Appendix E
FCT Document Cover Sheet

Name/Title of Deliverable/Milestone: PNNL Support to Finalize Method and Approach Document

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This deliverable was prepared in accordance with Pacific Northwest National Laboratory *(Participant/National Laboratory Name)*

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other: ______

This Deliverable was subjected to:

☐ Technical Review ☐ Peer Review

Technical Review (TR)
Review Documentation Provided

☐ Signed TR Report, or

TR Report No.: ______

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Peer Review (PR)
Review Documentation Provided

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*Note: In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation, or the documented review of the issued document through the document control process) of the completion of the activity along with the Document Cover Sheet is sufficient to demonstrate achieving the milestone. QRL for such milestones may also be marked N/A in the work package provided the work package clearly specifies the requirement to use the Document Cover Sheet and provide supporting documentation.

USED FUEL DISPOSITION CAMPAIGN

Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport - Method and Approach

Fuel Cycle Research & Development

Prepared for

U.S. Department of Energy

Used Fuel Disposition Campaign

January 31, 2013

FCRD-TIO-2011-000050

PNNL-22221

EXECUTIVE SUMMARY

Under current regulations, it is not sufficient for used nuclear fuel (UNF) to simply maintain its integrity during the storage period, it must maintain its integrity in such a way that it can withstand the physical forces of handling and transportation associated with restaging the fuel and moving it to a treatment/recycling facility or a geologic repository. Hence it is necessary to understand the performance characteristics of aged UNF cladding and ancillary components under loadings stemming from transport initiatives. Researchers within the Used Fuel Disposition Campaign (UFDC) and Nuclear Fuels Storage and Transportation (NFST) communities would like to demonstrate that enough information, experimental support, and modeling and simulation capabilities exist to establish a preliminary determination of UNF structural performance under normal conditions of transport (NCT).

A steering team composed of national laboratory, U.S. Department of Energy, and U.S. Nuclear Regulatory Commission staff met to determine the feasibility of such an undertaking. The group identified the necessary information required to establish a rudimentary path for a successful research, development, and demonstration (RD&D) plan. This document was assembled to capture and communicate the proceeds of the working meeting.

An approach is proposed to drive the RD&D of a methodology, including development and use of analytical tools, to evaluate loading and associated mechanical responses of UNF rods and key structural components. This methodology will be used to provide a preliminary assessment of the performance characteristics of UNF cladding and ancillary components under rail-related NCT loading. The developed methodology is expected to couple modeling and simulation and experimental efforts currently under way within UFDC. It will involve sensible/limited uncertainty quantification focused around available fuel and ancillary fuel structure properties exclusively. The proposed technical support work will include collecting information via literature review, soliciting input/guidance from subject matter experts, developing and demonstrating a methodology, performing computational analyses, planning experimental measurement and possible execution (depending on timing), and preparing a variety of supporting documents that will feed in to and provide the basis for future initiatives.

Another meeting will be held to identify all specific inputs needed to develop a focused overall RD&D project implementation plan, based on input from subject matter experts selected for their expertise related to this effort. An implementation plan (roadmap) will be developed using this document as the foundation. The work scope will then be executed by the implementation team.

The RD&D of the methodology will focus on structural performance evaluation of WE 17×17 pressurized water reactor fuel assemblies with a discharge burnup range of 30-58 GWd/MTU (assembly average), loaded in a representative high-capacity (≥32 fuel rod assemblies) transportation package. Evaluations will be performed for representative normal conditions of rail transport involving a rail conveyance capable of meeting AAR S-2043 specification. Modeling of the UNF is anticipated to be defined down to the pellet-cladding level and take in to account influences associated with spacer grids, intermediate fluid mixers, and control

components. The influence of common degradation issues such as ductile-to-brittle-transition will also be accounted for. All tool development and analysis will be performed with commercially available software packages exclusively. The completion date for the identified work scope is the end of FY2013.

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ACRONYMS

AAR	Association of American Railroads
BWR	boiling water reactor
CRIEPI	Central Research Institute of Electric Power Industry, a research institute of the Japanese nuclear industry
DBTT	ductile-to-brittle-transition temperature
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
FY	fiscal year
GWd	gigawatt-days
M&S	modeling and simulation
MTU	metric tons (Tonnes) of uranium
NCT	normal conditions of transport
NFST	Nuclear Fuels Storage and Transportation
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
RD&D	research, development, and demonstration
SME	subject matter expert
UFDC	Used Fuel Disposition Campaign
UNF	used nuclear fuel
UQ	uncertainty quantification
WBS	work breakdown structure

USED FUEL DISPOSITION CAMPAIGN
Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport - Method and Approach

1. INTRODUCTION

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development activities related to storage, transportation, and disposal of used nuclear fuel (UNF) and high-level radioactive waste. Within the UFDC, the UNF assessment capabilities task has been created to address issues of extended or long-term storage and transportation. The near-term objective of this task is to use a science-based, engineering-driven approach to develop the technical bases for transport of high burnup fuel, as well as low and high burnup fuel after extended dry storage.

Under current regulations, it is not sufficient for UNF to simply maintain its integrity during the storage period. It must maintain its integrity in such a way that it can withstand the physical forces of handling and transportation associated with restaging the fuel and moving it to a different location (such as an interim storage site, a geologic repository, or a treatment/recycling facility). Because limited information is available on the properties of high burnup fuel (exceeding 45 gigawatt-days per metric ton [Tonnes] of uranium [GWd/MTU]), and because much of the fuel currently discharged from today's reactors exceeds this burnup threshold, this initiative will pay special attention to high burnup fuels.

1.1 Background

In the United States, the UNF inventory continues to build as nuclear power generation, part of the nation's commercial power generation portfolio, continues to assist in meeting the country's energy demands. At the end of 2012, it has been estimated that the commercial nuclear industry has generated approximately 70,000 MTU of UNF contained in about 245,000 assemblies (140,000 from boiling water reactors [BWRs] and 105,000 from pressurized water reactors [PWRs]). By 2020, the projected total UNF discharges will be approximately 88,000 MTU (Carter et al. 2012). By then, roughly 35,000 metric tons of heavy metal is expected to be in dry storage with the remaining 53,000 metric tons of heavy metal in the reactor pools. At the time waste acceptance starts, the fuel in dry storage represents a legacy that must be dealt with regardless of what approach is taken to managing newly discharged fuel going forward. By 2060, when all currently licensed reactors will have reached the end of their operational lives, assuming a 60-year maximum, there will be approximately 140,000 MTU of UNF discharged from the reactor fleet (Carter et al. 2012).

Of particular interest are assemblies with high burnup, because concerns have been raised relative to cladding integrity of high-burnup fuel. The average discharge burnup for PWRs is approximately 48 GWd/MTU, and for BWRs it is approximately 43 GWd/MTU (EPRI 2010). However, by 2020 it is projected that the average discharge burnups will be 58 GWd/MTU for PWRs and 48 GWd/MTU for BWRs.

