SAND2019-1995C

INTERNATIONAL MULTI-MODAL SPENT NUCLEAR FUEL TRANSPORTATION TEST: THE TRANSPORTATION TEST TRIATHLON

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Abstract

Can Spent Nuclear Fuel withstand the shocks and vibrations experienced during normal conditions of transport? This question was the motivation for the multi-modal transportation test conducted in June-October 2017. In this project the US Department of Energy (DOE) (through Sandia National Laboratories and Pacific Northwest National Laboratory) collaborated with the Equipos Nucleares SA, SME (ENSA), Empresa Nacional de Residuos Radiactivos S.A. (ENRESA), and ENUSA Industrias Avanzadas, SA SME (ENUSA) of Spain and Korea Radioactive Waste Agency (KORAD), Korea Atomic Energy Research Institute (KAERI), and Korea Electric Power Corporation Nuclear Fuel (KEPCO NF). The ENsa UNiversal (ENUN) 32P dual-purpose rail cask containing three surrogate PWR assemblies (the assemblies did not contain radioactive fuel) and 29 dummy assemblies (concrete masses) was instrumented with the accelerometers and strain gauges. The basket, cask, cradle, and transportation platform were also instrumented. The accelerations and strains were measured during the heavy-haul truck, ship, and rail transport, handling operations, and controlled rail tests at the Transportation Technology Center, Inc. (TTCI), a railroad testing and training facility in Pueblo, Colorado. During the test, 40 accelerometers, 37 strain gauges, and three Global Positioning System channels were used to collect 6 terabytes of data over the 54-day, 7-country, 12-state, and 8,500 miles of travel. While strains and accelerations have been measured on the exterior of transportation and storage containers, these measurements have never been collected on the fuel inside the container. The greatest strains and accelerations were observed during the testing at TTCI, specifically during the coupling test. Water transport strains and accelerations were the lowest and heavy haul and rail transport strains and accelerations were comparable. The handling tests were somewhat higher than the most extreme rail tests, except coupling. The observed strains were well below the yield points for spent nuclear fuel cladding.

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1. INTRODUCTION

The multi-modal spent nuclear fuel (SNF) transportation test was conducted in June-October 2017. The test was sponsored by the US Department of Energy (DOE). Two national laboratories (Sandia National Laboratories (SNL) and Pacific Northwest National Laboratory (PNNL)) participated in the design and implementation of the test. The international collaborators were Equipos Nucleares SA, SME (ENSA), Empresa Nacional de Residuos Radiactivos S.A. (ENRESA), and ENUSA Industrias Avanzadas, SA SME (ENUSA) of Spain and Korea Radioactive Waste Agency (KORAD), Korea Atomic Energy Research Institute (KAERI), and Korea Electric Power Corporation Nuclear Fuel (KEPCO NF).

Three 17x17 PWR surrogate assemblies were placed within the thirty-two cell ENsa UNiversal (ENUN) 32P dual-purpose rail cask basket along with twenty-nine dummy assemblies (concrete masses). The ENUN 32 P cask was provided by ENSA. One surrogate assembly was from SNL, one from Spain, and one from Korea. Selected rods within the PWR assemblies were instrumented with strain gauges and accelerometers. The ENSA ENUN 32P cask/cradle was placed, sequentially, on a heavy-haul truck, ships (coastal and transoceanic), and a railcar. The ENSA ENUN 32P cask, cask cradle, and transportation platforms (truck trailer, ship trailers, and railcar) were instrumented with accelerometers. During the test, 40 accelerometers, 37 strain gauges, and three Global Positioning System channels were used to collect 6 terabytes of data over the 54-day, 7-country, 12-state, and 8,500 miles of travel. The processing and analysis of the data was performed in 2018.

The test presented a unique opportunity to collect shock and vibration data for surrogate spent fuel assemblies in a full-scale transportation cask since data was collected for three different modes of transportation (heavy-haul truck, ship, and rail) and for intermodal transfer. Data was also collected during operations simulating the vertical placement of the ENSA ENUN 32P cask onto a surrogate storage pad. In addition, a series of short-duration controlled rail tests were performed at the Transportation Technology Center, Inc. (TTCI), a railroad testing and training facility in Pueblo, Colorado. The combination of different modes of transportation and handling offered an understanding of the cumulative effects of transportation and handling of SNF during normal conditions of transport.

