Integrated Data and Analysis System for Commercial Used Nuclear Fuel Safety Assessments – 14657

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ABSTRACT

Uncertainties related to meeting packaging and transportation regulatory criteria are increasing as commercial UNF is being stored at reactor sites for longer time intervals than originally foreseen. As the storage times continue to lengthen, issues associated with aging management and the potential consequences of the deleterious effects of aging will need to be assessed. The assessments would be used to demonstrate the continued efficacy of the storage system over extended storage (ES) periods and to evaluate safety for subsequent transportation following ES. Licensed storage and transportation cask systems have well-defined assembly-loading criteria (e.g., specifications for "approved contents" in a storage cask system's Certificate of Compliance). These specifications are typically used to define limiting loading conditions and characteristics for which the cask system's safety analysis report has demonstrated compliance with the applicable regulatory requirements. In practice, because of the diversity in the discharged UNF available for loading (e.g., variations in UNF assembly burnup values, initial enrichments, discharge date), it is not possible to load a cask system with UNF assemblies that correspond exactly to the limiting licensing conditions. Hence, cask systems are loaded with assemblies that satisfy the limiting loading conditions with some amount of unquantified, uncredited margin. This reality in storage and transportation cask loading provides additional conservatism with respect to the regulatory safety requirements. These potentially large (depending on the specific loading conditions) safety margins may be quantified and potentially credited in the future to offset uncertainties in safety margins associated with ES and high-burnup fuel issues. To investigate this possibility, a new comprehensive and integrated data and analysis tool—UNF–Storage, Transportation & Disposal Analysis Resource and Data System (UNF–ST&DARDS)—has been developed. UNF inventory data, fuel assembly design data, site-specific cask loading data, and reactor operating data are coupled with fuel depletion, criticality safety, and thermal computational analysis capabilities to provide out-of-reactor nuclear safety evaluations in a highly automated manner. Comparisons with limiting loading specifications are used to quantify the available margin present in a variety of cask systems being used at different nuclear sites, and show that, at least for some loaded casks, significant uncredited safety margins are available.

INTRODUCTION

The management of UNF and HLW generated by the fleet of US nuclear reactors is complex. Complexities are introduced from a variety of factors, including the possibility that the UNF may be stored, transported, and handled multiple times before resting in a geologic repository; the large number of different fuel assembly types that have been and are being used by nuclear reactors; the number of reactor sites involved; the variety of dry storage systems in use; the changing inventory of fuel in dry storage; different approaches for transporting UNF from the reactor sites; changing nuclear and mechanical properties over time; uncertainties from materials aging; uncertainties regarding geologic disposal requirements; and the transfer of knowledge across multiple generations. One of the most important aspects for any large, complex system or project is a reliable source of information with a capability to dynamically update system parameters based on new information or changes in direction.

Performing different types of analyses required to understand the changing nuclear and mechanical characteristics of the UNF, and understanding how these changing characteristics affect the different storage, transportation, and disposal options, can require many tools and types of data. To streamline analysis capabilities for the waste management system, a comprehensive, integrated data and analysis tool has been assembled—UNF-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS). UNF-ST&DARDS provides a unified domestic UNF system database and associated key analysis capabilities to support numerous Department of Energy (DOE) waste management and fuel cycle–related objectives, as well as the foundation for tracking UNF from reactor power production through ultimate disposition. UNF-ST&DARDS provides a controlled source of technical data for various waste management system analysis/evaluation tools, as well as fuel cycle system analyses and safeguards and security studies; access to key technical data and analysis capabilities to characterize the UNF inventory; and enhanced capability to assess safety, risks, and uncertainties throughout the waste management system.

A unique, unprecedented capability within UNF-ST&DARDS is the performance of actual cask-specific evaluations. This capability is a novel approach allowing quantification of realistic safety margins and conditions of actual as-loaded UNF in existing dry cask storage systems. Overly conservative analyses based on bounding generic applications could lead to prematurely invoking compensatory measures within the waste management system, such as repackaging already packaged fuel, canning a significant fraction of UNF before storage, or requiring additional criticality control before transport and disposal (e.g., inserting control rod assemblies). For example, current thermal analysis methods typically overpredict the time-dependent temperature profiles by an amount that is not readily quantifiable in general, and that would vary widely based on the individual characteristics of a given site. This would hinder efforts to accurately predict the potential for confinement breaches due to low-temperature degradation phenomena (e.g., deliquescence) and would tend to overpredict the number of fuel rods that may fail during ES and/or transportation because of thermally driven mechanical property changes (e.g., hydride reorientation).

METHODOLOGY

Initial development of UNF-ST&DARDS has been a collaborative effort among multiple national laboratories and several utilities. The system infrastructure is composed of a UNF database (which is designed to be fully comprehensive, with new data still being added) coupled with analysis tools for out-of-reactor nuclear safety analyses. Automation sequences have been developed and initiated to generate data that can be used to assess the state of specific populations of the UNF over time, including UNF characterizations, neutronics analyses, and thermal analyses. Other technical areas such as dose, containment, and structural analyses are expected to be incorporated in the future. Additionally, plans are under way for integration with different systems and logistics analysis tools.