As the burnup increases, a number of changes occur that may affect the performance of the fuel, cladding, and assembly hardware in storage and transportation. These changes include increased thickness of the cladding corrosion layer, increased hydrogen content in the cladding, increased creep strain in the cladding, increased fission gas release, and the formation of the high burnup structure at the surface of the fuel pellets. Because of these changes and the lack of fuel performance data at higher burnups, especially under design basis accident conditions the current maximum rod-averaged burnup is limited by the U.S. Nuclear Regulatory Commission (NRC) to 62 GWd/MTU. Newer cladding materials such as ZIRLO™ and M5® were developed to mitigate the effects on cladding associated with these higher burnups. However, because these materials are relatively new, very limited data are available publicly that can be used to determine how these materials may perform under storage and transportation conditions (DOE 2012).

Depending on the drying process and/or storage conditions, the ductile-to-brittle-transition temperature (DBTT) of specific types of high burnup cladding may increase substantially because of hydride reorientation. As the fuel cools during storage, it may cool below the DBTT before the fuel is handled and transported at the end of interim storage. If the UNF cladding temperature at the time of transport is below the DBTT, the chances for damage to the fuel cladding under normal conditions of transport (NCT) will increase.

The implementation of consolidated interim storage of UNF, consistent with the Blue Ribbon Commission on America's Nuclear Future recommendation, and DOE's recently published *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*[a], would also necessitate the implementation of a large-scale transportation program. Some of the used fuel in the inventory would be transported at least twice to get it to a repository—once from the reactor to the consolidated interim storage facility and then to a repository for final disposal—after an unknown storage duration. Given the uncertainty in material properties of high burnup fuel, variability in storage duration, and the potential variability in the magnitude and duration of normal loading during transport, it is appropriate to investigate whether or not one or multiple transports would have a negative impact on fuel integrity and its suitability to meet the regulations for interim and final storage after transport. Hence, understanding performance characteristics of UNF cladding and ancillary components under cumulative loading stemming from storage, transfer (from storage container to transport container if needed), and NCT is necessary as it establishes the safety basis via definition of the primary containment boundary, maintains criticality safety, and is one of the critical components to the preservation of retrievability.

[a] U.S. Department of Energy, January, 2013, http://energy.gov/downloads/strategy-management-and-disposal-used-nuclear-fuel-and-high-level-radioactive-waste

Researchers within the UFDC and Nuclear Fuels Storage and Transportation (NFST) communities would like to demonstrate that enough information, experimental support and modeling and simulation capabilities exist to establish a preliminary determination of UNF structural performance under NCT. A steering team composed of national laboratories, DOE, and NRC staff met to discuss project feasibility. The group identified the basic information required and established a rudimentary path for a successful research, development, and demonstration (RD&D) plan. The Steering Team Meeting took place at the DOE National Nuclear Security Administration (NNSA) Nevada Site Office December 11-12, 2012. The Steering Team list of participants is provided in Appendix A. This document presents the decisions made by the team and the proceedings from the meeting.

Another meeting is planned for February 2013. Subject matter experts (SMEs) were selected to identify the specific inputs needed to develop a focused overall RD&D project implementation plan. A subset of the SMEs will be selected as the implementation team, and this document will serve as the foundation for the RD&D project implementation plan. The plan will contribute to an over-arching blueprint for resolving the numerous technical challenges related to extended storage and transportation of UNF.

1.2 Objectives

The objective of the work is to determine the mechanical loads, with quantified uncertainties, on used nuclear fuel, cladding, and key structural components of the fuel assembly during NCT and storage and to assess the response of the used fuel and assembly to those loads. To the extent possible, high-priority literature reviews have been initiated already. Scoping modeling and simulation (M&S) activities determined to be of high priority and value will be initiated at the earliest possible date. The work scope will support development and integration of UNF data and analysis capabilities, as well as support the UFDC mission regarding scientific research and technology development to strengthen the technical basis for storage and transportation of UNF. The UFDC mission technical support includes, but is not limited to, collecting information via literature review, soliciting input from SMEs, developing and demonstrating methodology, performing computational analyses, planning and executing experimental measurement, and preparing a variety of supporting documentation that will feed into and provide the basis for future initiatives. The completion date for the work scope identified herein is the end of fiscal year (FY) 2013. The fundamental near-term objectives of this initiative are:

1. **Perform literature reviews to establish the quantity and type of information available in three specific areas: mechanical loading during storage and transportation, system and UNF material properties, and state-of-the-art modeling and simulation techniques.** This review process will serve to identify, assemble, and document encompassing data and information as well as inputs yielded, and identify information gaps. The resulting information will be used to establish databases to support work performed under this initiative, as well as future programs and tasks. Specific details and associated guidance are provided in subsequent sections of this document.

2. **Develop database of information required for modeling via the literature reviews and associated topical influencing factors.** Information stemming from material properties, specified loading conditions, applicable boundary conditions, etc., will be consolidated, and sensitivity ranges will be selected for implementation in future M&S efforts. Uncertainty quantification (UQ) will be limited to UNF mechanical properties during this initiative because of the volume of work scheduled to be conducted and the associated aggressive period of performance.

3. **Apply information from the literature reviews to construct M&S tools capable of performing high resolution deterministic structural evaluations.** These M&S tools will be constructed and documented in a fashion that is conducive to future upgrades and modifications/alterations for performing alternate simulations, and readily accommodates the incorporation of information as it becomes available. Fundamentally, these tools will be constructed so that they may be readily implemented in future initiatives/assessments to address issues or questions as they arise.

4. **Select and perform one or more validation cases to establish the credibility of the methodology as well as the capability of M&S tools' predictive capability.** The number and type of validation cases will be selected based on availability and pertinence to the deterministic predictions intended to be performed for this initiative.

5. **Provide an initial demonstration of the developed tool's capabilities by performing preliminary deterministic evaluations of moderate-to-high burnup UNF performance under storage and NCT conditions.** The completion of this demonstration will serve to identify all data and information gaps that might exist, and the types of testing that might be needed to fill those gaps. It will also showcase the development and integration of UNF data and analysis capabilities as well as couple M&S and experimental efforts with focused UQ techniques.

The long-term over-arching goals and objectives of the initiative are to:

- provide an analytical assessment of used fuel integrity subjected to NCT and the type of ductility demands that would be required to ensure adequate high burnup UNF performance and survivability under a normal transport campaign
- answer open questions relative to the ability of high burnup used fuel to maintain its integrity and retrievability as it moves through each step of the waste management process (storage, transportation, repackaging, and disposal)
- generate validated tools and information to aid in making critical future decisions regarding determination of storage and disposal paths
- identify those future tests that would be sufficient to address technical issues that need to be resolved
- contribute to an overarching blueprint for resolving the numerous technical challenges related to extended storage and transportation of UNF.

