EQUIPOS NUCLEARES, S.A./U.S. DEPARTMENT OF ENERGY TEST PLAN MODELING SUPPORT

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign

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SUMMARY

This report fulfills the M3 milestone M3FT-16PN080204012 “Finite Element & Modeling in Support of S&V Test Plan” under work package FT-16PN08020401.

This task used finite element analysis to determine optimal locations for instrumented fuel assemblies and accelerometers. In the sketch below (Figure S-1), tri-axial accelerometers are recommended to be placed within the basket rails at positions marked with X, and instrumented fuel assemblies are recommended to be placed in fuel compartments marked with a Y. The accelerometers are placed at those locations to best record the rigid body motion of the basket and the rocking motion that is expected to occur during transport. The lower fuel assembly location is based on the system response to imposed lateral motion. The upper fuel assembly location is based on the potential for rocking motion that could affect the fuel assemblies in the top row more strongly than any others.

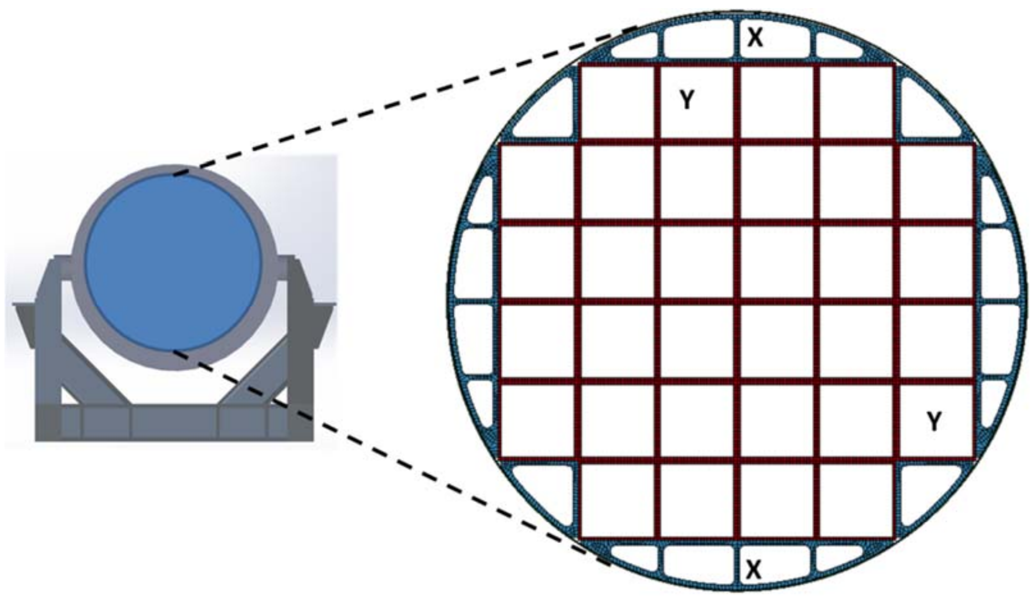

Figure S-1: Accelerometer Locations (X) and Instrumented Fuel Locations (Y)

This task also considered the battery box location. Currently, not enough information is available to build models of the full railcar system to determine the effect of the battery box placement on the fuel assembly loads. Instead, the recommendation is to balance the battery box weight evenly on the railcar and minimize the effect on mass moment of inertia by placing the battery box as close to the centerline as is practical. Modeling will be performed after the testing is complete to determine the effect of the battery box on the system response.

This task also performed preliminary analysis of the ENUN 32P cask and cradle system. Modal analysis predicts that the natural frequency in the lateral direction has the greatest potential significance and the longitudinal natural frequency is potentially significant, but the vertical natural frequency appears to be so high that it will not have a significant effect on load transmission through the railcar system to the used nuclear fuel.

A frequency response analysis was performed to determine amplification factors for cyclical loads originating at the railcar deck and working their way through the cradle structure to the trunnions. Below 15 Hz, no cyclical load amplification is expected. Loads at the railcar deck are expected to be transferred directly to the trunnions as an approximately rigid body. Above 15 Hz, particularly in the lateral direction, cyclical loads on the trunnions are expected to reach a higher magnitude than the railcar deck loads due to resonance effects. It remains to be seen if this frequency-dependent phenomenon will have a practical effect on the loads transmitted to the fuel, but this is something to be aware of when evaluating the test data and validating future numerical models.

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EQUIPOS NUCLEARES, S.A./U.S. DEPARTMENT OF ENERGY TEST PLAN MODELING SUPPORT

1. INTRODUCTION

This report identifies recommendations for the Equipos Nucleares, S.A./U.S. Department of Energy normal conditions of transport rail test plan that are based on structural dynamic finite element modeling and other analytical techniques. This report also discusses some of the preliminary modeling steps that have been taken to develop the numerical modeling tools needed to evaluate the recorded test data and project the data onto numerical models of real used nuclear fuel.

Section 2 describes a structural dynamic finite element analysis of the ENUN 32P package that is focused on the basket and fuel assembly representative masses. Prescribed motion is applied to the package, and within the package, the basket and fuel assemblies respond according to the loads that are transmitted to them. The basket and fuel assemblies are modeled with elastic materials, so elastic deformation plays a role in transmitting loads throughout the system. Studying the response of applied one-dimensional pulses provides insight into the system behavior; from this analysis, recommendations are made for the placement of accelerometers and the location of instrumented fuel assemblies in the test campaign.

Section 3 evaluates the issue of data acquisition system battery placement. The data collection requires a significant mass and volume of batteries that must be carried by the system. Adding the mass of batteries and additional structure to house the batteries has been considered, and a number of recommendations for battery placement are made based on fundamental parameters like mass, moment of inertia, and center of mass.

Section 4 provides an initial evaluation of the ENUN 32P cask and cradle system. This is a preliminary modeling step in establishing the set of models that are needed to evaluate the test data and project loads from as-tested conditions to actual used fuel transportation conditions.

Section 5 summarizes the main conclusions of this support task.

