Abstract

A Spent Nuclear Fuel (SNF) can, which is called the High Integrity Can (HIC), is being designed at the Idaho National Engineering and Environmental Laboratory (INEEL). Its intended use is to contain SNF sent to the Idaho Nuclear Technology and Engineering Center (INTEC). INTEC will then do the final work with the HIC to send it to the repository at Yucca Mountain, Nevada, for long-term storage. One portion of the analysis, which was required for the HIC, was accidental drop scenarios. This consisted of 19 simulated drops from a height of 30-feet with impact on a flat rigid surface. Elastic/plastic analyses were performed for the simulated drops. Additionally, two elastic/plastic analyses were performed for drops from a height of 17-feet with impact on a rigid surface having a narrow raised portion across its center. The purpose of the analyses was to determine if any breach occurred which opened a crack wider than 0.05-inches from these drop scenarios. Also, some plastic deformations were needed from certain drop scenarios to support the Criticality Safety documentation.

The analytical results for the simulated drop scenarios showed that, though the seal in the lid may be broken, no 0.05-inch breach occurred. Also, the deformations for Criticality Safety documentation were calculated and shown on the applicable output plots.

Introduction

A spent nuclear fuel storage can named the High Integrity Can (HIC) is required for transport and indefinite storage of spent nuclear fuel. Many factors drive the geometry of the HIC. First, an array of HICs must fit into an Irradiated Fuel Storage Facility (IFSF) canister for temporary storage at the Idaho National Engineering and Environmental Laboratory (INEEL). Second, a similar array must fit into a Standard Canister that is used for indefinite storage in the Repository at Yucca Mountain. Third, the HIC must have a large opening in the top relative to the outside diameter to allow a variety of spent nuclear fuels to be contained within it. Fourth, Criticality Safety concerns must be considered to prevent an unsafe configuration where a criticality could result. Fifth, the wall thickness surrounding the spent nuclear fuel must be at least 1/4 inch thick to meet the corrosion requirements for indefinite storage. Finally, there must be a means of lifting the can and installing and removing the lid.

Based on the requirements discussed above, a HIC design was agreed upon with an outside diameter of 5 3/8 inches and an opening at the top of 4 3/8 inches in diameter. This makes it possible to fit an array of seven HIC's in either the IFSF canister or the Standard Canister while allowing a large variety of spent nuclear fuel to fit through the opening in the top. The design length agreed upon could range from having a minimum cavity length of 36 inches to having a maximum overall length of 101 inches. The length variation makes it possible for the company sending the spent nuclear fuel to select which length works best for their needs. Additional design requirements defined a maximum spent nuclear fuel weight of 4.7 pounds per inch of can cavity. Also, the spent nuclear fuel must not cause a pressure that exceeds the 250 psig within the HIC.

When being transported to the INEEL, the HIC will have a screw top lid. The lid, when installed, presses on a pressure plate that in turn presses on a C-ring. During transport to the INEEL this C-ring (shown in Figures 2) provides the necessary seal. When transported from the INEEL to the Repository an additional weld will be added (in the location shown in Figure 2) which provides a more permanent seal. Once the weld for sending the HIC to the Repository is in place, the can will provide the required 1/4 inch material thickness all the way around the contained spent nuclear fuel.

At the top of the HIC there is a lifting lug (as shown in Figure 1) which will mate with the lifting equipment at the INEEL. Also, notches in the top of the lid will be used to install and remove the lid and the holes in the side of the HIC top will aid in installation and removal if needed.

A thorough structural analysis on the HIC has been completed. Only the portion of the analysis related to the drop scenarios will be covered in this paper, however.
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Figure 1 – High Integrity Can (HIC).

Figure 2 – Cut away view of the HIC. (The pipe length may vary.)
The material used for all the structural portions of the HIC is Hastelloy C-22. The C-ring is Hastelloy C-276 with a silver coating. The Standard canister that is modeled in two of the drop scenarios is made from 316 stainless steel. Table 1 shows the material properties used in the HIC design [1][2][3][4] and the Standard Canister [8]:

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength [psi]</th>
<th>Yield Strength [psi]</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hastelloy C-22</td>
<td>100,000</td>
<td>45,000</td>
<td>0.45</td>
</tr>
<tr>
<td>316 stainless steel</td>
<td>75,000</td>
<td>30,000</td>
<td>0.40</td>
</tr>
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</table>

Loads

The following loads are considered for the drop scenarios of the HIC design:

- **Deadweight**: Deadweight of the HIC includes the mass of the empty HIC and the maximum spent nuclear fuel mass based on the HIC length.
- **Pressure**: Pressure load includes a 250 psig internal pressure that is applied for some drop scenarios and not applied for others.
- **Mechanical**: Mechanical loads include the loads applied when sealing the HIC. These include a 5200 pound load that the lid applies to the pressure plate to seat the C-ring [9] and seal a 250 psig internal pressure.

