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COBRA-SFS Transportation Template Development for UNF-ST&DARDS

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ABSTRACT

In the United States there are over 2,500 loaded spent nuclear fuel dry storage systems in operation. Eventually the canisters stored in these systems will need to be transported to interim storage and/or disposal sites. Analysis is needed to make sure that the canisters, fuel, and transportation casks meet thermal, shielding and criticality requirements. DOE has developed the Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) to help perform this task. Through the use of multiple analysis codes and a large amount of data collection this tool has the capability to ascertain the site-specific conditions of fuel around the country and whether or not it is transportable. COBRA-SFS is the thermal analysis tool used to develop modeling templates for this task. Thermal conditions are critical because most systems have a lower design basis heat load for transport than for storage. This paper details the recent thermal template development work conducted at Pacific Northwest National Laboratory (PNNL) and the template development process needed to have both general and site-specific template models.

INTRODUCTION

Spent nuclear fuel storage and transportation system designs have specific requirements for transportation primarily based off of thermal, criticality and shielding characteristics. Each of the over 2,500 loaded storage systems has unique fuel and loading configurations. To plan a major transportation campaign, fleetwide analysis is needed to determine when the loaded storage systems will be in a transportable state. To accomplish this, UNF-ST&DARDS was developed to gather data from across the U.S. reactor fleet and analyze the thermal, shielding and criticality status of any loaded storage system. COBRA-SFS serves as the thermal analysis tool for this code. The mechanism for this involves developing model templates that can be modified with different fuel types, decay heat loads, and environmental conditions. This paper details the COBRA-SFS template development work that is underway at Pacific Northwest National Laboratory (PNNL) and uses the HI-STAR 190 template as a case study.

UNF-ST&DARDS

The UNF-ST&DARDS (Banerjee et. al. 2016) tool developed at Oak Ridge National Laboratory (ORNL) is a framework that calls a variety of codes that are needed to calculate the state of spent fuel from a thermal, criticality and shielding perspective. Figure 1 shows the basic UNF-ST&DARDS data and modeling flow.

