Vacuum Drying of Spent Fuel Storage Canisters/Casks – “Just How Much Water Could be Left in There, Anyway?” - 15233

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ABSTRACT

The process of moving spent fuel assemblies from wet storage in the spent fuel pool to dry storage in an inert gas environment within a canister or cask typically involves two main stages. In the first stage, the bulk of the water is removed by a draining or siphoning operation, conducted with pressure inside the canister maintained at 1.3 to 2 atm. This process removes most of the water in the cask cavity, but residual water can be left behind, in three main regions. The largest region, typically, is the bottom of the cavity below the end of the siphon tube. A second general class of locations, also located at the bottom of the cask cavity, consists of the “dashpots” at the ends of the various non-fuel tubular structures within the fuel assemblies. For PWR assemblies, these are the control rod guide sleeve tubes and instrumentation thimbles. For BWR assemblies, these are the water rods of various designs and control blade ends in some configurations. A third class of locations consists of porous material within the cavity that can absorb water, such as thin ceramic neutron poison plates, and ostensibly intact fuel rods that nevertheless might have pinholes or fine cracks in the cladding that could allow pool water to creep inside the fuel rod.

To remove residual water from these locations, the second stage of drying operations utilizes vacuum drying, by reducing the pressure sufficiently to convert the water to vapor that can then be pumped out of the canister cavity. In this operation, the cask cavity pressure is *slowly* reduced from the nominal condition of (1.3-2.0 atm (1000-1520 torr), to a final target pressure below 3 torr (0.004 atm). This is typically accomplished in three to five stages, with prescribed “hold” points defined in procedures or in the Technical Specifications, to preclude sudden pressure spikes due to flashing of water to steam, or development of large local temperature gradients in the fuel rods or other cask internal components. This paper discusses the various locations in the system where residual water may “hang up” in the cask, and presents a discussion of the physical basis for the effectiveness of vacuum drying for removing it.

Results and conclusions based on realistic qualitative and quantitative evaluations of the transient heat transfer behavior of the system are presented, based on detailed modeling of a range of spent fuel canister designs and decay heat loads, most notably the 24P Dry Shielded Canisters (DSCs) stored at the Rancho Seco Independent Spent Fuel Storage Installation (ISFSI), the NAC-MPC modules at Maine Yankee, the 24P DSCs stored at Calvert Cliffs, and the Holtec HI-STORM modules at Hope Creek. The evaluations presented here show that ice formation within a spent fuel canister is highly unlikely, due to the availability of a large thermal source term in the form of the decay heat load of the spent fuel. The formation of ice is an operational concern, since it mainly affects operation of equipment external to the canister (i.e., the hoses, valves, and fittings of the vacuum drying equipment.) Evaluations are presented for quantifying the amount of residual water that could remain in the cask cavity, even after successful drying operations,

since vacuum drying is a limit process, and by definition, cannot remove all of the water from the cavity, no matter how long the operation goes on, even if all of it is in vapor form.

INTRODUCTION

As part of the U. S. Department of Energy (DOE) Nuclear Fuels Storage and Transportation (NFST) Planning Project, work is currently under way to develop thermal analysis models for the UNF-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) [1]. This is a multi-laboratory effort, with work performed in collaboration between Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL) to develop a complete database of cask storage and transportation system model templates that incorporates site-specific characteristics (e.g., as-built system configurations and cask/canister initial decay heat loading information). The primary computational tool selected for thermal modeling of these storage systems is the COBRA-SFS code [2].

The work reported here is focused mainly on developing appropriate modeling tools for evaluating the thermal conditions that used nuclear fuel (UNF) is subjected to in the process of transfer from wet-to-dry storage. The approach utilizes the COBRA-SFS code, developing templates and procedures that can be incorporated into UNF-ST&DARDS, to facilitate assessment of realistic temperature profiles and in some cases conservatively low temperature profiles, for UNF in dry storage systems, in addition to bounding design-basis temperatures and temperature distributions. Because nearly all degradation mechanisms for materials and structures of dry storage and transportation systems are dependent on temperature, it has been recognized [3] that accurate characterization of local temperatures and temperature gradients for these systems, particularly the fuel rods, is a primary requirement for evaluation of UNF over the entire storage period. Although wet-to-dry transfer operations represent only a very short time interval in the long-term storage of UNF, it is during this transient process that the fuel cladding is expected to reach higher temperatures than would be typical of peak temperatures in storage, and the fuel may experience thermal cycling over potentially significant ranges of temperature. This short window of time is therefore likely to have a significant effect on the long-term structural and material properties of the fuel rods and assembly components.

GENERAL OVERVIEW OF VACUUM DRYING PROCESS

Actual vacuum drying practices [4] in the industry vary widely from site to site and have undergone some significant evolution over time. The basic operation, however, is relatively simple. Typically, the drying process proceeds in two distinct stages. In the first stage, the bulk of the water is removed from the package cavity by draining or siphoning (sometimes referred to as “blowdown”), with the system maintained at or slightly above atmospheric pressure, to avoid rapid phase change that could overpressurize the canister. When draining or siphoning has removed as much liquid water as the particular system can manage, the second stage is initiated. In this stage, the remaining residual water is vaporized in a vacuum drying process and as much as possible is removed by gas pumping. The process at this point typically involves slowly decreasing the pressure in the cavity from the starting pressure of 1000 to 1520 torr (1.3 to 2.0 atm) to the “target” pressure for the vacuum drying process, which is generally slightly below 3 torr (0.004 atm).

The vacuum drying process takes advantage of the physical properties of water at low pressure, as illustrated by the equilibrium phase diagram[a] in Figure 1. This diagram shows the solid/liquid/vapor triple point for water at 4.6 torr (0.006 atm) and 0°C (32°F), where water can exist in equilibrium as vapor, liquid, and solid. Below a pressure of 4.6 torr (0.006 atm), water does not have a stable liquid phase. For temperatures above the saturation value at pressures below the triple-point pressure, the equilibrium phase for water is vapor. Temperatures within the spent fuel canister during vacuum drying are expected to be in the range indicated on the diagram, due to the decay heat from the spent fuel. These temperature ranges are based on detailed modeling of a range of spent fuel canister designs and decay heat loads, most notably the 24P Dry Shielded Canisters (DSCs) stored at the Rancho Seco Independent Spent Fuel Storage Installation (ISFSI), the NAC MPC canisters at Maine Yankee, the 24P DSCs stored at Calvert Cliffs, and the Holtec HI-STORM modules at Hope Creek.

