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Full-Scale Accident Testing in Support of Spent Nuclear Fuel Transportation

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FULL-SCALE TRANSPORT ACCIDENT TESTING IN SUPPORT OF A SPENT NUCLEAR FUEL TRANSPORTATION CAMPAIGN

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Abstract

The safe transport of spent nuclear fuel and high-level radioactive waste is an important aspect of the waste management system of the United States. The Nuclear Regulatory Commission (NRC) currently certifies spent nuclear fuel rail cask designs based primarily on numerical modeling of hypothetical accident conditions augmented with some small scale testing. However, NRC initiated a Package Performance Study (PPS) in 2001 to examine the response of full-scale rail casks in extreme transportation accidents. The objectives of PPS were to demonstrate the safety of transportation casks and to provide high-fidelity data for validating the modeling. Although work on the PPS eventually stopped, the Blue Ribbon Commission on America's Nuclear Future recommended in 2012 that the test plans be re-examined. This recommendation was in recognition of substantial public feedback calling for a full-scale severe accident test of a rail cask to verify evaluations by NRC, which find that risk from the transport of spent fuel in certified casks is extremely low. This report, which serves as the re-assessment, provides a summary of the history of the PPS planning, identifies the objectives and technical issues that drove the scope of the PPS, and presents a possible path for moving forward in planning to conduct a full-scale cask test. Because full-scale testing is expensive, the value of such testing on public perceptions and public acceptance is important. Consequently, the path forward starts with a public perception component followed by two additional components: accident simulation and first responder training. The proposed path forward presents a series of study options with several points where the package performance study could be redirected if warranted.

EXECUTIVE SUMMARY

This report provides a summary of the history of the Performance Package Study (PPS), identifies the objectives and technical issues that drove the scope of the PPS, and presents a possible path for moving forward in planning to conduct a full-scale cask test. The PPS was a research initiative by the US Nuclear Regulatory Commission (NRC) to confirm, with public participation, the robustness of shipping casks for spent nuclear fuel (SNF) under extreme full-scale, accident conditions. The PPS resulted in two reports. The first report identified areas of public uncertainty, based on four public meetings, and recommended objectives of testing. Substantial public feedback called for a full-scale, severe accident test of a rail cask to verify evaluations by the NRC, which find that the risk from transporting SNF is extremely low. In the second report, the NRC suggested extra-regulatory tests to address this concern (i.e., tests that went beyond test conditions required by the regulations).

In the end, work on the PPS ceased because of the high cost and because the proposed Yucca Mountain repository project had been halted. Yet, a public perception exists that a large transportation campaign of SNF may eventually result in an accident that releases radioactivity. Such accidental releases of radioactivity are likely to remain an expressed public concern especially in light of the recent release of minute amounts of radionuclides at the Waste Isolation Pilot Plant (WIPP) in southern New Mexico. Furthermore, the Blue Ribbon Commission on America's Nuclear Future recommended in 2012 that DOE re-examine the PPS and suggestions of the National Academy of Sciences related to testing of transportation casks because of the need to develop a consolidated interim storage facility in the near future. This report is part of the re-examination requested.

Based on the history of the PPS planning and the issues that drove the scope of the PPS, this report presents a possible path for moving forward in planning to conduct a full-scale cask test. Because full-scale testing is expensive, the value of such testing on public perceptions and public acceptance is important. Consequently, the path forward starts with a public perception component followed by two additional components: accident simulation and first responder training. The three components would continue through several phases only if warranted. That is, the proposed path forward presents a series of study phases with several points where the PPS could be redirected if warranted by public desires or if the PPS becomes untenable because of cost or schedule constraints.

The first phase of the public perception component would determine the type of information and level of participation that the public desires in order for them to evaluate the safety of SNF transportation (Figure ES-1). The first phase would be a pilot where one region of the country would be selected. Of particular interest in this pilot phase would be the perceived value and public acceptance of modeling, testing, and first responder training on demonstrating the safety of rail transportation casks. Design of the other two components of the path forward (accident simulation and first responder training) would be influenced by this public perception component.

The second phase of this public perception component would be to measure public desires in other parts of the country. The final phase would implement the public perception study at communities that are along likely transportation routes or communities that are contemplating hosting a consolidated interim storage facility or repository after a consent-based siting process had been authorized by Congress (Figure ES-1).

The accident simulation component of the path forward consists of two elements: modeling and testing. Modeling would be conducted first followed by testing and additional modeling (Figure ES-1). The purpose of the modeling element is to demonstrate the general consensus that exists within the modeling community related to cask performance. This component of the package performance study might end at this point and the simulations used to demonstrate confidence in cask performance. If the PPS continued, the modeling element would help design the rail cask tests and provide pre-test predictions and post-test analysis.

The purpose of the testing element is to plan and implement the full-scale test of a rail car transportation cask in a simulated credible accident. The three general options for the full-scale testing include regulatory testing, extra-regulatory testing, or a realistic accident demonstration test. The public perception component would provide guidance as to major objectives of the testing element.

The third component of the path forward for the PPS involves the development and implementation of realistic first responder training. This component would be part of efforts already being conducted under Section 180(c) added by the Nuclear Waste Policy Amendments Act. This third component is important because well designed and publicized first responder training exercises in multiple communities along the transportation routes to the WIPP were a valuable process for the public to understand and eventually accept shipments of radioactive transuranic waste.

The first phase of the third component would be to conduct a workshop on proposed exercise training (Figure ES-1). The second phase would the development of training materials. The third phase would consist of a pilot training exercise prior to fully implementing first responder training. To enhance public visibility and participation, the final phase would implement first responder training near those communities along likely transportation routes for SNF and those communities considering hosting a consolidated interim storage facility or a repository after a consent-based siting process had been authorized by Congress.

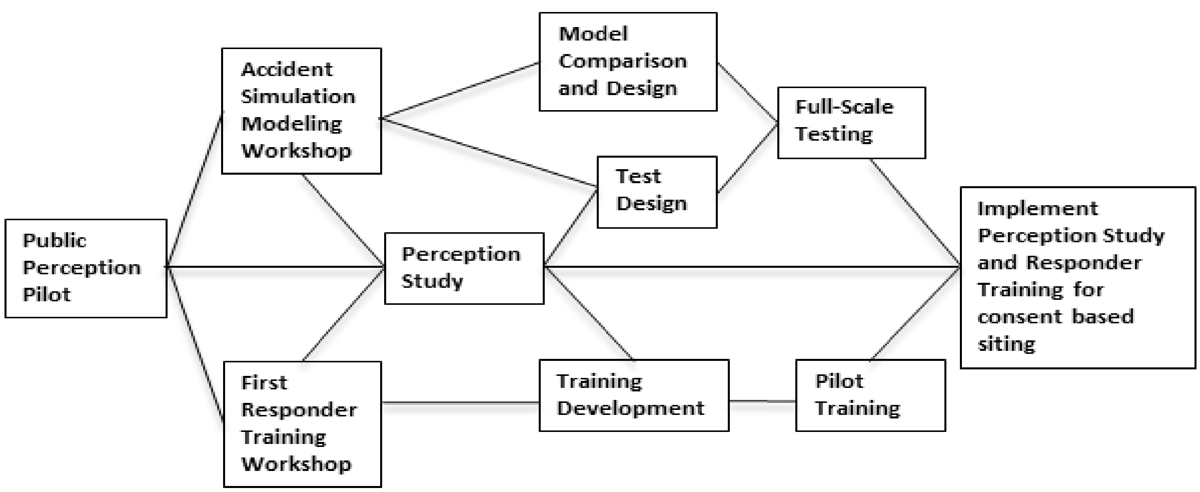

Figure ES-1. Three components of path forward for Package Performance Study: Public Perception Study, Accident Simulation, and First Responder Training

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NOMENCLATURE

AAR	American Association of Railroads
BAM	Bundesanstalt für Materialforschung und –prüfung (Federal Institute for Materials Research and Testing in Germany)
BRC	Blue Ribbon Commission on America's Nuclear Future
BWR	Boiling Water Reactor
CEGB	Central Electricity Generating Board
CFR	Code of Federal Regulations
CG	Center of Gravity
DOE	US Department of Energy
FDS	Fire Dynamics Simulator
GPS	Global Positioning System
GWd/MTHM	Gigawatt Days per Metric Ton of Heavy Metal (primarily uranium)
HAC	Hypothetical Accident Conditions
ISF	Interim Storage Facility
NAS	National Academy of Sciences
NIST	National Institute of Standards and Technology
NRC	US Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act of 1982
NWPAA	Nuclear Waste Policy Amendments Act of 1987
OCRWM	Office of Civilian Radioactive Waste Management of DOE
PPS	Package Performance Study
PWR	Pressurized Water Reactor
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
TTCI	Transportation Technology Center, Inc.

1 INTRODUCTION

The safe transport of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) is an integral component of the nuclear fuel cycle policy of the United States. Current fuel rail cask designs are certified based on numerical modeling of hypothetical accident conditions and some scale model testing. To some stakeholders, scale-model testing and modeling does not appear to be a sufficient demonstration of the ability of a cask design to withstand severe accident conditions.

