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Abstract – *The National Spent Nuclear Fuel Program (NSNFP) has pursued a number of structural testing projects that are intended to provide data that can be used to substantiate the position that U. S. Department of Energy(DOE)spent nuclear fuel (SNF) canisters, made from austenitic stainless steels, can maintain containment after an accidental drop event and that plastic finite element methods can be used to accurately predict the structural response of canister configurations not specifically tested. In particular, drop tests of full-scale canisters and material impact testing at varying strain rates reflecting accidental drop conditions have been completed or are in progress. This paper provides insights to conclusions achieved to date and what efforts are planned to fully address the pertinent issues necessary to demonstrate the safety of DOE SNF canisters subjected to accidental drop events.*

I. INTRODUCTION

Accidental drop events impose such high structural loads that the design of radioactive waste or spent nuclear fuel (SNF) canisters are typically governed by these impact loads. If the canister is required to satisfy stress-based design criteria for these accident conditions, final designs could incorporate significant wall thicknesses having reduced loading volumes or require the use of internal or external impact limiters. These design options are costly, increasing the number of required canisters or result in complicated impact limiter handling procedures, especially if radiation dose rates to personnel are a concern. However, with the appropriate choice of materials and designs, canisters can be developed that carry adequate amounts of radioactive material and be demonstrated to maintain containment after drop events, even though high strains (greater than 25%) may result in the containment boundary material. This approach is being pursued for Department of Energy (DOE) SNF canisters when handled at the proposed surface facility for the Yucca Mountain Project. Although developed for interim storage and transportation uses as well as repository disposal, it is usage at the nation's repository that is expected to be the most structurally challenging, due to potential accidental drops.

II. WORK DESCRIPTION

DOE has developed two distinct canister designs for the eventual repository disposal of DOE SNF. The National Spent Nuclear Fuel Program (NSNFP) at the Idaho National Laboratory (INL) has funded efforts in 1999 [1] and 2004 [2 and 3] to drop test full-scale representative spent nuclear fuel canisters in order to determine the actual structural response and leakage rate of these dropped canisters. Test specimens representing 457-mm (18-inch) standardized DOE SNF canisters and modified versions of the 610-mm (24-inch) standardized DOE SNF canister as well as Hanford's Multi-Canister Overpack (MCO) were tested. Both the MCOs and the standardized DOE SNF canisters are collectively referred to as the DOE SNF canisters.

II.A. 1999 Drop Testing of 457-mm (18-inch) Standardized DOE SNF Canisters

Starting in 1998, the NSNFP funded efforts to develop both a 457-mm (18-inch) and a 610-mm (24-inch) diameter standardized DOE SNF canister, shown in Figure 1, for the DOE SNF inventory not designated for the MCO canister and excluding U.S. Navy SNF. The canister design (similar for both diameters) incorporated an energy-absorbing skirt that deforms on impact during accidental drop events, providing a significant amount of protection to the actual containment boundary of the canister, including the welds. This deformed skirt can even be removed (cut off) if necessary without disrupting the canister containment, enhancing the canister's ability to still fit into other containers after a drop event. After preliminary proof-of-concept testing, nine representative 457-mm (18-inch) diameter test specimens were built at the INL, and drop tested in 1999. In 1999, 610-mm (24-inch) standardized DOE SNF canisters were not expected to be used. The internals used for the drop tests (typically a pipe with protruding plates, referred to as a spoked-wheel) were chosen to challenge the containment boundary of the representative test canisters. An internal sleeve was typically placed into the test canisters. The sleeve would normally be incorporated for those instances during actual use where sharp-edged SNF or baskets would impinge directly on the interior of the canister. The sleeve would reduce the resulting localized strains and increase safety margins. Reinforcing bar (rebar) was used to simulate the SNF and to increase test canister weights to the maximum limits. The internal impact plates (both top and bottom) were designated to be axially held in place via the baskets or other appropriate internals or contents.

Seven of the nine 457-mm (18-inch) test canisters were dropped from 9 m (30 feet) onto an essentially unyielding surface at Sandia National Laboratories. The two remaining drop tests were a 1-m (40-inch) drop onto a 15-cm (6-inch) diameter puncture bar and a 0.6-m (2-foot) drop onto a representative waste package or transportation cask lip.

