Modeling and Analysis to Support Spent Nuclear Fuel Drop Tests

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

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September 30, 2019
SFWD-SFWST-M3SF-19PN010202012
PNNL-29164

SUMMARY

This report completes the milestone deliverable for M3SF-19PN010202012.

This report describes finite element analyses (FEA) that supported the one-third-scale spent nuclear fuel (SNF) package drop test campaign sponsored by the U.S. Department of Energy (DOE) in December 2018. FEA was used in pre-test modeling studies to help inform the test plan. FEA was the basis for recommendations concerning the number and location of accelerometers. FEA was also the basis for recommending a second package drop test to investigate the effect of the basket orientation of the fuel assembly on impact response.

After the test was completed, an initial comparison of test data to FEA model results was made. In general, the FEA model results agree reasonably well with the aggregated test data, but a more precise comparison of test results to an FEA model that is configured to match the test configuration is still needed. One area of FEA model adjustment needed to match test conditions is the fuel assembly to fuel basket gap condition at the time of impact. The data indicates that the fuel assemblies are not in contact with the basket at the moment of impact because there is a delay in the acceleration response of the fuel assembly accelerometers compared to the other accelerometer locations. The FEA models of this study considered two different initial gap conditions and neither gap case provided a perfect match to the observed test data.

Another important adjustment that needs to be made to the FEA models is to implement the correct impact angle observed during testing. The FEA models analyzed precisely horizontal impacts, but the test data indicate the packages impacted the target surface at a slight angle. A more precise model validation needs to be done when the geometry of the FEA model is adjusted to match the precise impact angle observed in testing. The effect of the impact angle is visible in the test data, and a properly functioning FEA model should be able to match the response at each accelerometer location. This level of validation remains to be completed in future work.

Secondary impacts are observed in the test data and in FEA models that have a non-zero gap condition. The primary impact phenomenon is the package impacting the target surface. Secondary impacts are when the fuel assemblies impact the fuel basket and exhibit short duration, relatively high accelerations that are higher than the average system response. It is important to understand secondary impacts and their potential to damage fuel assembly components. From a structural analysis perspective, the question is how to properly account for secondary impacts on fuel assembly components. Best practice frequency filtering on FEA results, and the effect of the secondary impacts on SNF rods and fuel assembly hardware are topics that remain to be explored in future work.

The test data collected during this test campaign are valuable for validating FEA models and establishing FEA best practices. It is recommended that the data be used to validate models and analysis methods, and that the validated models and methods eventually be applied to other package drop configurations of interest. The ultimate goal is to close the stress profiles knowledge gap that currently remains a high priority in addressing unknowns related to the storage and transportation of SNF.

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ACKNOWLEDGEMENTS

The authors would like to express our sincere thanks to the project's DOE sponsors, Ned Larson and John Orchard for supporting and funding this work.

The authors would also like to thank our collaborators on the drop test campaign, including staff from Equipos Nucleares S.A, S.M.E (ENSA), Bundesanstalt für Materialforschung und -prüfung (BAM), Sandia National Laboratories (SNL), and Pacific Northwest National Laboratory (PNNL).

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ACRONYMS

BAM	Bundesanstalt für Materialforschung und -prüfung
ENSA	Equipos Nucleares S.A, S.M.E
DOE	U.S. Department of Energy
FEA	finite element analyses
FY	fiscal year
g	multiples of the acceleration of gravity, 9.81 m/s^2
PNNL	Pacific Northwest National Laboratory
R&D	research and development
SNF	spent nuclear fuel
SNL	Sandia National Laboratories

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SPENT FUEL AND WASTE SCIENCE AND TECHNOLOGY/STORAGE AND TRANPORTATION

MODELING AND ANALYSIS TO SUPPORT SPENT NUCLEAR FUEL DROP TESTS

1.0 INTRODUCTION

This report describes the structural dynamic finite element modeling studies that supported a one-third scale spent nuclear fuel (SNF) package drop test campaign that was performed in December of 2018 by a multinational team at a drop test facility in Berlin, Germany. The test campaign consisted of two horizontal 30 cm drops of a one-third scale SNF package that was instrumented inside and outside with accelerometers to record the impact. This report refers to the two drop tests individually as Test 1 and Test 2, numbered in order of their occurrence. The two drop tests together, plus all the pre-test planning and post-test data analysis, are referred to generally as the drop test campaign.

The participating organizations included the U.S. Department of Energy (DOE), Equipos Nucleares S.A, S.M.E (ENSA), and Bundesanstalt für Materialforschung und -prüfung (BAM). ENSA provided the one-third scale package model, which included simulated fuel assemblies inside the package. Testing was performed at a BAM test facility in Berlin. BAM technical staff performed the drop tests and recorded data on BAM's data acquisition system. The DOE team included Sandia National Laboratories (SNL) and Pacific Northwest National Laboratory (PNNL). SNL led the collaboration team and was responsible for instrumenting the package. SNL will issue a report describing the test and test results in detail, but some details are currently available in Kalinina et al. 2019.

PNNL's role was to provide pre-test finite element analysis (FEA) to inform the test plan and post-test FEA to validate modeling methods and develop best-practices for future package impact modeling. This report describes in depth the models and analysis methods employed in this activity.

The drop test campaign is based on a one-third scale physical model of the ENSA ENUN 32P dual-purpose SNF package. The one-third-scale model was used in certification testing performed by SNL in 2010. A key difference between the current test campaign and the previous tests is that in the current test campaign the dummy fuel assemblies inside the package were instrumented with accelerometers to measure the response of the dummy assemblies to impact. The previous tests were concerned with the impact limiter, basket, and closure performance, and only measured the acceleration response of the outside of the package body (cask). Previous analytical work, such as the article by Klymyshyn et al. 2013a, has identified that the response of the fuel assemblies inside a cask can potentially experience higher acceleration loads than would be measured on the outside of the cask.

Section 2 of this report describes the pre-test finite element analysis (FEA) that was done to inform the test plan. It includes half-symmetry and fully three-dimensional (3-D) finite element models of the package and all of its major components. The section describes recommendations made for instrumentation placement, and a request for a second horizontal drop test with a 45-degree axial rotation of the package.

Section 3 of this report describes post-test FEA and compares test results to the FEA results. The intent is to validate the FEA models and develop a credible model that can be used to predict loads on the fuel in other package impact orientations in future analyses. Although this model validation work is not complete, the initial indications are that the FEA model predicts the fuel assembly response reasonably well. More detailed model validation is recommended as future work.

Section 4 discusses conclusions and observations of this work that are relevant to FEA modeling and testing. Package impact physics are generally well understood, but the mechanical loads applicable to fuel assembly components is a knowledge gap that the research and development (R&D) efforts in this area are working to close.

2.0 PRE-TEST ONE-THIRD SCALE PACKAGE MODELING

The package drop testing was focused on the horizontal drop orientation. The initial scope was a single 30 cm drop test using the package and components supplied by ENSA at one of BAM's test facilities. SNL was responsible for instrumentation and interfaced with BAM's data collection systems. PNNL's role was to recommend the best locations at which to place instrumentation and use FEA to make pre-test predictions of what would happen during the test.

Section 2.1 describes the package models that were used to explore the package system impact response prior to testing. A half-symmetry model was used first, and a full 3-D model was used to investigate the value of performing a second drop test.

