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RESULTS OF THE NORMAL CONDITIONS OF TRANSPORT OF SPENT NUCLEAR FUEL MULTI-YEAR EXPERIMENTAL PROGRAM

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ABSTRACT

Spent nuclear fuel (SNF) in the U.S. is stored at 75 reactor sites in 35 states. The total SNF inventory is estimated to be ~140,000 MTU. Since 1986, the SNF has been transferred from at-reactor pools into at-reactor dry storage. The total number of loaded dry storage canisters will exceed 10,000. Transporting SNF from the reactor sites to a geologic repository and possibly to a consolidated interim storage facility will take decades. The primary mode of transport will be by freight rail. However, some sites will require heavy-haul and/or barge transport. The most probable transportation mechanism will be by placing the dry storage canisters with SNF into transportation casks. Currently, there are 17 transportation cask designs certified by the US NRC for use in the US. The regulations (10 CFR Part 71) postulate the requirements on the transportation casks, including those for normal conditions of transport (NCT), but do not specify the mechanical loads on the SNF. Because of a concern regarding the integrity of the SNF during NCT, especially when transported after a long period of dry storage, the DOE funded an experimental program to quantify the mechanical loads on the SNF rods during NCT. A shake table test of a surrogate fuel assembly with vertical accelerations representing truck transport was performed in 2013. An over-the-road truck test followed in 2014. A 6-degrees-of-freedom shake table test with accelerations representing truck and rail transport was performed in 2015. In 2017, an international collaboration made it possible to conduct the multi-modal transportation test (MMTT). An instrumented transportation cask containing 3 surrogate fuel assemblies was transported by truck, by ship, and by rail. The MMTT data covers the 54-day, 9,400 miles of travel and cask handling operations. A series of 30 cm drop tests was conducted in 2018-2020. This paper compares and summarizes the most important experimental results. The main conclusion of this work was that the SNF will maintain its integrity during NCT. This conclusion is applicable to different transportation configurations and systems and low and high burnup fuel as was demonstrated through modeling that was validated against the test results.

INTRODUCTION

Currently, there are 17 transportation cask designs certified by the US Nuclear Regulatory Commission (NRC) for use in the US. The regulations (10 CFR Part 71) postulate the requirements on the transportation casks, including those for normal conditions of transport (NCT), but do not specify the mechanical loads on the SNF. Because of a concern regarding the integrity of the SNF during NCT, especially when transported after a long period of dry storage, the Department of

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ONE-DEGREE-OF-FREEDOM SHAKE TABLE TEST (2013)

In 2013, Sandia National Laboratories (SNL) conducted a series of one-degree-of-freedom (DOF) shake table tests with a 17x17 pressurized water reactor (PWR) Westinghouse surrogate fuel assembly. The assembly was placed within a basket fabricated for the tests. The shake table inputs (vertical accelerations) were based on accelerations measured on representative casks (44,000 lbs and 56,000 lbs) during a 700-mile over-the-road truck test conducted in 1977 and documented in [1] and [2]. No other applicable transportation vibration environment data were available at the time of the test. The test setup is shown in Figure 1.

Figure 1. Surrogate assembly in the 1 DOF shake table test

Three assembly rods were instrumented. The maximum measured strain was 213 microstrain recorded by a strain gauge located in the mid-span of the one of the longer spans at the top-nozzle end of the assembly.

OVER-THE-ROAD TRUCK TEST (2014)

The over-the-road truck test was conducted with the same 17x17 surrogate assembly used in the 2013 shake table test. The surrogate assembly was place on the truck bed and secured on both sides by concrete blocks as shown in Figure 2. The measurements were made during a 40 mile transport in the Albuquerque (New Mexico) area. The route included a variety of road conditions - rough dirt to Interstate highway. The maximum strain measured during this test was 143 microstrain. It was measured during the transport on a rough dirt road.

Figure 2. Surrogate Assembly in the over-the-road truck transport test

6-DEGREES-OF-FREEDOM SHAKE TABLE TEST (2015)

In 2016, a series of 6 DOF shake table tests were conducted with the same 17x17 surrogate assembly used in the 2013 shake table test and 2014 over-the-road-truck test. The shake table inputs for simulating truck transport were the same as in the 2013 test, except horizontal accelerations were also specified. The shake table inputs for simulating rail transport were based on the accelerations measured on the railcar platform reported in [3]. The test setup is shown in Figure 3.

Figure 3. Surrogate Assembly in the 6 DOF shake table test

The maximum measured strains in microstrain were 241 (rail), 208 (coupling), and 301 (truck).

