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ANALYTICAL EVALUATION OF DROP TESTS PERFORMED ON NINE 18-INCH DIAMETER STANDARDIZED DOE SPENT NUCLEAR FUEL CANISTERS[1]

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ABSTRACT

During fiscal year 1999, a total of nine 18-inch diameter test canisters were fabricated at the Idaho National Engineering & Environmental Laboratory (INEEL) to represent the standardized Department of Energy (DOE) Spent Nuclear Fuel (SNF) canister design. Various "worst case" internal loadings were incorporated. Seven of the test canisters were 15-foot long and weighed approximately 6000 pounds, while two were 10-foot long and weighed 3000 and 3800 pounds. Seven of the test canisters were dropped from thirty feet onto an essentially unyielding flat surface and one of the test canisters was dropped from 40-inches onto a 6-inch diameter puncture post. The final test canister was dropped from 24 inches onto a 2-inch thick vertically oriented steel plate, and then tipped over to impact another 2-inch thick vertically oriented steel plate. This last test was attempting to represent a canister dropping onto another larger container such as a repository disposal container. All drop testing was performed at Sandia National Laboratory (SNL). The nine test canisters experienced varying degrees of damage to their skirts, lifting rings, and pressure boundary components (heads and main body). However, all of the canisters were shown to have maintained their pressure boundary (through pressure testing), and the four worst damaged canisters were also shown to be leaktight (via helium leak testing performed at the INEEL).

Pre-drop and post-drop test canister finite element modeling was performed at the INEEL in support of the canister drop test program. All model evaluations were performed using the ABAQUS/Explicit software. The finite element models representing the test canisters accurately (though at times, slightly conservatively) predicted the actual test canister responses during the defined drop events.

This paper will discuss highlights of the drop testing program and will give detailed comparisons of analysis versus actual test results.

INTRODUCTION

The DOE's National Spent Nuclear Fuel Program (NSNFP) has been working with the Departments' Office of Civilian Radioactive Waste Management (OCRWM), the INEEL, Hanford, Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), and the Savannah River Site (SRS) to develop a set of standard canisters for handling, interim storage, transportation, and disposal in the national repository of DOE SNF. Through these efforts the NSNFP has produced a design for such canisters, referred to as the "standardized DOE SNF canisters", that are 18 and 24 inches in outer diameter, and approximately 10 and 15 feet long. The standardized DOE SNF canister construction is required to meet the criteria of the ASME B&PV Code, Section III, Division 3, Subsections WA and WB.

Additionally, the NSNFP intended to further validate the standardized DOE SNF canister design by: (1) building a number of test canisters to verify the constructability of the design and verifying the ease of loading internals; (2) employing current volumetric weld inspection methods on the test canisters to assure their viability - especially on the final closure weld; (3) performing drop tests on the test canisters to simulate accidental drops during handling, with follow-up pressure tests and limited leak testing to demonstrate containment, (4) evaluating the deformations of the test canisters with regard to future over-packaging of a damaged canister, and (5) demonstrating the capability of finite element methods to accurately predict canister response during accidental drop events.

The scope of this paper was limited to the NSNFP further validation efforts (3) and (5) indicated above which were

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completed during fiscal year 1999 on 18-inch diameter test canisters. Only beginning-of-life material and structural conditions were considered.

The NSNFP decided to build and drop test a number of combinations of canisters and contents [internals plus representative (non-radioactive) SNF] that would most significantly challenge the standardized DOE SNF canister from a containment viewpoint. Considering budget limitations, a total of nine canister configurations were selected for drop testing. Canister and internals deformations were not considered important with respect to criticality for this drop testing effort. The main focus of the drop testing was to demonstrate that canister containment was maintained, regardless of the impact orientation. Canister deformation was also of interest with respect to the ability of a dropped canister to fit inside of another container, such as the repository waste package or a transportation cask.

Acceptance by both the DOE and the United States Nuclear Regulatory Commission (USNRC) of the drop testing and resulting data was desired. This mandated an NQA-1 quality program for the drop testing, a drop test facility with an essentially unyielding drop surface, and a fully calibrated and quality controlled data acquisition system. SNL had such a program and facilities and was, therefore, contracted to perform the drop testing. The construction of nine test canisters was completed at the INEEL in April of 1999. Drop testing of the canisters was performed in June of 1999 at SNL.

Several previous papers (Snow, 1999, Morton, 1999, and Rahl, 1999) discussed preliminary drop testing efforts performed at the INEEL and other aspects of the standardized DOE SNF canister work.

CANISTER DESIGN

The design for the 18-inch diameter standardized DOE SNF canisters as tested, shown in Fig.'s 1 and 2, included:

- Body made of longitudinally-welded SA-312 pipe, 3/8-inch nominally thick, 316L stainless steel,
- Heads are ASME flanged and dished, 3/8-inch nominal thickness, SA-240 316L stainless steel),
- Skirts made of longitudinally welded pipe to match the body material, 8 inches long,
- Lifting rings made of SA-240 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, A-36 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.