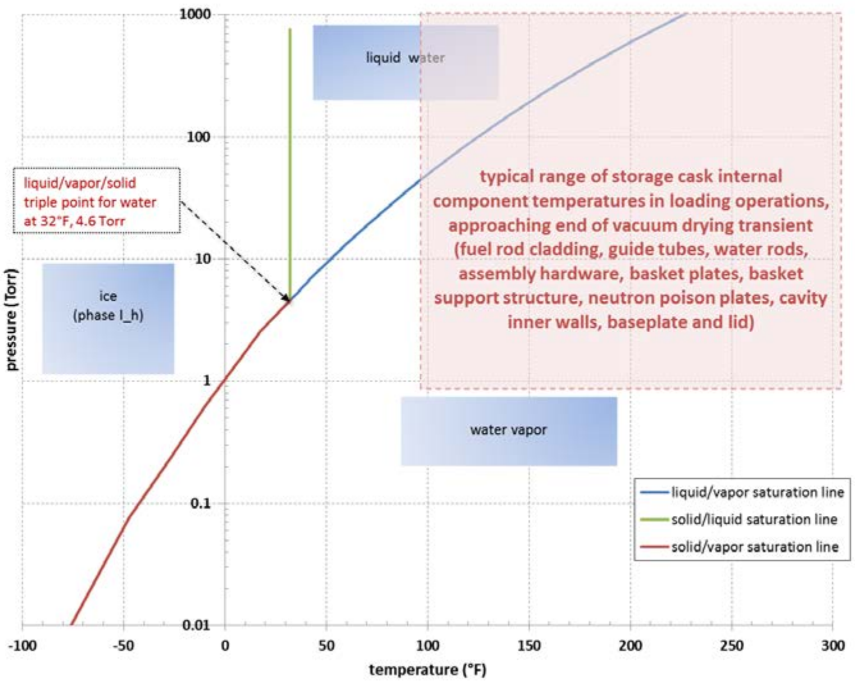

Fig. 1. Equilibrium Phase Diagram for Water; Pressure Range from 0.01 to 1000 torr (0.00001 to 1.3 atm), with Typical Range of Temperatures for a Spent Nuclear Fuel (SNF) Package near End of Vacuum Drying Transient

The typical temperature range summarized in Figure 1 suggests two significant features of vacuum drying of a spent fuel cask or canister. First, any unbound residual water should be readily converted to vapor phase at low pressure. Second, there should never be any issue of ice formation within the cask cavity in the vacuum drying process, if it is done according to established procedures and within limits typically prescribed in Technical Specifications. However, Figure 1 shows the *equilibrium* phase diagram for water, and vacuum drying is a *transient* process. The phase diagram shows the state that the water in the canister is being

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[a] Any classical thermodynamics textbook would include this type of detailed phase diagram for a range of materials that exhibit this behavior, water and carbon dioxide being the most familiar.

driven toward equilibrium by its physical properties, but does not show the process it might follow to get there. Water in liquid form that is suddenly (or even gradually) reduced in pressure from, for example, 1000 Torr (1.3 atm) to 3 torr (0.004 atm) must undergo phase change to assume its equilibrium vapor phase.

Phase change requires energy, and some amount of time, if it is to proceed without rapid changes in pressure, as is mandated in Technical Specifications for vacuum drying procedures. In a spent fuel cask, there is a source of energy that is for the purposes of the vacuum drying operation essentially inexhaustible and readily available for transfer to the liquid water. The main mode of heat transfer is conduction through solid components and through the cavity gas, modestly abetted by thermal radiation. In the early stages of the process, heat transfer may also receive a very minor assist from convection, but this mechanism is likely to have only a very small effect in a low-pressure gas environment. As the temperature of the residual water decreases due to evaporation, it tends to cool the solid surfaces it is in contact with, increasing the thermal gradients in the structures of the cask, and thereby increasing the rate of heat flow from the fuel rods to the water.

A spent fuel cask with a 24 kW decay heat load (typical design basis for many spent fuel canister types) will produce, in 50 hours of drying time, approximately $4.32\text{x}(10^6)$ kJ of energy. In a drying time of 10 hours, the spent fuel would produce $8.64\text{x}(10^6)$ kJ. A more typical initial decay heat load of 10 kW in a spent fuel canister will produce $1.8\text{x}(10^6)$ kJ of energy in 50 hours. This is more than sufficient to vaporize the amount of residual water that is likely to be left in a canister or cask following bulk removal of water by siphoning and draining, as discussed below.

Locations of Residual Water

There are three main areas where residual water can be left behind in the cavity at the end of the draining or siphoning process. These are (a) the bottom of the cavity below the siphon tube, (b) the dashpots at the ends of the various non-fuel tubular structures within the fuel assemblies (e.g., PWR assembly control rod guide sleeve tubes and instrumentation thimbles and BWR assembly water rods), and (c) porous material within the cavity that can absorb water. In some canister designs, water could also remain on various relatively flat horizontal surfaces of components comprising the basket or other support structures in the canister, such as support disks, flanges, and basket support structures (e.g., solid aluminum billets).

The amount of water left at the bottom of the canister or cask below the siphon tube obviously depends on simple geometry: the diameter of the cavity and the clearance between the end of the tube and the base of the cavity. This can be as much as ~2.54 cm (~1 inch). For a cavity inner diameter of ~1.5 m (~60 inches), this suggests that there could be as much as 30-38 L (8-10 gallons) of water in the bottom of the cavity, after accounting for the volume taken up by the ends of the fuel assemblies and other structures sitting on the base of the cavity. The amount of energy required to evaporate this quantity of water can be readily calculated as approximately 85,414 kJ, based on the latent heat of vaporization for water (40.65 kJ/mol) and its the molecular weight (18.016 gm/mol). As noted above, a typical spent fuel canister would generate enough energy, by at least two or three orders of magnitude, to evaporate this amount of water within typical drying times expected for the corresponding decay heat load.

Simply from considerations of geometry, it is obvious that the largest amount of residual water would be at the bottom of the cavity. The maximum amount of water trapped in the dashpot regions at the ends of guide tubes and water rods could be directly calculated from the geometry of the specific fuel assemblies loaded in the canister. However, the volume of water trapped within any single tube would be relatively small (on the order of ounces, rather than gallons), and the number of such tubes per assembly is typically no more than 25 guide tubes per PWR assembly, and only one or two water rods per BWR assembly. Similarly, bounding estimates of the maximum amount of water that might be pooled on horizontal structures within the basket, such as support disks and side support billets could be readily determined from geometry information on a particular design. For any design, however, this would be a relatively small volume of water, since it could only be present in a relatively thin film or sheet.

Water absorbed by porous material within the canister or cask has been identified as a particularly difficult problem in vacuum drying. Operational experience [5] suggests that canisters with ceramic plates require longer drying times than similar canisters with solid metallic neutron poison material, although how much longer is not quantified. It has also been speculated that another potential source of trapped water might be nominally intact fuel rods that have absorbed pool water through pinhole leaks or hairline cracks.