Data

Performing the different types of analyses required to understand the changing nuclear and mechanical characteristics of the UNF and the different storage, transportation, and disposal systems at various stages within the waste management system requires many tools and types of data. Technical data required for these types of analyses include commercial fuel assembly discharge information, fuel assembly design data, reactor-specific operation data, and cask design and loading data. Useful and relevant data are not consolidated or readily available (and actually may be lost over time), and the collection and availability of data related to spent fuel characteristics—particularly reactor exposure conditions and physical fuel conditions—could be used to reduce current analysis conservatisms (which would correspond to cost savings) and positively influence decision making related to design and licensing. Hence, efforts have been initiated to collect and consolidate the various sets of technical data into a single controlled, unified database system. The unified database will provide a consistent set of UNF data to support waste management system program planning, design, and operational requirements.

A visual depiction of the information flow within UNF-ST&DARDS is provided in Fig. 1. As can be seen, basic UNF information from a variety of sources is brought into the unified database. Nuclear fuel discharge and storage data from US commercial reactors are available through December 31, 2002 [1]. These data, referred to as the RW 859 database, contain basic discharge information for 70,292 PWR UNF assemblies and 93,351 BWR assemblies. The UNF assemblies in the RW-859 database are categorized into assembly classes based on assembly outside dimensions, which are further subdivided by assembly type for a total of 134 individual fuel assembly types discharged from both US PWRs and BWRs [2]. The discharge fuel data collection authorization is under the auspices of the DOE Energy Information Administration in coordination with the Office of the General Counsel. A new GC-859 database is currently being assembled to update the inventory information to the year 2013. Other data brought in come from a variety of open literature sources and from available nonproprietary vendor and utility data. Additional data collection efforts by the nuclear industry are ongoing with the help of the Nuclear Energy Institute. Reactor operating data, cask loading information, assembly dimensional specifications, and component specifications are some of the types of data being requested and incorporated into the unified database as they become available for inclusion. The unified database currently stores data as a function of decay for ~150,000 UNF assemblies and several hundred currently loaded cask systems. Additionally, the system has been designed to maintain full data traceability within the database system. The data are organized in relational structured query language (SQL) data tables within a MySQL database.

The unified database was initially designed to perform assembly-specific and cask-specific neutronics and thermal analyses for actual as-loaded cask systems currently in use. Different computational analysis packages can be linked to the unified database to receive data, generate results, and then write pertinent results back to the unified database for other tools or various data interrogations. Overall, UNF-ST&DARDS has been designed to be expandable. A new effort was recently initiated to incorporate additional information within the unified database to support systems and logistics analyses codes such as CALVIN (Civilian Radioactive Waste Management System Analysis and Logistics Visually Interactive) [3], TSM (Total System Modeling) [4], and TOM (Transportation Operations Model) [5], as well as to support development of the next-generation system architecture tools. The data and information flow needs and specifications for TSM, TOM, TSL-CALVIN, and the next-generation tools are currently being evaluated and developed to ensure database normalization (i.e., the process of reducing redundancy in and defining the relationships between database tables). In Fig. 1, the solid black arrows indicate where pipelines for information flow have been established with the unified database, the dotted red arrows indicate where data flow requirements are being considered for further development but have not been initiated yet, and the information outlined by the black dotted line boxes and the dotted black arrows show data sets in the process (at the time of this writing) of being imported into the database.

