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ENSA/DOE Transport Shock and Vibration Test Plan

Steven Ross[1,8], Ralph Best[2], Philip Jensen[1], Nicholas Klymyshyn[1], Paul McConnell[3], William Uncapher[3], Sylvia Saltzstein[3], Ken Sorenson[3], Brady Hanson[1], William Shust[4], David Garrido[5], Jeff England[6],Russ Walker[7], Stan Gurule[7], Ruben Pena[7]
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[1]Pacific Northwest National Laboratory, Richland, WA, United States of America
[2]Pacific Northwest National Laboratory - Subcontractor, Richland, WA, United States of America
[3]Sandia National Laboratories (SNL), Albuquerque, NM
[4]Objective Engineers Inc., Naperville, IL
[5]Equipos Nucleares S.A. (ENSA), 39600 Maliaño, Cantabria (Spain)
[6]Savannah River Nuclear Solutions (SRNS), Aiken, SC
[7]Transportation Technology Center Inc.,(TTCI), Pueblo, CO
[8](509)372-4513; Steven.Ross@PNNL.gov

Abstract

The objective of the shock and vibration testing program is to quantify mechanical loads on fuel assembly components that would occur during normal conditions of transportation (NCT) of various modes. This information will guide materials research and establish a technical basis for review organizations such as the U.S. Nuclear Regulatory Commission (NRC). A significant body of experimental and numerical modeling data exists to quantify loads and failure limits applicable to NCT rail transport, but the data are either out-of-date relative to present day railroad operations and equipment, or are based on assumptions that can only be verified through experimental testing. The summary presented herein represents a collaboration among many stakeholders to define the path for acquiring new data that is needed to validate the assumptions of previous work, validate modelling methods that will be needed to evaluate the mechanical responses of irradiated fuel that will be transported in the future in large rail casks, and inform material test campaigns on the anticipated range of stresses that will be imposed on nuclear fuel cladding. This work will include full scale testing of a Used Nuclear Fuel Cask, Cradle, Rail Car, and Surrogate Fuel Assemblies and will encompass intermodal transloading, heavy-haul truck transport, barge transport, ocean going vessel transport, and rail transport as well as captive track tests. The ultimate goal of this testing will be to close some of the existing knowledge gaps related to the mechanical loads that would be imposed on used fuel under NCT conditions transportation and inform the experiments and analysis. This work is sponsored by U.S. Department of Energy Office of Nuclear Energy, Used Fuel Disposition Campaign (UFDC). The mission of the UFDC is to identify alternatives and conduct scientific research and technology development to enable storage, transportation, and disposal of used nuclear fuel (UNF) and wastes generated by existing and future nuclear fuel cycles. The Storage and Transportation staff members within the UFDC are responsible for addressing issues regarding the extended or long-term storage of UNF and its subsequent transportation.

Introduction

This report discusses the transport cask normal conditions of transportation shock and vibration testing planned for FY 2017 using the Equipos Nucleares S.A. (ENSA) ENUN-32P cask.

These tests present a unique opportunity to collect shock and vibration data for surrogate used nuclear fuel assemblies in a full-scale transportation cask. The data will be collected for four different modes of transportation (heavy-haul truck, barge, ship, and rail) and for intermodal transfer. The combination of these modes of transportation and handling will contribute to an understanding of the cumulative effects of future transportation and handling of high burnup used nuclear fuel and allow the collection of data necessary for closing the Stress Profiles technical data gap as identified in Hanson et al. (2012).

Gap closure with respect to stresses in the fuel assembly cladding associated with cask movement and normal conditions of transport will be accomplished by measuring and quantifying the mechanical loads (e.g., strains and accelerations) on various components, but especially on the surrogate fuel assembly. In addition, data to evaluate the transmissibility of loads from one component to another (e.g., wheels to bed to cradle to trunions to cask to basket to fuel assembly to fuel rods) will be obtained. This information will guide materials research and establish a technical basis for review organizations such as the U.S. Nuclear Regulatory Commission. While limited experimental and numerical modeling data of loads and failure limits applicable to normal conditions of rail transport exist, the data are either outdated relative to present-day railroad operations and equipment, or are based on assumptions that can only be verified through experimental testing.

Structural performance models using the material properties of the cask and surrogate assembly components used in this testing program will be validated by comparing their results against the stress profile data. Material properties and mechanical response of actual used fuel will be obtained separately from testing of sister rods (Hanson et al. 2016) as part of the Electric Power Research Institute/U.S. Department of Energy (DOE) High Burnup Spent Fuel Data Project. These properties can then be substituted into the structural performance models, together with design changes for different cask/canister systems, and subjected to the stress profile loads obtained from this testing program provide confidence in predictions of the performance of used nuclear fuel when it is transported.