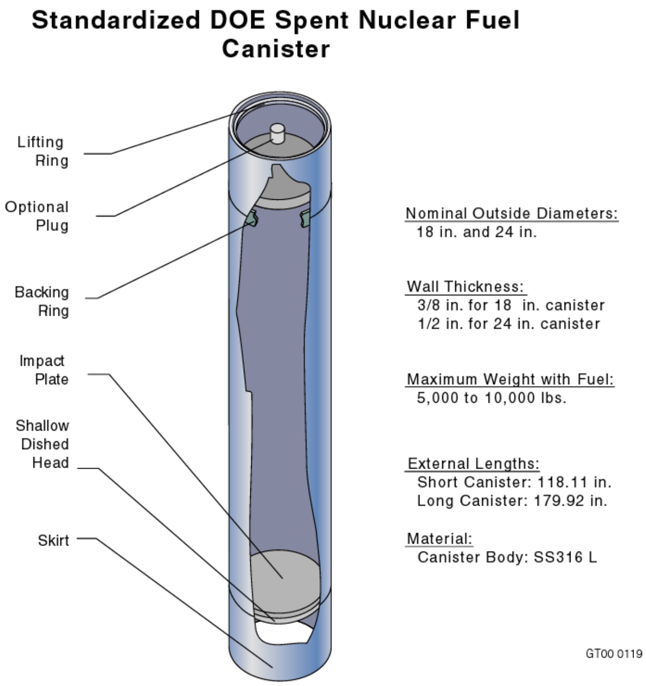

Fig. 1. Illustration of the Standardized DOE SNF Canister.

II.B. 2004 Drop Testing of 610-mm (24-inch) Modified Standardized DOE SNF Canisters

Foster Wheeler Environmental Corporation (FWENC) [later renamed Tetra Tech FW, Inc.], under contract to DOE to build an interim SNF storage facility at the INL, was to use the standardized DOE SNF canister design with their interim storage facility. In 2002, FWENC decided to use both the 457-mm (18-inch) and the 610-mm (24-inch) canister sizes and to modify the design of each. This modified design is hereafter referred to as the Idaho Spent Fuel Project (ISFP) canister.

Pre-test analytical predictions [4] of the modified design resulted in higher strains than those analytically predicted in the 1999 457-mm (18-inch) standardized canister drop tests. Therefore, efforts were pursued starting in 2004 to drop test representative full-scale test specimens of the 610-mm (24-inch) ISFP canister design. The following highlights a number of the significant design modifications made by FWENC to the 610-mm (24-inch) diameter canister:

1. Use of non-standard vessel heads with a nominal 19-mm (¾-inch) thickness requiring machining to match the 610-mm (24-inch) diameter, 12.7-mm (½-inch) thick shell geometry,
2. Incorporation of an internal shield plug with and without a welded support ring,
3. Welded retaining rings for the internal impact plates,
4. No internal sleeves were used.

Two representative test canisters, reflecting the ISFP canister design, were designated to be fabricated and tested. The INL procured material, fabricated the test ISFP canisters and internals, loaded the ISFP test canisters, and completed the final closure weld. The internals reflected an actual ISFP canister design to be used for the Shippingport Reflector Rod. These internals consisted of a bottom spacer made from 508-mm (20-inch) Schedule 60 pipe with 25.4-mm (1-inch) thick plates top and bottom, a spoked-wheel assembly made from 203-mm (8-inch) Schedule 100 pipe and 12.7-mm (½-inch) thick plate (replacing the Shippingport Reflector Rod), rebar, and a shield plug made from 581-mm (22.875-inch) diameter bar stock and 508-mm (20-inch) Schedule 60 pipe.

Both of the ISFP test canisters were subjected to 9-m (30-foot) drops onto an essentially unyielding surface at Sandia National Laboratories. Impact orientations were at a 45-degree angle and at a 70-degree (from vertical) angle to achieve a slapdown event.