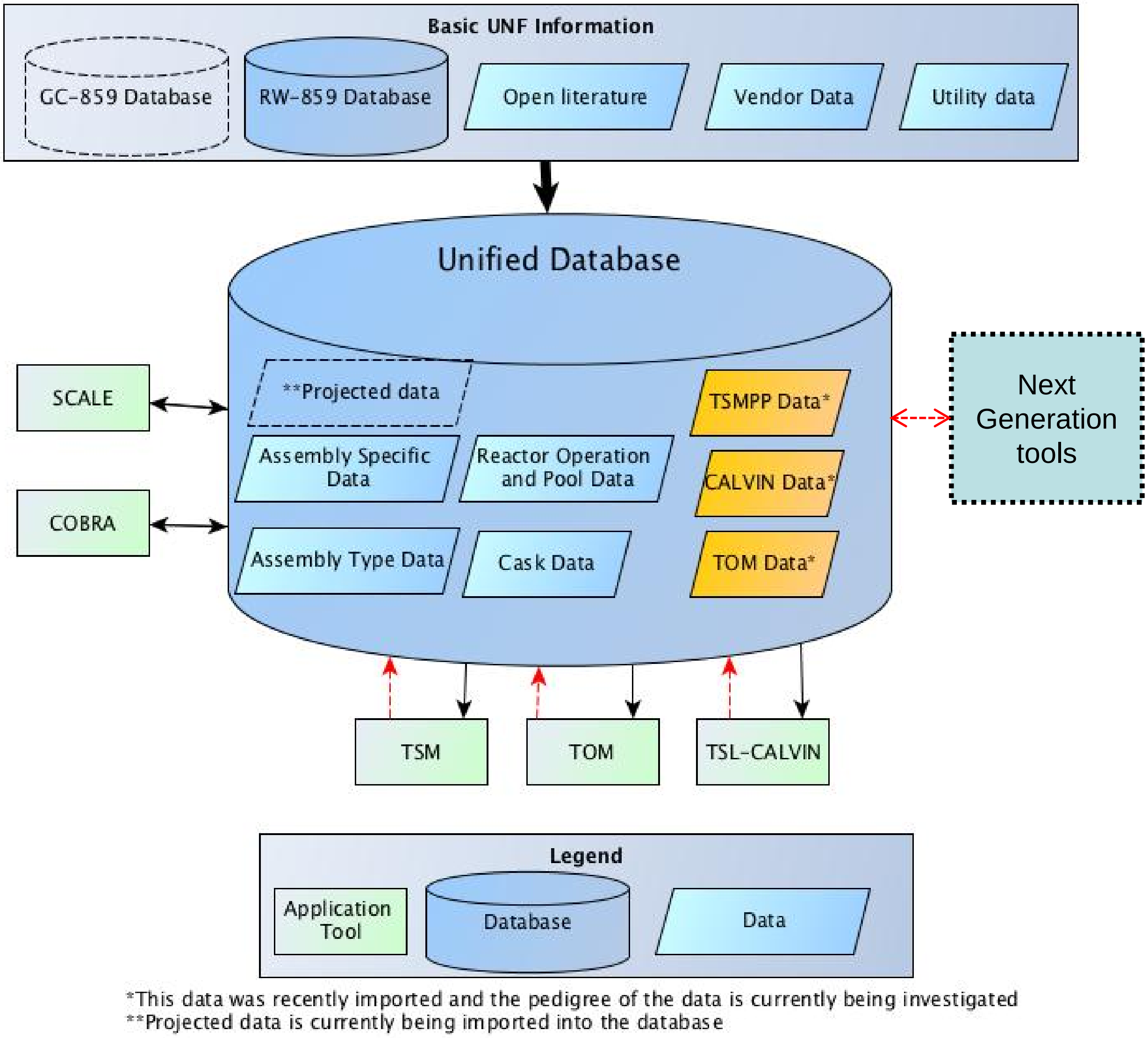

Fig. 1. Illustration of information flow for UNF-ST&DARDS.

Computational Analysis Automation

Various computational analysis tools can be linked with the unified database. A key database design element facilitating computational analysis automation is the data relations defined within the database that provide a foundation for data visualization/interpretation and comprehensive parameter sets from which integrated analysis can take place. To date, technical data collection and its synthesis into appropriate formats have been based on the well-established Standardized Computer Analysis for Licensing Evaluation (SCALE) code system [6] and the thermal-hydraulic analysis code COolant Boiling in Rod Arrays–Spent Fuel Storage (COBRA–SFS) [7] input requirements. The UNF-ST&DARDS automation system has been built around the SCALE and COBRA-SFS codes, but the automated input building process is independent of code choice. It could be readily adapted for other tool packages so that information from the unified database could be used directly once input requirements for the other tool packages are understood. The data relationships that have been defined allow the inputs to the respective codes to be built autonomously when basic information about the UNF and cask system is provided, and they reduce the user interaction required to build the large volume of inputs for characterizing the UNF for each respective site. Initial analysis capabilities have been focused on neutronics analyses and thermal analyses. Neutronics analyses are used to demonstrate key safety requirements [8, 9] and include depletion, decay, and criticality calculations. Thermal analyses are used to calculate component temperatures (e.g., cladding temperature) and are also fundamental to understanding cask surface degradation mechanisms.

To perform neutronics and thermal analyses, a library of model templates for SCALE and COBRA-SFS has been developed for different reactor sites and storage and transportation system variants. Within UNF-ST&DARDS, a template engine (or template processor) is used to combine site-specific input parameters from the unified database with the model templates and sub-templates developed for the neutronics and thermal calculations to produce complete input files for those types of calculations. A template engine is a string substitution program designed to take advantage of repeated structures in text files. The template engine takes the input parameter data structures represented by a JavaScript Object Notation (JSON) data structure and the root template file. With these two components, the template engine conducts attribute replacement and sub-template imports. The model templates contain three basic components: (1) input data blocks that do not vary as a function of fuel assembly characteristics (e.g., description of cask dimensions and construction materials for criticality or thermal calculations), (2) input parameters that vary as a function of assembly characteristics (e.g., fuel pin dimensions in an assembly model for depletion calculations or nuclide concentrations in a cask model for criticality calculations), and (3) sub-templates to be imported (e.g., templates describing fuel pin arrays for depletion or criticality calculations). Model template development, update, and review are conducted using the Mercurial distributed source control management tool [10], which is widely used for version control of files.