2. ENUN 32P BASKET ANALYSIS

One of the important characteristics of the ENUN 32P package is the design of the basket and basket rails. The basket rails are bolted to the basket structure and form a single body that will be referred to as the *basket cylinder*. The basket cylinder slides into the package cavity, which has a slightly larger diameter. The difference in diameters suggests that the basket cylinder has some freedom to roll within the package cavity as the package is oriented horizontally during transport. This is a classic cylinder-to-cylinder contact problem, with one cylinder situated inside the other. Contact between the basket rails and the package is expected to occur in a relatively thin strip at the 6 o'clock position when the system is oriented horizontally for transport. When the system is at rest, the fuel basket cylinder can be expected to find a balanced orientation. When the system is transported, lateral vibrations and shocks can be expected to tilt the basket out of its balanced equilibrium. The amount of room available for the basket to roll is very small compared to the size of a fuel assembly, but it represents an extra amount of freedom in a complex system that is subject to random vibration. The test data will help determine if the basket roll is a significant consideration or not.

A structural dynamic finite element model of the ENUN 32P basket system was constructed in LS-DYNA (LSTC 2013) to study the dynamics and transmission of loads throughout the system in order to help identify optimal locations for accelerometers and instrumented fuel assemblies during the test series. The models represent the basket, basket rails, and fuel assembly surrogates as deformable bodies. The package is represented as a rigid body, and postulated loads are applied to the system by prescribing motion to the package. The deformable nature of the basket and basket rails is important because the loads are transmitted through the elastic structure to each individual fuel assembly. The elastic deformation of the basket cylinder is not large relative to the dimensions of the structure, but the elastic behavior can be significant in transmitting loads to individual fuel assemblies.

The finite element model used in this study is based on the model developed for the ENUN 32P 30 cm package drop analysis (Klymyshyn and Jensen 2016). A detailed fuel assembly was not used in this study due to the computational requirements. Instead, all 32 fuel compartments contain low element count representations of the surrogate mass used in 1/3 scale package drop testing. This approximates each fuel assembly with an elastic mass and volume, which is expected to be a close approximation of a real fuel assembly's rigid body motion. The model is shown in Figure 1.

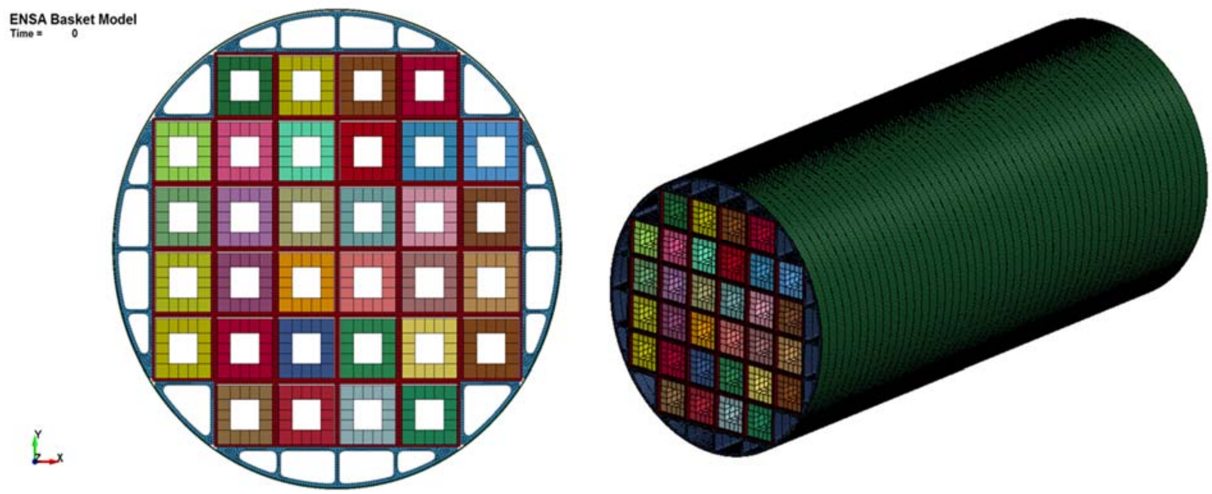

Figure 1: ENUN 32P Basket Model

The model was evaluated for three postulated pulse cases, with a velocity pulse in one direction at a time (X, Y, and Z). Each load case begins with a period of zero velocity to allow settling of the system under the gravity load. Then a 0.010 second duration velocity pulse that ramps from 0.0 m/s to a maximum of 0.1 m/s in one translational direction, with all other translational directions and rotations constrained. This causes a displacement of the system of just 0.5 mm. After the pulse, the package is fixed in space and the package contents continue to respond until the analysis ends at 0.2 seconds.

2.1 Accelerometer Locations

The basket accelerometer data is needed to determine the dynamic response of the basket throughout all phases of transportation. The design of the package does not fix the basket to the package, so some amount of additional motion is expected. Accelerometers will be placed on the outside of the package. Basket accelerometer data can be compared against the package accelerometer data to determine how much additional motion is happening at the basket level, and consequently how much of the total loading on the fuel assemblies is caused by the basket design.

The basket rails are a good location to place accelerometers because they have long open channels. It is a working assumption that the basket rails are secured to the basket with a bolted or other type of connection that makes the basket and rails move together as one body. This makes the motion of any location of the basket rail approximately equivalent to the nearby locations of the basket. Two types of basket rails are used in the ENUN 32P, one that spans one fuel compartment and one that spans four compartments. Figure 2 shows the type that spans four compartments and shows possible locations to place the accelerometers. The orange cylinder identifies the ideal location on the vertical web, but it requires an attachment that must survive the entire campaign. The green cylinder offers a good compromise that places the accelerometer on a horizontal surface. It should be placed as close to the vertical web as practical to avoid the potential bending deflections that could occur in the horizontal web/plate material. The blue cylinder is another location that would work because the basket rail will behave approximately like a rigid body. Closer to the central web is most desirable because it is closer to the center of mass so measurements are most representative of the rigid body behavior of the basket rail as opposed to local deformations.