Data from shock and vibration tests will be important to the worldwide nuclear power industry, regulators such as the NRC, and to the DOE. These tests will provide information to regulators regarding shock and vibration loads during normal conditions of transportation including movements associated with dry storage operations. The results will help ensure that used fuel can be handled safely—considering aging of used nuclear fuel placed in dry storage and the ability to safely transport large amounts of used nuclear fuel to an off-site destination. The data will also assist the UFDC in confirming and validating models needed to provide confidence in assurances of the robustness of used nuclear fuel properties for extended storage periods and for potentially multiple transport and handling activities.

The data from these transport shock and vibration tests can be used to support predictive modeling and simulation of high or low burnup used fuel performance under conditions of normal transportation. The simulation results will then be supported by observations of the condition of high-burnup used nuclear fuel at the end of the High Burnup Spent Fuel Data Project, when the Research Project Cask is opened, the fuel recovered, and the aged (and transported) fuel rods are characterized. All of these data can be used by industry in support of their extended dry storage licensing strategies and to support certification of transportation casks for shipping high-burnup and long-cooled used nuclear fuel.

Surrogate Assemblies

Because it is not possible to instrument and use actual UNF assemblies in this test, surrogate pressurized water reactor (PWR) fuel assemblies will be used to measure the response of spent nuclear fuel (as simulated) to normal multimodal transport and handling shock and vibration when transported in a state-of-the-art large transportation cask.

Two surrogate PWR fuel assemblies will be used in the tests to provide shock and vibration response data representative of responses that would be expected for used nuclear fuel being transported by road, sea, and rail in large transportation casks. The surrogate assembly built by Sandia National Laboratories (SNL) using a typical Westinghouse PWR 17x17 fuel assembly skeleton as used in previous shaker table (McConnell 2015) and truck (DOE 2014) tests will be used. The surrogate fuel assembly has 253 copper tubes filled with lead rope. The copper tubes are not instrumented, but there are three Zircaloy tubes that are instrumented. The core of the Zircaloy tubes in the SNL assembly will be varied, with different fuel representations used in different rods to evaluate the effect of the fuel representation on cladding response. One tube contains lead rope, the second has lead pellets, and the third has molybdenum pellets. The use of epoxy along the full length of a rod containing one of the pellet types to simulate fuel-to-cladding bonding is being considered. Also, the grid springs in one Zircaloy rod location being doubly relaxed, to have one rod that represents a bounding grid relaxation case is being evaluated. A second assembly to be provided by ENSA will have the same dimensions as the SNL surrogate; however, all rods in this second assembly will be ZIRLO® cladding and contain lead pellets.

The instrumented fuel assemblies will provide key technical information about the loading environment the fuel can be expected to experience during normal conditions of transport. No similar data are known to exist. The test conditions will attempt to simulate the loads transmitted to the fuel assemblies as authentically as is possible, and numerical modeling will be used to account for any departure from realistic UNF transportation configurations or realistic UNF structural dynamic behavior.

ENSA ENUN 32P Cask and Impact Limiters

The ENSA ENUN 32P transport cask will be used for the testing campaign. The transport cask has a two-lid closure system. Each lid for the cask is bolted to the cask body and includes metallic seals inside the bolt circle at its periphery. The two lids have a combined weight of about 27,500 lb. When used for transporting UNF, impact limiters must be included and together add approximately 25,000 lb. to overall weight. These two components of the cask's total mass will need to be considered in the dynamic interactions of the cask, cradle, and railcar (and thus the total system) during rail test operations.

However, impact limiters are very costly and have not yet been fabricated. Because the dynamic effects of the impact limiters can be simulated using bolt-on mass surrogates, impact limiters will not be used in these tests. Instead, when preparing the cask at its facility in Maliaño (Cantabria), Spain, ENSA will represent the mass of the impact limiters with alternative means including additional mass in the instrumentation lid, additional mass associated with the instrumentation enclosure, and/or additional bolted-on mass that will reasonably simulate the mass of the ENSA ENUN 32P cask's impact limiters. Staff at Pacific Northwest National Laboratory (PNNL) will collaborate with ENSA to ensure the mass of the impact limiters is represented in the system mass and that it reasonably represents the mass and dynamic effects of the combined mass of the ENSA ENUN 32P cask's impact limiters and inner and outer lids. This evaluation will also consider the mass of the data acquisition system and associated batteries and equipment. ENSA will design and construct the test lid and install it on the cask.