2. TEST CONFIGURATION AND TRANSPORT ROUTES

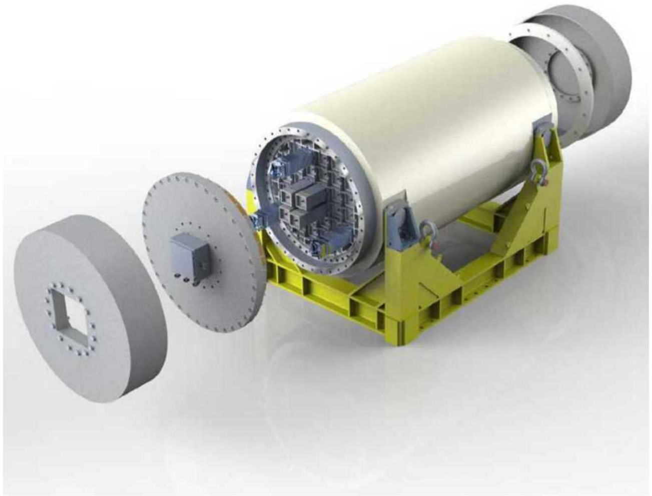
A diagram of the interior of the ENUN 32P basket, instrumentation lid, and the surrogate impact limiters is shown in Figure 1. As configured for this test, the cask measured 5 meters in length with a body diameter of 2.65 meters. The loaded weight of the carbon steel cask was 120 tons and 137 tons with the surrogate impact limiters. Used to add the necessary weight, surrogate impact limiters were needed as real impact limiters would impede access to the cask for data collection.

The instrumentation of the surrogate assemblies is shown in Figure 2. A total of 13 accelerometers and 37 strain gauges were installed on the assemblies and 6 accelerometers were installed on the basket (3 on the top and 3 on the bottom). The instrumentation of the exterior of the transportation system is shown in Figure 3. A total of 21 accelerometers were installed on the transportation platform, cask, and cradle.

The data acquisition system and instrumentation were powered by twenty LifeLine Model GPL-8DL 12-volt batteries. Twenty batteries were sufficient to power the entire system for approximately three weeks.

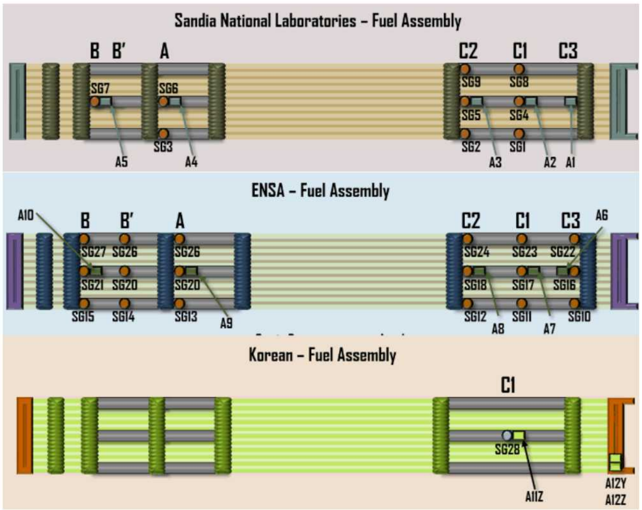
The first data collection took place during the dry storage handling simulation tests. These tests were conducted at ENSA’s facilities in Maliaño, Spain. The data were also collected while the cask was loaded into the heavy haul truck. Figure 4 shows the cask handling test.

The rail-cask was then transported by heavy-haul truck within northern Spain (the transport started and ended at ENSA’s facility), by a smaller ship (coastal transport) from Port of Santander (Spain) to Port of Zeebrugge (Belgium), by a larger ship (trans ocean transport) from Port of Zeebrugge to Port of Baltimore), and by rail (round-trip from Baltimore to the TTCI near Pueblo, Colorado). Kasgro KRL 370 12-axle heavy-duty rail flatcar was leased for rail transport. The transportation route is shown in Figure 5. A number of short duration tests were conducted at the TTCI using the same railcar that transported the cask there. A short video documenting the major test events is available on YouTube [1].



