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# Shock Environments for the Nuclear Fuel Transportation System (Transportation Platform, Cask, Basket, and Surrogate Assemblies) during Heavy-Haul Transport and Handling

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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 shocks 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), 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 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 heavy-haul transport and handling tests. The results from the other tests are presented in three related PATRAM 2019 papers.

To understand the shock environment during handling, tests were conducted at ENSA's facilities prior to the heavy-haul transport. Three ENSA crane operators lowered the cask on the pad three times. The data were also collected when the cask was placed in the cradle.

Heavy-haul truck data were recorded from the ENSA facility in Maliaño, Spain via a 245 mi route. The truck maintained a 25 mph speed and was in motion for 13 hours. A total of 36 shock events were identified. The majority of the events were caused by a vertical upset in the road such as abutment from the roadway to a bridge, crosswalk, a patchwork in asphalt, and imperfections in the road surface.

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## 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 shocks 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), 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.

The instrumented ENUN P32 transportation cask containing surrogate fuel assemblies from the US, Spain, and Korea was transported by 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 54-days, 7-countries, 12-states, 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 heavy-haul transport and handling tests. The results from the other tests are presented in three related PATRAM 2019 papers [1], [2], and [3]. A short video documenting the major test events is available on YouTube [4]. The preliminary results of the multi-modal transportation test were reported in [5].

To understand the shock environment during handling, a few tests were conducted at ENSA's facilities prior to the heavy-haul transport. Three ENSA crane operators lowered the cask on the pad three times. The data were also collected when the cask was placed in the cradle. The cask exterior and interior were instrumented as described below, and the data were collected at 10,240 Hz for the handling tests.

Prior to the heavy-haul test, the instrumentation was placed on the cradle and the transportation platform. The accelerometers on the truck 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 truck 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 1 provides an illustration of the external system 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 had Zircaloy-4 cladding, one was 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.

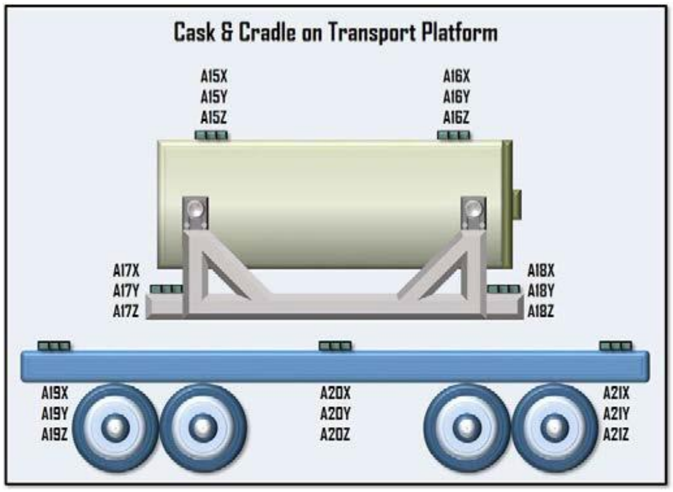
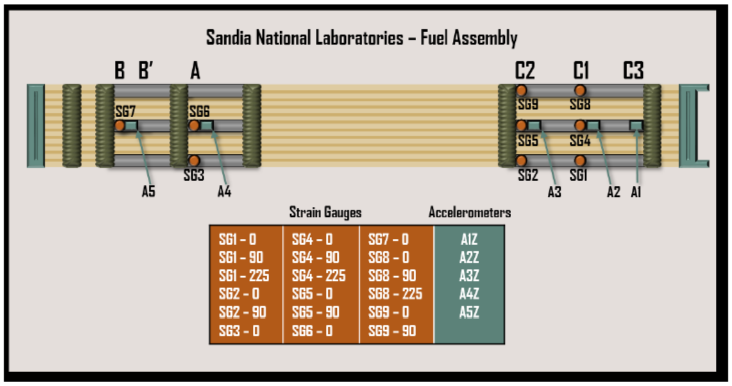


