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UNF-ST&DARDS: A Unique Tool for Automated Characterization of Spent Nuclear Fuel and Related Systems*

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Abstract

The Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) is being developed at Oak Ridge National Laboratory in collaboration with multiple national laboratories and nuclear industry participants (utilities, fuel vendors, and cask vendors) for integrating spent nuclear fuel (SNF) management through its final disposition. UNF-ST&DARDS seamlessly integrates a unified SNF relational database (the Unified Database) and key analysis capabilities to simplify and automate the characterization of SNF and related systems to support numerous SNF management and fuel-cycle-related activities. To date, UNF-ST&DARDS accomplishments have included (1) explicit depletion and decay analysis of every fuel assembly (~245 thousand) discharged from the commercial US reactors through June 2013 with 13 cooling time steps (results include 142 isotopes); and (2) criticality, shielding, thermal (steady state and transient), and containment analyses of hundreds of loaded casks. Additionally, UNF-ST&DARDS also provides various automated report generation capabilities with dynamic figure and plot updates based on changes made to the Unified Database.

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Introduction

Commercial spent nuclear fuel (SNF) in the United States is stored at 74 nuclear reactor sites, including currently operating and shutdown sites, as shown in Fig. 1. A small number of SNF assemblies are also stored at a private storage facility (GE Morris in Illinois) and at US Department of Energy (DOE) facilities (e.g., Idaho National Laboratory [INL]). Many of the reactor sites consist of more than one nuclear reactor and multiple SNF pools and dry storage pads. The US SNF inventory currently consists of approximately 76,000 metric ton of uranium (MTU) [1], and the US commercial reactors are discharging approximately 2000 MTU every year. This large volume of SNF inventory is also very diverse in terms of originating reactors (pressurized water reactors [PWRs] and boiling water reactors); fuel assembly class (e.g., 15×15, 16×16, 17×17, 8×8, 9×9, 10×10, and reactor-specific designs such as the 13×14 configuration used at Indian Point Unit 1); historical and current fuel manufacturers (e.g., Framatome [Historical], Areva, Global Nuclear Fuels [GNF], Westinghouse), and fuel assembly types (e.g., Westinghouse 17×17 Standard, GNF2). Most of the SNF assemblies (~66% [1]) are stored in the SNF pools; however, as pools have reached capacity limits, US utilities have implemented dry cask storage at a current rate of ~200 new casks loaded per year. The dry cask systems are also very diverse because the three major cask vendors, Areva TN, Holtec International, and NAC International, introduce new designs periodically to improve operational efficiencies. Figure 2 presents the population of various cask systems used by the US utilities. Because of the large volume and diverse systems, nationwide SNF management through its final disposition is a complex undertaking.

Figure 1 SNF stored (both wet in SNF pools and dry at dry storage pads) at reactor sites in the United States. Data source: the Unified Database, last updated March, 2016, based on GC-859 data released by the Energy Information Administration [2].

Because onsite dry storage is expected to extend beyond the 20 years specified in the original license of the dry storage systems and installations, SNF management also needs to take into account the uncertainties related to aging of structures, systems, and components (SSCs) at operating and shutdown reactor sites. The current trend of irradiating nuclear fuel assemblies to high burnup values (> 45 GWd/MTU) is also contributing to the uncertainties related to the aging SSCs. Regardless of the length of the storage period, SNF must eventually be transported from the reactor sites to off-site interim storage facilities (ISFs) or to a geological repository. Realistic time-dependent characterization of the SNF and related systems (e.g., cask systems) is therefore essential to (1) manage SNF during extended storage; (2) support a successful large-scale transportation campaign; (3) plan for, design, and operate ISFs; and (4) underpin eventual geological disposition of SNF.

The Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) is being developed as a foundational resource for the DOE Office of Nuclear Energy to streamline computational analysis capabilities for the time-dependent characterization of SNF and related systems. The major objective is to provide system-wide waste management integration. UNF-ST&DARDS incorporates the Unified Database (UDB), a comprehensive, controlled, domestic SNF system database that is integrated with nuclear analysis capabilities to support various objectives related to SNF management and the fuel cycle analyses. The UDB is designed to preserve various assembly-specific and system-specific (e.g., dry-cask-specific) information for generations and can even be used to inform future generations after final disposition of SNF.

This paper discusses direct application of UNF-ST&DARDS through various examples and shows how this unique tool can be used to provide integration between the major components of waste management, namely storage, transportation, and final disposition.

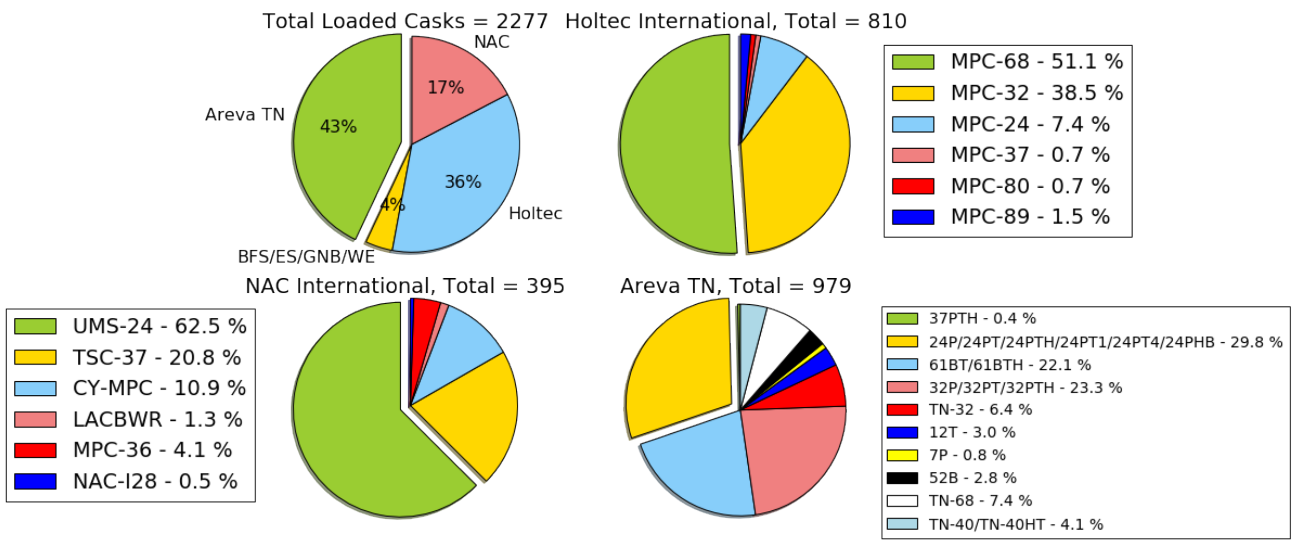


Figure 2 The US cask inventory by major cask vendors. Data source: the Unified Database, last updated March, 2016, based on StoreFuel [3].

