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

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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), 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 tests conducted at TTCI. The other results are presented in three related PATRAM 2019 papers.

The TTCI tests were short-duration tests with known conditions and with the design parameters (track design, speeds, and coupling impact velocities) somewhat beyond expected commercial railroad conditions. These tests provided valuable insights on the responses of the transportation system to different types of transient inputs in 125 test cases. The tests addressed the following conditions: Twist and Roll, Pitch and Bounce, Dynamic Curve, Class 2 rail track, Single Bump, Crossing Diamond, Hunting, and Coupling Impact. The TTCI tests with the highest accelerations and strains (except Coupling Impact Test) were: Single Bump, Pitch and Bounce, and Hunting. The Coupling Impact Test, particularly at high velocity, was the most severe event observed.

This work was found by the US Department of Energy, Office of Nuclear Energy.

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), 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 32P 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 tests performed at TTCI. 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].

The ENUN 32P cask was transported to TTCI from the port of Baltimore on a Kasgro 12-axle railcar. This railcar was used at TTCI for all the tests. Figure 1 shows the cask system on the Kasgro 12-axle railcar at TTCI.

Figure 1. ENUN 32P cask on Kasgro 12-axle railcar at TTCI.

The instrumentation of the exterior of the transportation system is shown in Figure 2. 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 tri-axial accelerometers recorded data in the longitudinal (X), lateral (Y), and vertical (Z) directions.

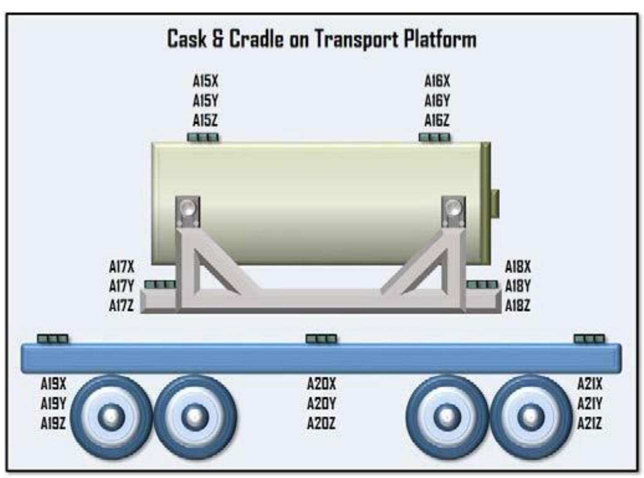


Figure 2. Railcar platform, cask, and cradle accelerometer configuration.

Instrumentation was also placed inside the cask. The basket was instrumented with the tri-axial accelerometers A13 and A14. Three surrogate 17x17 PWR assemblies (SNL, ENSA, and KEPCO) were instrumented as well. 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 end and A4 and A5 in the back end. All accelerometers on the SNL assembly were located on the middle rod and recorded only the vertical (Z) direction. Strain Gauges (SG) 1-9 were placed at either 0˚, 90˚, or 225˚ with respect to cask position. **Error! Reference source not found.**Figure 3 shows the configuration of both strain gauges and accelerometers on the SNL assembly.

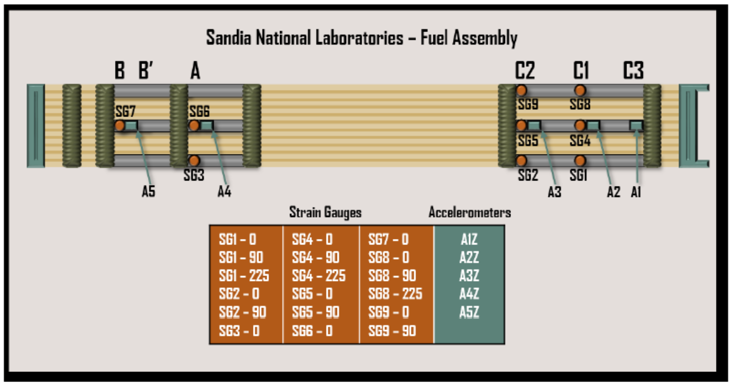


Figure 3. Location and nomenclature of instruments on the SNL assembly.

The TTCI tests were short-duration tests with known conditions and with the design parameters (track design, speeds, and coupling impact velocities) somewhat beyond expected commercial railroad conditions. TTCI data were collected at 10,240 Hz. Anti-aliasing filters applied to the data provide 5,120 Hz of analyzable data. These tests provided valuable insights on the responses of the transportation system to different types of transient inputs in 125 test cases conducted in different conditions and different speeds. Understanding of these responses was crucial for the analysis of the rail data on the route from Baltimore, Maryland to Pueblo, Colorado and back.