An application of UNF-ST&DARDS can be executed through a graphical user interface (GUI) or via command line interface. Upon execution, UNF-ST&DARDS creates JSON files that are used with the template engine and previously generated templates to create an input file that is then run by the appropriate code. The root template file is the main template for a given code's input file, and it guides the template engine in assembling the various input parameter blocks and structures. An example of a TRITON root template file, *TDepl.tmpl*, is presented in Fig. 2. Note that the root template file is not assembly dependent (i.e., it applies to all TRITON assembly models). The main template imports other sub-templates based on different JSON objects such as *<assembly.type>*. Parameter names enclosed in < > parentheses are substituted directly from the parameters stored within the database. The "#" symbol is used to tell the template engine to execute a command. The commands are executed by the template engine in series, and the resultant code input file is generated once all sequences within the root template file have been executed. For example, referring to the circled region in Fig. 2, the command *#import compositions/<assembly.type>.tmpl* would import the sub-template *compositions/<assembly.type>.tmpl*, which provides some information but also imports the sub-template *<assembly.type>.fuel.tmpl*. The JSON values are provided by the database; they are color coded in this example to show where those values would be substituted into the corresponding template files. The TRITON Input Bloc is the result of the circled command.

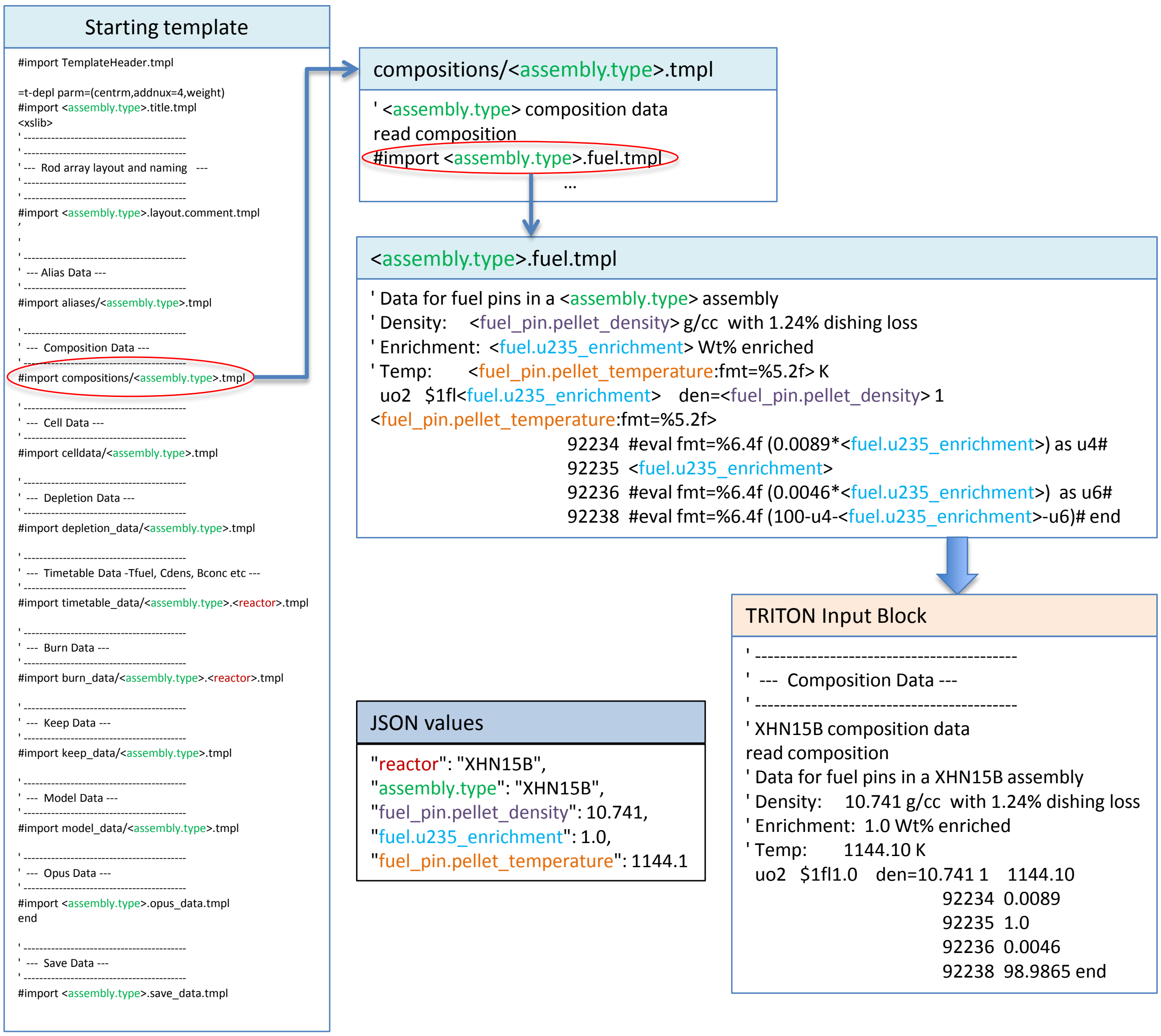

Fig. 2. Example file structure and JSON objects for input file generation.