**Figure 1. Truck platform, cask, and cradle accelerometer configuration.**

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 on 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 2 shows the configuration of both strain gauges and accelerometers on the SNL assembly.



| Strain Gauges |  |  | Accelerometers |
|---|---|---|---|
| SG1 – 0 | SG4 – 0 | SG7 – 0 | A1Z |
| SG1 – 90 | SG4 – 90 | SG8 – 0 | A2Z |
| SG1 – 225 | SG4 – 225 | SG8 – 90 | A3Z |
| SG2 – 0 | SG5 – 0 | SG8 – 225 | A4Z |
| SG2 – 90 | SG5 – 90 | SG9 – 0 | A5Z |
| SG3 – 0 | SG6 – 0 | SG9 – 90 |  |

**Figure 2. 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 truck data from NUREG 766510 (SAND76-0427) [6] is shown in Figure 3.

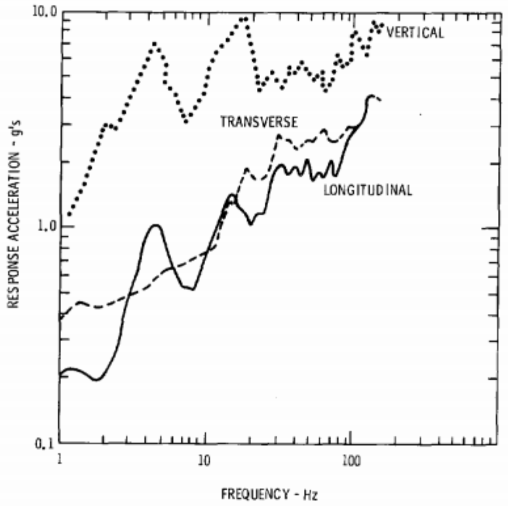


**Figure 3. Shock response for truck transport from NUREG 766510 (SAND76-0427) [6].**

This paper provides an analysis of the shock events over the entire 245 mi heavy-haul route. The responses of all the transportation system elements, including the surrogate assemblies, are considered.

## DATA ANALYSIS METHOD

Heavy-haul transportation data were collected at 512 Hz over the 245-mile route. The truck stopped 4 times, splitting the trip into 5 blocks of motion that in total amount to 13 hours of travel. To quantify shock events during heavy-haul transport the time histories of each block of motion were analyzed. An example is shown in Figure 4 for the first 3 blocks of motion recorded (accelerometer A19Z). A19Z was used to select events because the truck platform consistently experienced the highest accelerations, especially the back end. The events with the platform accelerations equal to or exceeding +/- 1.0 g were classified as shock events. The analysis of these events is presented in the following section.

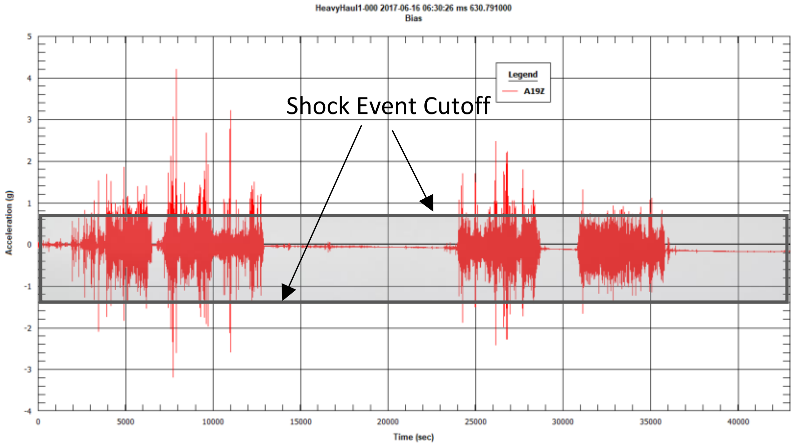


**Figure 4. Platform acceleration time history (A19Z).**

The trailer used in testing is pictured in Figure 5 and may vary from trailers used in heavy-haul transport in the US. Like railcars used in the US, most heavy-haul trailers have span bolsters that better divide the wheel reactions to the overall vertical load. The trailer shown below does not have span bolsters, and therefore most likely experienced lower vertical loads on the first few and last few trailer axles.