The Package Performance Study (PPS) was initiated by the US Nuclear Regulatory Commission (NRC) in 2001 to examine the response of full-scale rail casks to extreme transportation accidents in realistic test conditions. The objectives of these tests were to demonstrate the inherent safety of spent nuclear fuel transport packages and to provide high-fidelity data for the validation of simulations. The PPS planning progressed through expert elicitation, independent reviews, and stakeholder meetings that resulted in a framework for a test plan that would meet the stated objectives and address input from a wide range of stakeholders. In the end, work on the PPS ceased because of the estimated cost and because the Yucca Mountain project was halted. Conducting such a test many years prior to the need for high-volume movement of SNF could render results from the PPS obsolete.

In July 2012, as part of its recommendations, the Blue Ribbon Commission (BRC) on America's Nuclear Future (BRC 2012) stated "the NRC should reassess its plans for the Package Performance Study without regard to the status of the Yucca Mountain project" because consolidated interim storage was a desirable component of the waste management system and would require numerous shipments of SNF in the near future.

On this basis, this report serves as the reassessment requested by the Department of Energy (DOE) and provides a summary of the history of the PPS planning, identifies the objectives and technical issues that tended to drive the scope of the PPS, and presents a series of potential alternatives for moving forward in planning to conduct a full-scale test of rail cask for SNF.

1.1 Background

A series of reports over the past 35 years have sought to estimate the radiological environmental consequences of shipping used fuel across the continental US. The NRC conducts such studies on a periodic basis to re-assess their regulations as new data becomes available and as computation modeling techniques advance. Each report in this series of re-assessments has confirmed the adequacy of the regulations in protecting the public and environment from radiological exposures during transport. Starting with NUREG-0170 (NRC 1977), these studies have incorporated the best available information regarding shipping routes, accident frequencies, and computational modeling of cask and fuel failure mechanisms. These studies consistently chose very conservative assumptions where lack of information or understanding existed. Each subsequent assessment represented more refined methodologies and approaches to modeling and areas of conservatism. Furthermore, each study has estimated substantially smaller radiological risk to the public than for comparable accident conditions. Specifically, the "Modal Study," NUREG/CR-4829 (Fischer 1987), introduced event trees and a simple fuel failure model, whereas the earlier Urban Study (Finley 1980) chose 100% release of volatiles from the fuel.

The "Reexamination Report," NUREG/CR-6672 (Sprung 2000), added an evaluation of shipping routes to determine accident frequencies and incorporated new computer hardware platforms with improved structural and thermal modeling software. The most recent report, NUREG-2125 (NRC 2014), represents the most recent evaluation and accurate analysis of spent nuclear fuel packages subjected to transport accident conditions and supersedes NUREG/CR-6672.

Comments on the results reported in NUREG/CR-6672 indicated concern about the lack of a requirement for full-scale tests of cask designs prior to certification. To address this concern, the NRC opened a research initiative to evaluate the accuracy of current modeling to simulate transportation accident conditions and thus demonstrate the safety of modern transportation casks. These efforts, collectively called the "Package Performance Study," resulted in two reports. The Issues report (NUREG/CR-6768) (a) identified principal areas of uncertainty, based on four public meetings, and (b) recommended testing to address these issues (Sprung 2002). The Protocols Report (NUREG-1768) developed a range of test protocols, based on NUREG/CR-6768 (NRC 2003). Figure 1-1 provides a timeline for these NRC reports.

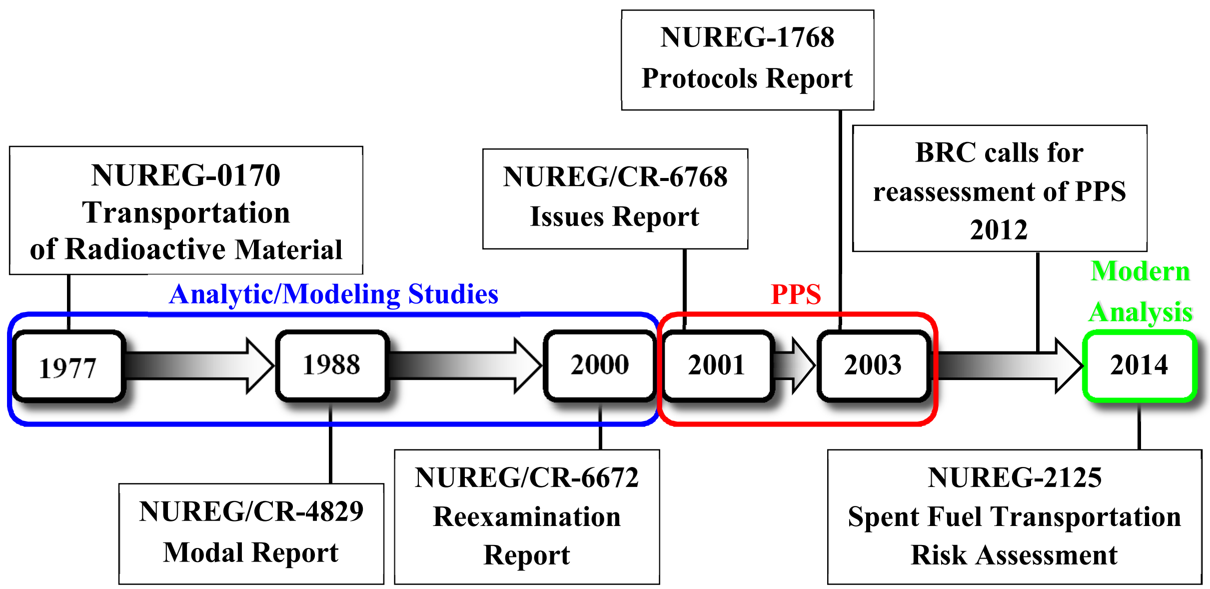

Figure 1-1 Significant publications on the safety of spent nuclear fuel transportation.

1.2 Definition of Programmatic Participation

When the Protocols Report (NRC 2003) was developed, the DOE decided that the DOE and NRC had a mutual interest and so the DOE would provide a portion of the funding for the PPS. However, the NRC would take the lead in conducting the PPS because the DOE did not intend to add any requirements to the cask certification beyond what the NRC had already imposed (i.e., in accordance with the Nuclear Waste Policy Act of 1982 (NWPA), the DOE would purchase NRC-approved casks). If results from the PPS suggested new or amended requirements for certification, it would ultimately be up to the NRC to include those items in the requirements for a cask manufacturer when applying for a cask Certificate of Compliance.

1.3 Similar Programs

1.3.1 Central Electricity Generating Board Flask Test Project ("Operation Smash Hit")

In the mid-1980's, the British Central Electricity Generating Board (CEGB) performed an integrated full-scale testing, scaled testing, and modeling campaign for a Magnox spent nuclear fuel package (NAS 2006). This campaign culminated in full-scale regulatory and demonstration tests. Figure 1-2 shows photographs of the various scale models used in testing, which ranged from 1/8th to full-scale. Also shown are comparative images of the different scale models during corner impact regulatory tests. In general, the accelerations and strains measured in the scaled and full-scale impact tests were in good agreement. The conclusion of these tests was that scaled testing can accurately represent package response if the significant features and geometry of the full-scale cask are properly represented and sized according to well-established scaling laws (Buckingham 1914).

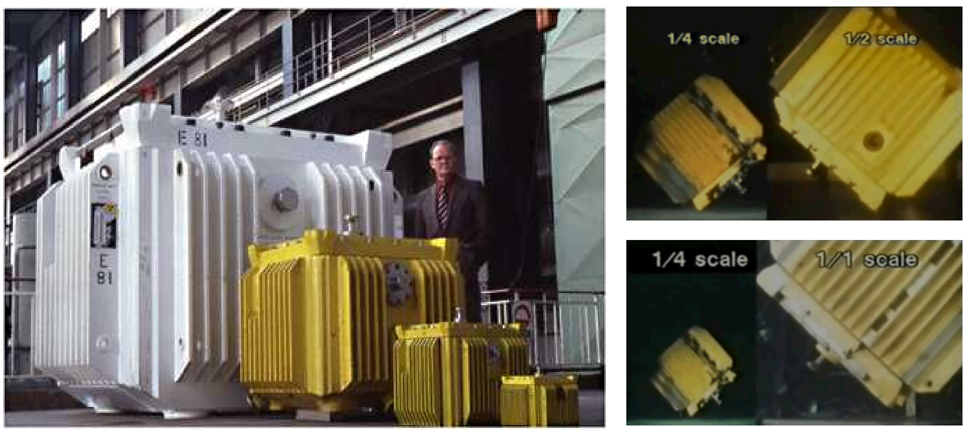

Figure 1-2 Photographs showing (left) a Magnox spent nuclear fuel flask ranging from full-scale to 1/8th-scale and (right) visual comparisons of flasks of various scales during corner impact testing (Magnox Electric Ltd).