Figure 2: Large Basket Rail Accelerometer Locations (Orange, Green, and Blue Cylinders)

The pulse response analyses indicate that the four large basket rails are good locations for placing accelerometers, but they can be prioritized according to Figure 3. Accelerometer location 1 is at the top of basket cylinder when the package is in the horizontal transportation orientation. It is the best location for an accelerometer because it has the greatest freedom to move laterally as the basket cylinder can potentially rock back and forth within the package cavity. If only one accelerometer is available, location 1 is the place to put it because it will register the maximum motion of any point on the basket. The lateral pulse response is shown in Figure 4. The vertical pulse and longitudinal pulse showed little to no difference in the motion of locations A, B, C, and D. Figure 4 shows the basket cylinder rocking response in point D, as the initial motion of point D is opposite the direction of applied motion. At the top of its cycle, point D moves farther than any of the other three points, but then it rocks back into the negative X direction. Presumably, the rocking motion would keep cycling until the system comes to rest. An accelerometer attached to point D would capture the rocking motion, but an accelerometer at point A shows only the smallest indication of rocking, which could be lost in the noise of the signal.

The ideal situation is to collect tri-axial accelerometer data at A and D in Figure 4 (locations 1 and 2 in Figure 3). Point A tracks the motion of the pivot point of the basket cylinder. The data from A and D can be compared to determine how much translation is occurring to the basket and how much of the motion is due to rocking. The two accelerometers will theoretically provide enough information to fully recreate the basket motion. With just one accelerometer, part of that information is lost.

Locations 3 and 4 in Figure 4 are identified as potential alternate locations in case 1 and 2 are not practical for some reason. As shown in Figure 4, the B and C curves overlay each other, which shows that the basket cylinder is demonstrating an approximately rigid body response.