2. PERSPECTIVES AND CONSIDERATIONS

Understanding performance characteristics of UNF under loading stemming from storage, transfer (from storage container to transport container if needed), and NCT and quantifying cumulative effects is important to maintaining safety bases and preserving fuel retrievability. However, integration of supporting information and all possible loading influences is beyond the scope of this initiative. With this in mind, the steering team elected to focus on constructing the computational tools to accurately evaluate transportation loading scenarios. Because this initial effort is focused on computational tool development, literature data will be utilized wherever possible and actual experimental work will be limited. As such, limited work will be performed for determination of possible loadings during, and evaluation of, storage configurations and an initial fuel material condition/state will be assumed based on the best information available to date. The intent is to address cumulative effects through a multi-staged approach. This will be handled by modularizing the computational tools so that the capability to account for storage and transfer conditions outside those assumed in this study can be readily incorporated in the future.

Even though it is anticipated that the M&S tools developed during this initiative will be capable of performing accident-related performance assessments, no accident-related evaluations will be performed. This decision is influenced by the fact that storage and transportation packages involved in an event (beyond the definition of normal or off-normal conditions per 10 CFR 71 or 10 CFR 72) would have a unique and different disposition path than normal packages. Additionally, despite a possible safety basis shift to the canister level or alteration in the definition of retrievability, understanding of UNF structural performance is still necessary to demonstrate that regulatory safety basis requirements are met.

2.1 Transportation Modes

Understanding the influence of rail and over-the-road transportation modes is necessary. A relative conclusion established in the National Transportation Plan (DOE 2009) is that a vast majority (possibly even greater than 90 percent) of the UNF inventory will be transported by rail. Per this document, DOE selected the mostly rail scenario as the transportation mode to be analyzed in a repository related Environmental Impact Statement. Additionally, The Office of Civilian Radioactive Waste Management issued a policy stating that dedicated trains will be the usual mode of rail transportation for UNF and high-level radioactive waste.

UNF rail transport conveyances will need to meet the proposed Association of American Railroads (AAR) *Performance Specification for Trains Used to Carry High Level Radioactive Materials*, AAR Specification S-2043. An example of this type of conveyance is the Naval UNF Transporter M-290-0001 Cask Car shown in Figure 2.1. The specified peak accelerations provided by a conveyance meeting this standard are also reduced substantially in comparison to those measured in previous studies (such as Magnuson 1978) for truck transport, or from loading that would be anticipated from a typical conveyance device designed to meet ANSI N14.23 restraint requirement. Over-the-road transportation information will be collected during the literature review portion of this initiative. Truck transport associated loading is anticipated to bound that of rail and will eventually require evaluation. However, rail will remain the primary focus at least until an order of magnitude deterministic assessment on the ductility requirements of UNF under this mode of transport is fully realized.

Figure 2.1. Naval UNF Transporter M-290-0001 Cask Car (Meets AAR S-2043)

2.2 Selection of Representative Transport Configuration and Used Nuclear Fuel for Model Development and Analysis

For economic reasons, the nuclear industry is currently using large dry storage systems with canister capacities up to 37 PWR and 80 BWR fuel assemblies, with larger capacity canisters being considered for future use.

A total of 1,570 loaded canisters in dry storage systems are currently in use at active or decommissioned reactors. Figure 2.2 shows the proportion of the total made up by each canister type. This same data are re-plotted in Figure 2.3 with the individual canister types grouped based on design and vendor. Canister systems from a single vendor often share design features such as physical dimensions and material compositions. The five most currently used canisters, in descending order, are the HI-STORM MPC-68 (Holtec), the NAC-UMS UMS-24 (NAC International), the NUHOMS 24P (Transnuclear), the HI-STORM MPC-32 (Holtec), and the NUHOMS 61BT (Transnuclear). When broken down by vendor/design, just three vendors have provided approximately 75% of the total canisters in use. These are, in descending order: NUHOMS (Transnuclear), HI-STORM (Holtec), and NAC-UMS UMS-24 (NAC International) (Miller et al. 2012).

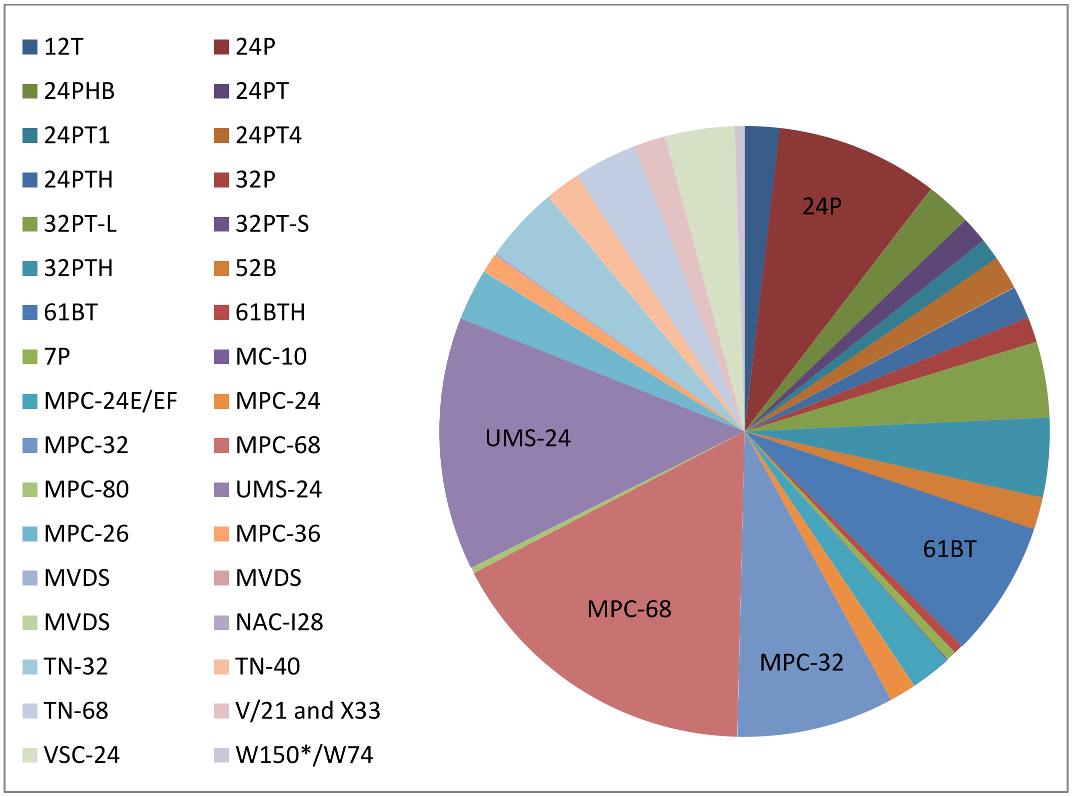

Figure 2.2. Relative Frequency of Storage Systems in Use (Source: Miller et al. 2012)