Best known of the tests in the CEGB program is the "Operation Smash Hit" demonstration test in which a locomotive was driven at 162 km/h (100 mph) into a pressurized Magnox cask. Although visually compelling (Figure 1-3), this demonstration test actually resulted in loads 2.5 times less than the regulatory test and was therefore less severe.

One of the objectives of this test program was to demonstrate that these casks could withstand very severe accident conditions. British television broadcast the test. This test program was successful in demonstrating that casks designed and manufactured under existing regulations could withstand severe accident conditions. It also validated the use of scale-model tests and computational analysis for estimating full-scale response.

Figure 1-3 Still images of the Operation Smash Hit demonstration test (Magnox Electric Ltd).

1.3.2 Bundesanstalt für Materialforschung und –prüfung (BAM)

Several full-scale tests have been conducted by BAM, the Federal Institute for Materials Research and Testing in Germany, to test the integrity of shipping casks. The most modern and relevant of these were conducted with the CONSTOR V/TC (Figure 1-4) and MSF-69BG (Figure 1-5) casks at the 220 ton drop facility in Horstwalde, Germany. While neither of these cask designs is approved for transportation in the US, the results of the tests show that these full-scale rail cask designs can withstand the regulatory impact conditions. These tests also provide important data with which to benchmark computational tools and approaches.

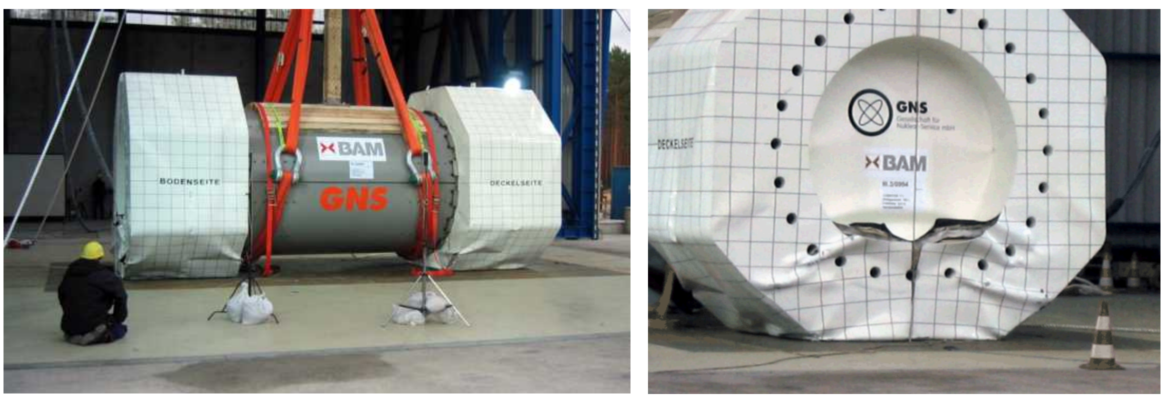

Figure 1-4 BAM CASTOR V/TC side impact test (BAM public website).

Figure 1-5 BAM MHI-MSF69 BG shallow angle drop test (BAM public website).

1.3.3 Sandia National Laboratories

Several full-scale, demonstration tests were conducted in the late 1970's at Sandia National Laboratories (SNL) with obsolete truck and rail casks that were no longer certified by the NRC. Figure 1-6 shows a truck cask impacting at 130 km/h (80 mph) during pre-impact, impact, and post-impact. Other tests included impact of a locomotive into a truck cask mounted on a trailer at 130 km/h and a rail cask mounted on a railcar into a concrete target at 130 km/h. This test program was preceded by simplistic lumped parameter modeling and $1/8^{th}$ scaled testing to predict and understand the damage mechanisms during the full-scale tests.

One of the objectives of these tests was to perform engineering tests on these packages to better understand gross response to severe impact. A second objective was to provide some limited data to support the early development of finite element codes at SNL. However, the casks were not heavily instrumented and so not much data was obtained. The transportation packages all survived the tests with minimal damage and would not have caused measurable radiological exposure to the public. Yet, critiques questioned the use of obsolete cask designs.

Figure 1-6 SNL truck cask demonstration test at 130 km/h (80 mph) (Jefferson 1978).

1.4 Development of the Package Performance Study

A primary testing objective of the original PPS was to demonstrate the robustness of used nuclear fuel transportation casks by conducting full-scale severe accident test(s) coupled with confirmatory research and enhanced public participation. The NRC authorized SNL to conduct a scoping study involving the public to identify the relevant technical issues and uncertainties. Four public meetings were held and comments from stakeholders were incorporated in the Issues Report, NUREG/CR-6768 (Sprung 2002). The four prevailing opinions from these comments were as follows.

1) NRC should conduct full-scale regulatory tests.
2) NRC should conduct realistic extra-regulatory tests based on viable, severe accident scenarios.
3) NRC should test the casks to failure.
4) NRC should address terrorism in the PPS.

With regard to the fourth opinion, the NRC staff noted that the subject of malevolent attack was being addressed by other ongoing NRC activities, many of which were conducted by SNL under contract with the NRC. Public dissemination of the results of these studies is restricted because of security requirements.

A technical basis for testing a cask to failure, the third opinion, is difficult to justify. The strongest argument is to quantify safety margin. The NRC staff recognized that testing to failure is incompatible with the second opinion because the accident condition needed to cause failure is far beyond what can be justified based on credible, severe accident conditions, as evaluated in NUREG/CR-6672. In the National Academy of Sciences (NAS) review of SNF transportation, *Going the Distance* (NAS 2006), NAS found testing to failure would be "marginally informative and is not justified" for similar reasons. In addition, it was recognized that testing to failure could elicit arguments that certified designs and the regulations upon which they were based did not produce sufficiently safe casks.

Based on the public comments and discussions between NRC and SNL, the NRC ultimately released NUREG-1768 (NRC 2003) in which the staff supported the second opinion for extra-regulatory, full-scale tests of rail and truck casks. Regulatory tests, the first opinion, were not included in the NUREG-1768 series of proposed testing.

The DOE Office of Civilian Radioactive Waste Management (OCRWM) also collaborated with the NRC to support planning for up-grading test facilities at SNL to accommodate a full-scale rail cask regulatory drop test and to work with external transportation stakeholders to develop a conceptual plan to conduct a severe accident test at the American Association of Railroads (AAR) Transportation Technology Center (TTC) rail testing facility in Pueblo, Colorado. Part of this planning included a high speed impact followed by a fire/thermal test. In addition, the possibility of adding an emergency response exercise to the end of the mechanical and thermal tests was considered.

During these discussions, OCRWM priorities were re-focused to finish the Yucca Mountain repository license application, and funding allocated for the test was re-directed to the license submittal work. While this planning process was never completed, substantial value in defining a test program that would best address concerns occurred from the external stakeholder discussions and from close collaboration with the AAR and TTC.

1.5 Previous Recommendations

1.5.1 Package Performance Study

The test protocols recommended in NUREG-1768 proposed extra-regulatory impact and fire tests of both truck and rail transportation casks. The full-scale tests recommended for consideration are as follows:

- Impact test of a rail cask with impact limiters into an unyielding target at 96 to 144 km/h (60 to 90 mph) at an unspecified orientation.
- "Back breaker" impact test of a truck cask onto a rigid semi-cylinder. The back breaker test is a configuration in which the impact limiters are by-passed and the full impact of the test is on the cask itself.
- Fully engulfing fire tests of both cask designs for durations beyond the 30 minute limit specified in 10 CFR 71.73 (U.S. 2014).

1.5.2 National Academy of Sciences

As noted earlier, the NAS completed a comprehensive review on the transportation of spent nuclear fuel and high-level radioactive waste in the US (NAS 2006). The NAS study, *Going the Distance*, strongly endorsed the following full-scale tests.

- Very long duration fire test with a well-instrumented package to provide validation-quality data.
- Regulatory and credible, extra-regulatory impact testing to support integrated analytical, simulation, and scaled testing efforts.

The BRC report specifically proposed that these recommendations be addressed in addition to suggesting that the NRC revisit the PPS.

1.5.3 Public Safety

Recently, stakeholders interested in safety and health reviewed the results of the major full-scale cask test programs and the recommendations of the BRC and the NAS. Their recommendations were as follows (Dilger 2012):

- Stakeholders should have a meaningful role in development of testing protocols and selection of test facilities and personnel.
- Full-scale regulatory tests (drop, puncture, fire, and immersion, in sequence) should be performed on each cask design, either prior to NRC certification, or prior to DOE procurement.
- A truck cask, and possibly a rail cask, should be subjected to an extra-regulatory fire test based on the Howard Street Tunnel Fire or MacArthur Maze Fire conditions. See Section 2.3.2.1.
- Failure thresholds of casks and fuel should be determined by simulations, scaled testing, and component testing (<u>not</u> by full-scale tests).

