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1. PURPOSE

The purpose of this calculation is to provide an effective thermal conductivity for use in predicting peak cladding temperatures in boiling water reactor (BWR) fuel assemblies with 7x7, 8x8, and 9x9 rod arrays. The first objective of this calculation is to describe the development and application of a finite element representation that predicts peak spent nuclear fuel temperatures for BWR assemblies. The second objective is to use the discrete representation to develop a basis for determining an effective thermal conductivity (described later) for a BWR assembly with smeared/homogeneous properties and to investigate the thermal behavior of a spent fuel assembly.

The scope of this calculation is limited to a steady-state two-dimensional representation of the waste package interior region. This calculation is subject to procedure AP-3.12Q, *Calculations* (Ref. 27) and guided by the applicable technical work plan (Ref. 14). While these evaluations were originally developed for the thermal analysis of conceptual waste package designs emplaced in the potential repository at Yucca Mountain, the methodology applies to storage and transportation thermal analyses as well. Note that the waste package sketch in Attachment V depicts a preliminary design, and should not be interpreted otherwise.

2. METHOD

Finite element analysis was the calculation method employed. Finite element representations of the geometry of 7x7, 8x8, and 9x9 BWR fuel assemblies were developed and solved using the solid modeling and thermal analysis capabilities of the commercially available ANSYS finite element software. The ANSYS results were used to calculate effective thermal conductivities for homogeneous 7x7, 8x8, and 9x9 BWR spent nuclear fuel assemblies. Spent nuclear fuel cladding temperatures were also determined using the Wootton-Epstein correlation (Ref. 26) for comparison purposes.

The control of electronic management of information was evaluated in accordance with the planned methods specified in Section 10 of the technical work plan (Ref. 14).

3. ASSUMPTIONS

3.1 Use of the material properties for A 516 carbon steel provided in Table 1 and Table 2 is assumed to adequately represent the basket material in any waste package. Particularly, the use of a constant value for density and emissivity is assumed to be adequate for this calculation. The rationale for this assumption is consistency with Attachment V, which lists A 516 carbon steel as the waste package fuel basket tube material. The temperature-dependent values of thermal conductivity and specific heat are specified well enough to cover the anticipated temperatures the assembly is expected to experience. Also, since the values of density and emissivity change only slightly over the expected range of temperatures, using a single value will not affect the results of the calculation. This assumption is used in Section 5.2.

3.2 The thermal properties of the spent fuel pellets can be adequately represented by the properties of unirradiated UO_2 at theoretical density. The rationale for this assumption is the following. The irradiation of fuel induces several changes in the porosity, composition, and stoichiometry of the fuel. These changes; however, are generally small in light water reactors where the burnup is only on the order of 3% of the initial fissile uranium atoms. Introduction of fission products into the fuel with burnup and fuel material cracking under thermal cycling lead to a slight decrease in the conductivity; however, these effects are neglected for simplification. Also neglected are the effects of fuel densification, swelling, restructuring, and plutonium content; and the oxygen-to-metal ratio of the uranium fuel is assumed to be the theoretical value of 2. All of these neglected effects may affect temperatures within the pellet; however, they will have little or no impact on the determination of cladding temperatures, which is the purpose of this calculation.

A fuel density of 95% of theoretical is given as an example on p. 2A-21 of Ref. 15 for the assembly types used in this calculation (see Assumptions 3.9, 3.10, and 3.11), and it is used as input to the thermal conductivity correlations for uranium oxide in Section 5.2. However, the 100% theoretical density is used in the ANSYS property file (Attachment III) for each assembly, but will not affect the solution results because the calculation is steady-state. The density of a material, in conjunction with its specific heat, affects its ability to store heat over time. The calculations herein are steady-state, and any thermal properties affecting only transient performance therefore do not affect the results and are included for completeness only. This assumption is used in Section 5.2.

3.3 The thermal properties of the unoxidized fuel cladding can be adequately represented by the properties of zircaloy-2. The rationale for this assumption is the following. Zircaloy thermal conductivity is primarily a function of temperature; however, other characteristics such as residual stress levels, crystal orientation, and minor composition differences may have secondary influences on conductivity. These effects as well as cladding dimensional changes

(creep down, thermal expansion, elastic deformation, stress irradiation growth) have been neglected in this calculation. It is beyond the scope of this calculation to include these secondary effects. This assumption is used in Sections 5.2 and 5.4.

- 3.4 BWR cladding is assumed to have a nominal $1.016 \cdot 10^{-4}$ m (4 mils) thick zirconium dioxide layer on its outer surface, which insulates the cladding and dominates its emissivity. The rationale for this assumption is the following. As seen on p. 2.1.3.1-3 of Ref. 24, 50 μ m (about 2 mils) is a conservative maximum thickness for pressurized water reactor (PWR) spent nuclear fuel with a burnup of around 40 GWd/MTU (gigawatt-days per metric ton of uranium); however, BWR environments induce significantly thicker cladding oxide layers for burnups in the 40 to 50 GWd/MTU range (see Assumption 3.24). The 4-mil oxide layer is intended to represent the upper bound. The oxidation layer and any exposed zircaloy surfaces are assumed to have the emissivity resulting from Equation 8 (see Assumption 3.6) and reported in Table 5. Also, since the density and specific heat of zirconium dioxide are not available, the oxide layer will be assumed to have the same density and specific heat as zircaloy. This assumption is used in Sections 5.2, 5.4, and 5.4.5.
- 3.5 The inner surface of the cladding is assumed to be unoxidized and clean, consistent with Assumption 3.2. The rationale for this assumption is that the inside of the cladding is relatively protected from the oxidizing environment. Also, the surface of the fuel pellet is assumed to be a regular curved surface, which is also consistent with Assumption 3.2. Thus, the emissivity of each material can be used to represent the radiative heat transfer between the pellet and cladding using the ANSYS code. The emissivity of the pellet and cladding are 0.79 (Table 4) and 0.806 (Table 5) respectively, and are entered into the ANSYS material properties input file accordingly (see Attachment III). This assumption is used in Section 5.4.
- 3.6 Fuel cladding surface temperatures are assumed not to have exceeded 1500 K during the life of the fuel assembly. Equation 8 on p. 23 is used to estimate the emissivity of a zirconium dioxide layer as a function of its thickness. The equation comes from p. 230 of Ref. 18, which states that the correlation is only applicable to fuel that has not exceeded 1500 K. The rationale for this assumption is the following. Peak cladding temperatures can reach 350-400°C in normal operation of light water reactors. Also, the reactor licensing loss of coolant accident (LOCA) limit for fuel center line temperatures is 2200°F (p. 24, Ref. 25), or 1478 K. The cladding temperatures under LOCA conditions will be below the fuel pin centerline temperature. Since the fuel in the repository will not have experienced LOCA conditions in-core, and peak temperatures during shipping/storing are typically less than 500°C, this assumption is reasonable. This assumption is used in Section 5.2 (Equation 8, p. 23).
- 3.7 The waste package (and therefore the basket containing the spent nuclear fuel assembly) is assumed to be evacuated and filled with helium, nitrogen, or argon gas, or left as a vacuum. The rationale for this assumption is that the backfill gas/vacuum process is considered on

pp. II.A.3-20, II.A.3-53, and II.A.4-2 of Ref. 8 as a method to meet the humidity requirement for the multi-purpose container internals and is presented in the REA 2023 cask experiments in Ref. 21 and Ref. 22. This assumption is used throughout the calculation.

- 3.8 The properties of helium, nitrogen, and argon at atmospheric pressure are assumed to be representative of the environment into which the assembly will be placed. The rationale for this assumption is the fact that a one atmosphere fill pressure is representative of industry standard for storage casks. Page 10 of Ref. 10 provides the highest pressure to which storage casks are filled as approximately 1.5 atmospheres, but most industry vendors use substantially lower pressure in their designs. Use of one atmosphere is representative of the most likely to be used. Although the internal pressure of the waste package will increase due to the temperature rise, the thermal conductivity of most gases is pressure independent, according to p. 255 of Ref. 28. This assumption is used in Section 5.2.
- 3.9 The General Electric (GE) 7x7 GE-2 BWR fuel assembly will adequately represent a typical 7x7 BWR assembly for the purpose of this calculation. The Advanced Nuclear Fuel (ANF) 7x7 BWR assembly will be examined to determine the effect of the central water rod and is assumed to be representative of 7x7 BWR assemblies with water rods. The rationale for this assumption is that the ANF 7x7 BWR assembly is the only 7x7 design with fewer than 49 fuel rods. Specific characteristics of these fuel assemblies are listed in Table 12 and Table 13. This assumption is used in Sections 5.4 and 5.5.
- 3.10 The General Electric 8x8 GE-5 BWR fuel assembly will adequately represent a typical 8x8 BWR assembly for the purpose of this calculation. The GE-9 8x8 fuel assembly will be examined to determine the effect of the central water rod and is assumed to provide the lower bound for all 8x8 BWR fuel assemblies with water rods. The dimensions of the water rod are assumed to be those listed in Table 15. The rationale for this assumption is the need to represent a water rod without a reference for specific dimensions, and the fact that the GE-9 8x8 fuel assembly displaces the maximum number of fuel rods from the center of the fuel assembly. Since peak temperatures occur in the center of the fuel assembly, displacing the maximum number of fuel rods from the center results in the greatest peak temperature difference between water-rod and no-water-rod configurations. Specific characteristics of these fuel assemblies are listed in Table 14 and Table 15. This assumption is used in Sections 5.4 and 5.5.
- 3.11 The Advanced Nuclear Fuel (ANF) 9x9 ANF-JP BWR fuel assembly will adequately represent a typical BWR assembly of its class for the purpose of this calculation. The ANF-9X 9x9 fuel assembly will be examined to determine the effect of the central water rod and is assumed to provide the lower bound for all 9x9 BWR fuel assemblies with water rods. The dimensions of the water rod ('water tube') are assumed to be those listed in Table 17. The rationale for this assumption is consistency with the values in Table 4.1-8 of Ref. 29, and the fact that the ANF-9X 9x9 fuel assembly displaces the maximum number of fuel rods from

the center of the assembly. Since peak temperatures occur in the center of the fuel assembly, displacing the maximum number of fuel rods from the center results in the greatest peak temperature difference between water-rod and no-water-rod configurations. This assumption is used in Sections 5.4 and 5.5.

- 3.12 For the benchmarks against the spent fuel storage cask tests at General Electric's Morris Operation (GE-MO) facility, the GE 7x7 GE-2 BWR fuel assembly will adequately represent the BWR assembly used in the tests. The rationale for this assumption is the following. The GE 7x7 GE-2 BWR assembly from the Cooper power station is indicated as the assembly used in a summary report of the GE-MO tests (pp. 3.1 and 3.2, Ref. 23). The test reports (Ref. 21 and Ref. 22) are consistent with the dimensions provided in Table 12. This assumption is used in Section 5.8.
- 3.13 GE and ANF place channels around all of their BWR fuel assembly designs. These channels come in three basic thicknesses: 80, 100, and 120 mils (p. 2.1.2.3-1, Ref. 24). These three channel thicknesses are assumed to be typical of all BWR channels, and are used in this calculation. Each channel is made of zircaloy, which builds up an oxide layer on both the inner and outer surfaces. A nominal oxide layer thickness of 6 mils on each surface is assumed to be an upper bound for the basic set of calculations presented in Sections 5.4 and 5.6. The rationale for this assumption is the need to represent a channel without a reference for specific dimensions. The effect of the channel oxide layer thickness, as well as the effect of the channel itself, is examined in the calculations. This assumption is used in Sections 5.2 and 5.4.2.
- 3.14 In the base calculation, the fuel basket opening is assumed to be 0.1524 m square and the basket wall is assumed to have a thickness of 0.01 m. The rationale for this assumption is consistency with the basket cell width of about 6.0 inches (0.1524 m) in the conceptual designs for the multi-purpose container (p. II.A.4-13, Ref. 8). The basket cell thickness is inconsequential, as basket wall temperature boundary conditions are applied to the inside wall surface in the finite element representation. This assumption is used in Sections 5.4, 5.5, and 5.7.
- 3.15 For the benchmarks against the spent fuel storage tests at GE-MO, the basket opening is assumed to be 0.1524 m square, and the basket wall is assumed to have a thickness of 0.01 m. The rationale for this assumption is consistency with the basket cell width of about 6.0 inches (0.1524 m) in the description of the REA 2023 cask basket design (p. 3.7, Ref. 21). The basket cell thickness is inconsequential, as basket wall temperature boundary conditions are applied to the inside wall surface in the finite element representation. The thermocouple positioning for the cask experiments is presented on pp. 5.2, 5.3, A.1 through A.12, and G.2 in Ref. 21. The benchmarks for this calculation will use the radial temperature measurement thermocouple data (pp. G.3 through G.19, Ref. 21) at the 3.33 m elevation. The thermocouples are placed along the 45-degree radial path from the center of

the cask to the outer surface. This arrangement places a thermocouple on diagonal corners of the fuel tubes and a thermocouple on the center rod of each fuel assembly in each tube. The fuel tube thermocouples are placed on the outer surface of the fuel tube. This calculation assumes that the fuel tube data is representative of the inside surface temperature. This is reasonable since the temperature drop across the fuel tube is typically less than 0.5°C . This assumption is used in Section 5.8.

- 3.16 It is assumed that a two-dimensional finite element representation of a cross section at the midsection of the fuel assembly will be representative of the hottest portion of the fuel assembly. This assumption requires that axial heat transfer does not significantly affect the solution (i.e., the flow of heat in the radial direction is assumed to dominate the solution). The rationale for this assumption is that the metal thermal conductivities and heat generation distributions are such that axial heat transfer is very small or negligible. This assumption is used in Section 5.4.
- 3.17 For the cross section representation of the fuel assembly, an axial power peaking factor of 1.25 is applied to the BWR heat generation rate. The rationale for this assumption is consistency with the axial power peaking factor reported on p. 3-26 of Ref. 7. The heat loads are multiplied by a peaking factor to approximate the axial center of the assembly with a two-dimensional representation. A fuel assembly is much hotter at the mid-length than at the ends, and it is conservative to represent the hottest cross-section. This assumption is used throughout the calculation.
- 3.18 For the benchmarks against the spent fuel storage tests at GE-MO, an axial power peaking factor of 1.20 is applied to the fuel assembly heat generation rate. The rationale for this assumption is the axial decay heat profile used in the REA 2023 computer simulations (Figure 4.4, p. 4.11, Ref. 22). A maximum factor of 1.20 is estimated from the figure. A fuel assembly is much hotter at the mid-length than at the ends, and it is conservative to represent the hottest cross-section. This assumption is used in Section 5.8.
- 3.19 The temperatures applied as boundary conditions to the fuel assembly representation are assumed uniform around the perimeter of the assembly, such that a one-quarter representation of the assembly is adequate. The rationale for this assumption is that the hottest fuel assemblies are in the center of a container where basket temperature gradients are lowest. Assumed uniform temperatures around the assembly allow the use of symmetry to reduce finite element representation size. This assumption is used in Section 5.4.
- 3.20 Heat generation due to the decay of spent nuclear fuel fission products and actinides is assumed to be evenly distributed in the axial plane throughout all of the UO_2 pellets. Radial power profiles within the pellets and within the fuel assembly are neglected, and heat generation in the cladding (and other non-fuel hardware) due to activation and radiation energy deposition are ignored. The rationale for this assumption is that it is beyond the

scope of this calculation to include these effects. Also, it is conservative to assume that all of the heat produced by the fuel assembly is produced in the uranium dioxide pellet, and not in the cladding. Attachment VI presents an analytical discussion of this assumption and demonstrates that the highest cladding temperatures result when all of the heat is produced in the pellet. This assumption is used in Section 5.4.

- 3.21 Components of the fuel assembly are assumed not to touch the basket wall or each other. The rationale for this assumption is the following. While the UO_2 pellets will likely have swelled and cracked after use in a reactor, and some spent fuel rods and/or channels may have bowed such that they contact each other or the basket, it is conservative to assume that there is no conductive contact between the components, such that all heat is transferred by thermal radiation and gaseous conduction. This assumption is used in Section 5.4.
- 3.22 Representing only conduction and radiation heat transfer inside the waste package is assumed to provide acceptably conservative results for this calculation. The rationale for this assumption is the following. The fill gas placed inside the waste package will allow a natural convective heat transfer to exist; however, since only a few small enclosed basket cavities exist and the temperature gradient in the enclosure is not significant, the fill gas circulation is insignificant. Thus, the problem may be represented with only the dominant heat transfer modes, with a negligible or conservative impact upon the results. This assumption is used throughout the calculation.
- 3.23 For the BWR spent nuclear fuel assembly representation, nine basket (boundary) temperatures will be considered: 25, 50, 100, 150, 200, 250, 300, 350, and 400°C. The rationale for this assumption is that it will bound the possible operational range of environments for repository disposal; from potential repository ambient rock temperatures of about 25°C (Figure 7.6-4, p. 54, Ref. 11) to greater than the fuel cladding limit of 350°C (p. 11 of Ref. 13). Radiation heat transfer within the fuel assembly introduces temperature non-linearities, resulting in a temperature-dependence of effective thermal conductivities. Due to the non-linearities, superposition cannot be applied and the representation must be evaluated at a variety of temperature levels. This assumption is used in Sections 5.2, 5.4.1, and 5.7.
- 3.24 For the BWR spent nuclear fuel assembly representation, six heat loads will be considered: 100, 200, 300, 400, 500, and 600 W/assembly. The rationale for this assumption is that it will encompass as much of the spent nuclear fuel that could be loaded into a waste package as possible. This assumption is used in Sections 5.4 and 5.7.
- 3.25 For the backcheck of the effective thermal conductivity, the density of the homogenized BWR fuel material is assumed to be 3892.42 kg/m³. The rationale for this assumption is the following. The density value is determined using the BWR assembly mass of 730 lbs (331.126 kg) (Table 5.1.1.2.1-1, p. 26, Ref. 9) and the assembly volume, which provides an

average density in kg/m^3 . The overall assembly width is 5.44 inches (0.138 m), and the assembly length is 175.87 inches (4.467 m) (p. 2A-20 of Ref. 15). The assembly volume is equal to the overall assembly width squared multiplied by the assembly length (volume = $\text{width}^2 \times \text{length}$). This assumption is used in Sections 5.6 and 5.7.

- 3.26 For the backcheck of the effective thermal conductivity, the specific heat of the homogenized spent nuclear fuel material is assumed to be $273.129 \text{ J/kg}\cdot\text{K}$. The rationale for this assumption is the following. The value was determined using: 1) the BWR assembly mass of 730 lbs (331.126 kg) and the uranium mass of 200 kg, from Table 5.1.1.2.1-1 on p. 26 of Ref. 9, and 2) the specific heat of uranium oxide of $247 \text{ J/kg}\cdot\text{K}$ (at 100°C) and zircaloy-2 of $330.0 \text{ J/kg}\cdot\text{K}$ (at 400°C) from Tables 8-1 and 8-2 on p. 296 of Ref. 25.

The assembly is assumed to be comprised only of uranium oxide and zircaloy-2; therefore, the homogenized specific heat is a simple mass weighted average (i.e., spent nuclear fuel $c_p = (c_{p,\text{UO}_2} \cdot \text{mass}_{\text{UO}_2} + c_{p,\text{Zr2}} \cdot \text{mass}_{\text{Zr2}}) / \text{mass of assembly}$). The mass of UO_2 is determined from the mass of uranium (i.e., $\text{mass}_{\text{UO}_2} = \text{mass}_{\text{U}} \cdot (\text{Atomic wt U} + 2 \cdot \text{Atomic wt of O}) / \text{Atomic wt of U} = 226.886 \text{ kg}$). The mass of zircaloy-2 is then equal to the difference between the total assembly mass and the UO_2 mass ($\text{mass}_{\text{Zr2}} = 104.240 \text{ kg}$). The specific heat value is then calculated to be: $c_{p,\text{eff}} = 273.129 \text{ J/kg}\cdot\text{K}$ and is used in the ANSYS input files included as listed in Attachment II. This assumption is used in Sections 5.6 and 5.7.

- 3.27 The thermal properties of nitrogen and air are assumed to be the same. The rationale for this assumption is the similarity in the thermal conductivity of the two gases (pp. 19.75 and 19.77 of Ref. 1). The results of two calculations performed specifically with air as the fill gas are included in files b7air0c_01a.parm and b7air8c_01a.parm, as listed in Attachment II. The maximum difference between the peak cladding temperatures determined for nitrogen and air fill gases was found to be 0.4°C . This assumption is used in Sections 5.2 and 5.4.3.
- 3.28 The minimum inside channel width is given as 5.268 in. on p. C-14 of Ref. 20. The inside channel width assumed for this calculation is 5.278 in. The rationale for this assumption is Note 1 in the upper-right-hand corner of p. C-14 of Ref. 20, which states an allowance for bowing of 0.010 in. This assumption is used in Section 5.2.
- 3.29 The ANF 7x7 BWR fuel assembly cladding dimensions given on p. 2A-15 of Ref. 15 are given as outer diameter of 0.570 in. and thickness of 0.036 – 0.046 in. The cladding thickness assumed for this calculation is 0.038 in. The water rod, which is simply a cladding without any fuel pellets inside, is assumed in this calculation to have the cladding outer diameter of 0.570 in. and a thickness of 0.046 in. The rationale for this assumption is the need to select a specific value within the range given in the reference. This assumption is used in Section 5.2.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE

The finite element analysis computer code used for this calculation is ANSYS Version 5.4 (hereafter referred to as 'ANSYS') (Ref. 12), which is identified as Computer Software Configuration Item (CSCI) 30040 V5.4 and was obtained from Software Configuration Management in accordance with appropriate procedures. ANSYS V5.4 is a qualified commercially available finite element thermal and mechanical analysis code and is appropriate for the thermal analysis of waste packages, waste package emplacements, and waste package environments as utilized in this calculation. ANSYS is located on a Hewlett-Packard J2240 server (Yucca Mountain Project CPU# 700887 located in Las Vegas, Nevada). The ANSYS evaluations performed in this calculation are fully within the range of validation. Access to and use of the code for the calculation was granted by Software Configuration Management and performed in accordance with appropriate procedures. Inputs and outputs to the ANSYS software are included as attachments and described in the following calculation.

4.2 MODELS

None used.

5. CALCULATION

5.1 INTRODUCTION

The method for waste package thermal evaluations involves a three-representation approach to determine the time dependent waste package thermal behavior. The first representation, a three-dimensional transient finite element representation of the waste package emplacement, provides the waste package surface temperature history. This surface temperature history is then used as a boundary condition in the second representation, a detailed waste package representation. Resulting basket wall temperature predictions from the waste package representation provide the boundary condition for an estimation of peak spent nuclear fuel cladding temperatures in the third representation. Cladding temperatures are predicted in the waste package representation using an effective thermal conductivity defined to represent a homogeneous fuel assembly. This calculation describes the last step of this three-step approach, in which the effective thermal conductivity is determined using a detailed third representation of an intact BWR fuel assembly evaluated over a range of temperatures and heat loads.

5.2 DESIGN PARAMETERS

Table 1 lists the density and emissivity of A 516 carbon steel (ASME designation SA-516 K02700) (see Assumption 3.1). The density of A 516 is taken from Section 14.1 of Ref. 3. The emissivity (average for smooth oxidized iron) is taken from Table 4.3.2 of Ref. 4.

Table 2 lists the thermal conductivity and specific heat of A 516 carbon steel. Values for thermal conductivity and thermal diffusivity of A 516 (C-Mn-Si) were taken from Section II, Table TCD of Ref. 2, and are converted here to conductivity and specific heat in SI units. The conversion of thermal diffusivity to specific heat (defined in Equation 1) requires the density listed in Table 1.

Table 1. Density and Emissivity of A 516 Carbon Steel

Density	Emissivity
7850 kg/m ³	0.80

$$\text{Thermal Diffusivity}(\text{ft}^2/\text{hr}) = \frac{\text{Thermal Conductivity}(\text{Btu/hr} \cdot \text{ft} \cdot ^\circ\text{F})}{\text{Density}(\text{lb}/\text{ft}^3) \times \text{Specific Heat}(\text{Btu}/\text{lb} \cdot ^\circ\text{F})}$$

Equation 1

Table 2. Thermal Conductivity and Specific Heat of A 516 Carbon Steel

Temperature		Thermal Conductivity (Btu/hr-ft-F)	Thermal Diffusivity (ft ² /hr)	Thermal Conductivity (W/m-K)	Specific Heat (J/kg-K)
°F	°C				
70	21.11	23.6	0.454	40.85	444.11
100	37.78	23.9	0.443	41.36	460.92
150	65.56	24.2	0.433	41.88	477.49
200	93.33	24.4	0.422	42.23	493.98
250	121.11	24.4	0.414	42.23	503.53
300	148.89	24.4	0.406	42.23	513.45
350	176.67	24.3	0.396	42.06	524.26
400	204.44	24.2	0.386	41.88	535.63
450	232.22	23.9	0.375	41.36	544.50
500	260.00	23.7	0.364	41.02	556.26
550	287.78	23.4	0.355	40.50	563.15
600	315.56	23.1	0.346	39.98	570.39
650	343.33	22.7	0.333	39.29	582.39
700	371.11	22.4	0.320	38.77	598.04
750	398.89	22.0	0.308	38.08	610.25
800	426.67	21.7	0.298	37.56	622.12

The thermal conductivity of unirradiated uranium oxide in the fuel pellets (see Assumption 3.2) is calculated from equations on pp. 302 – 303 of Ref. 25, which are repeated here:

$$k = \eta \left[\frac{B_1}{B_2 + T} + B_3 \exp(B_4 T) \right]$$

Equation 2

with a porosity correction factor given by:

$$\eta = \frac{1 - \beta (1 - \rho / \rho_{TD})}{1 - \beta (1 - 0.95)}$$

Equation 3

and:

$$\beta = 2.58 - 0.58 \times 10^{-3} T$$

Equation 4

with:

- T = temperature in degrees C
 ρ = density
 B₁ = constant = 40.4 W/cm
 B₂ = constant = 464°C

$$B_3 = \text{constant} = 1.216 \cdot 10^{-4} \text{ W/cm} \cdot ^\circ\text{C}$$

$$B_4 = \text{constant} = 1.867 \cdot 10^{-3} \text{ } ^\circ\text{C}^{-1}$$

Assuming a density that is 95% of theoretical ($\rho/\rho_{TD}=0.95$, see Assumption 3.2), then $\eta = 1$ and the UO_2 conductivity can be calculated as a function of temperature as shown in Table 3. The specific heat at 100°C and theoretical density at room temperature of UO_2 are given in Table 8-1 of Ref. 25 (p. 296) and are listed here in Table 4. The emissivity of UO_2 is described as a function of temperature (K) on p. 48 of Ref. 18, and repeated here:

$$\epsilon = 0.7856 + 1.5263 \times 10^{-5} T$$

Equation 5

Table 3. Thermal Conductivity of Spent Nuclear Fuel Rod Materials

Temperature		UO ₂ Conductivity (W/m·K)	Zircaloy Conductivity (W/m·K)	Zirconium Dioxide Conductivity (W/m·K)
(K)	(°C)			
273	0	8.72	12.29	1.94
283	10	8.54	12.44	1.94
293	20	8.36	12.58	1.94
303	30	8.19	12.72	1.94
313	40	8.03	12.87	1.94
323	50	7.87	13.01	1.94
333	60	7.72	13.15	1.94
343	70	7.58	13.28	1.95
353	80	7.44	13.42	1.95
363	90	7.31	13.55	1.95
373	100	7.18	13.69	1.95
383	110	7.05	13.82	1.95
393	120	6.93	13.95	1.95
403	130	6.82	14.08	1.95
413	140	6.70	14.21	1.96
423	150	6.60	14.34	1.96
433	160	6.49	14.46	1.96
443	170	6.39	14.59	1.96
453	180	6.29	14.72	1.96
463	190	6.19	14.84	1.97
473	200	6.10	14.96	1.97
483	210	6.01	15.09	1.97
493	220	5.92	15.21	1.97
503	230	5.84	15.33	1.98
513	240	5.76	15.45	1.98
523	250	5.68	15.57	1.98
533	260	5.60	15.69	1.98
543	270	5.52	15.81	1.99
553	280	5.45	15.93	1.99

563	290	5.38	16.05	1.99
573	300	5.31	16.17	2.00
583	310	5.24	16.29	2.00
593	320	5.18	16.40	2.00
603	330	5.11	16.52	2.01
613	340	5.05	16.64	2.01
623	350	4.99	16.76	2.01
633	360	4.93	16.88	2.02
643	370	4.87	16.99	2.02
653	380	4.81	17.11	2.02
663	390	4.76	17.23	2.03
673	400	4.70	17.35	2.03
683	410	4.65	17.46	2.03
693	420	4.60	17.58	2.04
703	430	4.55	17.70	2.04
713	440	4.50	17.82	2.04
723	450	4.45	17.94	2.05
733	460	4.40	18.06	2.05
743	470	4.35	18.18	2.06
753	480	4.31	18.30	2.06
763	490	4.27	18.42	2.06
773	500	4.22	18.54	2.07

Equation 5 does not vary significantly over the range of fuel assembly temperatures considered in this calculation (see Assumption 3.23). Evaluating Equation 5 at a temperature of 300°C (573 K) gives the value reported in Table 4.

Table 4. Material Properties of UO₂

Theoretical Density	Specific Heat	Emissivity
10,970 kg/m ³	247.0 J/kg·K	0.79

The thermal conductivity (W/m·K) of zircaloy cladding (see Assumption 3.3) is described as a function of temperature (K) on p. 217 of Ref. 18, and repeated here:

$$k = 7.51 + 2.09 \times 10^{-2} T - 1.45 \times 10^{-5} T^2 + 7.67 \times 10^{-9} T^3$$

Equation 6

Equation 6 was evaluated over a range of temperatures and the results are listed in Table 3. The density and specific heat of zircaloy at 400°C are given in Table 8-2 of Ref. 25 (p. 296), and are listed here in Table 5. The emissivity of zircaloy depends on the thickness of the oxidation layer as described below (see Assumption 3.4).

Table 5. Material Properties of Zircaloy

Density	Specific Heat	Emissivity
6560.0 kg/m ³	330.0 J/kg·K	0.806

The thermal conductivity (W/m·K) of zirconium dioxide (see Assumption 3.4) is described as a function of temperature (K) on p. 224 of Ref. 18, and repeated here:

$$k = 1.96 - 2.41 \times 10^{-4} T + 6.43 \times 10^{-7} T^2 - 1.95 \times 10^{-10} T^3$$

Equation 7

The results of Equation 7 evaluated over a range of temperatures are listed in Table 3. The specific heat and density of zirconium dioxide are as described in Assumption 3.4. For an oxide layer thickness of $3.88 \cdot 10^{-6}$ m (0.15 mils) or greater, the emissivity is described as a function of oxide thickness (m) on p. 230 of Ref. 18 (see Assumption 3.6), and repeated here:

$$\varepsilon = 0.808642 - 50.0 d$$

Equation 8

Given a zirconium dioxide thickness of $1.016 \cdot 10^{-4}$ m (4 mils, see Assumption 3.4), the cladding surface emissivity would be as reported in Table 5.