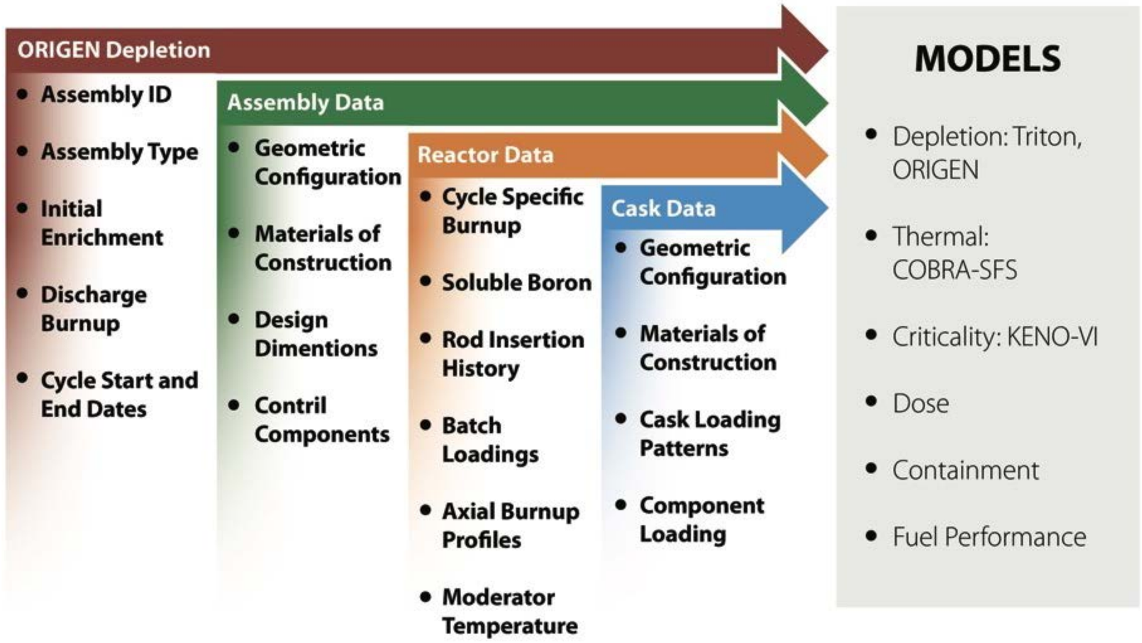


Figure 1 UNF-ST&DARDS Analysis Flow

The key basis of the tool is the availability and tracking of site-specific fuel data to run analysis with. Then Triton and ORIGEN are invoked to model the depletion and decay of the fuel respectively. These results are needed to feed every other analysis type that is done downstream including the thermal analysis.

COBRA-SFS

COBRA-SFS (Michener et. al. 2017) was chosen as the thermal analysis code for UNF-ST&DARDS for a variety of reasons. The code was purpose built to analyze spent fuel casks and has been extensively validated for this type of problem. Because of its purpose-built nature and its history of development in a time when computing resources were scarce the code currently runs as much as 20 times faster compared to its commercial CFD competitors and uses far less computing resources. Analysis can be done efficiently on average PCs as opposed to utilizing computing clusters for comparable CFD analysis. This speed is a major advantage for a planning tool because of the need to run a large number of cases to test sensitivities and different scenarios. There are also some key features of the code that make it well suited for integration with external tools. The input and output formats are text based which makes it easy to track for quality assurance (QA) and manipulate as a coupling method with other codes. UNF-ST&DARDS in particular relies on the text based input because it generates sections of the input file to model different fuel geometries, heat generation, and environmental conditions.

Template Types

In determining the transportability of site-specific fuel assembly types, each stage of the spent fuel lifecycle needs to be considered and the thermal behavior understood. Although the proposed spent fuel solutions vary there is usually the transfer of fuel to a canister, followed by storage, transport and then final disposition. If consolidated interim storage is involved some of the process will loop back on itself but ultimately it does not affect the thermal modeling capabilities needed. With the capability to model both transient and steady state cases, COBRA-SFS can analyze each phase of the spent fuel lifecycle no matter what the pathway is.

Loading and Transfer

Due to large changes in component temperatures and boundary conditions during the initial transfer operations (i.e., vacuum drying), a transient analysis is needed to capture the temperature response of the fuel. Although loading and drying procedures vary by cask vendor and site, a bounding analysis can always be used to determine peak clad temperatures. However, there is also the ability to use actual drying times and procedures where available.

Storage

During storage, fuel assembly temperatures are very stable through time, and the large temperature swings seen during the initial transfer phase will no longer be an issue. It is appropriate to model this phase of the process with a steady state model for a given point in the life cycle. COBRA-SFS gives the user the ability to quickly analyze the thermal behavior of storage systems with various heat loads, loading patterns and assembly types efficiently. One could determine the storability of certain contents and optimize the storage layout to remove as much high burn up fuel from the cooling pools as determinably safe. Also, COBRA-SFS allows for the user to specify ambient boundary conditions such as solar heat load, ambient temperature and convection heat transfer characteristics. Which is important in modeling site specific conditions in which ambient conditions such as climate, play a large role in the thermal behavior of storage systems.

Transport

Depending on the process in which site procedures prepare storage vessels for transport, either steady state or transient analyses may be deemed appropriate for the situation. For example, any instance where the canister is removed from the storage overpack and placed into the transport overpack imposes very large changes to boundary conditions seen by the system. This would warrant a transient analysis to determine the thermal response. This is true for many canister-based systems. On the other hand, many loaded storage systems are dual purpose designs. These are simply down ended and have impact limiters installed. In these systems the thermal characteristics are not dramatically altered by the transport configuration. However they may still have different heat load requirements for transport depending on how the system is designed and analyzed to satisfy the transportation regulations.

