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Shock Environments for the Nuclear Fuel Transportation System (Transportation Platform, Cask, Basket, and Surrogate Assemblies) during Rail Transport

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ABSTRACT

In 2017 a team lead by Sandia National Laboratories (SNL) conducted an international 8-month, 9,400-mile test to simulate transportation scenarios for spent nuclear fuel (SNF). The purpose of this project was to quantify the shock and vibration environments during routine transport. SNL conducted this test in collaboration with Pacific Northwest National Laboratory (PNNL) and ENSA (nuclear equipment global supplier). It involved coordination with an international shipping company (COORDINADORA), Korea Radioactive Waste Agency (KORAD) and Korea Atomic Energy Research Institute (KAERI), the Korea Electric Power Corporation Nuclear Fuel group (KEPCO NF), the Association of American Railroads (AAR), and Transportation Technology Center, Inc. (TTCI). Testing was performed using an ENSA ENUN 32P cask.

An instrumented transportation cask containing surrogate fuel assemblies from the US, Spain, and Korea was transported by heavy-haul truck in Spain, by barge to Belgium, by ship to Baltimore, and by rail to Colorado for rail tests at TTCI and back to Baltimore by rail. Six terabytes of data were collected over the 54-day, 7-country, 12-state, 9,400 miles of travel. For the first time, strains and accelerations were measured directly on the surrogate nuclear fuel assemblies and on the basket. The accelerations were also measured on the cask, cradle, and transportation platform. A total of 40 accelerometers and 37 strain gauges were used. The analysis of the transportation test data was performed in 2018. This paper presents the results of the rail transport. The other results are presented in three related PATRAM 2019 papers.

The dedicated rail transport covers a 1,950-mile route from the Port of Baltimore (Maryland) to Pueblo, Colorado. A Kasgro 12-axle railcar was used. The trip took approximately 6 days, during which the train was moving 59 hours. A total of 2,939 shock events were identified along the rail route. The major events were related to track switches (629) and grade crossings (1,029). The return rail shipment was on a non-dedicated train. The data collection stopped after 18 days near East St. Louis, Illinois, yielding a 1,125-mile route. This route provided a valuable opportunity for considering coupling events. Thirty coupling events were identified and analyzed. Only one coupling event was observed on the route to Pueblo, Colorado.

INTRODUCTION

In 2017 a team lead by Sandia National Laboratories (SNL) conducted an international 8-month, 9,400-mile test to simulate transportation scenarios for spent nuclear fuel (SNF). The purpose of this project was to quantify the shock and vibration environments during routine transport. SNL conducted this test in collaboration with Pacific Northwest National Laboratory (PNNL) and ENSA (nuclear equipment global supplier). It involved coordination with an international shipping company (COORDINADORA), Korea Radioactive Waste Agency (KORAD) and Korea Atomic Energy Research Institute (KAERI), the Korea Electric Power Corporation Nuclear Fuel group (KEPCO NF), the Association of American Railroads (AAR), and Transportation Technology Center, Inc. (TTCI). Testing was performed using an ENSA ENUN 32P cask.

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Rail transport included a dedicated train from Port of Baltimore to TTCI (Rail 1) and a general freight train from TTCI to the Port of Baltimore (Rail 2). Because Rail 1 utilized a dedicated train, the 1,950-mile journey took only 6 days and the data (GPS coordinates, accelerations, and strains) were collected for the entire route. During Rail 2 the data acquisition system stopped recording after 18 days, providing data from the TTCI to East St. Louis, Illinois, which is 1,125 miles of data. Both Rail 1 and Rail 2 data were collected at 512 Hz. Anti-aliasing filters applied to the data provide 256 Hz of analysable data. Figure 1 shows the cask system on the Kasgro 12-axle railcar that was used for rail transport.

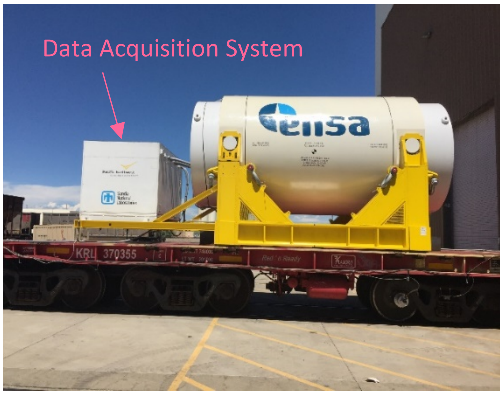


Figure 1. ENUN 32P cask on Kasgro 12-axle railcar used in rail transport.

Transportation system instrumentation was identical for both rail routes. The accelerometers on the railcar platform were the tri-axial accelerometers A19 (platform back end), A20 (platform middle), and A21 (platform front end). The cradle was placed in the center of the railcar platform with the tri-axial accelerometers A17 on the back end and A18 on the front end. The cask was instrumented with the tri-axial accelerometers A15 and A16 on the top back end and top front end respectively. The basket was instrumented with the tri-axial accelerometers A13 and A14. The tri-axial accelerometers recorded data in the longitudinal (X), lateral (Y), and vertical (Z) directions. Figure 2 provides an illustration of the external system configuration.

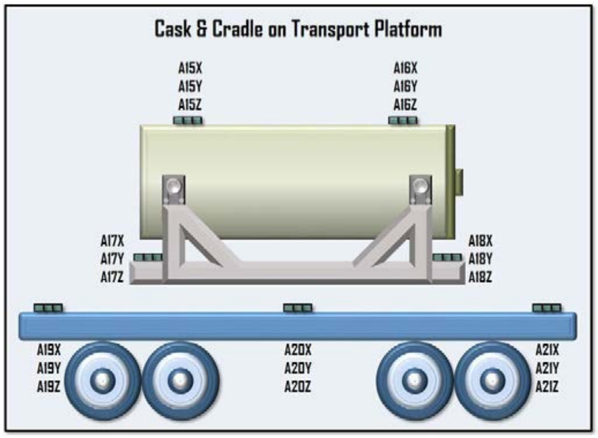


Figure 2. Railcar platform, cask, and cradle accelerometer configuration.