The TTCI has a variety of track configurations and test tracks to evaluate rail car performance under conditions encountered routinely on rail lines throughout the US (Figure 4). While the tests performed were not AAR certification tests, the TTCI used the following as guidelines in determining which tests to perform. The TTCI used AAR Specification M-976 [6], which describes track performance requirements for railcars, and AAR Standard S-2043 [7], which contains performance criteria for high-level radioactive material transport by rail.

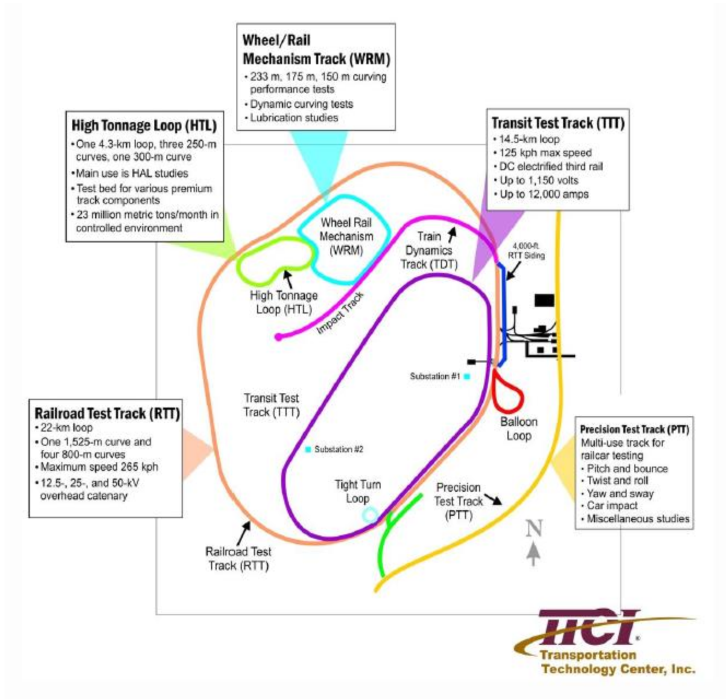


Figure 4. Graphical representation of track configuration at TTCI.

TEST SPECIFICATION

A series of eight tests were performed at TTCI: Twist and Roll, Pitch and Bounce, Dynamic Curve, Pueblo Chemical Depot (PCD), Single Bump, Crossing Diamond, Hunting, and Coupling Impact. Each series included a number of tests conducted at different speeds to capture the test specific resonant speed. The following is a description of these tests.

Twist and Roll Test

The Twist and Roll Test was designed to measure the rail car's ability to negotiate oscillatory cross level perturbations as shown in Figure 5 [8]. Historically, rail track sections of 39 feet each were connected using joint bars, producing jointed track. Over time, individual sections can deform resulting in dips, bowed rails, etc., which can also occur in a non-uniform manner across parallel tracks. Little perturbation is expected on new rail track because it is continuously welded. However, some segments of the old rail tracks can be encountered along a transportation route. The elevated perturbations in the track Twist and Roll Test Zone are designed to excite the natural twist and roll motion of the rail car that results from this rail track feature. Twist and Roll tests were conducted at the Precision Test Track (PTT) and were tested traveling forward from 10 to 26 mph in 2 mph increments, and in reverse between 8 and 14 mph.

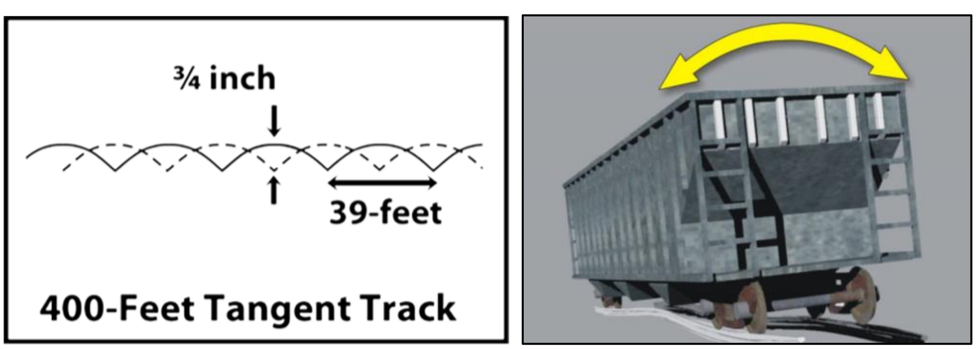


Figure 5. TTCI Twist and Roll Test track specification and railcar dynamics [8].

