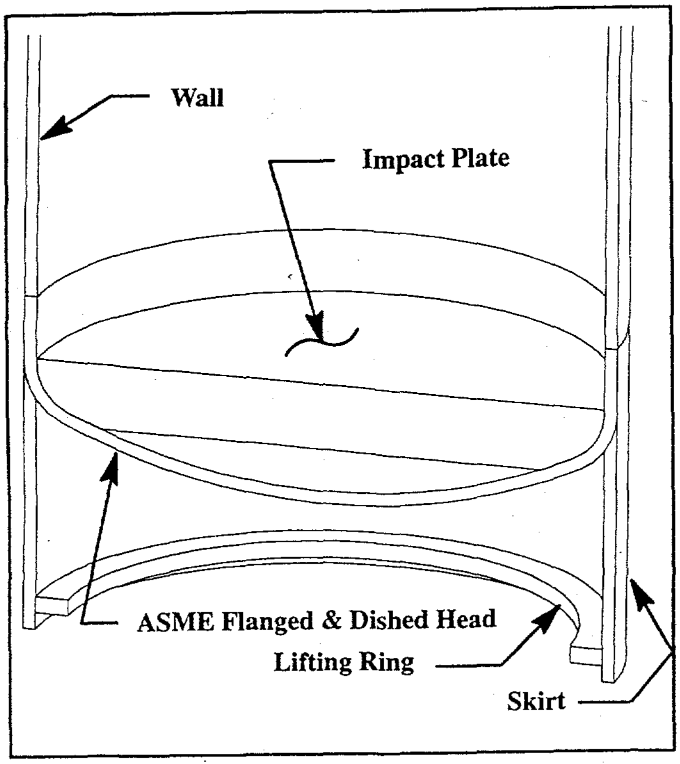

Figure 1. SNF Canister End Configuration (Section View)

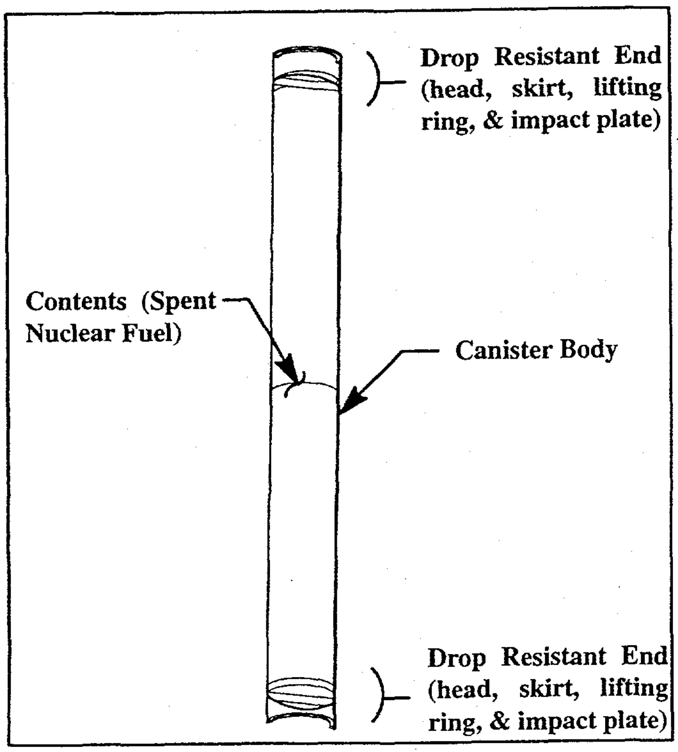

Figure 2. SNF Canister Overall Design (Section View)