UNF-ST&DARDS

UNF-ST&DARDS software architecture and safety analysis capabilities, including the capabilities to carry out criticality, shielding, and thermal analyses, were described in detail in Refs. 4 and 5. A brief description of UNF-ST&DARDS is provided in this section. Figure 3 is a graphical representation of UNF-ST&DARDS. UNF-ST&DARDS consists of six main elements: (1) a user interface (graphical as well as command line), (2) the UDB, (3) a UDB software development kit, (4) a template repository with constructs for specific nuclear safety analysis tools, (5) a template engine for processing and expanding templates to fully developed input files for nuclear analyses, and (6) a process manager that handles interactions between the different elements. The UDB can integrate with multiple computational tools and models and is being designed and developed to support systems and logistics analysis codes such as the Next Generation System Analysis Model, an integrated waste management system analysis tool being developed at Argonne National Laboratory. The nuclear safety analysis tools and their user interfaces are externally developed software tools that function independently but have been integrated into UNF-ST&DARDS for automating different analyses. Current nuclear safety analysis tools consist of SCALE [6], a comprehensive modeling and simulation suite for nuclear safety analysis and design, and COBRA-SFS [7], a thermal-hydraulic analysis code.

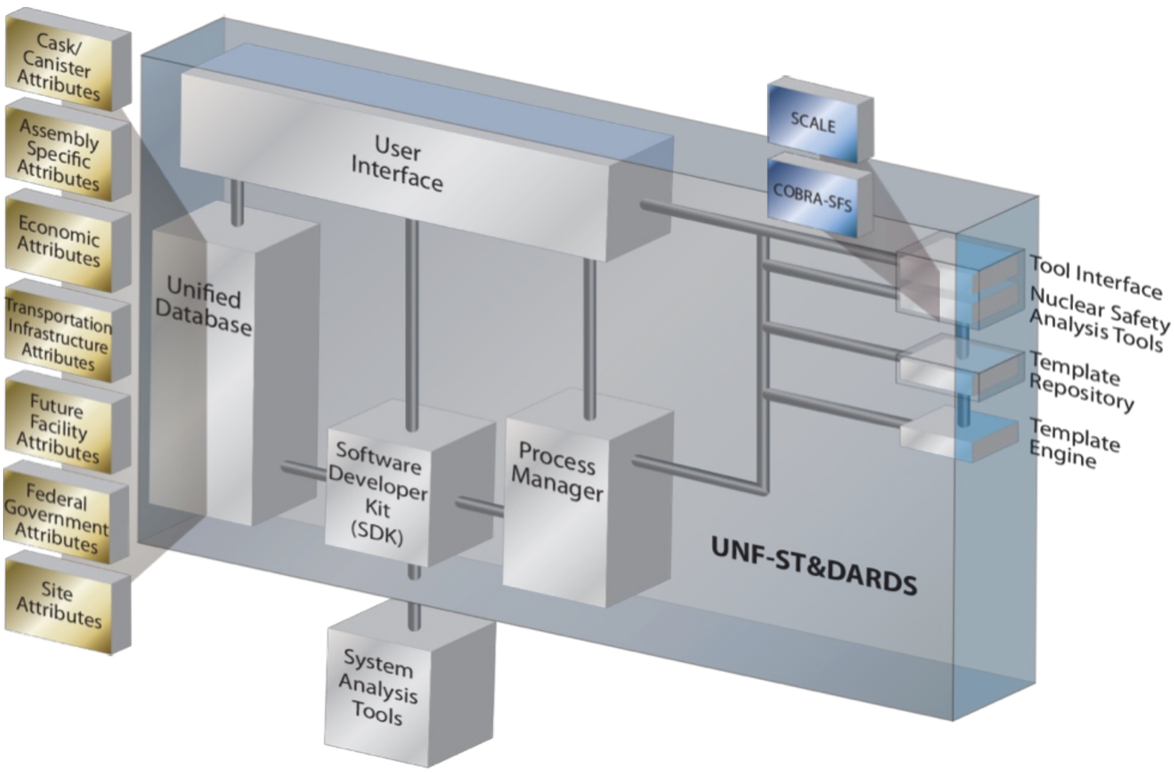


Figure 3 UNF-ST&DARDS architecture and information flow within UNF-ST&DARDS.

Various sets of technical data from multiple diverse sources (e.g., GC-859 [2], DOE studies, open literature, vendor data, utility data) are collected and consolidated into the UDB, a single controlled and relational database system. When basic information about the SNF and the cask system is provided, the data relationships defined in the UDB allow inputs to the respective codes to be built autonomously. These relationships eliminate the user interaction typically required to build the large number of computer code inputs needed for characterizing each site's SNF. UNF-ST&DARDS currently provides the following nuclear safety analyses capabilities:

- Depletion and decay: Provides SNF nuclide compositions (subsequently used in criticality analysis), heat load (subsequently used in thermal analysis), and radiation source (subsequently used in dose/shielding calculations);
- Criticality: Calculates the neutron multiplication factor (k_{eff}) for as-loaded casks;
- Thermal: Provides cladding and surface temperatures of as-loaded casks;
- Shielding: Provides radiation dose rate maps outside the as-loaded casks, and;
- Containment: calculates allowable leakage rate for as-loaded transportation casks.

UNF-ST&DARDS Applications

The three major SNF management components are SNF storage, transportation, and final disposal. The fundamental input required by the three components is the accurate characterization of SNF and related systems. The detailed assembly-specific (using assembly-specific data such as irradiation history) and cask-specific (using cask-specific data such as loading map) characterization as a function of time is a unique feature of UNF-ST&DARDS and facilitates proper understanding of the actual state of SNF at various stages before final disposition. In this section, specific applications of UNF-ST&DARDS are discussed with examples.