Section 2.2 describes the pre-test model results. Two cases are discussed: the nominal horizontal drop configuration (Test 1) and a horizontal drop with a 45° axial rotation of the package (Test 2).

Section 2.3 describes a modeling study of the effect of scaling. In FEA, it is easy to scale up the dimensions of a one-third-scale model to full scale. The results show that a one-third scaling factor on the accelerations of the one-third-scale package is valid for translating loads to full scale.

Section 2.4 discusses the effects of gaps between the dummy fuel assemblies and fuel basket. The gap assumptions can significantly alter the peak acceleration of fuel assemblies, and all FEA models of this type must choose an initial gap condition as a fundamental assumption. The test data indicates that an initial non-zero gap is to be expected in practical test conditions. This suggests that non-zero gaps can be expected in any practical package-handling drop event.

Section 2.5 documents the test recommendations that were made for SNL to consider in the instrumentation plan for the test. The justification for the second drop test is also documented.

2.1 Pre-Test Package Model Description

The SNF package is modeled in LS-DYNA (LSTC, 2013), a commercial general-purpose explicit dynamic finite element code that is well-suited to structural dynamic impact modeling. The model is a 3-D representation of the ENUN 32-P dual-purpose cask system. Figure 1 shows the package model in its half-symmetry configuration. A full 3D model was also generated from the half-symmetry finite element mesh (a mirror element generation) and used for final impact response calculations. This report will clarify when the symmetry or full 3-D versions of the model were used.

The geometry of the FEA model generally matches the scale test package in terms of mass and major dimensions. One simplification in the FEA model is that the cask body is approximated as a closed cylinder, rather than modeling the bolted lid in detail. For safety analysis models, the bolted lids are key features for evaluation, but in this application the lid area response is not relevant. Bolts provide sufficient tension and clamping force that the lid response is not expected to affect the rest of the package. In the horizontal drop orientation, the effect of the lid is limited because of geometry. The lid is located away from direct contact with fuel assemblies or the fuel basket. In this orientation, the structural significance of the lid is to complete the end of the open cylinder of the cask. If the lid was not present, the open end of the cask would be expected to deflect into a classic oval pattern under the inertia loading. With a lid bolted into place, some amount of structural rigidity is present, so deflection of the cask at the lid end is expected to be minimal, and comparable to the welded base plate end. Also note that the one-third scale package model was designed for certification testing, which included evaluation of the lid and bolted closure region. The as-modeled simplification of the lid end of the cask is expected to be a reasonable approximation of the bolted closure for the purposes of this test because the lid is not expected to have any significant effect on the transmission of forces from the cask body to the fuel basket to the dummy fuel assemblies.

Similarly, the impact limiters are modeled with homogeneous volumes of material (regions of polyurethane foam and aluminum honeycomb) instead of representing the details of the sheet metal impact limiter skin, impact limiter bolted attachment, or other precise details of the impact limiter. This is a simplified way to model impact limiters, but previous impact test data was available to choose crushable material properties that reasonably match the impact behavior. The package model impacts a perfectly rigid surface, so the crush strength of the foam and honeycomb materials are the primary parameters used to achieve the desired impact behavior.

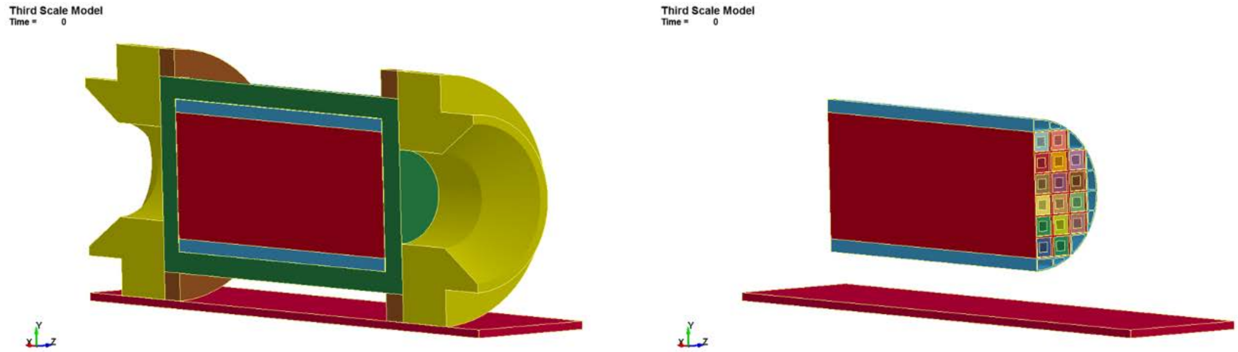

Figure 1. The package model in its half-symmetry configuration.

A full 3-D model was constructed from the half-symmetry model by an element mirroring operation. The elements of the half-symmetry model were duplicated and transformed relative to the symmetry plane, then a duplicate node operation was performed to search for and eliminate overlapping nodes. This process created the model shown in Figure 2. The only significant changes between the half-symmetry package model and the full 3-D model is the doubling of the number of elements and the removal of the symmetry plane node constraints. The full 3-D model was necessary to explore non-symmetric impact orientations, which are discussed later in this section.

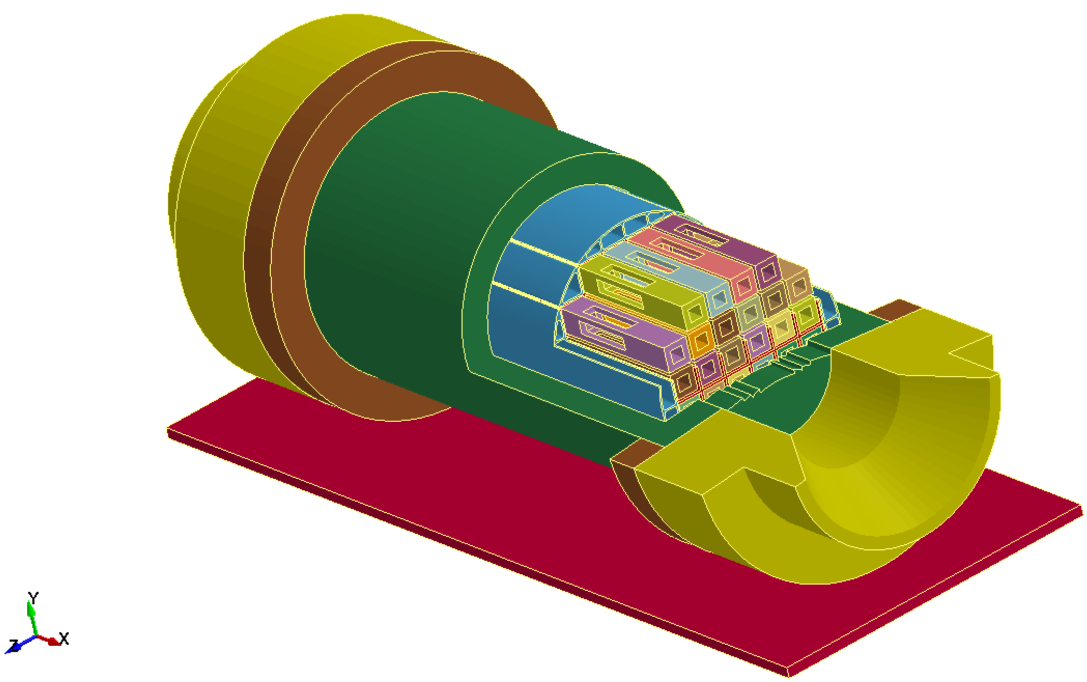

Figure 2. The full 3-D model constructed from the half-symmetry model.