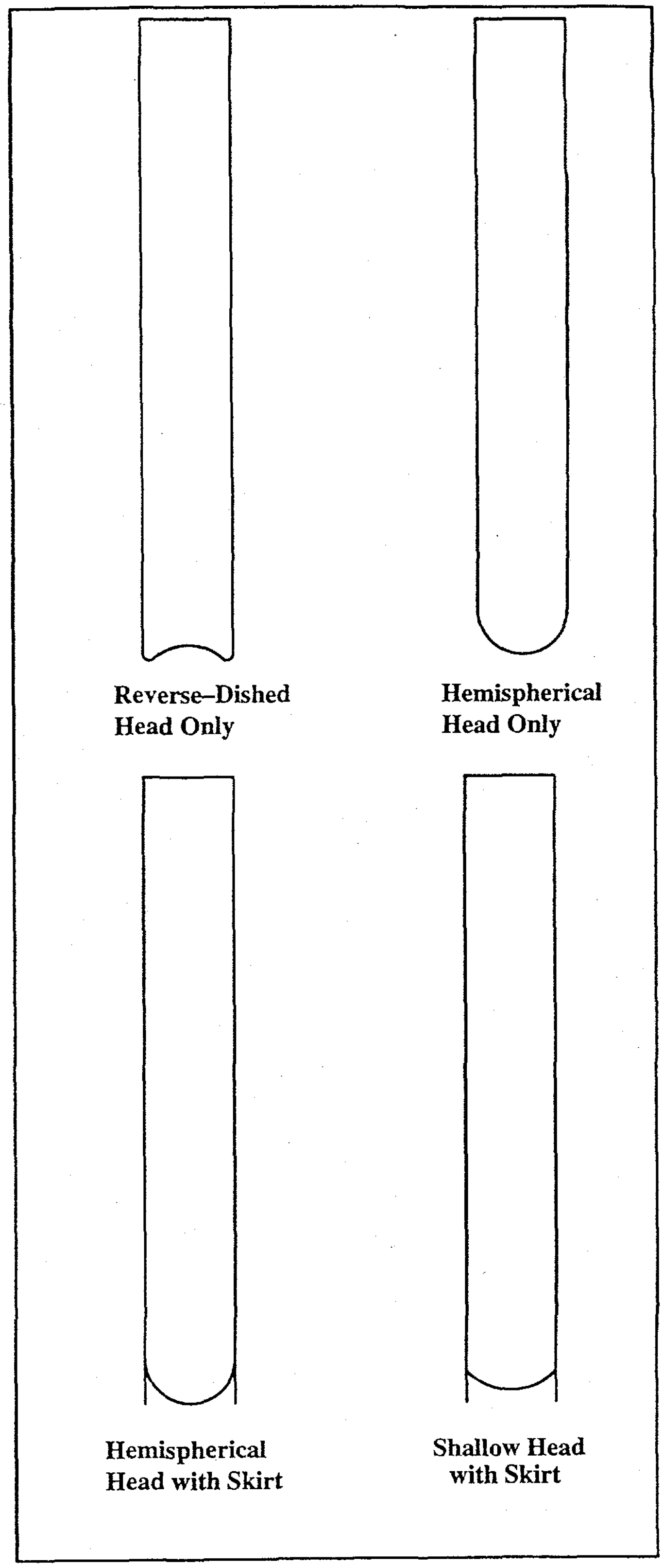

Figure 3. Preliminary Canister End Configurations Considered

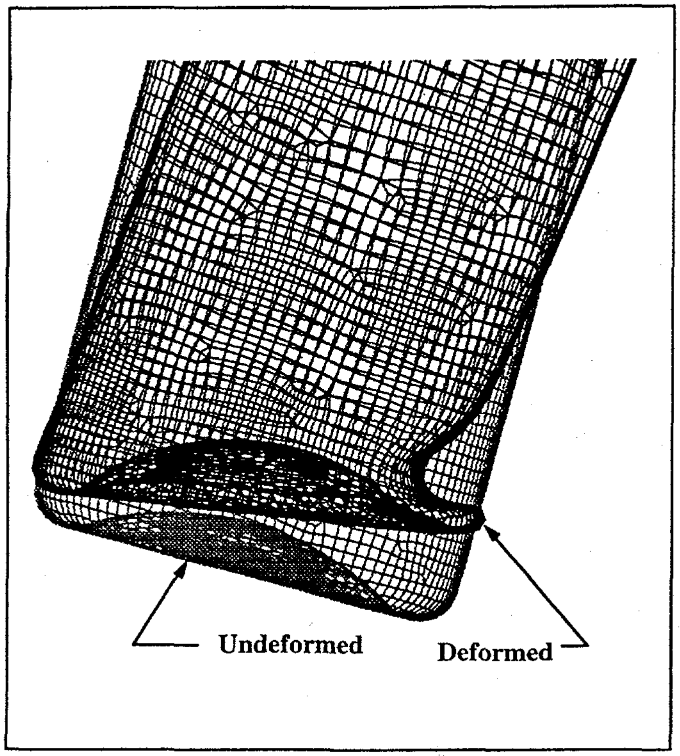

Figure 4. Reverse-Dished Head Canister