Test Lid

The test lid ENSA will install on the ENSA ENUN 32P cask at its facility will replace the inner and outer lids (Figure 1) of the cask and will provide additional mass to simulate the mass of the cask's top impact limiter.

The design of the test lid will be developed by ENSA and will provide channels (or a separate protective basket top-plate) on the bottom side and through-openings for instrument leads. The bottom-side channels and through-openings will be sufficient to accommodate leads from instrument sensors installed on components in the cask's interior including surrogate fuel assemblies, one or more dummy fuel assemblies, and one or more locations on the cask's basket.

The number of instrument leads that will need to be routed under the bottom of the test head and through the test head and locations in the cask's interior where the leads will originate will be specified by SNL and PNNL. Attachments of instrument sensors to internal components of the ENSA ENUN 32P cask will be determined by agreement between ENSA and the SNL instrumentation technicians who will be at the ENSA facility to facilitate placing instrumentation and other test components on the cask.

Figure 1. Artist Illustration of ENSA ENUN 32P Cask (Courtesy of ENSA)

Simulation Modeling of ENSA ENUN 32P Cask Test Unit on Railcar to Determine Instrumentation Requirements

Numerical modeling of the package, cradle, railcar, and other transportation systems will be performed prior to testing, during testing, and after testing is completed. Pre-test analyses and simulations will be performed as needed to answer technical questions that arise while preparing the test plan. Analyses during the test campaign will be performed to evaluate the test data as they are collected to determine if changes to the test program need to be made while it is in progress. Modeling and analysis will be performed after the test campaign is completed to assess the data that were collected. The loads that are recorded in the as-tested configuration will be projected onto used fuel in realistic transportation configurations and alternate configurations, as necessary, to close the stress profiles knowledge gap.

A number of pre-test analyses are documented in Finite Element & Modeling in Support of S&V Test Plan (Klymyshyn 2016), which makes recommendations where to place the fuel basket accelerometers and where to place the two instrumented fuel assemblies within the fuel basket. Klymyshyn also discusses options for placing the data acquisition system batteries on the railcar to minimize their effect on the railcar system. The report provides an initial analysis of the cask and cradle system frequency domain dynamic behavior, including a modal analysis and a frequency response analysis. These data are needed to help build the full rail conveyance system models during the test campaign and after.

The next set of models that need to be developed are the full as-tested configuration of the rail test system. The railcar to be used for testing in the United States has not been selected. When the railcar is selected, a NUCARS™ (TTCI 2015) model will be developed and coupling between the NUCARS model and models of the package and cradle system will be finalized. The coupling is currently expected to be accomplished by extracting railcar centerbowl forces from the NUCARS model and applying them to an LS-DYNA (Livermore Software Technologies 2013) model of the cradle and package system, to ultimately determine the loads transmitted to the fuel basket. The load transmission model will be validated against test data, so it will provide a credible translation of loads through the complex railcar system. The models will account for the data acquisition system, batteries, and any other equipment that will be present on the railcar during testing.

A significant amount of test data will be collected to understand the load transmission through the railcar (and other transportation mode) systems. Accelerometers on the cask and cradle, and in the basket and on fuel assemblies provide multiple layers of data collection coverage. All of these sensors will be used in all modes of transport. Additional sensors are mounted on the railcar, and instrumented wheelsets are expected to be used for captive track tests conducted at the TTCI facility. This assures that all levels of the railcar system model will have adequate validation data for the as-tested railcar system models. Similarly, sensors on the heavy-haul truck may be used to provide additional validation data for this mode of transport. All other modes (barge and ship) of transport will have model validation data limited to the cradle and package, but those are adequate for the purposes of this test campaign.

Figure 2 illustrates potential accelerometer and other sensor locations that may be used for the ENSA ENUN 32P cask and the associated railcar. Note that not all identified locations will be used in the testing.

Another important item that requires a model to be created is the surrogate fuel assemblies. The fuel assembly model will be created in LS-DYNA using similar methods and assumptions as the SNL surrogate assembly that has been used in recent years to support shaker table and truck transportation shock and vibration testing. Full fuel assembly models are computationally expensive, so they are used sparingly in the analytical process. Simulating 10 seconds of behavior can take roughly one week of real time on typical computer systems. The full fuel assembly models will be used primarily after testing is completed, but they may also be used during testing to help understand the results as they are collected.