II.C. 2004 Drop Testing of Multi-Canister Overpacks

During the late 1990s, the Hanford site developed the MCO, a SNF canister to be 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 river at Hanford. Over 400 of these MCOs have been loaded and moved to the newer canister storage building at Hanford. The MCOs initial design purpose was to only move the Hanford SNF away from the Columbia River and place it into interim storage. However, DOE wants to evaluate if the MCOs could also be used to transport the SNF to the repository and be disposed at the repository, without having to reopen or repackage the MCOs. Due to this identified repository use, the NSNFP decided to pursue a drop testing effort to demonstrate the structural response of a typical MCO and to gain insights into the ability of a dropped MCO to maintain its containment (to not breach). (Fluor Hanford was the M&O contractor at the DOE Hanford Site during this effort. In this paper, all work will be referred to as having been performed at or by "Hanford.").

Figure 2 illustrates the configuration of a typical MCO. The MCO is a stainless steel (304L) cylindrical vessel approximately 610 mm (24 inches) in diameter and 4.2 m (166 inches) long. SNF is placed into one of four types of baskets (either an intact SNF or a scrap fuel basket for either Mark 1A and Mark IV fuel). Structural integrity is required for the Mark 1A baskets for criticality control whereas the Mark IV baskets do not require structural integrity for criticality control. A fully loaded MCO holds five or six baskets (depending on type) and a shield plug fixed in place with a locking ring. A cover cap is welded on to the top-end to complete the package. Over 400 of the existing MCOs have had this cover welded on. A fully loaded MCO can weigh as much as 9070 kg (10 tons).

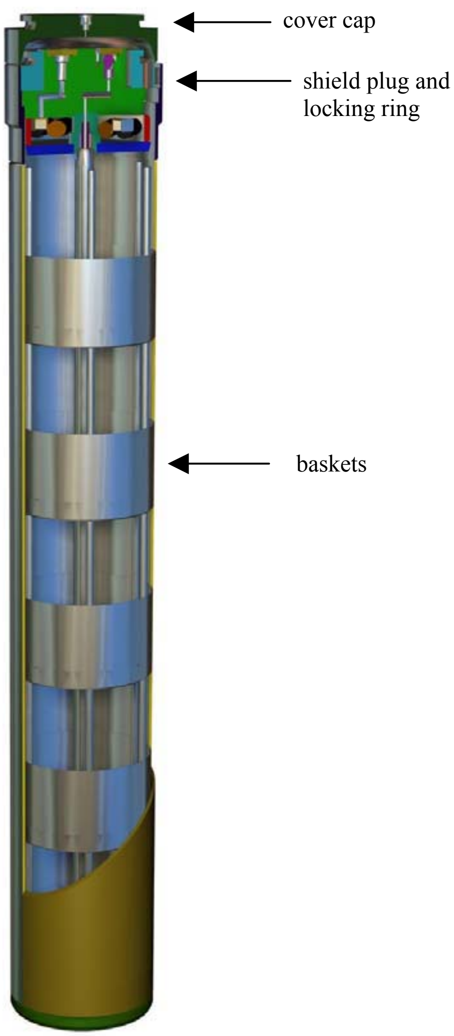

Fig. 2. Illustration of the Multi-Canister Overpack.

Each test MCO had four test baskets (a large solid bar installed on a representative Mark IV basket post and bottom plate) and a fifth representative basket consisting of a typical Mark IV basket loaded with 63-mm (2-1/2-inch) diameter bars that represented separate pieces of the SNF. These steel weights were machined at the INL and then shipped to Hanford where they were loaded into actual MCOs and sealed closed following standard procedures. These two test MCOs were then shipped back to the INL for final drop test preparation.

The representative test MCOs were dropped tested following the defined repository drop events [5]. One test MCO was dropped 8.2 m (27 feet) (vertical orientation) and the other was dropped 0.6 m (2 feet) (worst case orientation of 60 degrees for a slapdown event), each onto an essentially unyielding surface at Sandia National Laboratories.