2 DISCUSSION OF TRANSPORTATION PACKAGE SAFETY NEEDS

2.1 Consolidated Interim Storage

In response to the BRC recommendations, the DOE recently stated in a strategy report that the Administration, with the appropriate authorizations from Congress, intends to site, design, and license a pilot consolidated interim storage facility (ISF) by 2021 and a larger ISF by 2025 (DOE 2013). Because the Pilot ISF is planned to begin operations in 2021, planning a full-scale severe accident test now could demonstrate package performance prior to the start of a major shipping campaign that would receive much public exposure. The PPS test options outlined by NRC staff in SECY-04-0029 (NRC 2004a) detailed a test program lasting six years. If funding were made available starting in fiscal year 2015, the results of large-scale testing program could support the establishment of a consolidated interim storage facility.

2.2 Cask Selection

Despite the recent stakeholder desire to test each certified cask design, previous planning efforts for the PPS assumed that a single rail cask will be tested. The authors of these efforts also assumed that the most likely test effort will be for a single cask design, given the cost of testing. Various selection metrics can be considered when choosing the cask design for testing. These metrics can include but are not limited to the makeup of the current cask fleet in industry, trends toward high capacity canisters, and availability.

2.2.1 Current Cask Fleet

Dry cask storage systems fall into two main categories. The first category is a bare fuel, or direct load, cask in which SNF is loaded directly into a basket that is an integral part of the cask. These casks are typically all metal and are generally bolted close. The more common are casks that use a thin-walled, internal canister (89% as of 2012). Cask using internal canisters are expected to become an even larger percentage of the fleet in the future. Of the canister designs, canisters holding 24 PWR fuel assemblies are the most common (36%) as shown in Figure 2-2. These designs include VSC-24, MPC-24, UMS-24, and NUHOMS-24P(PT, PTH). This type is followed by canisters holding 68 BWR fuel assemblies (20%) and 32 PWR fuel assemblies (17%). The logical choice based on the current fleet would be a canister for 24 PWR fuel assemblies with the appropriate transport cask.

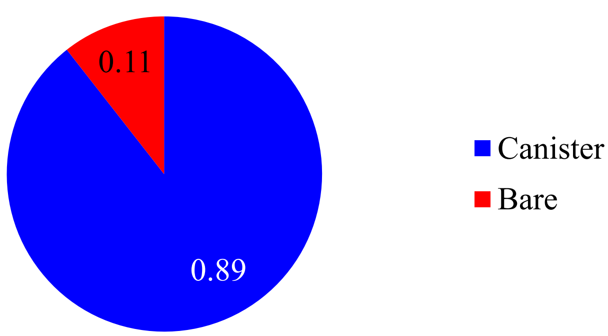

Figure 2-1 Makeup by cask design type of the current fleet.

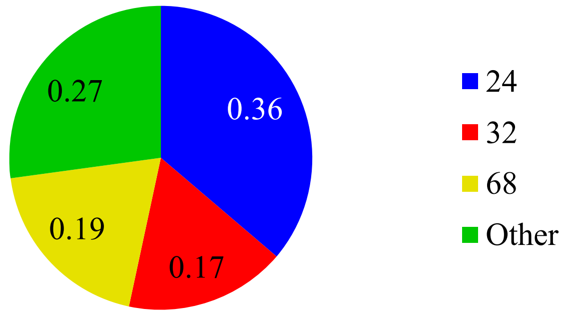

Figure 2-2 Breakdown of canister capacities in the current fleet.

2.2.2 High Capacity Canister Trends

The newest generation of dry storage canisters hold 37 PWR fuel assemblies or 87 to 89 BWR assemblies. Because the loads generated by the cask during a transportation accident are proportional to mass, these new cask designs represent the upper end of the accident spectrum. All three manufacturers in the US market have designs in this capacity class at various stages of licensing. Figure 2-3 shows the NAC International 37 PWR Transportable Storage Canister (TSC) and the associated transport cask with impact limiters. Similarly, Figure 2-4 shows the 37 PWR Multi-Purpose Canister (MPC) and HI-STAR 190 transport cask. If the industry continues to favor high capacity canisters, a 37 PWR transport cask system would be a logical selection for accident testing.

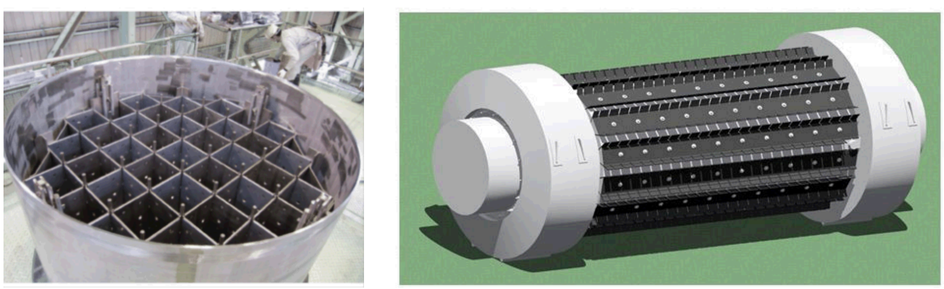

Figure 2-3 NAC International TSC-37 (left) and MAGNATRAN transport cask and impact limiters (right) (Greene 2013).

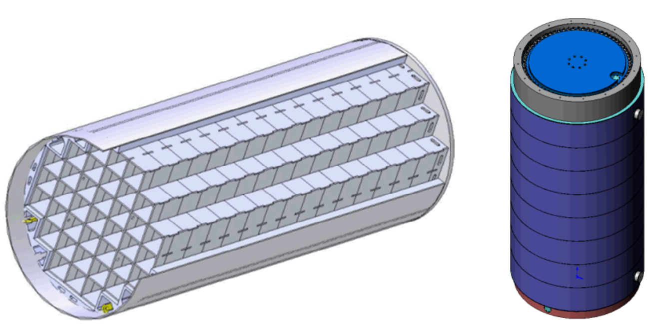

Figure 2-4 Holtec International MPC-37 (left) and HI-STAR 190 transport cask (right) (Greene 2013).

2.3 Spectrum of Test Options

2.3.1 Regulatory Test Series

Transportation casks are certified to withstand accidents without releasing radioactive material, provide shielding from radiation, and dissipate the heat generated by the fuel, based on four tests of a transportation cask (Figure 2–5): (1) dropping 9-m onto a unyielding surface, (2) dropping 1 m onto 0.15 m steel bar, (3) fully engulfed in fire for 30 minutes at 800 ^{o}C, (4) subjected to external water pressure of 2 MPa for 1 hr without collapse, buckling or leakage (10 CFR Part 71.73 and 71.61). Numerical modeling has progressed to the point that NRC typically accepts model results of these tests in lieu of full or sub-scale tests.

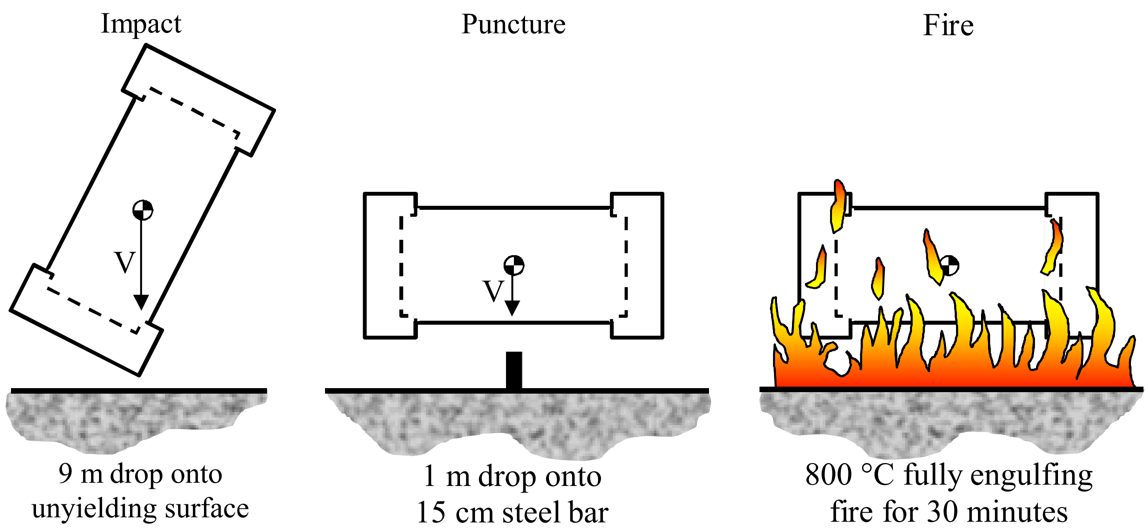

Figure 2-5 Illustration of transportation accident conditions as defined in 10 CFR 71.73.

Critics of the testing requirements listed in 10 CFR 71 argue that these test definitions do not represent the most severe and viable accident conditions. However, these requirements do bracket a vast majority of possible accident conditions, especially when considering impacts on unyielding surfaces. These comparisons to regulatory hypothetical accidents conditions to severe accident conditions are discussed in NUREG/CR-6672 and NUREG-2125.

