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Design Features that Enhance Spent Fuel Canister Integrity Under Drop Impact

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ABSTRACT

In many spent fuel dry cask storage systems a welded steel canister provides the confinement boundary that prevents the release of radionuclides, not only during normal conditions of storage, but also, in the unlikely event of a drop or tip-over accident. Transfer and storage casks that contain steel canisters are typically lifted and moved, and the canister transferred, in a vertical upright position. Any drop of the cask or canister, therefore, induces high longitudinal compressive stresses in the canister shell and, depending on the drop height, possible buckling of the shell at the base of the canister. The buckling of the canister shell, in turn, can introduce high bending strains in the circumferential weld joining the shell and base plate. (This weld and the longitudinal welds in the canister shell are 100% radiographed and hydrostatically tested.) However, the strains at this location, caused by such an accidental drop, can be significantly increased by local design features, such as welded attachments and basket supports, which may act to constrain the free buckling of the shell. This paper evaluates one such design feature, longitudinal basket supports, and shows how a simple modification to the design can reduce the maximum plastic strain at the circumferential weld by more than 20 percent and, in turn, reduce the probability of the initiation of a weld failure by more than a factor of 5.

INTRODUCTION

In many spent fuel dry cask storage systems a welded steel canister provides the confinement boundary that prevents the release of radionuclides, not only during normal conditions of storage, but also, in the unlikely event of a drop or tip-over accident. Transfer and storage casks that contain steel canisters are typically lifted and moved, and the canister transferred, in a vertical upright position. Any drop of the cask or canister, therefore, induces high longitudinal compressive stresses in the canister shell and, depending on the drop height, possible buckling of the shell at the base of the canister. The buckling of the canister shell, in turn, can introduce high bending strains in the circumferential weld joining the shell and base plate. (This weld and the longitudinal welds in the canister shell are 100% radiographed and hydrostatically tested.) However, the strains at this location caused by such an accidental drop can be significantly increased by local design features, such as welded attachments and basket supports, which may act to constrain the free buckling of the shell. This paper evaluates one such design feature, longitudinal basket supports.

Longitudinal basket supports are typically fabricated from solid steel bar stock or formed shapes and act as a spacer between the edges of the fuel assembly basket and canister shellto maintain the basket in its proper position. These supports are either continuously fillet welded or stitch welded to the shell along their entire length. The basket supports extend along most of the canister shell length, but typically terminate a few inches above the top of the base plate. This termination of the basket support just a few inches above the base plate creates a hard discontinuity and constraint that prevents the free buckling of the canister shell during a drop impact event. The results provided herein show that by simply not welding the basket support to the canister shell over the bottom 32 to 48 cm (12 to 18 inches) allows the free buckling of the shell to take place, which drastically reduces the maximum strain in the circumferential weld that joins the shell to the base plate.

METHODOLOGY

To evaluate the influence of basket supports on canister response due to a 6.1 meter (20 foot) vertical drop impact onto an unyielding surface, an LS-DYNA [1] finite element model was constructed. The model consists of a 1.27 cm (0.5 inch) thick cylindrical steel shell 173 cm (68 inches) in diameter and 457 cm (180 inches) long with a 25 cm (10 inch) thick welded lid and 13 cm (6 inch) thick base plate also welded to the shell. The basket supports, made from 2.5 cm (1 inch) by 5.1 cm (2 inch) bar stock, are continuously fillet welded to the shell on each side and circumferentially spaced at 22.5 degree intervals. Each basket support terminates 3.8 cm (1.5 inches) above the base plate.

To accurately capture the canister's response to drop impact, the canister shell finite element mesh consists of 5 solid elements through the shell thickness with a uniform element height to thickness ratio of 0.156 in the longitudinal direction. Figure 1 is a vertical (longitudinal) section taken adjacent to the basket support near the bottom of the canister and shows the finite element mesh of the base plate, shell and basket support bar. All elements use single point reduced integration.

The canister shell, lid, base plate and basket supports are made of stainless steel, which is represented in the model by a bilinear stress strain curve with an elastic modulus equal to179,400 MPa (26,000,000 psi), yield stress equal to 264 MPa (38,300 psi) and a tangent modulus equal to 407 MPa (59,000 psi). These mechanical properties are representative of an engineering stress strain curve at temperature, and therefore produce conservative results since LS-DYNA assumes the input is a true stress strain curve.