MULTI-MODAL TRANSPORTATION TEST (2017)

In 2017 a team led by SNL conducted an international multi-modal transportation test (MMTT). The test was funded by the DOE. Many US and international organizations participated in the MMTT. The purpose of the MMTT was to quantify the shock and vibration environments during NCT. Three 17x17 Westinghouse PWR surrogate assemblies from the US, Spain, and Korea were placed in the basket of the ENsa UNiversal (ENUN) 32P dual-purpose rail cask along with twenty-nine dummy assemblies (concrete masses with the same weight, cross-section, and length as the surrogate assembly). The ENUN 32P cask was provided by Equipos Nucleares SA, SME (ENSA). The instrumented transportation system (loaded cask, cradle, and impact limiters) was transported by heavy-haul truck in Spain, by coastal vessel to Belgium, by ship to Baltimore, and by rail to Colorado for rail tests at the Transportation Technologies Center, Inc (TTCI) and back to Baltimore by rail (on the way back to Baltimore only the first 1,125 miles were recorded). 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 fuel assemblies in a real transportation configuration. The accelerations were also measured on the basket, cask, cradle, and transportation platform. The transportation system was instrumented with 40 accelerometers and 37 strain gauges. The detailed analysis of the MMTT data is documented in [4]. The major results were published in [5], [6], [7], and [8]. A short video illustrating the main test events is available on YouTube [9]. The MMTT included the following:

- Cask handling tests at ENSA's facility in Santander (Spain)
- Heavy-haul truck tests in northern Spain (245 miles)
- Coastal vessel transport (929 miles) and ocean ship transport (4,290 miles)
- Rail transport from Baltimore to TTCI (1,950 miles)
- Specialized rail tests at TTCI
- Rail transport from TTCI to Baltimore (the recorded portion was 1,125 miles)

Figure 4 shows the MMTT transportation routes. Figure 5 shows the transportation system and its instrumentation.