Note: Surrogate assemblies are shown in blue and dummy assemblies are shown in gray. The ENSA assembly is on the top, the SNL assembly is at the bottom right and Korean assembly is at the bottom left.

FIG. 1. Schematic of the interior of the ENUN 32P basket, instrumentation lid, and the surrogate impact limiters.



Note: A is for accelerometers and SG is for strain gauges.

FIG. 2. Location and nomenclature of instruments on the fuel assemblies.

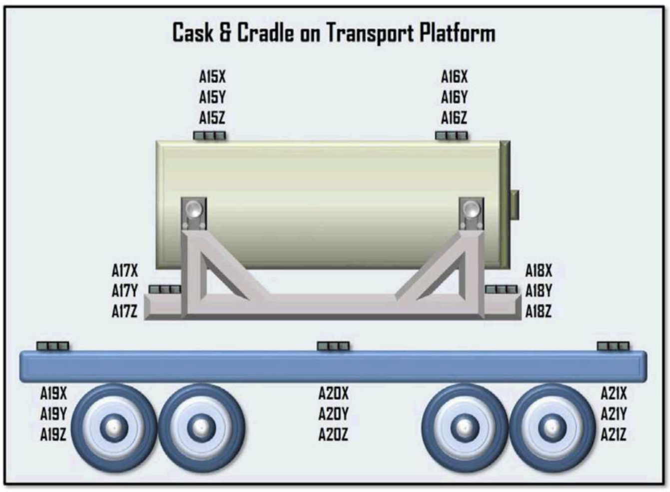


FIG. 3. Schematic of cask, cradle, and transportation platform accelerometer locations and nomenclature.

FIG. 4. Dry storage simulation test, ENSA's Facility in Maliaño, Spain.

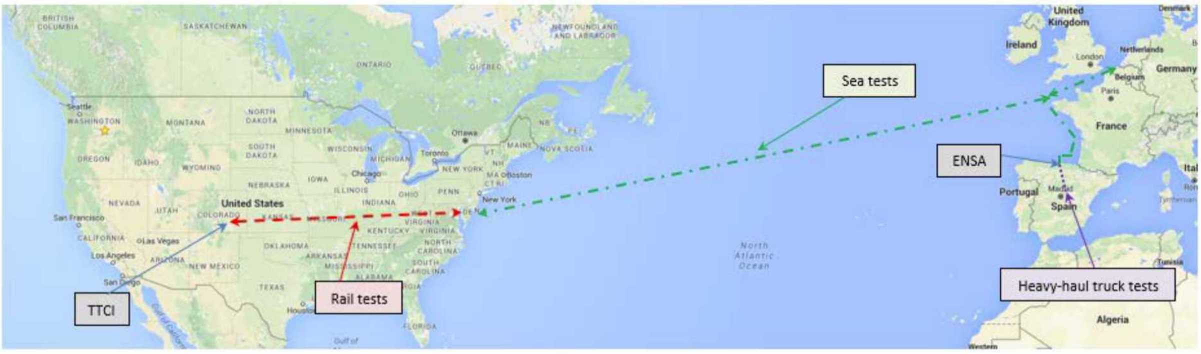


FIG. 5. Multi-modal transportation test route.

The test configuration used during the heavy-haul truck transport in Spain is shown in Figure 6. Figure 7 shows how the cask was transported in the larger ocean ship. The same configuration was used in the smaller ship during the coastal transport. Figure 8 shows the cask system on the Kasgro railcar. This configuration was used for the rail transport and in the TTCI tests.

FIG. 6. Heavy-haul truck transport in Spain.

FIG. 7. Cask lashed to the interior deck of the ocean ship "Tarago."

FIG. 8. Kasgro 12-axle railcar used for rail transport.

Table 1 provides the information on the distance and transfer time for each transport mode. The time of transfer from one transportation mode to another is not included because no data were collected. The rail transport to Pueblo was via dedicated train and the travel time was much shorter. The rail transport from Pueblo was via general freight and the data collection stopped near St. Louis (half way to Baltimore) when the data acquisition system batteries died.

Table 2 provides the description of the tests conducted at TTCI. The data frequency collection was 10,240 Hz during the TTCI tests and handling tests and 512 Hz during the other transportation.