Table 6 lists the density of helium (at 27°C). The density of helium is considered constant, because it fills the sealed waste package, a constant-volume system. Table 7 lists the thermal conductivity and specific heat of helium. Values for density, thermal conductivity, and specific heat are taken at a pressure of one atmosphere (see Assumption 3.8) from Ref. 1, p. 19.71.

Table 6. Density of Helium (at one atmosphere)

Density (kg/m ³)
0.1626

Table 7. Thermal Conductivity and Specific Heat of Helium (at one atmosphere)

Temperature		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(Btu/hr-ft-°F)	(W/m-K)	(Btu/lb-°F)	(J/kg-K)
0	-17.78	0.08064	0.1396	1.2412	5196.7
20	-6.67	0.08304	0.1437	1.2412	5196.7
40	4.44	0.08542	0.1478	1.2412	5196.7
60	15.56	0.08776	0.1519	1.2412	5196.7
80	26.67	0.09008	0.1559	1.2411	5196.2
100	37.78	0.09238	0.1599	1.2411	5196.2
120	48.89	0.09465	0.1638	1.2411	5196.2
140	60.00	0.09690	0.1677	1.2411	5196.2
160	71.11	0.09912	0.1715	1.2411	5196.2
180	82.22	0.10133	0.1754	1.2411	5196.2
200	93.33	0.10351	0.1791	1.2411	5196.2
240	115.56	0.10783	0.1866	1.2411	5196.2
280	137.78	0.11207	0.1940	1.2411	5196.2
320	160.00	0.11624	0.2012	1.2411	5196.2
360	182.22	0.12036	0.2083	1.2411	5196.2
400	204.44	0.12441	0.2153	1.2411	5196.2
440	226.67	0.12841	0.2222	1.2411	5196.2
480	248.89	0.13236	0.2291	1.2411	5196.2
520	271.11	0.13626	0.2358	1.2411	5196.2
560	293.33	0.14011	0.2425	1.2411	5196.2
600	315.56	0.14392	0.2491	1.2411	5196.2
640	337.78	0.14768	0.2556	1.2412	5196.7
680	360.00	0.15141	0.2684	1.2412	5196.7

Table 8 lists the density of nitrogen (at 27°C). The density of nitrogen is considered constant, because it fills the sealed waste package, a constant-volume system. Table 9 lists the thermal conductivity and specific heat of nitrogen. Values for density, thermal conductivity, and specific heat are taken at a pressure of one atmosphere (see Assumption 3.8) from Ref. 1, p. 19.75.

Table 8. Density of Nitrogen (at one atmosphere)

Density (kg/m ³)
1.1389

Table 9. Thermal Conductivity and Specific Heat of Nitrogen (at one atmosphere)

Temperature		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(Btu/hr-ft-°F)	(W/m-K)	(Btu/lb-°F)	(J/kg-K)
0	-17.78	0.01309	0.0227	0.2490	1042.5
20	-6.67	0.01355	0.0235	0.2489	1042.1
40	4.44	0.01401	0.0242	0.2489	1042.1
60	15.56	0.01446	0.0250	0.2489	1042.1
80	26.67	0.01491	0.0258	0.2489	1042.1
100	37.78	0.01534	0.0265	0.2489	1042.1
120	48.89	0.01578	0.0273	0.2489	1042.1
140	60.00	0.01620	0.0280	0.2490	1042.5
160	71.11	0.01662	0.0288	0.2491	1042.9
180	82.22	0.01704	0.0295	0.2492	1043.4
200	93.33	0.01745	0.0302	0.2493	1043.8
240	115.56	0.01826	0.0316	0.2496	1045.0
280	137.78	0.01906	0.0330	0.2499	1046.3
320	160.00	0.01985	0.0344	0.2504	1048.4
360	182.22	0.02062	0.0357	0.2510	1050.9
400	204.44	0.02140	0.0370	0.2517	1053.8
440	226.67	0.02216	0.0384	0.2525	1057.2
480	248.89	0.02292	0.0397	0.2534	1060.9
520	271.11	0.02368	0.0410	0.2543	1064.7
560	293.33	0.02444	0.0423	0.2553	1068.9
600	315.56	0.02519	0.0436	0.2564	1073.5
640	337.78	0.02594	0.0449	0.2575	1078.1
680	360.00	0.02670	0.0462	0.2587	1083.1

Table 10 lists the density of argon (at 27°C). The density of argon is considered constant, because it fills the sealed waste package, a constant-volume system. Table 11 lists the thermal conductivity and specific heat of argon. Values for density, thermal conductivity, and specific heat are taken at a pressure of one atmosphere (see Assumption 3.8) from Ref. 1, p. 19.81.

Table 10. Density of Argon (at one atmosphere)

Density (kg/m ³)
1.6243

Table 11. Thermal Conductivity and Specific Heat of Argon (at one atmosphere)

Temperature		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(Btu/hr-ft-°F)	(W/m-K)	(Btu/lb-°F)	(J/kg-K)
0	-17.78	0.00900	0.0156	0.1248	522.5
20	-6.67	0.00934	0.0162	0.1248	522.5
40	4.44	0.00967	0.0167	0.1247	522.1
60	15.56	0.00999	0.0173	0.1247	522.1
80	26.67	0.01031	0.0178	0.1247	522.1
100	37.78	0.01063	0.0184	0.1246	521.7
120	48.89	0.01094	0.0189	0.1246	521.7
140	60.00	0.01125	0.0195	0.1246	521.7
160	71.11	0.01155	0.0200	0.1246	521.7
180	82.22	0.01184	0.0205	0.1246	521.7
200	93.33	0.01214	0.0210	0.1245	521.3
240	115.56	0.01271	0.0220	0.1245	521.3
280	137.78	0.01327	0.0230	0.1245	521.3
320	160.00	0.01382	0.0239	0.1245	521.3
360	182.22	0.01435	0.0248	0.1245	521.3
400	204.44	0.01487	0.0257	0.1245	521.3
440	226.67	0.01538	0.0266	0.1244	520.8
480	248.89	0.01588	0.0275	0.1244	520.8
520	271.11	0.01637	0.0283	0.1244	520.8
560	293.33	0.01685	0.0292	0.1244	520.8
600	315.56	0.01733	0.0300	0.1244	520.8
640	337.78	0.01779	0.0308	0.1244	520.8
680	360.00	0.01825	0.0316	0.1244	520.8

The GE-2 7x7 BWR fuel assembly is used as the basis to determine the effective thermal conductivity of the 7x7 rod configuration, since experimental data exists for GE-2 7x7 BWR fuel in a storage cask configuration. The GE-2 7x7 BWR fuel assembly is also the basis for the benchmarks against the REA 2023 cask tests (see Assumption 3.12). The ANF 7x7 BWR fuel assembly is represented to show the effects of a central water rod on the prediction of peak cladding temperatures in 7x7 rod configurations (Assumption 3.9). The GE-5 8x8 BWR fuel assembly is used as the basis to determine the effective thermal conductivity of the 8x8 rod configuration. The GE-9 8x8 fuel assembly is presented to bound the effects of a central water rod on the prediction of peak cladding temperatures in 8x8 rod configurations (Assumption 3.10). The ANF-JP 9x9 BWR fuel assembly is used as the basis to determine the effective thermal conductivity of the 9x9 rod configuration. The ANF-9X 9x9 BWR fuel assembly is presented to bound the effects of a central water rod on the prediction of peak cladding temperatures (Assumption 3.11). The physical dimensions of these fuel assemblies are listed in Table 12 through Table 17.

Table 12. GE-2 7x7 BWR Assembly Dimensions (see Assumption 3.9)

Number of Rods	49	(p. 2A-20, Ref. 15)
Rod Pitch	18.75 mm (0.738 in.)	(p. 2A-20, Ref. 15)
UO ₂ Pellet Diameter	12.37 mm (0.487 in.)	(p. 2A-20, Ref. 15)
Cladding Outer Diameter	14.30 mm (0.563 in.)	(p. 2A-20, Ref. 15)
Cladding Thickness	0.8128 mm (0.032 in.)	(p. 2A-20, Ref. 15)
Number of Water Rods	0	(p. 2.1.2.3-7, Ref. 24)
Water Rod Outer Diameter	N/A	(p. 2.1.2.3-7, Ref. 24)
Water Rod Thickness	N/A	(p. 2.1.2.3-7, Ref. 24)
Channel Inside Width	134.06 mm (5.278 in.)	(Assumption 3.28)
Channel Thickness	2.03, 2.54, or 3.05 mm (0.080, 0.100, or 0.120 in.)	(Assumption 3.13)
Channel Corner Radius	9.65 mm (0.380 in.)	(p. C-14, Ref. 23)
Active Fuel Length	3657.6 mm (144.0 in.)	(p. 2A-20, Ref. 15)

Table 13. ANF 7x7 BWR Assembly Dimensions (see Assumption 3.9)

Number of Rods	48	(p. 2A-15, Ref. 15)
Rod Pitch	18.75 mm (0.738 in.)	(p. 2A-15, Ref. 15)
UO ₂ Pellet Diameter	12.45 mm (0.490 in.)	(p. 2A-15, Ref. 15)
Cladding Outer Diameter	14.48 mm (0.570 in.)	(p. 2A-15, Ref. 15)
Cladding Thickness	0.9652 mm (0.038 in.)	(Assumption 3.29)
Number of Water Rods	1*	(p. 2A-15, Ref. 15)
Water Rod Outer Diameter	14.48 mm (0.570 in.)	(Assumption 3.29)
Water Rod Thickness	1.1684 mm (0.046 in.)	(Assumption 3.29)
Channel Inside Width	134.06 mm (5.278 in.)	(Assumption 3.28)
Channel Thickness	2.03, 2.54, or 3.05 mm (0.080, 0.100, or 0.120 in.)	(Assumption 3.13)
Channel Corner Radius	9.65 mm (0.380 in.)	(p. C-14, Ref. 23)
Active Fuel Length	3657.6 mm (144.0 in.)	(p. 2A-15, Ref. 15)

* Implied by number of fuel rods. Vacant spots are filled with water rods ($7 \times 7 = 49 - 48 = 1$ vacant spot)

Table 14. GE-5 8x8 BWR Assembly Dimensions (see Assumption 3.10)

Number of Rods	62	(p. 2A-21, Ref. 15)
Rod Pitch	16.26 mm (0.640 in.)	(p. 2A-21, Ref. 15)
UO ₂ Pellet Diameter	10.41 mm (0.410 in.)	(p. 2A-21, Ref. 15)
Cladding Outer Diameter	12.27 mm (0.483 in.)	(p. 2A-21, Ref. 15)
Cladding Thickness	0.8128 mm (0.032 in.)	(p. 2A-21, Ref. 15)
Number of Water Rods	2*	(p. 2A-21, Ref. 15)
Channel Inside Width	134.06 mm (5.278 in.)	(Assumption 3.28)
Channel Thickness	2.03, 2.54, or 3.05 mm (0.080, 0.100, or 0.120 in.)	(Assumption 3.13)
Channel Corner Radius	9.65 mm (0.380 in.)	(p. C-14, Ref. 23)
Active Fuel Length	3810.0 mm (150.0 in.)	(p. 2A-21, Ref. 15)

* Implied by number of fuel rods. Vacant spots are filled with water rods ($8 \times 8 = 64 - 62 = 2$ vacant spots)

Table 15. GE-9 8x8 BWR Assembly Dimensions (see Assumption 3.10)

Number of Rods	60	(p. 2A-22, Ref. 15)
Rod Pitch	16.26 mm (0.640 in.)	(p. 2A-21, Ref. 15)*
UO ₂ Pellet Diameter	10.41 mm (0.410 in.)	(p. 2A-21, Ref. 15)*
Cladding Outer Diameter	12.27 mm (0.483 in.)	(p. 2A-21, Ref. 15)*
Cladding Thickness	0.8128 mm (0.032 in.)	(p. 2A-21, Ref. 15)*
Number of Water Rods	1 (Over Sized)	(Assumption 3.10)
Water Rod Outer Diameter	32.61 mm (1.284 in.)	(Assumption 3.10)
Water Rod Thickness	0.8128 mm (0.032 in.)	(Assumption 3.10)
Channel Inside Width	134.06 mm (5.278 in.)	(Assumption 3.28)
Channel Thickness	2.03, 2.54, or 3.05 mm (0.080, 0.100, or 0.120 in.)	(Assumption 3.13)
Channel Corner Radius	9.65 mm (0.380 in.)	(p. C-14, Ref. 23)
Active Fuel Length	3810.0 mm (150.0 in.)	(p. 2A-22, Ref. 15)

* GE-5 8x8 BWR assembly dimensions used as those of GE-9 8x8 BWR assembly

Table 16. ANF-JP 9x9 BWR Assembly Dimensions (see Assumption 3.11)

Number of Rods	79	(p. 2A-24, Ref. 15)
Rod Pitch	14.53 mm (0.572 in.)	(p. 2A-24, Ref. 15)
UO ₂ Pellet Diameter	9.06 mm (0.3565 in.)	(p. 2A-19, Ref. 15)
Cladding Outer Diameter	10.77 mm (0.424 in.)	(p. 2A-24, Ref. 15)
Cladding Thickness	0.76 mm (0.030 in.)	(p. 2A-24, Ref. 15)
Number of Water Rods	2*	(p. 2A-24, Ref. 15)
Channel Inside Width	134.06 mm (5.278 in.)	(Assumption 3.28)
Channel Thickness	2.03, 2.54, or 3.05 mm (0.080, 0.100, or 0.120 in.)	(Assumption 3.13)
Channel Corner Radius	9.65 mm (0.380 in.)	(p. C-14, Ref. 23)
Active Fuel Length	3810.0 mm (150.0 in.)	(p. 2A-24, Ref. 15)

* Implied by number of fuel rods. Vacant spots are filled with water rods ($9 \times 9 = 81 - 79 = 2$ vacant spots)

Table 17. ANF-9X 9x9 BWR Assembly Dimensions (see Assumption 3.11)

Number of Rods	72	(p. 2A-25, Ref. 15)
Rod Pitch	14.53 mm(0.572 in.)	(p. 2A-24, Ref. 15)**
UO ₂ Pellet Diameter	9.06 mm (0.3565 in.)	(p. 2A-19, Ref. 15)**
Cladding Outer Diameter	10.77 mm (0.424 in.)	(p. 2A-24, Ref. 15)**
Cladding Thickness	0.76 mm (0.030 in.)	(p. 2A-24, Ref. 15)**
Number of Water Rods	1 (Over Sized; Channel Shaped)	(p. 2A-25, Ref. 15)
Water Tube Inside Width	40.74 mm (1.604 in.)	(Assumption 3.11)
Water Tube Corner Radius	3.81 mm (0.150 in.)	(Assumption 3.11)
Water Tube Thickness	0.81 mm (0.032 in.)	(Assumption 3.11)
Channel Inside Width	134.06 mm (5.278 in.)	(Assumption 3.28)
Channel Thickness	2.03, 2.54, or 3.05 mm (0.080, 0.100, or 0.120 in.)	(Assumption 3.13)
Channel Corner Radius	9.65 mm (0.380 in.)	(p. C-14, Ref. 23)
Active Fuel Length	3810.0 mm (150.0 in.)	(p. 2A-24, Ref. 15)**

** ANF-JP BWR assembly dimensions used as those of ANF-9X BWR assembly

5.3 PREDICTING PEAK CLADDING TEMPERATURES

There are three methods available to estimate cladding temperatures inside a storage, transportation, or disposal device. The first and most involved method is to explicitly represent the canister and every fuel rod in every assembly within it. This representation would directly consider the internal fill gas convection and conduction and a matrix of radiation view factors between the rods. A fluid flow computer code could be used to perform such an evaluation. However, the fill gas convection would be dependent upon the orientation of the waste package and the assemblies with respect to both tilt and angle, and it would be very difficult to quantify. This is especially difficult if the assembly spacer grids are included. This method is costly in time of setup and computational time, and it does not lend itself to parametric evaluation, in which detail is desired in the basket structure, corrosion barriers, or near field rock, and not in an individual assembly.

The second method employs the Wooton-Epstein correlation (Ref. 26) to estimate the peak cladding temperature based on the highest steady-state temperature in the container basket structure. The Wooton-Epstein correlation has historically been the primary tool of transportation/storage cask vendors because it simplifies the calculation, and it has been previously accepted by the U.S. Nuclear Regulatory Commission. Thermal analyses of the multi-purpose container conceptual design (Ref. 8) (for storage and transportation) and the BR-100 spent fuel shipping cask (Ref. 5) calculated container basket temperatures, which are the input to Wooton-Epstein. In these representations, the fuel assemblies are represented only as an edge heat flux to the basket structure without internal heat generation. The Wooton-Epstein relation then generates the estimated maximum steady-state fuel cladding temperature. This method is not suited for waste package evaluations for the following reasons:

- it requires lengthy and multiple calculations,
- it does not easily address transient behavior of the fuel and basket,
- it does not easily predict the effects of differential loading of the container,
- it may adversely affect basket profiles by forcing constant, bounding fuel assembly surface heat flux rates because of the lengthy calculations required to consider the time-dependent problem,
- it was 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 correlation used to analyze any other geometry, fill gas, or consideration of axial power distribution will produce more inaccurate results.

Given design time requirements, this method usually forces the designer to use conservative bounding approaches to the calculation, which tend to over-design the final product. Despite limitations, the correlation has been shown to be conservative for the thermal evaluations of spent nuclear fuel in a storage or shipping container (p. II 3.6-18, Ref. 5). Spent nuclear fuel temperatures calculated in this document are compared to the Wooton-Epstein correlation predictions in Section 5.5.

The third method of estimating peak cladding temperatures is to prepare a finite element representation of the fuel assembly volume as a smeared solid with uniform internal volumetric heat generation as part of the entire waste package representation. Instead of explicitly representing the fuel rods, smeared properties for a homogenous assembly are assumed in the container representation that will estimate the radiative and conductive transport of heat from the rods to the basket structure. An effective thermal conductivity for the assembly volume can be defined that will simulate the temperature drop across a BWR assembly. If the effective thermal conductivity is chosen correctly, the finite element representation will predict peak temperatures in the smeared-property assembly volume that are close to actual expected temperatures.

The key to accurate fuel rod cladding temperature predictions using the effective thermal conductivity method lies in determining the proper conductivity for the assembly volume. The Wootton-Epstein correlation demonstrates that peak cladding temperatures are a function of the assembly type, the assembly decay heat, and the basket wall temperature.

Due to the limitation of the first two methods, the effective thermal conductivity method will be employed for the parametric thermal evaluation of canistered spent nuclear fuel (such as the multi-purpose container) and uncanistered fuel in multi-barrier waste package designs emplaced in the potential geologic repository at Yucca Mountain. To determine the appropriate effective thermal conductivity for a BWR assembly, a detailed two-dimensional representation of a typical BWR fuel assembly is developed using the ANSYS finite element code (see Section 4.1), including both conductive and radiative heat transfer. After this representation is run for a variety of spent fuel characteristics and temperature levels (Section 5.4), a temperature and heat-load dependent effective thermal conductivity for the homogeneous assembly is derived (Section 5.6).

5.4 SPENT NUCLEAR FUEL REPRESENTATION DEVELOPMENT

The assembly types stated in Assumptions 3.9 through 3.11 were chosen as the basis for the two-dimensional representations. The representations take advantage of the symmetry of the BWR fuel and represent one quarter of an assembly (Assumptions 3.16 and 3.19). Assuming two planes of symmetry, the representation includes the basket wall, fuel rods, and the exterior BWR assembly channel, which can be considered an integral part of the fuel assembly.

The finite element representation meshes developed are included in Attachment IV. The base representation detail included a 4-mil (0.004 in.) thick oxidation layer on the zircaloy-2 cladding (typical of fuel that has been in a reactor, see Assumptions 3.3 and 3.4), and a gaseous gap (assumed to be filled with helium, see Assumptions 3.5 and 3.21) between the uranium oxide pellet and the cladding. The representation was built based on the assumption of a uniform heat generation in the uranium pellets, which neglects the distributed gamma radiation energy deposition in the cladding and supporting structures (Assumption 3.20). It is conservative to assume that all of the heat produced by the spent nuclear fuel assembly is produced in the fuel pellet, with zero heat generation in the cladding or other structural components. Attachment VI provides an analytical discussion in

support of this position. The volumetric assembly heat, derived from the total fuel assembly heat production, is multiplied by an axial power peaking factor of 1.25 in the base representation (Assumption 3.17). The BWR fuel assembly dimensions used for the base representation are provided in Table 12, Table 14, and Table 16, with additional assembly type information provided in Table 13, Table 15, and Table 17.

Gaseous conduction and thermal radiation are assumed to be the only modes of heat transfer between the rods (Assumption 3.22). The boundary temperatures range from the highest basket temperatures expected (when the emplaced waste package internal temperatures peak) to ambient repository rock conditions (the coldest the waste package could be). To represent the radiation heat transfer, a matrix of radiation view factors is explicitly generated for each element face on the surface of the cladding and the basket wall using the ANSYS code. This method is also applied to represent the radiation heat transfer between the fuel pellet surface and the inner surface of the cladding. Radiation energy is exchanged between surfaces that are exposed to each other using view factors calculated explicitly for the geometry of the fuel rod array.

Material properties for each of the components of the spent nuclear fuel representation are specified in Table 1 through Table 11 (See also Assumptions 3.1 through 3.8). The material properties were formatted into an ANSYS readable file (Attachment III) and are used in the ANSYS solutions of Sections 5.4, 5.7, and 5.8. The physical dimensions used for the BWR fuel assemblies represented in this calculation are provided in Table 12 through Table 17 (See also Assumptions 3.9 through 3.13).

The input file used to generate the ANSYS solution is echoed to the output file. At the beginning of the output file, the input batch commands are numbered and printed, including comment lines. Each input file uses the material properties file (Attachment III) as input.

The first step in the calculation is to define parameters and dimensions. The second step is to define which ANSYS element types will be used, define any real constants which may be required, and read in the material property file described above. The third step is to define the two-dimensional plane of the representation geometry using a "bottom up" approach – key-points are defined, followed by lines, and then areas. Element mesh densities are then defined. Graphical representations of the two-dimensional meshes are provided in Attachment IV. With the finite element representation complete, the next step is to apply temperature and heat load boundary conditions and to perform a solution. A matrix of different characteristics was assumed for this calculation to encompass as much of the fuel that could be loaded into the waste package as possible. The range of temperature and heat loads are described in the following section and in Assumptions 3.23 and 3.24. The last step in the calculation is to report the resulting peak cladding temperatures for each of the cases in a parameter output file (included as listed in Attachment II) for use in the effective thermal conductivity calculation.

5.4.1 Matrix of Cases for the Base BWR Spent Nuclear Fuel Representation

A matrix of cases was developed for the base representations of the 7x7, 8x8, and 9x9 arrays in helium fill gas. The results of these cases will be used to determine the temperature and heat load dependence of the effective thermal conductivities calculated in Section 5.6. The basket temperatures and heat loads were selected to bound the possible operational range of BWR spent nuclear fuel environments for repository disposal (Assumptions 3.23 and 3.24).

The output files for the 7x7, 8x8, and 9x9 arrays in each fill gas environment are included as listed in Attachment II. In each ANSYS case, the results were also stored in an array parameter and written to a second output file (included as listed in Attachment II) specially formatted to be read as input into a subsequent ANSYS case. The peak cladding temperature results and cladding-to-basket temperature differences for the base cases are summarized in Table 18 through Table 23.

Benchmarks against reported spent nuclear fuel thermal tests in Section 5.8 indicate that the base BWR representation provides a "best estimate" of peak temperatures within a BWR assembly. The impact on the determination of effective thermal conductivities is discussed in Section 5.6.

Table 18. Peak Cladding Temperatures; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	33.1	41.0	48.7	56.2	63.5	70.7
50°C	57.5	64.7	71.8	78.8	85.6	92.2
100°C	106.3	112.5	118.6	124.6	130.4	136.1
150°C	155.4	160.7	165.9	171.0	176.1	181.1
200°C	204.6	209.2	213.7	218.1	222.5	226.8
250°C	254.0	257.9	261.8	265.6	269.4	273.1
300°C	303.4	306.8	310.2	313.5	316.8	320.1
350°C	353.0	355.9	358.8	361.6	364.5	367.3
400°C	402.6	405.2	407.8	410.3	412.9	415.4

Table 19. Cladding-to-Basket Delta T; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.1	16.0	23.7	31.2	38.5	45.7
50°C	7.5	14.7	21.8	28.8	35.6	42.2
100°C	6.3	12.5	18.6	24.6	30.4	36.1
150°C	5.4	10.7	15.9	21.0	26.1	31.1
200°C	4.6	9.2	13.7	18.1	22.5	26.8
250°C	4.0	7.9	11.8	15.6	19.4	23.1
300°C	3.4	6.8	10.2	13.5	16.8	20.1
350°C	3.0	5.9	8.8	11.6	14.5	17.3
400°C	2.6	5.2	7.8	10.3	12.9	15.4

Table 20. Peak Cladding Temperatures; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	33.1	41.0	48.7	56.2	63.5	70.6
50°C	57.5	64.7	71.9	78.8	85.6	92.3
100°C	106.4	112.6	118.7	124.7	130.6	136.4
150°C	155.5	160.8	166.1	171.3	176.4	181.5
200°C	204.7	209.3	213.9	218.4	222.9	227.3
250°C	254.1	258.1	262.1	266.0	269.9	273.7
300°C	303.5	307.0	310.5	313.9	317.3	320.7
350°C	353.1	356.1	359.1	362.1	365.0	368.0
400°C	402.7	405.4	408.1	410.8	413.4	416.1

Table 21. Cladding-to-Basket Delta T; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.1	16.0	23.7	31.2	38.5	45.6
50°C	7.5	14.7	21.9	28.8	35.6	42.3
100°C	6.4	12.6	18.7	24.7	30.6	36.4
150°C	5.5	10.8	16.1	21.3	26.4	31.5
200°C	4.7	9.3	13.9	18.4	22.9	27.3
250°C	4.1	8.1	12.1	16.0	19.9	23.7
300°C	3.5	7.0	10.5	13.9	17.3	20.7
350°C	3.1	6.1	9.1	12.1	15.0	18.0
400°C	2.7	5.4	8.1	10.8	13.4	16.1

Table 22. Peak Cladding Temperatures; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	33.3	41.3	49.1	56.7	64.2	71.5
50°C	57.6	65.0	72.3	79.4	86.3	93.1
100°C	106.5	112.9	119.1	125.2	131.2	137.1
150°C	155.6	161.0	166.4	171.7	176.9	182.1
200°C	204.8	209.5	214.2	218.8	223.3	227.8
250°C	254.1	258.2	262.3	266.3	270.2	274.1
300°C	303.6	307.1	310.7	314.1	317.6	321.0
350°C	353.1	356.2	359.2	362.2	365.2	368.2
400°C	402.7	405.5	408.2	410.9	413.6	416.2

Table 23. Cladding-to-Basket Delta T; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.3	16.3	24.1	31.7	39.2	46.5
50°C	7.6	15.0	22.3	29.4	36.3	43.1
100°C	6.5	12.9	19.1	25.2	31.2	37.1
150°C	5.6	11.0	16.4	21.7	26.9	32.1
200°C	4.8	9.5	14.2	18.8	23.3	27.8
250°C	4.1	8.2	12.3	16.3	20.2	24.1
300°C	3.6	7.1	10.7	14.1	17.6	21.0
350°C	3.1	6.2	9.2	12.2	15.2	18.2
400°C	2.7	5.5	8.2	10.9	13.6	16.2

5.4.2 Effect of the BWR Assembly Channel

Some BWR fuel assemblies are manufactured with a surrounding fairing, or channel, the cross-section of which is shown on p. C-14 of Ref. 20. The channel enclosing the BWR fuel assemblies for all BWR/2/3/4/5 reactor types has a square cross section with dimensions as stated in Assumption 3.13, and given in Table 12 through Table 17.

The channel can 1) act as an insulating material in a container by truncating any radiation view factors from the fuel rods to the container internal structures, 2) provide a path for axial conduction in a container to help evenly distribute the heat load and make heat rejection from the container more efficient, 3) provide a heat sink for accident conditions, and 4) provide a conduction contact with the container internal structure for a container in a horizontal position.

The base 7x7, 8x8, and 9x9 BWR fuel representations were generated with an 80-mil channel, which was standard issue for the GE-2, early GE-5, and early ANF-JP fuel assembly series (see Assumption 3.13). To assess the impact upon peak cladding temperatures the base 7x7 input was also modified to represent the 100-mil and 120-mil channel thicknesses, and another case with no channel. The peak cladding temperature results and cladding-to-basket temperature differences for these three cases are presented in Table 24 through Table 33. The peak cladding temperature parameter files and the ANSYS output files are included as listed in Attachment II.

Comparing the results of the no-channel case to those of the 80-mil channel case, the peak cladding temperatures decrease by a maximum of 2.5°C by removing the channel (Table 18 and Table 24 for the 7x7, Table 20 and Table 26 for the 8x8, and Table 22 and Table 28 for the 9x9 arrays).

Finally, comparing the peak cladding temperature results for the three channel thicknesses, each of the channel thicknesses generated the same peak cladding temperature results within 1.7°C (Table 18, Table 30, and Table 32).