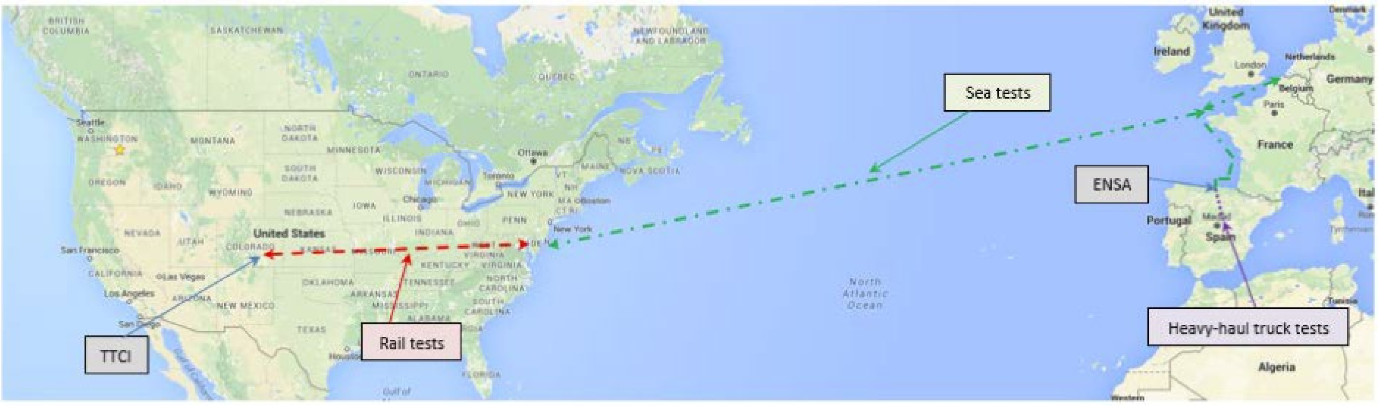

Figure 4. MMTT transportation routes

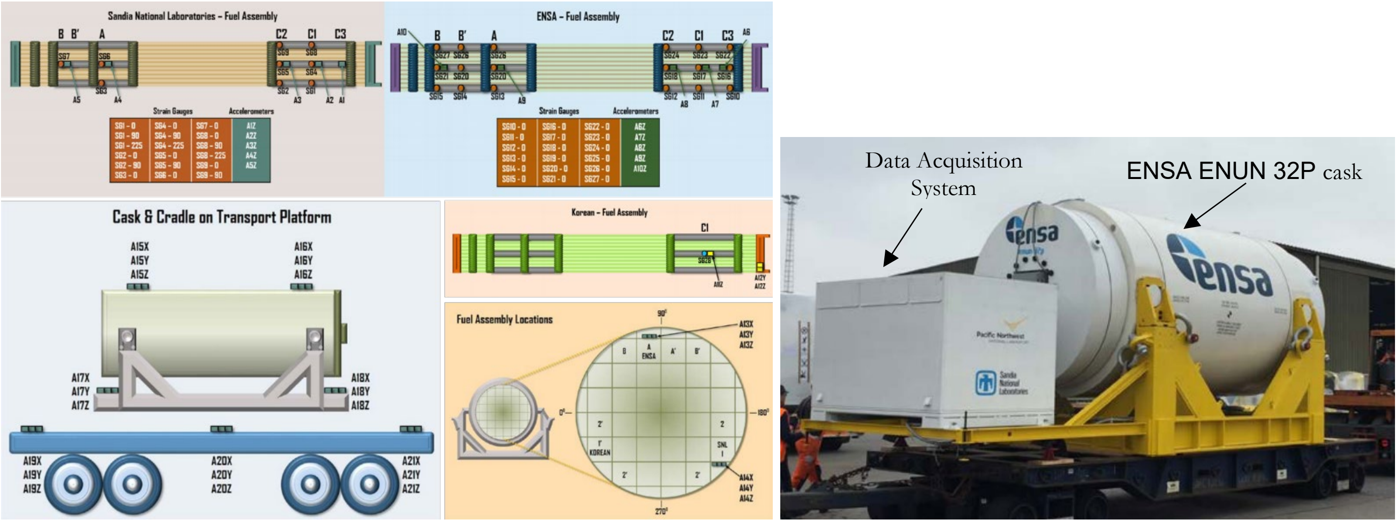

Figure 5. Transportation system and its instrumentation

Cask Handling Tests

The cask handling included (1) raising and lowering the cask three times by 3 different crane operators and (2) placing the cask into the cradle. The cask was loaded with the dummy assemblies and instrumented surrogate assemblies prior to these tests. The maximum strain measured on the surrogate assemblies was 82 microstrain (1) and 20 microstrain (2). Figure 6 shows the strain time histories in the handling test (raising and lowering cask) in which the highest strains than in the other tests were measured.

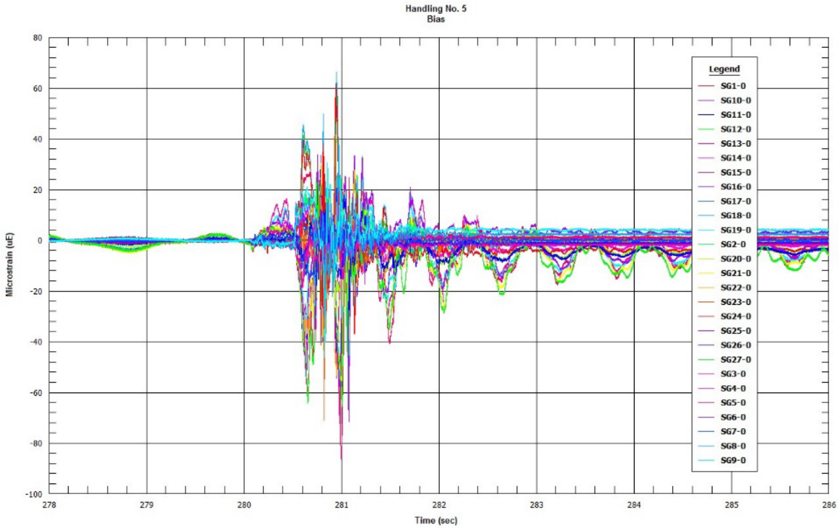

Figure 6. Strain time histories in one of the handling tests

Heavy Haul Transport in Spain

A total of 36 shock events were identified along the 245 mile heavy-haul route. The majority of the events (78%) were caused by a vertical upset in the road (a bridge, crosswalk, a patchwork in asphalt, and imperfection in road surface). Most of the other events were associated with turns. The maximum observed acceleration and strain on the surrogate assembly were 0.52 g and 15.6 microstrain, respectively. Figure 7 shows strain time histories on the surrogate assembly during the maximum acceleration and strain event, and the upset that caused the event.