<u>UDB</u>

The UDB is the central component of UNF-ST&DARDS and provides a credible, controlled data source for key information essential to each SNF management area (i.e., storage, transportation, and disposal) and preserves SNF-related information for future use. Any SNF-related analysis starts with the SNF inventory. The UDB within UNF-ST&DARDS contains data for ~245 thousand discharged assemblies from US commercial reactors (through June 2013), and is updated as additional information becomes available. Figure 4 shows the discharged assembly data binned as a function of burnup (gigawatt days per metric ton of uranium [GWd/MtU]) and cooling time (years). As illustrated in Fig. 4, the SNF discharge burnup has steadily trended upwards over the last couple of decades, going from the range of 20 to 30 GWd/MtU to 40 to 50 GWd/MtU. Therefore, most of the recently discharged (less cool) assemblies are at or near high burnup (i.e., ≥45 GWd/MTU). The UDB also contains both originating and current storage locations of all the discharged assemblies throughout June 2013. In Fig. 5, the plot of assembly location data from the UDB illustrates some of the historic SNF transfers within the United States between utilities and from utilities to DOE sites including national laboratories. Originating reactor information is essential for proper characterization of SNF assemblies, and understanding the material movement history is important for proper material accountancy. The UDB also stores various analysis results related to storage, transportation, and disposal (e.g., criticality analysis results for various disposal scenarios over a disposal time frame) that can be used for further interrogation and decision making.

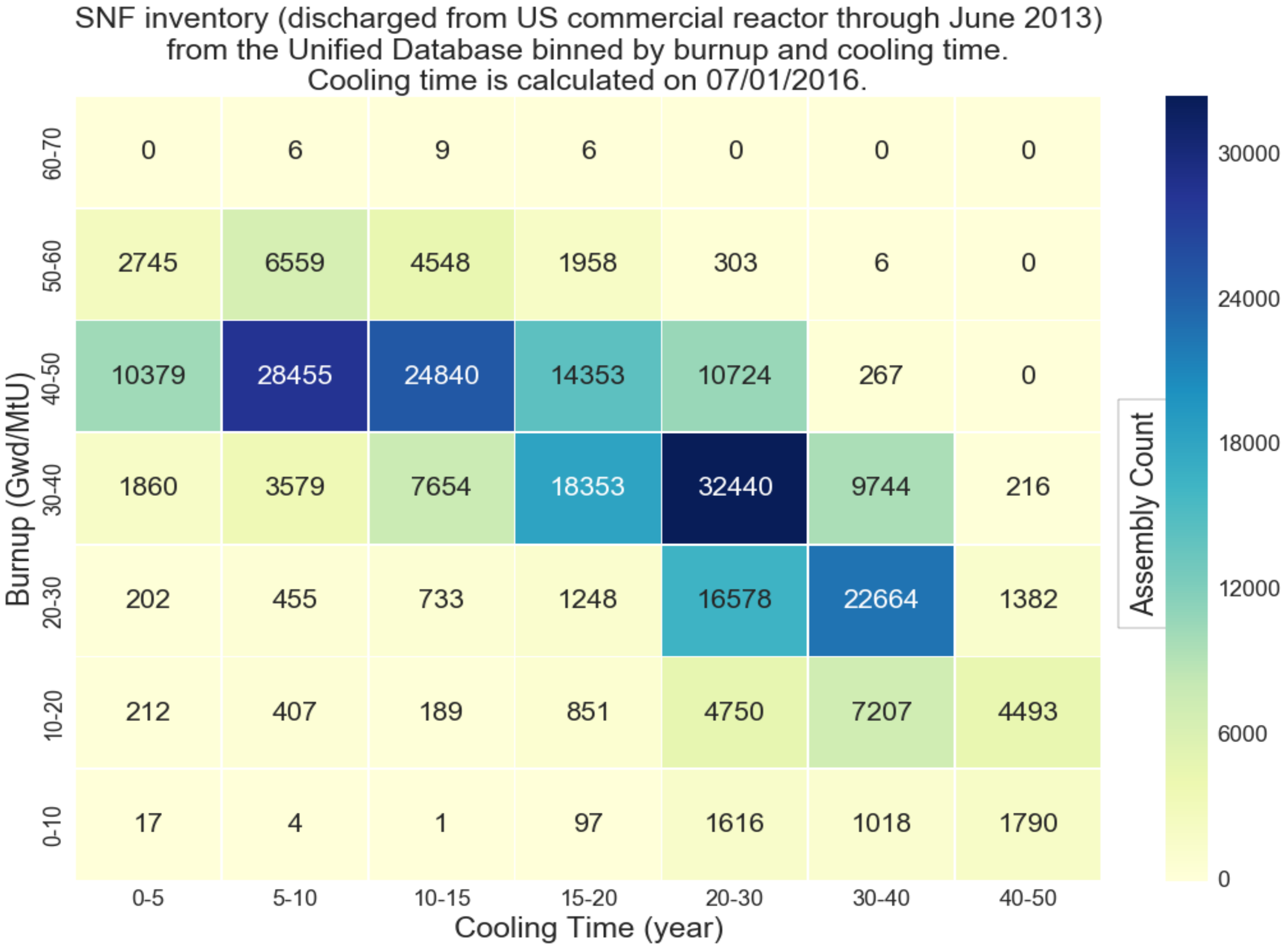


Figure 4 SNF inventory (discharged from US commercial reactors through June 2013).