Interim Storage/Disposal

One key aspect of the COBRA-SFS template framework is that it is destination independent. The fuel pathway could be storage-transport-interim storage-transport-disposal as opposed to the more commonly considered storage-transport-disposal framework. This change poses no difficulty to the framework laid out in this paper because templates can easily be developed for the storage systems that may be used at any consolidated interim storage (CIS) facility and the subsequent transportation overpacks that are necessary. Additionally, a UNF-ST&DARDS COBRA-SFS template could readily be developed for a waste package that would be used to house fuel for disposal. The thermal behavior of these types of packages needs to be understood for any repository and are highly similar to spent fuel storage analysis.

HI-STAR190 Case Study

The Holtec HI-STAR190 transportation system provides a case study for how a UNF-ST&DARDS template is developed and how it may be put to use. The UNF-ST&DARDS adjusts specific parameters so that site specific conditions can be modeled. These parameters include fuel type, heat load, heat loading pattern and ambient conditions. Specific to this case study, the HI-STAR190 transportation cask is designed to transport Multi Purpose Canisters (MPCs) certified for storage in most Holtec storage overpacks. These certified MPC's include the MPC-37 and the MPC-89 which hold PWR and BWR fuel assemblies respectively. The HI-STAR190 is designed to accept multiple site specific canisters with either the extended length (XL) or short length (SL) versions. The HI-STAR190 design incorporates several key heat transfer mechanisms that must be captured during thermal analysis.

Both canister's nominal conditions were modeled at steady state boundary conditions aimed to replicate the normal conditions of transport (NCT). It must be noted that this case study was performed using the nominal as built dimensions of both SL and XL designs. This section will be discussing design configurations of the system, the methods in which to change model inputs in addition to the future applications of COBRA-SFS with regards to UNF-ST&DARDS.

MPC 37 and MPC 89 Configurations

The MPC-37 and MPC-89 canisters were designed to serve both storage and transportation purposes. This configuration will change based on the cask in which the canister is placed. The MPC-37 and MPC-89 can hold up to 37 PWR assemblies and 89 BWR assemblies respectively. Both canister shells are comprised of stainless steel alloy and baskets constructed of Metamic-HT, a Holtec proprietary borated aluminum for the purpose of shielding and heat transfer (Holtec International). The basket supports consists of extruded 6061-T6 aluminum shims which are placed in between the basket and canister shell to restrict movement during transport and encourage conductive heat transfer (Holtec International).

HI-STAR 190 Transportation Cask Design Overview

The HI-STAR190 transportation cask is designed to accept the canisters certified for storage in the HI-STORM FW and HI-STORM UMAX storage casks. The allowable content of the HI-STAR 190 is much the same as the HI-STORM FW and HI-STORM UMAX with additional restrictions on heat load, burn up and fuel cooling times (Holtec International). Several heat transfer pathways have been included in the design of the cask through incorporation of high thermal conductivity materials in key components such as the MPC basket, shims and cask body carbon steel components. During transport the cask, is placed horizontally on the transport platform with impact limiters encasing both ends of the package. It has been designed for "load and go" transport procedures and passively dissipates generated heat through natural convection to the ambient.

Model Overview

Noding Schemes

COBRA-SFS noding schemes are two-dimensional representations of the system's radial cross-sectional geometry. The noding scheme also serves as a tool used in identifying heat transfer pathways from which the thermal analyst can use for model verification. Furthermore, it will remain independent from changes to other parameters. In other words, while boundary conditions and heat loads can be altered to match site specific conditions, the noding scheme will remain unchanged for a given storage system design.

The noding scheme for both the MPC-37 (Figure 3) and MPC-89 (Figure 4) HI-STAR190 models share many similarities. However, it is necessary to develop separate noding schemes for each system given the differences in MPC designs.