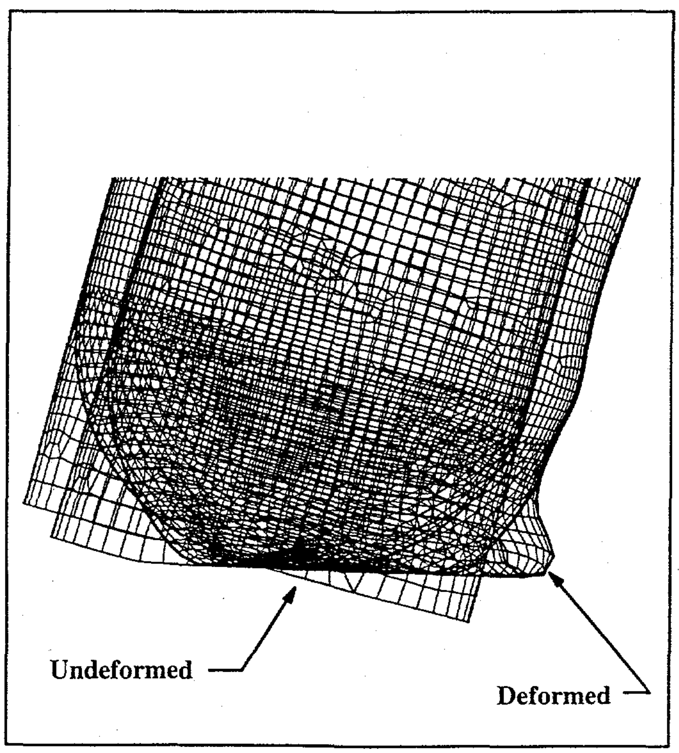

Figure 5. Hemispherical Head with Skirt Canister

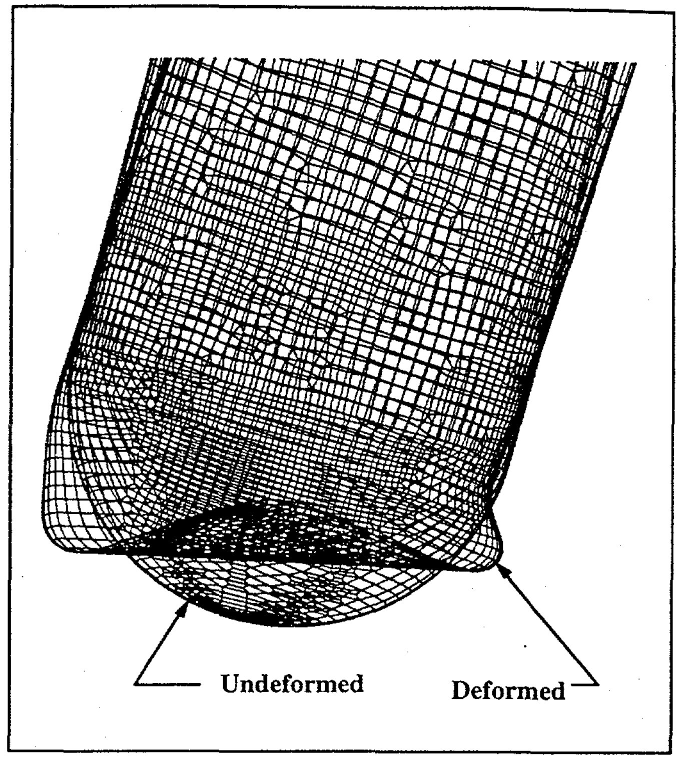

Figure 6. Hemispherical Head Canister