Table 24. Peak Cladding Temperatures; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	33.2	41.2	49.0	56.5	63.8	71.0
50°C	57.5	64.7	71.8	78.7	85.4	91.9
100°C	106.1	112.1	118.0	123.8	129.4	135.0
150°C	155.1	160.1	165.0	169.8	174.6	179.3
200°C	204.2	208.4	212.5	216.6	220.6	224.6
250°C	253.6	257.1	260.5	264.0	267.4	270.8
300°C	303.0	306.0	308.9	311.8	314.7	317.6
350°C	352.5	355.1	357.6	360.0	362.5	364.9
400°C	402.2	404.4	406.6	408.7	410.9	413.0

Table 25. Cladding-to-Basket Delta T; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.2	16.2	24.0	31.5	38.8	46.0
50°C	7.5	14.7	21.8	28.7	35.4	41.9
100°C	6.1	12.1	18.0	23.8	29.4	35.0
150°C	5.1	10.1	15.0	19.8	24.6	29.3
200°C	4.2	8.4	12.5	16.6	20.6	24.6
250°C	3.6	7.1	10.5	14.0	17.4	20.8
300°C	3.0	6.0	8.9	11.8	14.7	17.6
350°C	2.5	5.1	7.6	10.0	12.5	14.9
400°C	2.2	4.4	6.6	8.7	10.9	13.0

Table 26. Peak Cladding Temperatures; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	33.2	41.1	48.9	56.4	63.8	70.9
50°C	57.4	64.7	71.8	78.7	85.4	92.0
100°C	106.2	112.2	118.2	124.0	129.7	135.3
150°C	155.2	160.2	165.2	170.1	175.0	179.8
200°C	204.3	208.6	212.8	217.0	221.1	225.2
250°C	253.7	257.3	260.9	264.5	268.0	271.5
300°C	303.1	306.2	309.3	312.4	315.4	318.4
350°C	352.7	355.3	358.0	360.6	363.2	365.7
400°C	402.3	404.7	407.0	409.3	411.6	413.9

Table 27. Cladding-to-Basket Delta T; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.2	16.1	23.9	31.4	38.8	45.9
50°C	7.4	14.7	21.8	28.7	35.4	42.0
100°C	6.2	12.2	18.2	24.0	29.7	35.3
150°C	5.2	10.2	15.2	20.1	25.0	29.8
200°C	4.3	8.6	12.8	17.0	21.1	25.2
250°C	3.7	7.3	10.9	14.5	18.0	21.5
300°C	3.1	6.2	9.3	12.4	15.4	18.4
350°C	2.7	5.3	8.0	10.6	13.2	15.7
400°C	2.3	4.7	7.0	9.3	11.6	13.9

Table 28. Peak Cladding Temperatures; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	33.5	41.8	49.8	57.7	65.3	72.7
50°C	57.8	65.3	72.7	79.9	86.9	93.7
100°C	106.5	112.8	119.0	125.1	131.1	136.9
150°C	155.4	160.8	166.0	171.2	176.2	181.2
200°C	204.6	209.1	213.5	217.9	222.2	226.5
250°C	253.9	257.7	261.5	265.2	268.9	272.6
300°C	303.3	306.6	309.8	313.0	316.2	319.3
350°C	352.8	355.6	358.3	361.1	363.8	366.5
400°C	402.4	404.9	407.3	409.7	412.1	414.5

Table 29. Cladding-to-Basket Delta T; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.5	16.8	24.8	32.7	40.3	47.7
50°C	7.8	15.3	22.7	29.9	36.9	43.7
100°C	6.5	12.8	19.0	25.1	31.1	36.9
150°C	5.4	10.8	16.0	21.2	26.2	31.2
200°C	4.6	9.1	13.5	17.9	22.2	26.5
250°C	3.9	7.7	11.5	15.2	18.9	22.6
300°C	3.3	6.6	9.8	13.0	16.2	19.3
350°C	2.8	5.6	8.3	11.1	13.8	16.5
400°C	2.4	4.9	7.3	9.7	12.1	14.5

Table 30. Peak Cladding Temperatures; GE 7x7 GE-2 Fuel Assembly with 100-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	33.0	40.7	48.3	55.6	62.8	69.8
50°C	57.3	64.5	71.4	78.2	84.9	91.4
100°C	106.2	112.3	118.3	124.1	129.9	135.5
150°C	155.3	160.5	165.6	170.7	175.6	180.5
200°C	204.5	209.0	213.4	217.8	222.1	226.3
250°C	253.9	257.8	261.6	265.4	269.1	272.8
300°C	303.4	306.7	310.0	313.3	316.6	319.8
350°C	352.9	355.8	358.7	361.5	364.3	367.1
400°C	402.6	405.1	407.7	410.2	412.7	415.2

Table 31. Cladding-to-Basket Delta T; GE 7x7 GE-2 Fuel Assembly with 100-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	8.0	15.7	23.3	30.6	37.8	44.8
50°C	7.3	14.5	21.4	28.2	34.9	41.4
100°C	6.2	12.3	18.3	24.1	29.9	35.5
150°C	5.3	10.5	15.6	20.7	25.6	30.5
200°C	4.5	9.0	13.4	17.8	22.1	26.3
250°C	3.9	7.8	11.6	15.4	19.1	22.8
300°C	3.4	6.7	10.0	13.3	16.6	19.8
350°C	2.9	5.8	8.7	11.5	14.3	17.1
400°C	2.6	5.1	7.7	10.2	12.7	15.2

Table 32. Peak Cladding Temperatures; GE 7x7 GE-2 Fuel Assembly with 120-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	32.8	40.4	47.8	55.0	62.1	69.0
50°C	57.2	64.2	71.0	77.7	84.3	90.7
100°C	106.1	112.1	117.9	123.7	129.3	134.9
150°C	155.2	160.3	165.4	170.3	175.2	180.0
200°C	204.5	208.9	213.2	217.5	221.7	225.9
250°C	253.8	257.6	261.4	265.1	268.8	272.4
300°C	303.3	306.6	309.9	313.1	316.3	319.5
350°C	352.9	355.7	358.5	361.3	364.1	366.9
400°C	402.5	405.1	407.6	410.1	412.5	415.0

Table 33. Cladding-to-Basket Delta T; GE 7x7 GE-2 Fuel Assembly with 120-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	7.8	15.4	22.8	30.0	37.1	44.0
50°C	7.2	14.2	21.0	27.7	34.3	40.7
100°C	6.1	12.1	17.9	23.7	29.3	34.9
150°C	5.2	10.3	15.4	20.3	25.2	30.0
200°C	4.5	8.9	13.2	17.5	21.7	25.9
250°C	3.8	7.6	11.4	15.1	18.8	22.4
300°C	3.3	6.6	9.9	13.1	16.3	19.5
350°C	2.9	5.7	8.5	11.3	14.1	16.9
400°C	2.5	5.1	7.6	10.1	12.5	15.0

5.4.3 Fill Gas Selection

The base calculation set utilized helium as the fill gas. Results calculated with vacuum conditions and nitrogen and argon fill gases are also presented in this section. The thermal properties of nitrogen and air are nearly the same. Thus, for the purposes of this evaluation air will not be specifically examined and the results for air can be considered negligibly different from the results for nitrogen (Assumption 3.27). The following sections present the effect of varying fill gas environment on BWR assembly peak cladding temperatures.

Each of the 54 ANSYS solutions run for the base case with helium fill gas was altered to represent a vacuum, nitrogen fill gas, or argon fill gas outside the fuel rods. The four basic 7x7 rod configuration cases of no-channel, 80-mil channel, 100-mil channel, and 120-mil channel were executed in order to show that the channel thickness impact is not affected by the fill gas assumption. The two basic 8x8 and 9x9 rod configuration cases of no-channel and 80-mil channel were also executed in order to show the impact of removing the channel in each of the fill gas environments.

The ANSYS output files for these calculations are included as listed in Attachment II. In each case, the results were also stored in an array parameter and written to a second output file (included as listed in Attachment II) specially formatted to be read as input to a subsequent ANSYS calculation.

5.4.3.1 Vacuum Conditions

5.4.3.1.1 7x7 Rod Configuration

The peak cladding temperature results for the 7x7 array representation with each channel size are summarized in Table 34 through Table 41.

Comparing the results for vacuum conditions for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 26°C by removing the channel. Comparing Table 24 and Table 34 for the no-channel geometry and helium versus vacuum environment, peak cladding temperatures decrease by a maximum of 71°C by adding a helium fill gas. Comparing Table 18 and Table 36 for the 80-mil channel geometry and helium versus vacuum environment, peak cladding temperatures decrease by a maximum of 98°C by adding a helium fill gas.

Finally, comparing the peak cladding temperature results for the three channel thickness in a vacuum environment, each of the channel thicknesses generated the same peak cladding temperature results within 1.7°C. Thus, a radiation-only mode versus a radiation/conduction mode, which is available with a fill gas, does not affect the results for channel thickness variations.

Table 34. Peak Cladding Temperatures in a Vacuum; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	54.6	77.9	97.3	114.1	129.0	142.4
50°C	74.1	94.1	111.3	126.5	140.1	152.6
100°C	116.5	131.1	144.3	156.4	167.5	177.9
150°C	161.6	172.4	182.5	191.9	200.8	209.3
200°C	208.5	216.5	224.2	231.6	238.7	245.5
250°C	256.4	262.5	268.5	274.3	279.9	285.3
300°C	304.9	309.7	314.4	319.0	323.5	327.9
350°C	353.9	357.7	361.4	365.1	368.7	372.3
400°C	403.1	406.2	409.2	412.2	415.2	418.1

Table 35. Cladding-to-Basket Delta T in a Vacuum; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	29.6	52.9	72.3	89.1	104.0	117.4
50°C	24.1	44.1	61.3	76.5	90.1	102.6
100°C	16.5	31.1	44.3	56.4	67.5	77.9
150°C	11.6	22.4	32.5	41.9	50.8	59.3
200°C	8.5	16.5	24.2	31.6	38.7	45.5
250°C	6.4	12.5	18.5	24.3	29.9	35.3
300°C	4.9	9.7	14.4	19.0	23.5	27.9
350°C	3.9	7.7	11.4	15.1	18.7	22.3
400°C	3.1	6.2	9.2	12.2	15.2	18.1

Table 36. Peak Cladding Temperatures in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	63.8	92.6	115.9	135.7	153.1	168.6
50°C	82.0	107.1	128.2	146.4	162.6	177.1
100°C	122.1	141.1	157.8	172.8	186.5	199.1
150°C	165.8	180.0	193.1	205.2	216.4	226.9
200°C	211.6	222.4	232.6	242.2	251.3	260.0
250°C	258.7	267.1	275.0	282.7	290.1	297.2
300°C	306.7	313.3	319.6	325.8	331.7	337.5
350°C	355.3	360.5	365.6	370.6	375.5	380.2
400°C	404.3	408.5	412.6	416.7	420.7	424.7

Table 37. Cladding-to-Basket Delta T in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	38.8	67.6	90.9	110.7	128.1	143.6
50°C	32.0	57.1	78.2	96.4	112.6	127.1
100°C	22.1	41.1	57.8	72.8	86.5	99.1
150°C	15.8	30.0	43.1	55.2	66.4	76.9
200°C	11.6	22.4	32.6	42.2	51.3	60.0
250°C	8.7	17.1	25.0	32.7	40.1	47.2
300°C	6.7	13.3	19.6	25.8	31.7	37.5
350°C	5.3	10.5	15.6	20.6	25.5	30.2
400°C	4.3	8.5	12.6	16.7	20.7	24.7

Table 38. Peak Cladding Temperatures in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 100-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	63.7	92.4	115.7	135.4	152.7	168.2
50°C	81.9	107.0	128.0	146.1	162.2	176.8
100°C	122.0	140.9	157.6	172.6	186.2	198.7
150°C	165.7	179.9	192.9	204.9	216.2	226.7
200°C	211.5	222.3	232.4	242.0	251.1	259.7
250°C	258.7	267.0	274.9	282.6	289.9	297.0
300°C	306.7	313.2	319.5	325.6	331.6	337.4
350°C	355.3	360.5	365.5	370.5	375.3	380.1
400°C	404.3	408.5	412.6	416.7	420.6	424.6

Table 39. Cladding-to-Basket Delta T in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 100-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	38.7	67.4	90.7	110.4	127.7	143.2
50°C	31.9	57.0	78.0	96.1	112.2	126.8
100°C	22.0	40.9	57.6	72.6	86.2	98.7
150°C	15.7	29.9	42.9	54.9	66.2	76.7
200°C	11.5	22.3	32.4	42.0	51.1	59.7
250°C	8.7	17.0	24.9	32.6	39.9	47.0
300°C	6.7	13.2	19.5	25.6	31.6	37.4
350°C	5.3	10.5	15.5	20.5	25.3	30.1
400°C	4.3	8.5	12.6	16.7	20.6	24.6

Table 40. Peak Cladding Temperatures in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 120-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	63.6	92.2	115.4	135.2	152.4	167.8
50°C	81.7	106.8	127.7	145.9	161.9	176.5
100°C	122.0	140.8	157.4	172.3	185.9	198.4
150°C	165.6	179.8	192.8	204.8	215.9	226.4
200°C	211.5	222.2	232.3	241.8	250.9	259.5
250°C	258.7	266.9	274.8	282.4	289.7	296.8
300°C	306.7	313.2	319.4	325.5	331.5	337.2
350°C	355.3	360.4	365.5	370.4	375.2	380.0
400°C	404.3	408.4	412.5	416.6	420.6	424.5

Table 41. Cladding-to-Basket Delta T in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 120-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	38.6	67.2	90.4	110.2	127.4	142.8
50°C	31.7	56.8	77.7	95.9	111.9	126.5
100°C	22.0	40.8	57.4	72.3	85.9	98.4
150°C	15.6	29.8	42.8	54.8	65.9	76.4
200°C	11.5	22.2	32.3	41.8	50.9	59.5
250°C	8.7	16.9	24.8	32.4	39.7	46.8
300°C	6.7	13.2	19.4	25.5	31.5	37.2
350°C	5.3	10.4	15.5	20.4	25.2	30.0
400°C	4.3	8.4	12.5	16.6	20.6	24.5

5.4.3.1.2 8x8 Rod Configuration

The peak cladding temperature results for the 8x8 array representation with each channel size are summarized in Table 42 through Table 45.

Comparing the results for vacuum conditions for the no-channel and the 80-mil channel cases in an 8x8 rod configuration, the peak cladding temperatures decrease by a maximum of 22°C by removing the channel. Comparing Table 26 and Table 42 for the no-channel geometry with helium versus vacuum environment, peak cladding temperatures decrease by a maximum of 85°C by adding a helium fill gas. Comparing Table 20 and Table 44 for the 80-mil channel geometry with helium versus vacuum environment, peak cladding temperatures decrease by a maximum of 107°C by adding a helium fill gas.

Table 42. Peak Cladding Temperatures in a Vacuum; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	59.2	85.4	106.8	125.2	141.3	155.8
50°C	78.1	100.7	119.9	136.6	151.6	165.1
100°C	119.3	136.1	151.1	164.7	177.1	188.6
150°C	163.7	176.2	187.7	198.5	208.6	218.1
200°C	210.0	219.4	228.4	236.8	244.9	252.7
250°C	257.5	264.8	271.7	278.4	284.9	291.2
300°C	305.8	311.5	317.0	322.3	327.5	332.6
350°C	354.6	359.1	363.5	367.8	372.1	376.2
400°C	403.7	407.3	410.9	414.5	418.0	421.4

Table 43. Cladding-to-Basket Delta T in a Vacuum; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	34.2	60.4	81.8	100.2	116.3	130.8
50°C	28.1	50.7	69.9	86.6	101.6	115.1
100°C	19.3	36.1	51.1	64.7	77.1	88.6
150°C	13.7	26.2	37.7	48.5	58.6	68.1
200°C	10.0	19.4	28.4	36.8	44.9	52.7
250°C	7.5	14.8	21.7	28.4	34.9	41.2
300°C	5.8	11.5	17.0	22.3	27.5	32.6
350°C	4.6	9.1	13.5	17.8	22.1	26.2
400°C	3.7	7.3	10.9	14.5	18.0	21.4

Table 44. Peak Cladding Temperatures in a Vacuum; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	67.3	98.0	122.7	143.5	161.6	177.8
50°C	85.0	112.0	134.4	153.6	170.6	185.9
100°C	124.3	144.9	162.9	178.9	193.4	206.7
150°C	167.4	183.0	197.1	210.1	222.2	233.4
200°C	212.8	224.7	235.8	246.2	256.1	265.4
250°C	259.7	268.8	277.6	286.0	294.0	301.7
300°C	307.5	314.7	321.6	328.4	334.9	341.3
350°C	355.9	361.7	367.3	372.8	378.1	383.3
400°C	404.8	409.4	414.0	418.5	422.9	427.3

Table 45. Cladding-to-Basket Delta T in a Vacuum; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	42.3	73.0	97.7	118.5	136.6	152.8
50°C	35.0	62.0	84.4	103.6	120.6	135.9
100°C	24.3	44.9	62.9	78.9	93.4	106.7
150°C	17.4	33.0	47.1	60.1	72.2	83.4
200°C	12.8	24.7	35.8	46.2	56.1	65.4
250°C	9.7	18.8	27.6	36.0	44.0	51.7
300°C	7.5	14.7	21.6	28.4	34.9	41.3
350°C	5.9	11.7	17.3	22.8	28.1	33.3
400°C	4.8	9.4	14.0	18.5	22.9	27.3

5.4.3.1.3 9x9 Rod Configuration

The peak cladding temperature results for the 9x9 array representation with each channel size are summarized in Table 46 through Table 49.

Comparing the results for vacuum conditions for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 20°C by removing the channel. Comparing Table 28 and Table 46 for the no-channel geometry with helium versus vacuum environment, peak cladding temperatures decrease by a maximum of 86°C by adding a helium fill gas. Comparing Table 22 and Table 48 for the 80-mil channel geometry with helium versus vacuum environment, peak cladding temperatures decrease by a maximum of 108°C by adding a helium fill gas.

Table 46. Peak Cladding Temperatures in a Vacuum; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	60.4	87.2	109.1	127.9	144.3	159.0
50°C	79.1	102.3	122.0	139.1	154.3	168.1
100°C	120.0	137.3	152.7	166.6	179.3	191.0
150°C	164.1	177.0	188.9	200.0	210.3	220.1
200°C	210.3	220.0	229.2	237.9	246.2	254.2
250°C	257.8	265.2	272.3	279.2	285.9	292.3
300°C	306.0	311.8	317.4	322.9	328.2	333.4
350°C	354.7	359.3	363.8	368.2	372.5	376.8
400°C	403.8	407.5	411.1	414.7	418.3	421.7

Table 47. Cladding-to-Basket Delta T in a Vacuum; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	35.4	62.2	84.1	102.9	119.3	134.0
50°C	29.1	52.3	72.0	89.1	104.3	118.1
100°C	20.0	37.3	52.7	66.6	79.3	91.0
150°C	14.1	27.0	38.9	50.0	60.3	70.1
200°C	10.3	20.0	29.2	37.9	46.2	54.2
250°C	7.8	15.2	22.3	29.2	35.9	42.3
300°C	6.0	11.8	17.4	22.9	28.2	33.4
350°C	4.7	9.3	13.8	18.2	22.5	26.8
400°C	3.8	7.5	11.1	14.7	18.3	21.7

Table 48. Peak Cladding Temperatures in a Vacuum; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	67.9	98.9	123.7	144.7	162.9	179.1
50°C	85.4	112.8	135.3	154.7	171.8	187.1
100°C	124.6	145.4	163.6	179.7	194.3	207.7
150°C	167.6	183.3	197.6	210.7	222.8	234.2
200°C	212.9	224.9	236.1	246.6	256.5	265.9
250°C	259.7	269.0	277.8	286.2	294.2	302.0
300°C	307.5	314.8	321.7	328.5	335.0	341.4
350°C	355.9	361.7	367.3	372.8	378.1	383.3
400°C	404.8	409.4	414.0	418.5	422.9	427.2

Table 49. Cladding-to-Basket Delta T in a Vacuum; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	42.9	73.9	98.7	119.7	137.9	154.1
50°C	35.4	62.8	85.3	104.7	121.8	137.1
100°C	24.6	45.4	63.6	79.7	94.3	107.7
150°C	17.6	33.3	47.6	60.7	72.8	84.2
200°C	12.9	24.9	36.1	46.6	56.5	65.9
250°C	9.7	19.0	27.8	36.2	44.2	52.0
300°C	7.5	14.8	21.7	28.5	35.0	41.4
350°C	5.9	11.7	17.3	22.8	28.1	33.3
400°C	4.8	9.4	14.0	18.5	22.9	27.2

5.4.3.2 Nitrogen Fill Gas

5.4.3.2.1 7x7 Rod Configuration

The peak cladding temperature results for the 7x7 array representation with each channel size are summarized in Table 50 through Table 53.

Comparing the results for nitrogen conditions for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 13°C by removing the channel. Comparing Table 24 and Table 50 for the no-channel geometry with helium versus nitrogen fill gas, peak cladding temperatures decrease by a maximum of 49°C by changing to a helium fill gas. Comparing Table 18 and Table 52 for the 80-mil channel geometry with helium versus nitrogen, peak cladding temperatures decrease by a maximum of 62°C by adding a helium fill gas.

Table 50. Peak Cladding Temperatures in Nitrogen; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	45.6	63.6	79.6	94.2	107.5	119.8
50°C	67.4	83.0	97.2	110.2	122.2	133.4
100°C	112.7	124.4	135.4	145.7	155.4	164.7
150°C	159.4	168.4	176.9	185.0	192.8	200.3
200°C	207.2	214.1	220.7	227.2	233.4	239.5
250°C	255.6	261.0	266.2	271.4	276.4	281.3
300°C	304.4	308.7	312.9	317.1	321.1	325.1
350°C	353.5	357.0	360.4	363.8	367.2	370.5
400°C	402.9	405.8	408.6	411.4	414.2	416.9

Table 51. Cladding-to-Basket Delta T in Nitrogen; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	20.6	38.6	54.6	69.2	82.5	94.8
50°C	17.4	33.0	47.2	60.2	72.2	83.4
100°C	12.7	24.4	35.4	45.7	55.4	64.7
150°C	9.4	18.4	26.9	35.0	42.8	50.3
200°C	7.2	14.1	20.7	27.2	33.4	39.5
250°C	5.6	11.0	16.2	21.4	26.4	31.3
300°C	4.4	8.7	12.9	17.1	21.1	25.1
350°C	3.5	7.0	10.4	13.8	17.2	20.5
400°C	2.9	5.8	8.6	11.4	14.2	16.9

Table 52. Peak Cladding Temperatures in Nitrogen; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	48.8	69.4	87.6	104.1	119.0	132.8
50°C	70.5	88.7	105.0	119.9	133.7	146.4
100°C	115.4	129.5	142.6	154.7	166.1	176.9
150°C	161.7	172.7	183.1	193.0	202.4	211.4
200°C	209.1	217.8	226.1	234.1	241.8	249.2
250°C	257.1	264.1	270.8	277.3	283.6	289.7
300°C	305.7	311.3	316.7	322.1	327.3	332.4
350°C	354.6	359.2	363.7	368.0	372.4	376.6
400°C	403.8	407.6	411.3	415.0	418.7	422.2

Table 53. Cladding-to-Basket Delta T in Nitrogen; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	23.8	44.4	62.6	79.1	94.0	107.8
50°C	20.5	38.7	55.0	69.9	83.7	96.4
100°C	15.4	29.5	42.6	54.7	66.1	76.9
150°C	11.7	22.7	33.1	43.0	52.4	61.4
200°C	9.1	17.8	26.1	34.1	41.8	49.2
250°C	7.1	14.1	20.8	27.3	33.6	39.7
300°C	5.7	11.3	16.7	22.1	27.3	32.4
350°C	4.6	9.2	13.7	18.0	22.4	26.6
400°C	3.8	7.6	11.3	15.0	18.7	22.2

5.4.3.2.2 8x8 Rod Configuration

The peak cladding temperature results for the 8x8 array representation with each channel size are summarized in Table 54 through Table 57.

Comparing the results for nitrogen conditions for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 12°C by removing the channel. Comparing Table 26 and Table 54 for the no-channel geometry with helium versus nitrogen fill gas, peak cladding temperatures decrease by a maximum of 55°C by changing to a helium fill gas. Comparing Table 20 and Table 56 for the 80-mil channel geometry with helium versus nitrogen, peak cladding temperatures decrease by a maximum of 67°C by adding a helium fill gas.

Table 54. Peak Cladding Temperatures in Nitrogen; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	46.8	65.9	83.0	98.4	112.6	125.7
50°C	68.6	85.2	100.4	114.3	127.2	139.2
100°C	113.7	126.4	138.3	149.4	160.0	169.9
150°C	160.3	170.1	179.4	188.3	196.9	205.0
200°C	207.9	215.6	222.9	230.1	236.9	243.6
250°C	256.2	262.3	268.1	273.9	279.5	284.9
300°C	304.9	309.8	314.5	319.2	323.8	328.3
350°C	354.0	357.9	361.8	365.7	369.4	373.2
400°C	403.3	406.6	409.8	413.0	416.2	419.3

Table 55. Cladding-to-Basket Delta T in Nitrogen; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	21.8	40.9	58.0	73.4	87.6	100.7
50°C	18.6	35.2	50.4	64.3	77.2	89.2
100°C	13.7	26.4	38.3	49.4	60.0	69.9
150°C	10.3	20.1	29.4	38.3	46.9	55.0
200°C	7.9	15.6	22.9	30.1	36.9	43.6
250°C	6.2	12.3	18.1	23.9	29.5	34.9
300°C	4.9	9.8	14.5	19.2	23.8	28.3
350°C	4.0	7.9	11.8	15.7	19.4	23.2
400°C	3.3	6.6	9.8	13.0	16.2	19.3

Table 56. Peak Cladding Temperatures in Nitrogen; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	49.8	71.3	90.4	107.6	123.2	137.6
50°C	71.4	90.5	107.6	123.3	137.6	151.0
100°C	116.2	131.1	144.9	157.7	169.7	181.1
150°C	162.5	174.2	185.2	195.7	205.6	215.1
200°C	209.7	219.0	227.9	236.4	244.6	252.5
250°C	257.7	265.1	272.3	279.3	286.0	292.6
300°C	306.2	312.2	318.0	323.8	329.4	334.8
350°C	355.0	359.9	364.8	369.5	374.2	378.8
400°C	404.2	408.3	412.3	416.3	420.3	424.1

Table 57. Cladding-to-Basket Delta T in Nitrogen; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	24.8	46.3	65.4	82.6	98.2	112.6
50°C	21.4	40.5	57.6	73.3	87.6	101.0
100°C	16.2	31.1	44.9	57.7	69.7	81.1
150°C	12.5	24.2	35.2	45.7	55.6	65.1
200°C	9.7	19.0	27.9	36.4	44.6	52.5
250°C	7.7	15.1	22.3	29.3	36.0	42.6
300°C	6.2	12.2	18.0	23.8	29.4	34.8
350°C	5.0	9.9	14.8	19.5	24.2	28.8
400°C	4.2	8.3	12.3	16.3	20.3	24.1

5.4.3.2.3 9x9 Rod Configuration

The peak cladding temperature results for the 9x9 array representation with each channel size are summarized in Table 58 through Table 61.

Comparing the results for nitrogen conditions for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 9°C by removing the channel. Comparing Table 28 and Table 58 for the no-channel geometry with helium versus nitrogen fill gas, peak cladding temperatures decrease by a maximum of 58°C by changing to a helium fill gas. Comparing Table 22 and Table 60 for the 80-mil channel geometry with helium versus nitrogen, peak cladding temperatures decrease by a maximum of 68°C by adding a helium fill gas.

Table 58. Peak Cladding Temperatures in Nitrogen; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	48.2	68.3	86.1	102.2	116.8	130.2
50°C	69.8	87.3	103.2	117.7	131.0	143.4
100°C	114.6	128.0	140.5	152.1	163.1	173.4
150°C	161.0	171.3	181.1	190.4	199.3	207.8
200°C	208.4	216.4	224.2	231.6	238.8	245.7
250°C	256.5	262.9	269.0	275.0	280.9	286.5
300°C	305.2	310.2	315.2	320.1	324.8	329.5
350°C	354.2	358.3	362.3	366.3	370.2	374.0
400°C	403.4	406.8	410.1	413.4	416.7	419.9

Table 59. Cladding-to-Basket Delta T in Nitrogen; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	23.2	43.3	61.1	77.2	91.8	105.2
50°C	19.8	37.3	53.2	67.7	81.0	93.4
100°C	14.6	28.0	40.5	52.1	63.1	73.4
150°C	11.0	21.3	31.1	40.4	49.3	57.8
200°C	8.4	16.4	24.2	31.6	38.8	45.7
250°C	6.5	12.9	19.0	25.0	30.9	36.5
300°C	5.2	10.2	15.2	20.1	24.8	29.5
350°C	4.2	8.3	12.3	16.3	20.2	24.0
400°C	3.4	6.8	10.1	13.4	16.7	19.9

Table 60. Peak Cladding Temperatures in Nitrogen; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	50.4	72.4	91.7	109.1	125.0	139.5
50°C	72.0	91.4	108.8	124.7	139.3	152.7
100°C	116.6	131.8	145.8	158.9	171.0	182.5
150°C	162.7	174.7	185.9	196.5	206.6	216.2
200°C	209.9	219.4	228.4	237.0	245.3	253.3
250°C	257.8	265.4	272.7	279.7	286.6	293.2
300°C	306.3	312.3	318.3	324.1	329.7	335.2
350°C	355.1	360.0	364.9	369.7	374.4	379.0
400°C	404.2	408.3	412.4	416.4	420.4	424.3

Table 61. Cladding-to-Basket Delta T in Nitrogen; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	25.4	47.4	66.7	84.1	100.0	114.5
50°C	22.0	41.4	58.8	74.7	89.3	102.7
100°C	16.6	31.8	45.8	58.9	71.0	82.5
150°C	12.7	24.7	35.9	46.5	56.6	66.2
200°C	9.9	19.4	28.4	37.0	45.3	53.3
250°C	7.8	15.4	22.7	29.7	36.6	43.2
300°C	6.3	12.3	18.3	24.1	29.7	35.2
350°C	5.1	10.0	14.9	19.7	24.4	29.0
400°C	4.2	8.3	12.4	16.4	20.4	24.3

5.4.3.3 Argon Fill Gas

5.4.3.3.1 7x7 Rod Configuration

The peak cladding temperature results for the 7x7 array representation with each channel size are summarized in Table 62 through Table 65.

Comparing the results with argon fill gas for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 16°C by removing the channel. Comparing Table 24 and Table 62 for the no-channel geometry and helium versus argon, peak cladding temperatures decrease by a maximum of 55°C by changing to a helium fill gas. Comparing Table 18 and Table 64 for the 80-mil channel geometry and helium versus argon, peak cladding temperatures decrease by a maximum of 71°C by adding a helium fill gas.

Table 62. Peak Cladding Temperatures in Argon; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	47.7	67.1	84.1	99.4	113.2	125.9
50°C	69.0	85.8	100.8	114.4	127.0	138.6
100°C	113.6	126.1	137.7	148.5	158.6	168.2
150°C	160.0	169.4	178.4	186.9	195.0	202.7
200°C	207.5	214.7	221.7	228.4	234.9	241.1
250°C	255.8	261.4	266.9	272.2	277.4	282.4
300°C	304.5	309.0	313.3	317.6	321.8	325.9
350°C	353.6	357.2	360.7	364.2	367.6	371.0
400°C	403.0	405.9	408.8	411.7	414.5	417.3

Table 63. Cladding-to-Basket Delta T in Argon; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	22.7	42.1	59.1	74.4	88.2	100.9
50°C	19.0	35.8	50.8	64.4	77.0	88.6
100°C	13.6	26.1	37.7	48.5	58.6	68.2
150°C	10.0	19.4	28.4	36.9	45.0	52.7
200°C	7.5	14.7	21.7	28.4	34.9	41.1
250°C	5.8	11.4	16.9	22.2	27.4	32.4
300°C	4.5	9.0	13.3	17.6	21.8	25.9
350°C	3.6	7.2	10.7	14.2	17.6	21.0
400°C	3.0	5.9	8.8	11.7	14.5	17.3

Table 64. Peak Cladding Temperatures in Argon; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	52.0	74.7	94.4	111.9	127.6	142.0
50°C	73.0	92.9	110.6	126.5	140.9	154.3
100°C	116.9	132.3	146.3	159.2	171.3	182.6
150°C	162.7	174.5	185.7	196.1	206.0	215.4
200°C	209.7	219.0	227.8	236.2	244.3	252.1
250°C	257.6	264.9	271.9	278.7	285.3	291.8
300°C	306.0	311.8	317.5	323.1	328.5	333.8
350°C	354.8	359.6	364.2	368.8	373.3	377.7
400°C	404.0	407.9	411.7	415.5	419.3	423.0

Table 65. Cladding-to-Basket Delta T in Argon; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	27.0	49.7	69.4	86.9	102.6	117.0
50°C	23.0	42.9	60.6	76.5	90.9	104.3
100°C	16.9	32.3	46.3	59.2	71.3	82.6
150°C	12.7	24.5	35.7	46.1	56.0	65.4
200°C	9.7	19.0	27.8	36.2	44.3	52.1
250°C	7.6	14.9	21.9	28.7	35.3	41.8
300°C	6.0	11.8	17.5	23.1	28.5	33.8
350°C	4.8	9.6	14.2	18.8	23.3	27.7
400°C	4.0	7.9	11.7	15.5	19.3	23.0

5.4.3.3.2 8x8 Rod Configuration

The peak cladding temperature results for the 8x8 array representation with each channel size are summarized in Table 66 through Table 69.