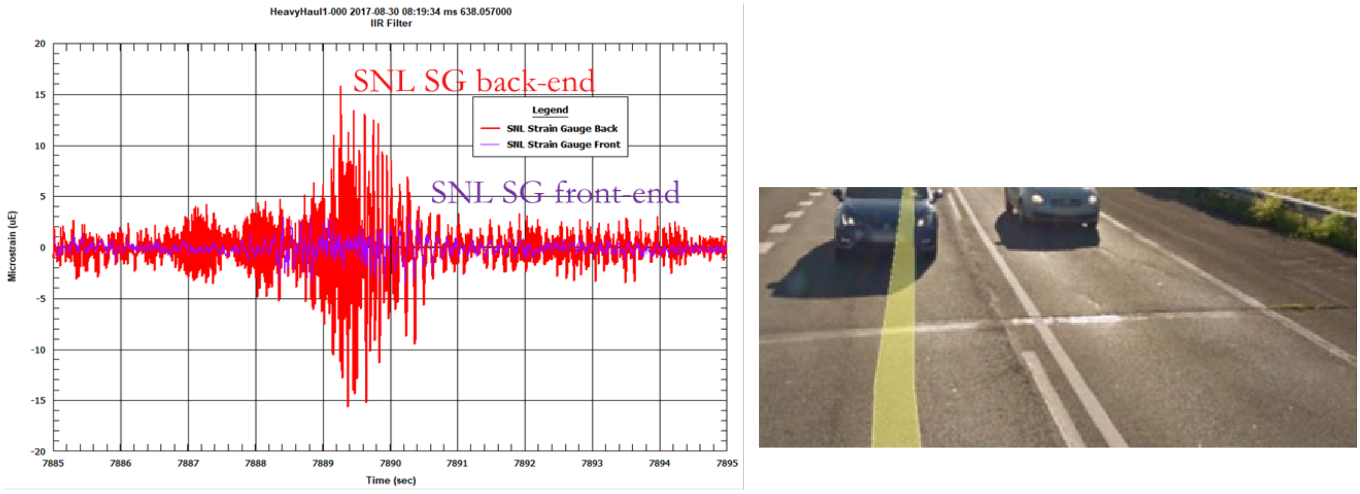

Figure 7. Heavy-haul transport maximum strain event strain time histories (left) and event road surface configuration (right)

<u>Ship Transport</u>

The accelerations and strains observed during coastal vessel and ship transport were very low. The maximum assembly acceleration was 0.12 g. The maximum strain on the assembly was 3.8 micro strain. The transportation platform was latched to the ship's deck and this significantly restricted its movement. Figure 8 shows the strain time history during the maximum strain event. The GPS was not functioning during the ship transport and the location of this event can be estimated only approximately. The shape of the signals in Figure 8 suggests that the shock event was caused by a short duration impact.

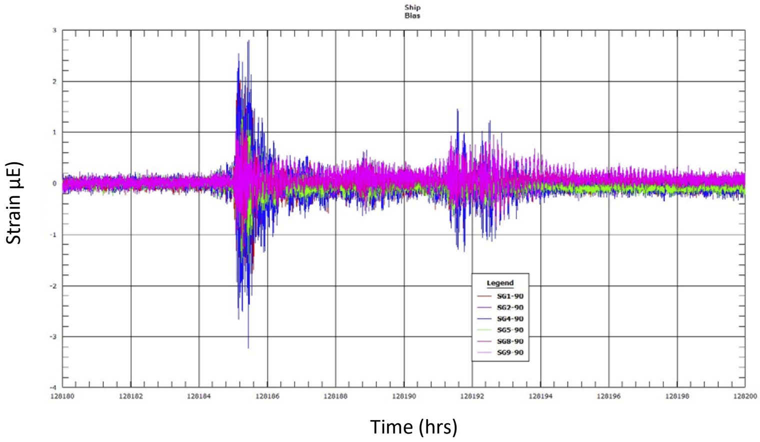

Figure 8. Maximum strain event strain time histories, ship transport

<u>Rail Transport (Baltimore to TTCI)</u>

The major shock events during the 1,950 mi rail transport from Baltimore to TTCI were track switches (629) and grade crossings (1,029). The maximum acceleration event occurred over a diamond-crossing in Jacksonville, Illinois while the railcar was traveling approximately 36 mph. The maximum assembly acceleration was 0.95 g. The maximum assembly strain was 20.7 microstrain.

The maximum strain event occurred when the train passed over a switch in Kendall, Kansas. The railcar was traveling approximately 45 mph. The maximum assembly acceleration was 0.66 g. The maximum strain on the assembly was 35.8 microstrain. The strain time histories for the maximum strain event and the location of this event are shown in Figure 9.