II.D. Material Impact Testing

Since the structural responses of the representative test canisters clearly involved high strains (greater than 25%), the plastic analyses performed needed to accurately reflect the strain rate effects of the materials used in the test canisters (304L and 316L stainless steels). However, the mechanical characteristics of these materials under dynamic (impact) loads in the moderate strain rate range of concern (10 to 200 per second) are not well documented. A 20% increase (of the stresses) was assumed in the associated material true stress-strain curves used for input into the drop test computer analyses to account for strain rate effects. However, justification of that elevated true stress-strain curve was deemed necessary.

Therefore, additional work funded by the NSNFP has commenced at the INL to improve the understanding of moderate strain rate phenomena on these canister materials. Utilizing a drop-weight Impact Testing Machine (ITM) and relatively large test specimens (up to 12.7-mm [1/2-inch] thick), test efforts to date have focused on the tensile behavior of the stainless steel materials during impact loading. Impact tests at varying strain rates, including 25 per second [6], were performed for comparison to their quasi-static tensile test properties. Current efforts have focused on material testing at nominal room temperatures.

The ITM will also be used to investigate material impact responses at varying cold and elevated temperatures of both base and welded materials. Material aging and flaw effects on material impact responses can also be investigated using the ITM. Determining these material impact responses that reflect the condition of the material when the canisters are being handled at the repository surface facility is important for proper structural evaluations.

Fig. 3. Photograph of the Impact Testing Machine.

III. RESULTS

III.A. Drop Testing

The 1999 and 2004 drop tests demonstrate that the 457-mm (18-inch) and 610-mm (24-inch) standardized DOE SNF canister and ISFP canister designs are indeed robust and can survive a 9-m (30-foot) drop onto a flat, essentially unyielding surface or a 1-m (40-inch) drop onto a 15-cm (6-inch) diameter puncture bar. Helium leak testing demonstrated that these dropped canisters could also maintain a leaktight containment (less than 10^{-7} std cc/sec).

Figures 4, 5, and 6 illustrate typical structural responses of a dropped standardized DOE SNF test canister and the analytical predictions of that same test canister. Analytical predictions of deformations were typically within 10%.

The MCO drop tests resulted in very little significant deformation of the MCO canister shell. However, the baskets were expected to experience significant deformation. Figure 7 shows the structural response of the bottom basket in the vertical test MCO drop and the analytical prediction. Analytical predictions of the basket deformations were within 5%. Helium leak testing demonstrated that the dropped MCOs did not breach.

These results show that current finite element plastic analysis techniques can be used to predict the structural deformations of canisters that are subjected to accidental drop events. However, these predictions can be improved with material definitions that consider strain rate effects.

III.B. Material Impact Testing

Elevated true stress-strain curves (reflecting strain rate effects) for the two stainless steel materials were determined using a “total impact energy” approach. This approach considered the deformation energy required to strain the specimens at a given strain rate. Two methods, based on energy content per material volume, were evaluated to map the elevated true stress-strain curves from the quasi-static curve, a factored method and a shifted method. Figure 8 shows an example of the resulting elevated true stress-strain curves (factored and shifted) for 304L material in comparison to the quasi-static true stress-strain curve (determined using typical tensile test methods) and the quasi-static curve increased by 20% (of the stresses) as was done for the analytical evaluations supporting the canister drop tests. All four of these true stress-strain curves were incorporated into analytical simulations of the actual impact tests to determine the validity of the elevated curves. Excellent agreement (deformations within 1 to 3 % difference) was achieved with both the factored and the shifted elevated true stress-strain curves. These analytical results were better than the results obtained using just the quasi-static curve (31% difference) or the 20% increased quasi-static curve (8% difference).