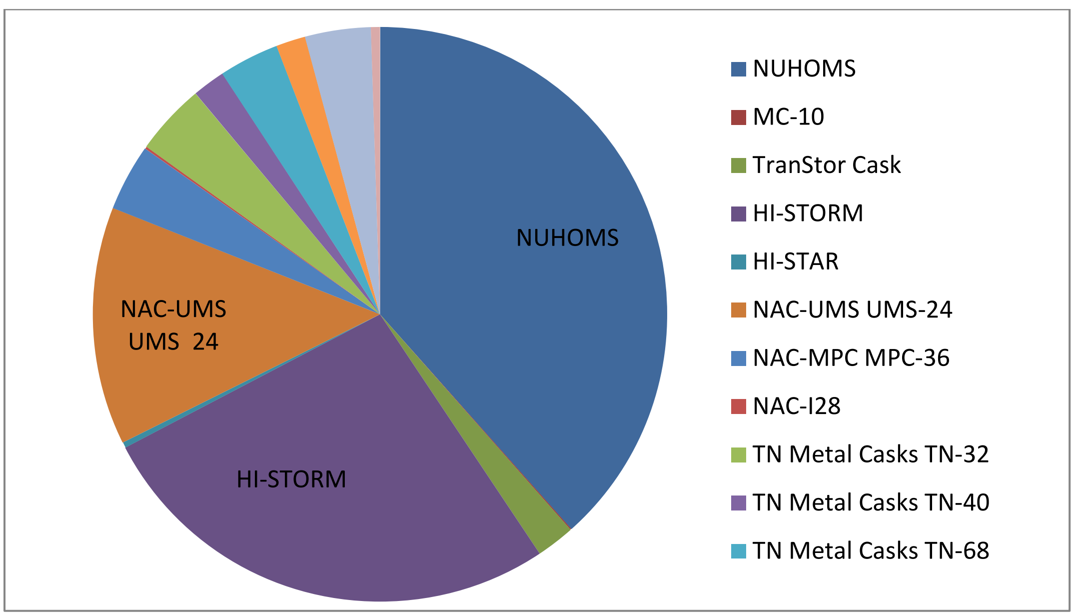

Figure 2.3. Relative Frequency of Existing Storage Systems Grouped by Design and Vendor (Source: Miller et al. 2012)

As shown in Figure 2.2 an abundance of UNF configurations requiring future transport exist. Of the highly utilized Light Water Reactor fuel assemblies, the BWR configuration is recognized to be more structurally robust due to its slightly larger rod diameter, cladding thickness, the presence of the fuel channel, and configuration of its ancillary support structure. As such, the PWR is targeted as a configuration of high interest. As of 1987, 35 percent of all PWR UNF inventory was WE 17×17 type fuel assemblies (Weihermiller and Allison 1979). By 1993, 50 percent of all PWR UNF inventory was WE 17×17 type fuel assemblies (Energy Information Administration 1995). Now, almost all PWRs (except Combustion Engineering plants) use WE 17×17 type fuel assemblies. As such, the WE 17×17 PWR fuel assemblies, or permutations of this base assembly configuration, will represent the greatest fraction of PWR UNF inventory.

The WE 17×17 fuel assembly type should represent the least robust configuration in comparison to other multi-rod PWR configurations because of reduced fuel rod diameter and cladding thickness. As such, the Steering Team decided that an initial transport packaging candidate must be representative of a high-capacity PWR (≥32 assembly payload) transportation package and would be defined to contain a payload initially comprising WE 17×17 fuel assemblies. This definition would also leave room to evaluate variants of the WE 17×17 fuel assemblies without making substantial changes to the initial M&S tool definitions.

Given the wide range of dry cask storage systems currently in use and the abundance of WE 17×17 PWR fuel, a generic 32 PWR canister model will be developed and used for the analyses.

2.3 Additional Influencing Factors

The steering team members clearly identified that integration of the capability to capture the influence of degraded fuel assembly components such as spacer grids, intermediate fluid mixers, and control components is a specific requirement. Also, the influence of interaction between fuel cladding and fuel pellets, and other influencing factors such as DBTT, etc., must also be considered based on the viability and availability of information required to do so. Temperature-sensitive material properties must be established, based on realistic thermal profiles stemming from anticipated NCT. The thermal profiles must also be based on prototypic decay heating established from reactor burn, pool cooling, and dry storage durations. Evaluations to establish possible decay heat loading and assembly material property definitions need to consider a spectrum of credible discharge burnup values. In the late 1970s assembly average discharge burnup was around 30 GWd/MTU. At that time, the energy policy in the United States was changed to focus on more efficient utilization of uranium in light water reactors. In response to this change, a number of programs were introduced under the sponsorship of the DOE, the Electric Power Research Institute (Smith et al. 1993), fuel vendors, and utilities. These programs collected data that demonstrated reliable fuel performance at increasing burnup. By the mid-1980s it had been demonstrated that assembly average burnups of 45 GWd/MTU was possible (Smith 1983; Dideon and Bain 1983) and by 1990, it had been demonstrated that assembly average burnup of 57 GWd/MTU was possible (Smith et al. 1993). Since this time, fuel assemblies have been discharged with a burnup of around 55-58 GWd/MTU. The peak rod average burnup limit is 62 GWd/MTU (OECD NEA 2012). Based on this history, values ranging from 30-58 GWd/MTU assembly average burnup are viewed to be credible for covering the current UNF candidates, as they include assemblies discharged between 1970 and 2005.

All analytical packages anticipated to be selected for tool development for this initiative will be commercially available and have a proven predictive capability for the intended application. Finally, generic transportation packaging definitions must be used wherever practical, yet all packaging definitions must resemble one that could readily be considered for obtaining a Certificate of Compliance for transport purposes. As such, all components that would influence the structural performance need to be captured and accounted for during tool generation. If these guidelines are implemented, no unfair advantage can inadvertently be provided to applicants, utilities, or manufacturers who select a particular design.

2.4 Quality Assurance

Inputs and analyses will be completely documented, all supporting information traceable, and bases defendable so as to be most useful to the DOE community and mission. In an effort to maintain cost effectiveness and provide the greatest impact within the limited period of performance, the Steering Team deemed that the laboratories' or participants' quality assurance programs are suitable for the current scope of work anticipated. The Steering Team also decided that this decision would be revisited at a later date and that a more regimented quality assurance program, such as NQA-1, may be required in the future.