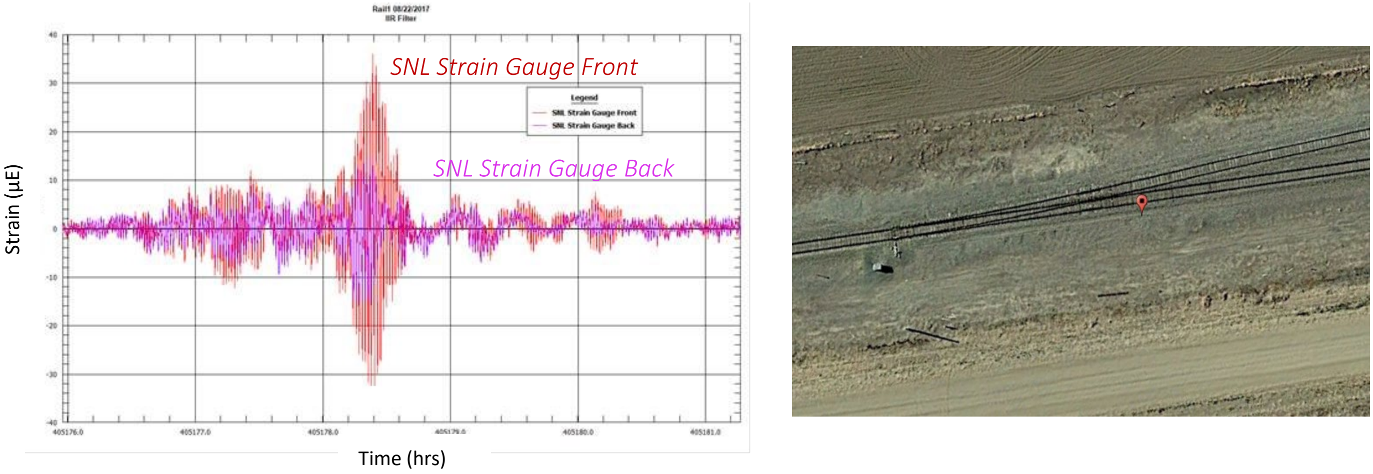

Figure 9. Rail transport maximum strain event strain time histories (left) and event location (right)

Rail Tests at TTCI

Eight series of tests were performed at the TTCI. Each series included a number of tests conducted at different speeds to capture the test specific resonant speed. The TTCI tests were short duration tests with known conditions and with design parameters somewhat beyond the ones expected on the commercial railroads (track conditions, train speeds, and coupling velocities). As a result, the strains observed on the surrogate assemblies in the TTCI tests were bounding of those observed during rail transport. The coupling impact test, particularly at high velocity (8 mph), was the most severe event observed. The maximum observed assembly strain in the coupling tests was 99 microstrain. Figure 10 shows the strain time histories for one of TTCI coupling tests conducted at a high coupling velocity.

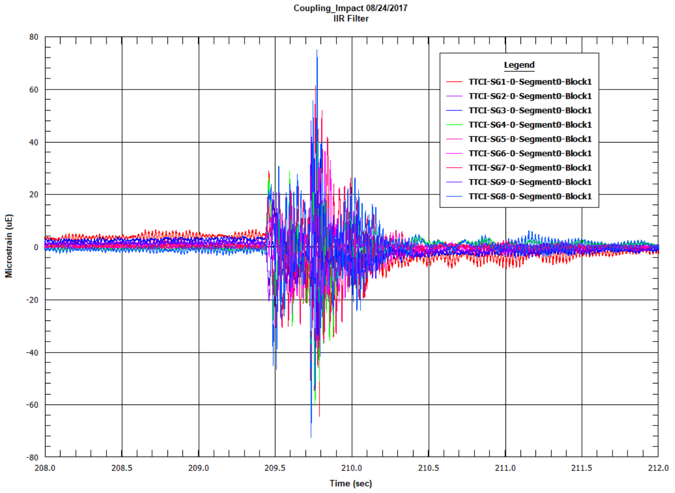

Figure 10. Strain time histories in one of the TTCI high velocity coupling tests

Thirteen coupling events were recorded during the rail transport from TTCI to Baltimore. The maximum observed assembly acceleration was 1.05 g. The maximum observed strain was 38 micro strain. This is consistent with coupling at the maximum allowed velocity of 4 mph as demonstrated by the coupling tests at TTCI.