The simulated (sometimes called "dummy") fuel assemblies used in the test are square steel tubes that have slots cut out of them. The FEA geometry is shown in Figure 3. The labels A, B, C, and D identify the relatively solid sections where the square tube is not modified by slots. Location A is closest to the package lid, and location D is at the opposite end, closest to the package base plate. Section 2.5 discusses how the accelerometer locations were chosen.

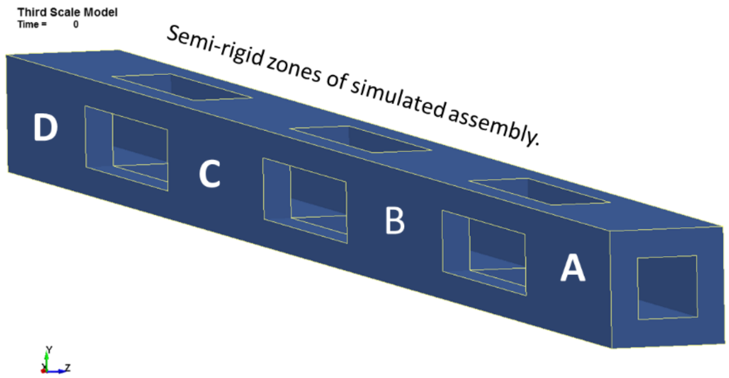

Figure 3. The FEA geometry of the simulated fuel assemblies.

It is important to note that the FEA models of the dummy assembly and the physical dummy assemblies used in the one-third scale package drop test are not perfect representations of SNF assemblies. The FEA model of the dummy assembly shown in Figure 3 is a defeatured approximation of the dummy assemblies used in the test. The FEA model has features like the side slots and central hole "squared off" instead of rounded and filleted in order to make it convenient to mesh with hexahedral elements. The FEA model and the actual test articles are expected to behave as nearly rigid bodies, with some minor bending deflections possible. A SNF assembly would behave differently during a horizontal drop event, with the bundle of evenly spaced fuel rods able to deflect in the transverse direction (in the direction of impact velocity) and potential compression at the spacer grids.

The difference between dummy assembly impact behavior and SNF assembly impact behavior is planned to be evaluated in a separate testing and modeling campaign, which is outside the scope of this report.

2.2 Pre-Test Package Model Results

The 30 cm package drop load case has an initial velocity of about 2.4 m/s. The model detects contact when the impact limiters touch the rigid target surface. It takes about 11 ms for the impact acceleration pulse to conclude. At the end of the pulse, the direction of the package velocity is reversed, indicating rebound has commenced. During the test, the package was observed to bounce a number of times after the initial impact. The analyses in this report all focus on the first impact and rebound phase, because they involve the most energy, as well as the highest forces and accelerations.

Figure 4 shows the deceleration pulse of the dummy fuel assemblies within the package in the Test 1 horizontal drop configuration. This model uses half-symmetry to minimize the scope of the model. Figure 4 plots the rigid body acceleration trace of each of the dummy fuel assemblies, labeled A through M, as shown in the sketch on the right side of the figure. Note that the accelerations were filtered with a low pass Butterworth filter that had a 300 Hz cutoff frequency. It is common practice to apply a low pass filter to eliminate high-frequency content in these types of models, and the cutoff frequency is based on the natural frequencies of the structural components. In this case, 300 Hz was chosen for the one-third-scale model because 100 Hz is estimated to be the highest frequency range of interest for pressurized water reactor fuel assemblies at full scale based on previous modeling and testing (Klymyshyn et al. 2013b). It remains to be confirmed whether 300 Hz is the best cutoff frequency for this task. Nonetheless, as will be shown later in this report, the 300 Hz cutoff frequency does lead to results that are comparable to the test data, so this appears to be a reasonable cutoff.

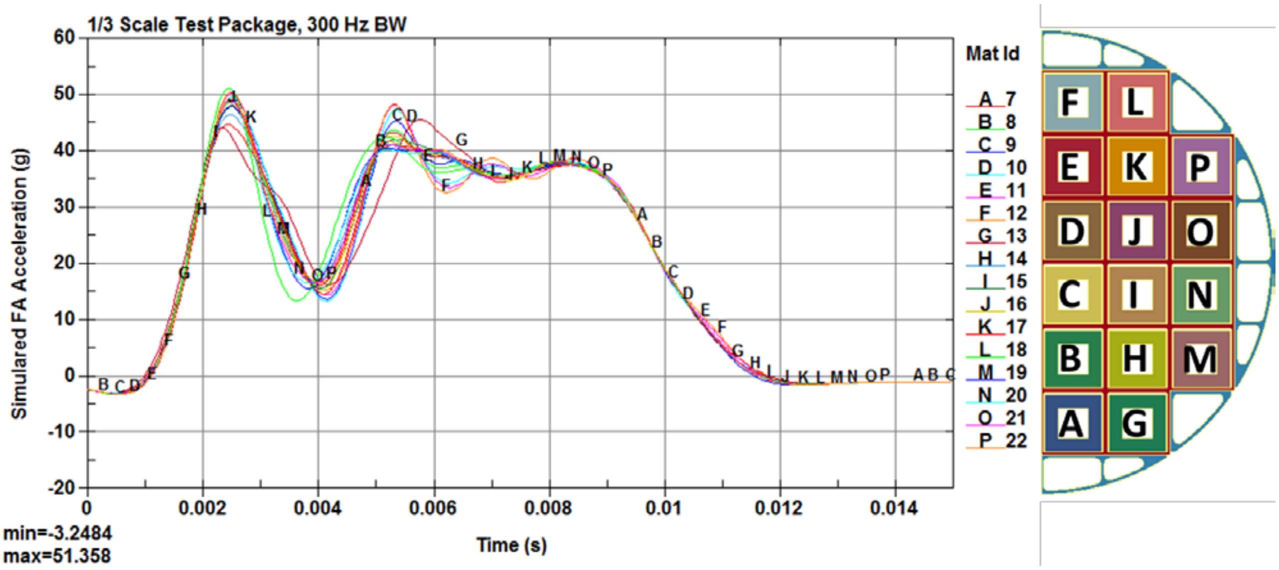

Figure 4. The deceleration pulse of the dummy fuel assemblies within the package in the Test 1 horizontal drop configuration. The rigid body acceleration trace of each of the dummy fuel assemblies, A through M, are plotted.

A few observations can be made about Figure 4. All fuel assemblies experience a similar deceleration pulse, with minor variations. The highest peak acceleration was for assembly L. The highest peak near 0.005 seconds was for assembly G. Assemblies L and G were assigned highest priority for accelerometers because they are two different local peaks on the acceleration-time curve, and they are relatively far away from each other in the basket. Note that A and G are closest to the impact surface and F and L are farthest away from the impact surface. The instrumentation recommendations are discussed in more detail in Section 2.5.

The acceleration results for the Test 1 and Test 2 configurations are plotted in Figure 5, in the top and bottom graphs, respectively. Note that the red line marks 50 g in both plots for comparison purposes. The top graph is identical to Figure 4. The bottom graph shows the fuel assembly response in the Test 2 orientation is predicted to have higher acceleration peaks and a less uniform distribution across basket locations. Figure 5 is the basis for recommending the conduct of a second drop test. The model predicts a significantly different response that is worth studying.