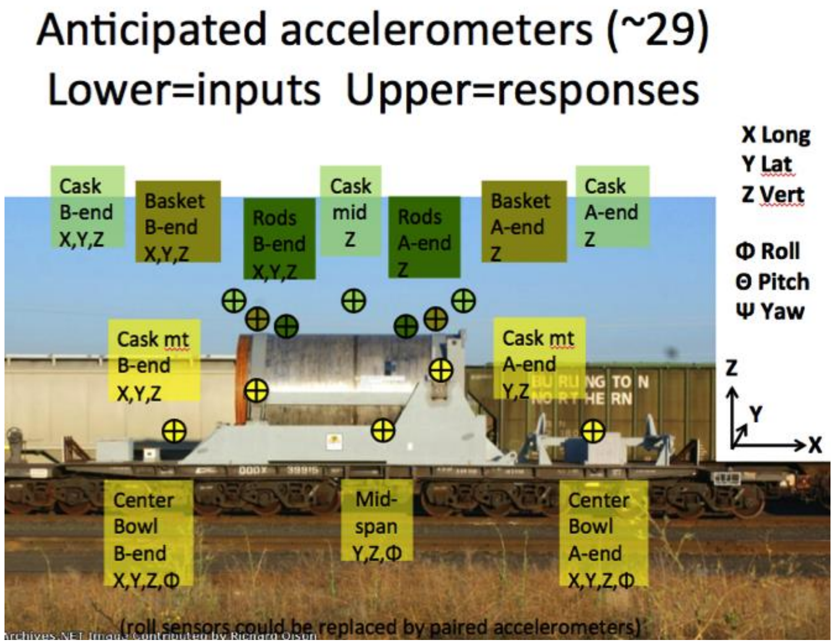

Figure 2. Example of Instrument Sensor Placements for Rail Shock and Vibration Testing

When it comes to the heavy-haul truck transportation segment, the barge transportation segment, and the deep water transportation segment, the modeling will be focused on the loading recorded at the cradle upward, and will not attempt to model the phenomena below the cradle unless the need to do so becomes apparent during testing. As discussed above, there are sufficient sensor data attached to the cradle and cask to provide validation of the models and characterize the shock and vibration loading environment. These modes of transportation are considered to be representative of the typical transportation loading environment, so the loads witnessed by the cradle and package unit during testing are considered representative of typical transportation loading conditions for real used nuclear fuel.

The railcar transportation segments are also considered to provide representative loads to the cradle and package unit, even though a standard heavy-duty rail car will be used. In the United States, shipments of UNF will be accomplished using railcars that conform to AAR S-2043 (AAR 2008), a design that is meant to prevent derailing of the railcars. An AAR S-2043 compliant railcar may also provide a gentler ride quality than a typical modern flat deck railcar, but the difference will be studied through modeling after the test campaign is completed. Table 1 summarizes the various numerical models that will be conducted for the project.

PNNL technical staff will need access to all technical information (design, construction, and materials) of the ENSA ENUN 32P cask: its basket, cradle, surrogate impact limiters, the SNL and ENSA surrogate fuel assemblies, and the railcar that will be used. Table 2 lists the information needed to develop the numerical models for the simulations discussed in this section.

Table 1. Simulation Analyses for the Rail Shock and Vibration Test Project

Simulation	**Purpose & Scope**
LS-DYNA Simulation of ENSA ENUN 32P Cask Basket	Provide insight into basket dynamics to inform the decision to place accelerometers and instrumented surrogate assemblies within basket.
LS-DYNA Fuel Assembly Response Analyses	Calculate cladding strains for as-tested or real used nuclear fuel. These will typically include just a single fuel basket compartment and one detailed fuel assembly.
LS-DYNA Full Package Response Analyses	Full model of the package to be used as-necessary to simulate the dynamic behaviour of the fully loaded system with detailed fuel assemblies and as-tested dummy fuel assemblies.
NUCARS Railcar Analyses	Validate the as-tested railcar configuration and predict the response of real used fuel transportation conditions
NUCARS/LS-DYNA Load Transmission Model	Provide a linkage between NUCARS railcar simulation and LS-DYNA fuel assembly simulation. Any loads calculated in NUCARS for a railcar can be translated through the railcar system to the fuel assembly using this model.
ANSYS Frequency Domain Analyses of Cradle and Package	Provide insight into load transmissibility from any general cradle excitation.