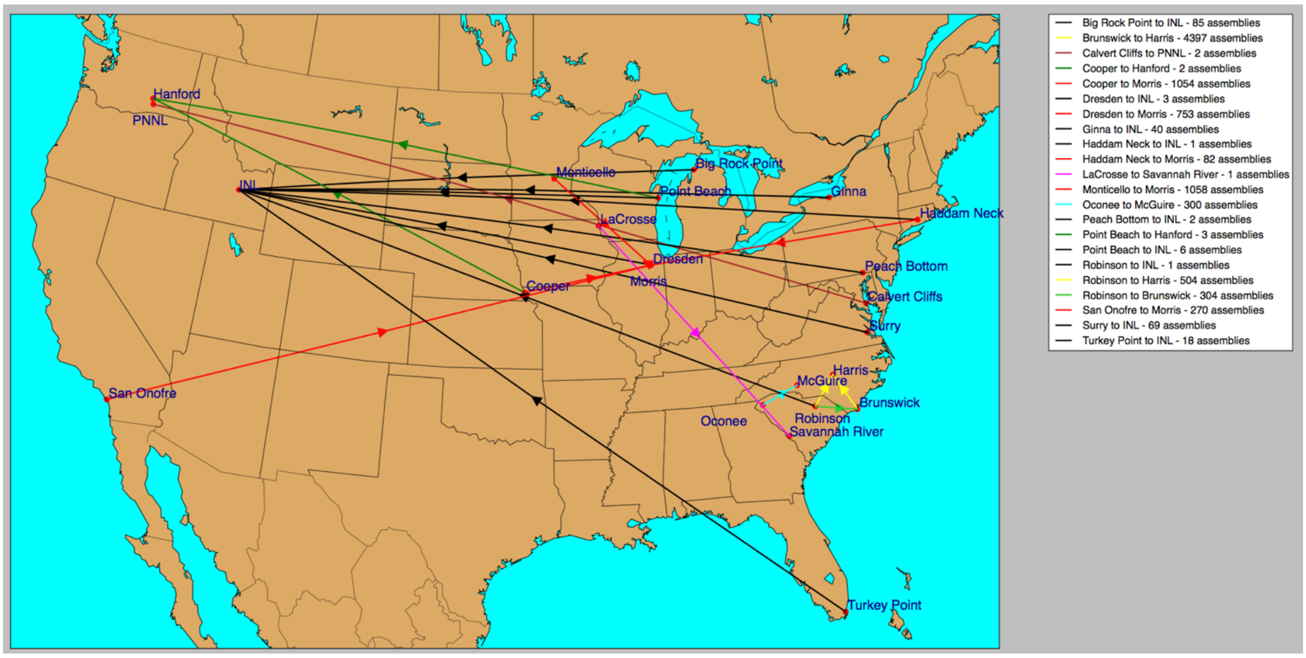


Figure 5 Historic SNF transfers within the United States.

Dry Storage Planning

The data presented in Fig. 4 facilitates assembly-specific decay heat analysis as a function of time (automated within UNF-ST&DARDS). When combined with a site-specific SNF pool inventory, the analysis can be used to determine the total heat load of a pool, as shown in Fig. 6. Figure 6 presents the decay heat load (indicated by color and bubble size), discharge burnup, and initial enrichment of all the assemblies in a single example SNF pool in July 2015. The assembly-specific decay heat, burnup, and enrichment as presented in Fig. 6 are the key inputs that determine when the assemblies are qualified for dry storage in a specific dry storage system in compliance with that system's certificate of compliance (COC).

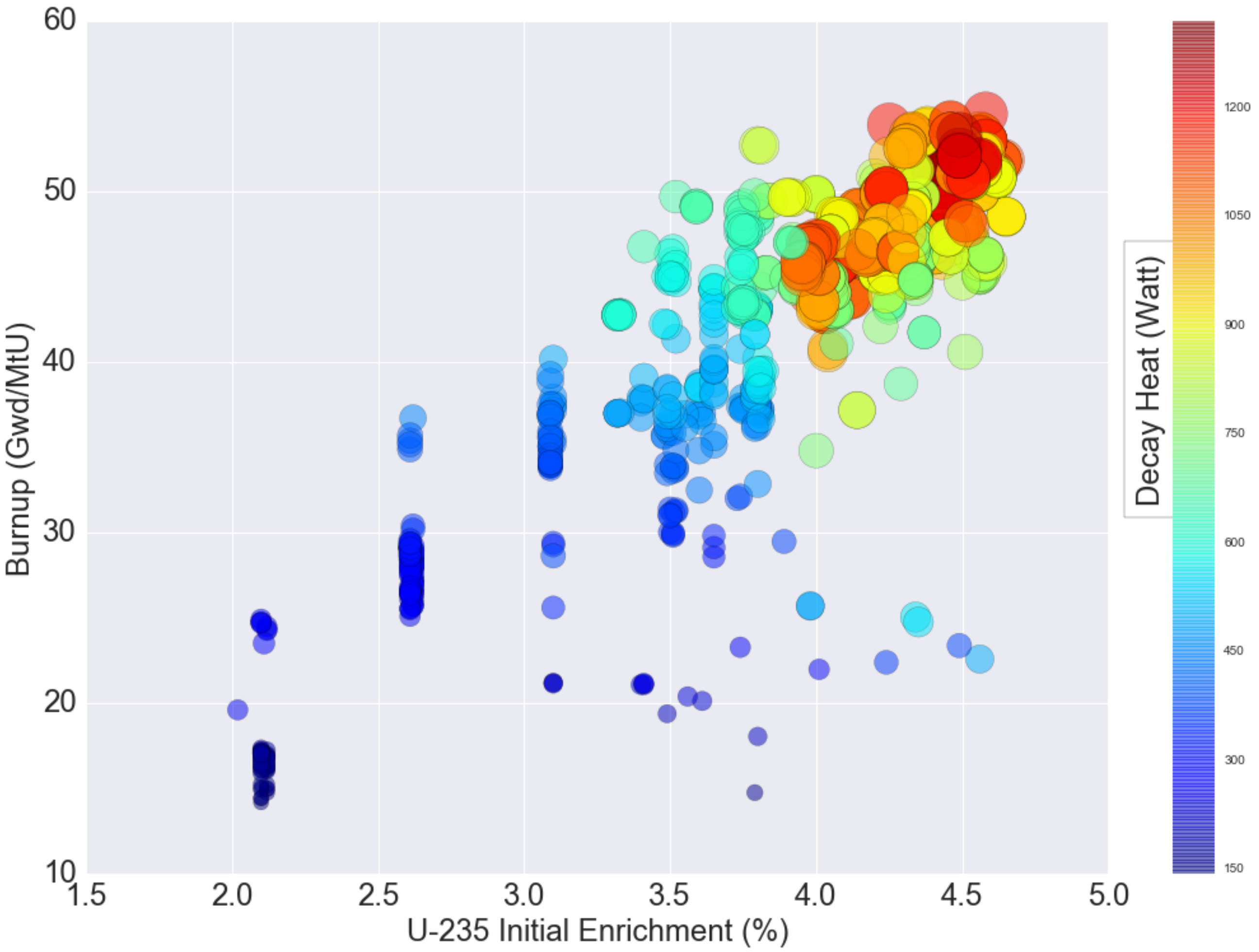


Figure 6 UNF-ST&DARDS site-specific results assembly decay heat by burnup and U-235 initial enrichment (%).