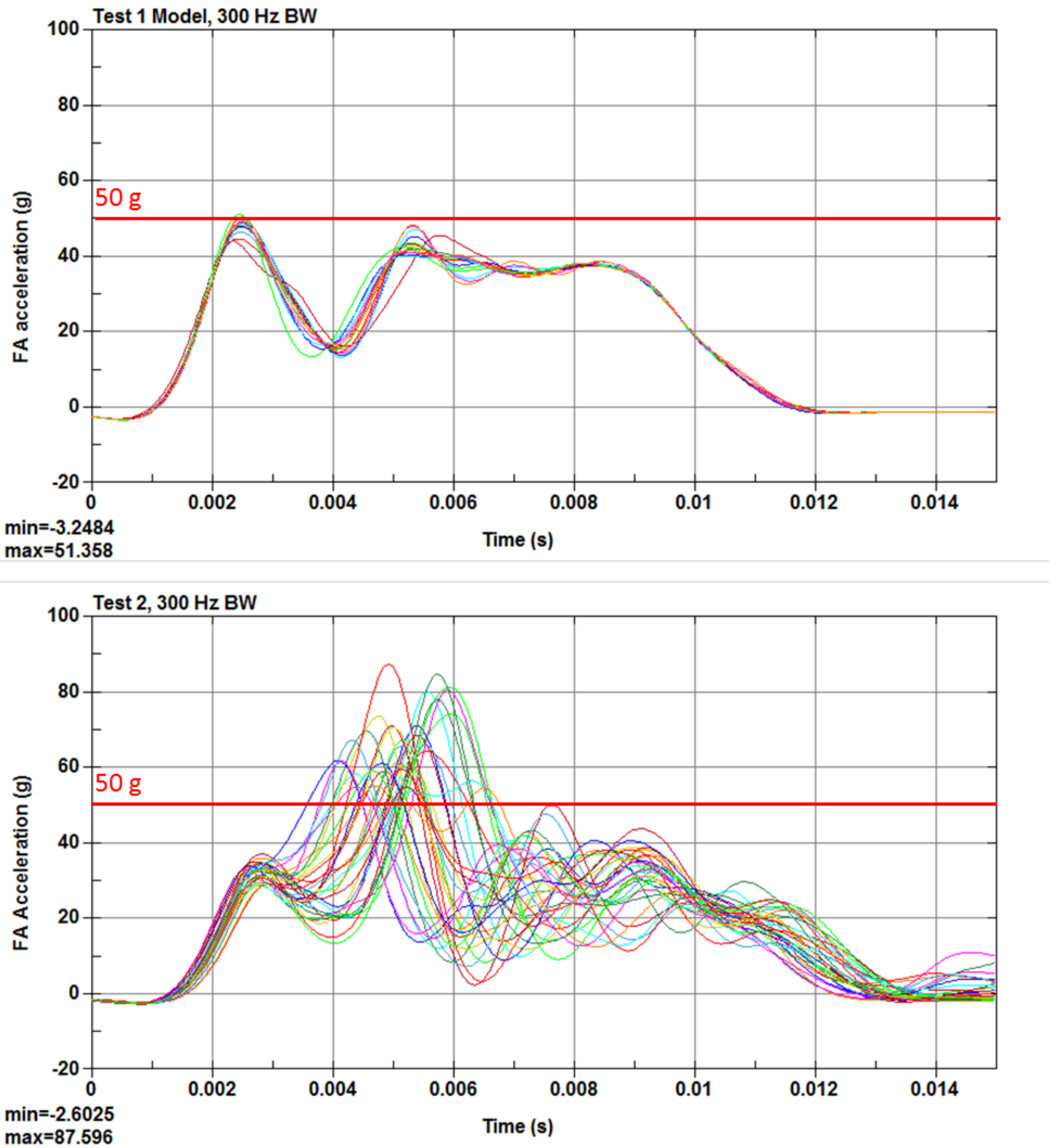

Figure 5. The calculated acceleration results for the Test 1 (top) and Test 2 (bottom) configurations.

2.3 Analysis of Scaling Effects

It is common to perform SNF package drop tests using scaled models instead of full-scale test articles. The overall cost of a full-scale package and the availability of high mass capacity drop facilities are both considerations that favor scale model testing. In FEA, the scaling of models is nearly inconsequential. Figure 6 shows the fuel assembly response in a one-third-scale and full-scale Test 1 30 cm drop configuration, in the top and bottom graph, respectively. The full-scale response has approximately one-third of the acceleration magnitude and three times the duration. The scaling factor of 3 comes from the fundamental differences in the geometry of the two cases. A one-third-scale model has 1/27 of the volume (and mass) and 1/9 of the impact area (impact limiter footprint). Since impact force is related to the area of the crushable impact limiter material, and it acts on the mass of the package to cause acceleration, the result is an acceleration scaling factor of 3. Because the impact velocity is the same for both cases, the lower acceleration case must have a longer duration to reverse the velocity into rebound. In Figure 6 there are only minor differences visible in the acceleration traces when the scaling factor of 3 is considered.