**Figure 5. ENUN 32P cask on the trailer used in heavy-haul transport.**

Google Earth Pro was used to analyze and compare the collected GPS and 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 the heavy-haul truck through Spain, with icons representing places where the truck stopped. GPS data were also used to calculate the truck speed with the Google Earth Ruler tool.

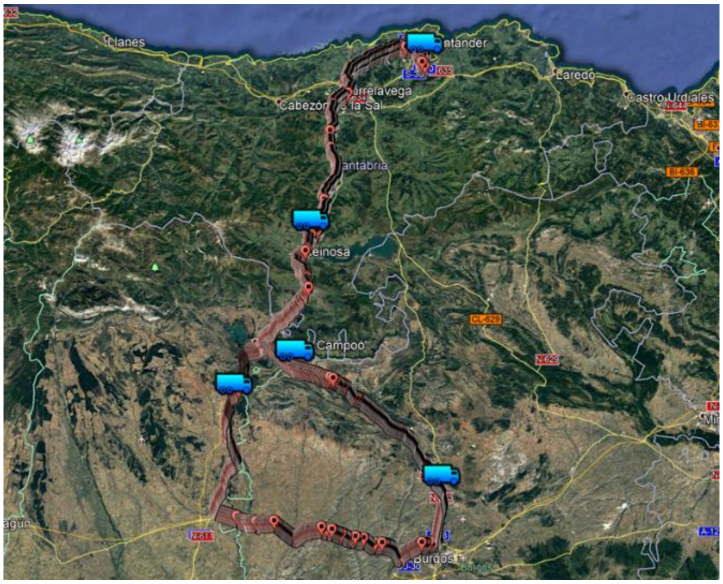


**Figure 6.  Geographic route of heavy-haul truck.**

Dry storage cask handling tests and heavy-haul handling tests were conducted to understand the fuel rod environment during handling.  To obtain a useful representation of cask handling, a range of cask impacts was performed. The dry storage cask handling test involved three ENSA crane operators raising and lowering the cask three times, where varying degrees of crane handling “aggressiveness” were used by each operator for their three respective tests. Figure 7 shows an operator (right) performing one of the dry storage handling simulation tests.

**Figure 7.  Dry storage cask handling test.**

Cask handling tests also included one heavy-haul handling test.  The cask was lifted in the vertical position and then rotated to the horizontal position while being placed into the cradle.

# DATA ANALYSIS RESULTS

## Heavy-Haul Transport

Shock events during heavy-haul transport were compiled and compared alongside GPS data to determine the cause of each event. 36 events were identified and analyzed to determine their cause. The shock events are classified as follows:

- 78% of events were caused by a vertical upset in the road. This was usually due to an abutment from the roadway to a bridge, specifically by a metal cutout perpendicular to the road. One event was caused by a crosswalk that elevated the road. Three events were caused by imperfections and uneven road surface.
- 11% of events were caused by a turn onto a major road or in a roundabout.
- 11% of events had no visible cause. This could have been due to poor image quality or no visible obstruction. Such events did not cause substantial acceleration in either the platform or the SNL assembly.

A Fréchet probability distribution function (PDF) with parameters $\alpha = 5.3$, $\sigma = 2.1$ was used to fit the platform acceleration data from all identified heavy-haul shock events. It is shown in Figure 8, with points on the distribution representing a 5th percentile event (1.73g), 50th percentile event (2.28g), and a 95th percentile event (3.75g).