This same process is used to perform analyses (depletion, decay, criticality, and thermal) for all UNF assemblies and canisters/casks at a given site. Upon execution, depletion and decay calculations are initiated in parallel for all UNF assemblies presently stored at the site for the user-prescribed date(s). Upon completion of the decay calculations, KENO-VI and COBRA-SFS input files are generated with the appropriate time-decayed UNF isotopic compositions and decay-heat source term information, respectively. These files are executed automatically and in parallel for all the loaded storage casks for each date specified. Full output files are archived, but pertinent results such as peak and minimum clad temperatures, component temperatures, cask surface temperatures, total decay heat, and k_{eff} values are extracted and stored in the database for future use and additional data interrogation or visualization through the GUI.

APPLICATION

A unique capability within UNF-ST&DARDS is the ability to perform actual as-loaded analyses to investigate the amount of unquantified, uncredited margin that may be available to offset uncertainties in

UNF evaluations. This capability has been applied to UNF storage, transportation, and disposal studies in the areas of criticality safety and with respect to as-loaded thermal analyses of actual cask systems, which are relevant to assessing the potential for material degradation phenomena and associated implications.

The primary metric used for assessing criticality safety is the effective neutron multiplication factor (k_{eff}) of a system. The regulations for dry cask storage (10 CFR 72) and transportation (10 CFR 71) [11, 12] require that the UNF systems remain subcritical for all normal, off-normal, and accident conditions. The recommended subcritical limit to demonstrate regulatory compliance is prescribed in the standard review plans [8, 9]. The final safety analysis report (FSAR) of a particular cask system documents the bounding models and calculations used to demonstrate that the system meets regulatory requirements under all credible and hypothetical conditions. Note that FSAR calculations and approved content specifications are intended to be bounding in nature to certify cask systems for a variety of fuel characteristics without imposing stringent used-fuel–loading requirements. Therefore, in general, licensed cask systems possess excess and uncredited safety margins.

Requirements related to the thermal design and performance of storage casks are included in 10 CFR 72.122 (h) and (l) and in 10 CFR 72.236 (b), (f), (g), and (h). The requirements cover the heat removal design of the cask, the retrievability of the fuel, and the safety function of the cask. The standard review plan for storage casks, NUREG-1536 [6], provides staff guidance relative to evaluating compliance with the 10 CFR 72 requirements. There are a number of criteria a cask system should meet under normal, off-normal, and accident conditions. For example, to ensure fuel rod integrity, the maximum cladding temperature under normal conditions of storage and short-term loading operations should remain below 400°C (752°F) for zirconium-based alloys and stainless steel cladding [8]. The maximum cladding temperature under off-normal and accident conditions is to remain below 570°C (1,058°F) for zirconium-based alloys and stainless steel cladding [8].

Applicable analyses for storage and transportation configurations have been performed with UNF-ST&DARDS to assess the available margin with regard to criticality and thermal requirements. Calculations were performed using the design basis licensing conditions documented in the FSARs to the extent applicable to confirm that the representative model supplies consistent results that provide a basis of comparison against the specific as-loaded fuel to determine the inherent uncredited safety margins. Note that unlike licensing evaluations designed to cover a broad range of UNF characteristics, cask-specific margin analyses are performed without attempting to establish bounding parameters and conditions. They are meant to provide a comparison between the licensing basis analysis and the as-loaded system when additional details (e.g., burnup credit, decay-time) are included to describe the individual cask. Estimated criticality margin results for Site A are illustrated in Fig. 3, total cask decay heat compared with the respective licensing limit is provided in Fig. 4, and a plot of peak clad temperature over time is shown in Fig. 5. These images illustrate some of the results available in the unified database for characterizing UNF.

