Effective Thermal Conductivity Method for Predicting Spent Nuclear Fuel Cladding Temperatures in a Dry Fill Gas

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Framatome Cogema Fuels has been active for more than five years in the Department of Energy's program to manage radioactive waste, particularly its disposal in a geologic repository. Recently, a significant milestone was reached in the development of a reliable methodology for the prediction of peak spent nuclear fuel (SNF) cladding temperatures within the waste disposal package. The effective thermal conductivity method, described below, provides a benchmarked process for estimating cladding temperatures and includes consideration of various fuel assembly designs and container fill gases. While the methodology was originally developed for the thermal analysis of conceptual waste package designs emplaced in the potential repository at Yucca Mountain, the methodology also applies to the thermal analysis of dry SNF in any container, such as for SNF storage or transportation.

Maximum temperature limitations for transportation, storage, and disposal of commercial SNF have been established to maintain the integrity of the fuel rods by preventing creep rupture failure. To receive a Nuclear Regulatory Commission (NRC) license for any SNF container, calculations must be performed demonstrating adequate knowledge of the temperatures and physical performance of the irradiated assemblies within the container. Three methods, as described below, are available to estimate cladding temperatures inside a storage, transportation, or disposal container with a dry fill gas.

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The first and most involved method is to explicitly model the container and every fuel rod in every assembly within it. This model would directly consider the internal fill gas convection and conduction and a matrix of radiation view factors between the rods. However, the fill gas convection would be dependent upon orientation of the container and the assemblies with respect to both tilt and angle and would be very difficult to quantify. This is especially difficult if the assembly spacer grids are included in the analysis. This detailed method is costly due to setup and computational time and does not lend itself to parametric design evaluation where detail is desired in the container structures and not in each individual assembly.

The second method employs the Wooton-Epstein correlation to estimate the peak cladding temperature based on the highest steady state temperature in the SNF basket structure. Since the 1960s, the Wooton-Epstein correlation has been the primary tool of transportation/storage vendors as it simplifies the analysis and has been previously accepted by the NRC. In a container thermal analysis using Wooton-Epstein, the SNF assemblies are modeled only as an edge heat flux to the basket structure. Then, the Wooton-Epstein correlation is used to estimate the maximum steady state spent fuel cladding temperature. This method is considered obsolete as it requires lengthy and multiple calculations, does not easily address transient behavior of the SNF and basket, does not easily predict the effects of differential loading of the canister, and may adversely affect basket profiles by forcing constant SNF assembly surface heat flux rates. Given design time requirements, this method usually forces the designer to use conservative bounding approaches to the analysis which tend to over-design the final product. Finally, the Wooton-Epstein correlation was

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Waste Package (WP) Thermal Model Using SNF Effective Thermal Conductivity

developed as an empirical fit to experimental data generated in 1963 using a single assembly array (17x18) in air with assembly axial power distribution neglected.

The third method of estimating peak cladding temperatures is to prepare a finite element or finite difference model of the SNF assembly volume as a smeared solid with uniform internal volumetric heat generation as part of the entire SNF container model (see figure above). Instead of explicitly modeling the SNF rods, smeared (distributed) properties for a homogeneous assembly are assumed in the container model that will estimate the combined radiation and gaseous transport of heat from the assembly rods to the basket structure. Assembly volume effective thermal conductivities can be defined to simulate the temperature drop across PWR and BWR

assemblies in various fill environments. This methodology has been utilized, in a limited manner, for the General Atomics truck casks, for the Nuclear Assurance Corporation Storable Transport Casks, and by the national laboratories which have been previously tasked by the NRC to verify vendor calculations.

The key to accurate SNF cladding temperature predictions using the effective thermal conductivity method lies in determining the proper conductivity to assume within the assembly volume. Assembly temperature distributions are a function of the assembly type, the assembly decay heat, and the container basket wall temperature. The basket temperature not only specifies the environment temperature for the assembly, but also impacts what portion of the decay heat is

transferred by thermal radiation (dependent on the fourth power of absolute temperature). That is, the higher the temperatures within the assembly, the more heat flows by thermal radiation compared to conduction and convection. Radiation heat transfer introduces nonlinearities into the otherwise linear heat transfer calculation. Therefore, any calculated effective thermal conductivity will be highly temperature-dependent (and non-linear) and cannot be specified by just one value for a given assembly type.

To determine appropriate effective thermal conductivities for PWR and BWR assemblies, detailed thermal models (see figure above) of typical fuel assemblies were developed using the ANSYS finite element code including both gaseous heat transport and thermal radiation (that is, we used the first method described above to develop the third). Evaluating a variety of spent fuel characteristics,

geometries, and temperature levels, temperature and heat-load dependent effective thermal conductivities for homogeneous "smeared" assemblies were derived. The analysis included PWR array sizes ranging from 14x14 to 17x17, and BWR sizes from 7x7 to 9x9 both with and without the channels present. Most importantly, effective thermal conductivities were developed for different fill gases (environments) including helium, nitrogen, argon, and vacuum. Helium, a typical dry storage fill gas, possesses significantly different heat transfer characteristics compared to air which was the only fill environment considered by the Wootton-Epstein correlation.

As expected, the effective thermal conductivities were found to be highly temperature dependent; however, there was little dependence on the assembly heat load. For a 14x14 PWR assembly with helium

fill gas, calculated effective thermal conductivities ranged from 0.41 W/m·K at a 25°C basket temperature to 1.41 W/m·K at 400°C. A complete range of conductivities were developed to allow for the thermal analysis of several SNF assembly types in any typical container fill gas.

The use of the calculated effective thermal conductivity method was compared to several previous applications using alternate methodologies and to actual testing of SNF storage casks performed at Idaho National Engineering Laboratory (INEL). The effective thermal conductivities developed were found to provide a best estimate of cladding temperatures within an SNF container. Benchmark calculations using the effective thermal conductivity methodology to predict assembly temperatures within the INEL test storage casks closely matched the experimental data and post-test calculations performed by Pacific Northwest Laboratory. Further, the effective thermal conductivities were found to be consistent with single-point values previously published by storage cask vendors.

The methodology not only advances the repository waste package design effort, but is also a valuable tool for the transportation and storage cask industry. The effective thermal conductivities provide a method for predicting (with a high level of confidence) a best estimate of peak cladding temperatures for SNF assemblies in a dry fill environment. The more accurate representation of SNF temperatures with this methodology will replace the bounding conservatism of empirical approximations which can constrain container design and limit the capacity of potential design concepts.

The effective thermal conductivity methodology was developed by Robert Bahney, Tom Lotz, and Tom Doering of Framatome Cogema Fuels.