2.3.2 Extra-Regulatory Testing

This testing category covers accident conditions that exceed the requirements defined in 10 CFR Part 71. The original test plan as described in NUREG-1768 recommended extra-regulatory tests involving a full-scale rail and truck cask at speeds between 96 to 144 km/h (60 to 90 mph) and fully engulfing fires for durations greater than 30 minutes. Figure 2-6 shows the finite element method (FEM) results for a rail cask subjected to end, corner, or side impacts at 145 km/h (90 mph) onto an unyielding target.

These simulations concluded that no radioactive material would be released from a cask with an inner welded canister. None of the fire accidents examined in NUREG-1768 resulted in releases of radioactive materials. Only loaded casks using bolted basket designs were shown to release small amounts radioactive materials, but the releases were neither acute nor lethal and would be released only in the most severe accidents.

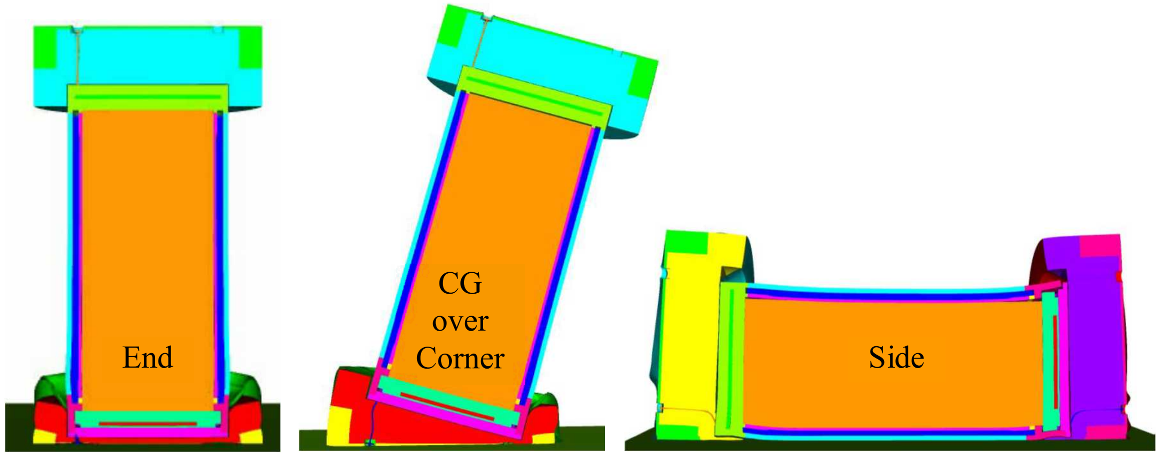

Figure 2-6 Deformed shape of a rail cask following a 145 km/h (90 mph) end, corner, or side impact onto an unyielding target (NRC 2014).

2.3.2.1 Extra-Regulatory Fire Testing

Special attention has been focused on two relatively recent fire accidents that exceeded the time and temperatures specified in 10 CFR 71. These two accidents are known as the MacArthur Maze Fire and the Howard Street Tunnel Fire. Public safety advocates cite the conditions produced during these two accidents when arguing that the regulatory requirements for transport casks are not sufficient.

2.3.2.1.1 Howard Street Tunnel Fire

The Howard Street Tunnel Fire started in Baltimore on 18 July 2001 as a result of the derailment of a freight train and the subsequent ignition of spilled hydrocarbon tanker contents. The fire burned intensely for at least 3 hours until a nearby water main failed. The fire continued to burn much less intensely until it self-extinguished after about 12 hours. Two major studies of this fire have been conducted in efforts to characterize the thermal environment produced. In the first study, the National Institute of Standards and Technology (NIST) (McGrattan 2003) performed a detailed numerical study of the Howard Street Fire using their Fire Dynamics Simulator (FDS) numerical fire model. The model has been extensively validated through a number of full-scale fire tests representing realistic scenarios. The most pertinent validation exercise involved a series of tunnel fire experiments conducted in the decommissioned Memorial Tunnel located in West Virginia in the mid-1990’s. The Memorial Tunnel is similar in size and construction to the Howard Street Tunnel and a series of 20 MW and 50 MW fires with natural ventilation closely represented the scenario of the Howard Street Tunnel fire. The agreement between the FDS predictions and the validation test data was excellent with regards to the thermal output and resulting temperature profiles in the Memorial Tunnel validation.

The FDS simulation for the Howard Street Tunnel fire was conducted for the time from ignition until the water main break after three hours. The simulations suggested the fire was oxygen starved with a thermal output of 50 MW. The calculated peak gas temperature within the flame region was about 1000 °C. The peak calculated wall temperature in the flame impingement region was about 800 °C.

In the second major study of the Howard Street Tunnel Fire thermal environment (Garabedian 2003), various rail car components were recovered from the train wreckage. The components included steel samples from box car roofs and aluminum components from air brake assemblies. Metallurgical analyses were conducted to provide estimates of the fire temperature and duration by measuring the oxide-scale thickness and metal loss on the steel samples. These results indicate that the most impacted roof sample reached temperatures between 750 °C and 850 °C for a period of approximately 4 hours.

2.3.2.1.2 MacArthur Maze Fire

The MacArthur Maze fire occurred on 29 April 2007 on an I-880 interchange in Oakland California when a gasoline tanker truck overturned and burned. The location of the accident placed the resulting fire directly under an overpass for I-580 causing the eventual collapse onto the tanker truck after 17 to 37 minutes. The fire continued to burn at reduced intensity for an additional 71 minutes. FDS modeling of the first 17 minutes placed an upper bound on the maximum fire temperature of 1100 °C (Bajwa 2012). Samples of the failed I-580 girders and the tanker truck were collected for metallurgical analysis. The microstructure of the ceiling girders revealed phase transformations and microstructure alterations consistent with exposure to temperatures in the range of 850 to 1000 °C. Analysis of the truck components indicated exposure to temperatures in the range of 700 to 930 °C.

2.3.2.1.3 Comparison to Regulatory Fire Test (10 CFR 71)

The hypothetical accident conditions (HAC) described in 10 CFR 71 (Figure 2–6) require the transportation package be subjected to a fully engulfing fire with an average flame of at least 800 °C for at least 30 minutes without sustaining damage that would result in a release of the cask contents or lead to increased external exposure to radiation. These tests are generally conducted with an open pan fire of jet fuel, which produces the required 800 °C boundary condition. Both the Howard Street Tunnel and the MacArthur Maze fires occurred in confined geometries that resulted in higher peak temperatures of 1000 to 1100 °C at the confining ceiling. However, metallurgical analysis of samples from the rail car and tanker truck engulfed in the fires indicated exposure to temperatures on the order of 800 °C. In both cases the location of the rail car and tanker truck was analogous to the location of a transportation cask in a HAC fire. Therefore, the engulfing fire boundary condition required by an HAC fire test was met.

2.3.2.1.4 Simulated Spent Fuel Transportation Package Response

The NRC has analyzed both the Howard Street Tunnel and MacArthur Maze fires to determine the potential impact of the accident conditions on various spent nuclear fuel transportation package designs. In both cases, the thermal environment of the accident was conservatively assumed to be the worst case or beyond the actual situation. Two NRC-certified spent fuel rail transportation package designs were analyzed for enhanced Howard Street Tunnel fire conditions, namely the TransNuclear TN-68 and HOLTEC HI-STAR 100. Both designs were shown to withstand the thermal conditions with only minor damage to peripheral components. Peak cladding temperatures would not exceed the regulatory limit of 570 °C for accident conditions. For the TN-68 package, the maximum temperature predicted in the region of the lid, vent and drain seals exceeded the temperature ratings, which leads to the possibility of seal failure. Seal failure may provide a leak path for particles that may spall off the fuel rod surface. However, no major release was predicted because the fuel rods all remained intact.

2.3.3 Demonstration Test

While visually impressive, an accident demonstration test offers limited technical usefulness and will likely not provide loading conditions to the cask that exceed regulatory conditions.. Figure 2-7 shows a model simulation of a locomotive impact into a truck cask at different times. Because of the amount of damage incurred by the locomotive, the amount of energy delivered to the cask is far below that delivered by impact into an unyielding target in the HAC requirements of 10 CFR 71. As a point of reference, the peak force delivered during the demonstration test "Operation Smash Hit" (locomotive traveling at 100 mph) was approximately 2.5 times less than occurred during the regulatory 9-m drop test (impact velocity of 30 mph) (NAS 2006).

While the 9-m drop test results in a cask speed of only 30 mph at impact, the driving factor in this test is the unyielding target. All of the kinetic energy of the cask developed during the free fall must be absorbed by deformation of the cask impact limiters and cask body. This provides a test condition that bounds almost all representative severe accident conditions that are on record.