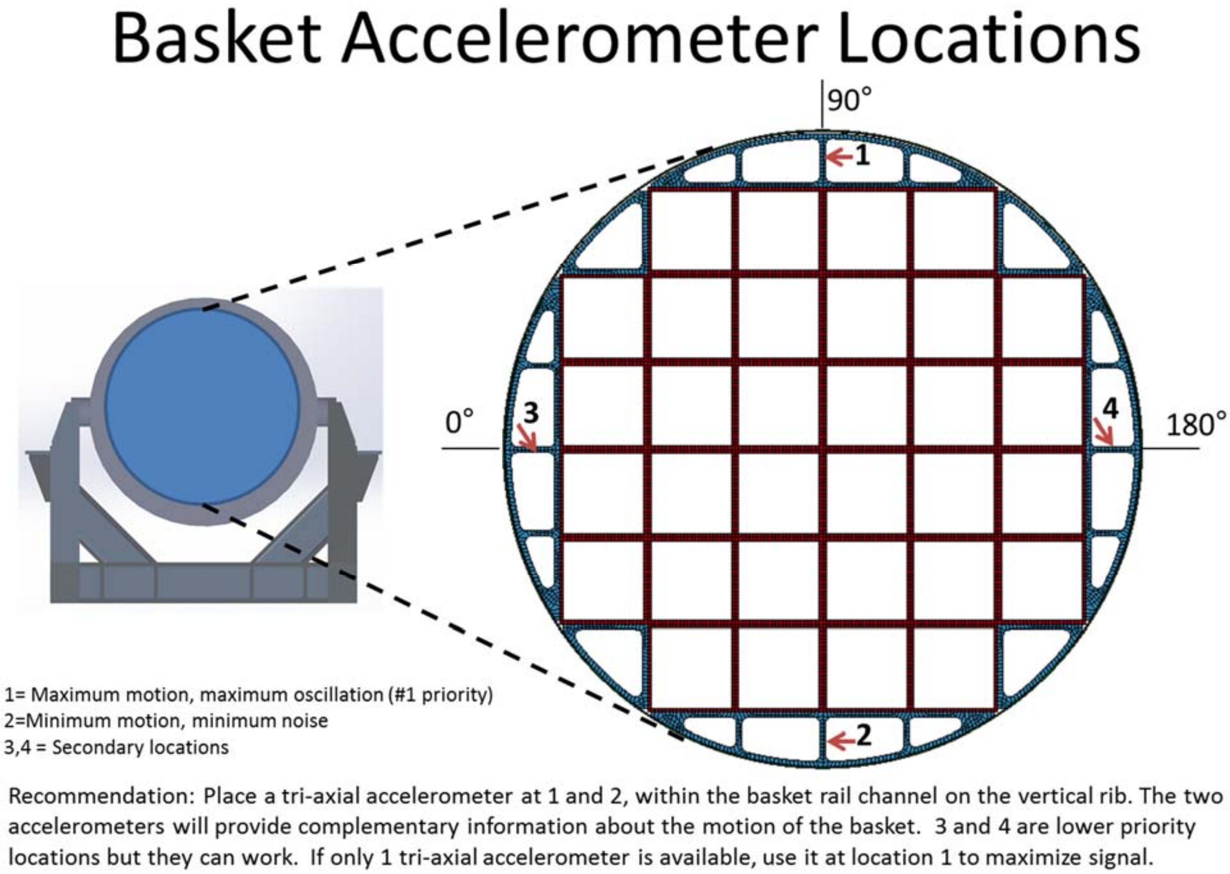

Figure 3: Recommended Basket Accelerometer Locations

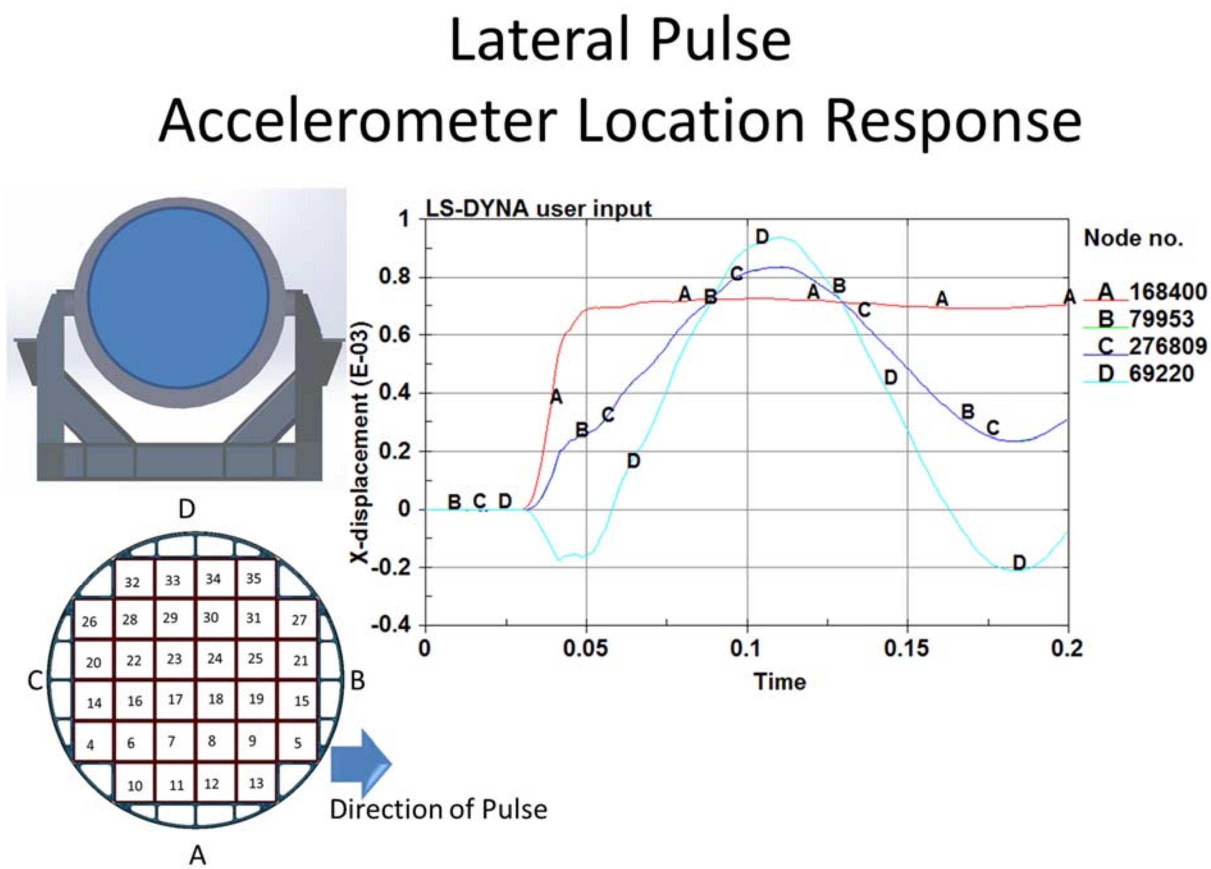

Figure 4: Lateral Pulse Finite Element Analysis Results

2.2 Fuel Locations

The same model provides insight into the fuel assembly behavior within each fuel compartment. As was the case with the accelerometer placement, the vertical and longitudinal pulse cases demonstrated little difference in the response of the fuel assemblies. Only in the side pulse case was there a distinct trend where some fuel assemblies responded more strongly than others due to their location. The fuel assembly response was evaluated based on the maximum kinetic energy calculated for a fuel surrogate. In the vertical and longitudinal pulse cases, all of the fuel assembly surrogates experienced a similar kinetic energy response. In the lateral pulse case, certain fuel assemblies had a notably higher kinetic energy imparted to them by the basket.

Figure 5 identifies the peak kinetic energy location with a 1. The fuel assembly in location 1 reached a peak kinetic energy that was about 60% higher than the typical fuel assembly in the basket. This is an indication that the loads transmitted to the fuel assembly from the basket happened to be higher than elsewhere in the basket. 1' is equivalent to location 1 when loading comes from the opposite direction. Realistically, transportation loads are expected to come from both directions, so it would be reasonable to put an instrumented fuel assembly in either location (1 or 1').

Figure 5 identifies secondary peak locations based on kinetic energy at locations marked with 2 and 2’. Secondary locations had peak kinetic energies that were about 30% higher than the typical fuel assembly in the basket. The finite element analysis results predict a similar fuel assembly response at the 1 and 2 locations, with location 1 being more effective in load transmission and location 2 still being a significant step up from the typical response.

The load transmittal that was evaluated through modeling represents a brief movement in one direction. The vertical and longitudinal direction pulses were insensitive to basket location. The lateral motion is sensitive to basket location, with location 1 being markedly stronger than 2, and location 2 being markedly stronger than the rest of the fuel assembly locations. This suggests that locations 1 or 1’ have the potential to register the highest loads in an instrumented fuel assembly, so either 1 or 1’ makes a reasonable place to put one of the two instrumented fuel assemblies. An argument could be made to put both fuel assemblies in 1 and 1’, but there are other considerations that suggest a different location for the second instrumented fuel assembly.

As discussed in the previous section, the basket cylinder has the ability to roll back and forth within the package during transport. The distance each fuel compartment can move is relatively small, but the compartments with the greatest potential to move are marked B, B’, A, and A’ in Figure 5. In addition to the rigid body motion of the basket cylinder, local elastic deflections of the basket occur under gravity and dynamic pulse loading. Basket deflection represents stored elastic energy that can be transferred to fuel assemblies out of phase with external loading. Location A is recommended for the second instrumented fuel assembly to record the response in a location that is expected to have near-maximum rigid body motion due to cylinder rocking and a relatively high potential to be influenced by dynamic basket deflections.

Location B has slightly more potential for rigid body motion during rocking and is closer to the opposite of location 1, but the basket deflection in the B and B’ columns was less than in the A and A’ columns. The choice between A and B is much less clear than the choice of 1 over 2, but A is recommended due to the basket deflections and B is a worthy alternative.

Location 1 is expected to have the strongest response to direct loading. Location A is expected to have a strong indirect loading response that lags behind package excitation. Location A is also expected to have relatively high vibration loading because of its location at the top of basket cylinder. Locations 1 and A are on opposite sides of the basket, and it is recommended to keep them on opposite sides of the basket (i.e., 1 + A, or 1’ + A’).