Pitch and Bounce Test

The Pitch and Bounce Test was designed to test the railcar's ability to negotiate parallel vertical rail perturbations as seen in Figure 6 [8]. This is caused by the historic 39-foot jointed track becoming deformed and creating uniform peaks and valleys in parallel track. This test is designed to excite the natural vertical pitch and bounce motions of the vehicle. The Pitch and Bounce Test had additional requirements. Instrumented Wheel Sets (IWS) with AAR1B wheel profiles in the lead axle position on both ends of the car were required for TTCI data collection. The test was to be performed on dry rail. Both a leading and trailing stable buffer car were required; the instrumentation car functioned as the leading buffer car and a TTX stable buffer car was attached on the trailing end. Pitch and Bounce Tests were conducted on the PTT, with speeds building from 30 to 70 mph in 5 mph increments.

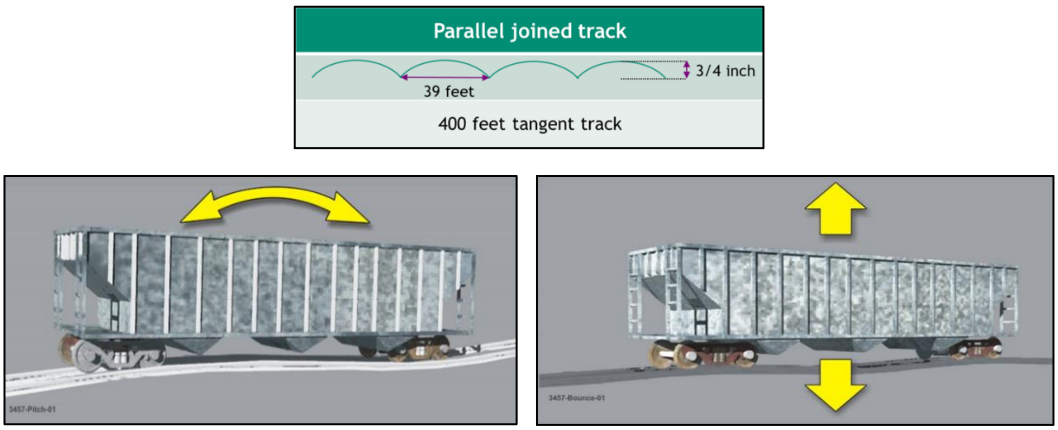


Figure 6. Pitch and Bounce Test track specifications and railcar dynamics [8].

<u>Dynamic Curve Test</u>

The Dynamic Curve Test is designed to test a rail car's ability to negotiate curving over jointed track. The curve contains jointed track that has a combination of lateral misalignment at the outer rail joints and elevation changes due to low joints on the staggered rails. This is illustrated in Figure 7 [8]. Due to asymmetry in the wheels, the Dynamic Curve Test was performed in the clockwise direction (CW) as well as the counterclockwise direction (CCW). The test requirements included IWS with AAR1B profiles in lead axle positions, measurement and documentation of rail friction greater than or equal to 0.4, and both leading/trailing stable buffer cars. The Dynamic Curve Test was performed in the 10° by-pass of the Wheel/Rail Mechanism (WRM) track at the TTCI in both CW and CCW directions from 10 mph to 32 mph in increments of 2 mph.

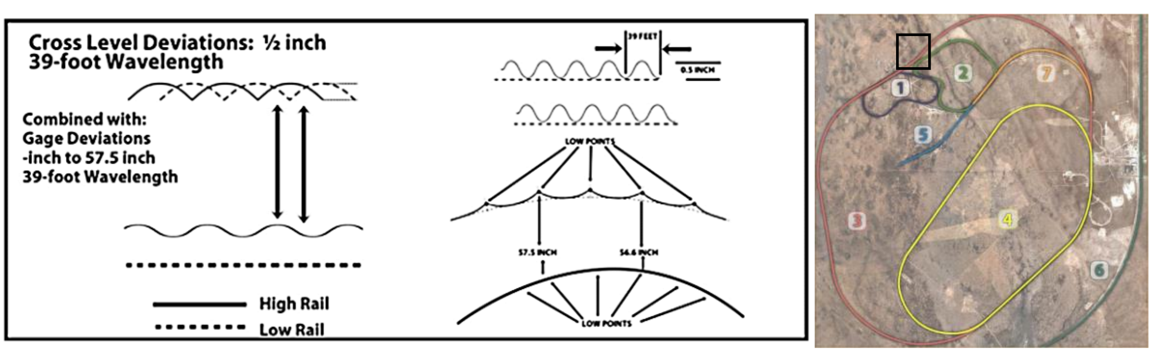


Figure 7. TTCI Dynamic Curve Test zone [8] (left) and geographic location (right).