Based on simple geometry of the porous material in the canister, and its actual porosity, it would be possible to calculate a bounding volume for the amount of water trapped in such material. Determining how rapidly it could be removed from the material, by the process of evaporation, would require additional evaluations of hydrodynamics within porous media, and possibly studies of the chemical behavior of water in contact with the material. Such studies are beyond the scope of the current work, and this paper does not address physisorbed or chemisorbed water. Further study is needed to appropriately characterize the form and amount of this potential source of residual water that might remain within a spent fuel canister after vacuum drying.

The potential for water to be trapped within nominally intact fuel rods, however, can be readily shown to be an insignificant source of residual water in a typical spent fuel canister or cask. Except for specific canister designs that are permitted to accept failed fuel, most dry storage canisters are limited to accepting only nominally intact fuel rods, which are typically defined as having no more than hairline cracks or pinhole leaks. (The potential for water penetrating into damaged fuel is beyond the scope of this paper.) For nominally intact fuel rods, it is essentially impossible for a significant amount of water to get inside the cladding while it is in storage in the spent fuel pool, due to very limited void space available. The pellet-clad gap is typically less than 4 mils at fabrication, and is generally much smaller after irradiation, often estimated as essentially zero. The UO_2 pellets have a very low porosity, as the ceramic material is typically at 95% theoretical density.

In addition to the limited volume available to trap water inside an intact fuel rod, the fuel rods (inside and out) are generally hot enough to readily boil off any trapped water, as the rod heats up in the vacuum drying transient. The *minimum* temperature of a fuel rod is generally likely to be far above the boiling point of water at the starting (relatively high) pressure of the vacuum drying portion of transient, at the end of the drain-down process. As the cavity pressure decreases, this difference only increases, and the fuel rods would continue to heat up as the transient proceeds. Any water that might have crept into a fuel rod while in the pool can be expected to make a hasty exit, in vapor form, fairly early in the drying transient. It will already be long gone by the latter stages of the drain-down, before the actual (low-pressure) vacuum drying stage begins.

Internal Heat Transfer Rates

As noted above, conduction through the solid structures of the canister internals (including the fuel assemblies) is the most readily available path for heat transfer to water pooled at the bottom of the cask. The fuel assemblies, including the ends of the rods, the ends of the guide tubes, and the assembly footings, would be "standing" in the water at the bottom of the cask. Similarly, the dashpot regions are located at the ends of metal tubes that generally extend the full length of the fuel assembly, and are located adjacent to heat generating fuel rods. Heat would tend to flow axially in an essentially one-dimensional conduction path along the fuel rod cladding, metal guide tubes, and water rods.

For zircaloy cladding, and an assumed typical temperature difference of approximately 100°C from the axial center of the fuel rod to the lower end, the heat flux is on the order of 0.5 to 1.0 kW/m^2. The area available for heat transfer for any one fuel rod is relatively small, but this area is multiplied by the several hundred fuel rods per assembly for a multi-assembly canister that may contain 24, 32, 68, or more fuel assemblies. Furthermore, the basket plates, which also stand on the bottom of the cavity, present a large cross-sectional conduit for heat flow, with a temperature difference (center to bottom) that closely echoes the gradient in the fuel rods.

This suggests that the total rate of heat transfer to the bottom of the canister should be more than sufficient to evaporate the water while maintaining material temperatures above ~100°C, and possibly driving them higher, since not all of the energy available would necessarily be used up in the phase change process. As noted in the evaluation of energy available from the spent fuel in a typical canister, less than 5% of the decay heat load would be needed to completely vaporize more than 38 L (10 gallons) of water over the range of typical drying time for a given decay heat load.

With respect to liquid water pooled on internal structures within the cavity, it should be remembered that a major purpose of those structures, in addition to supporting the weight of the fuel assemblies and basket, is to dissipate heat from the fuel assemblies to the outer shell of the canister. Simply from the standpoint of thermodynamics, there are few heat transfer conditions quite as readily conducive to evaporation as conduction to a thin liquid film on a heated plate. Water held up in such a manner would not last long in liquid form in any canister design, under any reasonable decay heat load.

Estimate of Water Left Behind

Aside from the issues related to physisorbed or chemisorbed water, bounding estimates of the amount of water remaining as vapor within the canister cavity at the end of vacuum drying can be obtained from relatively simple calculations. Vacuum drying is a limit process, and by definition, cannot remove all of the water from the cavity, no matter how long the operation goes on, even if all of it is in vapor form. That is not the goal of vacuum drying; it just has to remove enough water to satisfy regulatory requirements [6] related to protecting the integrity of spent fuel in dry storage.

The pumping operation of vacuum drying can remove water vapor only to the point of establishing a state where the partial pressure of water vapor is at some fraction of 3 torr (0.004 atm) at the average temperature of the cavity gas mixture. The cavity gas is a mixture of helium and water vapor at some specific temperature, and therefore the maximum amount of water vapor that could be present is the bounding case of 100% water vapor at 3 torr (0.004 atm) at that temperature.

For a postulated average temperature for the cavity gas and assumed typical cavity volume (on the order of 7 m^3, as a ballpark number), it is possible to directly estimate how much water vapor could be left behind in the cavity atmosphere, based on the ideal gas law. For a typical canister, based on a reasonable range of average gas temperature values, this could be on the order of 0.01–0.02 kg of water. (Additional water that might be physisorbed, chemisorbed, or otherwise trapped within enclosed structures within the particular canister would, of course, add to this quantity.)

Determining if this is a significant amount, in terms of potential interactions of the water with fuel cladding and cask internal structures over time is a materials performance issue. It must be addressed by evaluation of material properties of the canister components, and considerations of the time intervals involved for extended storage. Such analyses would also need to take into account the time interval during which the water remains in a vapor state, and the time frame required for local surface temperatures on components within the cavity to drop below the local saturation temperature, so that the water would condense as liquid. Hence the keen interest in developing a reliable means of obtaining reasonably accurate estimates of temperatures, temperature profiles, and temperature histories for spent fuel storage systems.

EXAMPLE OF THERMAL EVALUATION FOR VACUUM DRYING: RANCHO SECO

Having established that there is a need to know the temperature history of fuel assemblies during wet-to-dry storage transfer operations, a step-by-step procedure has been developed for setting up a series of calculations with COBRA-SFS to obtain this information for canisters at a specific site. This procedure discusses what is possible, given that detailed information is generally very difficult to obtain for specific sites. It also discusses what might be done, if required information were available. An example application of this procedure is provided, based on wet-to-dry storage transfer operations at the Rancho Seco site. The information is limited, but it is more than is generally available at any given ISFSI, particularly the ISFSI-only sites.