The three surrogate assemblies (SNL, ENSA, and KEPCO) used for the tests were surrogate 17 x 17 PWR assemblies. The SNL assembly was populated mostly with copper tubes filled with a continuous rod of lead (lead “rope”). Three of the rods were Zircaloy-4, one populated with a lead rod, one with lead pellets, and the third with molybdenum pellets. The total weight of the SNL assembly was 710 kg. The SNL assembly was instrumented with the uniaxial accelerometers A1, A2, A3 in the front and A4 and A5 in the back end. All accelerometers in the SNL assembly were located on the middle rod. The accelerometers recorded only the vertical (Z) direction. Strain gauges SG1 though SG9 were placed at either 0˚, 90˚, or 225˚ with respect to cask position. Figure 3 shows the configuration of both strain gauges and accelerometers on the SNL assembly.

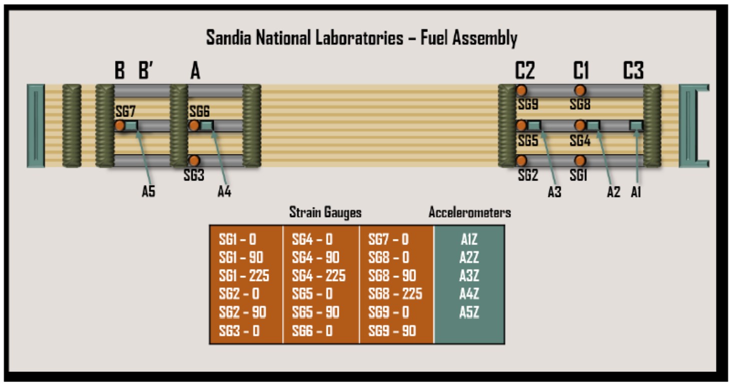


Figure 3. Location and nomenclature of instruments on the SNL assembly.

Most of the prior work on the transportation shock and vibration environments pertinent to the transportation of SNF was completed in the late 70s. The data were collected only on the transportation platform and the cask. The cask interior was not instrumented. The data collection was not continuous and covered only some characteristic events. The transportation casks were smaller than the current transportation cask and the cask attachments were different. An example of historic data from NUREG 766510 (SAND76-0427) [6] is shown in Figure 4 (left). This shock response spectra (SRS) was developed from the data collected at the railcar/cargo interface on a 100-mile rail route containing rail joints, switches, and run-in/out track features. 10 CFR 49, Part 174.589(c) states that cars transporting radioactive material are to be coupled together with a force no greater than that necessary to complete the coupling. The impact force is not specified. Previous work on railcar coupling is also from the late 70’s. Figure 4 (right) shows historic data from NUREG/CR-1277 (SAND79-216B) [7] from coupling a railcar containing a 70-ton cask at 8.0-11.2 mph impact velocities. Only the cask exterior was instrumented.

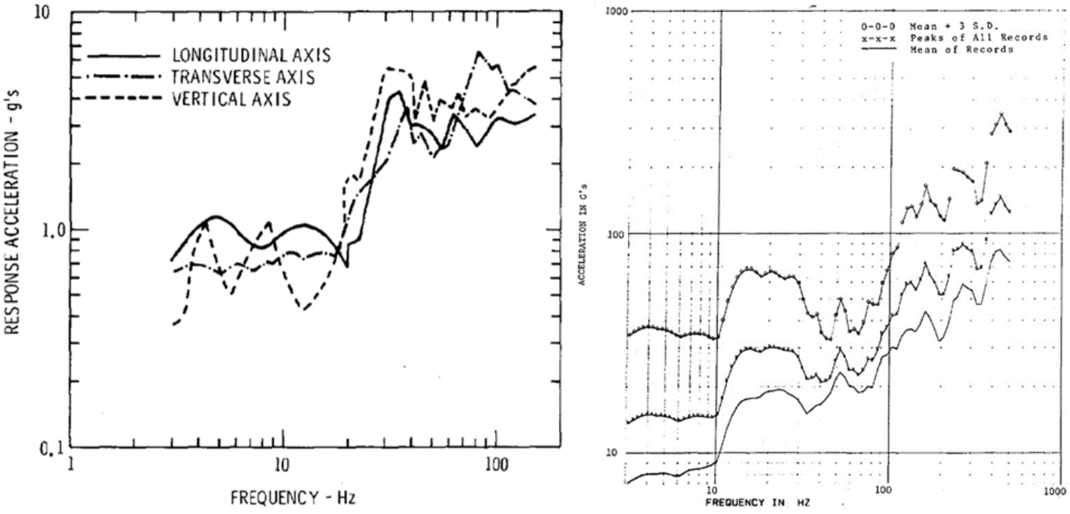


Figure 4. Shock response for rail transport (left) and a coupling event (right) from NUREG 766510 and NUREG/CR-1277.

This paper provides an analysis of the shock events over the entire 1,950 mi rail route (Rail 1) and the coupling events over the 1,125 mi route (Rail 2). The responses of all the transportation system elements, including the surrogate assemblies, are considered.

DATA ANALYSIS METHOD

The Rail 1 data is divided into segments 1 through 12, with all segments except 4, 5, and 12 containing movement. To quantify and analyze shock events during Rail 1 the time histories of each segment were viewed, such as segment 2 shown in Figure 5. A19Z was used to select events because the transportation platform consistently experienced the highest accelerations, especially at its the back end. The events with the platform accelerations equal to or exceeding +/- 2.0 g were classified as shock events. The analysis of these events is presented in the following section.