3. PROPOSED SCOPE

The proposed scope of this initiative will drive the RD&D of a methodology, including development and use of analytical tools, to evaluate loading and associated mechanical responses of UNF rods and key structural components. The developed methodology is expected to involve coupling M&S with experimental efforts currently underway within UFDC. It will include sensible/limited UQ focused around available fuel and ancillary fuel structure properties exclusively. The technical support work includes, but is not limited to, collecting information via literature review, soliciting input from SMEs, developing and demonstrating methodology, performing computational analyses, planning experimental measurement and possible execution (depending on timing), and preparing a variety of supporting documents that will feed into and provide the basis for future initiatives. A flow chart of the associated work scope is shown in Figure 3.1. As previously identified, the completion date for the work scope identified herein is the end of FY2013. A Gantt chart indicating interacting activities within the specified work scope and associated deliverable milestones is presented in Appendix B.

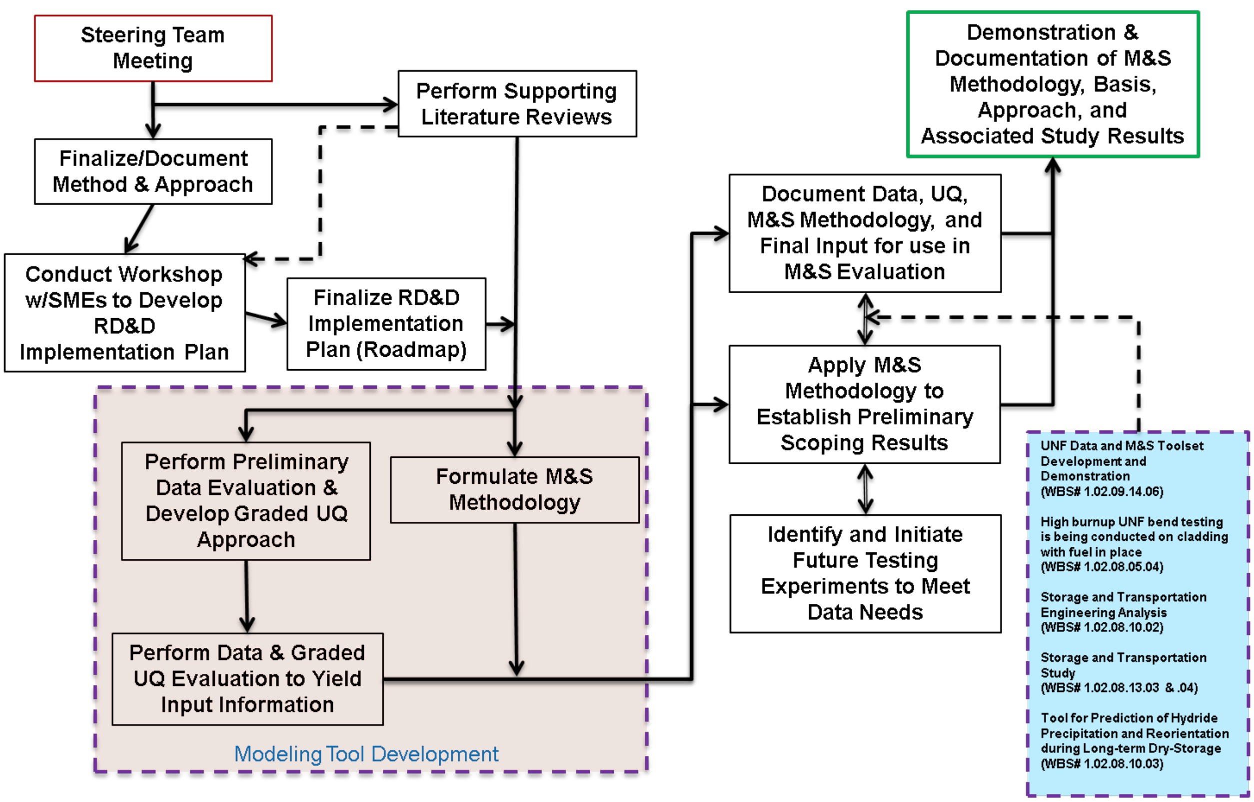

Figure 3.1. Work Scope Flow Chart

Integration of information stemming from DOE's UFDC and NFST M&S and experimental programs are vital to the success of this initiative. Integration will mitigate duplication of efforts, provide a flux between the supporting campaigns, potentially backfill previously identified information gaps, and aid in collectively evaluating and identifying additional information gaps that might need to be addressed. Work that should be evaluated for possible integration with supporting information is described as follows.

Storage and Transportation Engineering Analysis (WBS# 1.02.08.10.02)

A number of storage and transport systems have been studied under this work breakdown structure (WBS). Pre-test temperature distribution predictions have been, and will continue to be performed for full storage systems and associated components. The purpose of this work is to support storage site inspections. Thermal and stress profile work has been performed and is under way for prototypic storage and transport systems as well. Thermal and structural sensitivity evaluations are also being performed to establish and support the understanding of degradation mechanisms.

Storage and Transportation Study (WBS# 1.02.08.13.03 & .04)

Shaker table testing, M&S, and evaluations involving a standard WE 17×17-type PWR are being performed under these WBSs. Preliminary pre-test modeling has been performed to aid in determining instrumentation locations. Some pre-test simulations are underway and others are pending finalization of mockup material property verification. This work will involve more discrete modeling of mockup fuel pins such as explicit definition of the materials selected to mimic the cladding and fuel pellets. Some supporting scoping cask body influence evaluations need to be performed for this to directly tie to the initiative described herein. Physical testing is pending mockup completion. Algorithms converting LS-DYNA models into PRESTO (Livermore Software Technology 2007, SAND2011-1824) models are under construction. It is envisioned that these algorithms will aid in providing baseline analyses for future benchmarking and validation of modeling techniques involving PRESTO as well as cross-comparison between LS-DYNA and PRESTO. This work could also serve as part of the validation of the M&S methodologies anticipated to be developed for this initiative.

UNF Data and M&S Toolset Development and Demonstration (WBS# 1.02.09.14.06)

Radiation and shielding code SCALE (ORNL/TM-2005/39), and the thermal hydraulics code COBRA-SFS (Michener et al. 1995), are being coupled to yield an assessment tool that can be used to establish fully detailed radionuclide inventory and highly resolved shielding, dose, and temperature distribution characteristics for a specific UNF package. This work is being conducted under NFST sponsorship and direction.

High Burnup UNF Bend Testing Conducted on Cladding with Fuel in Place (WBS# 1.02.08.05.04)

This testing is being conducted on H.B. Robinson WE 15×15 rod segments with 63-67 GWd/MTU average assembly burnup. This work is currently being conducted under NRC sponsorship. UFDC is anticipating collaborating on follow-on research in FY2013.

Tool for Prediction of Hydride Precipitation and Reorientation during Long-term Dry-Storage (WBS# 1.02.08.10.03)

Hydride reorientation and cladding degradation modeling as well as other supporting cladding testing and experimentation are also under way. However, it is anticipated that this information will not become available until after this initiative has been completed.