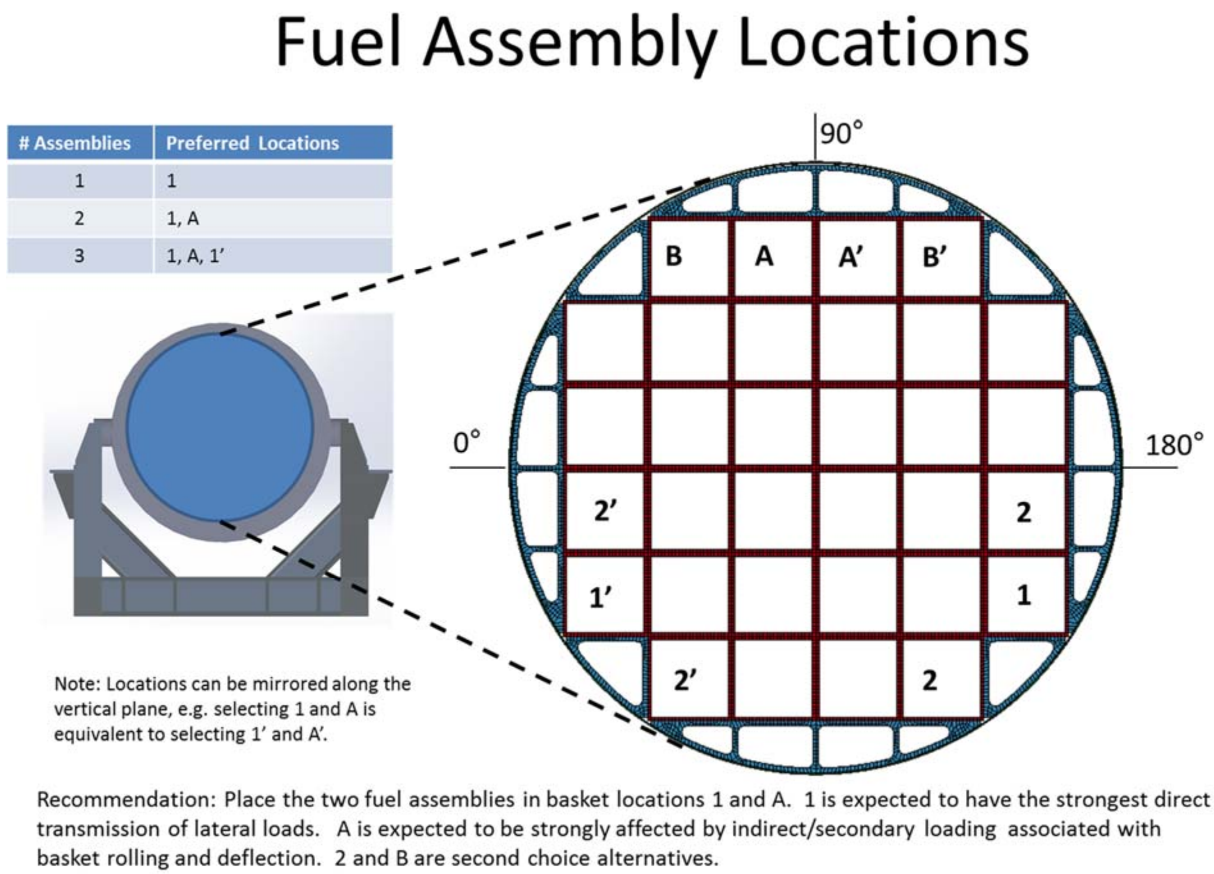

Figure 5: Recommended Fuel Assembly Locations

3. BATTERY BOX RECOMMENDATIONS

The data acquisition system is expected to require a large number of batteries to power the system through all legs of transportation. The consequence of adding this extra mass to the railcar is considered and recommendations are made.

In terms of mass, the batteries are on the order of 1% of the total package and cradle mass. The battery mass is on the order of 10% of the mass of the impact limiters (together). The batteries are also on the order of 10% of the cradle. The mass of the railcar is not known, but a typical railcar that would be suitable for hauling a fully loaded cask and cradle is expected to be somewhat heavier than its payload, making the batteries less than 0.5% of the total loaded railcar system mass.

While the battery mass is relatively small compared to the total system mass, its effect on the center of mass of the system and the mass moment of inertia of the system also need to be considered. The mass moment of inertia equal to the mass time the squared distance from the axis of rotation, so a 1% mass located at the extreme edge of the railcar deck will have a disproportionate effect on the system mass moment of inertia. The best place to put the batteries to avoid changing the system's mass moment of inertia is along the centerline of the railcar, where the distance from the axis of rotation is minimized. Configuration A in Figure 6 is ideal in terms of minimizing the change to center of mass and mass moment of inertia, but it is not clear that there is enough room directly beneath the package to fit the battery box and allow for access during transportation to change out the batteries. Configuration B in Figure 6 is expected to be more practical than A, but while it balances the weight of the batteries, the moment of inertia contribution about the X axis is almost maximized. (The X axis is the direction of travel.) Configuration C in Figure 6 is better than B because it reduces the mass moment of inertia contribution of the battery box. In order of preference, the battery box configurations are A, C, B.

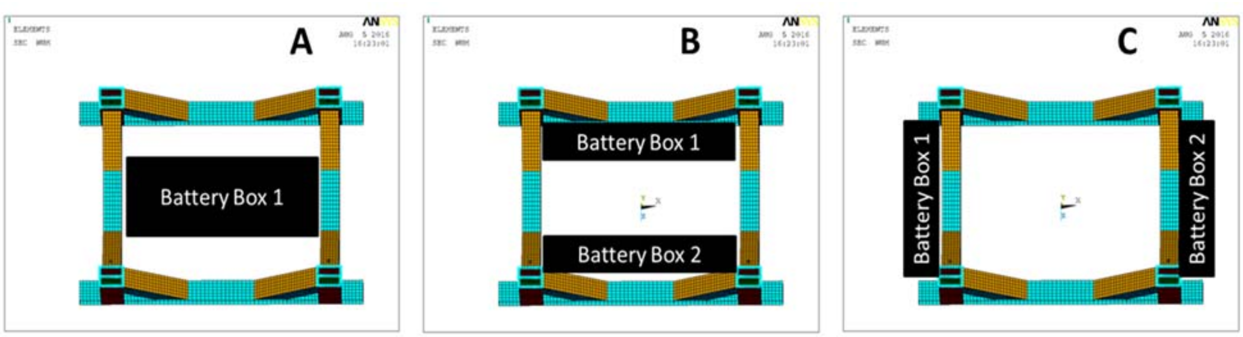

Figure 6: Battery Box Locations

The configuration to avoid is an unbalanced load located at an extreme distance from the X axis. For example, eliminating Battery Box 2 in configuration B of Figure 6 would eliminate the balance the two boxes provide while maintaining the maximum moment of inertia contribution to the system. Such an unbalanced system could artificially affect the loads transmitted to the instrumented fuel assemblies during testing. Not enough information is available about the full railcar system to determine the potential consequences. The best recommendation is to balance the battery load and minimize the moment of inertia contribution of the battery box, particularly about the X axis (railcar roll direction).