Pueblo Chemical Depot (PCD) Test

Tests were performed at the PCD over Federal Railroad Association (FRA) Class 2 railroad track, through a No. 8 turnout, and a No. 8 crossover. These tests are part of S-2043 certification for cars hauling high-level radioactive material [7]. These tests were performed at the PCD because No. 8 turnout and crossover track configurations aren't available at the TTCI (Figure 8). The FRA classification system for track quality establishes upper limit speeds for freight and passenger cars for each track class, where the track class is determined based on the track design characteristics and associated infrastructure [9] and [10]. FRA Class 2 track is rated for freight speeds up to 25 mph. Figure 8 has the schematic layout of the PCD track.

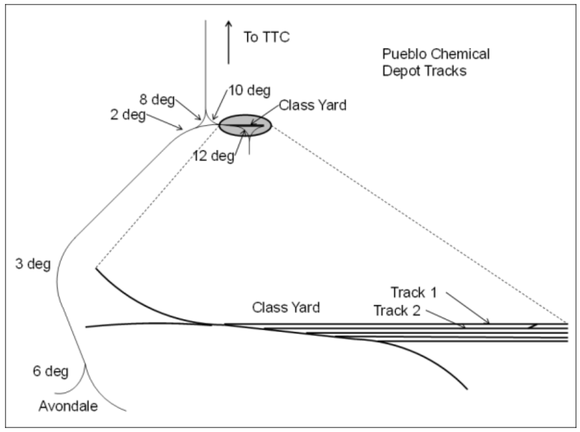


Figure 8. Schematic layout of the Pueblo Chemical Depot track.

Single Bump Test

The Single Bump Test was designed to imitate the vertical dynamic response experienced at grade crossings, which are a significant source of large vertical accelerations, shock, and vibration in freight cars. The bump itself comprises of a 1-inch bump on tangent (straight) track per the dimensions shown in Figure 9. Both sides of the track have identical bumps. This test was performed on the Transit Test Track (TTT), a 9.1-mile oval track with a third rail power system for vehicle performance and specification compliance testing. Vehicle performance testing can be conducted at speeds up to 80 mph over track segments with different construction, e.g., jointed rail vs. continuous welded rail, wood vs. concrete ties. The Single Bump Test was conducted from 40 mph to 75 mph in 5 mph increments.

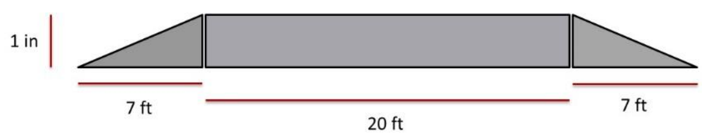


Figure 9. Single Bump Test bump specifications.

Crossing Diamond Test

The Crossing Diamond Test was intended to subject the vehicle to vertical impacts resulting from the wheels traversing gaps in the rails where tracks intersect. This is a common occurrence during rail travel. The crossing diamond was simulated at the TTCI by cutting gaps in the rails matching the dimensions of those that would be present on an actual crossing diamond. The tests took place on the Train Dynamics Track (TDT) and ranged from 10 mph to 40 mph in 5 mph increments, excluding testing at 15 mph due to avoiding resonant velocity.

High Speed Stability Test (Hunting)

The intent of Hunting Tests performed at the TTCI was to determine the vehicle's lateral stability at higher speeds. Hunting is the phenomena usually caused by worn wheel sets in which the rail car begins to experience lateral oscillatory motion, which when coupled with high speeds can lead to derailment. For tests performed at TTCI it was hoped that the installation of worn profile (KR) wheel sets would induce hunting behavior in the cask car, but none occurred. The tests were performed first on the Railroad Test Track (RTT) then again on the Transit Test Track (TTT). Hunting Tests were performed from 30 mph to 50 mph in 10 mph increments, as well as from 55 mph to 75 mph in 5 mph increments.