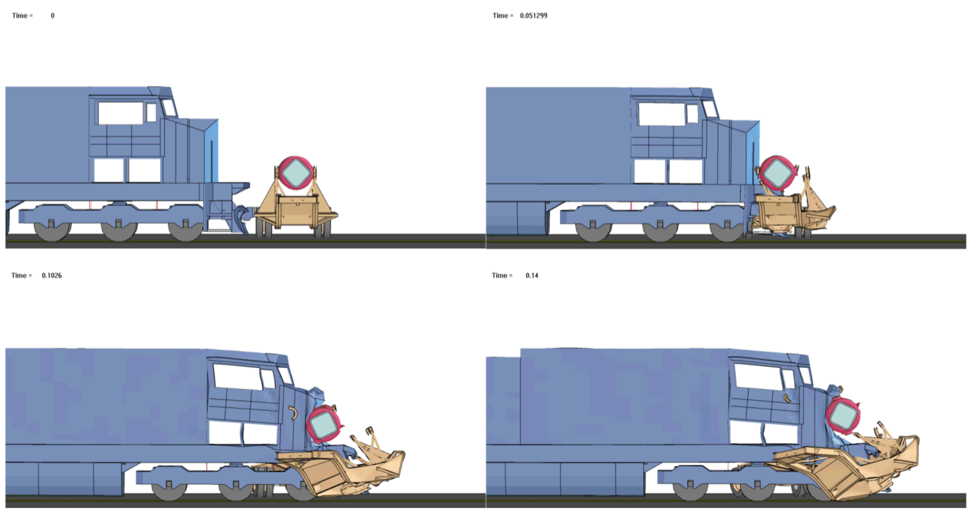

Figure 2-7 Sequential views of 90° impact of a locomotive into a truck cask (Ammerman 2005).

2.3.4 Small-Scale Testing for Fuel Response

In addition to cask response to a severe accident, the response of the spent nuclear fuel in the cask to mechanical loads is also of interest. In particular, very little data associated with high burnup spent nuclear fuel (> 45 GWd/MTHM) exists. The Issues Report (Sprung 2002) rated the importance of understanding the behavior of spent nuclear fuel under these conditions and the effects of burnup as a top priority research topic. An opportunity may exist to evaluate fuel response in the transportation configuration in supporting the overall transport system evaluation.

A wide range of fuel testing has been proposed to explore the failure mechanisms of spent nuclear fuel during transportation accidents. These mechanisms include cladding failure, pellet fracturing, effects of burnup, and material release to the cask from failed fuel. This testing may be conducted as a separate effort from the full-scale cask effort but represents an area of technical uncertainty.

2.3.5 Training Exercises for First-Responders

Developing techniques and training for first-responders to react to a severe accident site is also important to a national shipping campaign. Efforts are already being conducted under Section 180(c) added by the Nuclear Waste Policy Amendments Act of 1987(NWPAA):

> The Secretary shall provide technical assistance and funds to States for training for public safety officials of appropriate units of local government and Indian tribes through whose jurisdiction the Secretary plans to transport spent nuclear fuel or high-level radioactive waste under subtitle A or under subtitle C. Training shall cover procedures required for safe routine transportation of these materials, as well as procedures for dealing with emergency response situations. The Waste Fund shall be the source of funds for work carried out under this subsection.

In conjunction with this work, however, a simulated accident response could be integrated into an overall test plan or generated as a standalone effort. The probability of an accident with an increase in external dose rate above regulatory limits is exceedingly small, less than one in a billion (NRC 2014). Even in the extremely conservative cases examined in NUREG-2125, which postulated partial loss of shielding, the external dose rates are not likely to cause any adverse health effects in first responders. However, a training exercise could have some nontrivial, simulated radiation field. This affords the first-responders an opportunity to train and react to an accident site with increased radiation dose rates.

The simulated dose to each first-responder could be measured with a global positioning system (GPS) recording device such as a smartphone. An application written specifically for this purpose could then log the amount of time an individual spent in a predefined radiation field. The radiation field defines the dose rate as a function of location. Additional GPS devices could serve as simulated radiation detectors to inform the first-responders of their dose rate in real-time. GPS augmentation systems may be needed in order to increase the positional accuracy of each device. Figure 2-8 demonstrates the concept for simulated dose measurement during an accident training exercise. After experiencing an end-on impact at 193 km/h (120 mph), the lead shielding in the cask slumps toward the point of impact. The dose rates increase after a partial loss of shielding. The figure shows the approach of first-responders as they advance toward the cask, initially from a safe direction. The first-responders then enter a zone where gamma radiation is increased from the partial loss of lead shielding. The first-responders stop in this zone to inspect the cask. However, their radiation detector alerts them to the threat, and they vacate the area.

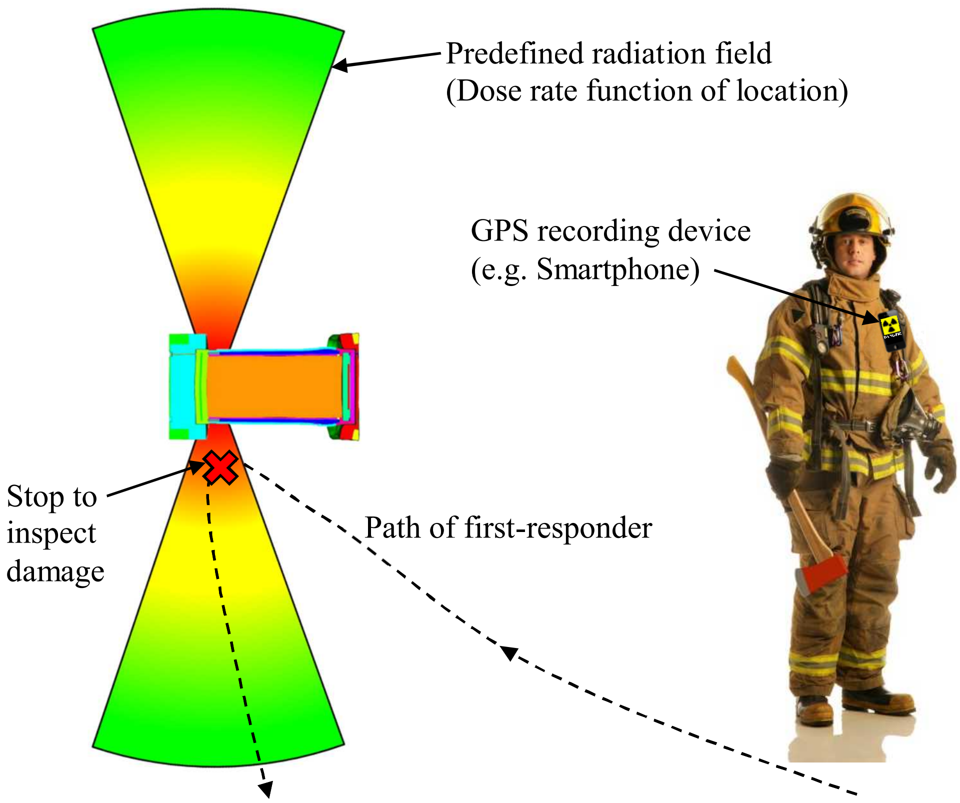

Figure 2-8 Simulated dose during accident training for first-responders in which cask has partial loss of lead shielding after a 193 km/h (120 mph) impact (from Figure 3-9 NRC 2014).

This concept for simulated radiation exposure training exercises with first-responders could also be applied for even more severe accident scenarios, which are extremely improbable (order of 10^{-11}) (NRC 2014). For example, the dose for scenarios with a release of a portion of the cask contents could be simulated. These scenarios only require that the dose rate be defined as a function of location, which could be predetermined using computer codes such as RADTRAN. It is also possible that the dose rates be defined as a function of time if the release is dynamically changing. For scenarios with a release, the dose application on the GPS recorder could also have the capability to record whether or not the first-responder is wearing a respirator, thus eliminating inhalation as an entry pathway for dose calculations. These exercises could also be combined with other activities such as firefighting and emergency medical response.

2.4 Evaluation of Technical Merit and Requirement Fulfillment

In an effort to quantify the technical merit and fulfillment of stakeholder's requirements, a rudimentary, qualitative scoring was applied to several proposed test program options as identified in NRC (2004a) and NRC (2005b) as shown in Table 2.1. The regulatory and extra-regulatory tests described in this ranking were assumed to include impact and fire tests. This scoring system emphasizes rail transport because a majority of spent nuclear fuel will ship via rail. Higher scores are also awarded for extra-regulatory tests because these types of tests provide a broader spectrum of validation data and serve to demonstrate the margin of safety. Finally, an additional score is awarded based on the breadth (same type of testing for truck and rail packages) and depth (regulatory and extra-regulatory testing of the same package) of the test program. In addition to the scoring, Table 2.1 also provides first order cost estimates that were developed for each of the proposals.

Table 2.1 Ranking of different test programs proposed by the NRC.