Whatever battery configuration is chosen, Pacific Northwest National Laboratory will create models with and without the battery box to determine what effect (if any) the inclusion of the battery has on the test configuration.

4. ENUN 32P CRADLE ANALYSES

The modal behavior and the frequency response of the cradle was determined using ANSYS Workbench 15.0.7 (http://www.ansys.com/Products/Platform). The ANSYS model was constructed from a detailed solid model of the cradle provided by ENSA. The solid model was defeatured and a mass representative of a loaded ENSA ENUN 32P cask was placed in the cradle. This defeatured model was then loaded into ANSYS Workbench, meshed, and separate modal and frequency response modeling cases were run. Figure 7 shows the defeatured cask and cradle.

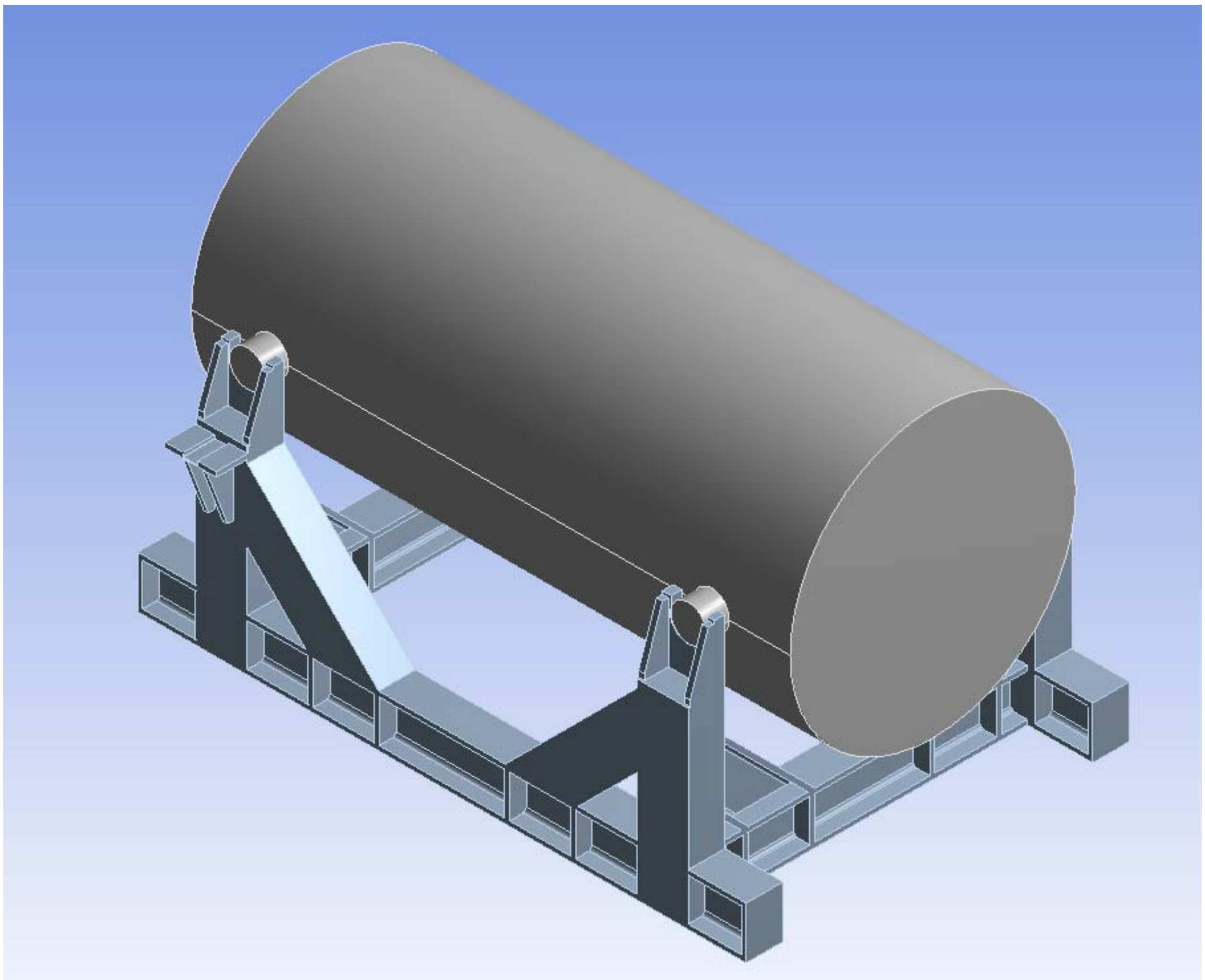

Figure 7: Defeatured Cask and Cradle

4.1 Modal Analysis

A preliminary modal analysis of the ENUN 32P cask and cradle was performed. The modal analysis was performed in two configurations, one without the impact limiters and one with an estimate of the impact limiter mass attached to the ends of the package. The two model configurations are intended to bound the actual test configuration and estimate the practical range of natural frequencies.

The vertical direction has a relatively high fundamental frequency, and based on similar transmissibility modeling, we suspect that the frequency is so high that it will not have a significant effect on the loads transmitted to the fuel assemblies.

The natural frequency in the direction of travel is closer to a range where it could have an amplification effect on the loads transmitted to the fuel; however, the direction of loading aligns with the axis of the fuel, so it is not likely to cause any significant bending.