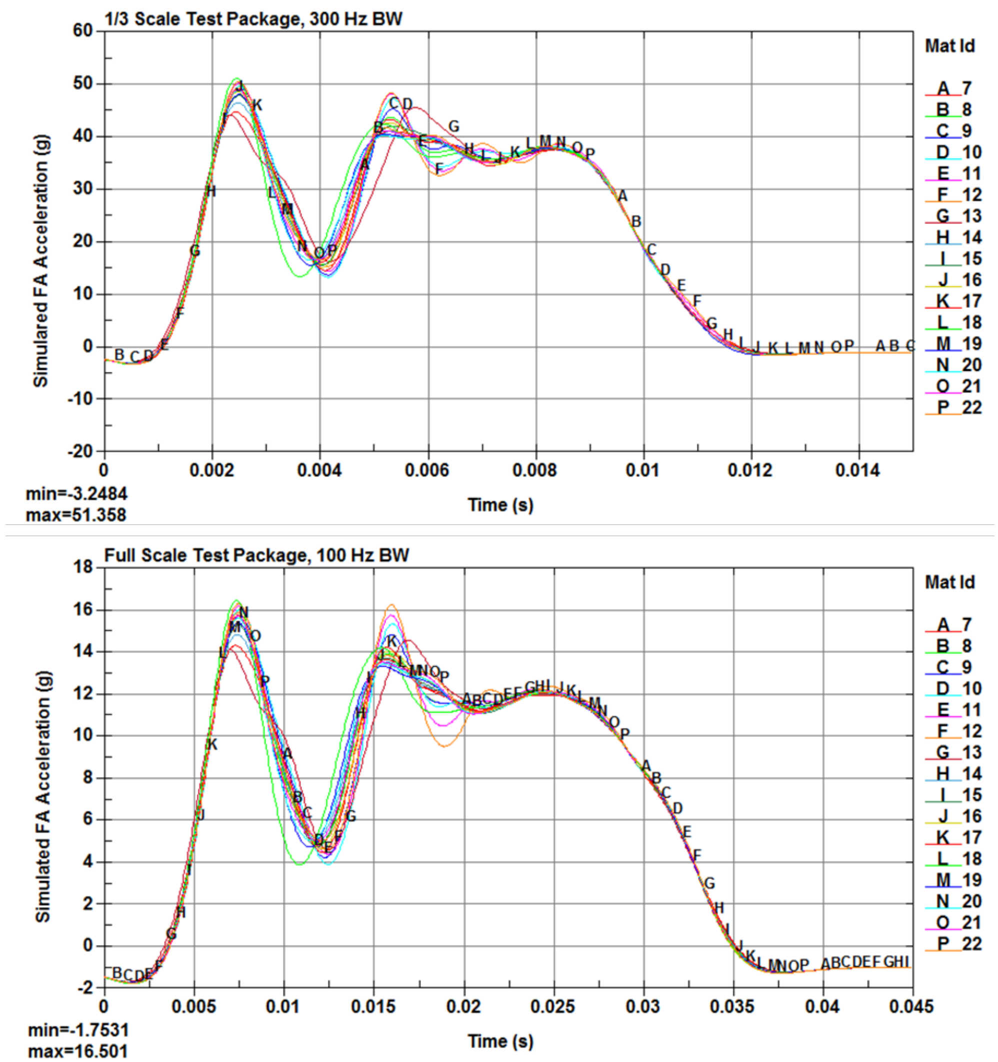

Figure 6. The calculated fuel assembly response in a one-third- scale (top) and full- scale (bottom) Test 1 30 cm drop configuration.

2.4 Analysis of Gap Conditions

In FEA, potential physical contact between separate bodies needs to be identified in the model, or else parts will pass through each other without recognizing that they are violating each other's volume. LS-DYNA has automatic contact options that check for contact between all parts in a defined set, which is convenient, but it requires some diligence from the analyst to confirm that the automatic contact is working as intended.

One of the parameters that affects contact behavior is the initial gap between bodies. Having some amount of initial gap is preferred because it makes the contact easier for the FEA code to sense automatically. Perfectly coincident contact surfaces can cause problems with the automatic contact detection, so they are generally avoided when using FEA. In this modeling application, the important gaps are the ones between the dummy fuel assemblies and the fuel basket walls. In the Test 1 pre-test model they were initially set to be about 0.3 mm (Figure 7). This contact configuration is called the nominal case. FEA studies also considered a much smaller gap, of less than 0.001 mm, which is called the zero gap case.

The size of the starting gap affects the package system impact response by delaying contact and the transmission of forces. When the gap is approximately zero, there is no delay in transmitting forces, and the fuel and the rest of the package all respond together. The nominal gap condition (about 0.3 mm) introduces a delay in contact response of about 2 ms, which is clearly visible in the FEA response as short-duration spikes in acceleration. These spikes caused by delayed contact are called secondary impacts. They represent the fuel assemblies impacting the package, after the package has already started decelerating from impact with the ground (target surface).

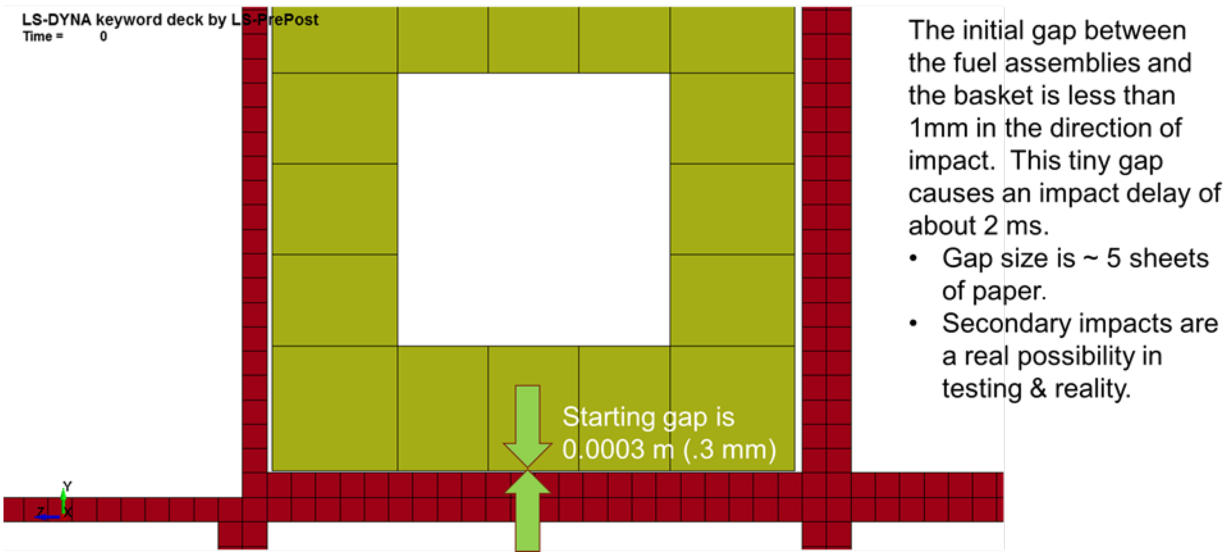

Figure 7. Test 1 pre-test model configuration of the gaps between the dummy fuel assemblies and the fuel basket walls.

The differences in package response from the fuel-to-basket gap condition are shown in Figure 8. The figure plots the acceleration of the package body over time. The nominal case shows a relatively higher initial pulse up to about 2 ms. Then a pronounced reverse spike occurs, which coincides with the fuel making contact with the basket and is an indication of secondary impacts. The zero gap case does not have any significant spikes. The blue curve is the nominal FEA response case that is modified by a 300 Hz low pass Butterworth frequency filter. The filter eliminates the spikes in the nominal case and smooths the acceleration pulse. The zero gap and filtered nominal case agree well with one another.

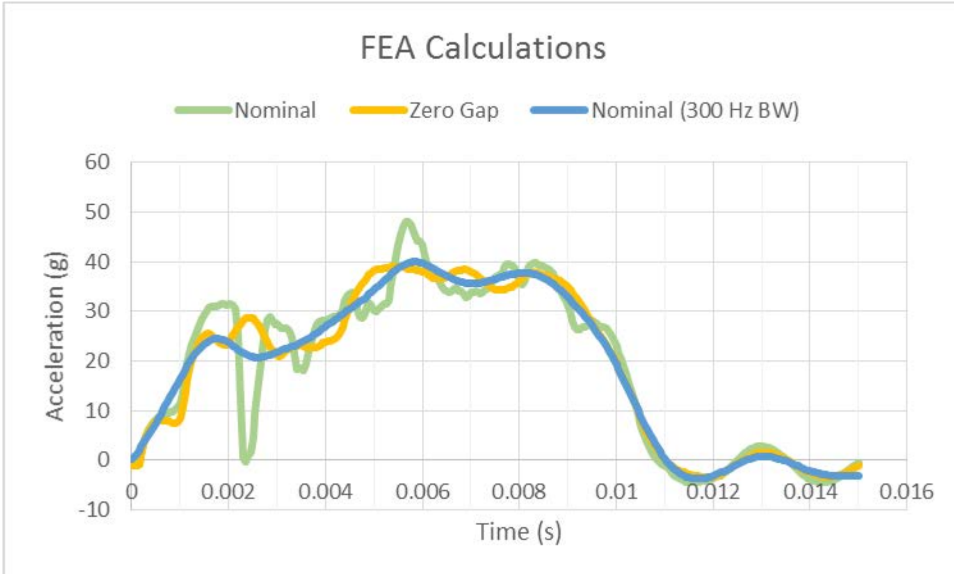

Figure 8. FEA package body deceleration pulse.