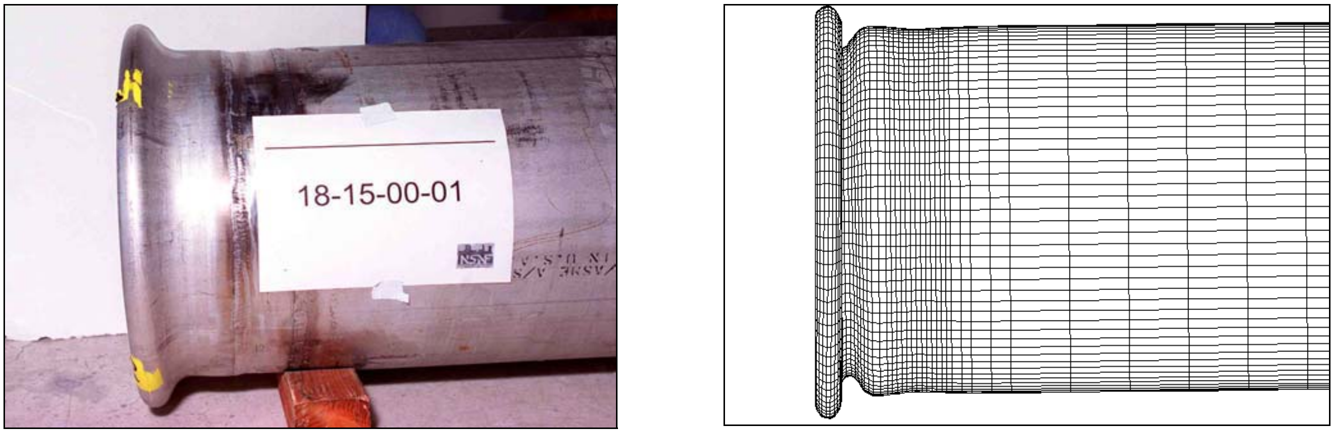

Fig. 4. Vertical drop of 457-mm (18-inch) standardized test canister response (left) and analytical prediction (right).

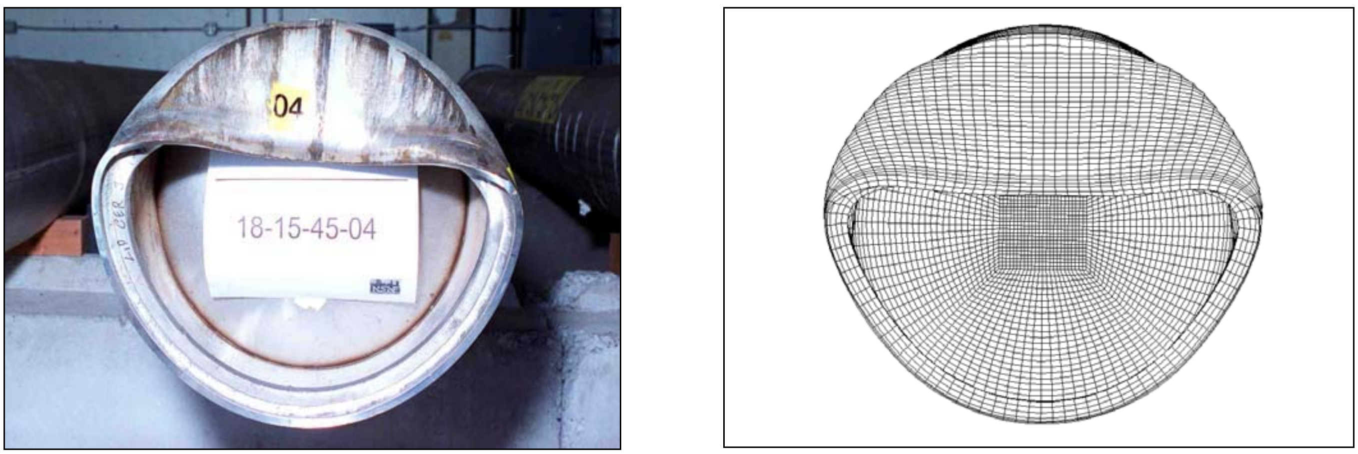

Fig. 5. Forty-five-degree drop of 457-mm (18-inch) standardized test canister response (left) and analytical prediction (right).