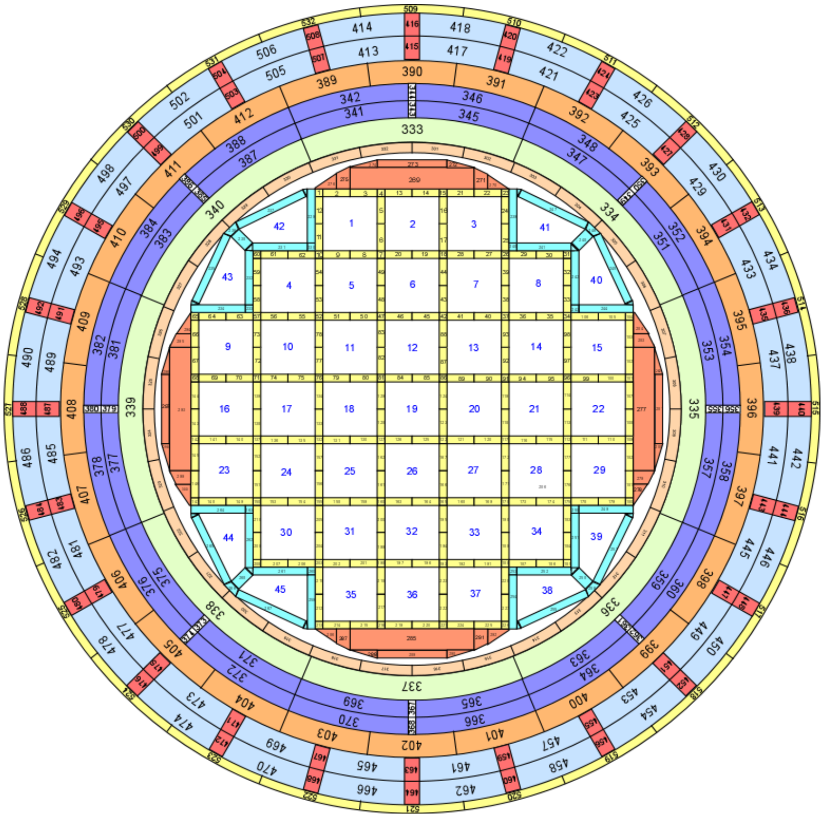


Figure 2 HI-STAR190 MPC-37 Node Map

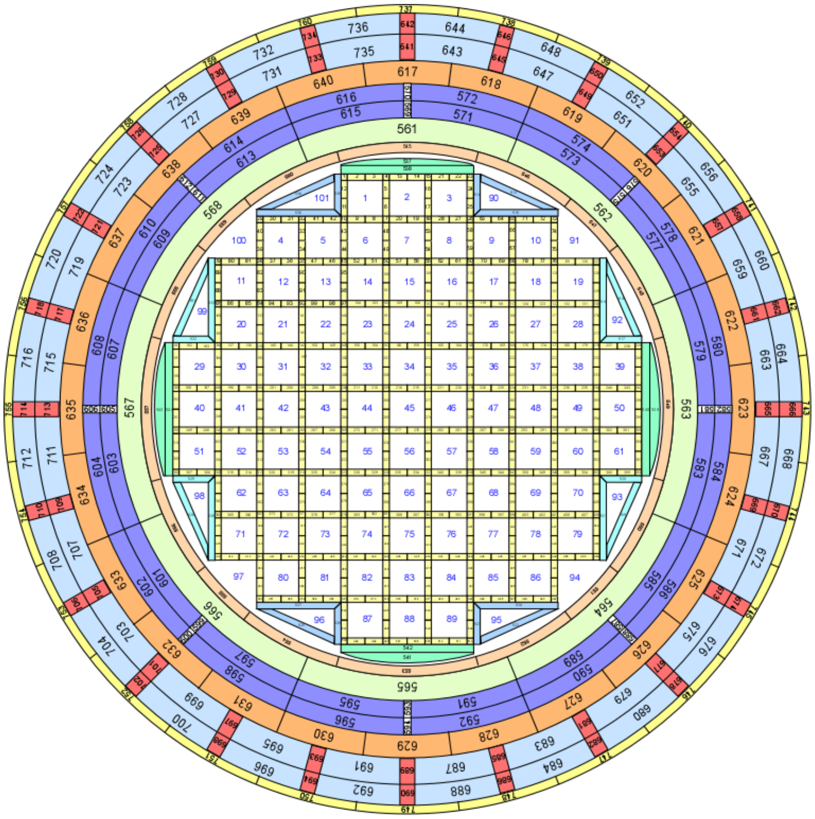


Figure 3 HI-STAR190 MPC-89 Node Map

Heat Load

A key feature of COBRA-SFS is its ability to accommodate numerous heating rates and assembly loading patterns for a given system. Heat generation can be specified for each assembly location and the axial power distribution can also be specified per assembly location in a simple and straight forward approach. This allows the user to determine loading patterns that exhibit adequate levels of safety in replicating site specific heat loads.

For this case study, template heat loads and loading patterns are bounded by the design basis heat loads and patterns outlined in the FSAR (Holtec International). For the MPC-37 