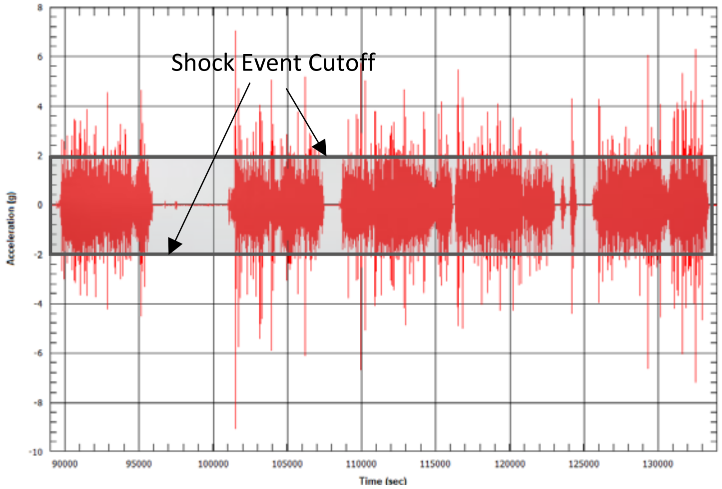


Figure 5. Time history of accelerometer A19Z (platform back end) during segment 2.

Google Earth Pro was used to analyze and compare the collected GPS, acceleration and strain data. Latitude and longitude data were collected at 200 Hz. Data were filtered to contain GPS location every 5 seconds and imported into Google Earth. Figure 6 shows the route taken by Rail 1 from the Port of Baltimore to TTCI, and the matching route recorded by Rail 2 from TTCI to Port of Baltimore, however due to Rail 2’s data acquisition system shutting off in East St. Louis, the only verifiable route of Rail 2 is from TTCI to East St. Louis, Illinois.

Figure 6. Geographic route of Rail 1 and Rail 2.

For each segment the satellite data were compared to a time history of accelerations. An example is shown in Figure 7 for the Rail 1 segment 7. In the satellite image the train is moving from the northeast corner to the southwest corner, and train icons indicate the train stops. This is reflected in the time history. The stops coincide with the periods of zero accelerations.

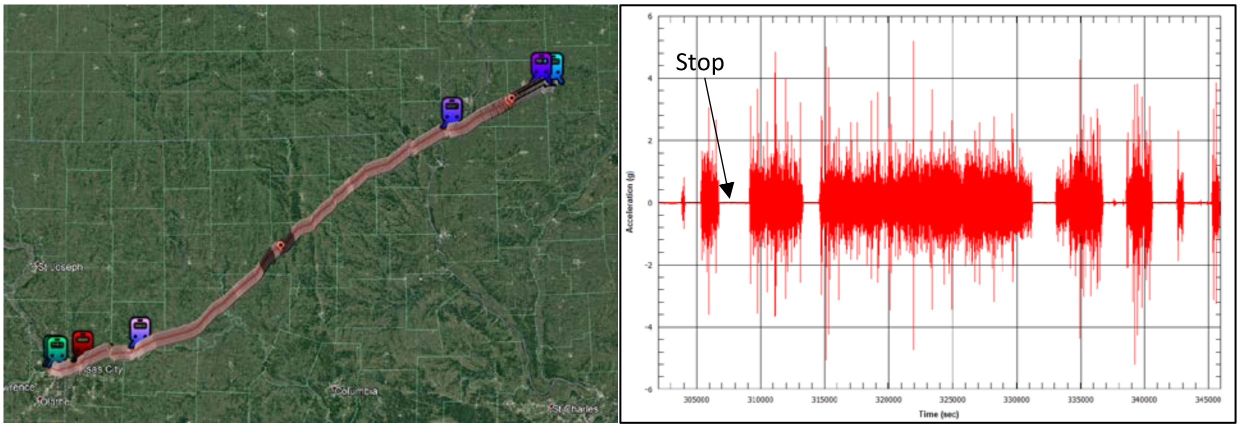


Figure 7. Rail 1 segment 7: GPS location (left) and acceleration time history of platform (right).

GPS data were also used to calculate the train speed with the Google Earth Ruler tool. The maximum allowable speed for a train carrying SNF is 50 mph [8]. There is also a maximum allowable speed of a freight train determined by the FRA rail Class. The maximum speed reached during Rail 1 transport was approximately 52 mph. Of the 1,950-mile journey, the train traveled at speeds between 0-10 mph less than 1% of the time, at speeds between 10-25 mph 9%, at speeds between 25-40 mph 68%, and at speeds between 40-52 mph 23%. Consequently, all speeds of interest were covered.

Shock events over the Rail 1 route were compiled and compared alongside GPS data to determine the cause of an event. The events fell into three categories:

- *Events Caused by a Track Switch* - observed when the train passed a switch either on the main track or side track, or the train passed a diamond crossing. These events are characterized by the presence of a common crossing, also referred to as a "frog".
- *Events Caused by a Track Bump* - observed when the train passed dips or humps in the rail. The "bump" may be caused by a road or bridge, by changes in rail crosstie quality, by vertical stiffness, by the presence of an insulated rail joint, and by a general imperfection in track geometry.
- *Events with No Visible Cause* – observed where the rail appears straight with no imperfections and no switches. These may be caused by degrading rail, soft subgrade, or a bump not visible in Google Earth due to poor image quality.