Two drop analyses are performed. In the first analysis the longitudinal basket support is continuously welded to the shell on each side along its entire length. In the second analysis the continuous fillet weld is eliminated from the bottom 48 cm (18 inches) of the bar. This is a simple and cost-effective modification and constitutes the only change.

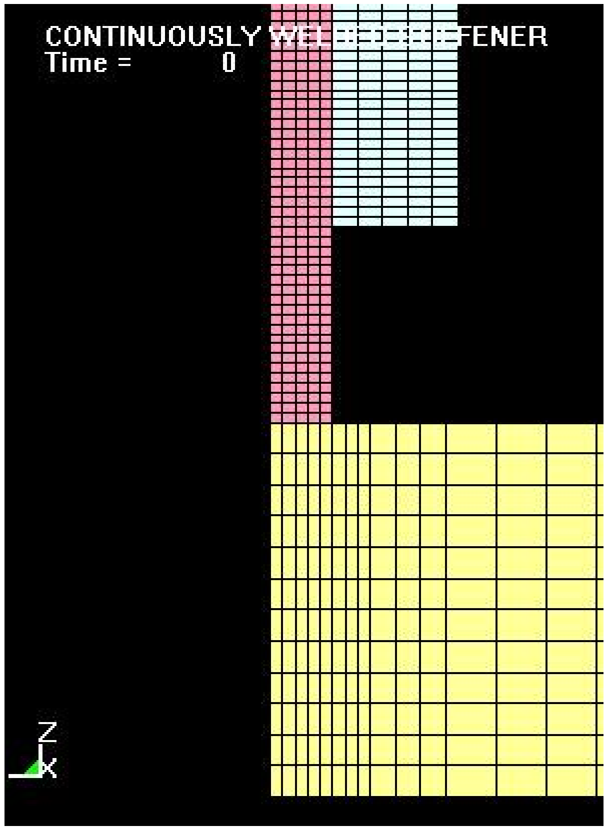

Figure 1: Vertical Section adjacent to basket support bar showing the finite element mesh of the shell, base plate and basket support.

RESULTS

For the fully welded basket support model, shell deformation due to the 6.1 m (20 foot) drop impact is primarily confined to the 3.8 cm (1.5 inches) between the base plate and the bottom of the basket support bar, as shown in Figure 2. The maximum effective plastic strain in the shell is 0.34 in/in and occurs in the circumferential weld, which joins the shell to the base plate.

In the second analysis the canister did not have the basket support bars welded to the shell along the lower 48 cm (18 inches) of the bar, and the behavior is quite different. In this case buckling is allowed to take place freely in the absence of any constraint imposed by the basket support bar, as shown in Figure 3. The maximum effective plastic strain in the shell is 0.27 in/in, which also occurs in the circumferential weld. Thus, the simple modification of not welding the lower 48 cm (18 inches) of the bar to the canister shell reduced the maximum effective plastic strain by more than 20 percent. At these strain levels, such a reduction in strain reduces the probability of weld metal failure by more than a factor of 5 [2]. The basis for the probability of weld failure is discussed in the next section.

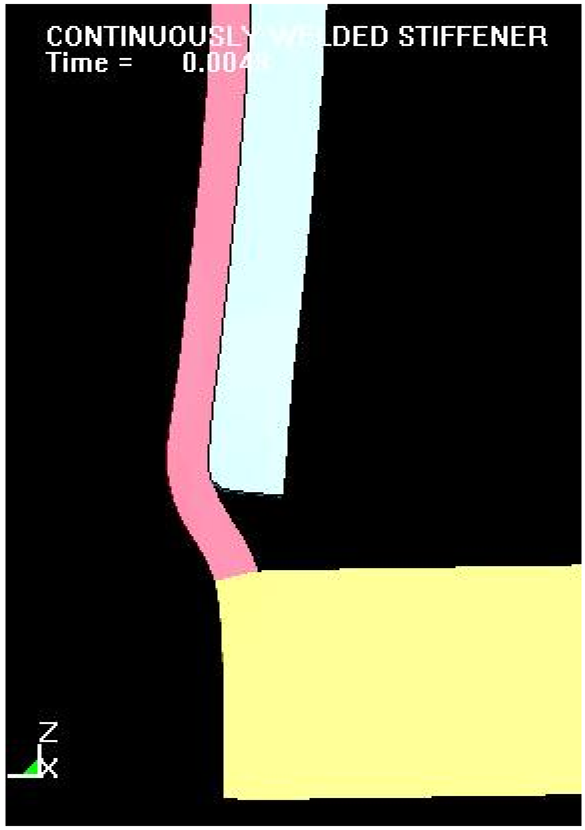

Figure 2: Canister shell deformation due to drop impact for the case of a fully welded basket support.