TABLE 1. TRANSPORTATION ROUTE PARAMETERS

Transport Mode	Total Distance (mi)	Total Transfer Time (hrs)
Heavy Haul	245	29
Barge	929	120
Ocean Ship	4290	193
Rail from Baltimore (Rail1)	1950	59
Rail from Pueblo (Rail2)	1125	420
Total	8539	918

TABLE 2. RAIL TESTS PERFORMED AT THE TTCI

Test Description	Number of Tests
Twist and Roll	19
Pitch and Bounce	9
Dynamic Curve	24
Class 2 Rail Track (PCD)	17
Single Bump	8
Crossing Diamond	6
Hunting	23
Coupling Impact	10

3. SUMMARY OF THE TRANSPORTATION TEST ANALYSIS

Approximately 6 terabytes of data were collected during the multi-modal transportation test. All the data were analysed in order to envelop the responses of the different elements of the transportation systems, such as the cask, the cradle, the basket, and especially the surrogate fuel assemblies. The data were not filtered to assured that the resonance frequencies of all the elements of the transportation system would be captured. The data analysis included determining minimum and maximum accelerations/strains for each of 40 accelerometers and 37 strain gages for each TTCI and handling test and for each significant shock event during heavy-haul, ship, and rail transport. Google Earth was used to analyse the location at which the event took place. The results of the preliminary data analysis can be found in [2]. A complete analysis is documented in [3]. The following sections summarize some results of the analysis.

3.1. Cask Handling Operations

To obtain a useful representation of cask handling, a range of cask impacts were performed. Three ENSA crane operators raised and lowered the cask three times, where varying degrees of crane handling “aggressiveness” were used by each operator for their three respective tests. Figure 9 compares the maximum accelerations on the SNL assembly in dry storage handling tests and heavy-haul handling test. 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 other tests. The maximum strain observed on the SNL assembly was 40 micro strain (Drop 2, Run 5).

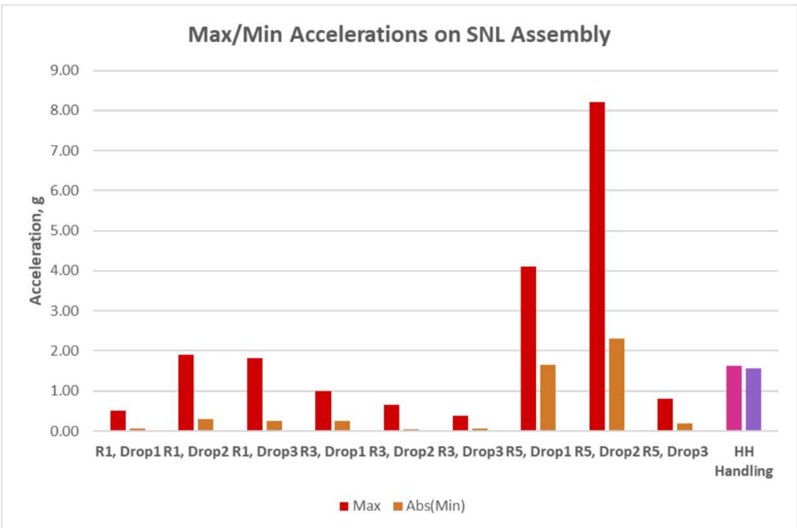


FIG. 9. Maximum accelerations on SNL assembly in Dry Storage Cask Handling Test and Heavy-Haul Cask Handling Test.

3.2. Heavy-Haul Transport

A total of 36 shock events were identified along the heavy-haul route, yielding one event per 6.8 mi. 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). 11% of the events were associated with the turns. The remaining events did not have visible cause. These events did not cause substantial acceleration on either the transportation platform or on the SNL assembly. The maximum acceleration observed during the heavy-haul transport was related to bridge abutment. The maximum vertical acceleration on the back end of the transportation platform was 4.52 g. The maximum acceleration on the back of the SNL assembly was 0.52 g. The maximum strain on the back of the SNL assembly was 15.6 micro strain. Figure 10 shows strain time history of the SNL assembly during the maximum acceleration and strain event.