Coupling Impact Test

The purpose of the Coupling Impact Test is to provide longitudinal inputs from rail car coupling at standard as well as at greater than standard speeds. These inputs are similar to the responses experienced by the rail car and test cask caused by longitudinal train action. The speed range in the test design was intended to be from 2 to 8 mph in 2 mph increments, with impacts on both the A (front) and B (back) ends of the cask. However, during testing the markers for the impacts were not in the correct locations, resulting in test speed being different than planned speeds. Tests were performed on the Performance Test Track (PTT) with the B-end leading first, with actual speeds of 2.1, 4.1, 3.9, 5.7, 6.8, and 8.0 mph. The consist was turned around and tests performed on the A-end had actual speeds of 3.7, 4.6, 5.8, and 7.5 mph.

TTCI TEST RESULTS

System behavior across all tests excluding Coupling Tests exhibited similar characteristics. A representative acceleration shock response spectra (SRS) of the TTCI tests is shown in Figure 10 using the Single Bump (Test 59) as an example. Attenuation from the transportation platform end to the cradle, cask, and assembly is observed in all frequencies except for those below 4 Hz. Attenuation from the transportation platform middle to the cradle, cask, and assembly is observed for frequencies above 50 Hz. The SRS peak around 2.5 Hz is associated with the resonant frequency of the rail car vertical suspension system. The peak around 7 Hz is associated with the resonant frequency of the rail car lateral suspension system. There is a distinct peak around 45 Hz in the assembly acceleration related to the SNL assembly resonant frequency.

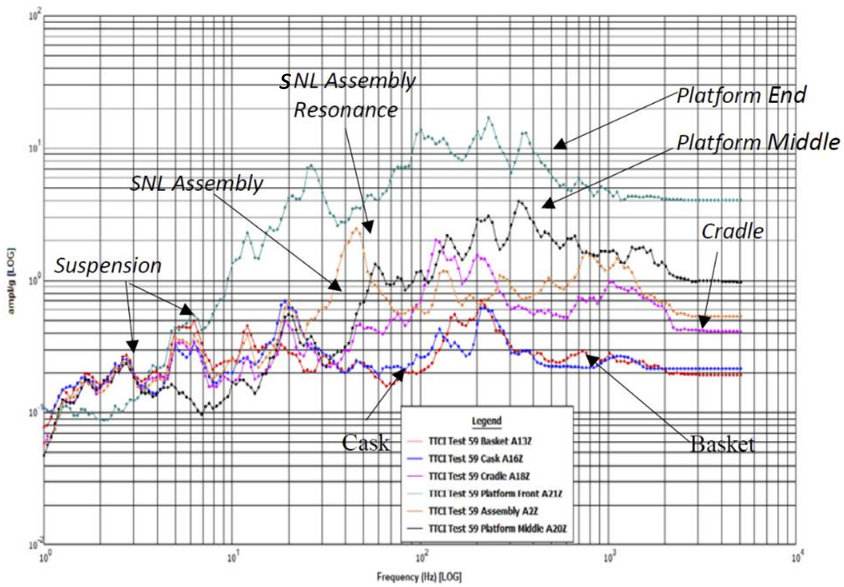


Figure 10. Representative transportation system SRS in the TTCI tests, except the Coupling Impact Test.

Figure 11 shows a strain Fast Fourier Transform (FFT) in the same Single Bump Test for the strain gauge SG4-0, located on the SNL assembly front. The assembly strain peaks coincide with the assembly acceleration peaks in Figure 10. The largest strain peaks are at 2.5 Hz (vertical suspension natural frequency) and 45 Hz (assembly natural frequency).

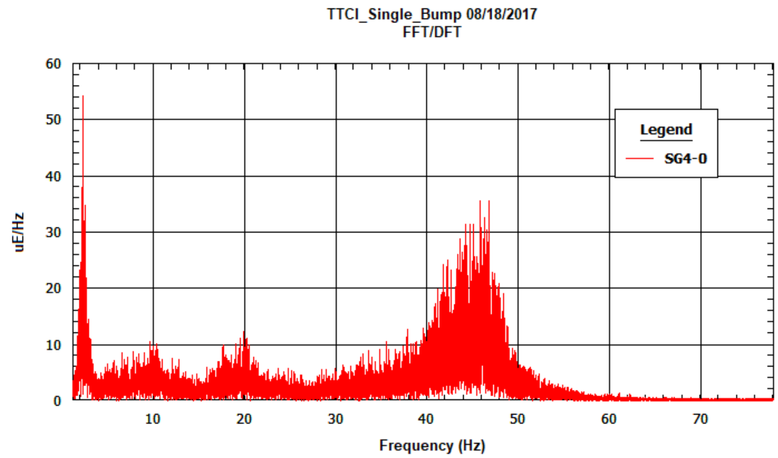


Figure 11. SNL assembly strain FFT in Single Bump test.