PWR configuration these include the following in Table 1 (Holtec International) which reference the provided diagram Figure 5 (Holtec International).

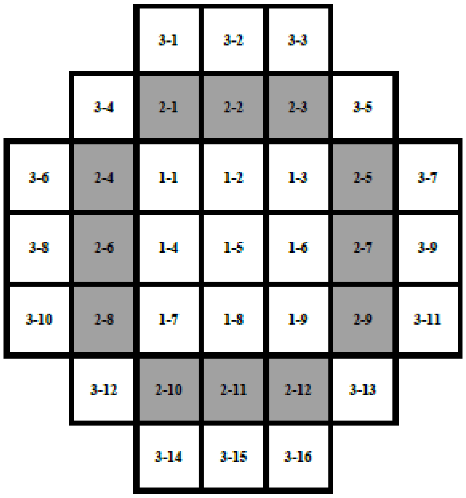
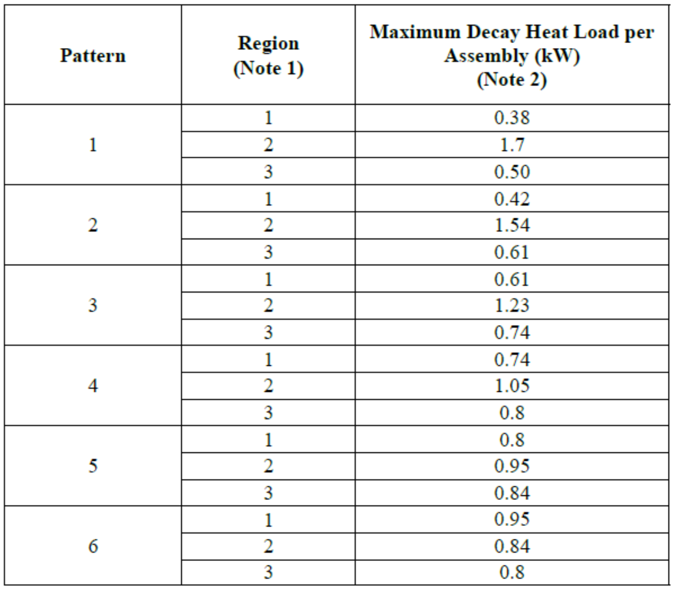


Figure 4 MPC-37 Fuel Assembly Map (Holtec International)

Table 1 MPC-37 Design Basis Decay Heats (Holtec International)



Pattern	Region (Note 1)	Maximum Decay Heat Load per Assembly (kW) (Note 2)
1	1	0.38
	2	1.7
	3	0.50
2	1	0.42
	2	1.54
	3	0.61
3	1	0.61
	2	1.23
	3	0.74
4	1	0.74
	2	1.05
	3	0.8
5	1	0.8
	2	0.95
	3	0.84
6	1	0.95
	2	0.84
	3	0.8

For the MPC-89 BWR assembly configuration the decay heat loads and loading patterns are given in Table 2 (Holtec International) with reference to the assembly region diagram in Figure 6 MPC-89 Fuel Assembly Map.