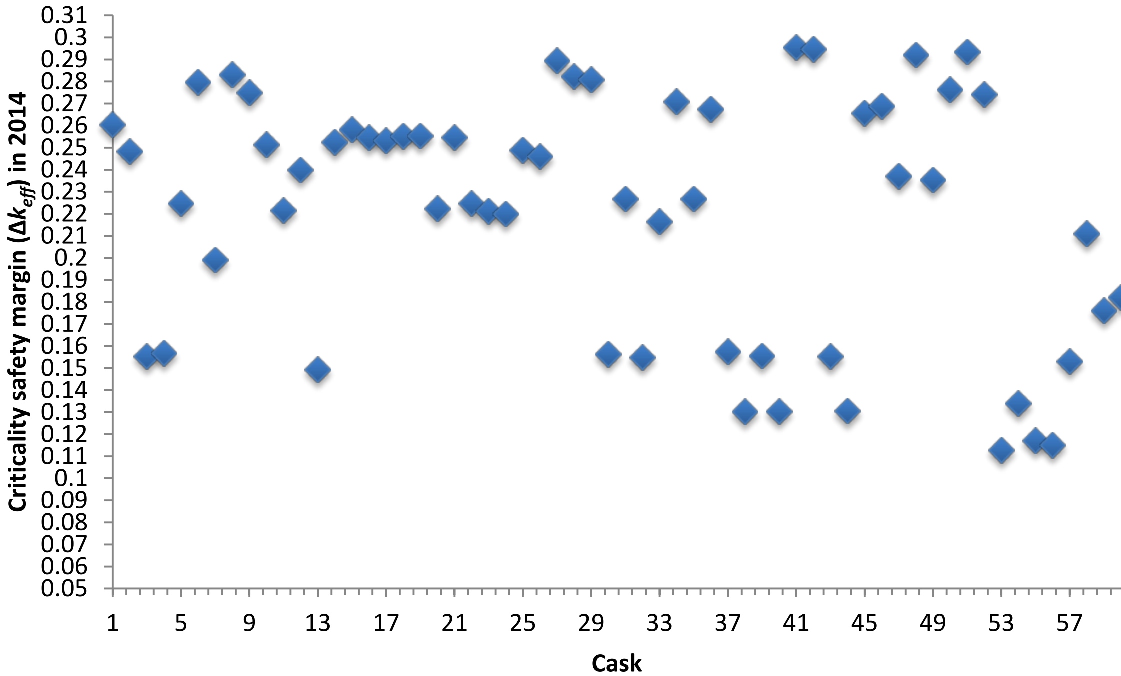

Fig. 3. Estimate of available criticality safety margin at Site A.

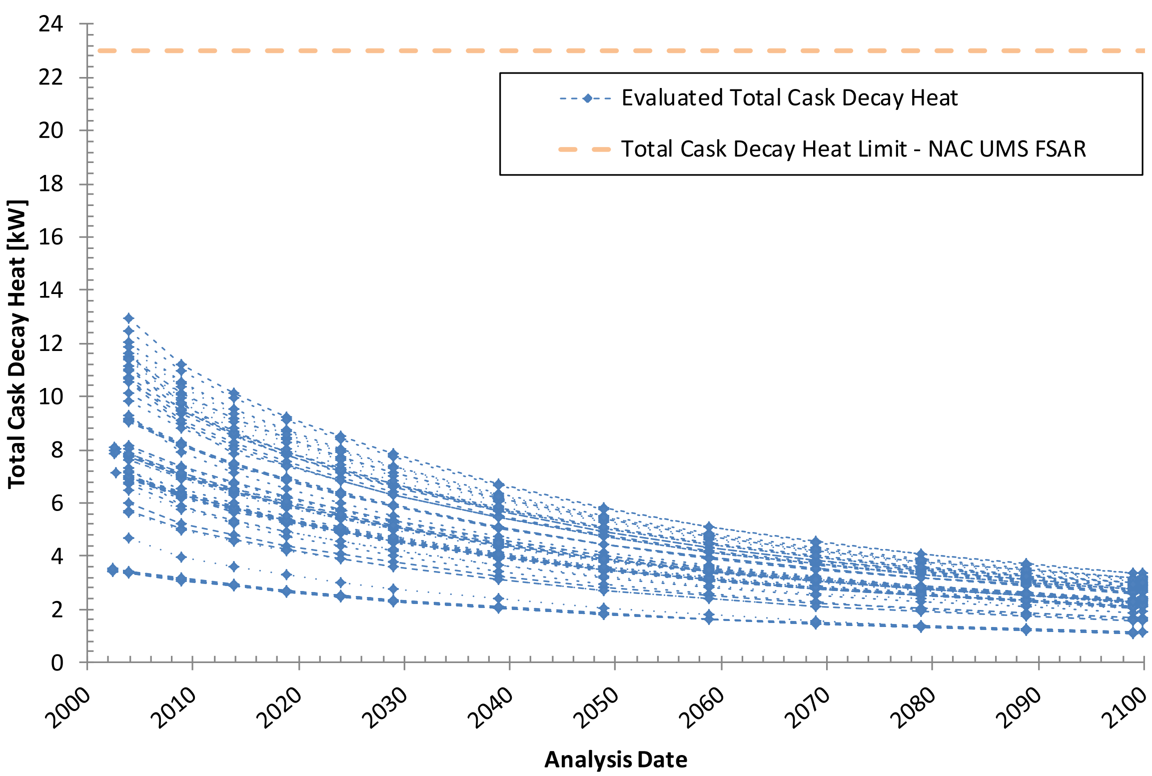

Fig. 4. Total cask decay heat comparison at Site A.