Drop Scenarios

To analyze the above loads, several load combinations were considered. These included 21 drop scenarios. In all of the drop scenarios except the last, there is an initial pressure plate to lid load of about 7000 pounds (for only the HIC of interest where several HICs are modeled in the same finite element model). The required mechanical load is about 5200 pounds; however, having an analyzed load 1800 pounds greater reduces the needed accuracy for remote installation of the lid. Additionally, all the impact scenarios were done such that the HIC impacted a rigid surface. In drop scenarios where the HIC was horizontal to the rigid surface, no elements representing fuel were put in the model. Rather, the density of the HIC pipe was increased to account for the fuel mass. By doing this, the fuel was not allowed to support the HIC pipe in an impact where the support would reduce damage to the HIC. The vertically oriented drop scenarios did have elements representing fuel inside the HIC.

Drop Scenarios 1-7 included a single HIC falling 30 feet with no internal pressure and impacting a rigid surface. The impact orientation was varied including an upside down vertical impact, a right side up vertical impact, a horizontal impact, an upside down impact 5 degrees off vertical, a right side up impact 5 degrees off vertical, an upside down impact 45 degrees off vertical, and a right side up impact 45 degrees off vertical. Drop Scenarios 8-14 were identical to Drop Scenarios 1-7; however, they included initial internal pressure of 250 psig. Drop Scenarios 15 and 16 were 30 foot horizontal drops with 7 HICs inside a Standard Canister. Drop Scenario 15 did not have the 250 psig initial internal pressure inside the HICs where Drop Scenario 16 did. Drop Scenarios 17 and 18 were 17 foot horizontal drops with a HIC hitting a 1/2 inch wide by 3 inch high edge, which ran perpendicular to the length of the HIC. Initial contact between the HIC and rigid surface edge occurred in the middle of the HIC and a once deformed, the HIC would contact a rigid surface at the base of the rigid edge. Drop Scenario 17 did not have a 250 psig initial internal pressure and Drop Scenario 18 did. Drop Scenarios 19 and 20 consisted of one vertical HIC impacting a second vertical HIC after falling 30 feet. The two HICs were offset to try to focus the load on one side. Drop Scenario 19 didn’t have the 250 psig initial internal pressure in the HICs and Drop Scenario 20 did. Drop Scenario 21 was a right side up vertical drop of a HIC that had dropped 30 feet. This model was done to check for penetration of the fuel through the bottom of the HIC and the fuel was modeled to envelop as many fuel sizes as possible.

The Repository weld (located as shown in Figure 2) is modeled only in Drop Scenarios 15 and 16. Drop Scenarios 17 and 18 were based on an accident that would happen after the Repository weld is in place. These drop scenarios are not modeled with a Repository weld, however. Modeling these drop scenarios with no weld is conservative and covers similar drops that might occur before the Repository weld is in place. Having the Repository weld makes the threads much less important and makes failure of the HIC top (at the base of the threads) much less likely.

Assumptions

This analysis is intended to encompass most loading conditions that the HIC could potentially see. It is the basic assumption of this analysis that the HIC user at each facility will review the design criteria and analysis and take responsibility for the HIC to meet their design requirements.

Acceptance Criteria

After a drop accident, failure in the HIC can not cause a breach that opens up a crack wider than 0.05 inches. If this condition exists, criticality displacements will be reported to Criticality Safety. Criticality Safety will then assess if the deformations are acceptable relative to causing a criticality.
Failure of elements in the plastic analyses was generally defined in terms of strain levels reached. The failure definition was imposed by applying failure criteria in the ABAQUS/Explicit [6] program (using *FAILURE). In the analyses, failure at a point was assumed to begin occurring when the equivalent plastic strain reached 2/3 of the ultimate strain of the material. The stress versus strain curve (shown in Figure 4) demonstrates how this was treated in ABAQUS/Explicit. The material goes to yield, then to 2/3 ultimate strain, and then ramps down to zero stress at ultimate strain. (This curve is input into the materials portion of the ABAQUS/Explicit input file for each material having failure criteria.) With this treatment, it was not necessary to compare calculated strains with allowable strains. Instead, any element whose strain reached the failure strain was effectively removed from the mesh.

![Figure 4 - Stress versus strain curve.](image)

These failure criteria were only applied to elements where failure of material was a concern. Elements, such as those for the spent nuclear fuel, were not given failure because their failure would reduce the loads seen by the HICs. That would not be conservative. Also, the true stress and true strain values used in the analysis were calculated using ASTM specified tensile stress and elongation.