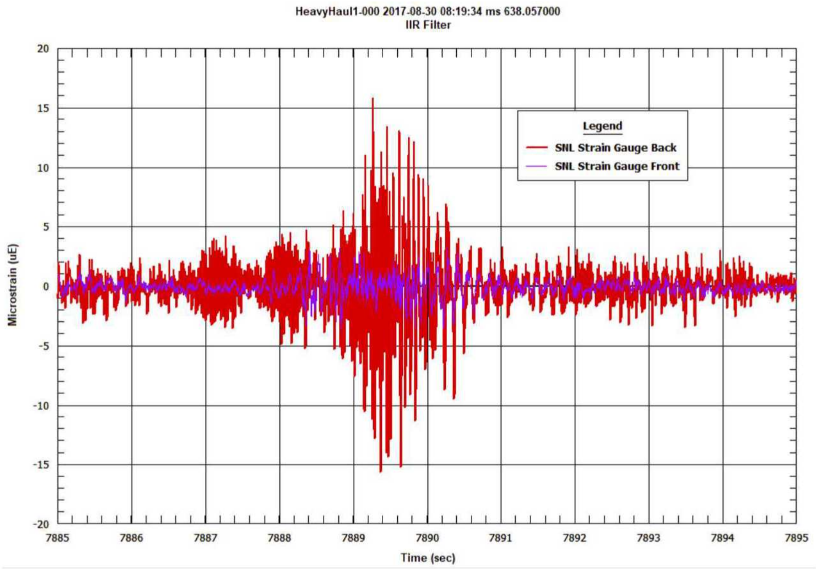


FIG. 10. Strain time history during maximum acceleration and strain event, heavy-haul transport.

3.3. Ship Transport

The accelerations and strains observed during barge and ship transport were very low. The accelerations observed were ≤0.3g (with a few exceptions) and the strains were ≤3 micro strain. The maximum acceleration on the transportation platform during ship transport was 0.38g. The maximum assembly acceleration was 0.12 g. The maximum strain on the SNL assembly was 3.15 micro strain.

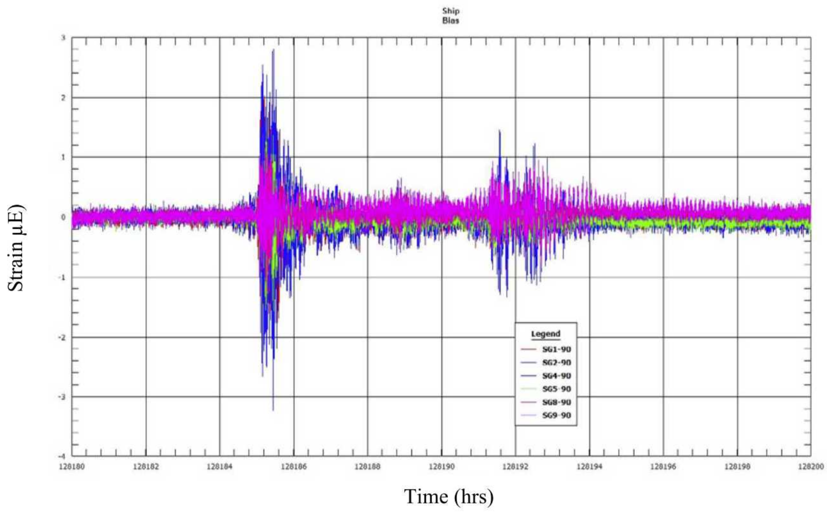


FIG. 11. Strain time history during maximum acceleration and strain event, ship transport.

3.4. Rail Transport from Baltimore to Pueblo, Colorado (Rail1)

During the dedicated train transport from Baltimore to Pueblo (Colorado) the train travelled in the speed range 25-40 mph 68% of the time, 40-50 mph 23% of the time, 10-35 mph 8.8%, and <10 mph 0.2% of the time. A total of 2,939 shock events were identified along the rail route—one shock event per 0.66 mi. The major events were track switches (629) and grade crossings (1,029).

The maximum acceleration event in Rail 1 transport occurred over a diamond-crossing in Jacksonville, Illinois. The railcar was traveling approximately 36 mph. The absolute maximum peak acceleration was 8.68 g on the transportation platform. The maximum absolute assembly acceleration of 0.95 g was on the ENSA assembly. The maximum absolute strain was 20.7 micro strain on the SNL assembly front.