<u>Transportability Determination of Already-Loaded Canisters</u>

Transportability of a loaded canister in dry storage is determined by considering various safety aspects with regard to decay heat, criticality, shielding (in designated transportation casks), thermal, containment, and structural integrity. This example shows how UNF-ST&DARDS assembly-specific and cask-specific characterization can use decay heat, criticality, shielding, and thermal data to assist with such a determination.

1. Decay Heat

Assembly-specific decay heat calculated for each assembly within UNF-ST&DARDS can be used to determine (1) when a loaded canister can be transported off site in accordance with its designated transportation cask's COC, (2) internal component temperatures including cladding temperatures (relevant to identifying potential issues related to fuel rod structural integrity), and (3) canister surface temperatures as a function of time (relevant to system aging effects, e.g., canister's susceptibility to stress corrosion cracking). Figure 7 shows the total calculated heat load of 1,821 loaded canisters at

56 sites at the beginning of July 2015 as a function of the number of casks per site, ordered by decreasing decay heat. From the total heat load perspective, most of the loaded canisters presented in Fig. 7 are currently transportable in their designated transportation casks. Heat limits of transportation casks that recently received a COC from the Nuclear Regulatory Commission (NRC) are about 20 kW. Higher-heat-load transportation casks proposed by the cask vendors are currently under NRC review.

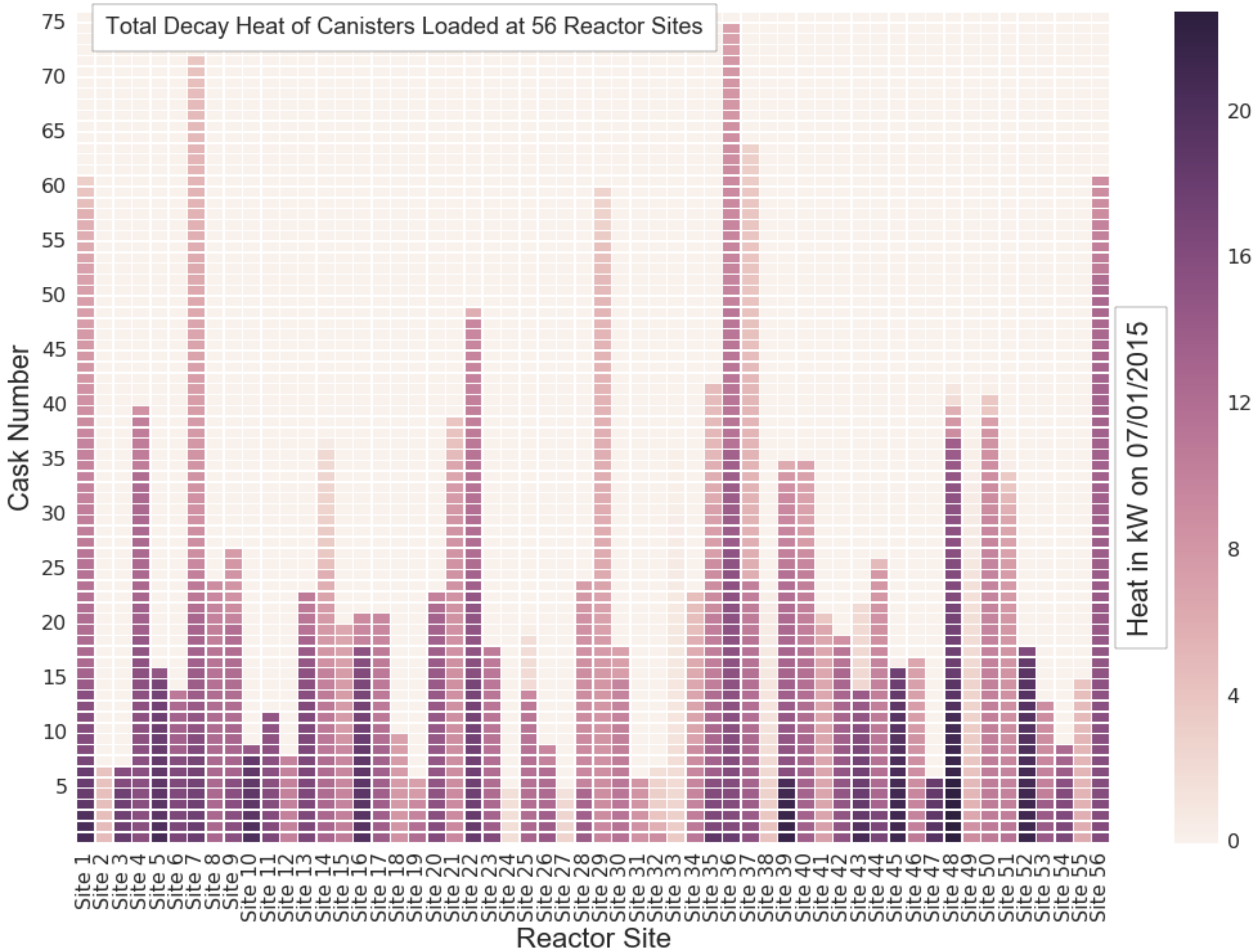
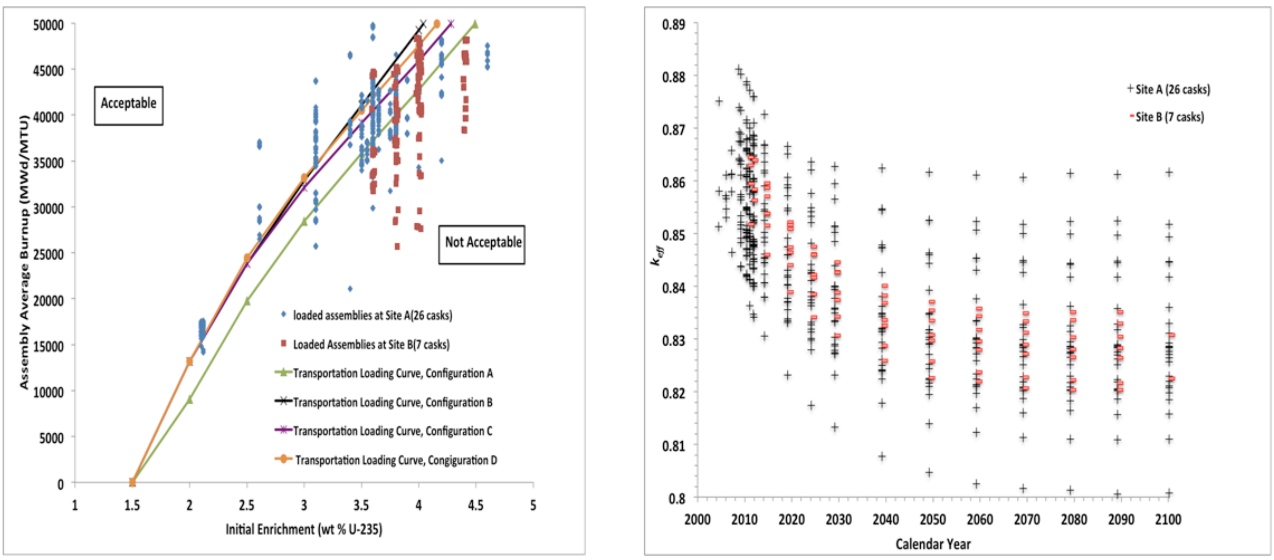