Calculations

To perform the drop analysis, several hand calculations were done to aid in setting up the finite element models. These are relatively simple and not shown in this paper.

The material properties used were ASTM material properties converted to true stress and true strain for ABAQUS/Explicit finite element model. The ASTM values used were the yield and ultimate stress and ultimate elongation. For the conversion to true stress and strain, it was assumed that the ASTM ultimate stress and elongation occurred at the same point. Second, a thread calculation using the Machin ery's Handbook [7] was needed. This calculation showed that there were sufficient threads to cause a failure to occur across a tensile cross section rather than shearing the threads. This made it unnecessary to check thread shear in the finite element model. Third, the required impact velocities and energies for the drop scenarios were found based on the drop height requirements of the design. The velocities used as input for the ABAQUS/Explicit models were increased slightly from that required by the hand calculations producing a higher than needed model energy. The energy curves produced by ABAQUS/Explicit model runs include an artificial energy curve. The artificial energy curve was considered to represent error in the analysis. To compensate, the artificial energy was subtracted from the higher than required energy in the model. This difference was then compared to the hand calculated energy. If the hand calculated energy was greater than the difference, then the model was considered an acceptable run.

Finite Element Models

All the finite element models were generated using SDRC IDEAS Master Series 6 [5]. Only a few that gave important results will be discussed. Figures 5-9 show some of the finite element model meshes used in the drop scenarios. Figures 5-7 show the finite element mesh of the HIC for Drop Scenarios 1-14. The main difference between the drop scenarios is the orientation of the rigid surface (not shown in the figures) being impacted, the velocity vector of the HIC, and the way the fuel is incorporated into the model. In all the models, linear solid brick and thin shell quadrilateral elements were used. Where transition from solid to thin shell elements was done, a surface coating of thin shells was put on the solid elements where the attachment occurred. These elements then shared nodes or were tied to the thin shells and solid element on either side of the line of attachment. By doing this, all the moments could be transferred from the six-degree of freedom thin shell elements to the three-degree of freedom solid elements. Figure 8 shows a portion of the finite element mesh used for Drop Scenarios 15 and 16 (seven HICs inside a Standard Canister). The HIC nearest the rigid surface (not shown in the figure) at impact is meshed as the one used in Drop Scenarios 1-14. The other six are modeled more course including thin shells only. Figure 9 shows part of the finite element mesh used for Drop Scenario 21. In regions away from where penetration was being checked, beam and shell elements were used mainly to account for the additional mass. A relatively fine solid mesh was used in the region where penetration was being checked.

With the meshing complete, input files were written for ABAQUS/Explicit [6] and the elastic/plastic runs were completed. The true stress, true strain material properties used in the models are shown in Table 2:

![Table 2 - True stress, true strain material properties.](table)

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Hastelloy C-22</td>
<td>145,000</td>
<td>45,068</td>
<td>0.370</td>
<td>0.247</td>
</tr>
<tr>
<td>316 stainless steel</td>
<td>105,000</td>
<td>30,032</td>
<td>0.335</td>
<td>0.224</td>
</tr>
</tbody>
</table>

To correctly model the impacts, contact between the different pieces had to be defined in the model. This was accomplished by defining element or node sets of the portions of the model where contact could occur. If two pieces could touch each other during the impact, a master surface and a slave surface or node set had to be defined. Some thought had to be put into choosing what definition to use. Though a surface contact is desirable, ABAQUS/Explicit becomes unstable if elements fail that are part of a surface. This caused all regions where failure occurred to be defined as node sets.

With contact defined, the model needed initial restraints. Only one restraint was defined which occurred throughout the impact. This restraint consisted of fixing the node that was reference by the rigid surface. The rigid surface reference node is not attached to any element and fixing it fixes the rigid surface in place.

Additionally, initial loads were needed. These loads included the initial pressure plate load from the lid of about 7000 pounds and the 250 psig internal pressure (for some drop scenarios). They were applied over several steps. For the 7000 pound load, an initial overlap occurred between the lid and pressure plate. At this point no
Figure 5 – Finite element model of a single HIC.

Figure 6 – Cut away view of the top portion of the HIC finite element model.

Figure 7 – Cut away view of the bottom portion of the HIC finite element model (without the elements representing fuel).
Where more than one HIC was modeled in a drop scenario, lid to pressure plate initial loading was only applied to the HIC of interest. The internal pressure was applied to all the HICs in a drop scenario having pressure included.

A gravitational load (386 in/sec^2) was also defined during impact on all the elements (excluding those in the rigid surface) in the direction of the impact velocity. Though basically insignificant, this load was applied to all the models.