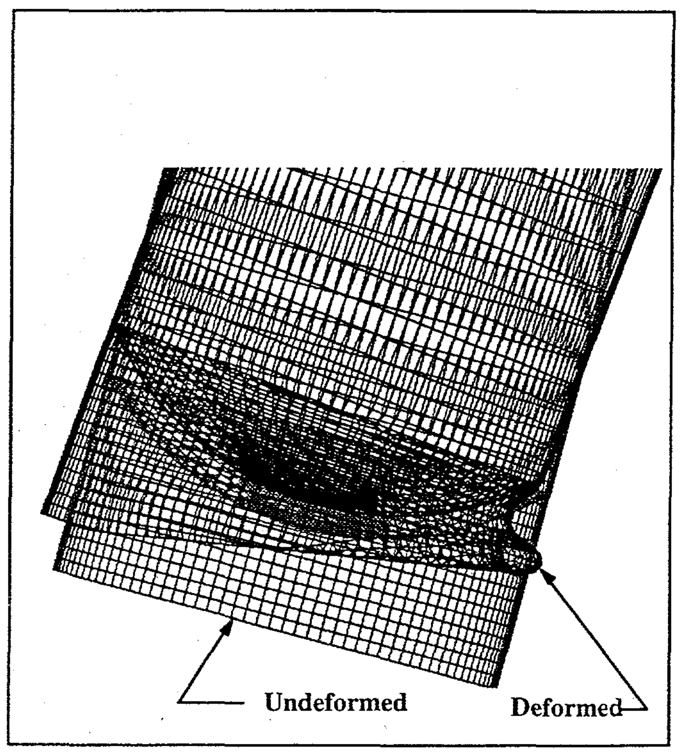

Figure 7. Shallow Head with Skirt Canister

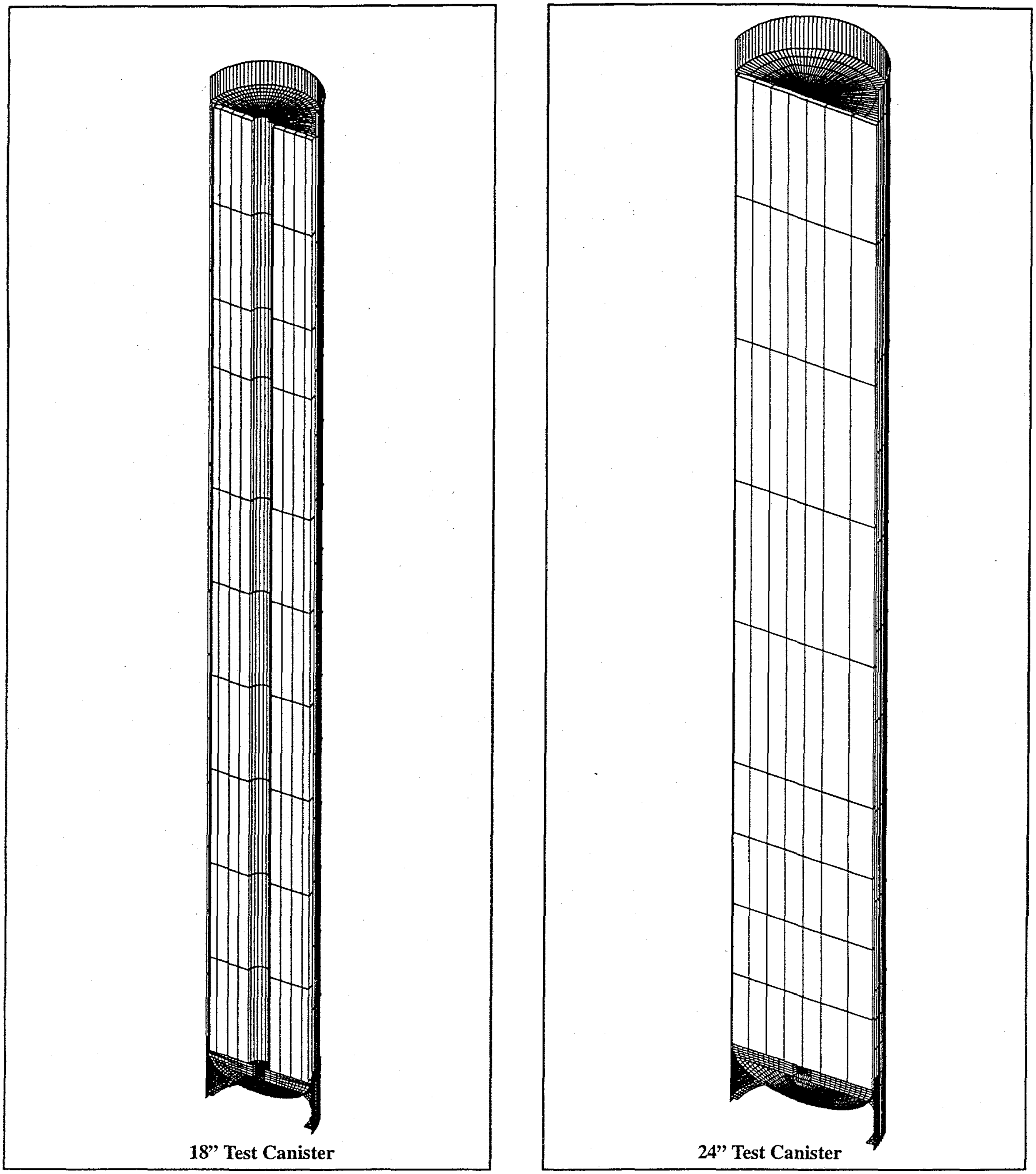

Figure 8. Test Canister Finite Element Models, Hidden Line View