Figure 8 shows a shock response spectra during a typical shock event on the Rail 1 route. The event occurred at 129,690 seconds and was caused by the train crossing over a road. The maximum platform end acceleration was 2.43 g (0.56 g at the platform middle). The maximum absolute acceleration on the SNL assembly was 0.38 g (back end). Amplification from the railcar platform end to the assembly, cask, cradle and basket was observed at frequencies 4.0 Hz and lower. Amplification from the railcar platform middle was observed at frequencies 60 Hz and lower. The middle of the platform experiences the load from the cask and responds differently than the platform ends. The 2.5 Hz peak is related to the natural frequency of the vertical railcar suspension. Attenuation from the railcar platform end to the system is present for all frequencies higher than 4.0 Hz. Attenuation from the railcar platform middle is observed for frequencies higher than 60 Hz. A peak for the SNL assembly is commonly observed around 45 Hz, which corresponds to the natural frequency of the assembly.

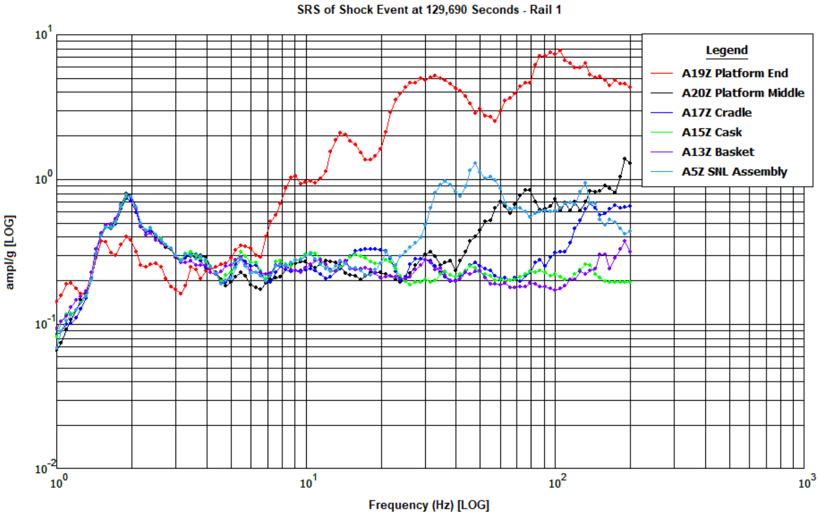


Figure 8. **Acceleration response of the transport system during a typical shock event.**

Rail 2 data were used to analyze the coupling events which were not present (with one exception) on the Rail 1 route because of the dedicated train. Figure 9 (left) shows the acceleration time history of a coupling event. Figure 9 (right) shows the GPS location during this event, confirming this event took place in a large rail yard southwest of TTCI.

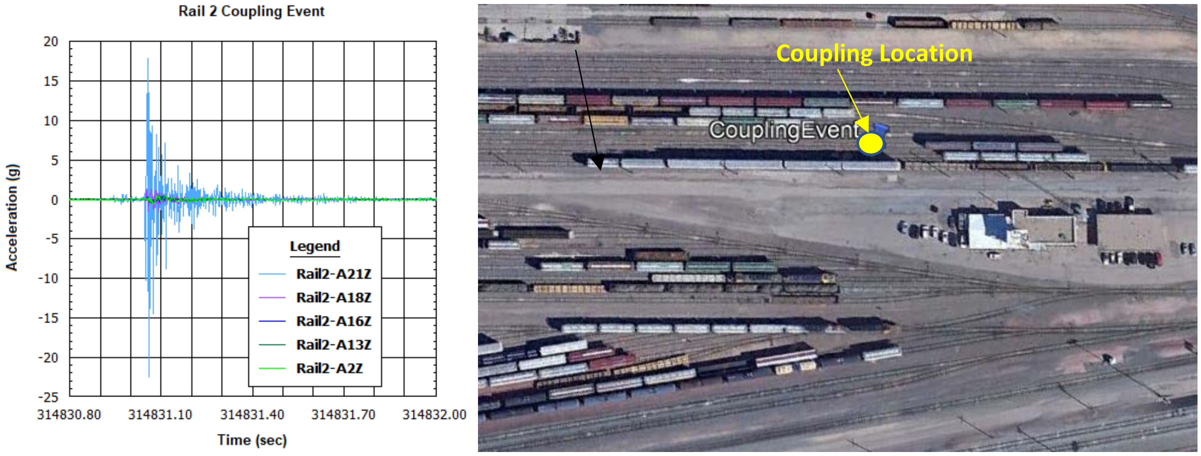


Figure 9. Rail 2 coupling event with acceleration time history (left) and location (right).

DATA ANALYSIS RESULTS

The accelerations and strains on the surrogate assemblies are some of the most important data because they make it possible to bound the behavior of the SNF cladding during routine transport. Figure 10 shows the maximum accelerations on the SNL assembly (for the accelerometer A2Z) during Rail 1 transport as a function of train speed (the 95% confidence interval is shown as well). The accelerations increase linearly as the train speed increases. Consequently, the more severe events occur at higher speeds. However, the maximum acceleration on the SNL assembly is expected to be less than or equal to 0.94g at 50 mph.