Conclusions from the MMTT

The common transportation assumption is that the cargo (and its internal content) response to the transient inputs is the same as the response of the transportation platform. The MMTT demonstrated that the elements of the transportation system respond differently to the transient inputs. This is illustrated in Figure 11 using, as an example, the acceleration shock response spectra (SRS) from the single bump test conducted at TTCI. In the frequency domain, the amplification from the middle of the transportation platform to the other elements of the transportation system is observed within the frequency band from 4 to 55 Hz. The attenuation is observed within the frequencies above 55 Hz. The response of the cradle is similar to the response of the middle of the platform. The amplification is observed from the cask and basket to the assemblies for frequencies above 5 Hz. The assembly SRS peak around 2.5 Hz is associated with the resonance frequency of the rail car vertical suspension system. The peak around 7 Hz is associated with the resonance frequency of the rail car lateral suspension system. The highest peak is around 45 Hz and it is related to the assembly natural frequency.

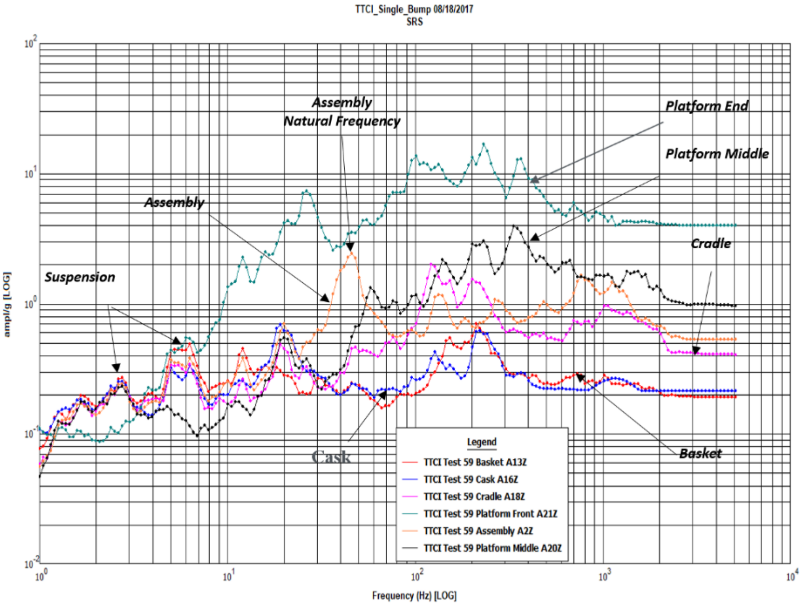

Figure 11. Transportation system acceleration SRS in one of the single bump tests at TTCI

The MMTT demonstrated that the maximum assembly strains during different modes of transport and handling operations are small – below 100 microstrain. Figure 12 compares the assembly strain SRS of the different transportation modes for the maximum strain events. Rail and heavy-haul SRS are very similar and have peaks around 45 Hz (assembly natural frequency). The ship SRS is similar in shape, but significantly lower in magnitude.

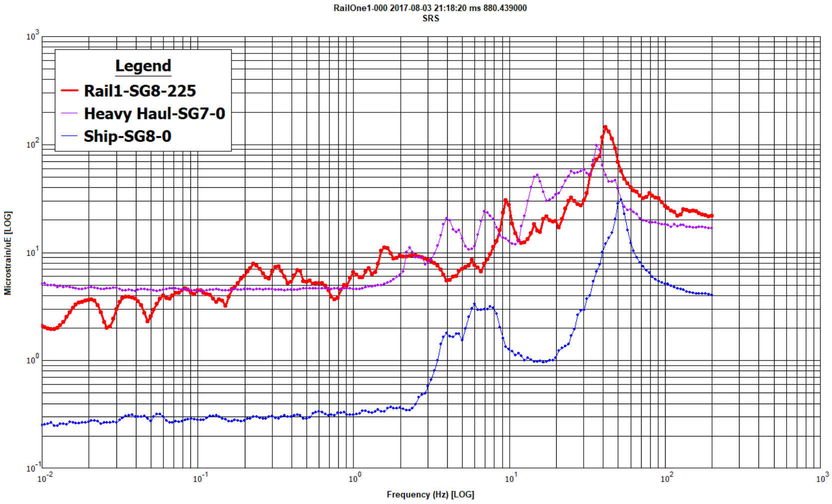

Figure 12. Assembly strain SRS for the different transportation mode for the maximum strain events

30 CM DROP TESTS (2018-2020)

The 30 cm drop was the remaining NRC NCT regulatory requirement (10 CFR 71.71) for which there were no data on the mechanical loads on the fuel rods. To make this test feasible, it was performed in 3 steps as documented in [10] and [11]. In 2018, two 30 cm drop tests were performed at the BAM test facility in Berlin using a 1/3 scale cask (a scaled mockup of an ENUN 32P cask) equipped with the impact limiters and loaded with 32 dummy assemblies (Figure 13, left). The goal of these tests was to measure the acceleration imparted to the 1/3 scale dummy assemblies. In

2019, 30 cm drop tests were performed with a full-scale dummy assembly. Felt pads were attached to the bottom of the dummy assembly to mimic the behaviour of the cask and the impact limiters. The goal of these tests was to find a felt pad configuration that accurately reproduced the maximum acceleration input to the dummy assembly as determined from a scaling of the 1/3 scale test results. In 2020, a 30 cm drop test was performed with the full-scale surrogate fuel assembly (same assembly that was used in the MMTT). The configuration of the felt pads derived in the tests with the full-scale dummy assembly was used. Figure 13 (right) shows the test setup.