Seven of the test canisters were 15-ft. long, and two were 10-ft. long.

CANISTER INTERNAL COMPONENTS

The seven 15-ft. long test canisters included a spoked-wheel divider and rebar to simulate a SNF and internal structure loading. This spoked-wheel divider was seen as being the most demanding of expected internal component configurations because the spokes would tend to concentrate loads during a drop event over a smaller area of the canister body. Five of those test canisters also included a 3/16-inch thick interior sleeve. These are shown in Fig. 3.

One of the 10-ft. long test canisters simulated two Shippingport PWR fuel bundles with carbon steel structural tubes and rebar, while the other 10-ft. long test canister simulated High Integrity Cans (HIC's) with stainless steel pipe and rebar. These are shown in Fig. 4.

DROP TEST DETAILS

The test canisters were labeled as follows: canister diameter (18-inch in all cases) - canister overall length (10 or 15 feet) - intended impact angle [0 (vertical) through 90 degrees (horizontal)] - unique identification number (01 through 09). For example, canister 18-15-00-01 was an 18-inch nominal diameter canister, approximately 15-feet in total length, intended to impact in a vertical orientation, and numbered canister 01. All canister labels followed this pattern except for the waste package and post puncture drops, which used "PW" and "PP" in place of the intended impact angle number.

A summary of the test canister configurations and intended impact orientations is given in Table 1.

Table 1. Test Canister Configurations and Orientations

Canister No.	Length (ft.)	Desired Impact Angle	Total Weight (lbs)	Drop Height (ft.)	Contents *
18-15-00-01	15	0	6033	30	S, S-W
18-15-06-02	15	6**	5948	30	S, S-W
18-15-90-03	15	90	5995	30	S, S-W
18-15-45-04	15	45	5995	30	S, S-W
18-15-80-05	15	80	5965	30	S, S-W
18-10-90-06	10	90	3802	30	HIC's
18-10-90-07	10	90	2997	30	Shipping-port
18-15-PW-08	15	0	5972	2	S-W
18-15-PP-09	15	90	6085	40 inches	S-W

* S = sleeve, S-W = spoked wheel divider. HIC's and Shippingport fuel were simulated. Contents included rebar for all canisters.
**Center-of-gravity-over-corner orientation.

The target at the drop test facility included a flat 4-inch thick (at the thinnest location) steel plate imbedded in heavily reinforced concrete (about 2 million pounds total weight). The design of the facility provided the desired "essentially unyielding surface". Test canisters 01 through 07 were dropped onto this flat surface from 30 ft.

Test canister 08 simulated a drop event onto a repository disposal container or waste package. The scenario assumed that a canister was dropped from a height of 24 inches onto the edge of the waste package (cylinder, about 2 inches thick and about 80 inches in outside diameter). Because the center-of-gravity of the canister was not directly above the impacted edge, the canister rotated and impacted the far edge of the waste package. Therefore, the intended initial orientation of canister 08 was vertical, impacting a flat, but vertically oriented 2-inch thick steel plate. The canister then rotated to impact another vertically oriented 2-inch thick plate set 78 inches away (80 inches from far-edge to far-edge).

The drop event simulated by canister 09 consisted of a 40-inch drop, with the test canister in a horizontal orientation, onto a 6-inch diameter steel (solid, 24-inch tall) bar welded to the steel surface. The center-of-gravity of the test canister was centered above the bar before the drop. The drop height and puncture bar (or post) dimensions were chosen to follow that specified by 10 CFR Part 71 for transportation packages.

ANALYTICAL MODELING

Test Canister Finite Elements: The test canisters were modeled using linear quadrilateral shell elements (ABAQUS element type S4R) for the canister body, upper and lower heads, skirts, and some lifting rings. Shell elements were located at the geometry midplane. The internal impact plates were simulated using solid linear brick elements (ABAQUS element type C3D8R) as were some lifting rings. The head-to-body joints and the lifting ring-to-skirt connections all consisted of full penetration welds and were represented by using common nodes. The skirt-to-head welds were also full penetration, but were modeled using common nodes and multipoint constraints (ABAQUS option MPC BEAM). Because midplane-to-midplane modeling was employed with all shell elements, the skirts required a tie back to the heads in the area of the attachment weld. Otherwise, the skirts would have appeared longer in the finite element (FE) model than in reality (which would affect their stiffness and buckling responses).

The internal components were also modeled with finite elements. The spoked-wheel dividers, sleeves, and empty simulated High Integrity Can (HIC) were all modeled using linear quadrilateral shell elements. The rebar, the simulated Shippingport PWR fuel bundles filled with rebar, and the five simulated HICs filled with rebar were modeled with solid linear brick elements.