The corresponding fuel assembly responses are plotted in Figure 9. The response of all fuel assemblies in the fuel basket are averaged together. Frequency filtering is not used. The nominal gap case shows a clear, prominent spike after 2 ms, after a period of zero deceleration. It can be seen in Figure 8 that the package is decelerating in the nominal case, but the deceleration pulse does not reach the fuel assemblies until the initial gap closes. When the gap does close, the secondary impact is relatively high. Also note that the nominal case touches zero twice before engaging in a relatively longer deceleration pulse. This is different from the zero gap case, which is engaged in a continuous deceleration pulse throughout the analysis. Secondary impacts are observed to occur in the nominal gap case, but not in the zero gap case. Prior to the test, it was not known whether the nominal gap case or the zero gap case would be more representative of the test conditions. A comparison to test data is made in Section 3.1.

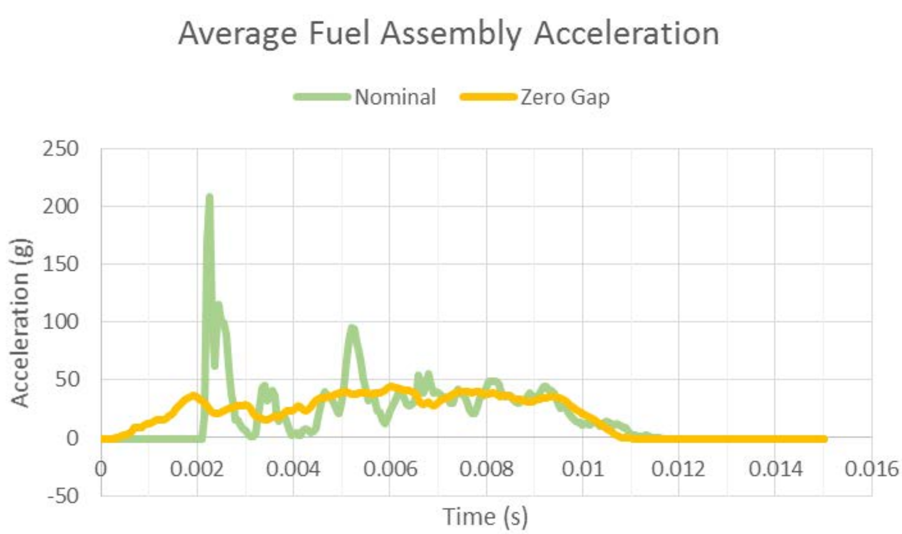

Figure 9. FEA fuel assembly deceleration pulse.

2.5 Test Recommendations Based on the Pre-test Package Models

This section summarizes the instrumentation and test plan recommendations made to SNL based on PNNL's analyses. Figure 10 shows a sketch of the dummy fuel assembly FEA model; location A is closest to the lid end. All 32 modeled fuel assemblies have the same shape. A study of the deflection response of the dummy assembly showed that all four lettered locations experienced similar deceleration histories. That made any one of the lettered locations suitable for accelerometer placement. PNNL recommended placing the accelerometers at any of the lettered locations, away from the cutouts. SNL chose to place most of the accelerometers at A, and a few at D to record the response at each end of the assembly.

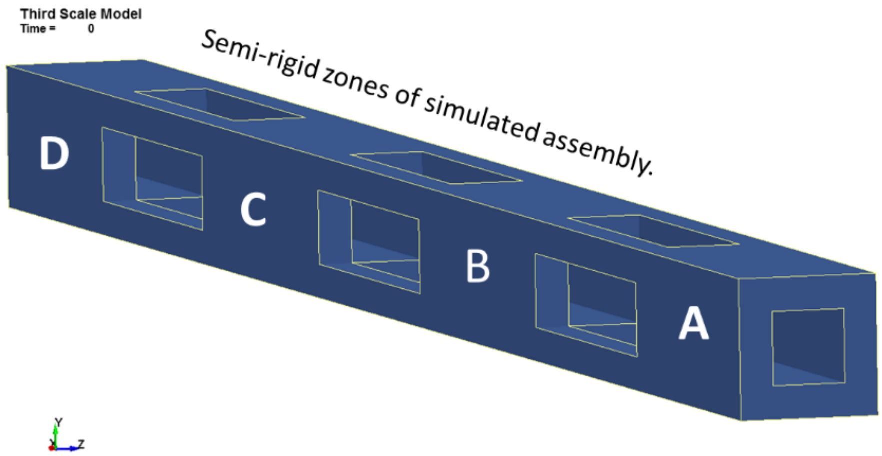

Figure 10. Sketch of the dummy fuel assembly FEA model (location A is closest to the lid end).

The fuel assembly locations in the basket were prioritized according to Figure 11. Numbers 1, 2, 3, and 4 cover the locations L and G from Figure 4, on both sides of the basket. Numbers 5, 6, and 7 cover the locations of instrumented fuel assemblies in the ENSA/DOE multimodal transportation test of 2017 (McConnell et al. 2018). Numbers 8, 9, 10, and 11 cover a number of potential locations in the middle of the basket. There was no reason in the FEA to recommend any more than the 11 locations. Note that Figure 11 shows the basket in the Test 1 orientation, with numbers 4 and 2 located closest to the impact surface.

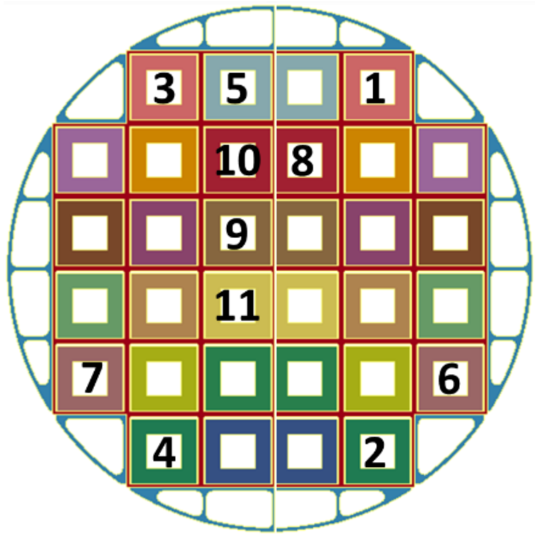

Figure 11. The prioritized locations of the fuel assemblies in the basket.

The drop test presented a rare opportunity for R&D testing. Early discussions established the horizontal drop test as the primary test. The feasibility of a second drop test was evaluated. FEA was performed on a 45 degree axial rotation of the package and the results (Figure 5) showed that the second test could be technically interesting. The second test would use the same impact limiters and not require the impact limiters to be rotated or reconfigured. It was a very economical test to perform and only used the materials needed for the primary horizontal test. The one challenge was defining the lift plan to perform the test, which is not a typical drop test orientation. Figure 12 shows the two drop configurations that were tested.