4. WORK SCOPE

The sections that follow define how subtasks of this initiative must be conducted and give recommendations for specific actions/activities to be performed based on SME recommended direction.

4.1 Literature Review

High-priority literature reviews have been initiated. The objective of these reviews is to establish the quantity and type of information available in three specific areas germane to this initiative. They are: mechanical loading during storage and transportation, system and UNF material properties, and state-of-the-art modeling and simulation techniques. In each area the following will be established:

- mechanical loading that UNF cladding and key structural components could be subjected to during NCT and storage. Mechanical loading inputs will take into account the possible types of conveyances and packaging configurations targeted for road and rail transport.
- applicable material properties for storage, transfer, and transport packages, conveyances, and especially properties of UNF cladding and ancillary components. However, transport related items will remain the primary focus.
- state-of-the-art M&S methodologies and their accompanying evaluation techniques commensurate with the objectives. In doing so, identify, gather, and consolidate literature on M&S (materials models, methodologies, computational framework, benchmark studies, possible methodology validation information, etc.).

The review process will serve to identify, assemble, and document applicable data and information, as well as inputs yielded, and identify information gaps. The resulting information will be used to establish databases to support work performed under this as well as future programs and tasks.

4.1.1 Transportation and Storage Loading, Boundary Conditions, and Applicable Regulations

A literature review will be performed to identify all loadings and governing regulations applicable to establishing preliminary performance characteristics of used fuel during normal conditions of storage and transport in the United States. In particular, all available measured data relative to mechanical loads on cladding and key assembly structural components will be identified, with an emphasis on data needed to perform analyses (e.g., input loads at a package surface), and data that could be used to validate analysis codes and predictions. Encompassing data and information as well as inputs yielded from this literature review, will be documented. Also, specific recommendations based on the information available will be documented, and guidance regarding implementation in future M&S evaluation work performed under this as well as possible future programs will be provided. Where possible, data gaps in supporting information and boundary conditions that may exist, will be identified. Recommendations for possible sources of information could include but are not limited to:

- Normal conditions of transport (transportation loading, boundary conditions, and applicable regulations for rail and over the road)
  - 10 CFR 71
  - Possible Conveyance Candidate(s) – (DOE's firm belief that SNF conveyances will all need to meet AAR S-2043 – Performance Specification for Trains Used to Carry High Level Radioactive Materials)
  - Sandia study of shock and vibration in truck transport (Magnuson 1978)
  - Possible data and information from Transportation Technology Center, Inc.
  - Transport loading time histories from fresh fuel transports
- Normal and Off-normal Storage Conditions
  - 10 CFR 72
  - Central Research Institute of Electric Power Industry (CRIEPI) Seismic Simulations
- Possible loading incurred during transfer
- Other available data to validate analysis codes, methodologies, and predictions that may exist in the literature.

As previously stated, storage and over-the-road transportation information will be collected during the literature review portion of this initiative. However, rail will remain the primary focus of this initiative at least until an order of magnitude deterministic assessment on ductility requirements of UNF under this mode of transport is fully realized.

4.1.2 Material Properties

A literature review will be performed to identify material properties relevant to moderate to high burnup used nuclear fuel, as well as associated storage and transport components, to establish a credible database to feed into M&S tools for determining cladding and fuel assembly specific mechanical performance characteristics. Applicable data and information as well as inputs yielded from this literature review will be documented. Also, specific recommendations based on the information available will be documented, and guidance regarding implementation in future M&S evaluation work performed under this, as well as possible future programs, will be provided. Data gaps in supporting information and boundary conditions that may exist will be identified. Possible sources of information could include but are not limited to:

- Documentation pertaining to storage and transport cask/packaging systems such as Safety Analysis Reports and vendor data sheets and specifications
  - establish preliminary focus on most viable high-capacity PWR ($\geq$32 assembly payload) transportation package candidates
- Available low/moderate/high burnup UNF information

- primary focus on PWR configurations with WE 17×17 type configuration of but should also include other smaller rod diameter PWR fuel configurations (e.g., WE 15×15) and associated cladding candidates
- assembly average burnup values ranging from 30-58 GWd/MTU are viewed to be credible and should be considered for data collection
- cladding test data and material information for degraded fuel assembly components such as spacer grids, intermediate fluid mixers, and control components
- realistic thermal profiles stemming from anticipated NCT.

Understanding performance characteristics of UNF under loadings stemming from storage, transfer, and NCT and establishing cumulative effects is viewed to be critical to maintaining safety bases and determination of fuel condition for retrievability purposes. However, integration of supporting information and all possible loading influences is viewed to be somewhat optimistic given the period of performance. As such, limited work will be performed for collection of information pertaining to any configurations other than transport, and an initial fuel material condition/state will be assumed, based on the best information available to date.

4.1.3 Modeling and Simulation

A literature review identifying modeling inputs and previously applied M&S methodologies will be performed to establish a credible basis and state-of-the-art analytical approach for determining used fuel mechanical performance. Modeling methodologies considered should be based on loading of fully featured models and fully resolved meshing of UNF assemblies and relevant assembly components. Applicable data, information, and previously implemented modeling methodologies as well as inputs yielded from this literature review will be documented. Also, specific recommendations based on the information available will be documented and guidance regarding implementation in future M&S evaluation work performed under this, as well as possible future programs, will be provided. Recommendations for sources of information could include but are not limited to:

- Identifying previously implemented
  - modeling inputs and constitutive relations
  - M&S methodologies and modeling approaches that are relevant to the current initiative/scope
  - codes and computational packages that are relevant to the current initiative/scope
    - note: code candidates must be commercially available (e.g., Abaqus, LS-DYNA, etc.)
  - verification and validation, and benchmarking studies
  - evaluations of codes and computational package capabilities that are applicable.

4.2 Solicitation of Input from Subject Matter Experts

A working meeting is scheduled to be held in February 2013 to identify all necessary inputs and strategies needed to develop a refined and focused overall RD&D project implementation plan. This plan will be constructed collectively by the SMEs based on their input and recommendations. Members of the contributing SMEs will be selected to form a core implementation team that will assist with execution of the implementation plan as documented. Near the conclusion of the working meeting, responsibilities will be established and deliverable dates will be communicated. The Implementation Team will initiate execution of the plan shortly after preliminary program review and approval, and at the discretion of the Initiative Lead.

4.3 Methodology Development

A methodology for generation of the M&S evaluation tools must be developed and documented based on previous literature findings, available information, and recommendations established by the contributing SMEs. This task will be performed by the Implementation Team and will focus on assembling the foundation for constructing tools for performing adequately resolved deterministic structural evaluations. The foundation for constructing the tools must allow for future upgrades/modifications/alterations for performing additional simulations, and readily accommodate the incorporation of information as it becomes available.