Comparing the results for argon fill gas for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 15°C by removing the channel. Comparing Table 26 and Table 66 for the no-channel geometry with helium versus argon fill gas, peak cladding temperatures decrease by a maximum of 63°C by changing to a helium fill gas. Comparing Table 20 and Table 68 for the 80-mil channel geometry with helium versus argon fill gas, peak cladding temperatures decrease by a maximum of 77°C by adding a helium fill gas.

Table 66. Peak Cladding Temperatures in Argon; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	49.4	70.3	88.6	105.0	119.8	133.4
50°C	70.6	88.7	105.0	119.7	133.2	145.7
100°C	115.0	128.7	141.4	153.2	164.2	174.6
150°C	161.1	171.6	181.5	190.9	199.8	208.4
200°C	208.4	216.5	224.3	231.8	239.0	246.0
250°C	256.5	262.9	269.1	275.1	280.9	286.6
300°C	305.2	310.2	315.2	320.0	324.8	329.4
350°C	354.2	358.3	362.3	366.3	370.2	374.0
400°C	403.4	406.8	410.1	413.4	416.7	419.9

Table 67. Cladding-to-Basket Delta T in Argon; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	24.4	45.3	63.6	80.0	94.8	108.4
50°C	20.6	38.7	55.0	69.7	83.2	95.7
100°C	15.0	28.7	41.4	53.2	64.2	74.6
150°C	11.1	21.6	31.5	40.9	49.8	58.4
200°C	8.4	16.5	24.3	31.8	39.0	46.0
250°C	6.5	12.9	19.1	25.1	30.9	36.6
300°C	5.2	10.2	15.2	20.0	24.8	29.4
350°C	4.2	8.3	12.3	16.3	20.2	24.0
400°C	3.4	6.8	10.1	13.4	16.7	19.9

Table 68. Peak Cladding Temperatures in Argon; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	53.4	77.3	98.0	116.3	132.8	147.9
50°C	74.3	95.3	113.9	130.6	145.9	159.9
100°C	118.0	134.3	149.2	162.9	175.7	187.6
150°C	163.6	176.3	188.1	199.3	209.8	219.8
200°C	210.5	220.4	229.9	238.9	247.6	255.9
250°C	258.2	266.1	273.7	281.0	288.1	295.0
300°C	306.5	312.8	319.0	325.0	330.9	336.6
350°C	355.3	360.4	365.5	370.4	375.3	380.0
400°C	404.3	408.6	412.8	416.9	421.0	425.0

Table 69. Cladding-to-Basket Delta T in Argon; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	28.4	52.3	73.0	91.3	107.8	122.9
50°C	24.3	45.3	63.9	80.6	95.9	109.9
100°C	18.0	34.3	49.2	62.9	75.7	87.6
150°C	13.6	26.3	38.1	49.3	59.8	69.8
200°C	10.5	20.4	29.9	38.9	47.6	55.9
250°C	8.2	16.1	23.7	31.0	38.1	45.0
300°C	6.5	12.8	19.0	25.0	30.9	36.6
350°C	5.3	10.4	15.5	20.4	25.3	30.0
400°C	4.3	8.6	12.8	16.9	21.0	25.0

5.4.3.3.3 9x9 Rod Configuration

The peak cladding temperature results for the 9x9 array representation with each channel size are summarized in Table 70 through Table 73.

Comparing the results for argon fill gas for the no-channel and the 80-mil channel cases, the peak cladding temperatures decrease by a maximum of 12°C by removing the channel. Comparing Table 28 and Table 70 for the no-channel geometry with helium versus argon fill gas, peak cladding temperatures decrease by a maximum of 65°C by changing to a helium fill gas. Comparing Table 22 and Table 72 for the 80-mil channel geometry with helium versus argon fill gas, peak cladding temperatures decrease by a maximum of 78°C by adding a helium fill gas.

Table 70. Peak Cladding Temperatures in Argon; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	50.9	72.8	91.8	108.7	124.0	137.9
50°C	71.9	90.9	107.9	123.1	137.1	149.9
100°C	115.9	130.3	143.6	155.8	167.3	178.0
150°C	161.8	172.8	183.1	192.9	202.2	211.1
200°C	208.9	217.4	225.5	233.3	240.8	248.0
250°C	256.9	263.5	269.9	276.2	282.2	288.1
300°C	305.4	310.7	315.8	320.9	325.8	330.6
350°C	354.3	358.6	362.7	366.8	370.9	374.8
400°C	403.5	407.0	410.4	413.8	417.2	420.5

Table 71. Cladding-to-Basket Delta T in Argon; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	25.9	47.8	66.8	83.7	99.0	112.9
50°C	21.9	40.9	57.9	73.1	87.1	99.9
100°C	15.9	30.3	43.6	55.8	67.3	78.0
150°C	11.8	22.8	33.1	42.9	52.2	61.1
200°C	8.9	17.4	25.5	33.3	40.8	48.0
250°C	6.9	13.5	19.9	26.2	32.2	38.1
300°C	5.4	10.7	15.8	20.9	25.8	30.6
350°C	4.3	8.6	12.7	16.8	20.9	24.8
400°C	3.5	7.0	10.4	13.8	17.2	20.5

Table 72. Peak Cladding Temperatures in Argon; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	54.1	78.4	99.4	117.9	134.6	149.7
50°C	74.9	96.3	115.2	132.1	147.5	161.6
100°C	118.5	135.1	150.2	164.1	176.9	189.0
150°C	163.9	176.8	188.8	200.1	210.8	220.9
200°C	210.7	220.8	230.4	239.5	248.3	256.7
250°C	258.3	266.3	274.0	281.4	288.6	295.6
300°C	306.6	313.0	319.2	325.3	331.2	337.0
350°C	355.3	360.5	365.6	370.6	375.5	380.3
400°C	404.4	408.6	412.9	417.0	421.1	425.1

Table 73. Cladding-to-Basket Delta T in Argon; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	29.1	53.4	74.4	92.9	109.6	124.7
50°C	24.9	46.3	65.2	82.1	97.5	111.6
100°C	18.5	35.1	50.2	64.1	76.9	89.0
150°C	13.9	26.8	38.8	50.1	60.8	70.9
200°C	10.7	20.8	30.4	39.5	48.3	56.7
250°C	8.3	16.3	24.0	31.4	38.6	45.6
300°C	6.6	13.0	19.2	25.3	31.2	37.0
350°C	5.3	10.5	15.6	20.6	25.5	30.3
400°C	4.4	8.6	12.9	17.0	21.1	25.1

5.4.4 Water Rod Effect on Peak Cladding Temperature

Some BWR fuel assemblies have a water rod substituted for one or more fuel rods. A water rod is a cladding tube which does not contain any fuel and functions as a water conduit. Early 8x8 designs used between one and four water rods in an assembly, and the early 9x9 designs used between two and five water rods in an assembly. Later designs for each used a single over sized water tube to replace multiple central fuel rods. The effect this has is to shift the heat generation to the remaining pins and to remove one or more heat generating pins from the center portion of the fuel assembly. Since the peak cladding temperature is typically at the centermost fuel rod, this could significantly reduce the peak cladding temperatures experienced by BWR fuel assembly designs which have a water rod.

Since the single oversized water rod geometry of the 8x8 and 9x9 assemblies displaces the largest number of central fuel rods, it will have the greatest reduction in peak cladding temperature and will provide a lower bound to all water rod configurations' effect on peak cladding temperatures. Thus,

only the oversized water rod designs will be considered for the 8x8 and 9x9 arrays.

BWR fuel assemblies historically come in two basic configurations: C-Lattice, which is completely symmetrical and in which the water rod is positioned at the center of a 7x7, 8x8, or 9x9 array, and D-Lattice, which is not completely symmetrical and in which the water rod is placed diagonally adjacent to the centermost fuel rod in the assembly. In terms of peak cladding temperature experienced by the fuel, the two configurations are bounded by the C-Lattice configuration, since it positions all of the heat generating fuel pins closer to the outer edge of the fuel assembly. The D-Lattice configuration leaves a fuel pin at the centermost location of a 7x7, 8x8, or 9x9 BWR fuel assembly, which is the least efficient heat rejection position for a fuel pin within the fuel assembly. Therefore, the C-Lattice configuration will have the largest impact (i.e., the largest temperature reduction) upon peak cladding temperature. Thus, only the C-Lattice configuration will be considered for the purpose of bounding the impact of a water rod configuration upon peak cladding temperatures.

The C-Lattice water rod configuration is represented in ANSYS using the base BWR configurations and replacing the center fuel pin with a water rod (in the 7x7 case), the center four fuel pins with a single oversized water rod (in the 8x8 case), or the center nine fuel pins with a single oversized water rod (in the 9x9 case). The heat generation in the uranium pellets is then adjusted to be based on the remaining fuel pins. These water rod BWR fuel assemblies were then solved for the base set of 54 basket wall temperature and assembly heat generation boundary condition combinations, with and without a channel, for each of the four fill gas environments. These results are documented in output files as listed in Attachment II.

Comparing solution results with the corresponding results generated for the base 7x7 BWR fuel assembly, the peak cladding temperatures calculated for the water rod 7x7 BWR fuel assembly are 0.0°C to 1.5°C less than the peak cladding temperatures calculated for the base 7x7 BWR fuel assembly. This is a relatively small reduction in peak cladding temperature. Thus, using the base 7x7 BWR assembly results to characterize 7x7 BWR assemblies with water rods is conservative.

Peak cladding temperature reduction is much greater for the 8x8 and 9x9 assemblies with a single oversized water rod, due to the displacement of the centermost fuel pins in the array, which has the effect of significantly shifting the interior heat generation toward the edge of the assembly. The 8x8 and 9x9 assemblies have a larger external heat transfer surface area than the 7x7 assembly, since the heat generation is spread to 12 more fuel pins for the 8x8 assembly and 24 more fuel pins for the 9x9 assembly (which reduces the individual fuel pin heat generation rate for equivalent assembly powers). The greatest peak cladding temperature reduction can be seen with the results for the vacuum environment, since there is no fill gas present to provide a conduction path for heat removal. The 8x8 and 9x9 assemblies have a slightly lower heat generation per fuel rod than that of the 7x7 assembly, and an additional rod surface area in each row which is exposed to the basket wall. Thus, the removal of four central fuel pins for the 8x8, and nine central fuel pins for the 9x9, provides a greater reduction in heat generation in the center and provides more radiation surface area at the

exterior of the fuel assembly.

Table 74 through Table 81 summarize the peak cladding temperature results for the 8x8 fuel assembly in each of the fill gas environments, with no channel and 80-mil channel. Table 82 through Table 89 summarize the peak cladding temperature results for the 9x9 fuel assembly in each of the fill gas environments, with no channel and 80-mil channel.

In helium fill gas, the peak cladding temperatures calculated for the water rod 8x8 BWR fuel assembly are 0.3°C to 5.4°C less than those calculated for the base 8x8 fuel assembly. In the vacuum environment they are 0.6°C to 19.2°C less, in nitrogen fill gas they are 0.7°C to 13.7°C less, and in argon fill gas they are 0.7°C to 15.1°C less than those calculated for the base 8x8 fuel assembly in each of the respective fill gas environments. In each fill gas environment, the no-channel and 80-mil channel cases displayed the same peak cladding temperature reduction.

In helium fill gas, the peak cladding temperatures calculated for the water rod 9x9 BWR fuel assembly are 0.5°C to 8.3°C less than those calculated for the base 9x9 fuel assembly. In the vacuum environment they are 0.9°C to 20.5°C less, in nitrogen fill gas they are 0.7°C to 17.2°C less, and in argon fill gas they are 0.8°C to 18.2°C less than those calculated for the base 9x9 fuel assembly in each of the respective fill gas environments. In each fill gas environment, the no-channel and 80-mil channel cases displayed the same peak cladding temperature reduction.

The 8x8 and 9x9 BWR fuel assembly designs which use from one to five fuel-rod-sized water rods will have peak cladding temperatures which fall in between those of the base cases (as the upper bound) and those of the oversized water rod cases (as the lower bound). Thus, using the base 8x8 and 9x9 BWR fuel assembly results to characterize 8x8 and 9x9 BWR assemblies with water rods is conservative.

Table 74. Peak Cladding Temperatures in Helium; GE 8x8 GE-9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	32.2	39.2	46.0	52.6	59.1	65.5
50°C	56.5	62.9	69.1	75.1	81.1	86.9
100°C	105.4	110.6	115.8	120.9	125.8	130.7
150°C	154.4	158.8	163.1	167.4	171.6	175.7
200°C	203.7	207.4	211.0	214.6	218.1	221.6
250°C	253.1	256.2	259.3	262.3	265.3	268.3
300°C	302.6	305.3	307.9	310.5	313.0	315.6
350°C	352.2	354.5	356.7	358.9	361.1	363.2
400°C	402.0	403.9	405.8	407.7	409.7	411.6

Table 75. Peak Cladding Temperatures in Helium; GE 8x8 GE-9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	32.1	39.0	45.8	52.4	58.9	65.2
50°C	56.5	62.9	69.2	75.3	81.3	87.2
100°C	105.5	111.0	116.4	121.6	126.8	131.9
150°C	154.7	159.4	164.0	168.6	173.0	177.5
200°C	204.1	208.1	212.1	216.0	219.9	223.7
250°C	253.5	257.0	260.4	263.8	267.2	270.6
300°C	303.0	306.1	309.0	312.0	314.9	317.9
350°C	352.6	355.2	357.8	360.4	362.9	365.5
400°C	402.3	404.6	406.9	409.2	411.5	413.8

Table 76. Peak Cladding Temperatures in a Vacuum; GE 8x8 GE-9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	52.6	74.7	93.2	109.3	123.6	136.6
50°C	72.5	91.3	107.7	122.1	135.2	147.1
100°C	115.3	129.0	141.4	152.9	163.5	173.4
150°C	160.8	170.8	180.3	189.2	197.6	205.6
200°C	207.9	215.4	222.6	229.5	236.1	242.5
250°C	255.9	261.6	267.2	272.6	277.8	282.9
300°C	304.6	309.0	313.4	317.6	321.8	325.9
350°C	353.6	357.1	360.6	364.0	367.4	370.7
400°C	402.9	405.8	408.6	411.4	414.1	416.9

Table 77. Peak Cladding Temperatures in a Vacuum; GE 8x8 GE-9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	63.3	91.8	114.9	134.6	151.8	167.1
50°C	81.5	106.4	127.3	145.3	161.3	175.8
100°C	121.8	140.5	157.0	171.9	185.4	197.8
150°C	165.5	179.6	192.4	204.3	215.5	225.9
200°C	211.4	222.0	232.0	241.5	250.5	259.1
250°C	258.6	266.8	274.6	282.1	289.4	296.4
300°C	306.6	313.0	319.3	325.3	331.2	336.9
350°C	355.2	360.3	365.3	370.2	375.0	379.7
400°C	404.2	408.3	412.4	416.4	420.3	424.2

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Table 78. Peak Cladding Temperatures in Nitrogen; GE 8x8 GE-9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	43.4	59.7	74.5	88.0	100.4	112.0
50°C	65.6	79.7	92.7	104.7	115.9	126.4
100°C	111.4	122.0	132.0	141.5	150.5	159.0
150°C	158.5	166.6	174.3	181.8	188.9	195.9
200°C	206.5	212.7	218.8	224.7	230.4	236.0
250°C	255.0	259.9	264.7	269.4	274.0	278.5
300°C	304.0	307.9	311.8	315.5	319.3	323.0
350°C	353.2	356.4	359.5	362.6	365.7	368.7
400°C	402.6	405.3	407.9	410.4	413.0	415.5

Table 79. Peak Cladding Temperatures in Nitrogen; GE 8x8 GE-9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	46.4	65.3	82.2	97.6	111.7	124.7
50°C	68.5	85.1	100.2	114.1	126.9	138.9
100°C	113.9	126.8	138.8	150.0	160.7	170.7
150°C	160.6	170.7	180.2	189.3	198.0	206.3
200°C	208.2	216.2	223.8	231.1	238.2	245.1
250°C	256.5	262.8	268.9	274.9	280.7	286.4
300°C	305.2	310.3	315.3	320.2	324.9	329.6
350°C	354.2	358.4	362.5	366.5	370.5	374.4
400°C	403.5	407.0	410.4	413.8	417.1	420.4

Table 80. Peak Cladding Temperatures in Argon; GE 8x8 GE-9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	45.4	63.2	79.0	93.3	106.3	118.3
50°C	67.1	82.4	96.3	109.0	120.8	131.7
100°C	112.3	123.7	134.3	144.3	153.8	162.7
150°C	159.0	167.6	175.8	183.7	191.2	198.4
200°C	206.8	213.4	219.8	225.9	231.9	237.7
250°C	255.3	260.4	265.4	270.3	275.1	279.7
300°C	304.1	308.2	312.2	316.1	320.0	323.8
350°C	353.3	356.6	359.8	363.0	366.2	369.3
400°C	402.7	405.4	408.1	410.7	413.3	415.9

Table 81. Peak Cladding Temperatures in Argon; GE 8x8 GE-9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	49.5	70.5	88.9	105.3	120.2	133.9
50°C	70.9	89.2	105.7	120.5	134.2	146.8
100°C	115.4	129.5	142.4	154.5	165.8	176.4
150°C	161.6	172.4	182.6	192.3	201.6	210.3
200°C	208.8	217.3	225.4	233.2	240.7	247.9
250°C	256.9	263.6	270.1	276.3	282.4	288.4
300°C	305.5	310.8	316.0	321.2	326.2	331.0
350°C	354.4	358.8	363.0	367.2	371.3	375.4
400°C	403.6	407.2	410.8	414.2	417.7	421.1

Table 82. Peak Cladding Temperatures in Helium; ANF-9X 9x9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	32.0	38.8	45.4	51.9	58.3	64.5
50°C	56.3	62.6	68.6	74.6	80.4	86.1
100°C	105.3	110.4	115.5	120.5	125.4	130.2
150°C	154.4	158.7	163.0	167.2	171.3	175.4
200°C	203.7	207.3	210.9	214.5	218.0	221.4
250°C	253.1	256.2	259.2	262.2	265.2	268.2
300°C	302.6	305.2	307.8	310.4	312.9	315.5
350°C	352.2	354.4	356.6	358.8	361.0	363.2
400°C	401.9	403.9	405.8	407.7	409.6	411.5

Table 83. Peak Cladding Temperatures in Helium; ANF-9X 9x9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	31.7	38.3	44.7	51.0	57.1	63.2
50°C	56.2	62.2	68.2	74.0	79.7	85.3
100°C	105.3	110.4	115.5	120.6	125.5	130.4
150°C	154.5	159.0	163.4	167.7	172.0	176.2
200°C	203.9	207.7	211.5	215.3	219.0	222.7
250°C	253.4	256.7	260.0	263.2	266.5	269.7
300°C	302.9	305.8	308.7	311.5	314.3	317.1
350°C	352.5	355.0	357.5	359.9	362.4	364.8
400°C	402.2	404.4	406.6	408.8	411.0	413.2

Table 84. Peak Cladding Temperatures in a Vacuum; ANF-9X 9x9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	53.3	75.8	94.6	110.9	125.4	138.5
50°C	73.0	92.3	108.9	123.5	136.8	148.9
100°C	115.7	129.6	142.3	154.0	164.7	174.7
150°C	161.0	171.3	180.9	189.9	198.5	206.6
200°C	208.0	215.7	223.0	230.0	236.7	243.2
250°C	256.0	261.8	267.5	272.9	278.3	283.4
300°C	304.6	309.1	313.5	317.9	322.1	326.2
350°C	353.6	357.2	360.7	364.2	367.6	370.9
400°C	402.9	405.8	408.6	411.4	414.2	416.9

Table 85. Peak Cladding Temperatures in a Vacuum; ANF-9X 9x9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	61.2	88.5	110.8	129.8	146.5	161.4
50°C	79.8	103.5	123.5	140.9	156.4	170.4
100°C	120.5	138.2	154.0	168.2	181.1	193.1
150°C	164.6	177.8	190.0	201.3	211.9	221.8
200°C	210.6	220.7	230.1	239.0	247.6	255.7
250°C	258.0	265.7	273.0	280.1	287.0	293.6
300°C	306.2	312.2	318.0	323.6	329.1	334.5
350°C	354.9	359.6	364.3	368.8	373.3	377.7
400°C	403.9	407.7	411.5	415.2	418.9	422.5

Table 86. Peak Cladding Temperatures in Nitrogen; ANF-9X 9x9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	43.7	60.2	75.2	88.8	101.4	113.0
50°C	65.8	80.2	93.3	105.5	116.8	127.4
100°C	111.6	122.4	132.6	142.2	151.3	160.0
150°C	158.6	166.9	174.8	182.4	189.6	196.6
200°C	206.6	213.0	219.1	225.1	230.9	236.6
250°C	255.1	260.1	265.0	269.8	274.4	279.0
300°C	304.0	308.0	311.9	315.8	319.6	323.3
350°C	353.3	356.5	359.6	362.8	365.9	368.9
400°C	402.7	405.3	407.9	410.5	413.1	415.6

Table 87. Peak Cladding Temperatures in Nitrogen; ANF-9X 9x9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	46.0	64.5	81.2	96.3	110.3	123.2
50°C	68.1	84.4	99.3	113.0	125.8	137.6
100°C	113.7	126.3	138.2	149.3	159.8	169.7
150°C	160.4	170.3	179.8	188.7	197.3	205.5
200°C	208.1	215.9	223.4	230.7	237.7	244.5
250°C	256.4	262.6	268.6	274.5	280.3	285.8
300°C	305.1	310.1	315.0	319.8	324.5	329.1
350°C	354.1	358.2	362.2	366.2	370.1	373.9
400°C	403.4	406.8	410.2	413.5	416.7	420.0

Table 88. Peak Cladding Temperatures in Argon; ANF-9X 9x9 Fuel Assembly with Water Rod and No Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	45.8	63.9	79.9	94.4	107.5	119.7
50°C	67.5	83.1	97.2	110.1	122.0	133.0
100°C	112.6	124.2	135.0	145.2	154.8	163.8
150°C	159.2	168.0	176.4	184.3	192.0	199.3
200°C	207.0	213.7	220.2	226.4	232.5	238.4
250°C	255.4	260.6	265.7	270.7	275.5	280.2
300°C	304.2	308.3	312.4	316.4	320.3	324.1
350°C	353.4	356.7	360.0	363.2	366.4	369.5
400°C	402.7	405.5	408.1	410.8	413.4	416.0

Table 89. Peak Cladding Temperatures in Argon; ANF-9X 9x9 Fuel Assembly with Water Rod and 80-mil Channel

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	49.1	69.9	88.1	104.4	119.2	132.8
50°C	70.6	88.7	105.0	119.7	133.3	145.8
100°C	115.2	129.1	142.0	153.9	165.1	175.6
150°C	161.4	172.2	182.3	191.9	201.0	209.7
200°C	208.7	217.1	225.1	232.8	240.2	247.4
250°C	256.8	263.4	269.8	276.0	282.0	287.9
300°C	305.4	310.7	315.8	320.9	325.8	330.6
350°C	354.3	358.6	362.8	366.9	371.0	375.0
400°C	403.6	407.1	410.5	414.0	417.4	420.7

5.4.5 Effect of Cladding Oxidation Layer Thickness on Peak Cladding Temperature

The cladding oxidation layer thickness has two effects on the heat transfer modes of spent nuclear fuel, the first is a change in cladding surface emissivity and the second is as an insulator. As presented by Equation 8 and Assumption 3.4: 1) the emissivity of spent nuclear fuel cladding changes very slowly with oxide thickness, 2) the oxide layer typically grows at a modest rate, 3) the oxide layer is typically very small (i.e., 2 to 4 mils or less), and 4) the oxide layer will have a very small or negligible effect upon the resulting peak cladding temperatures experienced by the fuel. The variation of cladding emissivity is discussed in the next section.

Thus, the focus of this section is the insulation effect that a growing cladding oxide layer will have on the prediction of peak cladding temperatures. Given the thermal conductivity values of zirconium dioxide in Table 3, and the range of conditions calculated by ANSYS (i.e., 100 to 600 W/assembly), the temperature drop across the oxide layer can be determined with Equation 3.27 on p. 91 of Ref. 19, derived for an annular thickness of material:

$$T_i - T_o = \frac{Q \cdot \ln\left(\frac{R_o}{R_i}\right)}{2 \cdot \pi \cdot L \cdot k}$$

Equation 9

Where: T_i is the temperature at the inner radius of the oxide layer
 T_o is the temperature at the outer radius of the oxide layer
 Q is the fuel rod heat generation rate
 R_i is the inner radius of the oxide layer
 R_o is the outer radius of the oxide layer
 L is the active length of the fuel assembly
 k is the effective thermal conductivity of the oxide layer

The oxide layer thickness can be defined:

$$\delta = R_o - R_i$$

Equation 10

Rewriting Equation 9:

$$T_i - T_o = \frac{Q \cdot \ln\left(1 + \frac{\delta}{R_i}\right)}{2 \cdot \pi \cdot L \cdot k}$$

Equation 11

Table 90 lists the results of Equation 11, evaluated with fuel rod and cladding dimensions from Table 12, and oxide layer thickness values of 4 mils, 8 mils, and 12 mils. For this range of oxide layer thickness values, peak cladding temperature predictions will vary by less than 0.002°C . These temperature drops do not have a significant impact upon predicting peak cladding temperatures.

Table 90. Oxide Layer Temperature Drop Versus Oxide Layer Thickness

Oxide Layer Thickness (in.)	Delta Temperature Range ($^{\circ}\text{C}$)
0.004 in.	$7.48 \cdot 10^{-5}$ to $5.94 \cdot 10^{-4}$
0.008 in.	$1.48 \cdot 10^{-4}$ to $1.18 \cdot 10^{-3}$
0.012 in.	$2.21 \cdot 10^{-4}$ to $1.76 \cdot 10^{-3}$

5.4.6 Effect of Emissivity Variations on Peak Cladding Temperature

The emissivity of both the fuel cladding and the basket wall can vary due to any number of items including, but not limited to, variances in the oxide layer, surface finish and fabrication variances, and material flaws. These variances in turn can alter the radiation heat transfer characteristics of the surfaces and therefore change the peak cladding temperatures. The post-test analysis for the REA 2023 BWR spent fuel storage cask, Ref. 22, examined the effect of surface emissivity variations. The analysis and conclusion that the peak cladding temperature is relatively insensitive to small changes in emissivity is documented on pp. 2.5, 5.64, 5.65, 5.117, 5.118, and 5.119 of Ref. 22.

Figure 1 shows the effect of large variation in basket wall emissivity on peak cladding temperature, for an example case with all other conditions fixed. The output file for this calculation is included as documented in Attachment II.

Figure 1. Effect of Basket Wall Emissivity Variation on Peak Cladding Temperature in a 7x7 Fuel Assembly Quarter-Symmetry Representation; Argon Fill Gas; Fuel Assembly Heat Output = 600 W; Fuel Basket Surface Temperature = 25°C

5.4.7 Effect of Basket Wall Temperature Gradient on Peak Cladding Temperature

The effective thermal conductivity calculation assumes a uniform temperature over the basket wall at any given time (see Assumption 3.19); however, this condition is rarely encountered in a storage cask. A temperature gradient exists from one corner of the basket to another. This variance can change the peak cladding temperatures. The post-test analysis for the REA 2023 BWR spent fuel storage cask, Ref. 22, examined the effect of a temperature gradient across the basket. The analysis and conclusions concerning the effect of basket wall temperature gradients on peak cladding temperature is documented on pp. 5.61 and 5.62 of Ref. 22.

5.5 WOOTON-EPSTEIN COMPARISON

To check the base results of Section 5.4, the Wooton-Epstein correlation (Ref. 26) was applied for each of the cases. This empirically-derived correlation was shown to be conservative for helium fill gas on p. II 3.6-18 of Ref. 5. The Wooton-Epstein relationship is described by Equation 12.

$$q'' = \sigma \frac{C_1}{\frac{1}{\epsilon_{cl}} + \frac{1}{\epsilon_{ba}} - 1} (T_{cl}^4 - T_{ba}^4) + C_2 (T_{cl} - T_{ba})^{\frac{4}{3}}$$

Equation 12

Where:

- q'' = heat flux from spent nuclear fuel, based on the basket inner surface heat transfer area (Btu/hr-ft²)
- C_1 = constant depending on the spent fuel rod array size,
= $4N/(N+1)^2$ for odd N
= $4/(N+2)$ for even N
- C_2 = regression constant = 0.118
- N = number of fuel pins in a single row of a square spent fuel assembly
- T_{cl} = cladding surface temperature (absolute scale, °R)
- T_{ba} = basket surface temperature (absolute scale, °R)
- ϵ_{cl} = cladding surface emissivity
- ϵ_{ba} = basket surface emissivity
- σ = Stefan-Boltzmann constant (Btu/hr-ft²·°R⁴)

The relationship has two terms – one representing radiation heat transfer, and one representing gaseous convection in an array of heat-producing rods. Because the cladding temperature appears in both terms, the relation must be solved iteratively. A complete description of the correlation development is given in the Wooton-Epstein paper (Ref. 26). For this calculation, the same material properties and conditions were assumed with the Wooton-Epstein relation that were used in the ANSYS BWR representation:

Stefan-Boltzmann constant	1.714·10 ⁻⁹ (Btu/hr-ft ² ·°R ⁴)
Cladding emissivity	0.806 (Table 5)
Basket emissivity	0.800 (Table 1)
Basket cell width	152.4 mm (6.0 inches, Assumption 3.14)
Fuel assembly array size (N)	7, 8, or 9 rods (Assumptions 3.9, 3.10, and 3.11)
Assembly active length	3657.6 mm (144.0 inches) for the 7x7 configuration (Table 12 and Table 13) 3810.0 mm (150.0 inches) for the 8x8 and 9x9 configurations (Table

Axial peaking factor 14 through Table 17)
1.25 (Assumption 3.17)

Table 91 through Table 96 summarize the peak cladding temperature results and the cladding-to-basket temperature drops (ΔT) of the Wooton-Epstein calculation for the 7x7, 8x8, and 9x9 configurations. The values in Table 91 through Table 96 are those which would be reported for any BWR fuel assembly for the corresponding conditions (i.e., basket temperature, decay heat powers, and material emissivity values). The Wooton-Epstein correlation does not contain any terms which account for a channel, water rod positions in the central region of the fuel assembly, or part-length fuel rods.