The element sizes for the 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 beyond use before the event was completed. At the other extreme, elements that were too large would not respond properly (e.g., a bulge in the canister would be shown as a sharp edge instead of a smooth curve) and the results would be in question. (Further details on the element size details will not be given herein.)

Fig.'s 5 through 8 show several of the FE models employed in the evaluation of the test canisters for the defined drop events.

Impact Surface Modeling: The impact surfaces (flat surface, puncture post, and vertically oriented 2-inch thick plates) were generally modeled using rigid elements (ABAQUS element type R3D4). (Solid elements with base nodes fixed in space were used in a couple of cases as well.)

Canister Material Modeling: Tensile testing was performed at the INEEL on the test canister material (316L stainless steel) to determine stress-strain properties. However, the load rate on the tensile testing was 24,000 pounds per minute (400 lbs./sec.). This was very low when compared to the load rate that would occur during the test drop events (in the order of a million or more pounds in a fraction of a second). It was known that 316L stainless steel, and most other ductile materials as well, experienced an increase in strength when subjected to high loading rates. However, information on material behavior and property changes under dynamic loading was still far from complete. Therefore, it was assumed that the dynamic stress-strain curve was 20% above that obtained in the low load-rate tensile testing, with the assumption that uniform elongation equaled plastic strain. This was conservative.

Drop Event Simulation: The drop event was simulated by placing the test canister just above the impact surface and then applying an initial velocity and a gravitational acceleration.

Energy Loss: The actual test canister drop events showed the drop energy being absorbed primarily in the canister structure, with some energy absorption in the internal components (e.g., rebar, spoked-wheel divider, sleeve, etc.) as expected. Because the simplified FE modeling used solid brick elements to represent the internal rebar, very little drop energy was expended in their deformation. This meant that the FE models would force more drop energy into the canister structure than actually experienced.

ANALYTICAL VS. ACTUAL DEFORMATION RESULTS

Fig.'s 9 through 26 show photographs of the test canisters after drop testing next to (side-by-side) FE model plots of the deformed geometry.

Test canisters 01 and 02 were dropped from 30 feet onto the flat impact surface, oriented vertically and 6° off-vertical, respectively. The FE models showed that the calculated deformed shape compared well (within 8% for 01, within 16% for 02) with that of the actual test canisters, but with a slightly deeper deformation depth predicted (meaning that the lower head came closer to the impact surface - though not touching it). However, post-drop measurements showed that the modeled lower skirts also did not flare out at the base as much as the actual skirts. What this showed was that the lower skirts buckled in similar, but slightly different, patterns. This was not surprising since buckling is so dependent on the initial configuration of the loaded member. In this case the actual skirts, not initially being perfectly cylindrical (reality), were each welded to a lower head and lifting ring. These welds caused some surface bending in the actual skirts that was not included in the FE models. Thus the similar - but slightly different - buckling patterns. The energy loss conservatism discussed above also played a role in the modeled canister deformations. (Note that the skirts experienced a significant amount of damage, while protecting the canister pressure boundary - as intended.)

Test canisters 03, 06, and 07 were all subjected to horizontal drops from 30 feet onto the flat impact surface. The photos showed a flattening of the entire length of the test canisters, which was also seen in the FE models. What was clearly visible in the FE models was the bulging of the heads in response to their edge flattening on impact. The actual test canisters also exhibited this deformation. Unfortunately, this could not be shown in photos without sectioning the canisters in that area. These FE models matched quite well (within 10%) the actual deformations of canisters 03, 06, and 07.

Test canister 04 was dropped from 30 feet onto the flat impact surface, oriented at 45° off-vertical. The figures showed that the FE model deformations matched very well (within 6%) those of the actual test canister. This was also the case with test canister 05, which was dropped from 30 feet onto the flat impact surface, oriented at 80° off-vertical. This test simulated the expected worst-case slapdown event on the test canister. The figures showed an excellent match (within 4%) between the FE model and the actual canister. Again, note the head bulge in response to the edge flattening on impact shown in the FE model. This was also seen in the actual canister.

Test canister 08, simulating a drop onto a repository waste package, was dropped from 2 feet onto a vertically oriented 2-inch plate. It then rotated to impact another 2-inch plate. The figures showed the impact on the first plate. The FE model and the actual test canister experienced matching deformation patterns (within 2%).

Test canister 09 was dropped from 40 inches onto a 6-inch diameter solid steel post. The figures showed that the FE model deformation pattern was the same as that of the actual canister.