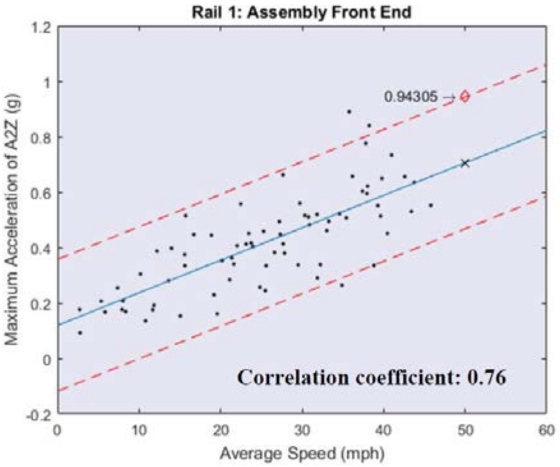


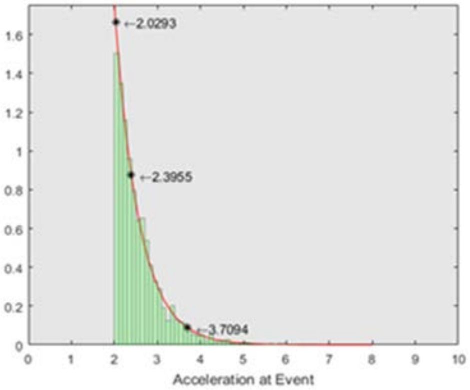
Figure 10. Maximum acceleration on SNL assembly as a function of train speed.

Every event that took place on the Rail 1 route was analyzed to determine its cause. Table 1 provides a summary of this analysis. Overall, 56% of the events were categorized based on visual inspection. Over the 1,950-mile journey of Rail 1 an event occurred on average every 0.66 miles.

Table 1. Summary of the Rail 1 event analysis.

	Occurrences	*Maximum Transportation Platform End Acceleration (g)*	*Average Frequency (mi/event)*
Event Switch	629	7.97	3.1
Event Bump	1,029	5.10	1.9
Event w/out Visible Cause	1,281	4.79	1.52
All events	2,939	7.97	0.66

The platform acceleration histogram for the Rail 1 events is shown in Figure 11, with an exponential distribution fit with rate parameter λ = 0.57. Points labelled represent the 5th (2.03g), 50th (2.4g), and 95th (3.71g) percentile accelerations along the probability density function. The probability of an event with platform end acceleration greater than 3.71 g is less than 5%.



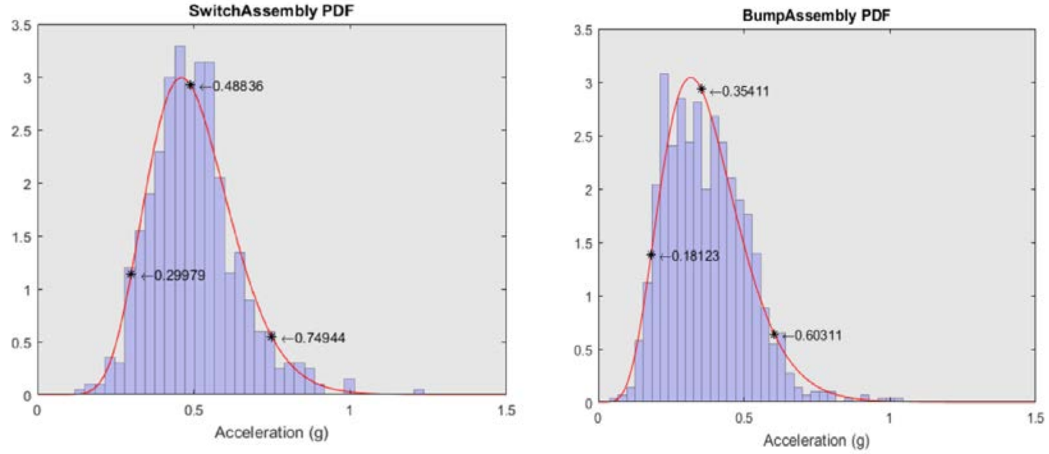
11. Platform end acceleration histogram and exponential distribution PDF for all observed Rail 1 events.

When analyzing the accelerations on the SNL assembly, the shock events were separated based on type with the focus on the switch type and bump type events that have higher accelerations. A Gamma distribution provided good fit for the SNL assembly data. This distribution is suitable for predicting low probability events.

Acceleration data from the back-end of the SNL assembly (A5Z) are plotted against a Gamma distribution in Figure 12 for the switch (left) and bump (right) events. The accelerometer A5Z was chosen because it consistently experienced the highest acceleration of all SNL assembly accelerometers during Rail 1 transport. The probability density function is shown below, defined using a standard Gamma function, and parameters k and θ estimated using the maximum likelihood estimation.

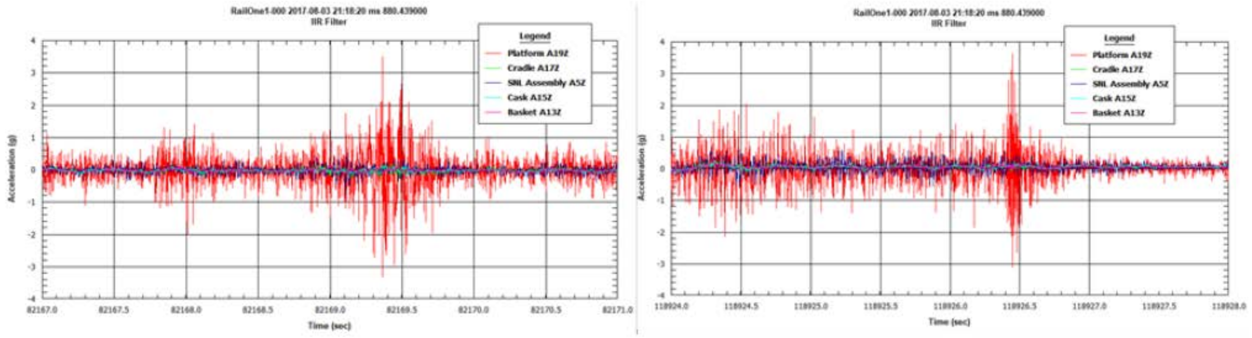
$$PDF(x) = \left(\frac{1}{\Gamma(k)\theta^k}\right) x^{k-1} e^{-\frac{x}{\theta}} \qquad (1)$$

In Figure 12 the Gamma distribution fit to switch events has parameters k = 13.06 and θ = 0.038. The Gamma distribution fit to bump events has parameters k = 7.014 and θ = 0.053. Points labelled represent acceleration at the 5th, 50th, and 95th percentile of the data.