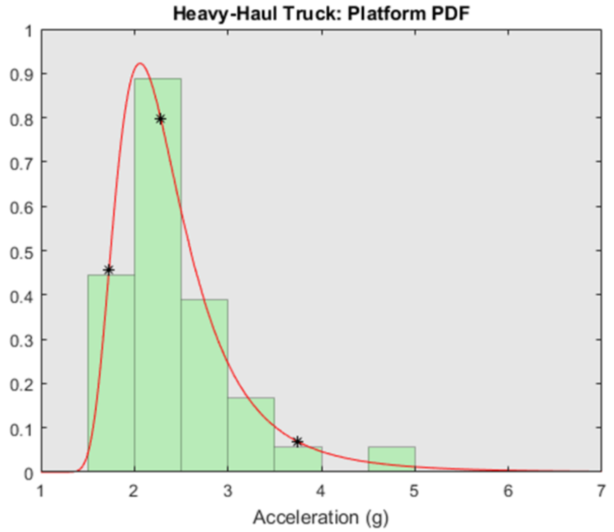


**Figure 8. Truck platform acceleration histogram and Fréchet PDF for heavy-haul transport.**

The highest platform acceleration recorded during the heavy-haul transport occurred at 7,890 seconds, in the third hour of transport. The maximum acceleration was 4.53 g in accelerometer A19Z located on the back end of the transportation platform, putting this event in the 97th percentile. The maximum SNL assembly acceleration was 0.42 g in accelerometer A5Z (assembly back end). The maximum strain reached during this event was 15.9 µE, making this shock event the cause of both the highest recorded system acceleration and highest recorded assembly strain during the heavy-haul transport. This event occurred while the truck was traveling 24 mph and was caused by the bridge abutment shown in Figure 9.

**Figure 9. Location of the heavy-haul transport maximum acceleration and SNL assembly strain event.**

A SRS of the transportation system accelerometers during the heavy-haul truck test's maximum event is shown in Figure 10 (left). Note that the middle of the platform experiences the load from the cask and responds differently from the platform ends. The acceleration peaks at 2.5 Hz and 7 Hz are related to the truck vertical and horizontal suspension natural frequencies respectively. The acceleration peak at 14 Hz is possibly caused by the truck body natural frequency. The SNL assembly acceleration peak at 45 Hz is related to the assembly natural frequency. The SNL assembly strain peaks coincide with the acceleration peaks. The maximum strain of 15.9 μE observed during 245 mi heavy-haul truck route with 36 shock events was a small fraction of the yield limit for the assembly cladding [7].

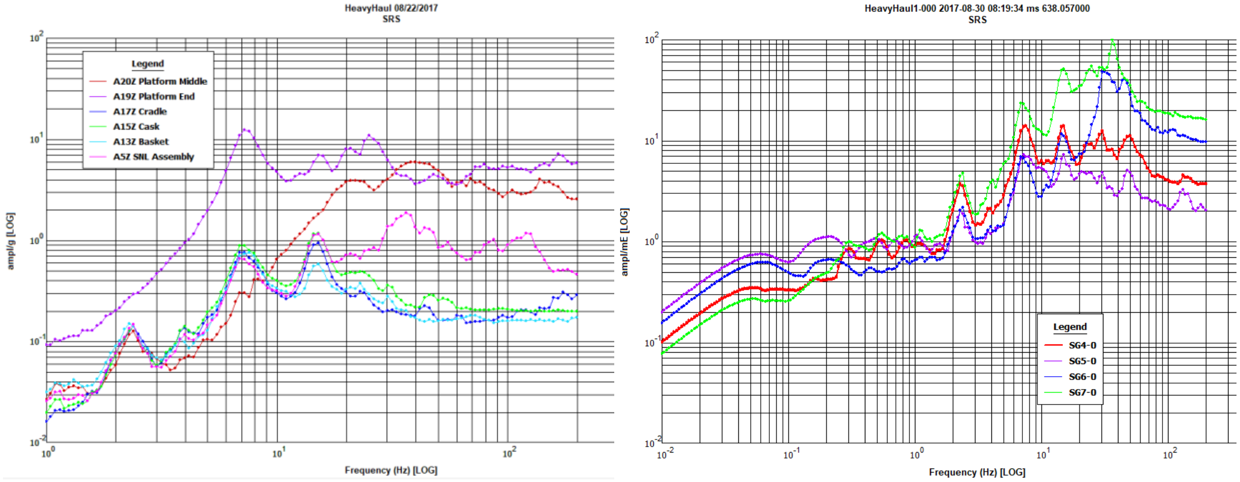


**Figure 10. SRS of accelerometers (left) and SNL strain gauges (right) of heavy-haul transport response during maximum acceleration and strain event.**