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 (Figure 12 and Figure 13). The Single Bump and Pitch and Bounce tests represent the vertical inputs associated with grade crossings. The Coupling Impact Test, particularly at high velocity, was the most severe event observed. The maximum measured strain was -99.0 μE in the coupling at 7.5 mph test.

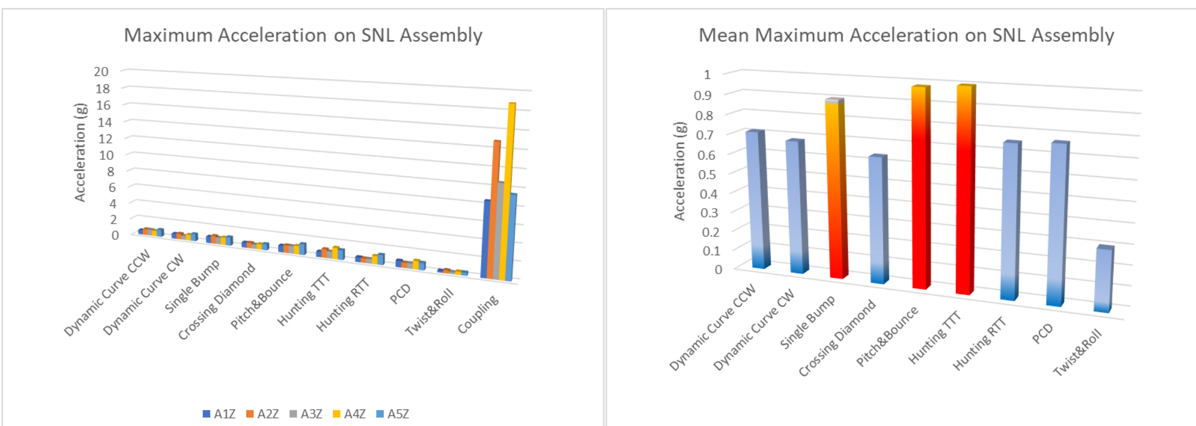


Figure 12. Maximum accelerations on SNL assembly in TTCI tests (left) and mean maximum acceleration in TTCI tests excluding Coupling Impact.

The maximum strains versus maximum accelerations on the SNL assembly front (accelerometer A2Z) in the TTCI tests (except coupling) is shown in Figure 14. The trend line for the acceleration versus the vertical strain (SG4-0) has a steeper angle than the trend line for the acceleration versus the lateral strain (SG4-90). This is a consistent trend across most cases, where the highest acceleration is in the vertical direction. The observed accelerations were up to 1 g and the observed strains were up to 30 μE.

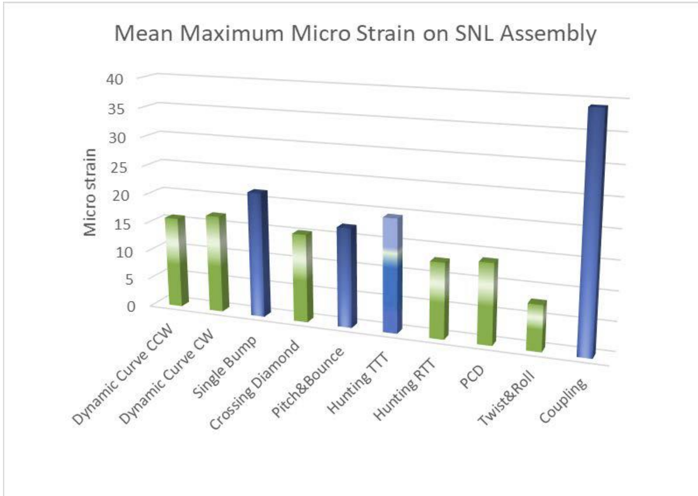


Figure 13. Mean maximum strains on the SNL assembly in TTCI tests.