Description	Cask Type	Regulatory	Extrareg.	Breadth Depth	Total Score	Cost ($M 2004)
Extra-Reg. Truck and Rail (NUREG-1768)	Truck	--	2	2	8	37
	Rail	--	4	--		
Reg. Rail, Extra-Reg. Rail and Truck (SECY-04-0029)	Truck	--	2	2	15	47
	Rail	3	4	4		
Reg. and Extra-Reg. Rail (SECY-04-0029)	Truck	--	--	--	11	32
	Rail	3	4	4		
Reg. Rail and Truck (SECY-04-0029)	Truck	1	--	2	6	37
	Rail	3	--	--		
Demonstration Rail (SECY-05-0051)	Truck	--	--	--	4	11
	Rail	--	4	--		

Figure 2-9 shows a plot of the various test programs estimated cost as a function of total score. A test program incorporating a regulatory and extra-regulatory test of the same type of cask design appears to be the most inclusive of all stakeholder's concerns and objectives. Given that the large majority of spent nuclear fuel will be loaded and transported in canistered, high-capacity rail casks, a full-scale testing program would be best served by focusing limited funding and resources on tests conducted using a rail cask.

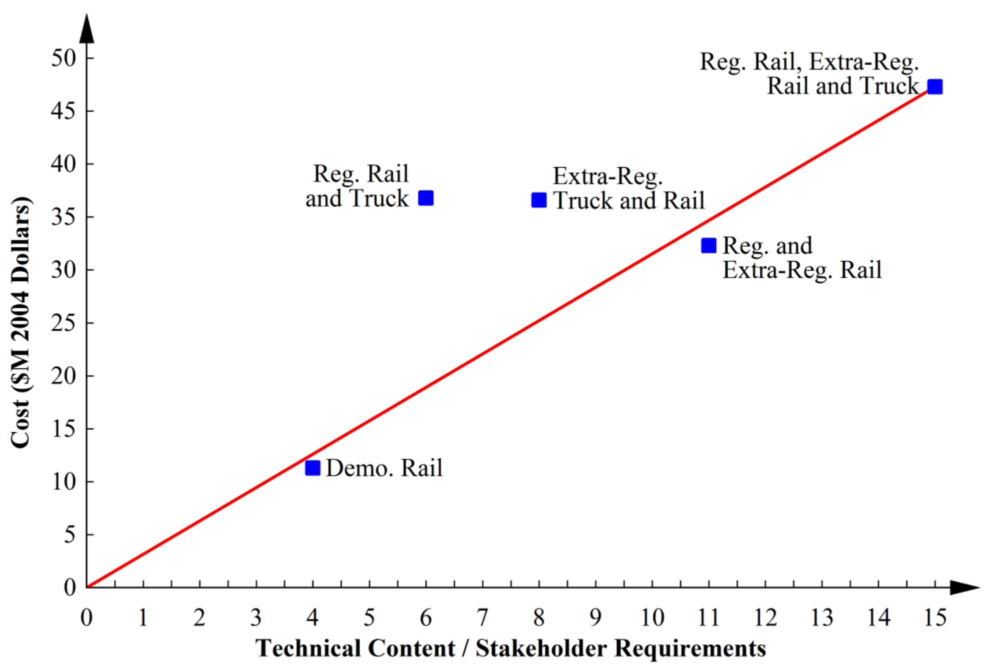

Figure 2-9 Estimated project cost for different test programs versus perceived technical merit and fulfillment of stakeholder requirements.

2.5 Assessment of Existing Test Facilities

During PPS planning, a survey of potential test facilities was made to ascertain options and rank facilities capable of conducting the tests, given the specific test parameters that were being developed. It was decided that this survey would be conducted for US facilities only. One of the constraints for this test program is the need for an unyielding target. Regulatory guidance for an unyielding target is that the target must have a mass at least 10 times greater than the fully loaded package. For a fully loaded rail cask, transport loads can reach 175 tons. This would require a target of 1750 tons. Currently there are no sites in the US with horizontal unyielding targets of this size. However, SNL does have a vertical target appropriate for impacts of rocket-accelerated packages up to 200 tons.

As discussions progressed, the consensus on the PPS approach was (1) to conduct an extra-regulatory test (not the HAC required in 10 CFR 71.73) and (2) to include an emergency response component. With this thinking, a possible host facility is the aforementioned TTC. TTC is located in Pueblo, Colorado and is operated by Transportation Technology Center Inc. (TTCI), a wholly owned subsidiary of the AAR. It has a state- of-the-art test track and the ability to conduct high speed accident tests. It could also incorporate an emergency response component to the testing, if this was desired.

3 PATH FORWARD FOR THE PACKAGE PERFORMANCE STUDY

For certifying a transportation cask for SNF, NRC requires showing that the cask will not release radionuclides in four hypothetical accident conditions (Figure 2-5, based on 10 CFR Part 71.73 and 71.61): (1) dropping cask 9 m onto a unyielding surface, (2) dropping cask 1 m onto 0.15 m steel bar, (3) fully engulfing the cask in a fire for 30 minutes at 800 ^{o}C, (4) subjecting the cask to an external water pressure of 2 MPa for 1 hour without collapse, buckling or leakage. Numerical modeling has progressed to the point that the NRC typically accepts model results in lieu of small- or full-scale testing. Thus, the NRC and DOE have concluded that most technical questions related to transportation casks have been addressed.

Hence, the primary purpose of full-scale tests of severe accident conditions would be for public acceptance. Because full-scale testing would be expensive ($30 to $50 million—Figure 2-9), the value of such testing on public perceptions and public acceptance is very important. Consequently, the path forward would start with a public perception component followed by two additional components: accident simulation and first responder training. After each major phase, a decision would be made as to whether to stop or continue on with subsequent phases of each component (Figure 3-1).

3.1 Public Perception Component

Based on studies in the literature, it is unclear to the extent full-scale testing of transportation casks would influence acceptance and support for transporting SNF by members of the public along routes proximate to their communities. Hence, the first component of study is to determine the type of information and level of participation that the public desires in order for them to evaluate the safety of SNF transportation. Although a national survey instrument might be proposed to assess public perceptions, transportation issues are usually regional and community dependent. Because the ultimate goal of the public perception component would be to assist in consent based siting, the development of a measurement instrument based on focus groups is proposed. This measurement approach can be expensive and so a pilot phase would be conducted to fine tune the approach (Figure 3-1).

The first phase would be a pilot where one region of the country would be selected and various approaches and levels of information explored. Of particular interest in this initial phase would be the perceived value and public acceptance of modeling, testing, and first responder training on demonstrating the safety of NRC certified rail casks.

Provided there is perceived value, design of the other two components of the path forward (accident simulation and first responder training) would be influenced by the results of the public perception component. For example, public comments on the more recent NRC analysis of transportation casks in NUREG-2125 (NRC 2014) suggested a desire for investigation of long duration fires. Other less important but nonetheless useful information would be discussion of issues related to regulatory versus extra-regulatory testing; integration of mechanical, thermal, and emergency response components; types of casks and number of tests; inclusion of truck casks for testing; and impact orientation.

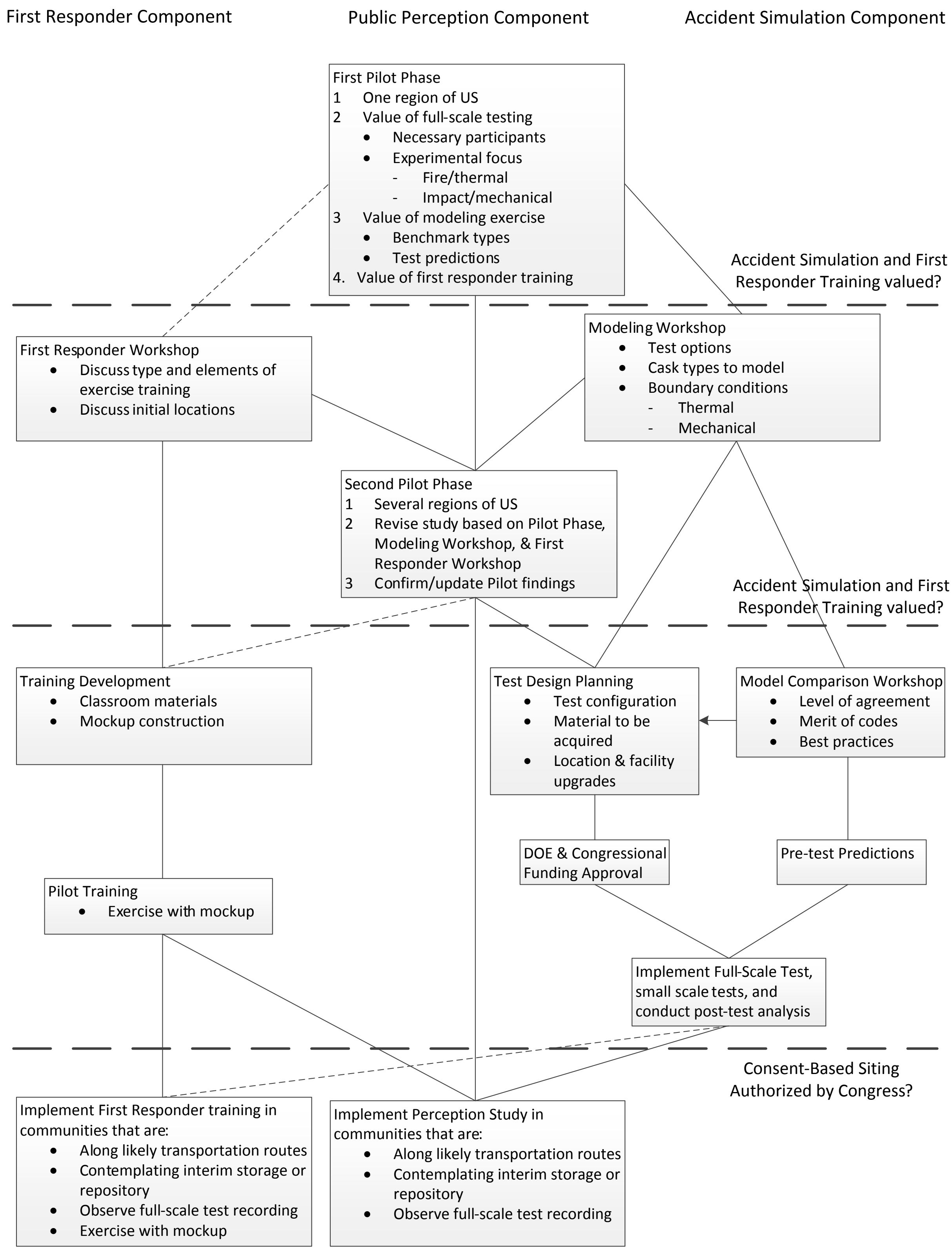

Figure 3-1. Interrelationship between three components of path forward for package performance study