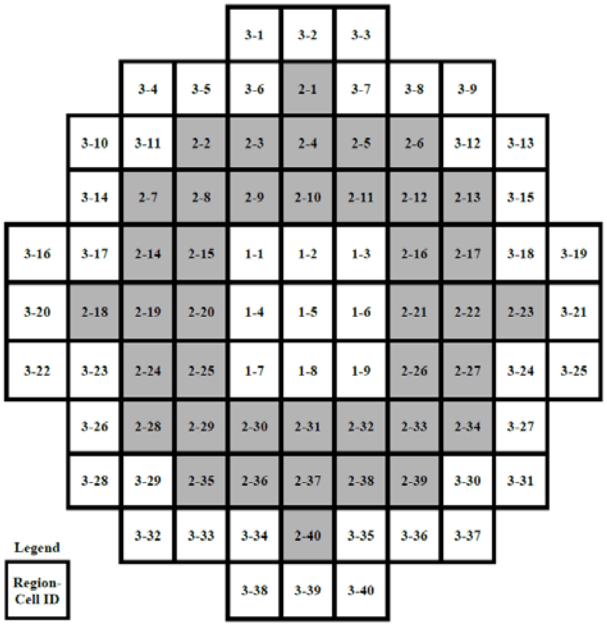
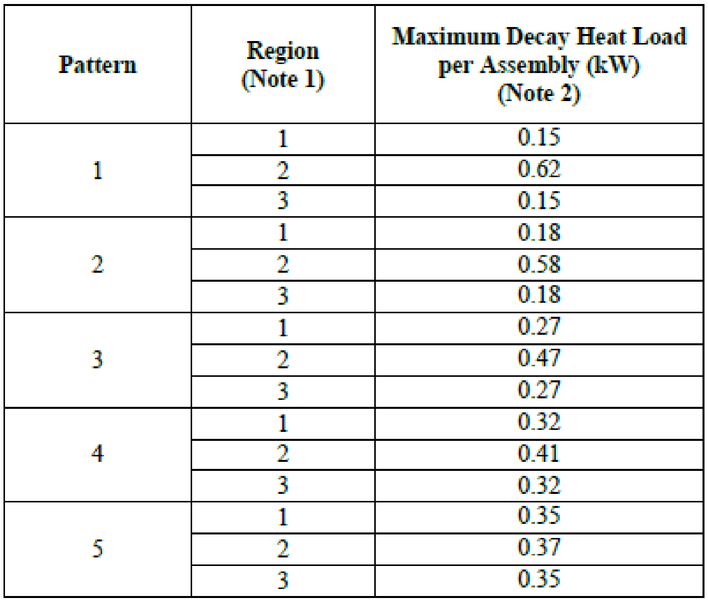


Figure 5 MPC-89 Fuel Assembly Map (Holtec International)

Table 2 MPC-89 Design Basis Decay Heats (Holtec International)



Pattern	Region (Note 1)	Maximum Decay Heat Load per Assembly (kW) (Note 2)
1	1	0.15
	2	0.62
	3	0.15
2	1	0.18
	2	0.58
	3	0.18
3	1	0.27
	2	0.47
	3	0.27
4	1	0.32
	2	0.41
	3	0.32
5	1	0.35
	2	0.37
	3	0.35

Fuel Assembly Geometry

Given the variety of fuel assembly designs in use it may be necessary to analyze a system containing multiple different assembly designs. In comparison with other more traditional finite element modeling codes, COBRA-SFS has the benefit of finely resolving fuel assembly regions in which each rod and rod sub channel is modeled explicitly as opposed to the porous media representation. This allows for quick adjustments to several parameters specifying rod and sub channel geometry for each assembly. The MPC-37 configuration template uses Westinghouse 17 x 17 fuel assemblies as the prototypic assembly because of their prevalence in the U.S.

and similarity to other PWR designs for the purposes of spent fuel modeling. A 2-D schematic representation of this is presented in Figure 7. These assemblies contain 264 active fuel rods, 25 guide tubes and 324 rod sub channels (Holtec International). The fuel assembly hardware such as spacer grids, nozzles and springs are not explicitly modeled in COBRA-SFS however they are taken into account with flow loss coefficients. This is generally applicable to the low velocity gas flows that are seen in spent fuel systems.