Table 91. Peak Cladding Temperatures from the Wooton-Epstein Correlation; GE-2 7x7 Fuel Assembly

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	39.4	50.5	60.2	69.2	77.5	85.3
50°C	63.0	73.2	82.3	90.7	98.5	105.9
100°C	110.4	119.0	126.7	134.0	140.8	147.2
150°C	158.2	165.3	171.8	177.9	183.7	189.3
200°C	206.4	212.2	217.6	222.7	227.6	232.3
250°C	255.1	259.7	264.1	268.4	272.5	276.5
300°C	304.0	307.8	311.4	314.9	318.3	321.6
350°C	353.2	356.3	359.2	362.1	365.0	367.7
400°C	402.6	405.1	407.6	410.0	412.3	414.6

Table 92. Cladding-to-Basket ΔT from the Wooton-Epstein Correlation; GE-2 7x7 Fuel Assembly

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	14.4	25.5	35.2	44.2	52.5	60.3
50°C	13.0	23.2	32.3	40.7	48.5	55.9
100°C	10.4	19.0	26.7	34.0	40.8	47.2
150°C	8.2	15.3	21.8	27.9	33.7	39.3
200°C	6.4	12.2	17.6	22.7	27.6	32.3
250°C	5.1	9.7	14.1	18.4	22.5	26.5
300°C	4.0	7.8	11.4	14.9	18.3	21.6
350°C	3.2	6.3	9.2	12.1	15.0	17.7
400°C	2.6	5.1	7.6	10.0	12.3	14.6

Table 93. Peak Cladding Temperatures from the Wooton-Epstein Correlation; GE-5 8x8 Fuel Assembly

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	39.5	50.4	60.2	69.0	77.3	85.2
50°C	63.1	73.3	82.4	90.7	98.6	106.0
100°C	110.6	119.2	127.0	134.3	141.1	147.6
150°C	158.4	165.6	172.2	178.4	184.3	189.9
200°C	206.6	212.5	218.0	223.2	228.2	233.0
250°C	255.2	260.0	264.6	268.9	273.1	277.2
300°C	304.2	308.1	311.8	315.4	318.9	322.3
350°C	353.3	356.5	359.6	362.6	365.5	368.4
400°C	402.7	405.3	407.9	410.4	412.8	415.2

Table 94. Cladding-to-Basket Delta T from the Wooton-Epstein Correlation; GE-5 8x8 Fuel Assembly

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	14.5	25.4	35.2	44.0	52.3	60.2
50°C	13.1	23.3	32.4	40.7	48.6	56.0
100°C	10.6	19.2	27.0	34.3	41.1	47.6
150°C	8.4	15.6	22.2	28.4	34.3	39.9
200°C	6.6	12.5	18.0	23.2	28.2	33.0
250°C	5.2	10.0	14.6	18.9	23.1	27.2
300°C	4.2	8.1	11.8	15.4	18.9	22.3
350°C	3.3	6.5	9.6	12.6	15.5	18.4
400°C	2.7	5.3	7.9	10.4	12.8	15.2

Table 95. Peak Cladding Temperatures from the Wooton-Epstein Correlation; ANF-JP 9x9 Fuel Assembly

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	40.0	51.4	61.4	70.5	79.0	87.1
50°C	63.7	74.3	83.7	92.3	100.4	108.0
100°C	111.2	120.3	128.4	136.0	143.1	149.9
150°C	159.0	166.6	173.6	180.1	186.3	192.2
200°C	207.2	213.5	219.3	224.9	230.2	235.2
250°C	255.7	260.9	265.7	270.4	274.9	279.2
300°C	304.6	308.8	312.8	316.7	320.5	324.2
350°C	353.7	357.1	360.5	363.7	366.9	370.0
400°C	403.0	405.8	408.6	411.3	414.0	416.6

Table 96. Cladding-to-Basket Delta T from the Wooton-Epstein Correlation; ANF-JP 9x9 Fuel Assembly

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	15.0	26.4	36.4	45.5	54.0	62.1
50°C	13.7	24.3	33.7	42.3	50.4	58.0
100°C	11.2	20.3	28.4	36.0	43.1	49.9
150°C	9.0	16.6	23.6	30.1	36.3	42.2
200°C	7.2	13.5	19.3	24.9	30.2	35.2
250°C	5.7	10.9	15.7	20.4	24.9	29.2
300°C	4.6	8.8	12.8	16.7	20.5	24.2
350°C	3.7	7.1	10.5	13.7	16.9	20.0
400°C	3.0	5.8	8.6	11.3	14.0	16.6

The Wooton-Epstein correlation is mostly conservative, compared to the ANSYS BWR representations presented in Section 5.4, for the helium fill gas cases. However, for the vacuum, nitrogen, and argon cases, the Wooton-Epstein correlation is not conservative. This is due to the fact that the Wooton-Epstein correlation was developed from experimental data based on air with convection and radiation heat transfer in a 17x18 rod array. The ANSYS representations do not include the convection heat transfer mode (even with this difference, the Wooton-Epstein correlation is still conservative relative to the helium fill gas cases). The vacuum case does not need to account for conduction or convection heat transfer modes. However, the same temperature trends with heat load and basket wall temperature variations are observed with the peak cladding temperatures predicted by the Wooton-Epstein correlation as with those predicted by the spent nuclear fuel representation. Similar behavior is also observed for the cladding-to-basket temperature drop.

5.6 EFFECTIVE THERMAL CONDUCTIVITY

In the waste package thermal representation, the fuel assembly is represented by a solid square with smeared material properties. While the density and specific heat of the region can be calculated based on a weighted average of the materials present (Assumptions 3.25 and 3.26), the thermal conductivity of the fuel assembly area must take into account convection, conduction, and radiation heat transfer across the assembly. As observed in the previous sections, a single value for an effective thermal conductivity is not sufficient, due to the radiation-induced non-linearities present.

5.6.1 Effective Thermal Conductivity Method Development

The purpose of the effective thermal conductivity is to relate the temperature drop of a homogeneous heat-generating square to the temperature drop across an actual assembly. Given the heat load and temperature drop calculated with a discrete representation of a fuel assembly, we wish to calculate here the effective thermal conductivity of the homogenous heat-generating square. An analytical solution of the heat diffusion equation for a steady temperature in a rectangle with heat generation is given by Equation 5.5-6 in Carslaw and Jaeger (p. 171, Ref. 6). Since we are considering a square with isotropic thermal conductivity, $a=b$ and $k=1$, the correlation can be simplified to Equation 13 below.

$$T(x,y) = \frac{q'''(a^2 - x^2)}{2k} - \frac{16q'''a^2}{k\pi^3} \sum_{n=0}^{\infty} \frac{(-1)^n \cos[(2n+1)\pi x/2a] \cosh[(2n+1)\pi y/2a]}{(2n+1)^3 \cosh[(2n+1)\pi/2]}$$

Equation 13

In Equation 13, q''' is the volumetric heat generation, k is the conductivity, and a is one-half of the basket cell width. We are interested in the maximum temperature, which occurs at $x=y=0$; therefore, Equation 13 can be reduced to:

$$T(0,0) = \frac{q'''a^2}{2k} - \frac{16q'''a^2}{k\pi^3} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)^3 \cosh[(2n+1)\pi/2]}$$

Equation 14

Because of the strong divergence of cosh, the sum converges quickly. Evaluating the sum:

$$T(0,0) = \frac{q'''a^2}{k} (0.29468541)$$

Equation 15

Assuming superposition (non-zero wall temperature T_s) and substituting $q'''=Q/4a^2L_a$ gives:

$$T_o = \frac{Q}{4 L_a k} (0.29468541) + T_s$$

Equation 16

Finally, solving for an effective thermal conductivity (k_e) results in Equation 17:

$$k_e = \frac{Q}{4 L_a (T_o - T_s)} (0.29468541)$$

Equation 17

Where:

- Q = Assembly heat generation (W)
- L_a = Assembly active length (meters)
- T_o = Center temperature (peak cladding)
- T_s = Surface temperature (basket wall)

As a reality check to Equation 17, an analytical solution for the effective thermal conductivity of a homogeneous heat-generating cylinder (circular cross section) can be derived from Equation 3.53 on p. 107 of Ref. 19. This equation for the temperature distribution of a homogeneous solid cylinder with volumetric heat generation q''' and radius r_o is repeated as Equation 18 below.

$$T(r) = \frac{q''' r_o^2}{4k} \left(1 - \frac{r^2}{r_o^2}\right) + T_s$$

Equation 18

Evaluating at $r=0$, substituting $q'''=Q/\pi r_o^2 L_a$, evaluating $1/\pi$ as 0.3183, and solving for effective thermal conductivity (k_e) results in Equation 19, which is very similar in form to Equation 17.

$$k_e = \frac{Q}{4 L_a (T_o - T_s)} (0.3183)$$

Equation 19

Comparison of Equation 17 and Equation 19 shows that a homogeneous heat generating square and a homogeneous heat generating cylinder (circle) have an 8 percent difference in their predicted effective thermal conductivities.

5.6.2 Effective Thermal Conductivity for Known Basket Wall Temperatures

5.6.2.1 7x7 Rod Configuration

Equation 17 is used to predict an effective thermal conductivity for each temperature and heat load used. The calculation is performed for the ANSYS 7x7 BWR representation solutions for both with and without a channel, each gas backfill environment, and for the Wooton-Epstein comparison provided in Section 5.5. The ANSYS output files for each fill gas and geometry are provided as indicated in Attachment II. These attachments also provide the information presented in Table 97 through Table 108. Table 97 through Table 104 summarize the effective thermal conductivity determination for the BWR fuel with and without a channel, in each of the four fill gases. Table 105 summarizes the effective thermal conductivity determination from the Wooton-Epstein correlation. The effective thermal conductivity is highly temperature dependent, but there is relatively little dependence on the assembly heat load. This is contrasted to the Wooton-Epstein results in which there is some dependence on heat load, though less evident than the temperature dependence.

Table 97. Effective Thermal Conductivity in Helium; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m-K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.306	0.310	0.315	0.320	0.324	0.329
50°C	0.338	0.342	0.347	0.351	0.356	0.360
100°C	0.410	0.415	0.419	0.423	0.428	0.432
150°C	0.495	0.499	0.504	0.508	0.512	0.516
200°C	0.594	0.598	0.602	0.606	0.611	0.615
250°C	0.708	0.712	0.716	0.720	0.724	0.728
300°C	0.838	0.842	0.846	0.850	0.854	0.858
350°C	0.991	0.995	0.999	1.003	1.007	1.011
400°C	1.144	1.147	1.150	1.154	1.157	1.160

Table 98. Effective Thermal Conductivity in Helium; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.310	0.314	0.318	0.323	0.327	0.331
50°C	0.337	0.342	0.346	0.350	0.354	0.358
100°C	0.398	0.402	0.406	0.410	0.414	0.418
150°C	0.467	0.471	0.475	0.479	0.483	0.486
200°C	0.545	0.549	0.553	0.557	0.561	0.564
250°C	0.634	0.638	0.642	0.646	0.649	0.653
300°C	0.735	0.739	0.742	0.746	0.749	0.753
350°C	0.853	0.857	0.861	0.865	0.869	0.872
400°C	0.966	0.969	0.972	0.975	0.978	0.981

Table 99. Effective Thermal Conductivity in a Vacuum; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.085	0.095	0.104	0.113	0.121	0.129
50°C	0.104	0.114	0.123	0.132	0.140	0.147
100°C	0.153	0.162	0.171	0.179	0.186	0.194
150°C	0.217	0.225	0.233	0.240	0.248	0.255
200°C	0.297	0.304	0.312	0.319	0.326	0.332
250°C	0.395	0.402	0.408	0.415	0.421	0.428
300°C	0.512	0.518	0.524	0.530	0.536	0.542
350°C	0.650	0.655	0.661	0.666	0.672	0.677
400°C	0.807	0.812	0.817	0.822	0.827	0.832

Table 100. Effective Thermal Conductivity in a Vacuum; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.065	0.074	0.083	0.091	0.098	0.105
50°C	0.079	0.088	0.097	0.104	0.112	0.119
100°C	0.114	0.123	0.131	0.138	0.146	0.153
150°C	0.160	0.168	0.175	0.183	0.190	0.196
200°C	0.218	0.225	0.232	0.239	0.245	0.252
250°C	0.288	0.295	0.302	0.308	0.314	0.320
300°C	0.373	0.379	0.385	0.391	0.397	0.403
350°C	0.472	0.478	0.484	0.489	0.494	0.500
400°C	0.587	0.592	0.597	0.602	0.607	0.612

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Table 101. Effective Thermal Conductivity in Nitrogen; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.122	0.131	0.138	0.146	0.153	0.159
50°C	0.145	0.153	0.160	0.167	0.174	0.181
100°C	0.199	0.206	0.213	0.220	0.227	0.234
150°C	0.267	0.274	0.281	0.288	0.294	0.300
200°C	0.352	0.358	0.364	0.371	0.377	0.383
250°C	0.453	0.459	0.465	0.471	0.477	0.482
300°C	0.574	0.579	0.585	0.590	0.595	0.601
350°C	0.713	0.719	0.724	0.729	0.734	0.738
400°C	0.870	0.874	0.879	0.883	0.888	0.893

Table 102. Effective Thermal Conductivity in Nitrogen; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.106	0.113	0.121	0.127	0.134	0.140
50°C	0.123	0.130	0.137	0.144	0.150	0.157
100°C	0.164	0.171	0.177	0.184	0.190	0.196
150°C	0.215	0.221	0.228	0.234	0.240	0.246
200°C	0.277	0.283	0.290	0.295	0.301	0.307
250°C	0.352	0.358	0.364	0.369	0.375	0.380
300°C	0.441	0.446	0.451	0.457	0.462	0.467
350°C	0.543	0.548	0.553	0.558	0.563	0.567
400°C	0.657	0.661	0.666	0.670	0.675	0.679

Table 103. Effective Thermal Conductivity in Argon; GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.111	0.120	0.128	0.135	0.143	0.150
50°C	0.132	0.141	0.149	0.156	0.164	0.171
100°C	0.185	0.193	0.200	0.208	0.215	0.221
150°C	0.252	0.259	0.266	0.273	0.280	0.286
200°C	0.335	0.342	0.348	0.355	0.361	0.367
250°C	0.436	0.442	0.448	0.454	0.460	0.466
300°C	0.555	0.561	0.566	0.572	0.577	0.583
350°C	0.694	0.699	0.704	0.709	0.714	0.719
400°C	0.850	0.855	0.860	0.864	0.869	0.874

Table 104. Effective Thermal Conductivity in Argon; GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.093	0.101	0.109	0.116	0.123	0.129
50°C	0.109	0.117	0.125	0.132	0.138	0.145
100°C	0.149	0.156	0.163	0.170	0.177	0.183
150°C	0.198	0.205	0.212	0.218	0.225	0.231
200°C	0.259	0.266	0.272	0.278	0.284	0.290
250°C	0.333	0.339	0.345	0.350	0.356	0.362
300°C	0.420	0.425	0.431	0.436	0.442	0.447
350°C	0.521	0.526	0.531	0.536	0.541	0.546
400°C	0.635	0.640	0.644	0.649	0.654	0.658

Table 105. Effective Thermal Conductivity; Wooton-Epstein Correlation for GE 7x7 GE-2 Fuel Assembly

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.174	0.198	0.214	0.228	0.240	0.250
50°C	0.193	0.217	0.234	0.248	0.260	0.270
100°C	0.242	0.265	0.282	0.297	0.309	0.320
150°C	0.307	0.330	0.347	0.361	0.374	0.385
200°C	0.392	0.414	0.430	0.444	0.456	0.468
250°C	0.498	0.519	0.535	0.548	0.560	0.571
300°C	0.628	0.648	0.663	0.676	0.687	0.698
350°C	0.784	0.803	0.817	0.830	0.841	0.851
400°C	0.968	0.986	1.000	1.012	1.023	1.033

Table 97 through Table 105 represent a fuel assembly average thermal conductivity which is to be applied to the entire fuel assembly in order to accurately predict peak cladding temperatures. If the heat load dependence for the effective thermal conductivity can be shown to be relatively small, then a more useful conductivity can be defined that is a function of temperature only. The heat load dependence is shown to be minor, relative to the temperature dependence, however, and we can assume the effective thermal conductivities to be dependent on only basket wall temperature, with a negligible impact on the ability to predict peak cladding temperatures. Thus, a temperature-dependent effective thermal conductivity can be determined for each basket temperature by averaging the values for each heat load condition. As described earlier, this temperature-dependent conductivity can then be used to predict peak cladding temperatures in the waste package representation, given a peak basket wall temperature and Equation 17.

Table 106 presents effective thermal conductivities for intact BWR spent nuclear fuel (calculated from pp. 3.6-1 and 3.2-2 of Ref. 17) and intact PWR spent nuclear fuel (p. 3.6-1, Ref. 16) which have been documented in past analyses. Table 106 also presents the averages over the heat loads

from Table 105 for the Wooton-Epstein correlation for the GE-2 7x7 BWR fuel assembly geometry. These values are included for reference only, and have no bearing on this calculation. They can be compared to the BWR effective thermal conductivities presented in Table 107 and Table 108 for each geometry and gas backfill environment analyzed in Section 5.4. Table 107 and Table 108 present the averages over the heat loads and backfill gas selections from Table 97 through Table 104.

The calculation of these values is performed in the files as listed in Attachment II. Notice that the 7x7 BWR assemblies are shorter than the 8x8 and 9x9 BWR assemblies (as indicated in Table 12 through Table 17) which accounts for some of the change in effective thermal conductivity values between BWR assembly types.

Table 106. Comparison of Reference Temperature-Dependent Effective Thermal Conductivities of 7x7 Rod Configurations (All Values are for Helium Backfill Gas Environment)

Basket Wall Temperature	Average k_s (Wooton-Epstein) (W/m·K)	Intact BWR Spent Nuclear Fuel k_s (Ref. 17) (W/m·K)	Intact PWR Spent Nuclear Fuel k_s (Ref. 16) (W/m·K)
25°C	0.217	0.457	0.431
50°C	0.237	0.498	0.466
100°C	0.286	0.593	0.544
150°C	0.351	0.705	0.634
200°C	0.434	0.837	0.737
250°C	0.538	0.991	0.855
300°C	0.667	1.168	0.990
350°C	0.821	1.372	1.143
400°C	1.004	1.605	1.316

Table 107. Comparison of Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.317	0.108	0.141	0.131
50°C	0.349	0.127	0.163	0.152
100°C	0.421	0.174	0.217	0.204
150°C	0.506	0.236	0.284	0.270
200°C	0.604	0.315	0.367	0.351
250°C	0.718	0.411	0.468	0.451
300°C	0.848	0.527	0.587	0.569
350°C	1.001	0.663	0.726	0.707
400°C	1.152	0.820	0.881	0.862

Table 108. Comparison of Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m-K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.320	0.086	0.124	0.112
50°C	0.348	0.100	0.140	0.128
100°C	0.408	0.134	0.180	0.166
150°C	0.477	0.179	0.231	0.215
200°C	0.555	0.235	0.292	0.275
250°C	0.644	0.305	0.366	0.347
300°C	0.744	0.388	0.454	0.434
350°C	0.863	0.486	0.555	0.534
400°C	0.973	0.600	0.668	0.647

In order to make the use of Equation 16 easier to calculate peak cladding temperatures with a given basket wall temperature, a polynomial curve fit has been performed for the 7x7 rod configuration in each environment and channel/no-channel geometry (Table 109). A polynomial curve fit for the Wooton-Epstein correlation is also included here for comparison. This equation can be substituted into Equation 16, which then provides peak cladding temperatures as a function of basket temperature (°C), thus eliminating the table lookup to determine a value for k_e .

$$k_e = c_0 + c_1 \cdot T + c_2 \cdot T^2 + c_3 \cdot T^3$$

Table 109. Correlation Coefficients for GE 7x7 GE-2 Fuel Assembly Effective Thermal Conductivity Based on Basket Wall Temperature

Conditions		c_0 (W/m-K)	c_1 (W/m-K ²)	c_2 (W/m-K ³)	c_3 (W/m-K ⁴)
Helium	No Channel	2.9198E-01	9.8704E-04	2.8707E-06	1.3338E-10
Helium	Channel	2.9887E-01	8.5758E-04	2.1827E-06	-2.3586E-10
Vacuum	No Channel	9.3230E-02	5.3444E-04	2.5436E-06	1.6585E-09
Vacuum	Channel	7.5344E-02	3.9434E-04	1.7597E-06	1.3297E-09
Nitrogen	No Channel	1.2426E-01	6.4089E-04	2.6389E-06	1.2335E-09
Nitrogen	Channel	1.1028E-01	4.9787E-04	1.9000E-06	8.6163E-10
Argon	No Channel	1.1441E-01	6.1579E-04	2.5782E-06	1.3946E-09
Argon	Channel	9.9149E-02	4.7378E-04	1.8254E-06	1.0354E-09
Wooton-Epstein		2.0134E-01	5.9307E-04	2.1704E-06	3.4045E-09

Figure 2 and Figure 3 provide a graphical comparison of the effective thermal conductivities of Table 107 and Table 108. The results in Table 106 through Table 108 indicate varying degrees of conservatism in determining an effective thermal conductivity.

Figure 2. Effective Thermal Conductivity for 7x7 BWR Spent Nuclear Fuel Without a Channel

Figure 3. Effective Thermal Conductivity for 7x7 BWR Spent Nuclear Fuel With a Channel

5.6.2.2 8x8 Rod Configuration

Equation 17 is used to predict an effective thermal conductivity for each temperature and heat load used. The calculation is performed for the ANSYS 8x8 BWR representation solutions for both with and without a channel, each gas backfill environment, and for the Wooton-Epstein comparison provided in Section 5.5. The ANSYS output files for each fill gas and geometry are provided as listed in Attachment II. These attachments also provide the information presented in Table 110 through Table 121. Table 110 through Table 117 summarize the effective thermal conductivity determination for the BWR fuel with and without a channel, in each of the four fill gases. Table 118 summarizes the effective thermal conductivity determination from the Wooton-Epstein correlation. The effective thermal conductivity is highly temperature dependent, but there is relatively little dependence on the assembly heat load. This is contrasted to the Wooton-Epstein results in which there is some dependence on heat load, though less evident than the temperature dependence.

Table 110. Effective Thermal Conductivity in Helium; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.295	0.299	0.304	0.308	0.312	0.316
50°C	0.325	0.329	0.333	0.337	0.341	0.345
100°C	0.391	0.395	0.399	0.403	0.407	0.411
150°C	0.469	0.472	0.476	0.480	0.484	0.487
200°C	0.557	0.561	0.564	0.568	0.572	0.575
250°C	0.658	0.661	0.665	0.668	0.672	0.675
300°C	0.772	0.775	0.778	0.782	0.785	0.788
350°C	0.904	0.908	0.912	0.915	0.919	0.922
400°C	1.033	1.036	1.038	1.041	1.044	1.046

Table 111. Effective Thermal Conductivity in Helium; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.299	0.303	0.306	0.310	0.314	0.318
50°C	0.324	0.328	0.332	0.335	0.339	0.343
100°C	0.380	0.384	0.387	0.391	0.394	0.398
150°C	0.443	0.447	0.450	0.454	0.457	0.461
200°C	0.514	0.518	0.521	0.525	0.528	0.531
250°C	0.595	0.598	0.601	0.605	0.608	0.611
300°C	0.685	0.688	0.691	0.694	0.697	0.701
350°C	0.791	0.794	0.798	0.801	0.804	0.807
400°C	0.889	0.891	0.894	0.896	0.899	0.902

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Table 112. Effective Thermal Conductivity in a Vacuum; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.071	0.080	0.089	0.097	0.104	0.111
50°C	0.086	0.095	0.104	0.112	0.119	0.126
100°C	0.125	0.134	0.142	0.150	0.157	0.164
150°C	0.177	0.185	0.192	0.199	0.206	0.213
200°C	0.242	0.249	0.256	0.262	0.269	0.275
250°C	0.321	0.327	0.334	0.340	0.346	0.352
300°C	0.416	0.422	0.427	0.433	0.439	0.444
350°C	0.526	0.532	0.537	0.542	0.548	0.553
400°C	0.653	0.658	0.663	0.668	0.673	0.678

Table 113. Effective Thermal Conductivity in a Vacuum; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.057	0.066	0.074	0.082	0.088	0.095
50°C	0.069	0.078	0.086	0.093	0.100	0.107
100°C	0.099	0.108	0.115	0.123	0.129	0.136
150°C	0.139	0.147	0.154	0.161	0.167	0.174
200°C	0.189	0.196	0.203	0.209	0.216	0.222
250°C	0.250	0.257	0.263	0.269	0.275	0.281
300°C	0.323	0.329	0.335	0.341	0.346	0.352
350°C	0.409	0.414	0.420	0.425	0.430	0.435
400°C	0.508	0.513	0.517	0.522	0.527	0.532

Table 114. Effective Thermal Conductivity in Nitrogen; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.111	0.118	0.125	0.132	0.138	0.144
50°C	0.130	0.137	0.144	0.150	0.157	0.163
100°C	0.176	0.183	0.189	0.196	0.202	0.207
150°C	0.234	0.240	0.246	0.252	0.258	0.264
200°C	0.304	0.310	0.316	0.322	0.327	0.333
250°C	0.389	0.394	0.400	0.405	0.410	0.415
300°C	0.488	0.493	0.498	0.503	0.508	0.513
350°C	0.604	0.608	0.613	0.617	0.622	0.626
400°C	0.731	0.735	0.739	0.743	0.747	0.752

Table 115. Effective Thermal Conductivity in Nitrogen; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.098	0.104	0.111	0.117	0.123	0.129
50°C	0.113	0.119	0.126	0.132	0.138	0.144
100°C	0.149	0.155	0.162	0.168	0.173	0.179
150°C	0.194	0.200	0.206	0.212	0.217	0.223
200°C	0.249	0.255	0.260	0.266	0.271	0.276
250°C	0.315	0.320	0.325	0.330	0.336	0.341
300°C	0.392	0.397	0.402	0.407	0.412	0.416
350°C	0.481	0.486	0.491	0.495	0.500	0.504
400°C	0.580	0.584	0.588	0.592	0.597	0.601

Table 116. Effective Thermal Conductivity in Argon; GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.099	0.107	0.114	0.121	0.127	0.134
50°C	0.117	0.125	0.132	0.139	0.145	0.151
100°C	0.162	0.169	0.175	0.182	0.188	0.194
150°C	0.217	0.224	0.230	0.237	0.243	0.248
200°C	0.286	0.292	0.298	0.304	0.310	0.315
250°C	0.369	0.375	0.380	0.386	0.391	0.396
300°C	0.467	0.472	0.477	0.482	0.488	0.493
350°C	0.581	0.585	0.590	0.595	0.600	0.604
400°C	0.708	0.712	0.717	0.721	0.725	0.730

Table 117. Effective Thermal Conductivity in Argon; GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.085	0.092	0.099	0.106	0.112	0.118
50°C	0.099	0.107	0.113	0.120	0.126	0.132
100°C	0.134	0.141	0.147	0.154	0.160	0.166
150°C	0.178	0.184	0.190	0.196	0.202	0.208
200°C	0.231	0.237	0.243	0.249	0.254	0.260
250°C	0.295	0.301	0.306	0.312	0.317	0.322
300°C	0.371	0.376	0.382	0.387	0.392	0.396
350°C	0.459	0.464	0.469	0.474	0.478	0.483
400°C	0.558	0.562	0.567	0.571	0.575	0.580

Table 118. Effective Thermal Conductivity; Wooton-Epstein Correlation for GE 8x8 GE-5 Fuel Assembly

Basket Wall Temperature	Effective Thermal Conductivity (W/m-K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.167	0.190	0.206	0.219	0.231	0.241
50°C	0.184	0.207	0.224	0.237	0.249	0.259
100°C	0.229	0.252	0.268	0.282	0.294	0.304
150°C	0.288	0.310	0.327	0.341	0.353	0.364
200°C	0.365	0.386	0.403	0.416	0.428	0.439
250°C	0.461	0.482	0.498	0.511	0.523	0.533
300°C	0.580	0.600	0.615	0.627	0.639	0.649
350°C	0.722	0.741	0.755	0.768	0.779	0.789
400°C	0.891	0.908	0.922	0.934	0.944	0.954

Table 110 through Table 118 represent a fuel assembly average thermal conductivity which is to be applied to the entire fuel assembly in order to accurately predict peak cladding temperatures. As described in Section 5.6.2.1, this temperature-dependent conductivity can be used to predict peak cladding temperatures in the cask or waste package representation, given a peak basket wall temperature and Equation 17.

Table 119 presents effective thermal conductivities for intact BWR spent nuclear fuel (calculated from pp. 3.6-1 and 3.2-2 of Ref. 17) and intact PWR spent nuclear fuel (p. 3.6-1, Ref. 16) which have been documented in past analyses. Table 119 also presents the averages over the heat loads from Table 118 for the Wooton-Epstein correlation for the GE-5 8x8 BWR spent nuclear fuel geometry. These values are included for reference only, and have no bearing on this calculation. They can be compared to the BWR effective thermal conductivities presented in Table 120 and Table 121 for each geometry and gas backfill environment analyzed in Section 5.4. Table 120 and Table 121 present the averages over the heat loads and backfill gas selections from Table 110 through 117. The calculation of these values is performed in the files as listed in Attachment II.