PRESSURE AND LEAK TESTING

After the nine test canisters were drop-tested as discussed herein, each canister was pressurized to 50 psig with air. This was done through the threaded plug on the top head of each canister. The pressure supply was then disconnected from the canisters and a pressure gauge was monitored for one hour. In every case the 50 psig internal pressure remained constant - no loss in pressure - for the one hour monitoring period. This showed that the pressure boundary had been maintained for all canisters after the drop tests.

Four of the test canisters were helium leak tested after the drop and pressure testing. Test canisters 01, 04, 05, and 09 were helium leak tested and found to have a maximum leak rate of less than 1×10^{-7} standard cubic centimeters per second (std. cc/sec.). This was considered leaktight and additional proof that containment was maintained.

CALCULATED STRAINS

The previous section showed that the FE models performed well in predicting the deformed shape of the test canisters. The peak equivalent plastic strain levels calculated in those models will now be summarized. Table 2 lists the analytically predicted peak equivalent plastic strains in the canister models. The peak strain in the outside surface did not necessarily occur at the same location as the peak strain in the inside surface or mid-plane surface.

The maximum surface strain for any canister pressure boundary component was 62%. This occurred on the canister 07 head straight flanges due to the impact of the internal simulated Shippingport PWR fuel bundles. This peak strain was generated as a result of very conservative modeling of the fuel bundles. (The simulated Shippingport PWR fuel bundles were made of steel tubing with rebar within, but were simply modeled as solid steel sections. The actual tubes deformed significantly in the canister head areas, where the modeled tubes did not - forcing the deformation to occur in the heads.) The actual peak straining for canister 07 was estimated to be below that reported for canister 06.

The next largest surface strain for any canister pressure boundary component was 57%. This occurred on the upper head of canister 05 due to the slapdown event discussed previously. The maximum middle surface strain for any canister pressure boundary component was 23%. This occurred on the upper head of canister 08 after the canister tipped over the second vertical plate and impacted the surface beyond. (This was an unexpected result since the drop event was designed with an interest in the impact with the two vertical plates, not the subsequent impact onto the surface beyond as the canister came to rest.)

Table 2. Calculated Peak Equivalent Plastic Strains

Canister	Peak Equivalent Plastic Strain					
	Pressure Boundary Components			Skirts and Lifting Rings		
	Out-side	Mid-dle	In-side	Out-side	Mid-dle	In-side
18-15-00-01	7	3	6	91	17	75
18-15-06-02	9	3	10	107	21	94
18-15-90-03	40	15	26	10	10	10
18-15-45-04	33	9	36	52	33	84
18-15-80-05	57	19	42	24	20	19
18-10-90-06	44	17	31	21	10	18
18-10-90-07	62[1]	22[1]	42[1]	11	10	10
18-15-PW-08	55[2]	23[2]	46[2]	38	38	38
18-15-PP-09	39	14	40			

1. Peak strains due to conservative modeling of internals discussed above. Actual peak straining estimated below that reported for canister 18-10-90-06.

2. These strains occurred in the upper head as discussed above. Peak pressure boundary strains due to impact with the second vertical plate were below 21%.

Due to the lack of clarity available from black and white contour plots, the equivalent plastic strains in the canister component surfaces will not be included herein.

Although the above table was done using equivalent plastic strain, which is a measure of the accumulated plastic strain in all directions, most of the straining was due to bending about one main axis. The important question at this point was, were the calculated equivalent plastic strains high enough that rupture of any canister pressure boundary component was predicted? The tensile testing referred to earlier for this 316L stainless steel showed that a minimum (and considered very conservative) ultimate strain of 48% could be anticipated before rupture would occur. The peak middle surface strain in all test canisters was 23% or less. Therefore, rupture of the pressure boundary components for these test canisters was not predicted. (This was confirmed by the pressure and leak testing already discussed.)

CONCLUSIONS

In conclusion, the nine test canisters representing the 18-inch standardized DOE SNF canister with various simulated internals maintained their pressure boundaries and containment systems under the defined accidental drop events. Additionally, the FE models representing the test canisters, evaluated with the ABAQUS/Explicit software, accurately (though at times, slightly conservatively) predicted the actual test canister responses during the defined accidental drop events.

PROPOSED 2000 TASKS

The frictional behavior of the test canisters as they impacted the essentially unyielding flat surface was modeled based on limited data acquired during the preliminary testing performed previously (Snow, 1999). This data was considered adequate in evaluating the vertical (or near vertical) and horizontal (or near horizontal) drop orientations of eight of the test canisters evaluated herein (all but the 45° drop). However, data on that frictional behavior for drops from 20° to 70° off-vertical was lacking. Such data was needed to accurately predict the canister deformations in those drop events. (Preliminary analyses showed that there was a strong dependence in at least part of the 20° to70° drop angle range.)

Testing scheduled for Fiscal Year 2000 includes specimens to be used to investigate the dependence of deformed canister shape on friction.

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NOTICE