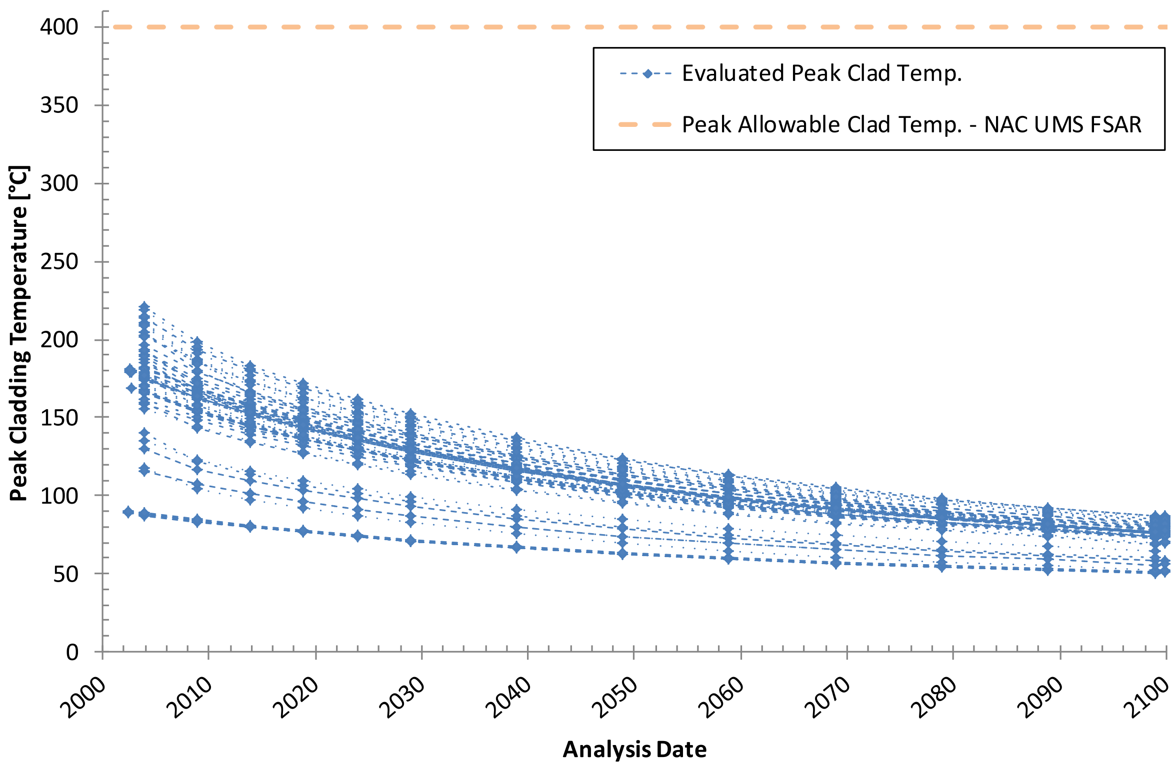

Fig. 5. Peak clad temperature data as a function of time for Site A.

Cask-specific analyses applied to disposal studies include an initial assessment of the feasibility of direct disposal of existing dual-purpose casks (DPCs) from a criticality safety perspective. These types of best-estimate analyses enable an understanding of the sensitivity of the overall system to different degradation mechanisms, geometry changes, and identification of areas for further research to quantify the likelihood of achieving a given configuration. Using UNF-ST&DARDS, a configuration template can be developed once and the cask-specific analysis executed for all DPCs of a particular variant to understand the sensitivity of the various DPC loadings to the different configuration conditions.

Data Visualization

Data can be accessed and viewed through the database system via query lookups or interactively through the GUI. Some of the default display options through the GUI are illustrated in Fig. 6 and Fig. 7. As shown in Fig. 6, independent spent fuel storage installation (ISFSI) site locations are illustrated on a map of the United States. Information about the sites, such as reactor status and wet and dry inventory, are viewable, as well as a satellite photo of the ISFSI from which individual cask-specific characteristics can be observed. Cask-specific characteristics include loading maps, fuel assembly initial enrichments, isotopic compositions, burnups, and discharge dates, as well as a thermal map of the fuel rod temperature distribution that can be displayed radially, axially, and as a function of time. Results can also be observed simultaneously on a per-site basis for the entire fuel inventory, such as the fuel decay heat distribution per assembly shown in Fig. 7.