Table 119. Comparison of Reference Temperature-Dependent Effective Thermal Conductivities of 8x8 Rod Configurations (All Values are for Helium Backfill Gas Environment)

Basket Wall Temperature	Average k_s Wootton-Epstein (W/m·K)	Intact BWR Spent Nuclear Fuel k_s (Ref. 17) (W/m·K)	Intact PWR Spent Nuclear Fuel k_s (Ref. 16) (W/m·K)
25°C	0.209	0.457	0.431
50°C	0.227	0.498	0.466
100°C	0.271	0.593	0.544
150°C	0.330	0.705	0.634
200°C	0.406	0.837	0.737
250°C	0.501	0.991	0.855
300°C	0.618	1.168	0.990
350°C	0.759	1.372	1.143
400°C	0.926	1.605	1.316

Table 120. Comparison of Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.306	0.092	0.128	0.117
50°C	0.335	0.107	0.147	0.135
100°C	0.401	0.145	0.192	0.178
150°C	0.478	0.195	0.249	0.233
200°C	0.566	0.259	0.319	0.301
250°C	0.667	0.337	0.402	0.383
300°C	0.780	0.430	0.501	0.480
350°C	0.913	0.540	0.615	0.592
400°C	1.040	0.666	0.741	0.719

Table 121. Comparison of Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.308	0.077	0.114	0.102
50°C	0.334	0.089	0.129	0.116
100°C	0.389	0.118	0.164	0.150
150°C	0.452	0.157	0.209	0.193
200°C	0.523	0.206	0.263	0.246
250°C	0.603	0.266	0.328	0.309
300°C	0.693	0.338	0.404	0.384
350°C	0.799	0.422	0.493	0.471
400°C	0.895	0.520	0.590	0.569

In order to make the use of Equation 16 easier to calculate peak cladding temperatures with a given basket wall temperature, a polynomial curve fit has been performed for the 8x8 rod configuration in each environment and channel/no-channel geometry (Table 122). A polynomial curve fit for the Wooton-Epstein correlation is also included here for comparison. This equation can be substituted into Equation 16, which then provides peak cladding temperatures as a function of basket temperature (°C), thus eliminating the table lookup to determine a value for k_e .

$$k_e = c_0 + c_1 \cdot T + c_2 \cdot T^2 + c_3 \cdot T^3$$

Table 122. Correlation Coefficients for GE 8x8 GE-5 Fuel Assembly Effective Thermal Conductivity Based on Basket Wall Temperature

Conditions		c_0 (W/m·K)	c_1 (W/m·K ²)	c_2 (W/m·K ³)	c_3 (W/m·K ⁴)
Helium	No Channel	2.8227E-01	9.1371E-04	2.6364E-06	-4.2296E-10
Helium	Channel	2.8838E-01	7.9363E-04	2.0095E-06	-4.5836E-10
Vacuum	No Channel	7.9912E-02	4.3099E-04	2.0614E-06	1.3081E-09
Vacuum	Channel	6.7761E-02	3.4034E-04	1.5287E-06	1.1160E-09
Nitrogen	No Channel	1.1319E-01	5.5478E-04	2.2085E-06	8.3440E-10
Nitrogen	Channel	1.0186E-01	4.4415E-04	1.6829E-06	6.5778E-10
Argon	No Channel	1.0284E-01	5.2714E-04	2.1221E-06	1.0323E-09
Argon	Channel	9.0909E-02	4.2076E-04	1.6018E-06	8.3861E-10
Wooton-Epstein		1.9436E-01	5.4247E-04	1.9597E-06	3.1359E-09

Figure 4 and Figure 5 provide a graphical comparison of the effective thermal conductivities of Table 120 and Table 121. The results in Table 119 through Table 121 indicate varying degrees of conservatism in determining an effective thermal conductivity.

Figure 4. Effective Thermal Conductivity for 8x8 BWR Spent Nuclear Fuel Without a Channel

Figure 5. Effective Thermal Conductivity for 8x8 BWR Spent Nuclear Fuel With a Channel

5.6.2.3 9x9 Rod Configuration

Equation 17 is used to predict an effective thermal conductivity for each temperature and heat load used. The calculation is performed for the ANSYS 9x9 BWR representation solutions for both with and without a channel, each gas backfill environment, and for the Wooton-Epstein comparison provided in Section 5.5. The ANSYS output files for each fill gas and geometry are provided as listed in Attachment II. These attachments also provide the information presented in Table 123 through Table 134. Table 123 through Table 130 summarize the effective thermal conductivity determination for the BWR fuel with and without a channel, in each of the four fill gases. Table 131 summarizes the effective thermal conductivity determination from the Wooton-Epstein correlation. The effective thermal conductivity is highly temperature dependent, but there is relatively little dependence on the assembly heat load. This is contrasted to the Wooton-Epstein results in which there is some dependence on heat load, though less evident than the temperature dependence.

Table 123. Effective Thermal Conductivity in Helium; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.283	0.288	0.292	0.296	0.300	0.304
50°C	0.311	0.315	0.319	0.323	0.328	0.331
100°C	0.373	0.377	0.381	0.385	0.389	0.393
150°C	0.445	0.449	0.453	0.457	0.461	0.465
200°C	0.529	0.532	0.536	0.540	0.544	0.547
250°C	0.624	0.628	0.632	0.635	0.639	0.642
300°C	0.733	0.737	0.740	0.744	0.747	0.751
350°C	0.862	0.866	0.870	0.873	0.877	0.880
400°C	0.988	0.991	0.994	0.997	1.000	1.003

Table 124. Effective Thermal Conductivity in Helium; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.293	0.297	0.301	0.305	0.308	0.312
50°C	0.318	0.322	0.325	0.329	0.333	0.337
100°C	0.372	0.376	0.380	0.384	0.387	0.391
150°C	0.434	0.438	0.442	0.445	0.449	0.452
200°C	0.505	0.508	0.512	0.515	0.519	0.522
250°C	0.584	0.588	0.591	0.595	0.598	0.601
300°C	0.674	0.677	0.681	0.684	0.687	0.691
350°C	0.780	0.784	0.788	0.791	0.795	0.798
400°C	0.880	0.883	0.886	0.888	0.891	0.894

Table 125. Effective Thermal Conductivity in a Vacuum; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.068	0.078	0.086	0.094	0.101	0.108
50°C	0.083	0.092	0.101	0.109	0.116	0.123
100°C	0.121	0.130	0.138	0.145	0.152	0.159
150°C	0.171	0.179	0.186	0.193	0.200	0.207
200°C	0.234	0.241	0.248	0.255	0.261	0.268
250°C	0.312	0.318	0.324	0.331	0.337	0.343
300°C	0.405	0.411	0.417	0.422	0.428	0.434
350°C	0.515	0.520	0.526	0.531	0.536	0.542
400°C	0.642	0.647	0.652	0.657	0.662	0.667

Table 126. Effective Thermal Conductivity in a Vacuum; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.056	0.065	0.073	0.081	0.088	0.094
50°C	0.068	0.077	0.085	0.092	0.099	0.106
100°C	0.098	0.106	0.114	0.121	0.128	0.135
150°C	0.137	0.145	0.152	0.159	0.166	0.172
200°C	0.187	0.194	0.201	0.208	0.214	0.220
250°C	0.248	0.255	0.261	0.267	0.273	0.279
300°C	0.322	0.328	0.334	0.339	0.345	0.350
350°C	0.408	0.414	0.419	0.425	0.430	0.435
400°C	0.509	0.514	0.519	0.524	0.529	0.533

Table 127. Effective Thermal Conductivity in Nitrogen; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m·K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.104	0.112	0.119	0.125	0.132	0.138
50°C	0.122	0.129	0.136	0.143	0.149	0.155
100°C	0.166	0.173	0.179	0.185	0.192	0.198
150°C	0.221	0.227	0.233	0.239	0.245	0.251
200°C	0.288	0.294	0.300	0.306	0.311	0.317
250°C	0.370	0.375	0.381	0.386	0.392	0.397
300°C	0.466	0.472	0.477	0.482	0.487	0.492
350°C	0.579	0.584	0.589	0.594	0.599	0.603
400°C	0.706	0.710	0.715	0.719	0.724	0.728

Table 128. Effective Thermal Conductivity in Nitrogen; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m-K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.095	0.102	0.109	0.115	0.121	0.127
50°C	0.110	0.117	0.123	0.129	0.135	0.141
100°C	0.145	0.152	0.158	0.164	0.170	0.176
150°C	0.190	0.196	0.202	0.208	0.213	0.219
200°C	0.244	0.250	0.255	0.261	0.267	0.272
250°C	0.309	0.315	0.320	0.325	0.331	0.336
300°C	0.386	0.392	0.397	0.402	0.407	0.412
350°C	0.476	0.481	0.486	0.491	0.495	0.500
400°C	0.576	0.580	0.585	0.589	0.593	0.598

Table 129. Effective Thermal Conductivity in Argon; ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m-K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.093	0.101	0.108	0.115	0.122	0.128
50°C	0.110	0.118	0.125	0.132	0.139	0.145
100°C	0.152	0.160	0.166	0.173	0.180	0.186
150°C	0.206	0.212	0.219	0.225	0.231	0.238
200°C	0.272	0.278	0.284	0.290	0.296	0.302
250°C	0.352	0.358	0.364	0.369	0.375	0.380
300°C	0.448	0.453	0.458	0.464	0.469	0.474
350°C	0.559	0.564	0.569	0.574	0.579	0.584
400°C	0.686	0.691	0.695	0.700	0.704	0.709

Table 130. Effective Thermal Conductivity in Argon; ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Effective Thermal Conductivity (W/m-K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.083	0.090	0.097	0.104	0.110	0.116
50°C	0.097	0.104	0.111	0.118	0.124	0.130
100°C	0.131	0.138	0.145	0.151	0.157	0.163
150°C	0.174	0.180	0.187	0.193	0.199	0.205
200°C	0.227	0.233	0.239	0.245	0.250	0.256
250°C	0.291	0.296	0.302	0.307	0.313	0.318
300°C	0.366	0.372	0.377	0.382	0.387	0.392
350°C	0.455	0.460	0.465	0.470	0.475	0.479
400°C	0.555	0.560	0.564	0.569	0.573	0.577

Table 131. Effective Thermal Conductivity; Wooton-Epstein Correlation for ANF-JP 9x9 Fuel Assembly

Basket Wall Temperature	Effective Thermal Conductivity (W/m-K)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.161	0.183	0.199	0.212	0.224	0.234
50°C	0.176	0.199	0.215	0.228	0.240	0.250
100°C	0.216	0.239	0.255	0.269	0.280	0.291
150°C	0.269	0.291	0.308	0.321	0.333	0.344
200°C	0.337	0.359	0.375	0.389	0.401	0.411
250°C	0.424	0.445	0.461	0.474	0.485	0.496
300°C	0.530	0.550	0.565	0.578	0.589	0.600
350°C	0.658	0.677	0.691	0.704	0.715	0.725
400°C	0.809	0.827	0.841	0.853	0.863	0.873

Table 123 through Table 131 represent a fuel assembly average thermal conductivity which is to be applied to the entire fuel assembly in order to accurately predict peak cladding temperatures. As described in Section 5.6.2.1, this temperature-dependent conductivity can be used to predict peak cladding temperatures in the cask or waste package representation, given a peak basket wall temperature and Equation 17.

Table 132 presents effective thermal conductivities for intact BWR spent nuclear fuel (calculated from pp. 3.6-1 and 3.2-2 of Ref. 17) and intact PWR spent nuclear fuel (p. 3.6-1, Ref. 16) which have been documented in past analyses. Table 132 also presents the averages over the heat loads from Table 131 for the Wooton-Epstein correlation for the ANF-JP 9x9 BWR spent nuclear fuel geometry. These values are included for reference only, and have no bearing on this calculation. They can be compared to the BWR effective thermal conductivities presented in Table 133 and Table 134 for each geometry and gas backfill environment analyzed in Section 5.4. Table 133 and Table 134 present the averages over the heat loads and backfill gas selections from Table 123 through Table 130. The calculation of these values is performed in the files as listed in Attachment II.

Table 132. Comparison of Reference Temperature-Dependent Effective Thermal Conductivities of 9x9 Rod Configurations (All Values are for Helium Backfill Gas Environment)

Basket Wall Temperature	Average k_e Wootton-Epstein (W/m·K)	Intact BWR Spent Nuclear Fuel k_e (Ref. 17) (W/m·K)	Intact PWR Spent Nuclear Fuel k_e (Ref. 16) (W/m·K)
25°C	0.202	0.457	0.431
50°C	0.218	0.498	0.466
100°C	0.258	0.593	0.544
150°C	0.311	0.705	0.634
200°C	0.379	0.837	0.737
250°C	0.464	0.991	0.855
300°C	0.569	1.168	0.990
350°C	0.695	1.372	1.143
400°C	0.844	1.605	1.316

Table 133. Comparison of Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.294	0.089	0.122	0.111
50°C	0.321	0.104	0.139	0.128
100°C	0.383	0.141	0.182	0.169
150°C	0.455	0.189	0.236	0.222
200°C	0.538	0.251	0.303	0.287
250°C	0.633	0.327	0.383	0.366
300°C	0.742	0.419	0.479	0.461
350°C	0.871	0.528	0.591	0.572
400°C	0.996	0.654	0.717	0.697

Table 134. Comparison of Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.303	0.076	0.111	0.100
50°C	0.327	0.088	0.126	0.114
100°C	0.382	0.117	0.161	0.147
150°C	0.443	0.155	0.205	0.189
200°C	0.513	0.204	0.258	0.241
250°C	0.593	0.264	0.323	0.305
300°C	0.682	0.336	0.399	0.380
350°C	0.789	0.422	0.488	0.467
400°C	0.887	0.521	0.587	0.566

In order to make the use of Equation 16 easier to calculate peak cladding temperatures with a given basket wall temperature, a polynomial curve fit has been performed for the 9x9 rod configuration in each environment and channel/no-channel geometry (Table 135). A polynomial curve fit for the Wooton-Epstein correlation is also included here for comparison. This equation can be substituted into Equation 16, which then provides peak cladding temperatures as a function of basket temperature (°C), thus eliminating the table lookup to determine a value for k_e .

$$k_e = c_0 + c_1 \cdot T + c_2 \cdot T^2 + c_3 \cdot T^3$$

Table 135. Correlation Coefficients for ANF-JP 9x9 Fuel Assembly Effective Thermal Conductivity Based on Basket Wall Temperature

Conditions		c_0 (W/m·K)	c_1 (W/m·K ²)	c_2 (W/m·K ³)	c_3 (W/m·K ⁴)
Helium	No Channel	2.7207E-01	8.5784E-04	2.3676E-06	6.6068E-11
Helium	Channel	2.8305E-01	7.7863E-04	1.9332E-06	-2.2046E-10
Vacuum	No Channel	7.7585E-02	4.2590E-04	1.8864E-06	1.6377E-09
Vacuum	Channel	6.6946E-02	3.4174E-04	1.4545E-06	1.3261E-09
Nitrogen	No Channel	1.0751E-01	5.2627E-04	2.0213E-06	1.1903E-09
Nitrogen	Channel	9.9771E-02	4.3710E-04	1.6101E-06	8.6314E-10
Argon	No Channel	9.7944E-02	5.0284E-04	1.9501E-06	1.3558E-09
Argon	Channel	8.9172E-02	4.1506E-04	1.5332E-06	1.0329E-09
Wooton-Epstein		1.8886E-01	4.9062E-04	1.7284E-06	2.8522E-09

Figure 6 and Figure 7 provide a graphical comparison of the effective thermal conductivities of Table 133 and Table 134. The results in Table 132 through Table 134 indicate varying degrees of conservatism in determining an effective thermal conductivity.

Figure 6. Effective Thermal Conductivity for 9x9 BWR Spent Nuclear Fuel Without a Channel

Figure 7. Effective Thermal Conductivity for 9x9 BWR Spent Nuclear Fuel With a Channel

5.6.3 Effective Thermal Conductivity for use in Finite Element Analysis

The effective thermal conductivity presented in Section 5.6.2 is an average thermal conductivity required to provide the correct peak cladding temperature, given the basket wall temperature. However, finite element codes determine the material property values used for a node location based on the node temperature, not an external temperature like a basket wall temperature. Also, the basket wall temperature is usually being calculated by the finite element analysis, and is therefore not available to determine the appropriate thermal conductivity value to use. If the thermal conductivity tables provided in Section 5.6.2 were used directly by a finite element code, the local node temperature, which is typically much higher than the basket wall temperature, would be used to determine a local thermal conductivity which is much higher than the average thermal conductivity selected based on the basket wall temperature. This would be true for every local node from the center of the fuel assembly to the basket wall. Thus, the average material thermal conductivity determined by the finite element code would be higher for a given basket wall temperature and therefore would consistently under-predict the peak cladding temperature. This would be a consistently non-conservative bias for any use of the Section 5.6.2 thermal conductivity values with finite element codes.

Conversely, if the effective thermal conductivity were re-scaled to a peak cladding temperature basis rather than that of the basket wall temperature, by algebraically adjusting Equation 16, it would make the finite element code consistently over-predict the peak cladding temperature and would introduce a consistently conservative bias for the calculations. This method, while consistently conservative, is not desirable since the amount of conservatism may be quite large.

A general form of the effective thermal conductivity based on local nodal temperatures is not obvious, but we can make use of the current formulation by using the conclusions provided in Section 5.6.2. Section 5.6.2 suggests that, for a given geometry and fill gas, the effective thermal conductivity is relatively independent of the heat load and depends only on temperatures. Thus, we can define a characteristic temperature as the average of the peak cladding temperature and the basket wall temperature, called the "median temperature". Each thermal conductivity provided in Table 97 through Table 104, Table 110 through Table 117, and Table 123 through Table 130 has an associated median temperature as determined from temperature drop values provided in Section 5.4, for each of the basket wall temperature and geometry conditions. We now have 54 values for each fill gas and geometry condition with which to determine an effective thermal conductivity which can easily and accurately be used with finite element codes.

The use of an effective thermal conductivity determined with Equation 17 with a temperature scale based on a "median temperature" will allow a finite element code to over-predict the effective thermal conductivity on roughly half of the local nodes and under-predict the effective thermal conductivity on the remaining half of the local nodes. In this manner, the average thermal conductivity for the global fuel assembly will be the same as the average effective thermal

conductivity determined with the basket wall temperature and the Section 5.6.2 information. This method is backchecked as documented in Section 5.7 and benchmarked as documented in Section 5.8. Thermal results using the finite element effective thermal conductivities calculated with this method provide a "best estimate" of peak cladding temperatures compared to the conservative predictions derived from Wooton-Epstein (conservative with helium fill gas) or previous conservative effective thermal conductivities.

The following recommendations should be followed when using the effective thermal conductivity method with finite element codes:

- 1) It should be noted that only even mesh grids (i.e., 10x10, 14x14, etc.) should be used when applying the effective thermal conductivity method with finite element codes. This mesh spacing places a local node at the center of the fuel assembly and will calculate a temperature at this location directly. If an odd spacing is used, the mesh will interpolate this point consistent with the finite element method.
- 2) When calculating the heat load to apply to the fuel region, use the cross sectional area or volume of the entire represented region, not the area or volume of the fuel assembly. Using the fuel assembly area or volume will result in a larger volumetric heat generation for the represented region and the calculation will over-predict the peak cladding temperatures.
- 3) The size of the basket opening does not affect the calculation or invalidate the effective thermal conductivity. The effective thermal conductivity does not depend on the basket opening – it is an average thermal conductivity for the region being represented. Increasing the gap between the edge of the assembly and the basket wall by a small amount does not significantly change the effective thermal conductivity, since the heat transfer is dominated by radiation. However, larger changes in the gap size will begin to have a significant effect upon the effective thermal conductivity, since conduction heat transfer becomes a larger factor. Generally, for reasonable basket designs the gap size will not have an impact upon the effective thermal conductivity calculation.

5.6.3.1 7x7 Rod Configuration

Table 136 and Table 137 present the finite element formulation of the effective thermal conductivity for each fill gas and channel size selection from Table 97 through Table 104. Table 136 and Table 137, which show that a small change in effective thermal conductivity can have a significant impact on peak cladding temperatures, can be compared to the BWR effective thermal conductivities in Table 107 and Table 108. In order to simplify the finite element code material property input and to make use of Equation 16 easier for any finite element code which allows the input of an equation rather than tabular data, a polynomial curve fit was performed for each environment and channel/no-channel geometry (Table 138). This equation can be substituted into Equation 16, which provides peak cladding temperature as a function of median temperature, thus eliminating the table lookup to determine a value for k_e .

Table 136. Comparison of Finite Element Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with No Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.303	0.076	0.115	0.103
50°C	0.332	0.095	0.137	0.124
75°C	0.366	0.118	0.162	0.148
100°C	0.403	0.144	0.190	0.176
125°C	0.444	0.174	0.223	0.208
150°C	0.489	0.209	0.260	0.244
175°C	0.537	0.247	0.300	0.284
200°C	0.589	0.290	0.345	0.328
225°C	0.645	0.337	0.394	0.377
250°C	0.705	0.388	0.448	0.430
275°C	0.769	0.445	0.505	0.487
300°C	0.836	0.506	0.568	0.549
325°C	0.907	0.572	0.635	0.615
350°C	0.981	0.643	0.707	0.687
375°C	1.060	0.720	0.783	0.764
400°C	1.142	0.802	0.865	0.845

Table 137. Comparison of Finite Element Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.308	0.055	0.100	0.086
50°C	0.333	0.069	0.116	0.102
75°C	0.361	0.086	0.135	0.121
100°C	0.392	0.105	0.157	0.141
125°C	0.426	0.127	0.181	0.165
150°C	0.462	0.152	0.208	0.192
175°C	0.501	0.180	0.239	0.221
200°C	0.542	0.211	0.272	0.253
225°C	0.586	0.245	0.308	0.289
250°C	0.633	0.282	0.347	0.327
275°C	0.682	0.322	0.390	0.369
300°C	0.734	0.367	0.435	0.414
325°C	0.788	0.415	0.484	0.463
350°C	0.844	0.466	0.537	0.515
375°C	0.903	0.522	0.593	0.571
400°C	0.965	0.582	0.652	0.630

The following equation is for use with finite element codes representing 7x7 fuel assemblies and is based on the median temperature (°C):

$$k_e = c_0 + c_1 \cdot T + c_2 \cdot T^2 + c_3 \cdot T^3$$

Table 138. Correlation Coefficients for GE 7x7 GE-2 Fuel Assembly Effective Thermal Conductivity for Use with Finite Element Analysis

Conditions		c ₀ (W/m·K)	c ₁ (W/m·K ²)	c ₂ (W/m·K ³)	c ₃ (W/m·K ⁴)
Helium	No Channel	2.7659E-01	9.6156E-04	3.0200E-06	-4.1543E-11
Helium	Channel	2.8569E-01	8.4031E-04	2.2769E-06	-3.3451E-10
Vacuum	No Channel	5.9611E-02	5.7214E-04	2.5760E-06	1.5816E-09
Vacuum	Channel	4.3271E-02	4.3360E-04	1.7524E-06	1.3197E-09
Nitrogen	No Channel	9.7532E-02	6.3826E-04	2.7912E-06	1.0225E-09
Nitrogen	Channel	8.6368E-02	4.9797E-04	1.9912E-06	7.5363E-10
Argon	No Channel	8.5804E-02	6.2435E-04	2.6973E-06	1.2198E-09
Argon	Channel	7.3106E-02	4.8528E-04	1.8846E-06	9.6093E-10

Figure 8 and Figure 9 provide a graphical comparison of the effective thermal conductivities of Table 136 and Table 137.

Figure 8. Effective Thermal Conductivity for use in Finite Element Analysis for 7x7 BWR Spent Nuclear Fuel Without a Channel

Figure 9. Effective Thermal Conductivity for use in Finite Element Analysis for 7x7 BWR Spent Nuclear Fuel With a Channel

5.6.3.2 8x8 Rod Configuration

Table 139 and Table 140 present the finite element formulation of the effective thermal conductivity for each fill gas and channel size selection from Table 110 through Table 117. Table 139 and Table 140, which show that a small change in effective thermal conductivity can have a significant impact on peak cladding temperatures, can be compared to the BWR effective thermal conductivities in Table 120 and Table 121. In order to simplify the finite element code material property input and to make use of Equation 16 easier for any finite element code which allows the input of an equation rather than tabular data, a polynomial curve fit was performed for each environment and channel/no-channel geometry (Table 141). This equation can be substituted into Equation 16, which provides peak cladding temperature as a function of median temperature, thus eliminating the table lookup to determine a value for k_e .

Table 139. Comparison of Finite Element Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with No Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.292	0.062	0.104	0.092
50°C	0.319	0.077	0.122	0.109
75°C	0.350	0.096	0.144	0.130
100°C	0.384	0.117	0.168	0.153
125°C	0.422	0.142	0.196	0.180
150°C	0.462	0.169	0.226	0.210
175°C	0.506	0.201	0.260	0.243
200°C	0.553	0.235	0.298	0.280
225°C	0.602	0.273	0.339	0.320
250°C	0.655	0.315	0.383	0.363
275°C	0.711	0.360	0.431	0.410
300°C	0.769	0.410	0.483	0.461
325°C	0.831	0.463	0.538	0.516
350°C	0.895	0.521	0.597	0.574
375°C	0.962	0.582	0.660	0.637
400°C	1.031	0.648	0.726	0.703

Table 140. Comparison of Finite Element Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.297	0.048	0.092	0.079
50°C	0.320	0.060	0.106	0.092
75°C	0.346	0.075	0.123	0.109
100°C	0.374	0.092	0.142	0.127
125°C	0.405	0.111	0.164	0.148
150°C	0.438	0.132	0.188	0.171
175°C	0.474	0.156	0.214	0.197
200°C	0.511	0.183	0.243	0.225
225°C	0.551	0.212	0.275	0.256
250°C	0.593	0.244	0.310	0.290
275°C	0.637	0.279	0.347	0.326
300°C	0.683	0.317	0.387	0.366
325°C	0.732	0.359	0.430	0.408
350°C	0.782	0.403	0.475	0.453
375°C	0.834	0.451	0.524	0.502
400°C	0.888	0.503	0.576	0.553

The following equation is for use with finite element codes representing 8x8 fuel assemblies and is based on the median temperature (°C):

$$k_e = c_0 + c_1 \cdot T + c_2 \cdot T^2 + c_3 \cdot T^3$$

Table 141. Correlation Coefficients for GE 8x8 GE-5 Fuel Assembly Effective Thermal Conductivity for Use with Finite Element Analysis

Conditions		c_0 (W/m·K)	c_1 (W/m·K ²)	c_2 (W/m·K ³)	c_3 (W/m·K ⁴)
Helium	No Channel	2.6820E-01	8.8803E-04	2.7890E-06	-6.0506E-10
Helium	Channel	2.7634E-01	7.7518E-04	2.1092E-06	-5.6586E-10
Vacuum	No Channel	4.8604E-02	4.6438E-04	2.0888E-06	1.2482E-09
Vacuum	Channel	3.7532E-02	3.7707E-04	1.5170E-06	1.1171E-09
Nitrogen	No Channel	8.9222E-02	5.4310E-04	2.3840E-06	5.9699E-10
Nitrogen	Channel	7.9991E-02	4.3608E-04	1.8012E-06	5.1527E-10
Argon	No Channel	7.7043E-02	5.2636E-04	2.2630E-06	8.3433E-10
Argon	Channel	6.6936E-02	4.2435E-04	1.6854E-06	7.3392E-10

Figure 10 and Figure 11 provide a graphical comparison of the effective thermal conductivities of Table 139 and Table 140.

Figure 10. Effective Thermal Conductivity for use in Finite Element Analysis for 8x8 BWR Spent Nuclear Fuel Without a Channel

Figure 11. Effective Thermal Conductivity for use in Finite Element Analysis for 8x8 BWR Spent Nuclear Fuel With a Channel

5.6.3.3 9x9 Rod Configuration

Table 142 and Table 143 present the finite element formulation of the effective thermal conductivity for each fill gas and channel size selection from Table 123 through Table 130. Table 142 and Table 143, which show that a small change in effective thermal conductivity can have a significant impact on peak cladding temperatures, can be compared to the BWR effective thermal conductivities in Table 133 and Table 134. In order to simplify the finite element code material property input and to make use of Equation 16 easier for any finite element code which allows the input of an equation rather than tabular data, a polynomial curve fit was performed for each environment and channel/no-channel geometry (Table 144). This equation can be substituted into Equation 16, which provides peak cladding temperature as a function of median temperature, thus eliminating the table lookup to determine a value for k_e .

Table 142. Comparison of Finite Element Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with No Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.281	0.059	0.098	0.086
50°C	0.306	0.074	0.115	0.103
75°C	0.335	0.092	0.135	0.122
100°C	0.367	0.113	0.158	0.144
125°C	0.401	0.137	0.184	0.170
150°C	0.439	0.164	0.213	0.198
175°C	0.480	0.194	0.246	0.230
200°C	0.524	0.227	0.282	0.265
225°C	0.572	0.264	0.321	0.304
250°C	0.622	0.305	0.364	0.346
275°C	0.675	0.350	0.411	0.392
300°C	0.731	0.399	0.461	0.442
325°C	0.790	0.451	0.515	0.495
350°C	0.853	0.509	0.573	0.553
375°C	0.918	0.570	0.635	0.615
400°C	0.986	0.637	0.701	0.681

Table 143. Comparison of Finite Element Temperature-Dependent Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.291	0.047	0.090	0.076
50°C	0.314	0.059	0.104	0.090
75°C	0.339	0.074	0.120	0.106
100°C	0.367	0.090	0.139	0.124
125°C	0.397	0.109	0.160	0.145
150°C	0.430	0.130	0.184	0.167
175°C	0.464	0.154	0.210	0.193
200°C	0.502	0.181	0.238	0.221
225°C	0.541	0.210	0.270	0.252
250°C	0.583	0.242	0.304	0.285
275°C	0.627	0.277	0.341	0.322
300°C	0.673	0.316	0.381	0.361
325°C	0.721	0.357	0.424	0.404
350°C	0.772	0.403	0.470	0.449
375°C	0.824	0.451	0.520	0.498
400°C	0.879	0.504	0.572	0.550

The following equation is for use with finite element codes representing 9x9 fuel assemblies and is based on the median temperature (°C):

$$k_e = c_0 + c_1 \cdot T + c_2 \cdot T^2 + c_3 \cdot T^3$$

Table 144. Correlation Coefficients for ANF-JP 9x9 Fuel Assembly Effective Thermal Conductivity for Use with Finite Element Analysis

Conditions		c ₀ (W/m·K)	c ₁ (W/m·K ²)	c ₂ (W/m·K ³)	c ₃ (W/m·K ⁴)
Helium	No Channel	2.5834E-01	8.3409E-04	2.4976E-06	-8.2295E-11
Helium	Channel	2.7098E-01	7.6157E-04	2.0213E-06	-3.1162E-10
Vacuum	No Channel	4.6022E-02	4.6472E-04	1.8815E-06	1.6225E-09
Vacuum	Channel	3.6457E-02	3.8232E-04	1.4209E-06	1.3572E-09
Nitrogen	No Channel	8.3291E-02	5.2048E-04	2.1572E-06	1.0117E-09
Nitrogen	Channel	7.7614E-02	4.3409E-04	1.6989E-06	7.6270E-10
Argon	No Channel	7.1789E-02	5.0880E-04	2.0495E-06	1.2185E-09
Argon	Channel	6.4869E-02	4.2402E-04	1.5865E-06	9.7102E-10

Figure 12 and Figure 13 provide a graphical comparison of the effective thermal conductivities of Table 142 and Table 143.

Figure 12. Effective Thermal Conductivity for use in Finite Element Analysis for 9x9 BWR Spent Nuclear Fuel Without a Channel

Figure 13. Effective Thermal Conductivity for use in Finite Element Analysis for 9x9 BWR Spent Nuclear Fuel With a Channel

5.7 BACKCHECK OF EFFECTIVE THERMAL CONDUCTIVITY

To perform a simple check of the spent nuclear fuel effective thermal conductivity for use with finite element codes developed in Section 5.6.3, an ANSYS representation of a homogeneous fuel assembly was created and evaluated over the same range of temperatures and heat loads (Assumptions 3.23 and 3.24). A backcheck of the effective thermal conductivity based on knowledge of the basket wall temperature provided in Section 5.6.2 was not performed, since the same basket wall temperatures are used here that were used to develop the Section 5.6.2 information. Predicted peak temperatures are compared to the peak cladding temperatures calculated in Section 5.4.