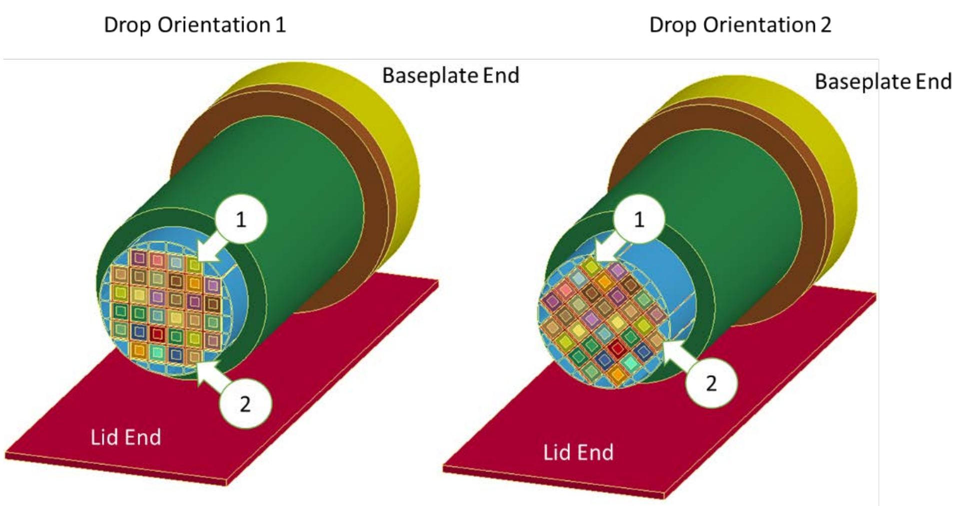

Figure 12. The two drop configurations that were tested.

3.0 POST-TEST ONE-THIRD-SCALE PACKAGE MODELING

The package drop testing performed at BAM was very successful, and a significant amount of data was collected. The data still needs to be fully processed and evaluated. This report includes an initial comparison of FEA model results and test data, using aggregations of the test data.

Section 3.1 compares select test data to FEA model results. The FEA model validation is still ongoing, but the current conclusion is that the FEA model matches the test data reasonably well. A more precise comparison of accelerometer channel data to specific model location results is planned for fiscal year 2020 (FY2020). Section 3.2 identifies the current conclusions and describes continuing analytical work proposed for FY2020.

3.1 Comparison of Test Data to FEA Results

The fuel assembly response is the primary interest in this testing and modeling effort. The goal of this work is to be able to define the shock pulse a fuel assembly would undergo during a drop event. The test data directly provides information about the drop response, but modeling is needed due to the use of scale models and dummy assemblies. Validated finite element models are needed to connect the test configurations to realistic fuel assembly loading conditions. Some amount of comparison to test data has been done, but much more remains to be completed.

The package response derived from Test 1 data is compared to the calculated FEA response in Figure 13. The nominal gap FEA case is filtered at 300 Hz to remove secondary impact effects and other high-frequency components. The cask average accelerometers curve averages the four vertical accelerometers located on the outer cask body. The plot shows that the FEA results and test data match reasonably well, but there is a significant 3 ms difference in the duration of the acceleration pulse. This was traced back to the fact that in the test the package impacted the target surface at a slight angle, but the FEA model assumed a perfectly horizontal impact. This is an important geometrical parameter to adjust in the FEA model before precise validation against test data can begin.

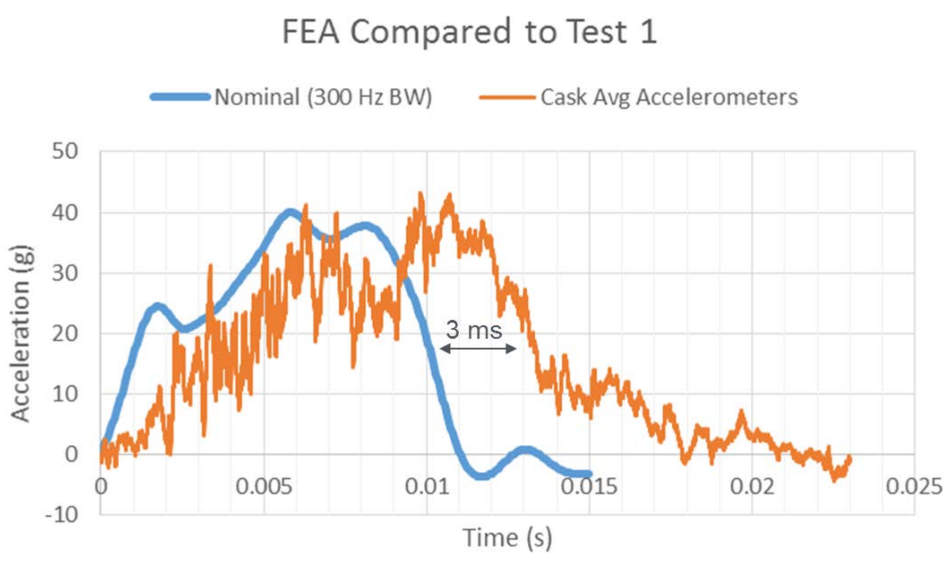

Figure 13. Comparison of the package response derived from Test 1 and the calculated FEA model response.

The fuel assembly response from Test 1 is illustrated in Figure 14. The FEA model results for the nominal and zero gap cases are identical to those in Figure 9. The Test 1 curve is the averaged vertical accelerometer response for all 18 vertical fuel assembly channels. The test data comes from 11 different fuel assemblies, in which accelerometers were placed at locations A and D. The average of the data from the 11 fuel assemblies is plotted as a way to simplify and aggregate the test data. Test 1 shows three separate shock pulses, which is an indication of secondary impacts. The slight impact angle described above was not accounted for in the model and probably influences the response. Also, the Test 1 curve includes accelerometers at both A and D locations (at opposite ends of the fuel assemblies). The model needs to be adjusted to have the correct impact angle, and the accelerometer data should be evaluated one channel at a time against the FEA model data to take the model validation any further.

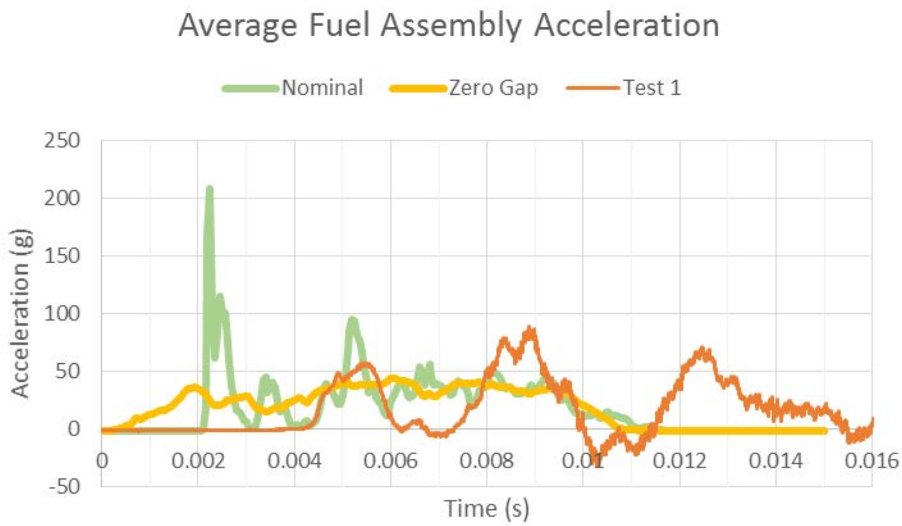

Figure 14. Fuel assembly deceleration, FEA results compared to test data.

Test 2 was conducted as planned. Figure 15 shows the average vertical cask accelerometer data for both tests (FEA results are not shown). It is important to note that the two tests generally overlay each other, which shows that the impact limiter performance was not affected in the second drop test. It is generally important to address any concerns about using impact limiters that had previously been dropped. For FEA modeling, the close agreement indicates that the impact limiter damage (or use) that was witnessed in testing does not need to be accounted for in FEA models.