Probability of Weld Metal Failure

Appendix A of Reference 2 evaluated the structural response of the MPC for various end drop scenarios. The objective was to determine the maximum effective plastic strain along the MPC confinement boundary for each of these scenarios. The analyses showed that the most highly stressed regions of the MPC are near the base of the cylindrical shell and the weld joining the shell to the base plate. To determine whether confinement boundary integrity is compromised, the maximum effective plastic strain (EPS) in the MPC must be compared to an appropriate failure criterion (strain). For a valid comparison, the conditions under which the maximum effective plastic strain is calculated, and the conditions under which the failure strain is measured, should be consistent. The comparison, therefore, must account for how the strain is measured, and include the effects of strain rate, temperature and state of stress. It is the objective of this section to establish a valid basis for this comparison, and to estimate the probability of a calculated failure strain being exceeded.

The LS-DYNA computer program considers the reduction in cross-sectional area of the finite elements in the computation of stress within the element. The calculation of effective plastic strain within LS-DYNA is based on true strain, and, therefore, the failure criterion should also be based on a true strain measure. The true strain at failure is calculated from the reduction in area (RA) within the necked-down region of a failed specimen. Based on a review of References 5 and 6, the typical RA of Type 304 stainless steel at room temperature and static loading is 70%. Using the equation

$$e_t = \ln(1/(1-RA)) \ldots\ldots. (1),$$

where e_t is the true strain at failure and RA is the reduction in area, the true strain at failure is 1.20 in/in or 120% strain. This value is consistent with typical true stress strain curves that can be found in Reference 8.

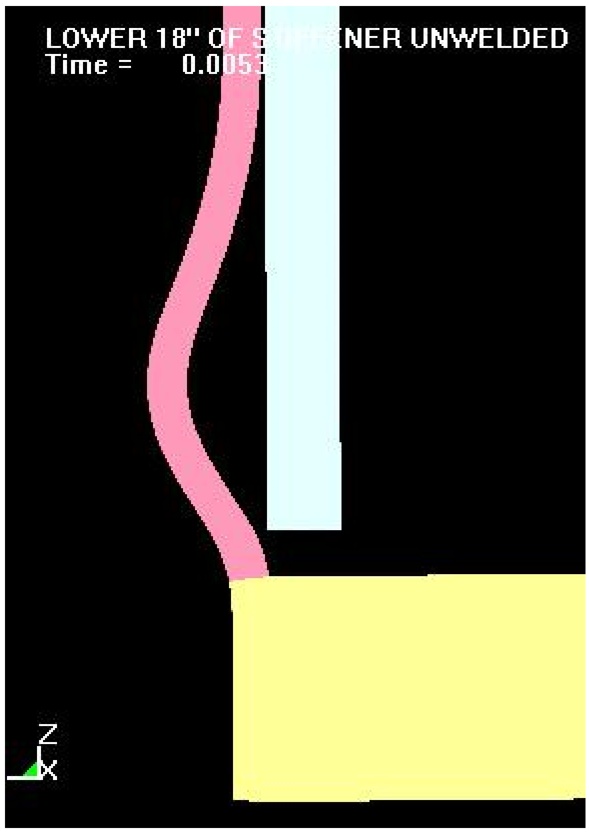

Figure 3: Canister shell deformation due to drop impact for the case of a partially welded basket support.

In the analyses performed herein no distinction is made between the base metal and weld metal in the MPC shell. Procurement of the weld material, which is typically Type 308 stainless steel, and fabrication of the MPC in accordance with the requirements of the ASME Code ensures that the weld strength is equal to or greater than the base metal. However, it is generally known that weld-deposited austenitic stainless steels (Type 308), although very ductile, have a tendency to be less ductile than the wrought (Type 304) product. At the high strain levels that may be encountered in beyond design basis events, such as severe drop impacts, this potential reduction in ductility of the deposited weld metal can be important to the structural integrity of the MPC shell.

In Reference 3, 24 Type 308 weld deposited metal specimens were cut from fabricated weldments and statically tested at room temperature. The specimens were taken from both transverse and longitudinal orientations within the weldments. The mean value of the RA was 59.7% with a standard deviation of 9.1%. This converts to a mean true strain at failure of 0.91 in/in. The mean true strains at failure minus one and two standard deviations are 0.71 in/in and 0.54 in/in respectively.