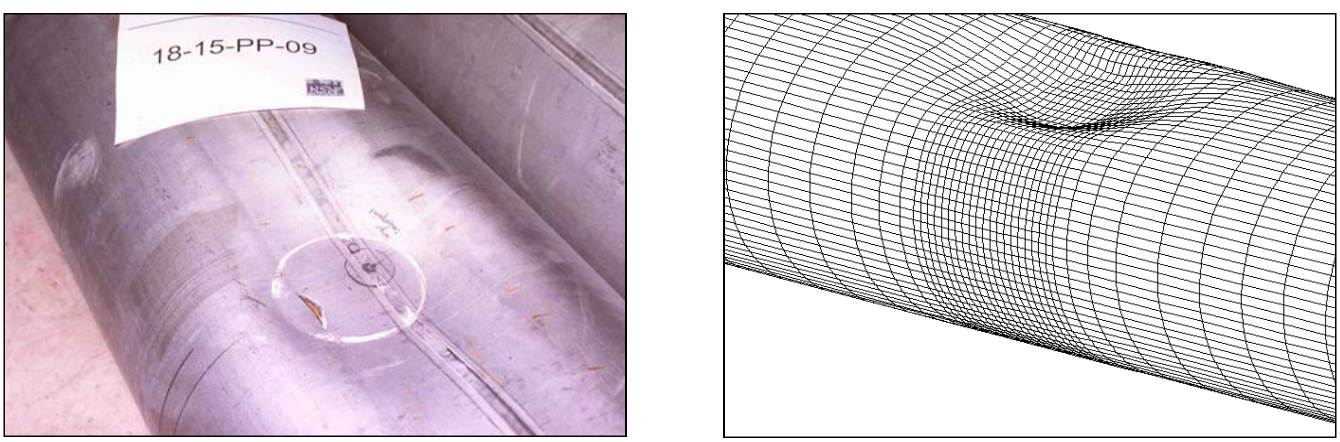

Fig. 6. Puncture drop of 457-mm (18-inch) standardized test canister response (left) and analytical prediction (right).

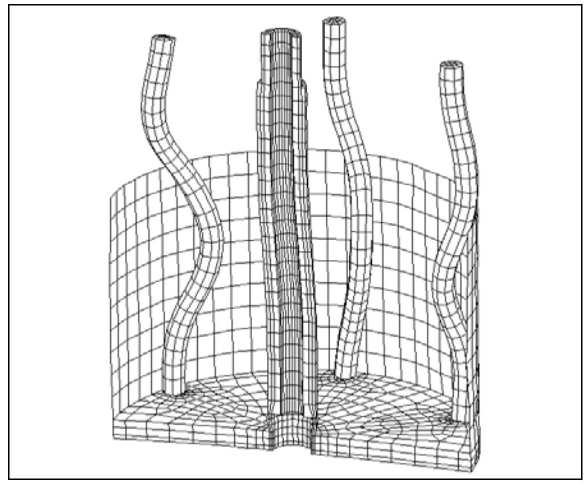

Fig. 7. Bottom basket of vertically dropped MCO (left) and analytical prediction (right).
(Cuts in the basket shroud are from post-drop examination efforts.)