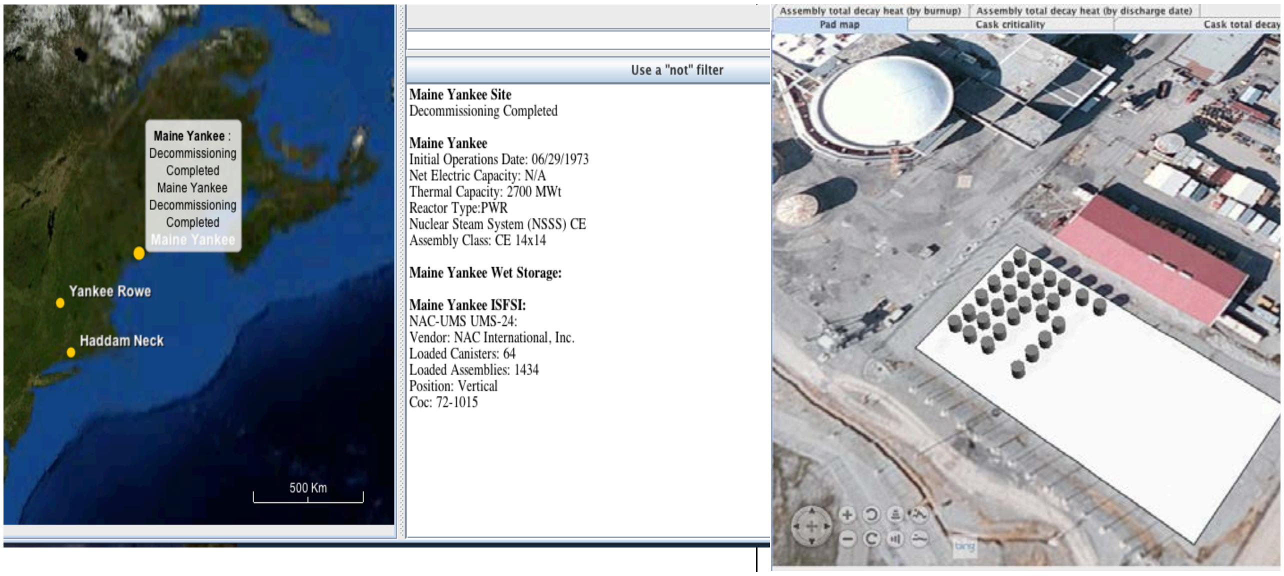

Fig. 6. Example GUI visualization capabilities for site characteristics.

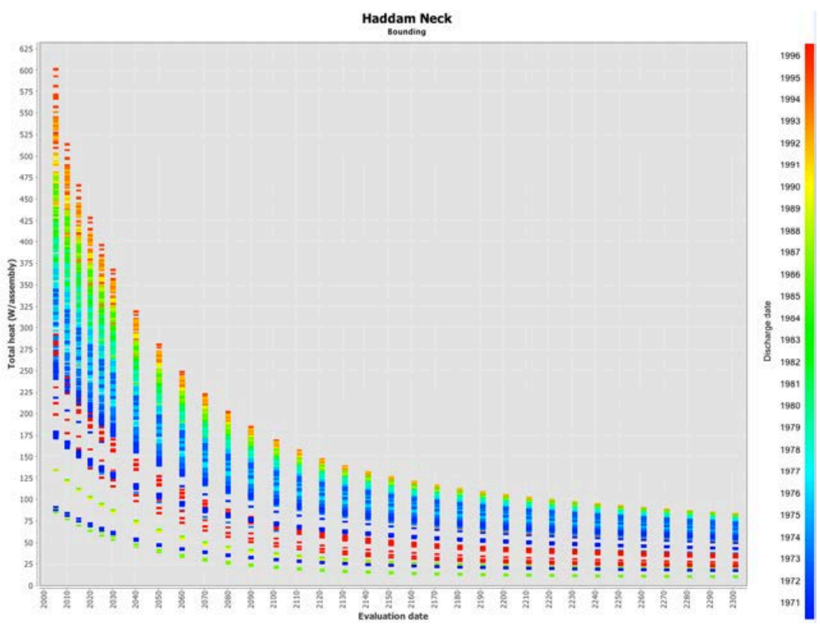

Fig. 7. Illustration of fuel assembly decay heat distribution.

CONCLUSIONS

Computational power and software tools have progressed to the point that accurate, efficient evaluation of safety margins for specific UNF canisters, accounting for the actual as-loaded contents, is possible. The information generated by UNF-ST&DARDS allows realistic assessments of the current and future state of the UNF assemblies and canister systems from both a nuclear and mechanical performance perspective. Integrating the UNF database with the analysis pipeline is a powerful feature of UNF-ST&DARDS, as it allows a basic set of templates to be generated and verified once for input development, parameter substitution implemented through the template engine for automated input file development, and code execution via the user interface (i.e., graphical or command line) for all UNF at the different reactor sites stored within the database. This combined data and analysis tool provides a vehicle for using limited resources more effectively, focusing on analyzing results, understanding sensitivities, making better-informed decisions, and decreasing the amount of time spent on generating results. The unified database provides a consistent set of reliable data that can be controlled and updated to support subsequent analyses and a variety tools as new information becomes available. It preserves the results and parameters that will be required for downstream assessments at different operational transitions within the waste management system.

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