**Finite Element Model Results**

To evaluate the results, no comparison to allowable stresses is made. This is because the acceptance criteria are covered by the failure criteria put on the elements. Any element having a strain great enough to fail the element will no longer carry a load and is removed from the model for display.

The displacements in general are given as plastic displacements occurring at some point after the HIC has begun to rebound. Because of elastic waves, the maximum instantaneous absolute displacements could exceed these values by a small amount.

Most of the drop scenarios required some initial loads and these loads were applied as described in the Finite Element Models section. Figure 10 shows the energy graph for the elastic energy of the model while the initial loads were applied. From 0 seconds to 0.005 seconds, loads were ramped up to separate the overlap of the lid and pressure plate. (The sine wave results from shock waves passing through the lid and pressure plate.) From 0.005 seconds to 0.010 seconds, contact was defined between the lid and pressure plate and the loads separating them were ramped back down to allow the
Figure 10 – Elastic energy versus time.

Figure 11 – Stresses in the upper portion of the HIC at 0.015 seconds (for a model with an internal pressure).
Figure 12 - Whole model energy versus time.

Figure 13 - Plastic equivalent strain for Drop Scenario 8.
Figure 14 – Plastic equivalent strain for Drop Scenario 14.

Maximum value = 0.3596 at node 39013
Minimum value = 0. at node 18862

Figure 15 – Deformation at the center of the Standard Canister for Drop Scenario 15.

Maximum value = 5.597 at node 45157
Minimum value = 0.2810 at node 19405
contact to occur. At 0.010 seconds the 7000 pound lid to pressure loads with the exception of adding gravity. For those requiring an internal pressure, the pressure load is ramped on from 0.010 seconds to 0.015 seconds.

The stress plot (shown in Figure 11) shows the stresses in the upper portion of the HIC at 0.015 seconds (for a drop scenario requiring an initial pressure). No plastic stresses occurred during the initial loading portions of the model runs.

Figure 12 shows the energy plots of an entire model run (this one is for Drop Scenario 9). It shows how the kinetic energy is increased as the HIC is accelerated to impact velocity (near 0.016 seconds). Then it shows how the HIC is allowed to drift a short period of time while it is no longer being accelerated (where the kinetic energy curve flattens out). Finally, impact occurs and the kinetic energy is converted to plastic energy and other miscellaneous energies. Once the energy curves appear to be maintaining a constant pattern, the initial impact is considered to be over. (The initial loading portion of the curves does not show up on this plot because it is minimal compared to the energy associated with accelerating the HIC to impact velocity.)

All of the model runs were done as described above. Figures 13, 14, and 16 show the plastic equivalent strains developed from some of the most damaging drop scenarios. These plots show only the portion of the HIC having the most damage in the given drop scenario and failed elements are removed for display. (If the failed elements were displayed, the maximum plastic equivalent strain would be the ultimate plastic strain and the failed elements would make it difficult to view the model.) Additionally, Figure 15 shows the deformations of concern to Criticality Safety are shown in the most deformed portion of the Standard Canister drop scenario. The portion shown is a cross section through the middle of the Standard Canister.

**Conclusions**

The proposed design for the HIC was analyzed for the loads and load conditions defined in the design criteria. For the drop scenarios, the results showed that, though the seal in the lid may be broken, no 0.05 inch breach occurred in any of the drop scenarios. Also, the deformations for Criticality Safety documentation were calculated and shown on the output plots that were applicable. Drop Scenario 21 covered a potential spent nuclear fuel penetration scenario. The mesh representing the fuel element in this scenario had a cross section of a half an inch square, a flat bottom, and a mass of 90 pounds (which is 1/5 the maximum spent nuclear fuel mass that could be carried by the heaviest HIC). It showed that the modeled spent nuclear fuel element would not penetrate the HIC base (or the HIC lid) given the material properties used. Spent nuclear fuel elements with more mass or a smaller cross section could potentially penetrate the HIC.

Testing is planned for this design. Results from the tests could cause changes to the HIC design. If significant changes occur, reanalysis or additional analysis maybe required.

**References**

1. ASTM B622-87a (SB-622), Specification for Seamless Nickel and Nickel-Cobalt Alloy Pipe and Tube.
2. ASTM B619-87a (SB-619), Specification for Welded Nickel and Nickel-Cobalt Alloy.
3. ASTM B574-85 (SB-574), Specification for Low-Carbon Nickel-Molybdenum-Chromium Alloy Rod.


5. SDRC I-DEAS Master Series 6, Structural Dynamics Research Corporation, 2000 Eastman Drive, Milford, Ohio 45150, (513)576-2400.


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