The Rancho Seco ISFSI is owned by the Sacramento Municipal Utility District (SMUD), and is located in Herald, California, at the decommissioned site of the Rancho Seco nuclear power plant. The site stores 493 fuel assemblies (B&W 15x15 Mark B, zircaloy-4 cladding, <40 GWd/MTU maximum burnup), in 21 NUHOMS®[b] 24P DSCs, in an 11x2 array of NUHOMS® Horizontal Storage Modules (HSMs). Figure 2 shows an external view of the storage modules at the decommissioned site. The DSCs were wet-loaded into an MP187 transportation cask for drying operations and on-site transfer to the storage modules, in 2001.

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[b] NUHOMS® is a registered trademark of Transnuclear Inc. (TN), a wholly-owned subsidiary of AREVA Inc.

Photo courtesy of Rancho Seco

Fig. 2. NUHOMS® HSM Array at Rancho Seco ISFSI (Maheras et al. 2013)

Two COBRA-SFS model templates were constructed at ORNL for the fuel/control Dry Shielded Canister (FC-DSC) and the fuel only Dry Shielded Canister (FO-DSC) configurations, for use with the UNF-ST&DARDS tool for evaluation of long-term storage conditions in the ISFSI. These models were provided to PNNL and modified to include the geometry of the MP187, configured as an on-site transfer cask, for evaluation of wet-to-dry transfer operations at the Rancho Seco site. Essential information on these operations was limited to documentation of assembly decay heat loads at time of loading, assembly loading pattern for each canister, and the nominal time span of drying operations for each canister. The initial decay heat load per canister was 8 to 9 kW, as illustrated in Figure 3. The time interval for drying operations ranged from a minimum of 42 hours to a maximum of 95 hours, as illustrated in Figure 4.

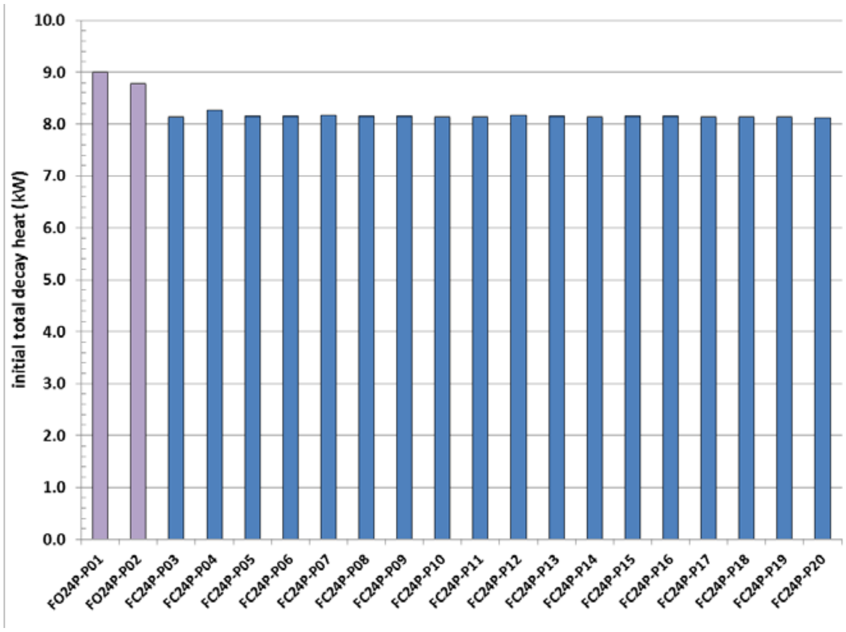

Fig. 3. Canister Decay Heat Load (kW) for FO24P and FC24P DSCs at Initial Loading

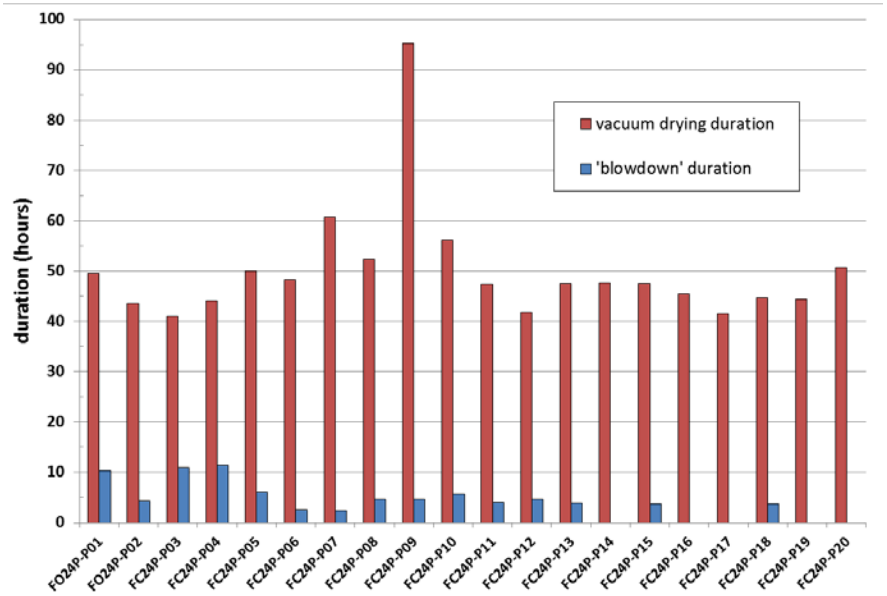

Fig. 4. Reported Drying Operations Duration (Hours) for 24P DSCs Loaded at Rancho Seco

Based on this limited operational data, and general information on the Rancho Seco site, the transfer operations were categorized into six “typical” cases that can be expected to more or less cover the range of thermal conditions experienced by the fuel in this process. The specific cases simulated with COBRA-SFS calculations for canisters in the Rancho Seco ISFSI are listed in Table I. Calculations were performed for the FC-24P-P04 canister, for both steady-state bounding cases and the vacuum drying transient. For comparison, and to evaluate the sensitivity of results to initial decay heat load over the relatively limited range in the canisters at Rancho Seco, a vacuum drying transient was also performed for FO-24P-P01, which had the highest initial decay heat load.