An interesting phenomenon observed during the heavy-haul transport was the strain gauge channels recording electromagnetic interference from powerlines. European utility frequency runs at 50 Hz, and cases of interference can be observed throughout the recorded data. Interference was discovered by looking at peaks in strain data that followed a characteristic pattern of smooth oscillatory motion, as seen in Figure 11, with strain data from the ENSA assembly in red and from the SNL assembly in purple. Most likely due to its positioning at the bottom of the cask, the SNL assembly did not experience as large of disruptive powerline interference as the other assemblies did. It was confirmed in both data and geographic location that the maximum strain and acceleration event was not influenced by powerline interference.

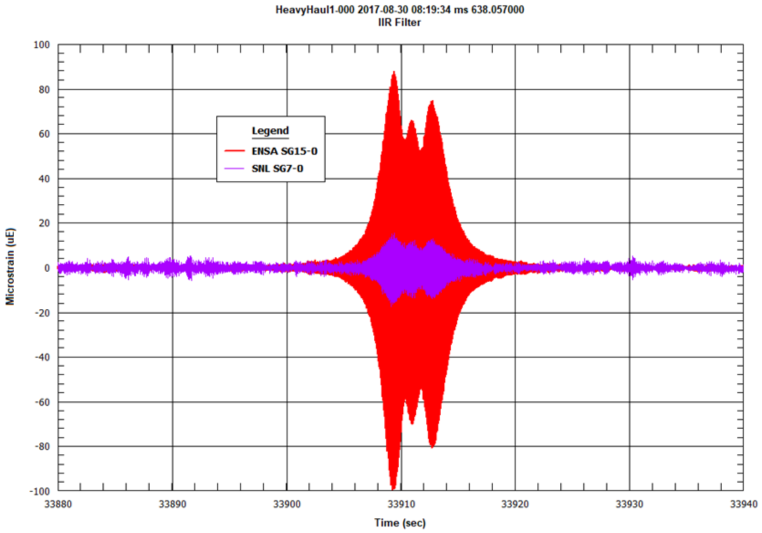


**Figure 11. Example of characteristic shape of powerline interference.**

## Handling

The maximum accelerations on the SNL assembly (A1Z through A5Z) in the dry storage handling tests and heavy-haul handling test are presented in Figure 12. The heavy-haul handling test is very similar to the handling tests in Run 1 and Run 3 (first and second crane operators). The two handling tests, Drop 1 and Drop 2, in Run 5 (third crane operator) are significantly higher than all the others. The accelerations in the handling are generally higher than during the heavy-haul transport, note that the acceleration data were not filtered.