Figure 7 UNF-ST&DARDS overview of cask decay heat results per reactor site.

2. Criticality

A dry storage system COC defines the limiting loading conditions and SNF characteristics for which the storage system's final safety analysis report has demonstrated compliance with the regulations related to dry storage in the United States, found in Title 10, Part 72, of the *Code of Federal Regulations* (CFR) [8]. Most of the currently loaded canisters also have designated and separately certified transportation casks. Similar to storage systems, certified transportation packages have well-defined and bounding loading criteria that describe the acceptable contents for transportation in compliance with 10 CFR Part 71 [9] (regulations related to packaging and transportation in the United States). This separate approval approaches for storage and transportation casks can lead to inconsistencies such that contents approved for storage in a given dual-purpose (storage and transport) system COC do not meet the approved transportation requirements for that system.

Burnup is typically not credited in dry SNF storage in the United States. Therefore, high-density PWR SNF canisters used for dry storage (32 or more assembly capacity) are typically loaded using soluble boron credit and moderator exclusion for criticality control. However, for obvious reasons, soluble boron cannot be credited during transportation, and burnup credit is sometimes used. Because of this inconsistent approach between storage and transportation approval processes, SNF loaded according to the storage COCs may fall into the "not acceptable" region of the transportation loading curves (average burnups vs. enrichments that yield equal reactivity) [Fig. 8(a)]. Therefore, SNF stored in an approved storage canister (approved under the storage system COC that hosts the canister) may not be transportable without substantially amending that canister's designated transportation cask's COC. However, loaded cask systems generally possess excess and uncredited criticality margins (i.e., the difference between the approval basis and the as-loaded calculations). This uncredited margin could be quantified by (1) employing more detailed cask-specific evaluations that credit the actual as-loaded cask inventory and (2) taking into account full (actinide and fission product) burnup credit. As-loaded analysis can be applied to integrate the analyses to demonstrate compliance with the dry cask storage (10 CFR Part 72) and transportation (10 CFR Part 71) regulations. This alternative approval approach would be analogous to 10 CFR Part 72 shielding evaluation where site-specific dose calculations are performed before actual loading to show compliance with 10 CFR Part 72 regulation. In this alternative approval approach, a general methodology for conducting as-loaded analysis would be developed and approved. The methodology would be applied during the loading process to confirm that the proposed loading meets the requirements of 10 CFR Parts 72 and 71. Calculated as-loaded k_{eff} results, which range from the loading date out to the year 2100 for Sites A and B, are presented in Fig. 8(b). Figure 8 shows that, in terms of criticality, UNF-ST&DARDS as-loaded analysis can be used to justify transportability of as-loaded canisters.



(a) (b)

Figure 8 (a) Burnups vs. enrichment of loaded SNF at sites A and B in MPC-32 cansiters along with MPC-32 transporation loading curves. Configurations are used to define reactor irradiation history (e.g., irradiation with control components) [11]. (b) Calculated k_{eff} results for as-loaded canisters as a function of time.

3. Shielding

A transportation package certified under 10 CFR Part 71 has dose limits on and near the external surfaces of the package. In addition to "as low as reasonably achievable" considerations (10 CFR Part 20 [10]), the only regulatory dose requirement for a storage system is the site boundary dose. Therefore, storage COCs allow loading of more active fuel assemblies than that of the transportation COCs. This could result in a scenario (depending on the loading combination) where dose rates could be more limiting for determining transportability of a loaded canister. Figure 9 depicts such a scenario. Figure 9 presents (1) decay heat (both assembly-specific and canister total) of five already-loaded BWR canisters at a site and (2) dose rates at 2 m from the designated transportation cask of the loaded BWR canisters in July 2020. Figure 9 shows that the five loaded canisters would be transportable in 2020 with respect to decay heat alone (both assembly-specific and total), but Fig. 9 also shows that their dose rates are higher than that required by transportation regulations, and thus they would not be transportable in 2020. Therefore, UNF-ST&DARDS as-loaded analyses (in this case both decay heat and shielding) can be used to accurately determine the transportability of a loaded canister on a given date considering all possible scenarios. Approved content defined in the transportation COC may also be used to determine transportability of already-loaded canisters. Because of the bounding nature of the approved content, such determination would be very conservative and thus penalizing for planning purposes.