TABLE I. Summary of Cases Simulated with COBRA-SFS for Wet-to-Dry Transfer Operations at Rancho Seco

Case #	Description	Modeled As	Ambient (°F)	DSC Backfill	DSC/MP187 Annulus	Exterior to MP187
3	vertical, indoors, on washdown platform; blowdown to ~3 torr, and vacuum drying	transient (44.2 hours)	85 (air)	helium (rarified)	pool water (stagnant)	air (natural circulation)
3a	same as Case #3; steady-state asymptote for vacuum drying conditions	steady state	85 (air)	helium (rarified)	pool water (stagnant)	air (natural circulation)
4	vertical, indoors, on washdown platform, operations before draining annulus	bounding steady state	85 (air)	helium (1 atm)	pool water (stagnant)	air (natural circulation)
5	vertical, indoors, on washdown platform, operations after		85 (air)	helium (1 atm)	air (stagnant)	air (natural circulation)

	draining annulus					
6	horizontal, outdoors on transport skid, going to ISFSI		100 (air)	helium (1 atm)	air (stagnant)	air (natural circulation)
7	horizontal, in NUHOMS® storage module	steady state	100 (air)	helium (1 atm)	air (stagnant)	n/a

Peak component temperatures, including the peak fuel cladding temperature, obtained with COBRA-SFS modeling for the cases are illustrated in Figure 5. The peak fuel cladding temperature calculated for the vacuum drying transient (Case #3 at 44.2 hours), is not generally expected to be the highest temperature experienced by the fuel in the transfer operations at Rancho Seco. The steady-state results for Case #4 and Case #5 show that even after vacuum drying is complete (i.e., the “3 torr for 30 minutes” criterion has been satisfied), and the canister has been backfilled with helium, fuel rod temperatures (and temperatures of all other components within the canister) would continue to rise during the subsequent operations (e.g., final sealing, seal inspection and testing, draining of the annulus). Depending on the time required, the peak temperatures in the transient drying operation could exceed the peak temperatures for initial storage conditions (Case #7) in the NUHOMS® module.

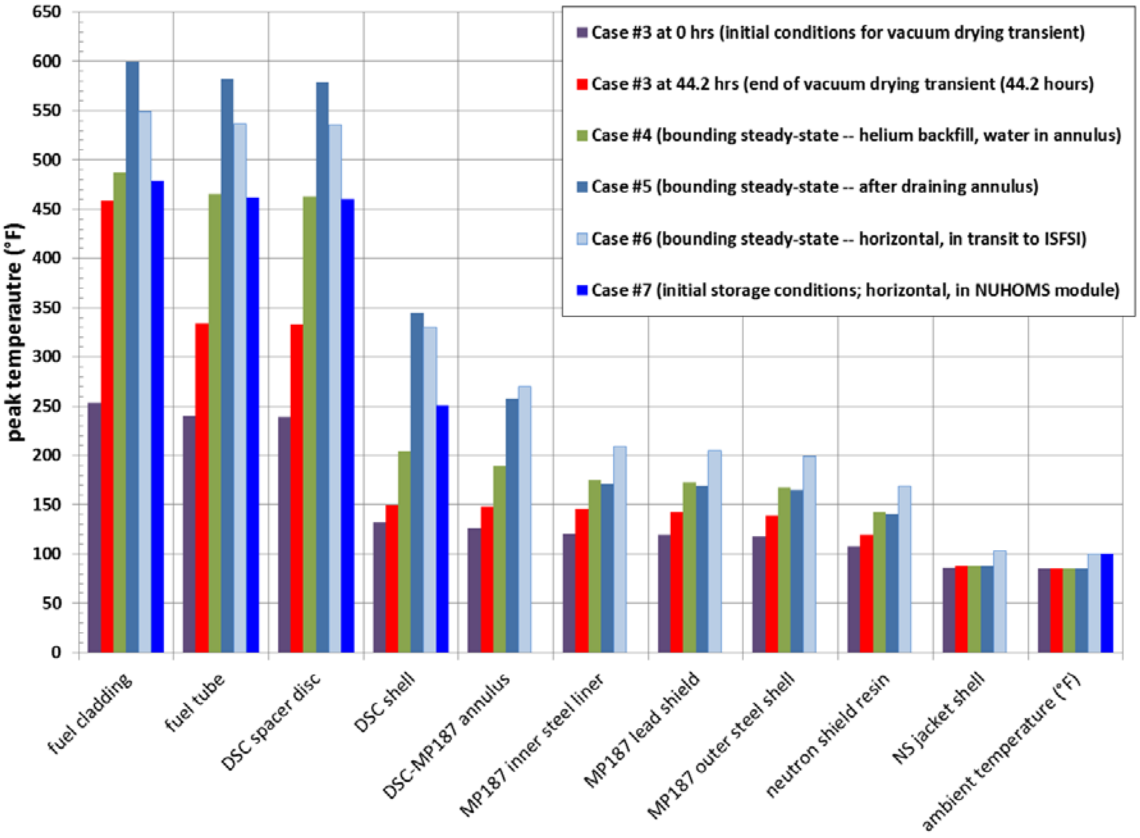

Fig. 5. Summary of Peak Component Temperatures Predicted with COBRA-SFS Modeling for Bounding Conditions in Transfer Operations at Rancho Seco for FC24P-P04

The peak temperatures experienced by the fuel in a particular canister at Rancho Seco during transfer operations may have been significantly lower than indicated by the bounding cases presented in Figure 5. The values reported in Figure 5 for Cases #4 and #5 correspond to the assumption that the specific steps in transfer operations after vacuum drying was complete took long enough for the DSC/MP187 to reach thermal equilibrium when vertical in the fuel handing building. The actual temperatures reached during these steps of the operation would require performing transient calculations for the duration of these steps. Since the duration of these steps in the process are not known for this site, these transients cannot be performed.

Transient evaluations for the actual vacuum drying step were performed with the COBRA-SFS models of the FC24P-P04 and FO24P-P01 in the MP187. Figure 6 shows the bounding path of the transient assumed in the calculations, in comparison to a more realistic hypothetical estimate of the path of the transient, superimposed on the phase diagram for water. Figure 7 shows the maximum cladding temperature rise in response to the vacuum drying transient for these two DSCs. Because of differences in per-assembly decay heat distribution, the slightly hotter DSC (FO-24P-P01) heats up slightly more slowly than the nominally cooler DSC (FC-24P-P04). However, this difference is small enough to be within the uncertainty in the total decay heat load for these canisters, and is therefore not in itself particularly significant for this analysis.

These results suggest that the small difference in total decay heat load for the two canisters is insignificant, and for the purposes of this evaluation, it is reasonable to assume that the vacuum drying transient would follow essentially the same path for all of the fully loaded canisters at the Rancho Seco ISFSI. The transient calculation for the FC24P-P04 was extended out to 100 hours, and the resulting maximum cladding temperature versus time profile was used to estimate the maximum temperature for the other DSCs in the ISFSI, based on their respective reported vacuum drying times. These results are illustrated graphically in Figure 8. The maximum cladding temperatures estimated for the vacuum drying transient are compared to the bounding steady-state cases for all DSCs in the Rancho Seco ISFSI, based on the COBRA-SFS modeling results, in Figure 9.