In Reference 4 the mechanical properties of archival Process Water System (primary coolant) piping and weld materials having approximately six years of service were measured. The Process Water System piping of the nuclear production reactors constructed in the 1950's at Savannah River Site was composed primarily of Type 304 stainless steel with Type 308 stainless steel weld filler. Tensile properties were measured for base metal, weld metal and heat-affected-zone (HAZ) materials. The test specimens represented both ASTM L-C and C-L orientations to allow comparison of the mechanical response for the cases of flaws oriented parallel and perpendicular to the pipe axis or rolling direction. The tensile properties of the archival piping material were found to be typical of recently-produced commercial melts of Type 304 stainless steel piping. The values of the mean RA and standard deviation of the base metal, weld metal and HAZ material for static loading at room temperature are shown in Table 1.

Stainless Steel Material	Mean Reduction in Area (RA)	Standard Deviation
Type 304 Base Metal	72%	9.0%
Type 308 Weld Metal	61%	10.0%
Heat-Affected Zone (HAZ)	71%	1.0%

Table 1: Mean and standard deviation test results for reduction in area at failure from Reference 1.

The mean RA for the base metal of 72% compares well to the typical values of 70% and 77% from References 5 and 6 respectively. Also, the mean RA for the weld metal of 61% and standard deviation of 10% compare well to the values of 59.7% and 9.1% cited in Reference 3. This data clearly shows that the 308 stainless steel weld metal is very ductile, although, its ductility is slightly less than the ductility of the Type 304 base metal.

The data for reduction in area (RA) of Type 308 stainless steel weld metal at room temperature and static loading used in the evaluation herein includes all the data in References 3 and 4, as well as dynamic test data at low strain rates (0.05/sec) from Reference 4. Combining this data of 37 tests gives a mean RA of 59.0% and a standard deviation of 9.7%.

The test data discussed above is for static loading at room temperature. To account for strain rates on the order of 100/sec and the elevated temperature (300F) at the base of the MPC shell, the mean RA of 59.0% for weld metal is reduced by the factor 0.88 (Reference 2, Appendix B). This results in a mean RA of 52%, accounting for both strain rate and temperature. The standard deviation is assumed to remain the same at 9.7%. From Equation (1) the true strain at failure of stainless steel weld metal in a uniaxial tension test, considering the effects of strain rate and temperature, can be estimated to be 0.73 in/in with a mean minus one and two standard deviations of 0.55 in/in and 0.40 in/in respectively. The Table 2 shows the mean true strain at failure minus several standard deviations along with the probability that the weld metal's true strain at failure is less than the tabulated value.

Standard Deviation from the Mean	True Strain at Failure (TSF)* (in/in)	Probability the TSF is Less than the Tabulated Value [P(x < TSF)]
0.0 (Mean)	0.73	0.5
0.5	0.64	0.3085
1.0	0.55	0.1587
1.5	0.47	0.0668
2.0	0.40	0.0228
2.5	0.32	0.0062
3.0	0.26	0.0013
3.5	0.20	0.00023
4.0	0.14	0.000032
4.5	0.087	0.000003
5.0	0.036	< 0.000001

* TSF values have been reduced for the effects strain rate and elevated temperature.

Table 2: Mean true strain at failure minus several standard deviations and the probability that the weld metal actual true strain at failure is less than the tabulated value.

The probability of failure of stainless steel weld metal at the plastic strains given in Table 2 are approximate since the amount of test data capturing true strain at failure (or RA) of stainless steel weldments at elevated temperature and high strain rates appears to be limited. Nonetheless, Table 2 does provide a reasonable estimate of weld failure probability in uniaxial tension at the strain rates and temperatures in the most highly stressed region of the MPC. [For the comparison study performed herein the effect of the state of stress on either reducing or increasing the true strain at failure is not considered. For information on how state of stress can be incorporated into a structural integrity evaluation, see Reference 2, Appendix B.]

CONCLUSION

In the unlikely event of an accidental drop of a spent fuel canister, the canister would very likely impact in a near vertical orientation. If dropped from a sufficient height in this orientation, buckling of the canister shell would be expected to occur just above the junction of the shell and base plate. Not welding the basket supports to the shell in this region eliminates the constraint to shell buckling imposed by the basket supports and results in a 20 percent reduction in maximum effective plastic strain in the shell to base plate weld. In turn, this reduction in strain reduces the probability of weld failure by more than a factor of 5 [2]. Based on these results it would be beneficial for canister designers to minimize discontinuities and constraint to shell buckling in the lower regions of the canister.

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