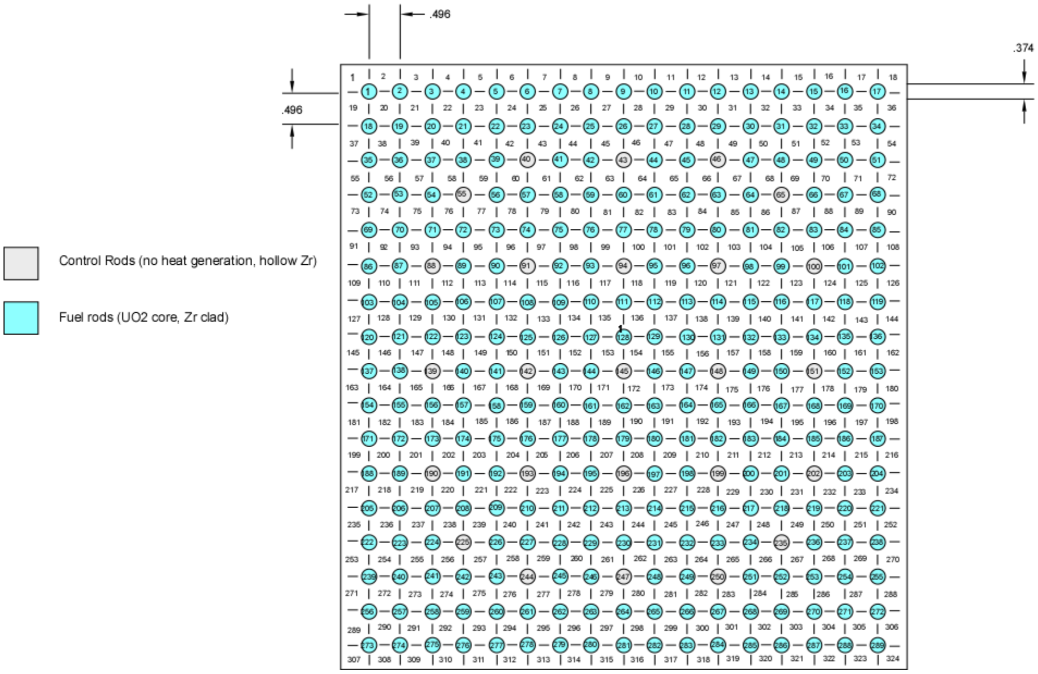


Figure 6 WE 17x17 Fuel Assembly Node Map

The MPC-89 configuration template uses a GE 10 x 10 fuel assembly (Figure 8) as for the prototypic assembly type. These assemblies contain 92 active fuel rods, 2 water rods and 119 rod sub channels (Holtec International). The water rods take up 8 fuel rod positions and can be modeled explicitly in COBRA-SFS along with the mounting hardware and fittings.