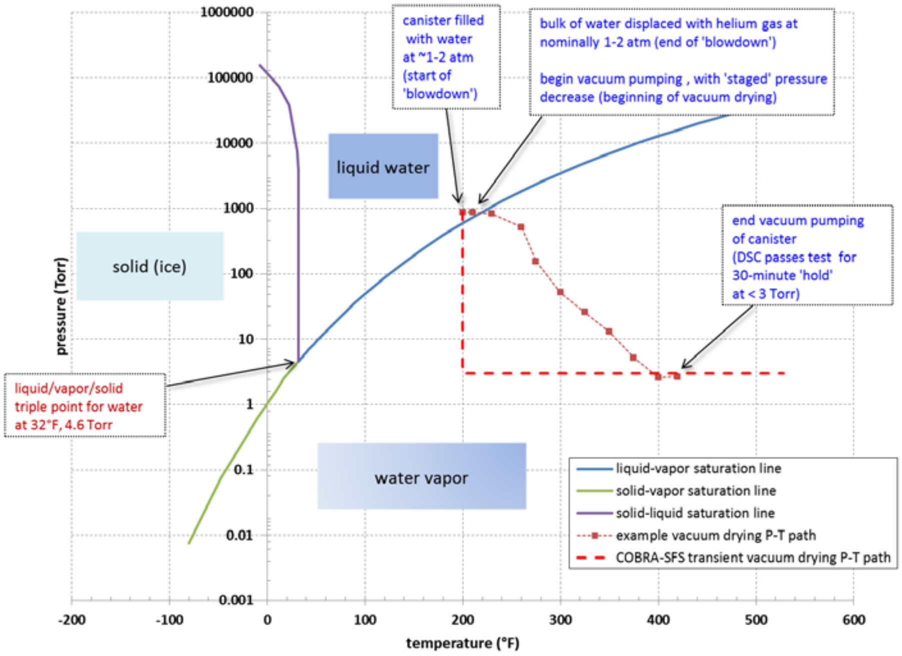

Fig. 6. Average Gas Temperature in Canister Cavity versus Pressure for Vacuum Drying Transient: Bounding Assumptions for COBRA-SFS Calculations Compared to Hypothetical Realistic Transient Path

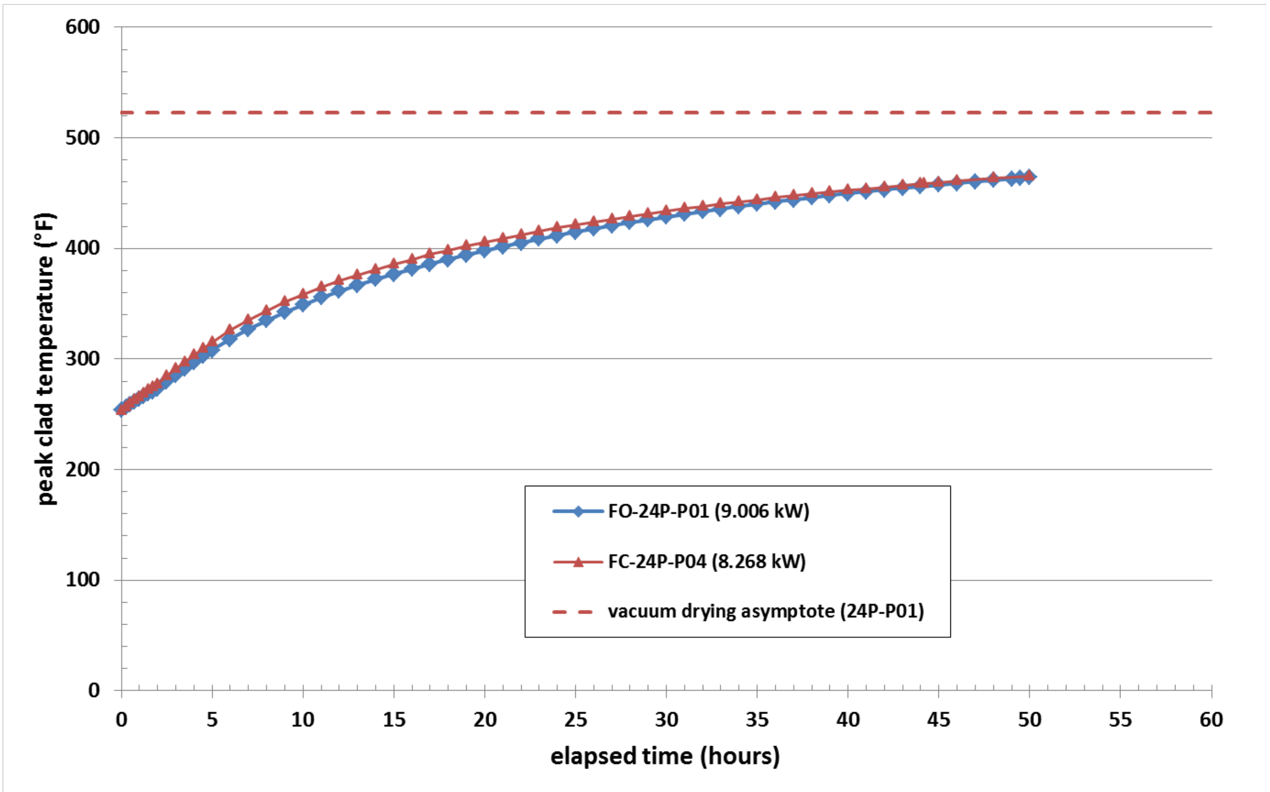

Fig. 7. COBRA-SFS Results for Vacuum Drying Transient in FO24P-P01 and FC24P-P04 Canisters in MP187