The most significant modal response is the lateral natural frequency of 15.8-16.9 Hz. This is also an interesting result because it is just outside the 15 Hz cutoff frequency specified by AAR S-2043 (AAR 2003).

	Without Impact Limiters	With Impact Limiters
Direction of Travel	24.4 Hz	22.8 Hz
Lateral	16.9 Hz	15.8 Hz
Vertical	58.3 Hz	54.4 Hz

4.2 Frequency Response Analyses

A frequency response analysis from 0-150 Hz was performed on the loaded ENSA cradle. This analysis was done by applying a 1G* base excitation to the defeatured model. Three separate analyses were performed to analyze the frequency response in the vertical, lateral, and longitudinal (direction of travel) orthogonal directions. In each case, the direction of the applied 1G* base excitation was modified to match the analysis case. In all cases, the system damping was assumed to be 3%.

Initially, the frequency response was measured at each trunnion. The result of this analysis indicated nearly identical load transmission at each trunnion. This result was expected, because the cradle is symmetric in construction. Therefore, the results presented herein display average frequency response of the four trunnions.

The results for each case are shown below in figures 8-12 and discussed in detail. However, in all cases, it can be observed that there is a negligible difference in frequency response between the cases with and without impact limiter mass. These results indicate that the system is not very sensitive to changes in configuration due to the presence of impact limiters.

* multiples of the acceleration due to gravity (9.81 m/s^2)

The frequency response in the vertical direction is shown in Figure 8. This case shows that the cradle responds as a rigid body between 0-20 Hz. The input excitation is amplified by one order of magnitude at the primary natural frequency of 54.4 Hz for the case with impact limiters and 58.3 Hz for the case without impact limiters. All input loads will be amplified to some extent between 21-67 Hz for the case with impact limiters and 21-71 Hz for the case without impact limiters. The input is attenuated at frequencies higher than 67 Hz for the case with impact limiters and 71 Hz for the case without.

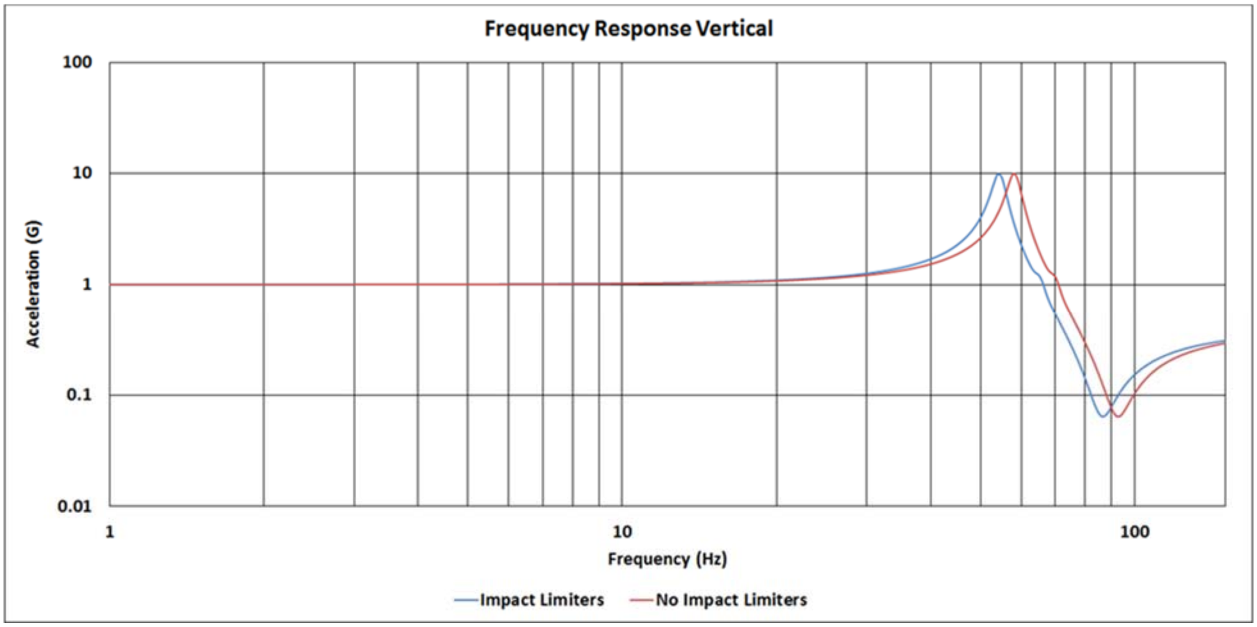

Figure 8: Frequency Response Vertical Direction

The frequency response in the lateral direction is shown in Figure 9. This case shows that the cradle responds as a rigid body between 0-3 Hz. The input excitation is amplified by approximately one order of magnitude at the primary natural frequency of 15.8 Hz for the case with impact limiters and 16.9 Hz for the case without impact limiters. All input loads will be amplified to some extent between 4-22 Hz for the case with impact limiters and 4-24 Hz for the case without impact limiters. The input is attenuated at frequencies higher than 22 Hz for the case with impact limiters and 24 Hz for the case without.