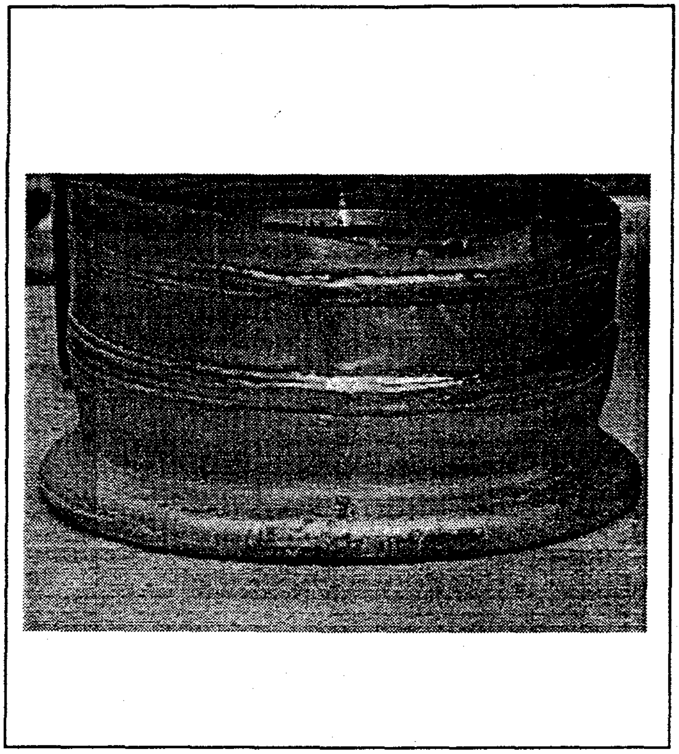

Figure 9. 18–Inch Test Canister after Testing

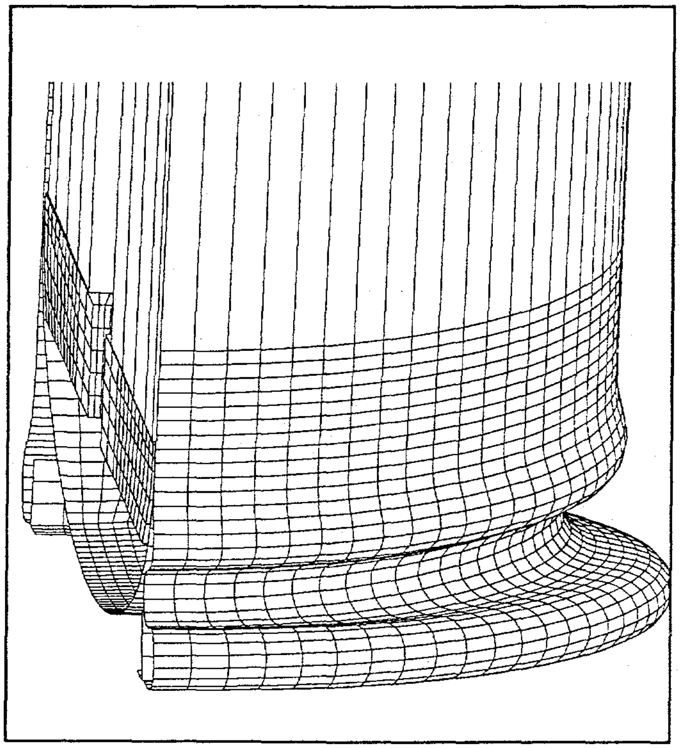

Figure 10. 18–Inch Test Canister Deformed Model