The maximum strain event occurred when the train passed over a switch in Kendall, Kansas. The railcar was traveling approximately 45 mph and experienced maximum absolute strain of 35.8 micro strain on SNL assembly. The absolute maximum accelerations were 3.78 g on transportation platform front, 0.66 g on the ENSA assembly front, and 0.63 g on the SNL assembly back end. The strain time history is shown in Figure 12.

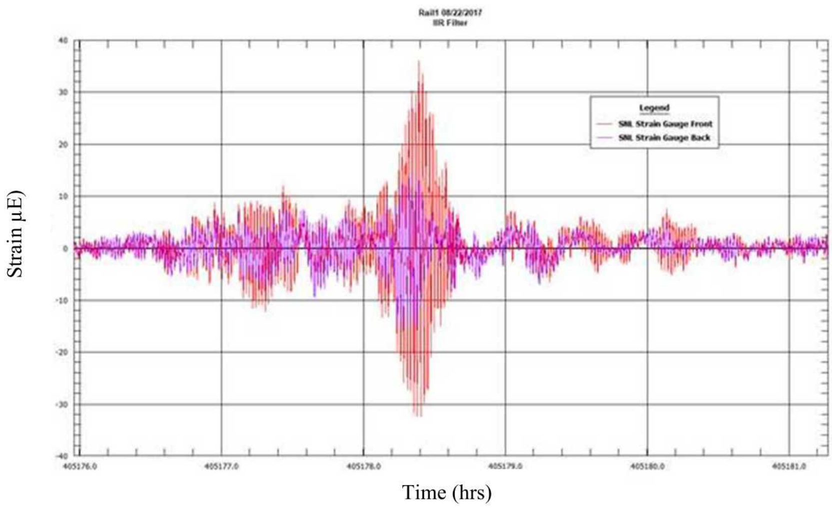


FIG. 12. Strain time history during maximum strain event, rail transport.

3.5. Rail Tests at TTCI

A series of eight 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). These tests provided valuable insight into the response of the transportation system to the different types of transient inputs. Understanding of these responses was crucial for the analysis of rail, heavy-haul, and ship data.

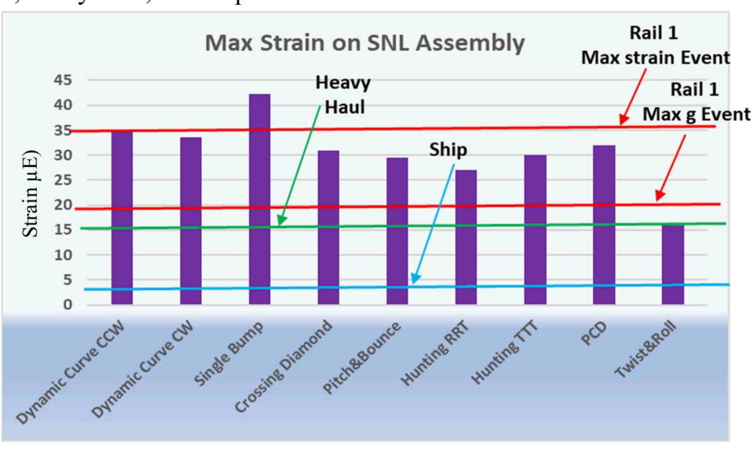


FIG. 13. Maximum strains on the SNL assembly in TTCI Tests compared to maximum strain in different modes of transport.

The TTCI tests with the highest accelerations and strains (except Coupling Impact Test) were: Single Bump Test, Pitch and Bounce Test, and Hunting on TTT Test. The Coupling Impact Test, particularly at high velocity, was the most severe event observed. Figure 13 compare maximum strains observed on the SNL assembly in the TTCI tests and different modes of transport. The tests at the TTCI bound the strains in rail, heavy-haul, and ship transport.

3.6. Rail Transport from Pueblo, Colorado, to Baltimore

The rail transport from Pueblo (Colorado) to Baltimore (Rail2) on a regular freight train provided a valuable opportunity for analysing coupling events. Thirty coupling events were identified. Twenty-three events took place in the major railyards and seven events took place in the small railyards. A few coupling operations were performed at each railyard. The maximum acceleration observed on the SNL assembly was 1.05 g. The maximum strain was 38 micro strain. The maximum strain observed during coupling at TTCI was 99.0 micro strain in the 7.5 mph coupling.