Table 2. Information Needed for Simulation Modeling

ENSA ENUN 32P Cask Test Unit Component	**Information Needed**
Surrogate Fuel Assemblies	Surrogate fuel assembly design information
Dummy Fuel Assembly	ENSA engineering drawings including bills of materials (BoM) (a).
ENSA ENUN 32P Cask • cask body (including trunnions) • bottom-end surrogate impact limiter • test head w/top-end surrogate impact limiter • cask basket	ENSA engineering drawings listed in the cask's safety analysis report including callouts for BoMs ENSA engineering drawing for test head including a BoM. ENSA engineering drawings for surrogate bottom and top impact limiters including a BoM.
ENSA ENUN 32P Cask Cradle	ENSA engineering drawing including BoM
Data Acquisition and Control System & Battery Power Supply Enclosure	ENSA engineering drawing including BoM
Heavy-Duty Railcar	Railroad industry manufacturing drawing including BoM

(a) A BoM is a multi-level document that provides build data for components and includes items such as mechanical characteristics, attached reference files, part specifications, computer-aided design files and schematics.

Assemble and Test ENSA ENUN 32P Cask Test Unit with Installed Data Acquisition, Control System and SAV-EM System at ENSA

After placing surrogate and dummy fuel assemblies into the ENSA ENUN 32P cask, installing the test lid and surrogate upper impact limiter, moving the assembled ENSA ENUN 32P cask onto the transport cradle, and installing the surrogate lower impact limiter and external instrument sensors, SNL and ENSA staff members will attach the power supply and Data Acquisition system (DAC) storage housing (to be designed by ENSA and SNL) to the transport cradle. The power supply and DAC storage housing configuration is still being discussed. It may attach to the transport cradle's cask top end or be distributed across the cask cradle to better distribute the load. For perspective, the outer lid of another ENSA cask design (ENSA-DPT) is on the visible end of the cask shown on a transport cradle in Figure 3. This figure is only for information and is not representative of the ENSA ENUN 32P design.

Figure 3. ENSA-DPT Dual Purpose Cask on Transport Cradle

The power supply and DAC storage housing will be fabricated by SNL, shipped to ENSA with the instrumented surrogate assemblies, and will be attached to the ENSA ENUN 32P cask's transport cradle at ENSA's facility in Maliaño (Cantabria), Spain.

The power supply and DAC housing will support, secure, and contain about 20 heavy-duty industrial batteries. Dimensions of the batteries are 53 cm by 28 cm by 25 cm and their weight is 70 kg each. In addition, the housing/enclosure will contain (and provide protection from weather) the DAC, the instrument panel on the cask's top-end, the SAV-EM unit including the SAV-EM global positioning system (GPS), and instrument leads.

The power supply and DAC housing must be very durable because the ENSA ENUN 32P cask will be loaded and transloaded onto and from and moved by heavy-haul trucks, ocean-going vessels, and railcars during transport tests. The structure of the housing and its attachments to the ENSA ENUN 32P cask's cradle will be capable of supporting and securing the housing's contents while sustaining forces imposed by *AAR Open Top Loading Rules Standards* (AAR 2010) for transport on U.S. railroads.

After the housing is securely attached to the ENSA ENUN 32P cask's transport cradle, ENSA, SNL, and Savannah River National Laboratory technical staff will install the battery power system, DAC, battery charger, and the SAV-EM System, and conduct a full-system functional test. The SAV-EM design includes an SAV-EM satellite receiver which can receive geolocation information anywhere on earth. It allows the receiver to pick up signals deep inside buildings[1]. The installation of all components is estimated to require 2-5 days, because each major installation step will be subject to independent test and verification that the installation(s) or connection(s) are correct, secure, and functional.

ENSA/DOE Transport Cask Transportation Nodes

The ENSA/DOE transport cask testing will include collecting data during the transloading operations as well as during the heavy-haul truck, barge, ship, and rail transportation as well as a variety of tests to be conducted at the Transportation Technology Center Inc. (TTCI) facilities in Pueblo, Colorado. Testing at TTCI is necessary for "captive track" events where the speed and track conditions are well defined, controlled, and known. Figure 4 provides a map of the suggested routing. Specific routes and destinations are still being evaluated.

Major activities associated with the ENSA/DOE transport cask testing will include:

- Simulated transloading activities at the ENSA facility
- Round-trip heavy-haul route in Spain with return to ENSA facilities or the Port of Santander, Spain (TBD location)
- Barge shipment to a European shipping port if access is provided (currently Belgium)
- Ocean going vessel to the Port of Baltimore, Maryland, USA (TBV).
- Rail Transport to TTCI facilities in Pueblo, Colorado
- Return trip (rail) to the Port of Baltimore, Maryland
- Return trip (ocean going vessel and barge) to ENSA.