12. SNL assembly acceleration histogram and Gamma distribution for switch (left) and bump (right) events.

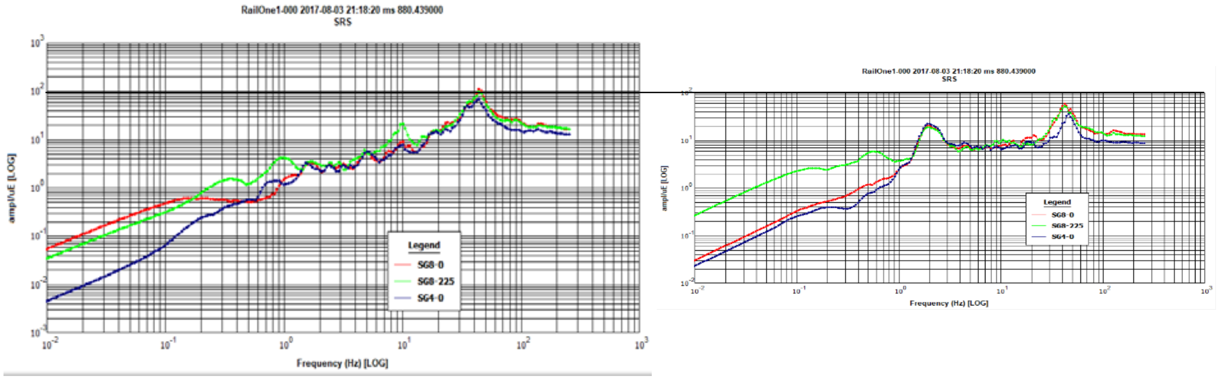
The probability of a switch event with the SNL assembly having acceleration greater than 0.75 g is less than 5%. The probability of a bump event with the SNL assembly having acceleration greater than 0.60 g is less than 5%. In general, the switch events result in higher accelerations on the assembly than the bump events. Figure 13 shows the acceleration time history data over matching lengths of time of two events in the 95th percentile of assembly acceleration. Figure 13 (left) is the system response when the railcar crosses over a track switch while Figure 13 (right) is the system response when the railcar crosses a bump.



13. SNL assembly acceleration time history during a switch event (left) and bump event (right).

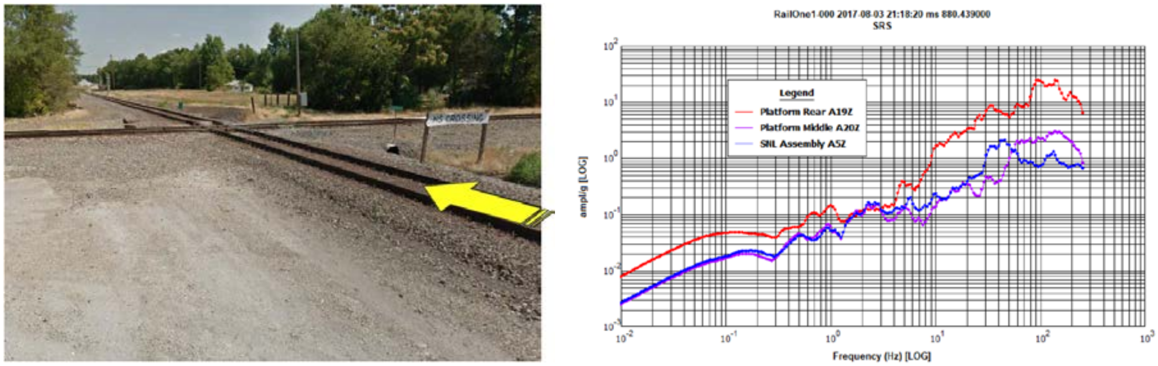
The switch event peak is broad while the bump event peak is narrow with equally high acceleration. This indicates that there is higher energy transfer during switch events as compared to bump events.

SRS of the strains on the SNL assembly for the 50th percentile switch and bump events are compared in Figure 14. Strain gauges SG8-0, SG8-225, and SG4-0 were used because they consistently recorded the highest strain within the SNL assembly. Since the resonant frequency of the assembly is 45 Hz, this peak is present in each event. A peak around 8-10 Hz on the switch event SRS is most likely caused by the natural frequency of the railcar's lateral suspension being amplified during the lateral motion of the railcar passing the switch. Similarly, the bump event SRS shows a large peak at 2 Hz. This is caused by the bump resonant frequency and amplified by the resonant frequency of the railcar's vertical suspension at 2.5 Hz.