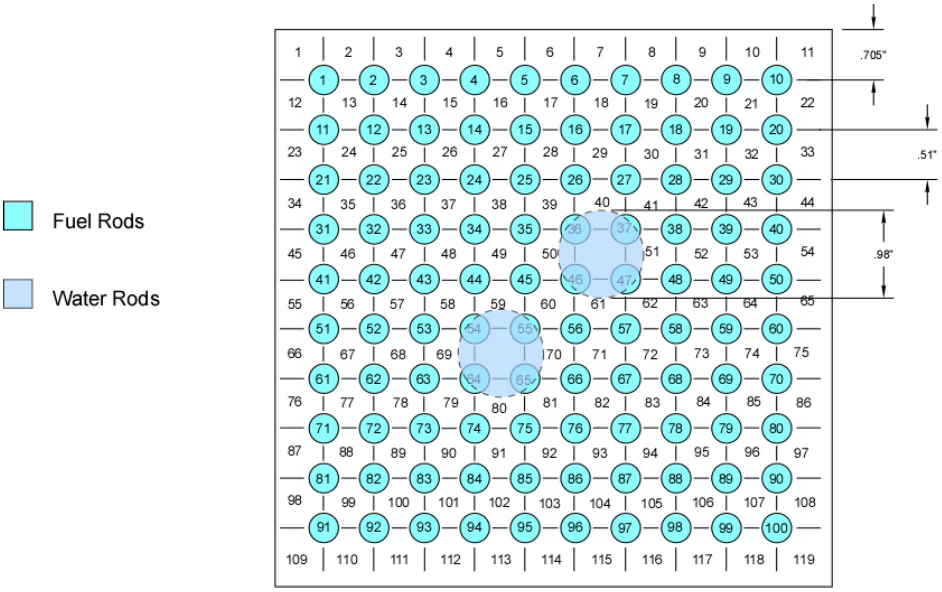


Figure 7 GE 10x10 Fuel Assembly Node Map

Boundary Conditions

Climatic boundary conditions can have substantial effects on the thermal behavior of spent fuel storage systems. When using COBRA-SFS the user can adjust several boundary condition parameters. These parameters include but are not limited to free or forced convection correlations, ambient temperature, insolation heat flux and cask orientation. These parameter adjustments are critical in replicating site specific conditions as climate variations may be drastic from site to site. For the HI-STAR 190 template a typical limiting temperature of 100 °F and steady state full solar insolation is used.

Transfer Operations

The canister modeling that was done for the HI-STAR 190 can support transfer operations through modifications of the canister modeling. In terms of UNF-ST&DARDS this would require a new template that utilizes an MPC-37 and MPC-89 in a HI-TRAC transfer cask.

Storage Conditions

Similar to the transfer cask template needed for the transfer operations section, there would need to be separate templates invoked to model the storage conditions of the MPC-37 and MPC-89 canisters. These canisters can be used in a variety of Holtec storage overpacks including the HI-STORM100, HI-STORM FW, and U-MAX.

Conditions of Transport

The HI-STAR190 is a licensed transportation cask making this stage of its lifecycle the primary application for the modeling described here. Normal conditions of transport NCT are best modeled with a steady state case that includes an appropriate boundary temperature and solar insolation. Hypothetical accident conditions (HAC) require a transient thermal model because of the rapidly changing boundary conditions and subsequent thermal response. In general this procedure is accomplished by modeling the NCT conditions as an initial condition then transitioning to the 30 minute fire and subsequent cool down. Due to the size of rail transportable casks the peak temperatures are usually hours after the fire is complete.

Interim Storage

The interim storage phase of this modeling would require the same types of considerations for application of the MPC-37 and MPC-89 models to a given storage system. Current concepts for CIS with Holtec systems utilize an underground module that can accommodate either of the canisters used in the HI-STAR 190 template. A storage template would need to be developed in this case.

Conclusions and Future Work

UNF-ST&DARDS with COBRA-SFS implemented as its thermal analysis code is an effective tool for analyzing spent fuel storage conditions and planning for aging management, transportation and disposal. This paper shows how thermal templates are developed and utilized for thermal analysis within the UNF-ST&DARDS framework. For each stage in the spent fuel lifecycle there are templates that have been developed allowing fuel to be analyzed all the way through the process for multiple designs.

In the future templates will continue to be developed to encompass all of the existing storage, transfer and transportation systems in use in the Unites States. This involves an extensive survey of the deployed storage designs and a determination as to whether site specific features need to be modeled individually. Another area for future work is code development of COBRA-SFS. Currently there are legacy characteristics of the code that make it difficult for the user to use and increase the complexity with UNF-ST&DARDS integration. These issues can be simply addressed through a program of code modernization and simple development that does not impact the underlying functionality and tremendous advantages of the code.

Acknowledgements

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