Figure 13. 30 cm drop test with 1/3 scale cask (left) and surrogate fuel assembly (right).

To provide consistency between the MMTT and 30 cm drop test, the full-scale surrogate assembly was instrumented in the same way as in the MMTT. Additional strain gauges were installed to provide data required for validation of finite element modeling. In summary, 11 vertical accelerometers and 28 strain gauges were installed on 3 rods. The pressure paper sheets were installed between 15 rods in 2 long spans and 2 short spans. The covered pressure range was from 7.2 psi to 7,100 psi. A wide range had to be used because no data existed regarding the possible rod-to-rod contact pressures.

The 30 cm drop resulted in the spacer grid deformation at the bottom of the grid. Some degree of deformation was observed at all locations except the grid that was the closest to the top nozzle. The maximum grid crushing was 6.1 mm. Figure 14 displays color maps of the peak negative and peak positive strains. Both, negative and peak positive peak strains are greater on the assembly bottom end. The maximum peak strain of 1,723.45 microstrain was observed at SG10.

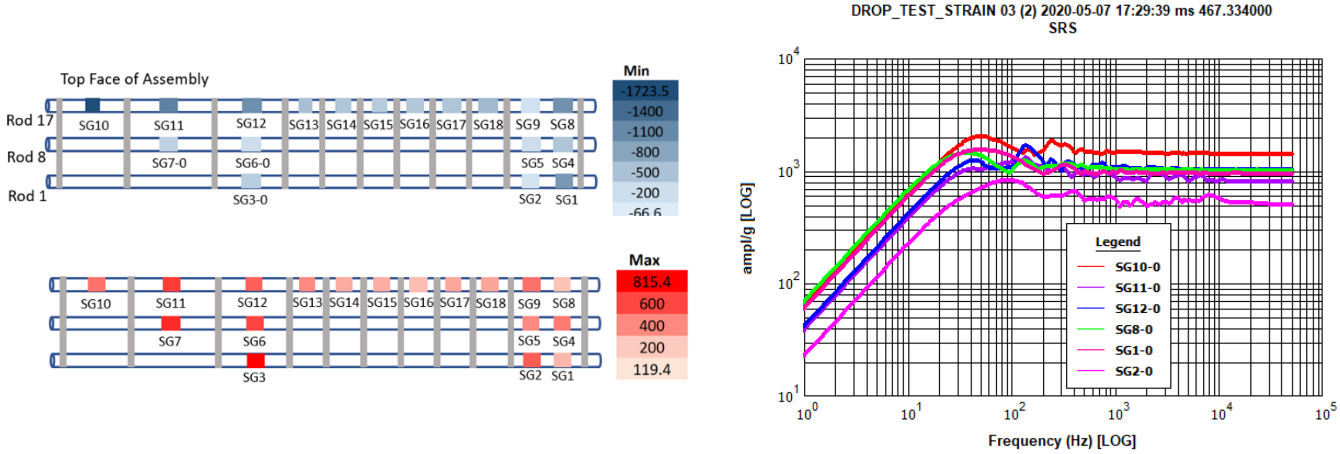

Figure 14. Peak negative and peak positive strain color map (left) and strain SRS (right).

Figure 14 (right) shows the strain SRS for the strain gauges SG1, SG2, and SG8 (assembly top end) and SG10, SG11, and SG12 (assembly bottom end). The peak strain is within the frequency domain up to 100 Hz and is associated with the assembly natural frequency (~45-50 Hz).

Pressure sensitive paper sheets inserted between the rods in two short spacer grid spans in the middle part of the surrogate assembly were blank indicating that there was no rod-to-rod contact. A number of the pressure sensitive paper sheets from two long spans between spacer grids indicated rod-to-rod contact. To obtain the contact pressure, the color of each pixel on the pressure sensitive paper was correlated to pressure. Figure 15 (left) shows a medium sensitivity paper sheet (1,400 to 7,100 psi) indicating rod-to-rod contact. The maximum calculated contact pressure was 4,100 p si. The top and bottom rods experienced much higher contact pressures than the rods in the middle. The rod-to-rod contact is also obvious from a snapshot from the high-speed camera recording shown in Figure 15 (right).