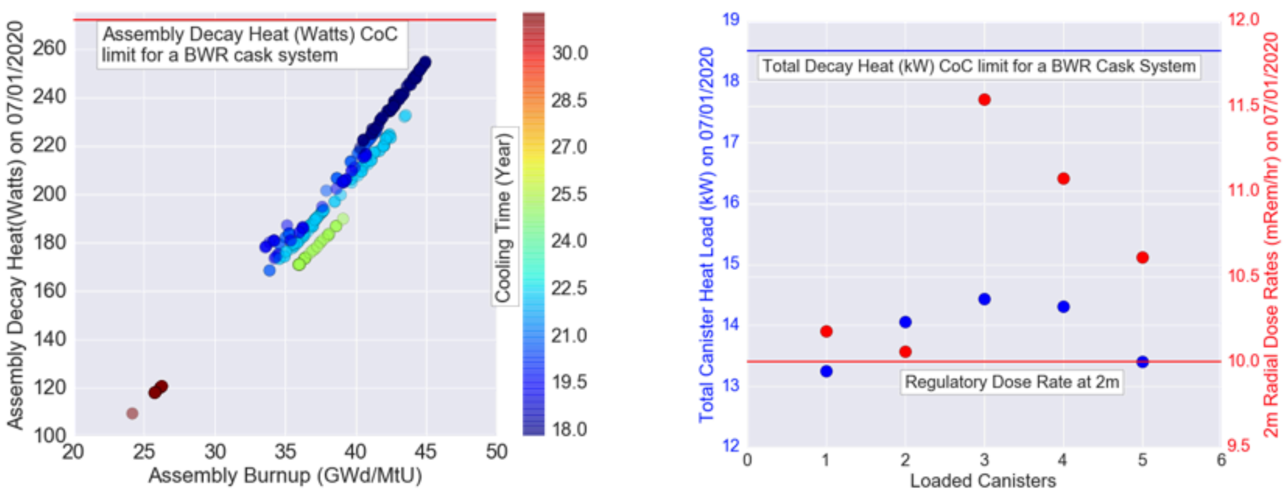


Figure 9 (a) Assembly-specific decay heat for all the assemblies loaded in five BWR canisters at a site- and assembly-specific decay heat limit of the BWR canister in its designated transportation cask (b) As-loaded total decay heat for the five BWR canisters and dose rates at 2 m from the designated transportation cask with

corresponding decay heat limit (certificate of compliance) and dose rate limit (regulatory).

4. Thermal

A wide range of degradation mechanisms related to fuel assemblies and canisters are affected by temperature. For the cladding, temperature-dependent phenomena include creep and annealing, hydride reorientation and embrittlement, and the ductile-to-brittle transition[12]. Temperature can also influence the long-term integrity of the cask system; phenomena induced by temperature over the long term include deliquescence, corrosion, and stress-corrosion cracking. Therefore, accurate determination of the temperatures of various components is needed to better determine potential safety-related issues during transportation after extended storage and to ensure retrievability after transportation.

The thermal analysis capability within UNF-ST&DARDS focuses on the ability to perform more realistic analyses (compared to conservative analyses used for approval) for as-loaded casks using COBRA-SFS, a subchannel code that provides pin-level resolution of temperatures within a canister. UNF-ST&DARDS includes the capability to assess the drying, transfer (from fuel handling building to storage pad), and long-term dry storage of the SNF. Figure 10 illustrates the peak cladding temperature (PCT) of the SNF within a specific as-loaded canister for a site. The PCT predictions are provided for the canister drying and transfer operations and for long-term storage in a horizontal storage module. Predicted as-loaded decay heat for each assembly and power profile are utilized. Figure 10 indicates that the PCT for this case is not favorable for hydride reorientation and related embrittlement. Therefore, this canister may be transportable within a certain time frame without adversely affecting assembly structural performance. Hydride reorientation and the resulting embrittlement of clad depend on several factors not considered here (e.g., fuel rod internal pressure). Assembly-specific fuel rod internal pressure analysis capability is currently under development for future inclusion in UNF-ST&DARDS.

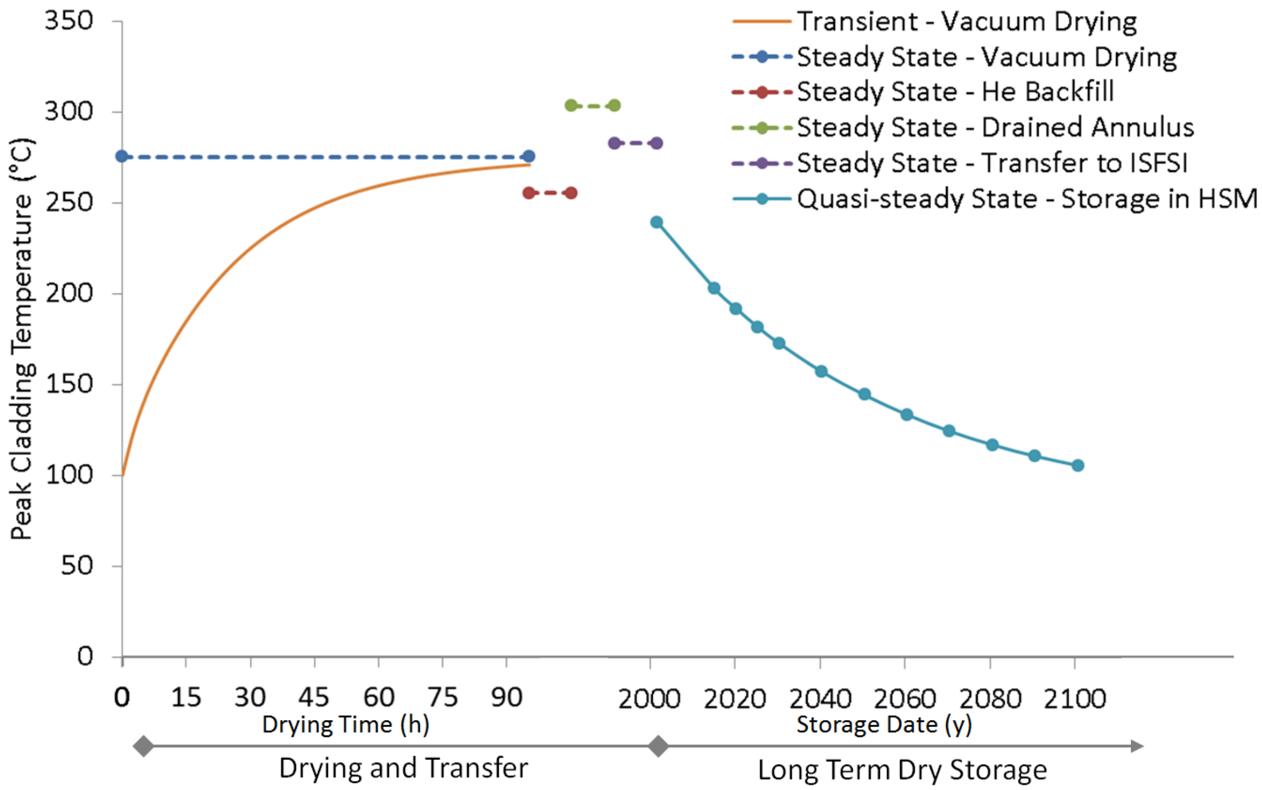


Figure 10 Peak cladding temperature as function of time.

Thus UNF-ST&DARDS can make a holistic determination of transportability of an already-loaded canister on a given date by evaluating various safety aspects in an integrated fashion.