Using the same basket cell width (Assumption 3.14), active fuel length (Table 12, Table 14, and Table 16 for 7x7, 8x8, and 9x9 fuel assemblies, respectively), and peaking factor (Assumption 3.17) of Section 5.3, a homogeneous assembly representation was developed with smeared material properties in the assembly area. A square grid (10 by 10) of elements was assumed in the smeared property assembly area. The density of the homogeneous assembly was assumed to be 3892.42 kg/m³ (Assumption 3.25) and the specific heat was assumed to be 273.129 J/kg·K (Assumption 3.26).

The homogeneous representation results indicate the ability of the effective thermal conductivity methodology used with finite element codes to predict "best estimate" cladding temperatures in a spent nuclear fuel assembly. Peak cladding temperatures predicted by the homogeneous representation were within 1.8°C of temperatures predicted by the discrete representation. The homogeneous representation results also show that for normal container design conditions the predicted peak cladding temperatures were consistently slightly conservative. Any trending which can be seen in the temperature differences with respect to basket wall temperature and heat load is strongly correlated with the curve fit used to generate the finite element effective thermal conductivities. Also, the accuracy and convergence of the calculation is such that the results of the discrete spent nuclear fuel representations and the homogeneous representations are not significantly different.

Care should be taken not to extrapolate the effective thermal conductivity results to alternate assembly designs (such as PWR assemblies) or alternate fill gases to which these results do not apply. As can be seen by the information presented in Sections 5.4, 5.5, and 5.6, small changes in the effective thermal conductivity values may have a significant effect on the peak cladding temperatures predicted.

Another issue to address is the question of minimum mesh density required to maintain the accuracy of the finite element effective thermal conductivity. In order to assess this requirement, ANSYS inputs were generated which used the homogeneous representation geometry for the vacuum environment, including the channel, with a 2x2, 4x4, 6x6, 8x8, 10x10, 12x12, and 14x14 mesh density for the spent nuclear fuel material region, to determine the required minimum mesh density

to obtain the desired level of accuracy. The ANSYS input file and the results generated for each solution are included as listed in Attachment II.

The selection of a mesh density is strongly dependent on the expected thermal gradients in the region to be meshed, and is therefore problem-dependent. However, for the relatively mild thermal gradients encountered in the homogeneous representations shown in the graphic files in Attachment IV, it is still instructive to determine the mesh density at which the solution results are not significantly affected. Since the gradients which are being examined are relatively mild, this mesh density would then be the absolute minimum mesh density for any problem. The vacuum environment with a channel was selected for the mesh density test because it displays the largest thermal gradient of all of the problems examined in Sections 5.4 and 5.6. Fundamentally, the behavior of the effective thermal conductivity for the other fill gas/geometry conditions will be the same or require a slightly reduced mesh density, due to the slightly smaller thermal gradients. Use of the minimum mesh density for the vacuum environment, with a channel, for any other fill gas environment should not impose any significant calculational penalty and therefore shall represent the minimum mesh density for all effective thermal conductivity formulations for BWR spent nuclear fuel.

The information included as listed in Attachment II shows that the results for mesh densities greater than 8x8 are reasonably steady, although some small differences due to convergence criteria and solution path are noticeable. The results for mesh densities less than 8x8 are clearly affected by the coarseness of the mesh, and thus are inadequate for the problem being analyzed. The results of the 8x8 mesh density appear to be reasonably accurate; however, a small improvement is seen changing to the 10x10 mesh density. Thus, it is reasonable to require a minimum 10x10 mesh density with the use of the BWR effective thermal conductivity method. If larger gradients than those analyzed in this report are expected, then the mesh density should be increased in order to maintain the accuracy of the method. Also, note that if a larger fuel assembly area is represented (i.e., PWR versus BWR spent nuclear fuel cross sectional area), the mesh density must be increased, since the distance between nodes is the important parameter.

5.7.1 7x7 Rod Configuration

The input file used to generate the ANSYS solution is echoed to the output file, which is included as listed in Attachment II for the 7x7 rod configuration. The ANSYS input was developed in the same manner as described in Section 5.3, and begins with the input of the average effective thermal conductivity (over the four heat loads) determined in Section 5.4, which was saved in ANSYS readable format as indicated in Attachment II.

A comparison of the homogeneous representation results and the results of the discrete representation of Sections 5.3 and 5.4 is provided for the 7x7 rod configuration in Table 145 through Table 152 for each fill gas environment and channel geometry condition. The conductivity values calculated by the ANSYS code were checked against those reported in Section 5.6.

Table 145. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with No Channel in Helium Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
50°C	-0.1	-0.1	-0.2	-0.3	-0.3	-0.3
100°C	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3
150°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2
200°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.1
250°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
300°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3

Table 146. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel in Helium Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.3
50°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.5
100°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
150°C	0.0	-0.1	-0.2	-0.2	-0.2	-0.3
200°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
250°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
300°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
350°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.3
400°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.4

Table 147. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with No Channel in Vacuum Environment; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.4	0.4	0.3	0.0	-0.2	-0.4
50°C	0.1	0.2	0.0	0.0	-0.3	-0.4
100°C	0.0	-0.1	-0.2	-0.2	-0.2	-0.3
150°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
200°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
400°C	0.0	-0.1	-0.3	-0.4	-0.6	-0.8

Table 148. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel in Vacuum Environment; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.3	0.2	-0.1	-0.4	-0.4	-0.7
50°C	0.1	0.1	-0.1	-0.3	-0.4	-0.6
100°C	0.0	0.0	-0.1	-0.2	-0.2	-0.4
150°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
200°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
250°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	-0.1	-0.2	-0.4	-0.7	-1.1	-1.5

Table 149. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with No Channel in Nitrogen Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.1	0.1	0.2	0.2	0.2	0.0
50°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
100°C	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3
150°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2
200°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	0.0	-0.1	-0.2	-0.3	-0.5	-0.7

Table 150. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel in Nitrogen Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.2	0.1	-0.1	-0.2	-0.6	-0.7
50°C	0.0	-0.1	-0.2	-0.4	-0.5	-0.7
100°C	0.0	-0.2	-0.3	-0.4	-0.5	-0.5
150°C	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
200°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	-0.1	-0.2	-0.3	-0.5	-0.8	-1.1

Table 151. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with No Channel in Argon Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.1	0.1	0.1	-0.1	0.0	-0.2
50°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.4
100°C	-0.1	-0.2	-0.3	-0.3	-0.3	-0.4
150°C	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
200°C	-0.1	-0.1	-0.1	-0.2	-0.2	-0.3
250°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	0.0	-0.1	-0.2	-0.4	-0.5	-0.7

Table 152. Peak Temperature Difference for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel in Argon Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.2	0.2	0.0	-0.3	-0.4	-0.8
50°C	0.1	0.1	-0.1	-0.2	-0.5	-0.5
100°C	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4
150°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.3
200°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	-0.1	-0.2	-0.4	-0.6	-0.9	-1.2

5.7.2 8x8 Rod Configuration

The input file used to generate the ANSYS solution is echoed to the output file, which is included as listed in Attachment II for the 8x8 rod configuration. The ANSYS input was developed in the same manner as described in Section 5.3, and begins with the input of the average effective thermal conductivity (over the four heat loads) determined in Section 5.4, which was saved in ANSYS readable format as listed in Attachment II.

A comparison of the homogeneous representation results and the results of the discrete representation of Sections 5.3 and 5.4 is provided for the 8x8 rod configuration in Table 153 through Table 160 for each fill gas environment and channel geometry condition. The conductivity values calculated by the ANSYS code were checked against those reported in Section 5.6.

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Table 153. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with No Channel in Helium Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.0	-0.1	-0.1	-0.2	-0.1	-0.1
50°C	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3
100°C	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3
150°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2
200°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.1
250°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
300°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3

Table 154. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel in Helium Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.3
50°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
100°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
150°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3
200°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
250°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
300°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
350°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.3
400°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.4

Table 155. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with No Channel in Vacuum Environment; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.5	0.5	0.2	0.1	-0.1	-0.3
50°C	0.2	0.2	0.1	-0.1	-0.3	-0.4
100°C	0.0	0.0	-0.1	-0.2	-0.3	-0.4
150°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
200°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	-0.1	-0.2	-0.3	-0.6	-0.8	-1.2

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Table 156. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel in Vacuum Environment; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.4	0.6	0.4	0.3	0.1	-0.4
50°C	0.4	0.5	0.3	0.2	0.0	-0.2
100°C	0.2	0.3	0.3	0.0	0.1	-0.2
150°C	0.0	0.0	0.0	-0.1	-0.1	-0.2
200°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
250°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.4
300°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
400°C	-0.1	-0.3	-0.5	-0.9	-1.3	-1.8

Table 157. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with No Channel in Nitrogen Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.0	0.0	0.1	0.2	0.1	0.3
50°C	-0.2	-0.2	-0.2	-0.1	0.0	0.1
100°C	-0.1	-0.2	-0.2	-0.3	-0.2	-0.2
150°C	-0.1	-0.2	-0.3	-0.3	-0.3	-0.2
200°C	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2
250°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	0.0	-0.1	-0.3	-0.4	-0.6	-0.8

Table 158. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel in Nitrogen Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.2	0.1	0.0	-0.1	-0.4	-0.3
50°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
100°C	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4
150°C	-0.1	-0.1	-0.2	-0.3	-0.3	-0.3
200°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
350°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3
400°C	-0.1	-0.2	-0.4	-0.6	-0.9	-1.2

Table 159. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with No Channel in Argon Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.1	0.1	0.2	0.2	0.3	0.2
50°C	-0.1	-0.1	-0.1	0.0	0.0	0.0
100°C	-0.1	-0.2	-0.2	-0.2	-0.2	-0.1
150°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.1
200°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.1
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	-0.1	-0.1	-0.3	-0.5	-0.7	-0.9

Table 160. Peak Temperature Difference for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel in Argon Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.2	0.2	0.1	-0.1	-0.1	-0.5
50°C	0.0	0.0	0.0	-0.1	-0.3	-0.2
100°C	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
150°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3
200°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
350°C	-0.1	-0.1	-0.1	-0.2	-0.2	-0.3
400°C	-0.1	-0.2	-0.4	-0.7	-1.0	-1.4

5.7.3 9x9 Rod Configuration

The input file used to generate the ANSYS solution is echoed to the output file, which is included as listed in Attachment II for the 9x9 rod configuration. The ANSYS input was developed in the same manner as described in Section 5.3, and begins with the input of the average effective thermal conductivity (over the four heat loads) determined in Section 5.4, which was saved in ANSYS readable format as listed in Attachment II.

A comparison of the homogeneous representation results and the results of the discrete representation of Sections 5.3 and 5.4 is provided for the 9x9 rod configuration in Table 161 through Table 168 for each fill gas environment and channel geometry condition. The conductivity values calculated by the ANSYS code were checked against those reported in Section 5.6.

Table 161. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with No Channel in Helium Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.0	0.0	-0.1	-0.2	-0.1	-0.2
50°C	-0.1	-0.1	-0.2	-0.3	-0.3	-0.3
100°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
150°C	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
200°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.1
250°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
300°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
400°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.4

Table 162. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with 80-mil Channel in Helium Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.3
50°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
100°C	-0.1	-0.2	-0.2	-0.3	-0.4	-0.4
150°C	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
200°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
250°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
300°C	0.0	0.0	-0.1	-0.1	-0.1	-0.1
350°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.3
400°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.4

Table 163. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with No Channel in Vacuum Environment; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.4	0.3	0.2	0.0	-0.3	-0.2
50°C	0.2	0.1	0.1	0.0	-0.2	-0.3
100°C	0.1	0.1	0.1	0.1	-0.1	-0.1
150°C	0.0	0.0	0.0	-0.1	-0.2	-0.2
200°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.3
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	-0.1	-0.2	-0.4	-0.6	-0.9	-1.2

Table 164. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with 80-mil Channel in Vacuum Environment; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.5	0.5	0.2	0.0	-0.1	-0.6
50°C	0.4	0.3	0.2	0.0	-0.2	-0.4
100°C	0.1	0.1	0.0	-0.2	-0.1	-0.4
150°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
200°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
250°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.3
300°C	0.0	-0.1	-0.2	-0.2	-0.3	-0.3
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	-0.1	-0.3	-0.5	-0.9	-1.3	-1.8

Table 165. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with No Channel in Nitrogen Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.2	0.2	0.2	0.2	0.0	0.1
50°C	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
100°C	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3
150°C	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2
200°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.1	-0.1	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
400°C	-0.1	-0.1	-0.3	-0.5	-0.7	-0.9

Table 166. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with 80-mil Channel in Nitrogen Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/ assembly	200 watts/ assembly	300 watts/ assembly	400 watts/ assembly	500 watts/ assembly	600 watts/ assembly
25°C	0.3	0.3	0.2	0.0	-0.3	-0.3
50°C	0.0	0.0	-0.1	-0.2	-0.4	-0.4
100°C	0.0	-0.1	-0.2	-0.3	-0.3	-0.4
150°C	0.0	-0.1	-0.1	-0.2	-0.3	-0.3
200°C	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
350°C	-0.1	-0.1	-0.1	-0.2	-0.2	-0.3
400°C	-0.1	-0.2	-0.4	-0.6	-0.9	-1.3

Table 167. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with No Channel in Argon Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.2	0.3	0.2	0.1	0.2	0.0
50°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
100°C	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3
150°C	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3
200°C	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
300°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
350°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
400°C	-0.1	-0.2	-0.3	-0.5	-0.7	-1.0

Table 168. Peak Temperature Difference for ANF-JP 9x9 Fuel Assembly with 80-mil Channel in Argon Fill Gas; Explicit Representation minus Homogeneous Representation

Basket Wall Temperature	Temperature (°C)					
	100 watts/assembly	200 watts/assembly	300 watts/assembly	400 watts/assembly	500 watts/assembly	600 watts/assembly
25°C	0.1	0.1	-0.1	-0.3	-0.2	-0.6
50°C	0.0	0.0	-0.1	-0.1	-0.5	-0.5
100°C	0.0	-0.1	-0.2	-0.3	-0.3	-0.4
150°C	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3
200°C	0.0	-0.1	-0.1	-0.1	-0.2	-0.3
250°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
300°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
350°C	0.0	-0.1	-0.1	-0.2	-0.2	-0.3
400°C	-0.1	-0.2	-0.4	-0.7	-1.1	-1.5

5.8 BENCHMARK EVALUATIONS

The following benchmarking evaluation was performed against a test of the REA 2023 BWR spent nuclear fuel storage cask conducted by PNL at the GE Morris Operation (GE-MO) facility (Ref. 21). In the REA 2023 test, intact GE 7x7 BWR fuel assemblies were loaded into the storage cask, and temperatures were measured with an array of thermocouples and compared to pre-test predictions with heat transfer computer codes.

Presented here are the benchmark results for the finite element effective thermal conductivity representation (i.e., a homogeneous representation of a BWR fuel assembly in a single fuel tube as presented in Section 5.7) against two of the fuel assemblies in the test, with helium, nitrogen, and vacuum fill gas environments in both vertical and horizontal configurations. In this benchmark, the finite element effective thermal conductivity representation described in Section 5.7 was modified to represent the GE-2 7x7 assembly, the REA 2023 storage cask geometry, and the GE-MO experiment conditions. Since the calculation performed in Section 5.4 is specifically for the GE-2 7x7, the only changes required were to enter the correct basket wall temperature, assembly heat generation rate, and the axial power peaking factor of 1.20 (Assumption 3.18). The ANSYS input was developed in the same manner as described in Section 5.7. The input is echoed to the output file for this calculation and is included as listed in Attachment II.

Two assemblies from the REA 2023 storage cask tests were chosen for this benchmark, with basket and center fuel rod cladding thermocouple measurements from each run of the experiment provided in Appendix G of Ref. 21. The chosen assemblies are identified as CZ346 and CZ246 in positions 2J and 2G in Figure 3.5 on p. 3.9 of Ref. 22. Thermocouple positions within the storage cask are displayed graphically in Ref. 21 (Figures 5.1, 5.2, and G.1, pp. 5.2, 5.3, and G.2, respectively) and reproduced here as Figure 14. The thermocouple positioning to determine the center rod cladding temperature is described in Appendix A of Ref. 21. Since the ANSYS representation is a two-dimensional slice of a homogenized assembly, thermocouple measurements near the axial mid-length of the cask were used, where temperatures are highest. The axial location at 3.33 m as shown in Figure 5.1 of Ref. 21 was selected for this benchmark calculation. The thermocouple data for the selected BWR assemblies at the desired radial and axial positions, corresponding to the basket wall and fuel assembly center rod cladding temperatures, for the represented experiment runs 6B, 7, 10, and 11A, are listed in Table 169.

Figure 14. Basket Thermocouple Locations for the REA 2023 Test

Table 169. Thermocouple Temperatures (Elevation 3.33 m, from Tables G.8, G.9, G.12, and G.13, Ref. 21)

Assembly	Thermocouple Radial Position	Position Description	Temperature
Run 6B Position 2J ID Number CZ346	0.25 m	Tube Wall Between 2J & 2G	132.2°C
	0.13 m	Center - Rod Clad of 2J	172.8°C
Run 7 Position 2G ID Number CZ246	0.25 m	Tube Wall Between 2J & 2G	116.0°C
	0.38 m	Center - Rod Clad of 2G	146.3°C
Run 10 Position 2J ID Number CZ346	0.25 m	Tube Wall Between 2J & 2G	73.3°C
	0.13 m	Center - Rod Clad of 2J	92.1°C
Run 11A Position 2J ID Number CZ346	0.25 m	Tube Wall Between 2J & 2G	86.7°C
	0.13 m	Center - Rod Clad of 2J	105.9°C

The fuel tube temperature selected as the uniform basket wall temperature was the corner that had the highest temperature. There is a copper thermal shunt from the center location to the shell of the storage cask, which lowers the temperature below the temperature of the next diagonal corner. Thus, the basket wall temperature was not taken from the thermocouple at the 0.0 m radial position, but the 0.25 m radial position.

The assembly heat generation rate for each of the test assemblies on 1/13/85, along with a reduction in the assembly heat generation rate in watts/day, is provided in Figure 3.5 on p. 3.9 of Ref. 22. Thus, the assembly heat production on the day of each selected experiment can be determined by 1) determining the number of days after 1/13/85 the experiment was run, 2) multiplying this number of days by the daily decay rate for the selected assembly, and 3) subtracting this value from the assembly heat production value for 1/13/85. The selected experiments for this benchmark effort are the following:

- Vertical vacuum test (Run 6B, assembly CZ346) performed on 01/19/85 (Table G.8, Ref. 21)
- Vertical nitrogen test (Run 7, assembly CZ246) performed on 01/25/85 (Table G.9, Ref. 21)
- Horizontal helium test (Run 10, assembly CZ346) performed on 02/14/85 (Table G.12, Ref. 21)
- Vertical helium test (Run 11A, assembly CZ346) performed on 02/05/85 (Table G.13, Ref. 21)

Table 170 provides the results of the heat determination.

Table 170. Assembly Heat Productions (Based on Figure 3.5, p. 3.9, Ref. 22)

Assembly / Experiment Date	Heat at Date 01/13/85	Daily Decay Rate	Heat at Date of Experiment
Position 2J – ID CZ346 Run 6B 1/19/85	360.0 watts	0.36 watts/day	357.8 watts
Position 2G – ID CZ246 Run 7 1/25/85	316.0 watts	0.36 watts/day	311.7 watts
Position 2J – ID CZ346 Run 10 2/14/85	360.0 watts	0.36 watts/day	348.5 watts
Position 2J – ID CZ346 Run 11A 2/05/85	360.0 watts	0.36 watts/day	351.7 watts

For each of the benchmark assemblies, the basket temperature (used as an edge boundary condition) and assembly heat load are applied to the finite element effective thermal conductivity representation for the homogeneous BWR assembly as described above. The results of the ANSYS calculation are provided in the solution output file as listed in Attachment II. To complete the benchmark, calculated peak cladding temperatures are compared to those measured in the REA 2023 storage cask test. Measured and calculated cladding temperatures are compared in Table 171. For each case, peak cladding temperatures predicted by the finite element thermal conductivity representation are compared to post-test predictions performed by Pacific Northwest Laboratory as part of the REA 2023 storage cask testing (estimated from Appendix D and Appendix E of Ref. 22).

Additional calculations of estimated peak cladding temperature were also performed using the Wootton-Epstein correlation. The Wootton-Epstein correlation is used as described in Section 5.5, with the fuel assembly and basket dimensions of Table 12 and Assumption 3.15. The fuel tube temperatures of Table 169, assembly heats of Table 170, and a peaking factor of 1.20 were also used.

Table 171 demonstrates the “best estimate” peak cladding temperature predictions from the finite element effective thermal conductivity representation. It slightly over-predicts the peak cladding temperatures for each of the experimental conditions by a maximum of 3.6°C. The over-prediction of peak cladding temperatures may be due to the method used to place thermocouples near the cladding. The thermocouple was placed on a thin metal bracket, which was then friction-fitted into the BWR assembly such that the thermocouple was next to the center rod cladding and the other end of the bracket was on the outer edge of the BWR assembly. Thus, a small conduction path from the center rod to the outer edge of the assembly was created at this location by the metal bracket. This may have influenced the local temperature and lowered the cladding temperature measurements.

The benchmarks are for both vertical and horizontal orientations. The effective thermal conductivity over-predicted peak cladding temperatures for the horizontal orientation by the largest margin of 3.6°C. Since the effective thermal conductivity development was based on the fuel assembly not contacting the basket wall, it should be expected that peak cladding temperatures will be consistently high for horizontal orientations.

Table 171. REA 2023 Storage Cask Benchmark Comparisons

Assembly	Result Source	Peak Cladding Temperature
Position 2J - ID CZ346 Run 6B 1/19/85 Vertical / Vacuum	REA 2023 Measured	172.8°C
	Spent Nuclear Fuel k_o Representation	173.1°C
	COBRA-SFS (p. E.8, Ref. 22)	166.6°C
	HYDRA (p. D.8, Ref. 22)	179.1°C
	Wooton-Epstein	158.5°C
Position 2G - ID CZ246 Run 7 1/25/85 Vertical / Nitrogen	REA 2023 Measured	146.3°C
	Spent Nuclear Fuel k_o Representation	148.5°C
	COBRA-SFS (p. E.9, Ref. 22)	133.3°C
	HYDRA (p. D.9, Ref. 22)	129.2°C
	Wooton-Epstein	141.0°C
Position 2J - ID CZ346 Run 10 2/14/85 Horizontal / Helium	REA 2023 Measured	92.1°C
	Spent Nuclear Fuel k_o Representation	95.7°C
	COBRA-SFS (p. E.11, Ref. 22)	95.8°C
	HYDRA (p. D.11, Ref. 22)	112.5°C
	Wooton-Epstein	105.7°C
Position 2J - ID CZ346 Run 11A 2/05/85 Vertical / Helium	REA 2023 Measured	105.9°C
	Spent Nuclear Fuel k_o Representation	108.2°C
	COBRA-SFS (p. E.12, Ref. 22)	118.1°C
	HYDRA (p. D.12, Ref. 22)	116.6°C
	Wooton-Epstein	117.8°C

However, if the effective thermal conductivity method were used in a full representation of the REA 2023 storage cask, a range of boundary temperatures would result around each assembly, and predicted peak temperatures could be slightly different than those reported in this calculation, since this calculation assumes a uniform basket wall temperature. Also, the assembly positions selected for the benchmarks are in the center of the storage cask where radial basket temperature gradients are the lowest.

Results from the benchmarking of two other finite element codes in Ref. 22 are also included in Table 171 for comparison.

The Wooton-Epstein correlation over-predicted the peak cladding temperatures for the helium fill gas benchmarks, but under-predicted peak cladding temperatures for the vacuum and nitrogen cases. This should be expected, since Wooton-Epstein was developed from experimental data based on air, which has a significantly lower thermal conductivity than helium, and accounted for convection and radiation heat transfer in a 17x18 rod array.

6. RESULTS

To determine spent nuclear fuel peak cladding temperatures in each of the conceptual waste package designs, a three-level approach has been assumed:

- 1) The boundary conditions for the waste package-scale representation are determined from a repository-scale representation.
- 2) The effective thermal properties, most importantly the effective thermal conductivity, for each fuel assembly are determined. This can be done either by applying the Wooton-Epstein correlation or by using another explicit representation of a fuel assembly cross section.
- 3) The boundary conditions determined in (1) and the effective properties determined in (2) are used in a waste package-scale representation, to determine peak cladding temperatures.

The effective thermal conductivities, both the basket-temperature-based values and the finite-element-based values, presented in Section 5.6 can be applied to containers in a vertical or horizontal orientation. In a vertical orientation, the effective thermal conductivity as developed in this calculation is more conservative than in a horizontal orientation, since it does not account for the natural convection heat transfer occurring in the long vertical convection cells. However, in a horizontal orientation, the effective thermal conductivity is still conservative, since it does not account for conductive paths due to contact between the fuel assembly and the basket wall.

ANSYS results were compared to those obtained with the Wooton-Epstein correlation (Ref. 26). For most helium fill gas cases, the temperature drop predicted by Wooton-Epstein was significantly greater than that predicted by the ANSYS representation. The finite element effective thermal conductivity representation was also compared to numerical and experimental studies performed for the REA 2023 storage cask (Ref. 21 and Ref. 22). The ANSYS finite element effective thermal conductivity representation slightly over-predicted the BWR assembly center rod cladding temperature compared to experimental thermocouple data reported, and it predicted peak cladding temperatures similar to those predicted by the numerical calculation in the REA 2023 test.

A backcheck calculation of the finite element effective thermal conductivities resulted in cladding temperatures within 1.8°C of those estimated with the discrete representation. For an intact BWR fuel assembly, the conductivities derived from the representation should provide a best estimate of cladding temperatures (for at least the center of a fuel canister, where basket thermal gradients are low). Care should be taken not to extrapolate the effective thermal conductivity results to alternate assembly designs (such as pressurized water reactor (PWR) assemblies) or alternate fill gases.

Table 172 through Table 177 summarize the effective thermal conductivity values derived in Section 5.6, to be used in conjunction with Equation 16, for analyses which predict the basket temperature without modeling the fuel assembly. Table 178 through Table 183 summarize the effective thermal conductivity values derived in Section 5.6, to be used with finite element methods which explicitly

represent the fuel assembly.

Table 172. Effective Thermal Conductivities (Basket Wall Temperature Based Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with No Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.317	0.108	0.141	0.131
50°C	0.349	0.127	0.163	0.152
100°C	0.421	0.174	0.217	0.204
150°C	0.506	0.236	0.284	0.270
200°C	0.604	0.315	0.367	0.351
250°C	0.718	0.411	0.468	0.451
300°C	0.848	0.527	0.587	0.569
350°C	1.001	0.663	0.726	0.707
400°C	1.152	0.820	0.881	0.862

Table 173. Effective Thermal Conductivities (Basket Wall Temperature Based Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.320	0.086	0.124	0.112
50°C	0.348	0.100	0.140	0.128
100°C	0.408	0.134	0.180	0.166
150°C	0.477	0.179	0.231	0.215
200°C	0.555	0.235	0.292	0.275
250°C	0.644	0.305	0.366	0.347
300°C	0.744	0.388	0.454	0.434
350°C	0.863	0.486	0.555	0.534
400°C	0.973	0.600	0.668	0.647

Table 174. Effective Thermal Conductivities (Basket Wall Temperature Based Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with No Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.306	0.092	0.128	0.117
50°C	0.335	0.107	0.147	0.135
100°C	0.401	0.145	0.192	0.178
150°C	0.478	0.195	0.249	0.233
200°C	0.566	0.259	0.319	0.301
250°C	0.667	0.337	0.402	0.383
300°C	0.780	0.430	0.501	0.480
350°C	0.913	0.540	0.615	0.592
400°C	1.040	0.666	0.741	0.719

Table 175. Effective Thermal Conductivities (Basket Wall Temperature Based Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.308	0.077	0.114	0.102
50°C	0.334	0.089	0.129	0.116
100°C	0.389	0.118	0.164	0.150
150°C	0.452	0.157	0.209	0.193
200°C	0.523	0.206	0.263	0.246
250°C	0.603	0.266	0.328	0.309
300°C	0.693	0.338	0.404	0.384
350°C	0.799	0.422	0.493	0.471
400°C	0.895	0.520	0.590	0.569

Table 176. Effective Thermal Conductivities (Basket Wall Temperature Based Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with No Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.294	0.089	0.122	0.111
50°C	0.321	0.104	0.139	0.128
100°C	0.383	0.141	0.182	0.169
150°C	0.455	0.189	0.236	0.222
200°C	0.538	0.251	0.303	0.287
250°C	0.633	0.327	0.383	0.366
300°C	0.742	0.419	0.479	0.461
350°C	0.871	0.528	0.591	0.572
400°C	0.996	0.654	0.717	0.697

Table 177. Effective Thermal Conductivities (Basket Wall Temperature Based Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Basket Wall Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.303	0.076	0.111	0.100
50°C	0.327	0.088	0.126	0.114
100°C	0.382	0.117	0.161	0.147
150°C	0.443	0.155	0.205	0.189
200°C	0.513	0.204	0.258	0.241
250°C	0.593	0.264	0.323	0.305
300°C	0.682	0.336	0.399	0.380
350°C	0.789	0.422	0.488	0.467
400°C	0.887	0.521	0.587	0.566

Table 178. Finite Element Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with No Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.303	0.076	0.115	0.103
50°C	0.332	0.095	0.137	0.124
75°C	0.366	0.118	0.162	0.148
100°C	0.403	0.144	0.190	0.176
125°C	0.444	0.174	0.223	0.208
150°C	0.489	0.209	0.260	0.244
175°C	0.537	0.247	0.300	0.284
200°C	0.589	0.290	0.345	0.328
225°C	0.645	0.337	0.394	0.377
250°C	0.705	0.388	0.448	0.430
275°C	0.769	0.445	0.505	0.487
300°C	0.836	0.506	0.568	0.549
325°C	0.907	0.572	0.635	0.615
350°C	0.981	0.643	0.707	0.687
375°C	1.060	0.720	0.783	0.764
400°C	1.142	0.802	0.865	0.845

Table 179. Finite Element Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 7x7 GE-2 Fuel Assembly with 80-mil Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.308	0.055	0.100	0.086
50°C	0.333	0.069	0.116	0.102
75°C	0.361	0.086	0.135	0.121
100°C	0.392	0.105	0.157	0.141
125°C	0.426	0.127	0.181	0.165
150°C	0.462	0.152	0.208	0.192
175°C	0.501	0.180	0.239	0.221
200°C	0.542	0.211	0.272	0.253
225°C	0.586	0.245	0.308	0.289
250°C	0.633	0.282	0.347	0.327
275°C	0.682	0.322	0.390	0.369
300°C	0.734	0.367	0.435	0.414
325°C	0.788	0.415	0.484	0.463
350°C	0.844	0.466	0.537	0.515
375°C	0.903	0.522	0.593	0.571
400°C	0.965	0.582	0.652	0.630

Table 180. Finite Element Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with No Channel

Median Temperature	Average Effective Thermal Conductivity (W/m-K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.292	0.062	0.104	0.092
50°C	0.319	0.077	0.122	0.109
75°C	0.350	0.096	0.144	0.130
100°C	0.384	0.117	0.168	0.153
125°C	0.422	0.142	0.196	0.180
150°C	0.462	0.169	0.226	0.210
175°C	0.506	0.201	0.260	0.243
200°C	0.553	0.235	0.298	0.280
225°C	0.602	0.273	0.339	0.320
250°C	0.655	0.315	0.383	0.363
275°C	0.711	0.360	0.431	0.410
300°C	0.769	0.410	0.483	0.461
325°C	0.831	0.463	0.538	0.516
350°C	0.895	0.521	0.597	0.574
375°C	0.962	0.582	0.660	0.637
400°C	1.031	0.648	0.726	0.703

Table 181. Finite Element Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for GE 8x8 GE-5 Fuel Assembly with 80-mil Channel

Median Temperature	Average Effective Thermal Conductivity (W/m-K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.297	0.048	0.092	0.079
50°C	0.320	0.060	0.106	0.092
75°C	0.346	0.075	0.123	0.109
100°C	0.374	0.092	0.142	0.127
125°C	0.405	0.111	0.164	0.148
150°C	0.438	0.132	0.188	0.171
175°C	0.474	0.156	0.214	0.197
200°C	0.511	0.183	0.243	0.225
225°C	0.551	0.212	0.275	0.256
250°C	0.593	0.244	0.310	0.290
275°C	0.637	0.279	0.347	0.326
300°C	0.683	0.317	0.387	0.366
325°C	0.732	0.359	0.430	0.408
350°C	0.782	0.403	0.475	0.453
375°C	0.834	0.451	0.524	0.502
400°C	0.888	0.503	0.576	0.553

Table 182. Finite Element Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with No Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.281	0.059	0.098	0.086
50°C	0.306	0.074	0.115	0.103
75°C	0.335	0.092	0.135	0.122
100°C	0.367	0.113	0.158	0.144
125°C	0.401	0.137	0.184	0.170
150°C	0.439	0.164	0.213	0.198
175°C	0.480	0.194	0.246	0.230
200°C	0.524	0.227	0.282	0.265
225°C	0.572	0.264	0.321	0.304
250°C	0.622	0.305	0.364	0.346
275°C	0.675	0.350	0.411	0.392
300°C	0.731	0.399	0.461	0.442
325°C	0.790	0.451	0.515	0.495
350°C	0.853	0.509	0.573	0.553
375°C	0.918	0.570	0.635	0.615
400°C	0.986	0.637	0.701	0.681

Table 183. Finite Element Effective Thermal Conductivities (Average Values) Versus Fill Gas Environment for ANF-JP 9x9 Fuel Assembly with 80-mil Channel

Median Temperature	Average Effective Thermal Conductivity (W/m·K)			
	Helium	Vacuum	Nitrogen	Argon
25°C	0.291	0.047	0.090	0.076
50°C	0.314	0.059	0.104	0.090
75°C	0.339	0.074	0.120	0.106
100°C	0.367	0.090	0.139	0.124
125°C	0.397	0.109	0.160	0.145
150°C	0.430	0.130	0.184	0.167
175°C	0.464	0.154	0.210	0.193
200°C	0.502	0.181	0.238	0.221
225°C	0.541	0.210	0.270	0.252
250°C	0.583	0.242	0.304	0.285
275°C	0.627	0.277	0.341	0.322
300°C	0.673	0.316	0.381	0.361
325°C	0.721	0.357	0.424	0.404
350°C	0.772	0.403	0.470	0.449
375°C	0.824	0.451	0.520	0.498
400°C	0.879	0.504	0.572	0.550

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8. ATTACHMENTS

Attachments to this calculation are summarized in Table 184. Each attachment is identified by its specific number, file name, date, and number of pages.