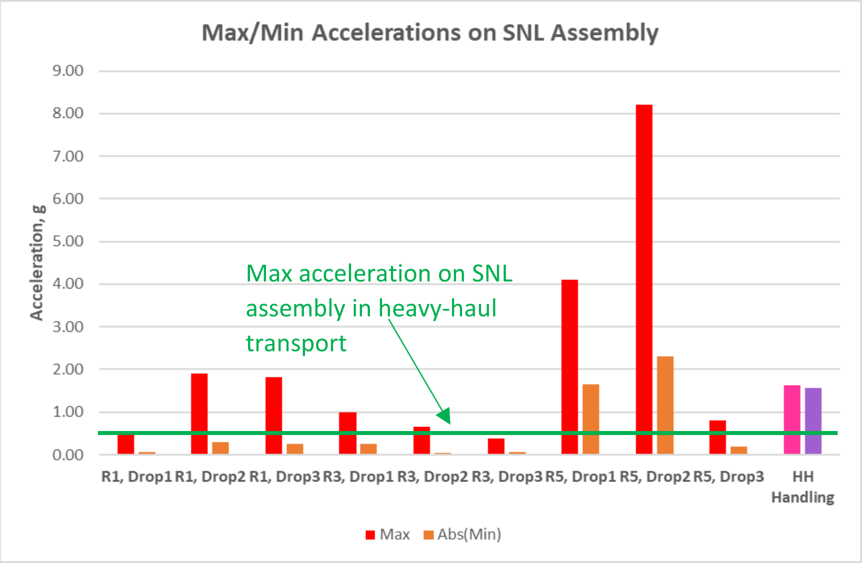


**Figure 12. Maximum accelerations in dry storage and heavy-haul cask handling tests compared with maximum acceleration during heavy-haul transportation.**

The strain on the SNL assembly in Run 5 Drop 2 are shown in Figure ***13*** for all the assembly strain gauges. The strain gauges at the assembly back end are shown in yellow (maximum) and purple (absolute of minimum). The strains are higher at the assembly top. The strains in the handling are generally higher than during the heavy-haul transport. The maximum observed strain was 48.5

µE on the SNL assembly. The overall maximum was 82 µE on SG15-0 (ENSA assembly, not shown in Figure 13).

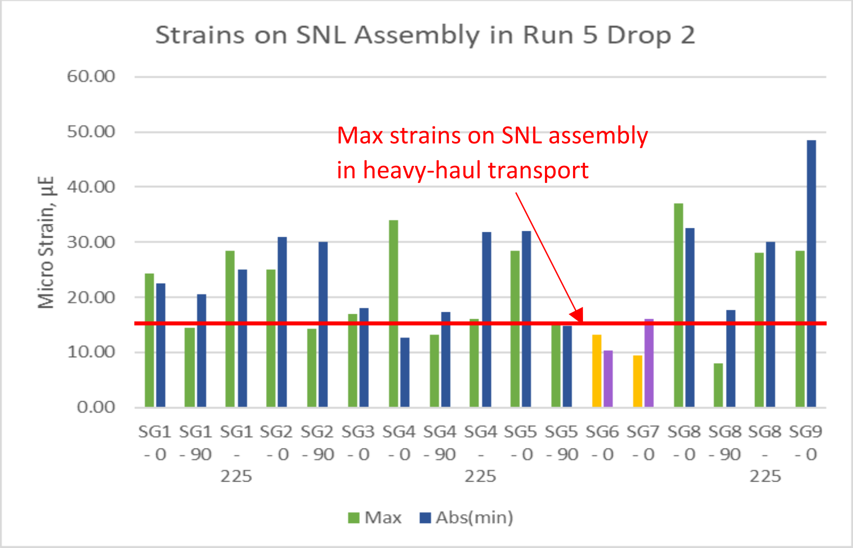


**Figure 13. Strain on the SNL assembly in the most severe dry storage cask handling test.**

## SUMMARY

36 shock events were identified during the 245 mi heavy-haul transport in Spain. The events with the higher accelerations were caused either by a vertical upset of the road or turn onto a major road or in a roundabout. The maximum overall acceleration on the SNL assembly observed during heavy-haul transport was 0.52 g. The maximum observed strain was 15.9 µE.

Nine dry storage handling tests and one heavy-haul handling tests were conducted prior to the heavy-haul transport. The accelerations and strains on the SNL assembly during handling were somewhat higher than during the heavy-haul shock events. The maximum strain on the SNL assembly was 48.5 µE. Note that only a few handling operations are expected while the SNF is in storage and transport.

It is commonly assumed that the cargo and the transportation platform respond similarly to the transient inputs during transport. The heavy-haul 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 accelerations and strains occur at the assembly natural frequency around 45 Hz.

The test results provided a compelling technical basis for the safe transport of spent fuel under normal conditions of transport and during dry storage handling. During normal conditions of heavy-haul transport the strain on the assembly are expected to be below 20 µE. During the dry storage handling operations, the strains are expected to be below 100 µE. Consequently, the stresses the fuel rods experience are far below yield limits for cladding [7].

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