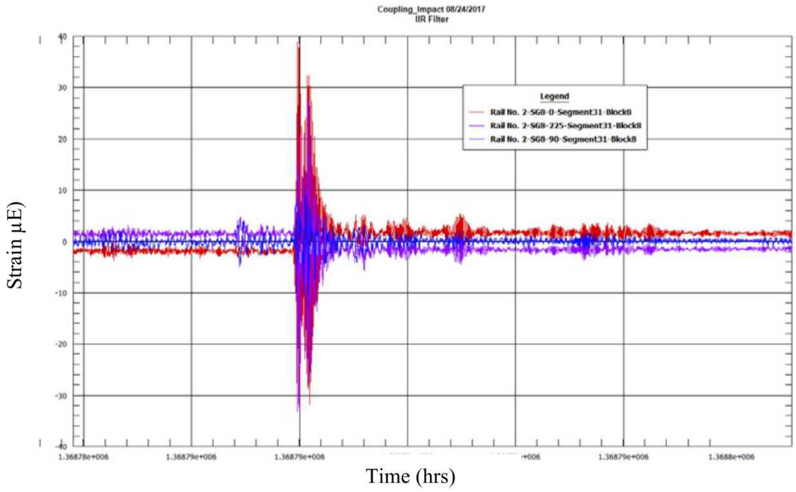


FIG. !4. Strain time histories on the SNL assembly front end, maximum amplitude coupling event during rail transport.

3.7. Fatigue Analysis

The strain data collected during the multi-modal transportation test were used to perform a fatigue analysis on the fuel cladding [4]. The ASTM Standard E1049 rainflow counting method was used to count the number of strain cycles in the data. Accumulated fatigue damage was calculated according to Miner's Rule, using an established irradiated zirconium alloy fatigue design curve [5]. Figure 15 shows the accumulated damage fractions for each strain gage for the Rail1 transport. A damage fraction of 1.0 indicates a fatigue failure, and accumulated damage in all cases is below 1E-10. This calculation method estimates that it would take 10 billion cross-country trips (2,000 miles each) to challenge the fatigue strength of irradiated fuel cladding.

Another way to evaluate fatigue is to note that the maximum strain recorded during the MMTT was less than 100 micro strain, and that strain is too small to cause any practical amount of fatigue damage to the material during a single trip. Using either analysis method, the conclusion is that cladding fatigue is not an issue during normal conditions of transport.

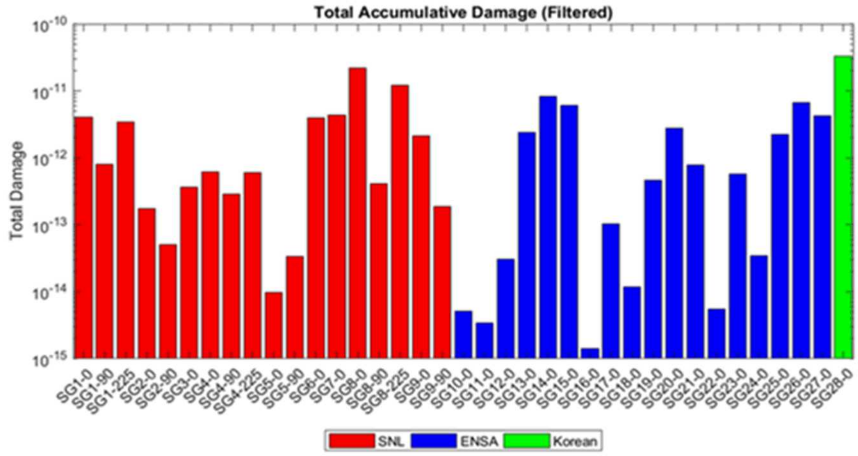


FIG. 15. Accumulated fatigue damage in Rail1 Transport (Baltimore, MD to Pueblo, CO).

4. REFERENCES

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ACKNOWLEDGEMENTS

The authors thank Ned Larson and John Orchard of DOE/LV for their support and advice for the cask transport tests. The authors would like to acknowledge the important contribution made by Paul McConnell, a principal investigator for the Cask Transport Tests Project, who has recently retired.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. SAND2017- 8240 A.