The second phase of this public perception component would be the measure of public desires through focus groups in other parts of the country. The results from these later focus groups would be used to further refine or curtail the other two components of this path forward for the package performance study. Several years would likely be necessary and thereby the costs could be spread out.

The final phase would be implementation of the public perception study at communities that are along likely transportation routes or communities that are contemplating hosting a consolidated interim storage facility or repository after a consent-based siting process has been authorized by Congress (Figure 3-1).

3.2 Modeling Element of Accident Simulation Component

The accident simulation component of the path forward consists of two elements: modeling and testing. Modeling would be conducted first followed by testing and additional modeling. The design of the modeling exercise and testing would be predicated on the results of the pilot phase of the public perception component. Consequently, the proposed modeling and testing programs as outlined would be subject to change.

The first purpose of the modeling element is to demonstrate the general consensus that exists within the modeling community related to cask performance. One approach that has been used in the past to assess or demonstrate modeling consensus is to develop a series of benchmark problems that are then solved by a suite of high-fidelity codes. Two modeling workshops could be funded, with participants invited from the national laboratories, industry, and universities that (1) develop a series of benchmark problems and measures of comparison, and (2) then compare results and establish best practices. For bolstering confidence in the modeling exercise, however, some type of stakeholder concurrence on the approach would be necessary, both through input from the public performance component and inclusion of stakeholders at the modeling workshops.

This component of the package performance study might end at this point and the simulations used to demonstrate confidence in cask performance. Yet, the public might still desire full-scale testing, in which case the modeling element would provide support in the design of the rail cask tests. Furthermore, additional modeling of the cask in the potential impact and fire tests would consist of both pre-test predictions and post-test analysis.

3.3 Testing Element of Accident Simulation Component

The purpose of the testing element is to plan and implement the full-scale test of a transportation cask in a credible accident along with some small-scale testing. The three general options for the full-scale testing of the rail car transportation cask include regulatory testing, extra-regulatory testing, or a realistic accident demonstration test. Although a highly instrumented regulatory or extra-regulatory cask test would produce the most useful data for validating model results, a more visually realistic accident demonstration may be more beneficial for public perception. Furthermore, a given option would not necessarily be conducted in its entirety; pertinent elements of the options could be combined to best address public concerns based on the public perception component and the modeling element. For example, an accident demonstration test could be conducted followed by an extra-regulatory fire test.

Although the public perception component would provide updated guidance as to major objectives of the testing element, previous guidance for testing would still be pertinent as reviewed in Chapters 1 and 2 and summarized here.

3.3.1 Previous Guidance for Full-Scale Test of Transportation Cask

3.3.1.1 NAS Report

An NAS study strongly endorsed full-scale tests on transportation casks (NAS 2006),:

- Very long duration fire test with a well-instrumented package to provide validation-quality data.
- Regulatory and credible, extra-regulatory impact testing to support integrated analytical, simulation, and scaled testing efforts.

3.3.1.2 Package Performance Study

In the PPS study, the NRC suggested extra-regulatory, full-scale tests to address this concern (NRC 2003). Given that the majority of spent nuclear fuel in dry storage is currently loaded in dual purpose canisters capable of transport only by rail and given the prevalence of welded canister designs over bolted basket designs the test should be on welded canister, rail-transport system. Other guidance for the extra-regulatory tests included (a) use of a currently certified cask (b) severe mechanical and thermal loading conditions, but no test to failure; and (c) demonstration of cask integrity through leak-tightness of the closure system and evidence of no breach in the containment boundary.

Specific test conditions suggested were

- Impact test of a rail cask with impact limiters into an unyielding target at 96 to 144 km/h (60 to 90 mph). The orientation was unspecified.
- “Back breaker” impact test of a truck cask onto a rigid semi-cylinder. The back breaker test is a configuration in which the impact limiters are by-passed and the full impact of the test is on the cask itself.
- Fully engulfing, optically dense fire tests of both cask designs for a duration beyond the 30 minute criterion specified in 10 CFR 71.73 (U.S. 2014)

3.3.2 Additional Suggested Test Parameters and Conditions

3.3.2.1 Nature of Regulatory Testing

The purpose of the tests would be to gather quality data to justify the current certification methods. The purpose would not be to propose full-scale tests that should be required for certification of transportation casks.

3.3.2.2 Nature of Extra-Regulatory Testing

The speed and orientation of a credible, severe accident condition remains to be defined. Because recent FEM results indicate that a side impact results in the highest acceleration and contact force for a given impact velocity (NRC 2014), a side impact should probably be tested for conservatism, whether in a demonstration test or extra, regulatory test. The probability of a rail cask impacting a hard rock surface at speeds of 96 to 144 km/h (60 to 90 mph) has been reported as 10^{-6} to 10^{-8} per year, respectively. Hence, the test speed should be 144 km/h or less, nothing greater is warranted.

3.3.2.3 Cask Selection

As discussed in Chapter 2, the capacities of dry cask systems have increased significantly since first introduced. The more prevalent designs have 32 PWR assemblies. The newest cask designs store 37 PWR assemblies. Similarly, the capacity for a boiling water reactor (BWR) cask has increased from 68 to 89 fuel assemblies. Although the more prevalent designs are more likely to ship to a pilot consolidated interim storage facility, testing should probably be conducted on those casks with the potential to create the highest peak forces in an accident impact; thus, the newest case that would be available in the near future.

3.3.2.4 Small-Scale Testing

In addition to the full-scale testing, a useful component of an integrated analysis effort is small-scale testing. Small-scales can significantly increase the understanding of information gathered from the full-scale tests. Thus, small-scale testing should be included to gain the maximum understanding of the cask during the accident conditions.

3.4 First Responder Training Component

The third component of the path forward for the package performance study involves the development and implementation of realistic first responder training. This component would be part of efforts already being conducted under Section 180(c) added by the NWPAA. Developing techniques and training for first-responders to react to a severe accident site is important to a national shipping campaign. This third component is also important because well designed and publicized first responder training exercises in multiple communities along the transportation routes to the Waste Isolation Pilot Plant in southern New Mexico was a valuable process for the public to understand and eventually accept shipments of radioactive transuranic waste. It is expected that a similar training program would benefit a national shipping campaign for SNF.

The first phase would be conducting a workshop on proposed exercise training to include for first responders. The first phase could explore techniques with which to enhance the safety of first-responders called to an accident. Discussion between first responders would allow exchange of information about potential risks and the most efficient arrangement of resources to minimize exposure to onsite personnel and the public in general.

It is envisioned that results from this first phase would inform the accident simulation component and the second phase of the public perception component. For example, it is possible that a simulated accident response could be integrated into an overall test plan for the full-scale testing, once the experimental part of the test was concluded, and used as part of a training video.

The second phase would be the development of training materials and construction of realistic mockups. It is envisioned that results from second phase of the public perception component and aspects of the accident simulation component would contribute to the development of these materials (Figure 3-1).

The probability of an accident with an increase in external dose rate above regulatory limits is exceedingly small, less than one in a billion (NUREG-2125). Even in the extremely conservative cases in NUREG-2125 that caused partial loss of shielding, the external dose rates were not likely to cause any adverse health effects to first responders. However, a training exercise could have some nontrivial, simulated radiation field as discussed in Chapter 2. This affords the first-responders an opportunity to train and react to an accident site with increased radiation dose rates and could bolster public acceptance.

The third phase would consist of a pilot training exercise to screen the training material prior to being fully implemented. In the final phase (and similar to the public perception component), the first responder training would be implemented near those communities along likely transportation routes for SNF and those communities considering hosting a consolidated interim storage facility or a repository, once a consent-based siting process has been authorized by Congress, to enhance public visibility and participation (Figure 3-1).

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