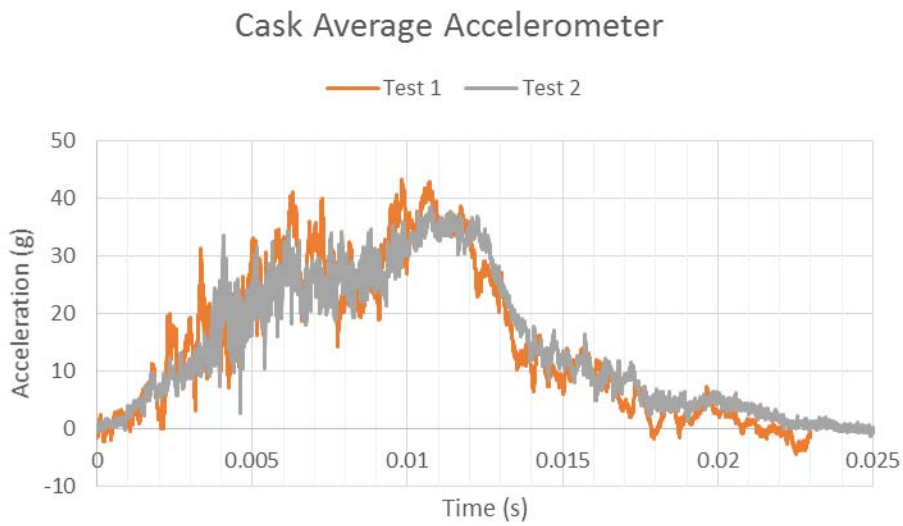

Figure 15. Package body test data, Test 1 and Test 2.

The fuel assembly response in Test 2 is shown in Figure 16. The plot includes curves for the nominal gap case and the zero gap case (in this figure, zero gap is called "Closed Gap FEA"). Each curve is an average of the acceleration over time for all fuel assemblies in the package. The Test 2 curve averages the responses of fuel assemblies 1, 2, 3 and 4 instead of all channels because the 45-degree rotation affects the orientation of the accelerometers. Assemblies 1 through 4 have triaxial accelerometers, whose data can be resolved into the necessary coordinate system. Most fuel assemblies have only vertical accelerometers in the Test 1 orientation, which are rotated 45 degrees from the impact velocity vector in the Test 2 orientation. Because of this, the Test 2 data set is not as complete as the Test 1 data set, but the test was still worth doing as a secondary test to collect some extra data.

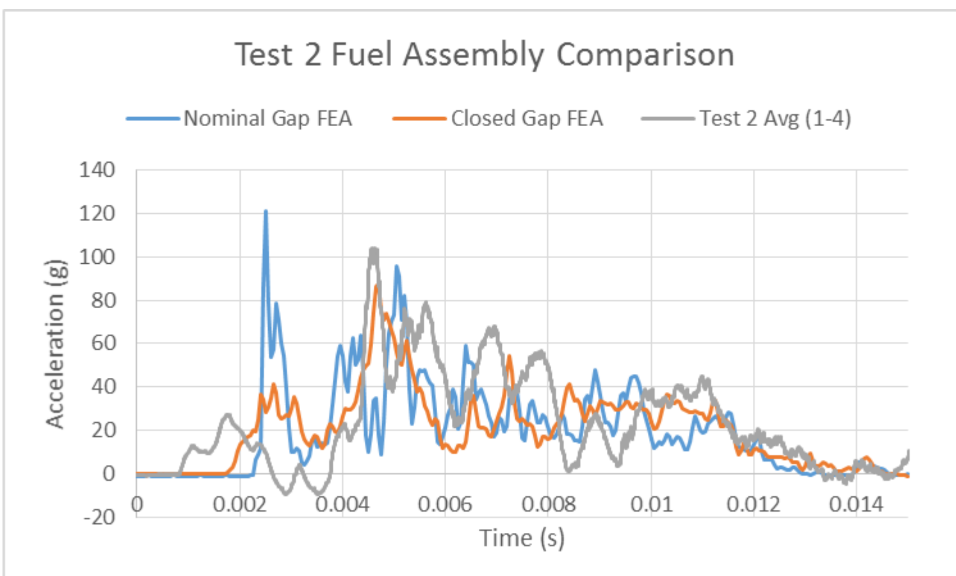

Figure 16. Fuel assembly FEA results compared to Test 2 data.

Like the Test 1 case, the FEA model needs to be adjusted to the correct impact angle, and a channel-by-channel comparison to FEA results needs to be completed to precisely validate model results.

Nonetheless, Figure 16 shows that the test data generally falls within the FEA range predicted by the nominal and zero gap cases.

3.2 Post-Test Package Modeling Conclusions

In general, the FEA model results agree reasonably well with the test data. The test data generally falls within the response range predicted by nominal gap condition and zero gap condition models. A more precise analysis of the data is needed to determine actual gap sizes from the test data. The test data are expected to provide enough evidence to quantify the gaps on an assembly-by-assembly basis for all of the instrumented dummy assemblies. Delays in response between accelerometer channels is observed in the test data, so an analysis of the impact response delays should permit the estimation of gap sizes for each instrumented assembly. Dummy assemblies that have accelerometers located at opposite ends should have the best gap estimation potential. While there is no direct information to estimate initial gaps in the non-instrumented assemblies, it might be possible to infer the gaps using the FEA model to study the interaction between dummy fuel assemblies inside the cask.

The next steps need to include a more precise comparison of the test data to the FEA model results. This report has documented an aggregate comparison of test data to FEA model results, but the data exist to perform a more careful and precise comparison of test data to model data. It is expected that this careful consideration of test data and FEA data will lead to FEA modeling best practices that will advance the state of the art in SNF package and SNF assembly modeling.

The test data shows evidence of secondary impacts, which result in relatively short-duration (high-frequency) dynamic effects on the package system. 300 Hz low pass filtering eliminates the secondary impact effects of the FEA model. Going forward, it is a priority to determine whether secondary impact effects are capable of damaging fuel assemblies.

4.0 CONCLUSIONS AND FUTURE WORK

The preceding sections of this report described pre-test and post-test FEA and discussed a limited amount of test data collected at the December 2018 package drop test. The pre-test FEA models were used to inform the test plan. The post-test FEA and comparison of modeling results to test data were performed to identify the physical phenomena that are important to include in the FEA models. The post-test data evaluation and model comparison are not complete but are anticipated to be completed in FY2020.

The test data indicates that secondary impacts are a natural phenomenon to be expected in SNF package drop events. Package drop FEA models need to choose a starting gap condition. If gaps are approximately zero, the models predict no secondary impacts. When gaps are large enough, secondary impacts occur in the FEA models. It is not yet clear what the starting gap size should be. The test data needs to be more precisely evaluated to determine what the correct gap size should be. This is a topic that is intended to be studied in FY2020.

In general, a more precise comparison of test data to FEA model results is needed to validate the FEA models. One necessary change in the FEA models is to implement the correct impact angle. The current FEA specifies a precisely horizontal impact, which needs to be adjusted to match the test conditions. Once the FEA models are adjusted, a precise comparison of test data (collected at specific accelerometer locations) can be compared to calculated acceleration results at specific locations of the FEA model (that match the accelerometer locations). The value of this comparison is in validating the models, defining modeling best practices, and eventually being able to apply the validated models and methods to other package drop configurations and other packages.

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