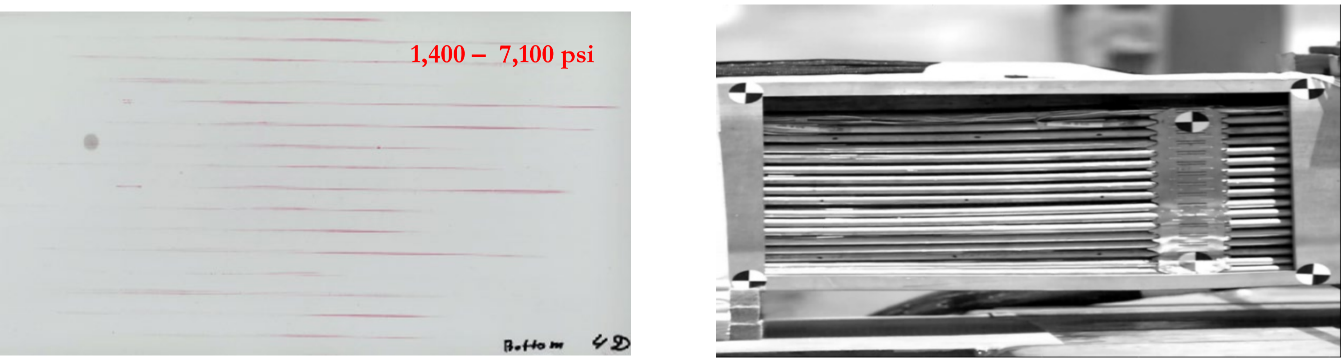

Figure 15. Medium sensitivity pressure paper (left) and snapshot from the high-speed camera (right).

The measured strains in the 30 cm drop test were from 67 to 1,723 microstrain. The stress corresponding to the maximum strain is 22.3 ksi. The maximum rod-to-rod contact pressure was 4.1 ksi. Both values are significantly below the yield strength of the cladding.

CONCLUSIONS

The maximum strains observed in the different tests are shown in Figure 16.

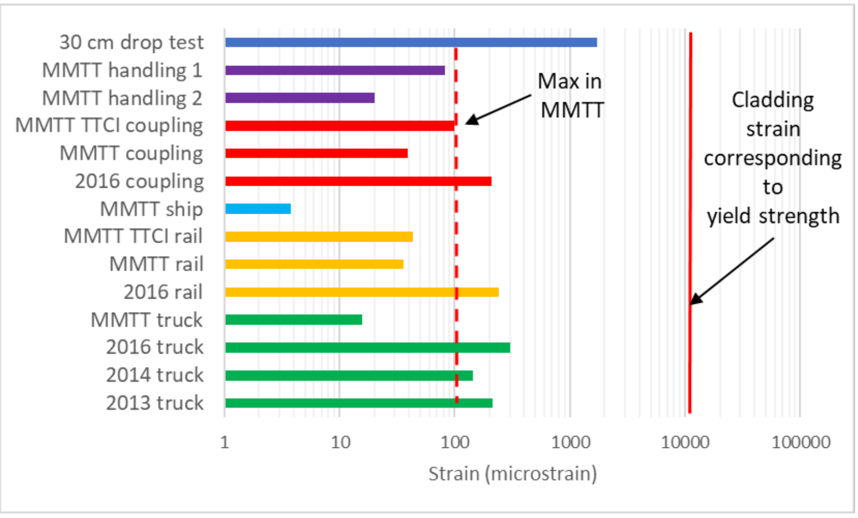

Figure 16. Maximum strain on assembly rods observed in the different tests

All strains are significantly lower than the strain corresponding to the low burnup cladding yield strength [12]. The strains observed in shake table tests and over-the-road truck test are noticeably higher than the maximum strain observed in the MMTT during the coupling at high velocity. In the MMTT tests, there was an attenuation from the transportation platform to the cask. This attenuation was not possible in the 2013-2016 test in which the surrogate assembly was placed either on the shake table representing the transportation platform or on the trailer bed. The test results provided a compelling technical basis for the safe transport of SNF under NCT. During routine transport, including coupling, the strain on the fuel rods is expected to be below 100 microstrain. The strain is expected to be below 2,000 microstrain in the case of a 30 cm drop.

ACKNOWLEDGMENTS

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