<u>Disposability of Loaded Canister from the Standpoint of Criticality</u>

UNF-ST&DARDS as-loaded criticality analysis can be used to determine the disposability of currently loaded canisters [13]. The uncredited margins associated with actual fuel loading can offset the increase in reactivity because of canister flooding and the associated geometrical changes that can occur in the disposal environment as structures, systems, and components degrade. Figure 11 presents the as-loaded k_{eff}s of 339 loaded canisters (at 16 sites) for a degradation scenario that includes loss of basket neutron absorber. Out of 339 loaded canisters, only 36 (~11%) are above the criticality limit in calendar year 9999. Most of the canisters would exceed the criticality limit with loss of neutron absorbers if they were analyzed with the design-basis fuel used for approval process. Therefore, the UNF-ST&DARDS as-loaded criticality analysis can be used to accurately determine disposability of the loaded canisters and to determine other means (e.g., precondition the canisters with filler materials for moderator displacement), if needed, to supress criticality.

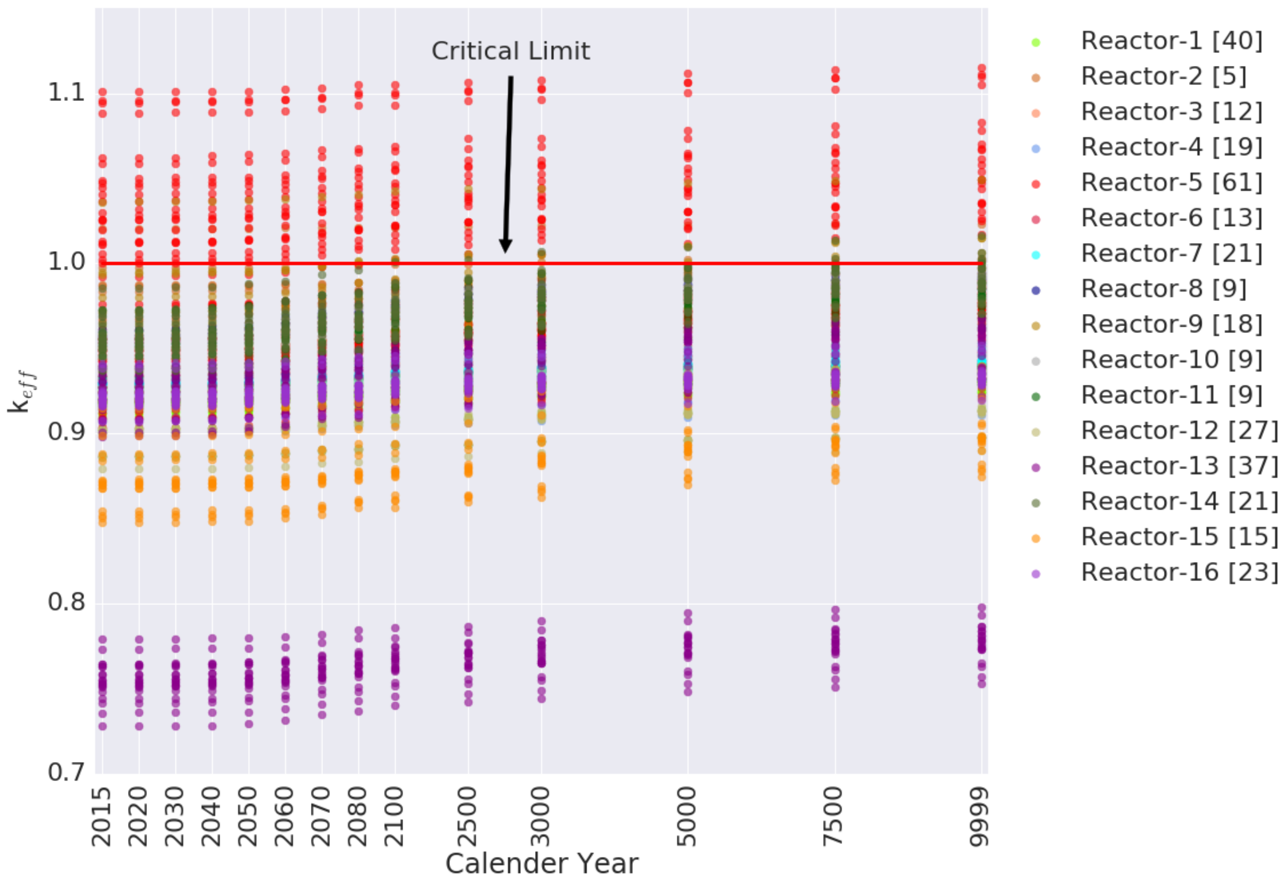


Figure 11 k_{eff} vs calendar year for a degradation scenario involving loss of basket neutron absorber, based on actual loading. The number within the bracket in the legend indicates number of canisters. The calendar year in *x*-axis is not to scale.

Conclusion

This paper discusses various features of UNF-ST&DARDS, including (1) a comprehensive SNF database and (2) automated assembly-specific and cask-specific characterization of SNF. This paper also discusses various applications of assembly-specific and cask-specific characterization that could be used to provide integration between storage, transportation, and eventual disposal. Other potential applications of UNF-ST&DARDS include

- fuel cycle analysis [14] (e.g., analysis of characteristics for fuel recycle);
- safeguard and security evaluation [15] using assembly-specific characteristics;
- cask/canister COC amendment (e.g., amending transportation COC to allow transport of all already-loaded canisters) [16];
- cask/canister new COC application/renewal (e.g., safety margin [4] from as-loaded analyses used to offset high-burnup fuel long-term performance and system aging-related uncertainties);
- planning for large-scale transportation (e.g., realistic assessment of worker dose and dose to a member of the general public);

- designing and licensing of an interim storage facility (e.g., realistic analysis of facility dose and dose during fuel handling); and
- research and development prioritization by identifying or eliminating data/knowledge gaps (e.g., whether the peak cladding temperature of loaded canisters were favorable for hydride reorientation).

The UDB continues to expand the set of data available for analysis, allowing UNF-ST&DARDS to continue adding to the list of streamlined, automated analyses. Automated report generation capabilities built on the UDB can currently generate fuel characteristics, inventory, and cask database reports in various formats (e.g., pdf, HTML) dynamically. A limited visualization of some of the UDB data can be found at https://curie.ornl.gov/map.

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