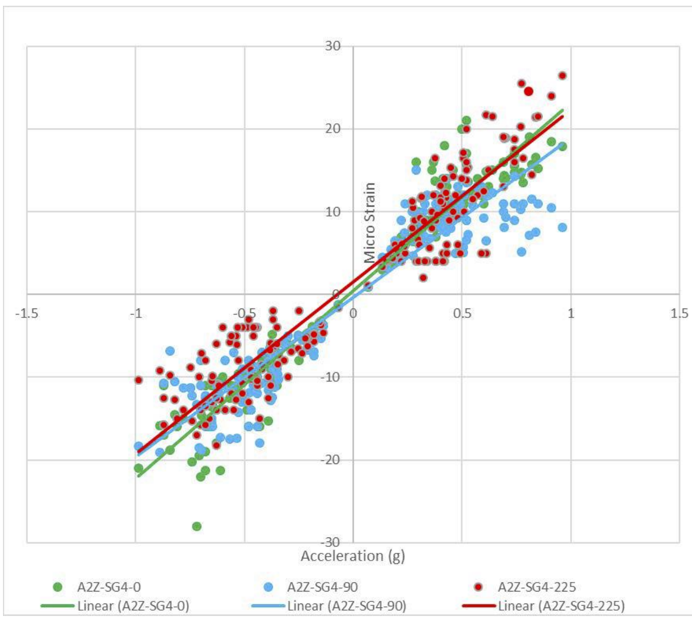


Figure 14. Maximum accelerations-strains on the SNL assembly front in the TTCI tests, except Coupling Impact.

The TTCI tests were compared to the rail transport [1] as well as to the other modes of transport ([2] and [3]). As demonstrated in Figure 15, the TTCI tests bound the strains and accelerations observed in rail, heavy-haul, and ship transport. The maximum strains and accelerations on the SNL assembly during rail transport are slightly higher than during the heavy-haul transport. The maximum strains and accelerations on the SNL assembly during ship transport are significantly lower than during the rail and heavy-haul transport.

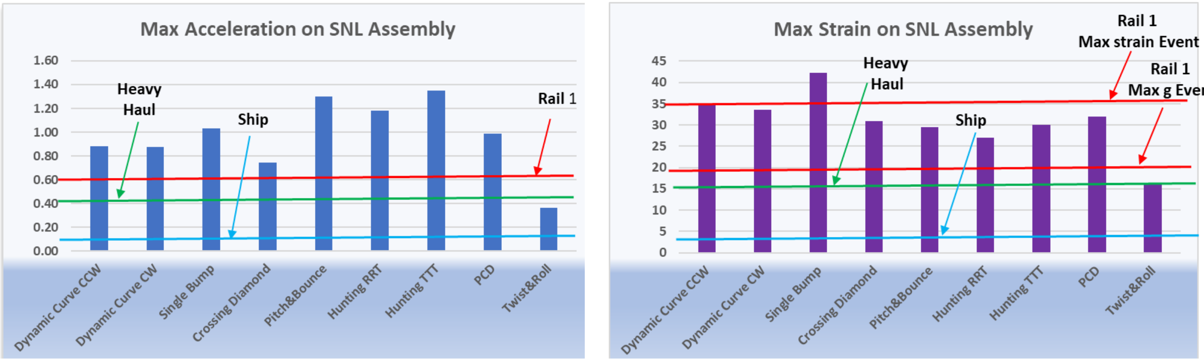


Figure 15. Maximum accelerations (left) and strains (right) observed on the SNL assembly in TTCI tests compared to different modes of transportation.

The rail coupling at TTCI was also bounding. Figure 16 shows the accelerations on the SNL assembly in the TTCI coupling tests (left vertical axis) and maximum impact force (right vertical axis) as a function of coupling speed. The accelerations and impact force increase rapidly at speeds greater than 6 mph. The purple line in this figure shows the maximum acceleration on the SNL assembly observed in 30 coupling events during rail transport. The accelerations are similar to the ones at TTCI completed at speeds below 6 mph. Accelerations are significantly lower than the ones at TTCI completed at speeds greater than 6 mph.