14. SNL assembly strain SRS for 50th percentile switch event (left) and bump event (right).

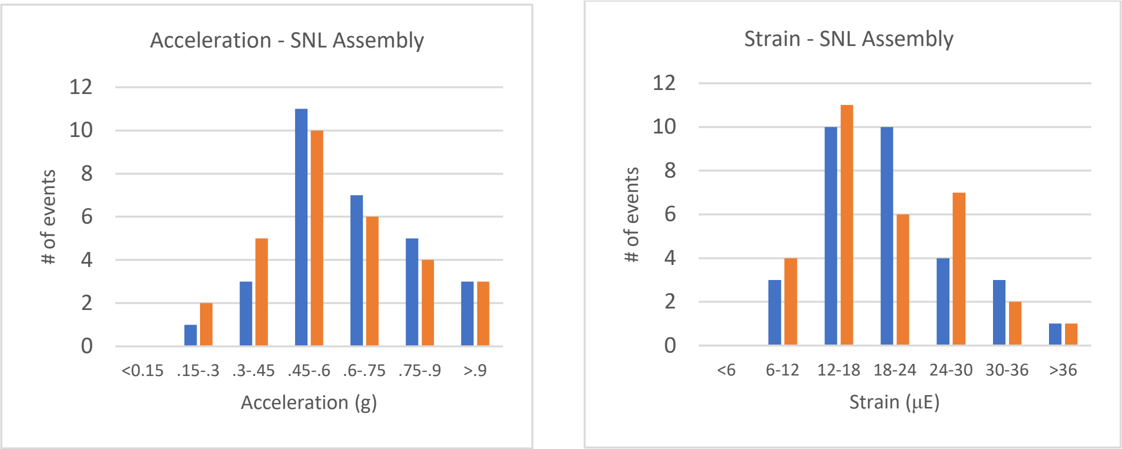
The maximum acceleration event that occurred during Rail 1 transport was caused by a diamond crossing in Jacksonville, Illinois. The railcar was traveling approximately 36 mph on FRA Class 3 track and experienced absolute maximum peak acceleration on the transportation platform end (A21Z) of 8.68 g. The maximum and minimum accelerations on the SNL assembly were 0.56/-0.65 g (A3Z/A5Z respectively). The maximum and minimum strains during this event were 19.22 µE in SG8-0 and 20.7 µE in SG8-225. Figure 15 (right) compares the accelerometer responses on the back end and middle of the railcar platform, along with the back end accelerometer on the SNL assembly's middle rod. Attenuation from the platform middle to the SNL assembly was observed for frequencies greater than 55 Hz.



15. Location (left) and SRS of platform and SNL assembly (right) for the maximum acceleration event

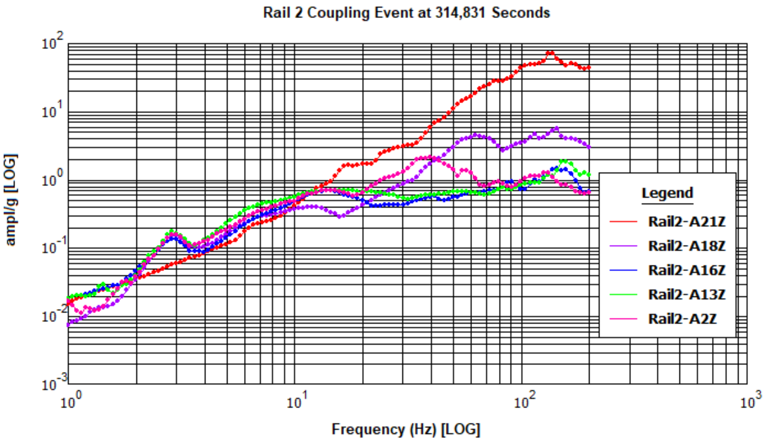
The maximum SNL assembly strain event occurred 113 hours into the trip when the train passed over a switch in Kendall, Kansas. The railcar was traveling approximately 45 mph over FRA Class 4 track and experienced maximum absolute strain on the SNL assembly of 35.8 µE (SG8-0). During this event the transportation platform end experienced maximum and minimum accelerations of 3.49/-3.78 g (A21Z). The maximum and minimum accelerations on the SNL assembly were 0.58/-0.63 g (A5Z). The maximum strain observed during the 1,950 mi rail route with 2,939 shock events was a small fraction of the yield limit for the assembly cladding.

Thirty coupling events that occurred at eight railyards were identified on the Rail 2 route between Pueblo, Colorado and East St. Louis, Illinois. Seven events occurred at small railyards, and the remaining 23 at large railyards. Acceleration and strain during coupling events are shown in Figure 16, with maximums shown in blue and absolute value of minimums shown in orange. Only a few events had accelerations greater than 0.9 g and only one event had strain greater than 36 µE. The maximum acceleration on the SNL assembly was 1.06 g and the maximum strain was 39 µE.



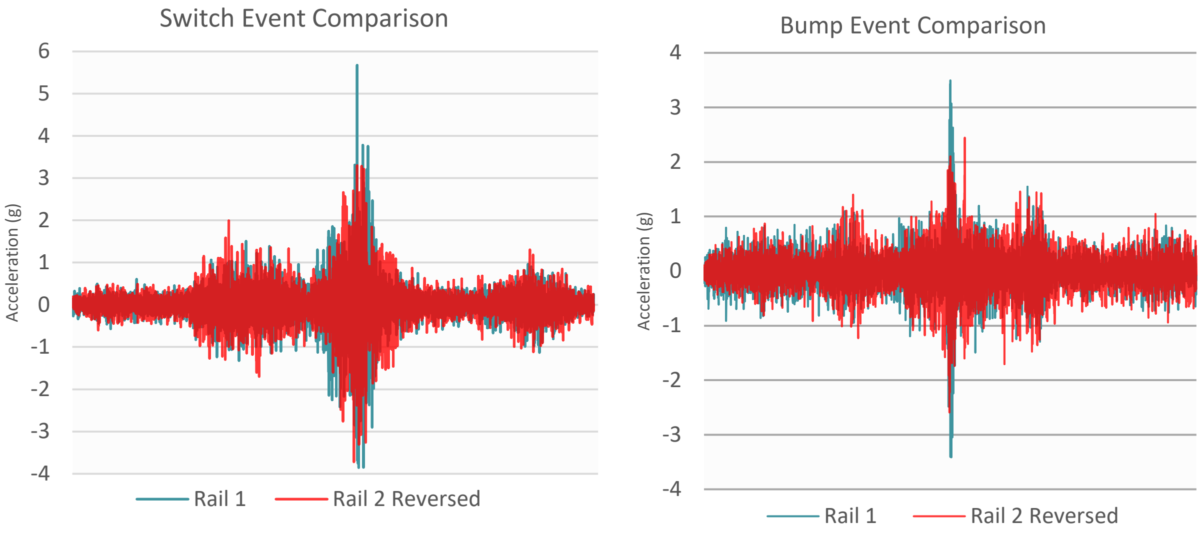
16. Histograms of maximum and absolute minimum accelerations (left) and strains (right) during coupling events on the Rail 2 route.