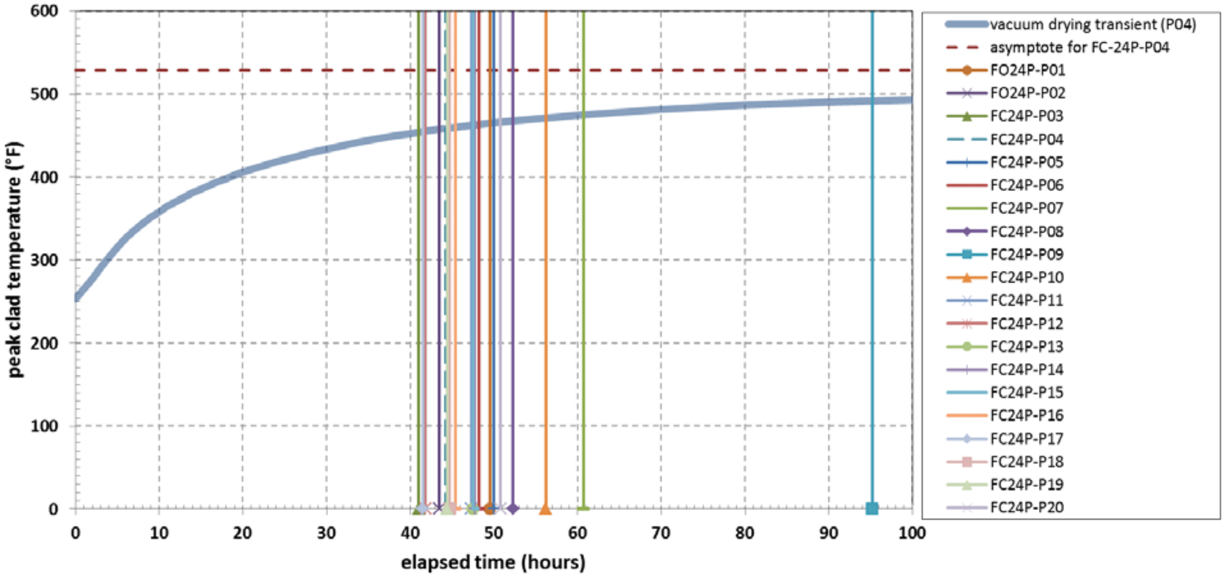

Fig. 8. Estimated Peak Cladding Temperature Rise for All DSCs, Based on Vacuum Drying Transient Time

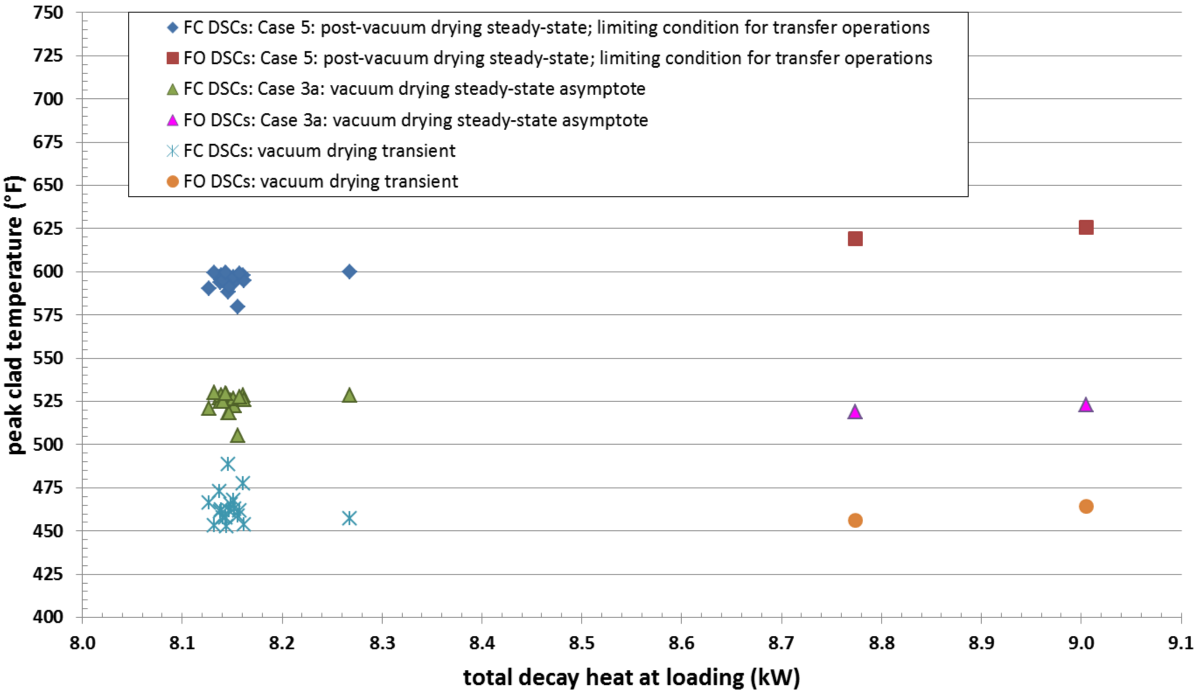

Fig. 9. Maximum Cladding Temperatures for Bounding Steady-State and Transient Conditions Assumed for All FC24P and FO24P DSCs at Rancho Seco

These results show that Case #5, the bounding steady state for the package vertical in the fuel handling building, after draining the water from the annulus between the 24P DSC and the MP187 outer shell, is the limiting condition for drying operations. However, it can reasonably be expected that operations following the vacuum drying transient would not be likely to take so long that the canister would reach steady state before being transported to the ISFSI and inserted into a storage module. Therefore, the peak fuel cladding temperature of Case #5 can be considered a conservative upper bound on the maximum temperature seen by the cladding in drying operations for these DSCs. A more realistic bounding estimate might be only moderately higher than the maximum temperature in the vacuum drying transient itself. But a firm estimate of this realistic bound would require knowing the duration of operations after the end of vacuum drying and backfilling the canister with helium. Since the actual time frame is not known, it is therefore rather difficult to justify any temperature estimates for the Rancho Seco fuel other than estimates based on steady-state bounding conditions.

The MP187 transportation cask was used as an on-site transfer cask when moving the Rancho Seco fuel from the spent fuel pool to dry storage in the ISFSI. With appropriate licensing authorizations, it could be used to transport the DSCs from Rancho Seco to an off-site location. As an illustration of bounding temperatures for normal conditions of transport (NCT) for the spent fuel storage canisters at Rancho Seco, the COBRA-SFS model for the vacuum drying evaluations was modified to represent the DSC/MP187 package configured for off-site transportation. The main revisions to the model were to assume horizontal orientation and add the bounding solar heat load (as per 10CFR71.71) for NCT.

In its transportation configuration, the MP187 package would be fitted with impact limiters, but documentation on the configuration of the impact limiters was not available at the time this work was performed. As a bounding assumption, the impact limiters are treated in the COBRA-SFS analysis as an adiabatic surface on the package ends. Since very little heat is dissipated from the package ends, this is not a major source of conservatism. It can, in fact, be considered simply as a realistic simplification of the modeling of heat transfer from the package ends.