M&S tool development activities determined to be of high priority and value will be initiated at the earliest possible date based on the recommendation provided by the Implementation Team. Models that Pacific Northwest National Laboratory has developed that could be used as a starting point are:

- Structural
  - Casks (Holtec HI-STAR 100, Transnuclear TN-68 & TN-40)
  - UNF (WE 17×17, GE 9×9)
- Thermal
  - Casks (Majority of transportation, transfer, and storage cask industry leaders modeled)
  - UNF (numerous PWR & BWR assemblies modeled)

Models are anticipated to be available from additional sources including other national laboratories that may be viable to implement as a starting point, such as those constructed by Sandia National Laboratories (NUREG-2125). The Implementation Team will evaluate the applicability of models available and make a determination regarding integration. Final approval will be at the discretion of the Initiative Lead.

4.4 Computer Code(s), Methods and Application Development

A number of analytical codes and computational methods are generally used only in the national laboratory environment, and specific modeling approaches strongly depend on the subject matter under evaluation. As previously identified, all code candidates selected for application to support this initiative must be commercially available (e.g., Abaqus, LS-DYNA, etc.). The Implementation Team will evaluate the applicability of codes and methods available and make a determination regarding integration of codes, as required. Final selections will be approved by the Initiative Lead prior to application.

4.5 M&S Validation

Modeling and simulation, and associated methodology validation will most likely come from studies and information yielded by the literature reviews being conducted for this initiative. This belief is based on the absence of physical modeling and coupled testing of UNF in the DOE and NRC sectors. The Shaker Table Simulations/Evaluations work being performed under UFDC S&T (WBS# 1.02.08.13.03 & .04) could potentially serve to establish a viable benchmarking and validation path. The Implementation Team will be responsible for developing and recommending a credible validation path. Final selection will be approved by the Initiative Lead prior to application.

4.6 Experimental Measurement Planning and Possible Execution

A lack of data and supporting information, or "gaps," may be revealed during M&S methodology development or within the preliminary calculation phases under this initiative. The Implementation Team will evaluate the significance of any such identified gap and form recommendations regarding resolution paths. If a particular gap can be resolved via experimental measurement and will fit within the budget constraints and performance period of this initiative, real-time planning and possible execution will be proposed. This information will then be fed back in to the finalized tools and reflected in the analyses results prior to conclusion of the initiative. Otherwise, planning and execution will be recommended for possible future consideration, and will be communicated within UFDC.

A possible example of this might apply to performing additional bend testing of a WE 17×17 rod using the test fixture at Oak Ridge National Laboratory. This might provide valuable information regarding influence of pellet-clad interaction based on rod size as the current testing at Oak Ridge National Laboratory is on an H.B. Robinson WE 15×15 high burnup UNF rod. This might also complement the shaker table testing work being conducted at SNL.

4.7 Methodology Demonstration

The methodology demonstration portion of this initiative will consist of exercising the tools developed during the M&S methodology development phase, which incorporates all retrieved and integrated bases and supporting information, to evaluate loading and associated mechanical responses of UNF rods and key structural components. These tools will be used to evaluate performance characteristics of UNF cladding and ancillary components under loading stemming from NCT. In doing so, a preliminary assessment of the regulatory basis will have been performed. This assessment will provide insight into the post-transport integrity of the UNF rods and effects on subsequent retrievability.

An encompassing Project Summary Report will document the overall results of the project, including methodology, analytical and experimental results, findings and associated interpretations (activity M2FT-13OR0822015-Demonstration of Approach and Results on Used Fuel Performance Characterization identified in the Gantt chart in Appendix B.). Recommendations for further work will also be developed and documented by the Implementation Team. Additionally, all inputs and analyses will be completely documented in a traceable and defendable manner, and analysis tools will be made available to DOE's UFDC & NFST communities for future assessment purposes.

5. CONCLUSIONS

An approach is proposed to drive the RD&D of a methodology, including development and use of analytical tools, to evaluate loading and associated mechanical responses of UNF rods and key structural components. This methodology will be used to provide a preliminary assessment of the performance characteristics of UNF cladding and ancillary components under rail-related NCT loading. The developed methodology is expected to involve coupling M&S and experimental efforts currently under way within UFDC. It will involve sensible/limited UQ focused around available fuel and ancillary fuel structure properties exclusively. The proposed technical support work will include collecting information via literature review, soliciting input/guidance from SMEs, developing and demonstrating a methodology, performing computational analyses, planning experimental measurements and possible execution (depending on timing), and preparing a variety of supporting documents that will feed into, and provide the basis for, future initiatives.

A steering team composed of national laboratory, DOE, and NRC staff met to identify the necessary information needed to establish a rudimentary path for this RD&D plan. This document was assembled to capture and communicate the proceeds of the working meeting. It was concluded that

- immediate benefit would come from an RD&D of a methodology, including and analytical tool development, that is focused on structural performance evaluations of a WE 17×17 PWR loaded in a representative high-capacity (≥32) transportation package
- an average assemble discharge burnup range of 30-58 GWd/MTU was most applicable
- influence of common degradation issues, such as DBTT, need to be accounted for
- evaluations need to be performed for representative normal conditions of rail transport involving a rail conveyance capable of meeting AAR S-2043 specification
- modeling of the UNF should be defined down to the pellet-cladding level and influences associated with spacer grids, IFMs, and control components should be taken into account
- all tool development and analysis must be performed with commercially available software packages exclusively (e.g., Abaqus, LS-DYNA, etc.).

Another meeting will be held in February 2013 to identify all specific inputs needed to develop a focused overall RD&D project implementation plan, based on input from SMEs selected for their expertise related to this effort. An implementation plan (roadmap) will be developed using this document as the foundation after SME input is received. The work scope will then be executed by an implementation team.

The completion date for the identified work scope is the end of FY2013.

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Appendix A

Steering Working Group Meeting Participants List

Appendix A

Steering Working Group Meeting Participants List

Used Nuclear Fuel Loading and Structural Performance under Normal Conditions of Transport & Storage Attendance List			
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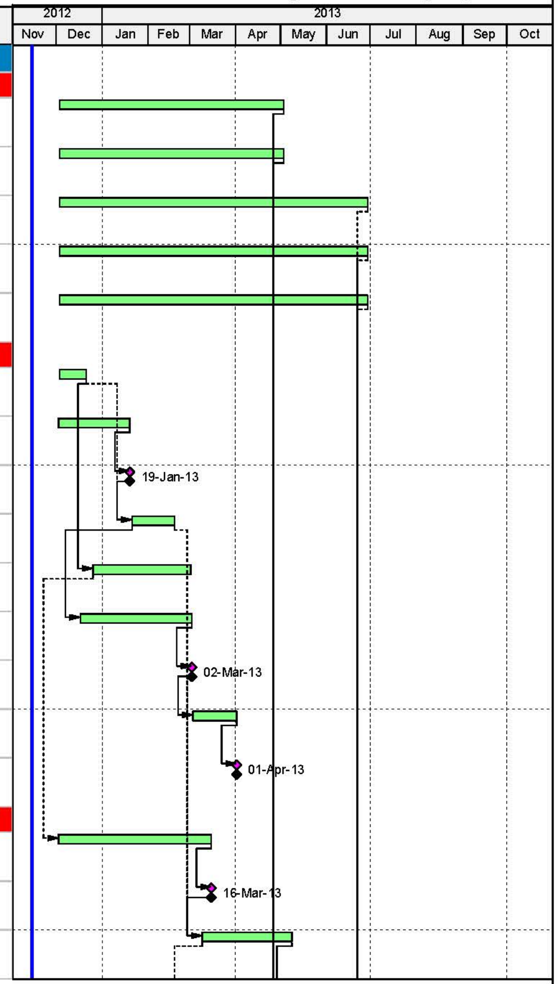
Appendix B