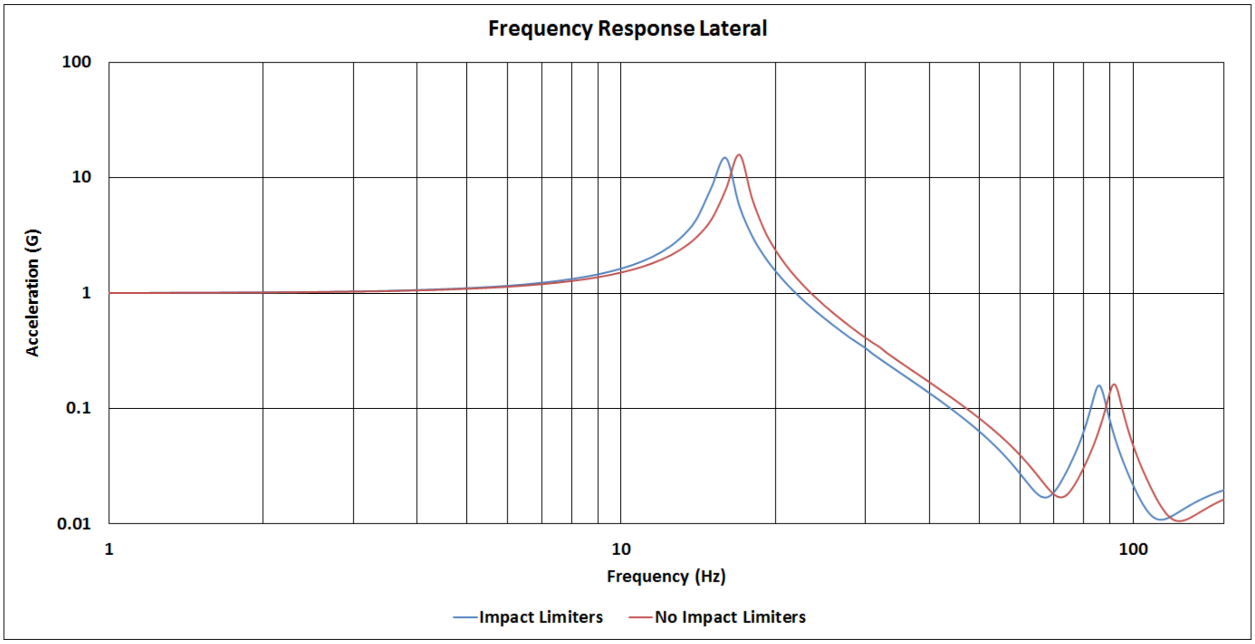

Figure 9: Frequency Response Lateral Direction

The frequency response in the direction of travel is shown in Figure 10. This case shows that the cradle responds as a rigid body between 0-5 Hz. The input excitation is amplified by approximately one order of magnitude at the primary natural frequency of 22.8 Hz for the case with impact limiters and 24.4 Hz for the case without impact limiters. All input loads will be amplified to some extent between 6-30 Hz for the case with impact limiters and 6-32 Hz for the case without impact limiters. The input is attenuated at frequencies higher than 30 Hz for the case with impact limiters and 32 Hz for the case without.

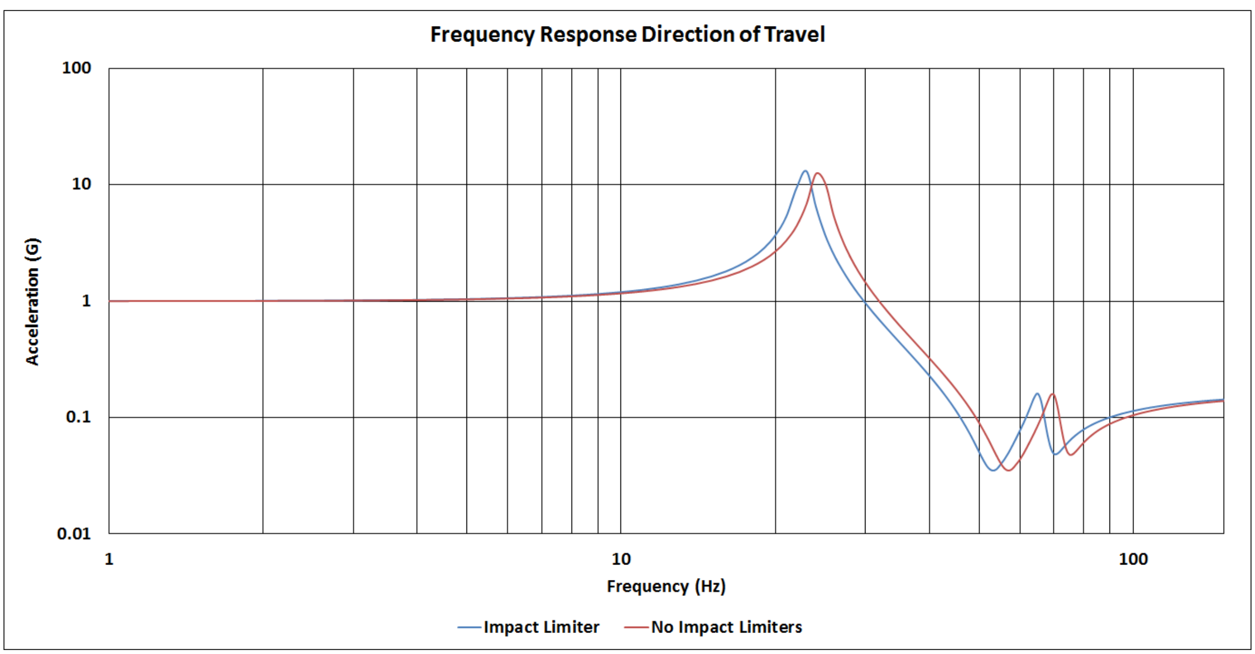

Figure 10: Frequency Response Direction of Travel

5. SUMMARY AND CONCLUSIONS

This report provides guidance on a number of topics for the test plan that is being developed for the Equipos Nucleares, S.A./U.S. Department of Energy rail shock and vibration test campaign that is scheduled for fiscal year 2017. Numerical modeling was used to determine ideal locations for accelerometers and instrumented fuel assemblies within the ENUN 32P basket. Currently, not enough information is available to use numerical modeling to evaluate the effect of adding a heavy battery box to the railcar, but the general recommendation can be made to balance the weight and minimize the rotational mass moment of inertia to minimize the impact to the behavior of the railcar system.

This report also used numerical models to analyze the ENUN 32P package and cradle system in the frequency domain. A modal analysis determined the mode shapes and natural frequencies. A frequency response analysis evaluated the response of the system to cyclical loading over a range of frequencies and identified frequency bands where the loads are amplified due to exciting the cradle near its natural frequencies. The lateral load direction (side-to-side motion of a railcar) is expected to have the greatest potential for load amplification, but it is not known if this will have any practical effect on the loads transmitted to the fuel assemblies carried by the railcar package system. This is a phenomenon to look for in the test data and include in future numerical models of the railcar system.

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