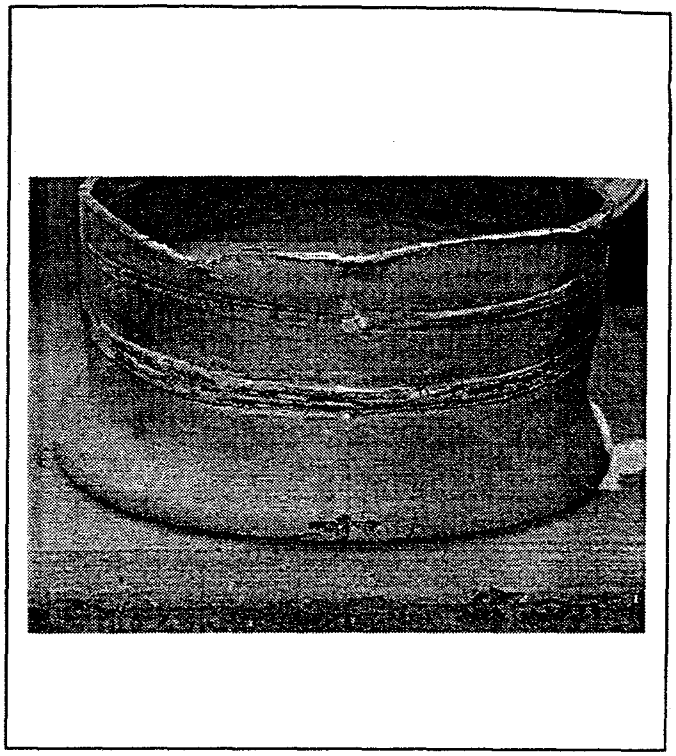

Figure 11. 24–Inch Test Canister After Testing

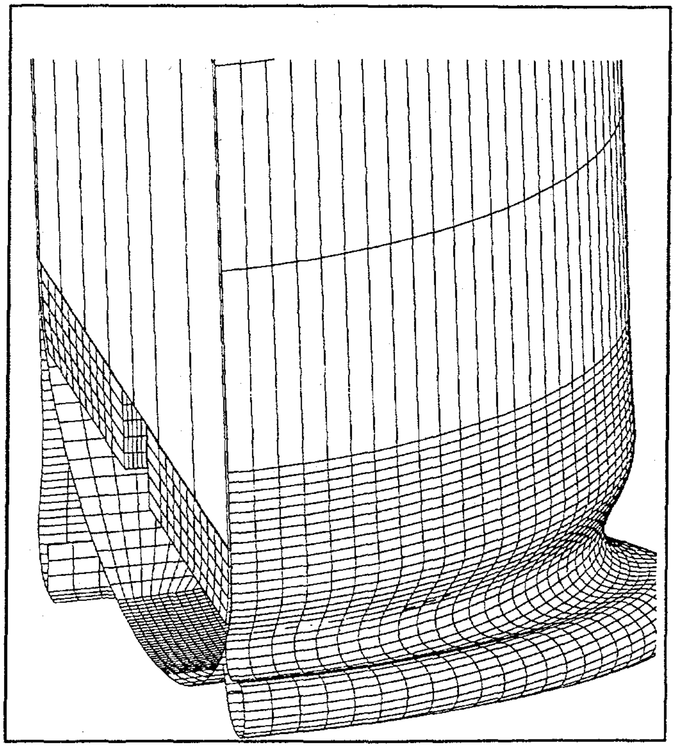

Figure 12. 24–Inch Test Canister Deformed Model