[1] The SAV-EM System is an autonomous satellite communication system that will operate independent of the ENSA ENUN 32P cask test unit's power supply and DAC. However, the DAC, when in operation, will transmit, via wire, a DAC clock synchronization signal to the SAV-EM System.

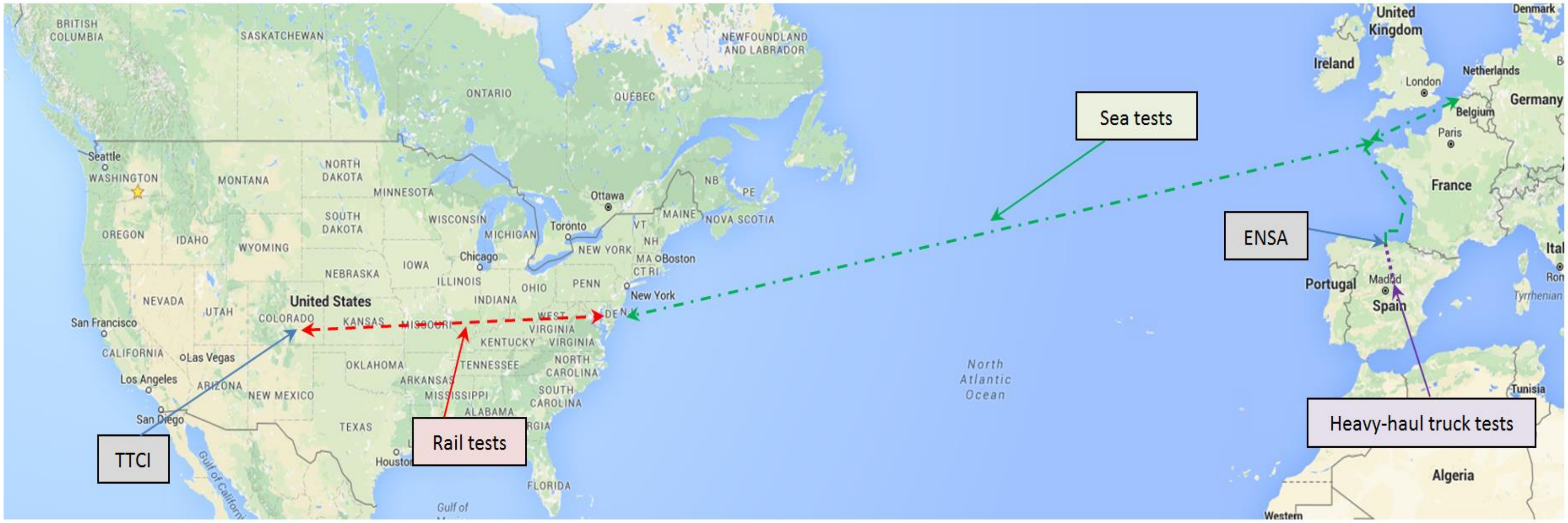

Figure 4. The Route of the ENSA Cask Test Unit from Spain to Colorado

Conclusions

The ENSA/DOE transport cask tests are expected to be completed near the end of FY17. The data of greatest interest will be the dynamic responses (accelerations and deflections) of individual fuel rods within the fuel assemblies and the resulting stresses and strains that occur in the fuel-rod cladding. Also of high importance is data on the transmissibility of loads from one component to another.

Post-testing numerical modeling will be used to determine how well the cladding strains recorded during this test campaign relate to strains that are predicted to occur to real UNF under realistic UNF conditions. Numerical models will be validated in the as-tested configuration by comparing directly with the data obtained in this program. Material and mechanical properties from separate testing on UNF will then be substituted for the properties of the surrogate assemblies to account for the as-expected UNF properties and to predict with confidence UNF cladding loads and strains under NCT conditions. If the loading environment the surrogate used nuclear fuel is exposed to in the test proves to be as benign as is expected, the cladding strains recorded during testing are expected to be low suggesting the same would be the case for future shipments of UNF from commercial reactor sites.

The biggest data need in this test campaign is establishing the realistic loading environment for a fuel assembly level under NCT conditions. This test campaign will collect sufficient accelerometer data at various locations on and internal to the transport vehicle, the cradle and package system to validate the numerical models and provide the confidence that the loading conditions the fuel assembly is subjected to during NCT rail are quantified and understood.

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