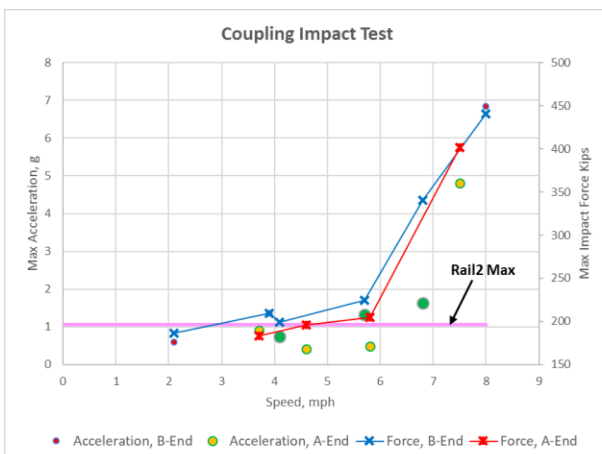
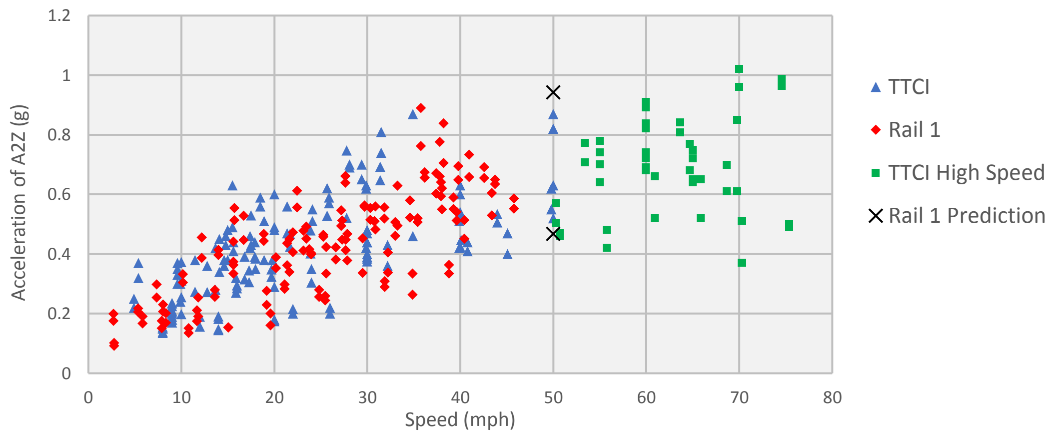


Figure 16. Maximum acceleration and impact force during TTCI Coupling Impact Test.

A number of tests at TTCI were done at train speeds exceeding 50 mph, which is the maximum allowable speed for a train carrying SNF [11]. The accelerations on the SNL assemblies in these tests are shown in green in Note: Rail 1 refers to the 1,950 mi dedicated train rail route from the Port of Baltimore to the TTCI.

Figure *17*. The accelerations for tests at or below 50 mph are shown in blue. They are in good agreement (similar trend) with the accelerations during rail transport [1] shown in red. This confirms that the acceleration responses of the SNL assembly to shock events during rail transport are consistent with tests at TTCI. Generally, higher speeds result in higher accelerations. However even at speeds above 50 mph the accelerations on the SNL assembly were below 1.05 g.



Note: Rail 1 refers to the 1,950 mi dedicated train rail route from the Port of Baltimore to the TTCI.

Figure 17. Accelerations versus speed on the SNL assembly in TTCI tests and rail transport.

SUMMARY

A series of eight tests were performed at TTCI. Each series included a number of tests conducted at different speeds to capture the test specific resonant speed. A total of 125 tests were completed. The TTCI tests were short-duration tests with known conditions and with the design parameters (track design, speeds, and coupling impact velocities) somewhat beyond expected commercial railroad conditions. These tests provided valuable insights on the responses of the transportation system to the different types of transient inputs.

The TTCI tests with the highest accelerations and strains (except Coupling Impact Test) on the SNL assembly were: Single Bump Test, Pitch and Bounce Test, and Hunting on TTT Test. The Single Bump and Pitch and Bounce tests represent the vertical inputs associated with grade crossings. The maximum observed strain in these tests was 43 µE. The Coupling Impact Test, particularly at high velocity, was the most severe event observed. The maximum measured strain was -99.0 µE in the coupling at 7.5 mph test.

It is commonly assumed that the cargo and the railcar platform respond similarly to the transient inputs during transport. The TTCI tests demonstrated that the responses of the different elements of the transportation platform 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 on the assemblies occur at the assembly natural frequency of 40-45 Hz.

The TTCI tests were compared to the rail transport as well as to the other modes of transport. The TTCI tests bound the strains and accelerations observed in rail, heavy-haul, and ship transport. The rail coupling at TTCI was also bounding compared to coupling during the rail transport.

A number of tests at TTCI were done at the train speeds exceeding 50 mph. However even at these speeds the accelerations on the SNL assembly were below 1.05 g. The accelerations at or below 50 mph are in good agreement with the accelerations during rail transport (the maximum speed during rail transport was 52 mph).

The test results provided a compelling technical basis for bounding the transportation system responses to the shock environment during rail transport, including coupling. The maximum strain observed during the tests results in stress that is far below yield limits for cladding [12].

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