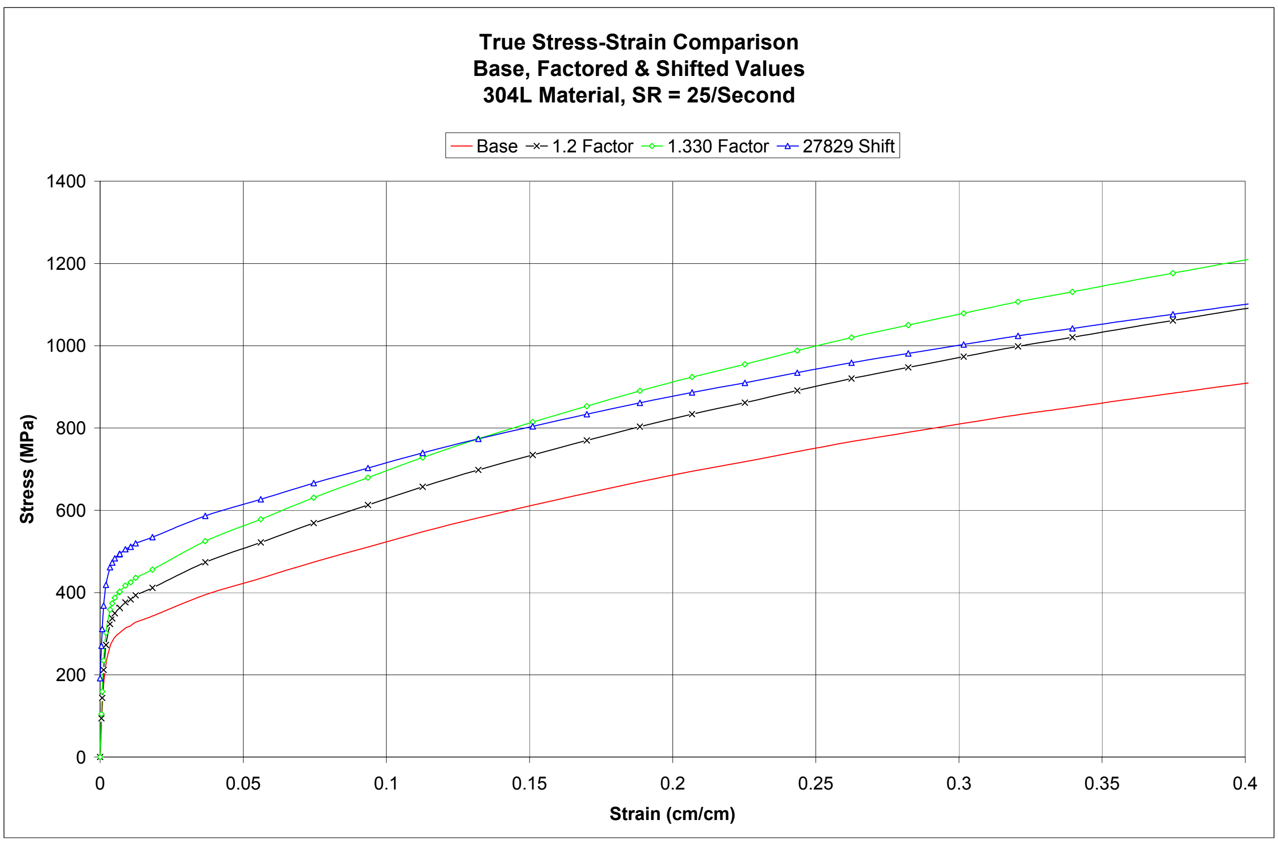

Fig. 8. True stress-strain curves comparison for 304L material at 25/second strain rate.

IV. CONCLUSIONS

The DOE SNF canisters are engineered barriers with safety as their first and foremost goal. These canisters can be disposable (placed directly into a repository waste package) and will simplify the handling of DOE SNF at the repository by not having to reopen the canisters, thereby reducing personnel exposure. Most importantly, drop testing representative full-scale specimens of these DOE SNF canisters has demonstrated the ability of DOE SNF canisters to maintain containment (not breach) following the drop event. Analytical evaluations of the drop tests have been performed and the results match well with the canister deformations. Insights regarding the justification of elevating the analytical true stress-strain curves to reflect strain rate effects in those analytical evaluations have also been obtained. Although the material impact testing results are considered preliminary (since further strain rate testing is necessary), the results to date indicate that elevated true stress-strain curves yield more accurate analysis results. Once all of the proposed material impact response data has been obtained, the canister material properties can be more accurately quantified, reflecting aged material and temperature conditions when the DOE SNF canisters are actually being handled at the repository surface facility. This will permit more accurate analytical evaluations that can be used as the basis for demonstrating the safe use of DOE SNF canisters.

NSNFP sponsored work to date at the INL has physically demonstrated that, with proper design and materials, canister containment can be maintained after accidental drop events that result in high plastic strains. The NSNFP work has also shown that canister inelastic evaluations can potentially replace the need for expensive, full-scale, physical drop tests.

Although currently there are potential design changes under discussion for the nation's spent nuclear fuel and high-level radioactive waste repository, achieving the final required safety goals of the Yucca Mountain Project is still paramount. The work described herein can be used to help support safety evaluations for a variety of final repository design options due to the need to consider accidental drop events when canisters are being handled. Much of the work described herein can also be applied to the commercial SNF to be transported to and handled at the repository. Results from this work can help gain regulatory as well as public acceptance of the repository.

ACKNOWLEDGMENTS

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