Program Gantt Chart

High Burnup Fuel Performance Modeling Plan Development

Updated: January 31, 2013

Activity ID	Activity Name	Start	Finish
HBUF	**High Burnup Fuel Perfomance Modeling Plan Development**	03-Dec-12	30-Sep-13
HBUF.1	**Complementary UFDC Program Information/Data**	03-Dec-12	28-Jun-13
0085	High burnup UNF bend testing is being conducted on cladding with fuel in place (WBS# 1.02.08.05.04)	03-Dec-12*	03-May-13
240	UNF Data and M&S Toolset Development and Demonstration (WBS# 1.02.09.14.06)	03-Dec-12*	03-May-13
250	Storage and Transportation Engineering Analysis (WBS# 1.02.08.10.02)	03-Dec-12*	28-Jun-13
260	Storage and Transportation Study (WBS# 1.02.08.13.03 & .04)	03-Dec-12*	28-Jun-13
270	Tool for Prediction of Hydride Precipitation and Reorientation during Long-term Dry-Storage (WBS# 1.02.08.10.03)	03-Dec-12*	28-Jun-13
HBUF.2	**HBUF Integration Plan**	03-Dec-12	01-Apr-13
0080	ActivityFT-13OR0822014 Conduct Core Team Meeting	03-Dec-12*	21-Dec-12
0060	Develop Final Method and Approach Document	03-Dec-12*	19-Jan-13
0070	M4FT-13OR0822019 Finalize Method and Approach Document		19-Jan-13
0050	ActivityFT-13OR0822012 Conduct Workshop on RD&D Plan with Implimentation Team	21-Jan-13*	18-Feb-13
0240	Perform Support Literature Reviews	26-Dec-12	01-Mar-13
0030	Develop Draft Modeling, Simulation and Experimental Integration RD&D Plan	17-Dec-12*	02-Mar-13
0040	M3FT-13OR0822013 Draft Modeling, Simulation and Experimental Integration RD&D Plan		02-Mar-13
0010	Develop Used Fuel Perfomance Modeling, Simulation and Experimental Integration Plan	03-Mar-13	01-Apr-13
0020	M2FT-13OR0822011 Used Fuel Performance Modeling, Simulation and Experimental Integration Plan		01-Apr-13
HBUF.3	**HBUF Finalize/Document Method & Approach**	03-Dec-12	08-May-13
220	Develop Documentation of data, material properties, modeling inputs and proposed analytical approaches	03-Dec-12*	16-Mar-13
230	M4FT-13OR08220111 Documentation of data, material properties, modeling inputs and proposed analytical approaches		16-Mar-13
200	Develop Doc of selected M&S methodology, proposed application of UQ established data and info., and selected dev. path	09-Mar-13	08-May-13



Actual Work ◆ ◆ Baseline Milestone

Remaining Work ◆ ◆ Milestone

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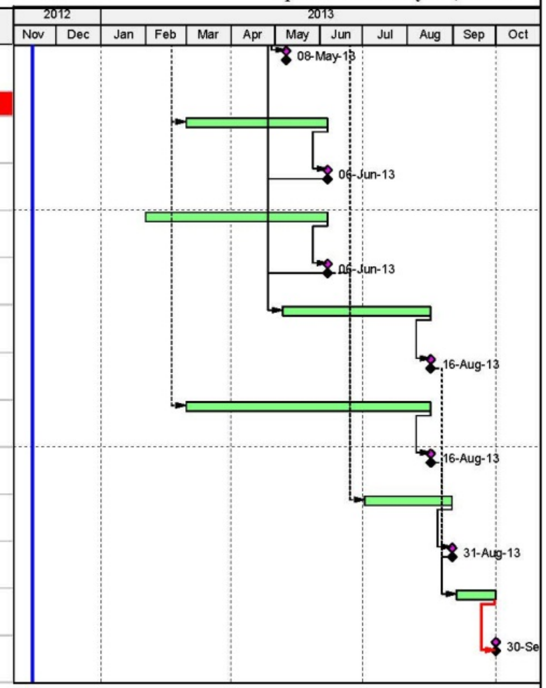
TASK filter: All Activities

High Burnup Fuel Performance Modeling Plan Development

Updated: January 31, 2013

Activity ID	Activity Name	Start	Finish
210	M4T-13OR08220113 Doc of selected M&S meth, proposed application of UQ established data and info., and selected dev. path		08-May-13
HBUF.4 HBUF Approach Demonstration		**01-Feb-13**	**30-Sep-13**
0170	Develop Report documenting final UQ development, approach, and resultsulting M&S input	01-Mar-13*	06-Jun-13
0180	M4FT-13OR08220110 Report documenting final UQ development, approach, and resultsulting M&S input		06-Jun-13
0190	Develop Report documenting experimental activities	01-Feb-13*	06-Jun-13
0200	M4FT-13OR08220112 Report documenting experimental activities		06-Jun-13
0130	Develop Report documenting final data, material property, and M&S input information	06-May-13*	16-Aug-13
0140	M4FT-13OR0822017 Report documenting final data, material property, and M&S input information		16-Aug-13
0150	Develop Report documenting final M&S methodology, basis, approach, and results	01-Mar-13*	16-Aug-13
0160	M4FT-13OR0822018 Report documenting final M&S methodology, basis, approach, and results		16-Aug-13
0110	Develop Draft Demonstration of Approach on Used Fuel Performance Characterization	02-Jul-13*	31-Aug-13
0120	M3FT-13OR0822016 Draft Demonstration of Approach on Used Fuel Performance Characterization		31-Aug-13
0090	Develop Approach and Results on Used Fuel Performance Characterization	03-Sep-13*	30-Sep-13
0100	M2FT-13OR0822015 Demonstration of Approach and Results on Used Fuel Performance Characterization		30-Sep-13



Actual Work ◆ ◆ Baseline Milestone
Remaining Work ◆ ◆ Milestone

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TASK filter: All Activities

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