Figure 17 shows the acceleration SRS of a coupling event that occurred 87-hours into the Rail 2 route. The response of the SNL assembly is attenuated with regard to the response of the transportation platform end at frequencies greater than 10 Hz, although is amplified for frequencies less than 2.5 Hz. The SNL assembly SRS (A2Z) has peak around 45 Hz, which is related to the assembly natural frequency. The accelerations and strains during the coupling events are generally somewhat higher than during the switch and bump events.



17. Acceleration SRS of a Rail 2 coupling event.

Since the Rail 1 and Rail 2 routes were near identical, the same shock event locations were passed on the way to and from Pueblo. The responses at the same locations should be similar and affected mainly by the train speed (Figure 10). A few of these locations, primarily a switch-type event and bump-type event, were analyzed using Rail 1 and Rail 2 data. During the switch event on Rail 1 the train was traveling 40.1 mph. The train was traveling 29.9 mph at the same location during Rail 2 transport. During the bump event the train for Rail 1 was traveling 44.3 mph. The train was traveling 44.6 mph at the same location during Rail 2 transport. Figure 18 shows the platform acceleration time histories of both events with Rail 2 data reversed and overlaid on Rail 1 data. The accelerations are very similar and only slightly higher on Rail 1 due to the higher train speed.



18. Platform acceleration time history during Rail 1 and Rail 2 for a switch (left) and a bump (right).

SUMMARY

2,939 shock events were identified during the 1,950 mi dedicated train rail route (Rail 1) from Baltimore to Pueblo (Colorado). The events with the highest accelerations were either switch or bump events. The estimated probability of a switch event with the SNL assembly acceleration greater than 0.75 g is less than 5%. The estimated probability of a bump event with the SNL assembly acceleration greater than 0.60 g is less than 5%. The maximum acceleration on the SNL assembly observed during Rail 1 transport was 1 g. The maximum observed strain was 35.8 μE.

Another factor affecting the accelerations is the train speed. The accelerations increase linearly as the train speed increases. Consequently, the more severe events occur at higher speeds. However, the maximum acceleration on the SNL assembly is predicted to be less than or equal to 0.94 g at 50 mph.

Thirty coupling events were identified during the 1,125 mi rail route (Rail 2) from Pueblo to East St. Louis. The accelerations and strains on the SNL assembly during coupling were slightly higher than during the switch or bump events. The maximum acceleration on the SNL assembly was 1.06 g and the maximum strain was 39 μE.

It is commonly assumed that the cargo and the railcar platform respond similarly to the transient inputs during transport. The rail test demonstrated that the responses of the different elements of the transportation system are different. There is attenuation from the platform to the cradle, cask, and assemblies at some frequency and amplification at other frequencies. The higher responses occur at the assembly natural frequency of 40-45 Hz.

The test results provided a compelling technical basis for the safe transport of spent fuel under routine transport. During routine transport, including coupling, the accelerations on the assembly are expected to be below 1 g and the strain is expected to be below 40 μE. Consequently, the stress the fuel rods experience is far below the yield stress for the cladding material [9].

REFERENCES

[1] Kalinina, E.A., Wright, C., Lujan, L., Saltzstein, S., 2019. *Shock Environments for the Nuclear Fuel Transportation System (Transportation Platform, Cask, Basket, and Surrogate Assemblies) during Specialized Rail Tests*, Proceedings, PATRAM-2019, New Orleans, LA, 2019.

[2] Kalinina, E.A., Wright, C., Lujan, L., Saltzstein, S., 2019. *Shock Environments for the Nuclear Fuel Transportation System (Transportation Platform, Cask, Basket, and Surrogate Assemblies) during Specialized Rail Tests*, Proceedings, PATRAM-2019, New Orleans, LA, 2019.

[3] Kalinina, E.A., Lujan, L., Wright, C., Saltzstein, S., 2019. *Shock Environments for the Nuclear Fuel Transportation System (Transportation Platform, Cask, Basket, and Surrogate Assemblies) during Ocean Transport*, Proceedings, PATRAM-2019, New Orleans, LA, 2019.

[4] Sandia National Laboratories, 2018. Cask Transportation Test, *https://www.youtube.com/watch?v=wGKtgrozrGM&feature=youtu.be*

[5] Kalinina, E.A., Gordon, N., Ammerman, D.J., Uncapher, W., Saltzstein, S.J., and Wright, C., 2018. *Results and Correlations from Analyses of the ENSA ENUN 32P Cask Transport Tests*, Pressure Vessels and Piping Conference, Prague, Czech Republic, 2018.

[6] Dorsey, K.B. (2016). Recommended Railroad Operating Practices for Transportation of Hazardous Materials. Circular No. OT-55-P (CPC-1321), Association of American Railroads, Washington, DC.

[7] Magnuson, C.F. and L.T. Wilson (1977). *Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks.* SAND76-0427 (NUREG766510), Sandia National Laboratories, Albuquerque, New Mexico.

[8] Magnuson, C.F. (1980). Shock Environments for Large Shipping Containers During Rail Coupling Operations. SAND79-2168 (NUREG/CR1277), Sandia National Laboratories, Albuquerque, New Mexico.

[9] NUREG/CR-7198, 2016. *Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications,* NUREG/CR-7198, Revision 1, ORNL/TM-2016/689.

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