The time of expected transport is not known for the fuel canisters stored at the Rancho Seco ISFSI, so the calculations for NCT were performed using the assembly decay heat values *at the time of loading* of the DSC. This is a bounding assumption, and is obviously very conservative, because loading of the Rancho Seco ISFSI was initiated in 2001. Calculations were performed for FO24P-P01, the DSC with an initial heat load of 9 kW, which was the highest initial heat load of all the DSCs stored in this ISFSI. For these bounding conditions, the peak clad temperature at NCT is predicted to be 323°C (613°F), and the minimum fuel cladding temperature is estimated as 159°C (318°F). Figure 10 shows a radial temperature profile through the package, including the temperatures of the fuel rods, through a line passing through the hottest fuel rod at the axial location of peak cladding temperature (PCT). Figure 11 summarizes the radial distribution of the peak component temperatures in the system, for these assumed conditions.

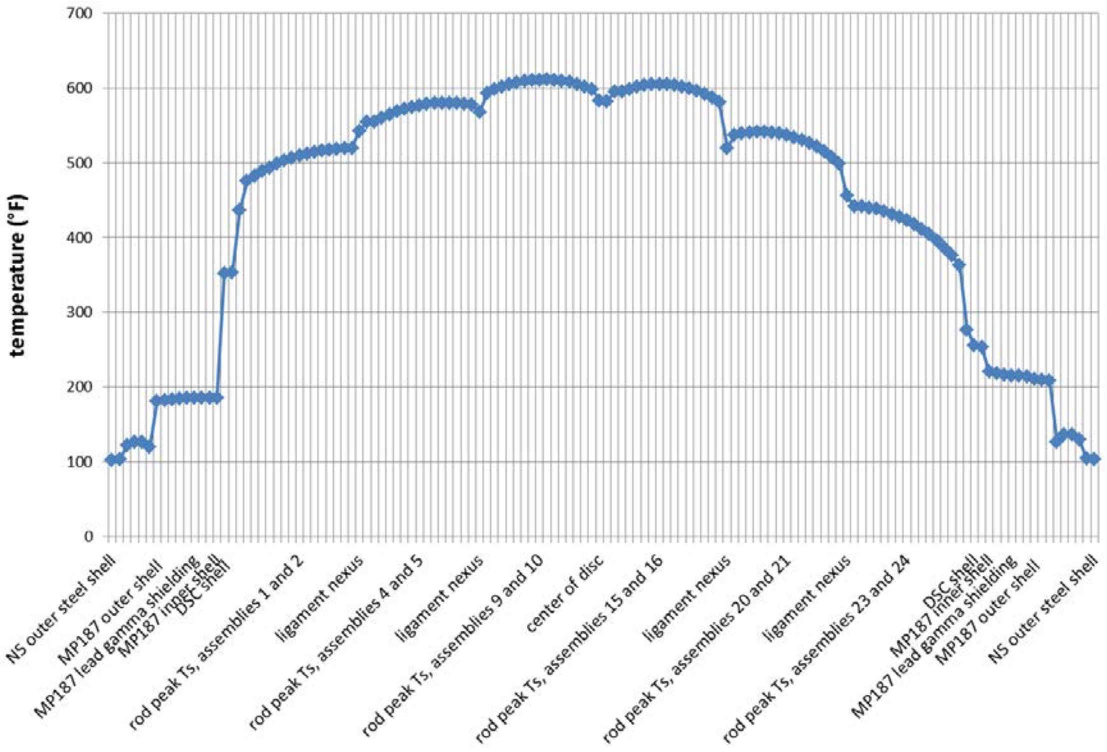

Fig. 10. Radial Temperature Profile at the Axial Location of PCT for FO24P-P01 DSC within MP187 for NCT (with Total Decay Heat of 9 kW)

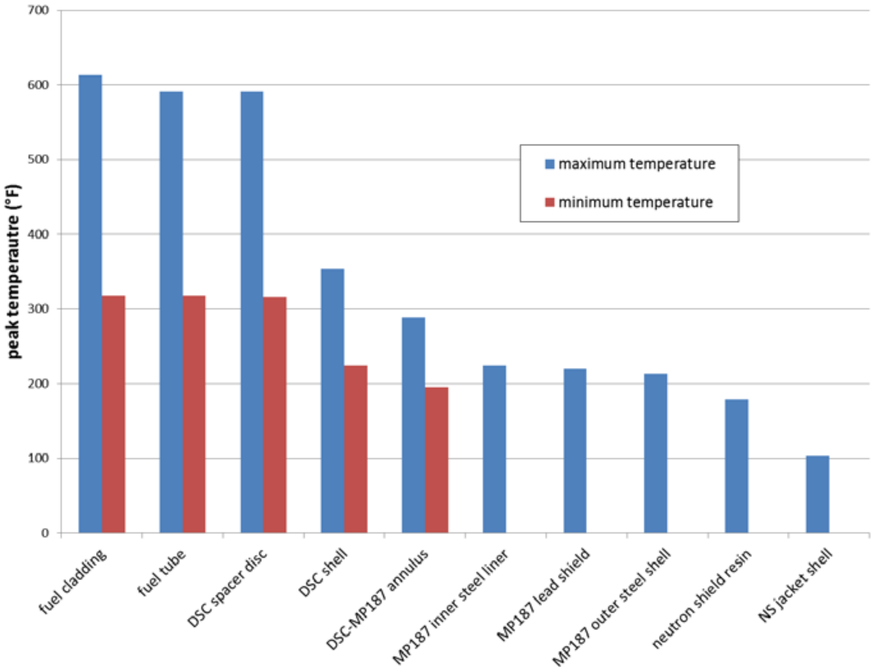

Fig. 11. Summary of Peak Component Temperatures for the FO24P-P01 DSC within the MP187 for NCT (with Total Decay Heat of 9 kW)

CONCLUSIONS

An overview of the basic vacuum drying process shows that in general, this approach is capable of removing most of the residual water remaining in a dry storage canister after bulk water removal. However, there are a number of possible mechanisms for retaining water, due to physical limitations on the process itself, or the procedures followed in vacuum drying. It is recommended that further studies be undertaken to investigate ways to determine realistic estimates of the amount and form of residual water that might remain in actual dry storage canisters, due to these limitations. It is further recommended that materials behavior studies be undertaken to determine bounding values for amounts of residual water, in whatever form, that might be potentially damaging to fuel integrity and retrievability.

Based on the available information from Rancho Seco, only a small portion of the temperature history can be accurately modeled, and transfer operations overall can be characterized only by bounding estimates of possible temperatures experienced by the fuel at various stages in this process. The poverty of data regarding the drying process in general is mainly because the focus of vacuum drying has been restricted to complying with specified limits for PCT and temperature cycling during transients. Now that ensuring the long-term integrity of spent fuel has become an important consideration, it is recommended that additional data on the wet-to-dry transfer operations be pursued. This information, such as may be available in facility logs, documents the actual procedures followed and the duration of specific steps in the process. It is also recommended that the full range of vacuum drying procedures and methods that have been used or are proposed for use at various facilities around the country be investigated and evaluated.

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