Table 184. List of Attachments

Attachment Number	Description	Date	Number of Pages
I	CD	7/23/01	N/A
II	Electronic File Listing for CD Attachment I	10/9/01	9
III	ANSYS Material Property File	10/9/01	4
IV	Finite Element Mesh Images and Temperature Result Contour Plots	10/9/01	32
V	44 BWR Waste Package Sketch	10/9/01	2
VI	Technical Basis for Assumption 3.20	10/9/01	4

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1. QA: QA

Page: 1 of: 1

Complete Only Applicable Items

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2. Record Date
10/17/2001

3. Accession Number

ATTN MOL. 20011101. 0005

4. Author Name(s)
MATTHEW D. HINDS

5. Author Organization
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10810

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ELECTRONIC FILE CERTIFICATION**

QA: N/A

1. DOCUMENT TITLE:

Determination of BWR Spent Nuclear Fuel Assembly Effective Thermal Conductivity

2. IDENTIFIER (e.g., DI OR PI):

CAL-WIS-TH-000011

3. REVISION DESIGNATOR:

Rev. 00

ATTACHED SOFTWARE FILE INFORMATION

4. PDF FILE SUBMITTED:

☐ YES

☒ NO

5. FILE NAMES(S) WITH FILE EXTENSION(S) PROVIDED BY THE SOFTWARE:

See Attached

6. DATE LAST MODIFIED:

See Attached

7. NATIVE APPLICATION:

(i.e., EXCEL, WORD, CORELDRAW)

Word

8. FILE SIZE IN KILOBYTES:

See Attached

9. FILE LINKAGE INSTRUCTIONS/INFORMATION:

Standard

10. PRINTER SPECIFICATION (I.E., HP4SI) INCLUDING POSTSCRIPT INFORMATION (I.E., PRINTER DRIVER) AND PRINTING PAGE SETUP: (I.E., LANDSCAPE, 11 X 17 PAPER)

8 1/2 x 11 (portrait)= 1024 Hewlett Packard Laser 5 sinx

11. COMPUTING PLATFORM USED: (I.E., PC, SUN, WIN 95, NT, HP)

PC# 116722

12. OPERATING SYSTEM AND VERSION: (I.E., WINDOWS UNIX, SOLARIS)

Windows

13. ADDITIONAL HARDWARE/SOFTWARE REQUIREMENT USED TO CREATE FILE(S):

None

14. ACCESS RESTRICTIONS: (COPYRIGHT OR LICENSE ISSUES)

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COMMENTS/SPECIAL INSTRUCTIONS

15. IS SOFTWARE AVAILABLE FROM SOFTWARE CONFIGURATION MANAGEMENT?

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CERTIFICATION

16. DOCUMENT OWNER (Print and Sign):

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10/24/2001

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28. DATE:

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Electronic File Listing for CD Attachment I

Filename	Ext.	Description	Size (kB)	Date	Results Used In
b7arg0c_01a	.out	Output for 7x7 case with argon fill gas, no channel, and no water rod	709	7/23/01	--
b7arg0c_01a	.parm	Parameter output for 7x7 case with argon fill gas, no channel, and no water rod	17	3/29/01	Tables 62, 63, 103, 107, 172
b7arg8c_01a	.out	Output for 7x7 case with argon fill gas, 80-mil channel, and no water rod	654	7/23/01	--
b7arg8c_01a	.parm	Parameter output for 7x7 case with argon fill gas, 80-mil channel, and no water rod	17	3/29/01	Tables 64, 65, 104, 108, 173
b7hel0c_01a	.out	Output for 7x7 case with helium fill gas, no channel, and no water rod	676	7/23/01	--
b7hel0c_01a	.parm	Parameter output for 7x7 case with helium fill gas, no channel, and no water rod	17	3/29/01	Tables 24, 25, 97, 107, 172
b7hel8c_01a	.out	Output for 7x7 case with helium fill gas, 80-mil channel, and no water rod	621	7/23/01	--
b7hel8c_01a_supp	.parm	Parameter output for 7x7 case with helium fill gas, 80-mil channel, and no water rod	17	4/2/01	Tables 18, 19, 98, 108, 173
b7hel10c_01a	.out	Output for 7x7 case with helium fill gas, 100-mil channel, and no water rod	621	7/23/01	--
b7hel10c_01a_supp	.parm	Parameter output for 7x7 case with helium fill gas, 100-mil channel, and no water rod	17	4/2/01	Tables 30 & 31
b7hel12c_01a	.out	Output for 7x7 case with helium fill gas, 120-mil channel, and no water rod	620	7/23/01	--
b7hel12c_01a_supp	.parm	Parameter output for 7x7 case with helium fill gas, 120-mil channel, and no water rod	17	4/2/01	Tables 32 & 33
b7nit0c_01a	.out	Output for 7x7 case with nitrogen fill gas, no channel, and no water rod	696	7/23/01	--
b7nit0c_01a	.parm	Parameter output for 7x7 case with nitrogen fill gas, no channel, and no water rod	17	3/29/01	Tables 50, 51, 101, 107, 172
b7nit8c_01a	.out	Output for 7x7 case with nitrogen fill gas, 80-mil channel, and no water rod	648	7/23/01	--
b7nit8c_01a	.parm	Parameter output for 7x7 case with nitrogen fill gas, 80-mil channel, and no water rod	17	3/29/01	Tables 52, 53, 102, 108, 173
b7vac0c_01a	.out	Output for 7x7 case with vacuum fill condition, no channel, and no water rod	530	7/23/01	--
b7vac0c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, no channel, and no water rod	17	3/29/01	Tables 34, 35, 99, 107, 172
b7vac8c_01a	.out	Output for 7x7 case with vacuum fill condition, 80-mil channel, and no water rod	543	7/23/01	--
b7vac8c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, 80-mil channel, and no water rod	17	3/29/01	Tables 36, 37, 100, 108, 173
b7vac10c_01a	.out	Output for 7x7 case with vacuum fill condition, 100-mil channel, and no water rod	543	7/23/01	--

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
b7vac10c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, 100-mil channel, and no water rod	17	3/29/01	Tables 38 & 39
b7vac12c_01a	.out	Output for 7x7 case with vacuum fill condition, 120-mil channel, and no water rod	543	7/23/01	--
b7vac12c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, 120-mil channel, and no water rod	17	3/29/01	Tables 40 & 41
b7air0c_01a	.out	Output for 7x7 case with air fill gas, no channel, and no water rod	694	7/23/01	--
b7air0c_01a	.parm	Parameter output for 7x7 case with air fill gas, no channel, and no water rod	17	4/4/01	Assumption 3.27
b7air8c_01a	.out	Output for 7x7 case with air fill gas, 80-mil channel, and no water rod	649	7/23/01	--
b7air8c_01a	.parm	Parameter output for 7x7 case with air fill gas, 80-mil channel, and no water rod	17	4/4/01	Assumption 3.27
w7arg0c_01b	.out	Output for 7x7 case with argon fill gas, no channel, and water rod	1,569	7/23/01	--
w7arg0c_01b	.parm	Parameter output for 7x7 case with argon fill gas, no channel, and water rod	5	5/7/01	Text of Section 5.4.4
w7arg8c_01c	.out	Output for 7x7 case with argon fill gas, 80-mil channel, and water rod	1,325	7/23/01	--
w7arg8c_01c	.parm	Parameter output for 7x7 case with argon fill gas, 80-mil channel, and water rod	5	7/19/01	Text of Section 5.4.4
w7hel0c_01c	.out	Output for 7x7 case with helium fill gas, no channel, and water rod	1,564	7/23/01	--
w7hel0c_01c	.parm	Parameter output for 7x7 case with helium fill gas, no channel, and water rod	5	7/19/01	Text of Section 5.4.4
w7hel8c_01a	.out	Output for 7x7 case with helium fill gas, 80-mil channel, and water rod (incomplete, see next row)	1,293	7/23/01	--
w7hel8c_01a	.parm	Parameter output for 7x7 case with helium fill gas, 80-mil channel, and water rod (incomplete, see next row)	2	5/7/01	Text of Section 5.4.4
w7hel8c_supp	.out	Supplemental post-processing file for w7hel8c_01a.out (above)	19	7/23/01	--
w7hel8c_supp	.parm	Supplemental parameter output for w7hel8c_01a.parm (above). Contains complete parameter output.	5	5/7/01	Text of Section 5.4.4
w7nit0c_01b	.out	Output for 7x7 case with nitrogen fill gas, no channel, and water rod	1,568	7/23/01	--
w7nit0c_01b	.parm	Parameter output for 7x7 case with nitrogen fill gas, no channel, and water rod	5	5/7/01	Text of Section 5.4.4
w7nit8c_01c	.out	Output for 7x7 case with nitrogen fill gas, 80-mil channel, and water rod	1,322	7/23/01	--
w7nit8c_01c	.parm	Parameter output for 7x7 case with nitrogen fill gas, 80-mil channel, and water rod	5	7/19/01	Text of Section 5.4.4

4810

Filename	Ext.	Description	Size (kB)	Date	Results Used In
w7vac0c_01b	.out	Output for 7x7 case with vacuum fill condition, no channel, and water rod	1,587	7/23/01	--
w7vac0c_01b	.parm	Parameter output for 7x7 case with vacuum fill condition, no channel, and water rod	5	5/7/01	Text of Section 5.4.4
w7vac8c_01c	.out	Output for 7x7 case with vacuum fill condition, 80-mil channel, and water rod	1,271	7/23/01	--
w7vac8c_01c	.parm	Parameter output for 7x7 case with vacuum fill condition, 80-mil channel, and water rod	5	7/19/01	Text of Section 5.4.4
b8arg0c_01	.out	Output for 8x8 case with argon fill gas, no channel, and no water rod	546	7/23/01	--
b8arg0c_01	.parm	Parameter output for 8x8 case with argon fill gas, no channel, and no water rod	13	4/5/01	Tables 66, 67, 116, 120, 174
b8arg8c_01	.out	Output for 8x8 case with argon fill gas, 80-mil channel, and no water rod	466	7/23/01	--
b8arg8c_01	.parm	Parameter output for 8x8 case with argon fill gas, 80-mil channel, and no water rod	13	4/5/01	Tables 68, 69, 117, 121, 175
b8hel0c_01	.out	Output for 8x8 case with helium fill gas, no channel, and no water rod	506	7/23/01	--
b8hel0c_01	.parm	Parameter output for 8x8 case with helium fill gas, no channel, and no water rod	13	4/5/01	Tables 26, 27, 110, 120, 174
b8hel8c_01	.out	Output for 8x8 case with helium fill gas, 80-mil channel, and no water rod	457	7/23/01	--
b8hel8c_01	.parm	Parameter output for 8x8 case with helium fill gas, 80-mil channel, and no water rod	13	4/5/01	Tables 20, 21, 111, 121, 175
b8nit0c_01	.out	Output for 8x8 case with nitrogen fill gas, no channel, and no water rod	540	7/23/01	--
b8nit0c_01	.parm	Parameter output for 8x8 case with nitrogen fill gas, no channel, and no water rod	13	4/5/01	Tables 54, 55, 114, 120, 174
b8nit8c_01	.out	Output for 8x8 case with nitrogen fill gas, 80-mil channel, and no water rod	463	7/23/01	--
b8nit8c_01	.parm	Parameter output for 8x8 case with nitrogen fill gas, 80-mil channel, and no water rod	13	4/5/01	Tables 56, 57, 115, 121, 175
b8vac0c_01	.out	Output for 8x8 case with vacuum fill condition, no channel, and no water rod	513	7/23/01	--
b8vac0c_01	.parm	Parameter output for 8x8 case with vacuum fill condition, no channel, and no water rod	13	4/5/01	Tables 42, 43, 112, 120, 174
b8vac8c_01	.out	Output for 8x8 case with vacuum fill condition, 80-mil channel, and no water rod	563	7/23/01	--
b8vac8c_01	.parm	Parameter output for 8x8 case with vacuum fill condition, 80-mil channel, and no water rod	13	4/5/01	Tables 44, 45, 113, 121, 175
w8arg0c_01	.out	Output for 8x8 case with argon fill gas, no channel, and water rod	542	7/23/01	--
w8arg0c_01	.parm	Parameter output for 8x8 case with argon fill gas, no channel, and water rod	17	5/7/01	Table 80

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
w8arg8c_01	.out	Output for 8x8 case with argon fill gas, 80-mil channel, and water rod	506	7/23/01	--
w8arg8c_01	.parm	Parameter output for 8x8 case with argon fill gas, 80-mil channel, and water rod	17	5/7/01	Table 81
w8hel0c_01	.out	Output for 8x8 case with helium fill gas, no channel, and water rod	530	7/23/01	--
w8hel0c_01	.parm	Parameter output for 8x8 case with helium fill gas, no channel, and water rod	17	5/7/01	Table 74
w8hel8c_01	.out	Output for 8x8 case with helium fill gas, 80-mil channel, and water rod	465	7/23/01	--
w8hel8c_01	.parm	Parameter output for 8x8 case with helium fill gas, 80-mil channel, and water rod	17	5/7/01	Table 75
w8nit0c_01	.out	Output for 8x8 case with nitrogen fill gas, no channel, and water rod	540	7/23/01	--
w8nit0c_01	.parm	Parameter output for 8x8 case with nitrogen fill gas, no channel, and water rod	17	5/7/01	Table 78
w8nit8c_01	.out	Output for 8x8 case with nitrogen fill gas, 80-mil channel, and water rod	505	7/23/01	--
w8nit8c_01	.parm	Parameter output for 8x8 case with nitrogen fill gas, 80-mil channel, and water rod	17	5/7/01	Table 79
w8vac0c_01	.out	Output for 8x8 case with vacuum fill condition, no channel, and water rod	582	7/23/01	--
w8vac0c_01	.parm	Parameter output for 8x8 case with vacuum fill condition, no channel, and water rod	17	5/7/01	Table 76
w8vac8c_01a	.out	Output for 8x8 case with vacuum fill condition, 80-mil channel, and water rod	556	7/23/01	--
w8vac8c_01a	.parm	Parameter output for 8x8 case with vacuum fill condition, 80-mil channel, and water rod	17	5/7/01	Table 77
b9arg0c_01	.out	Output for 9x9 case with argon fill gas, no channel, and no water rod	568	7/23/01	--
b9arg0c_01	.parm	Parameter output for 9x9 case with argon fill gas, no channel, and no water rod	17	4/5/01	Tables 70, 71, 129, 133, 176
b9arg8c_01a	.out	Output for 9x9 case with argon fill gas, 80-mil channel, and no water rod	614	7/23/01	--
b9arg8c_01a	.parm	Parameter output for 9x9 case with argon fill gas, 80-mil channel, and no water rod	17	4/5/01	Tables 72, 73, 130, 134, 177
b9hel0c_01	.out	Output for 9x9 case with helium fill gas, no channel, and no water rod	540	7/23/01	--
b9hel0c_01	.parm	Parameter output for 9x9 case with helium fill gas, no channel, and no water rod	17	4/5/01	Tables 28, 29, 123, 133, 176
b9hel8c_01a	.out	Output for 9x9 case with helium fill gas, 80-mil channel, and no water rod	550	7/23/01	--
b9hel8c_01a	.parm	Parameter output for 9x9 case with helium fill gas, 80-mil channel, and no water rod	17	4/5/01	Tables 22, 23, 124, 134, 177

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
b9nit0c_01	.out	Output for 9x9 case with nitrogen fill gas, no channel, and no water rod	573	7/23/01	--
b9nit0c_01	.parm	Parameter output for 9x9 case with nitrogen fill gas, no channel, and no water rod	17	4/5/01	Tables 58, 59, 127, 133, 176
b9nit8c_01a	.out	Output for 9x9 case with nitrogen fill gas, 80-mil channel, and no water rod	577	7/23/01	--
b9nit8c_01a	.parm	Parameter output for 9x9 case with nitrogen fill gas, 80-mil channel, and no water rod	17	4/5/01	Tables 60, 61, 128, 134, 177
b9vac0c_01	.out	Output for 9x9 case with vacuum fill condition, no channel, and no water rod	544	7/23/01	--
b9vac0c_01	.parm	Parameter output for 9x9 case with vacuum fill condition, no channel, and no water rod	17	4/5/01	Tables 46, 47, 125, 133, 176
b9vac8c_01a	.out	Output for 9x9 case with vacuum fill condition, 80-mil channel, and no water rod	548	7/23/01	--
b9vac8c_01a	.parm	Parameter output for 9x9 case with vacuum fill condition, 80-mil channel, and no water rod	17	4/5/01	Tables 48, 49, 126, 134, 177
w9arg0c_01b	.out	Output for 9x9 case with argon fill gas, no channel, and water rod	486	7/23/01	--
w9arg0c_restart	.out	Output file for restart of w9arg0c_01b.out case (above), which was interrupted	3,181	7/23/01	--
w9arg0c_01b	.parm	Parameter output for 9x9 case with argon fill gas, no channel, and water rod	17	5/7/01	Table 88
w9arg8c_01	.out	Output for 9x9 case with argon fill gas, 80-mil channel, and water rod	711	7/23/01	--
w9arg8c_01	.parm	Parameter output for 9x9 case with argon fill gas, 80-mil channel, and water rod	17	5/7/01	Table 89
w9hel0c_01b	.out	Output for 9x9 case with helium fill gas, no channel, and water rod	837	7/23/01	--
w9hel0c_01b	.parm	Parameter output for 9x9 case with helium fill gas, no channel, and water rod	17	5/7/01	Table 82
w9hel8c_01d	.out	Output for 9x9 case with helium fill gas, 80-mil channel, and water rod	596	7/23/01	--
w9hel8c_01d	.parm	Parameter output for 9x9 case with helium fill gas, 80-mil channel, and water rod	17	5/7/01	Table 83
w9nit0c_01b	.out	Output for 9x9 case with nitrogen fill gas, no channel, and water rod	2,904	7/23/01	--
w9nit0c_01b	.parm	Parameter output for 9x9 case with nitrogen fill gas, no channel, and water rod	17	5/7/01	Table 86
w9nit8c_01d	.out	Output for 9x9 case with nitrogen fill gas, 80-mil channel, and water rod	624	7/23/01	--
w9nit8c_01d	.parm	Parameter output for 9x9 case with nitrogen fill gas, 80-mil channel, and water rod	17	5/7/01	Table 87
w9vac0c_01	.out	Output for 9x9 case with vacuum fill condition, no channel, and water rod	572	7/23/01	--

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
w9vac0c_01	.parm	Parameter output for 9x9 case with vacuum fill condition, no channel, and water rod	17	5/7/01	Table 84
w9vac8c_01b	.out	Output for 9x9 case with vacuum fill condition, 80-mil channel, and water rod	616	7/23/01	--
w9vac8c_01b	.parm	Parameter output for 9x9 case with vacuum fill condition, 80-mil channel, and water rod	17	5/11/01	Table 85
h7stack_01	.out	Backcheck file for 7x7 cases, as referred to in Section 5.7 of the document. Parameter output files for each 7x7 case were read, and the peak cladding temperatures predicted with the effective thermal conductivity were backchecked against explicitly calculated values. This case created the eight files named h7*_01.parm, listed below in this table.	2,038	7/23/01	--
h7arg0c_01	.parm	Parameter output for backcheck of 7x7 case with argon fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 151
h7arg8c_01	.parm	Parameter output for backcheck of 7x7 case with argon fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 152
h7hel0c_01	.parm	Parameter output for backcheck of 7x7 case with helium fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 145
h7hel8c_01	.parm	Parameter output for backcheck of 7x7 case with a helium fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	13	4/27/01	Table 146
h7nit0c_01	.parm	Parameter output for backcheck of 7x7 case with nitrogen fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 149
h7nit8c_01	.parm	Parameter output for backcheck of 7x7 case with nitrogen fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 150
h7vac0c_01	.parm	Parameter output for backcheck of 7x7 case with vacuum fill condition, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 147
h7vac8c_01	.parm	Parameter output for backcheck of 7x7 case with vacuum fill condition, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 148

Filename	Ext.	Description	Size (kB)	Date	Results Used In
h8stack_02	.out	Backcheck file for 8x8 cases, as referred to in Section 5.7 of the document. Parameter output files for each 8x8 case were read, and the peak cladding temperatures predicted with the effective thermal conductivity were backchecked against explicitly calculated values. This case created the eight files named h8*_02.parm, listed below in this table.	2,010	7/23/01	--
h8arg0c_02	.parm	Parameter output for backcheck of 8x8 case with argon fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 159
h8arg8c_02	.parm	Parameter output for backcheck of 8x8 case with argon fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 160
h8hel0c_02	.parm	Parameter output for backcheck of 8x8 case with helium fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 153
h8hel8c_02	.parm	Parameter output for backcheck of 8x8 case with helium fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 154
h8nit0c_02	.parm	Parameter output for backcheck of 8x8 case with nitrogen fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 157
h8nit8c_02	.parm	Parameter output for backcheck of 8x8 case with nitrogen fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 158
h8vac0c_02	.parm	Parameter output for backcheck of 8x8 case with vacuum fill condition, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 155
h8vac8c_02	.parm	Parameter output for backcheck of 8x8 case with vacuum fill condition, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 156
h9stack_02	.out	Backcheck file for 9x9 cases, as referred to in Section 5.7 of the document. Parameter output files for each 9x9 case were read, and the peak cladding temperatures predicted with the effective thermal conductivity were backchecked against explicitly calculated values. This case created the eight files named h9*_02.parm, listed below in this table.	2,056	7/23/01	--

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
h9arg0c_02	.parm	Parameter output for backcheck of 9x9 case with argon fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 167
h9arg8c_02	.parm	Parameter output for backcheck of 9x9 case with argon fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 168
h9hel0c_02	.parm	Parameter output for backcheck of 9x9 case with helium fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 161
h9hel8c_02	.parm	Parameter output for backcheck of 9x9 case with helium fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 162
h9nit0c_02	.parm	Parameter output for backcheck of 9x9 case with nitrogen fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 165
h9nit8c_02	.parm	Parameter output for backcheck of 9x9 case with nitrogen fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 166
h9vac0c_02	.parm	Parameter output for backcheck of 9x9 case with vacuum fill condition, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 163
h9vac8c_02	.parm	Parameter output for backcheck of 9x9 case with vacuum fill condition, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 164
bench7_01	.out	Benchmark case of peak fuel temperatures predicted by effective thermal conductivity method against those measured in GE Morris Operation facility test. The difference between the two is output to the following four parameter files.	273	7/23/01	--
hel7b1	.parm	Parameter output for benchmark case against Run 11A of the GE Morris Operation facility test, at thermocouple position 2J – ID CZ346	1	7/23/01	Table 171
hel7b2	.parm	Parameter output for benchmark case against Run 10 of the GE Morris Operation facility test, at thermocouple position 2J – ID CZ346	1	7/23/01	Table 171
nit7b1	.parm	Parameter output for benchmark case against Run 7 of the GE Morris Operation facility test, at thermocouple position 2G – ID CZ246	1	7/23/01	Table 171
vac7b1	.parm	Parameter output for benchmark case against Run 6B of the GE Morris Operation facility test, at thermocouple position 2J – ID CZ346	1	7/23/01	Table 171

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
h7mstk1_01	.out	Output for mesh density sensitivity test – 7x7 rod array with vacuum fill condition, 80-mil channel, and no water rod. Parameter output from this calculation is included below (h7vac22.parm et al., the last seven rows of this table)	2,141	7/23/01	--
h7vac22	.parm	Parameter output for mesh density sensitivity test – 2x2 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac44	.parm	Parameter output for mesh density sensitivity test – 4x4 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac66	.parm	Parameter output for mesh density sensitivity test – 6x6 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac88	.parm	Parameter output for mesh density sensitivity test – 8x8 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac10	.parm	Parameter output for mesh density sensitivity test – 10x10 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac12	.parm	Parameter output for mesh density sensitivity test – 12x12 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac14	.parm	Parameter output for mesh density sensitivity test – 14x14 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
emis_sens_test	.out	Output for case determining sensitivity of peak cladding temperatures in a 7x7 fuel assembly to basket wall emissivity variations	3,660	7/23/01	--

Electronic File Listing for CD Attachment I

Filename	Ext.	Description	Size (kB)	Date	Results Used In
b7arg0c_01a	.out	Output for 7x7 case with argon fill gas, no channel, and no water rod	709	7/23/01	--
b7arg0c_01a	.parm	Parameter output for 7x7 case with argon fill gas, no channel, and no water rod	17	3/29/01	Tables 62, 63, 103, 107, 172
b7arg8c_01a	.out	Output for 7x7 case with argon fill gas, 80-mil channel, and no water rod	654	7/23/01	--
b7arg8c_01a	.parm	Parameter output for 7x7 case with argon fill gas, 80-mil channel, and no water rod	17	3/29/01	Tables 64, 65, 104, 108, 173
b7hel0c_01a	.out	Output for 7x7 case with helium fill gas, no channel, and no water rod	676	7/23/01	--
b7hel0c_01a	.parm	Parameter output for 7x7 case with helium fill gas, no channel, and no water rod	17	3/29/01	Tables 24, 25, 97, 107, 172
b7hel8c_01a	.out	Output for 7x7 case with helium fill gas, 80-mil channel, and no water rod	621	7/23/01	--
b7hel8c_01a_supp	.parm	Parameter output for 7x7 case with helium fill gas, 80-mil channel, and no water rod	17	4/2/01	Tables 18, 19, 98, 108, 173
b7hel10c_01a	.out	Output for 7x7 case with helium fill gas, 100-mil channel, and no water rod	621	7/23/01	--
b7hel10c_01a_supp	.parm	Parameter output for 7x7 case with helium fill gas, 100-mil channel, and no water rod	17	4/2/01	Tables 30 & 31
b7hel12c_01a	.out	Output for 7x7 case with helium fill gas, 120-mil channel, and no water rod	620	7/23/01	--
b7hel12c_01a_supp	.parm	Parameter output for 7x7 case with helium fill gas, 120-mil channel, and no water rod	17	4/2/01	Tables 32 & 33
b7nit0c_01a	.out	Output for 7x7 case with nitrogen fill gas, no channel, and no water rod	696	7/23/01	--
b7nit0c_01a	.parm	Parameter output for 7x7 case with nitrogen fill gas, no channel, and no water rod	17	3/29/01	Tables 50, 51, 101, 107, 172
b7nit8c_01a	.out	Output for 7x7 case with nitrogen fill gas, 80-mil channel, and no water rod	648	7/23/01	--
b7nit8c_01a	.parm	Parameter output for 7x7 case with nitrogen fill gas, 80-mil channel, and no water rod	17	3/29/01	Tables 52, 53, 102, 108, 173
b7vac0c_01a	.out	Output for 7x7 case with vacuum fill condition, no channel, and no water rod	530	7/23/01	--
b7vac0c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, no channel, and no water rod	17	3/29/01	Tables 34, 35, 99, 107, 172
b7vac8c_01a	.out	Output for 7x7 case with vacuum fill condition, 80-mil channel, and no water rod	543	7/23/01	--
b7vac8c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, 80-mil channel, and no water rod	17	3/29/01	Tables 36, 37, 100, 108, 173
b7vac10c_01a	.out	Output for 7x7 case with vacuum fill condition, 100-mil channel, and no water rod	543	7/23/01	--

Filename	Ext.	Description	Size (kB)	Date	Results Used In
b7vac10c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, 100-mil channel, and no water rod	17	3/29/01	Tables 38 & 39
b7vac12c_01a	.out	Output for 7x7 case with vacuum fill condition, 120-mil channel, and no water rod	543	7/23/01	--
b7vac12c_01a	.parm	Parameter output for 7x7 case with vacuum fill condition, 120-mil channel, and no water rod	17	3/29/01	Tables 40 & 41
b7air0c_01a	.out	Output for 7x7 case with air fill gas, no channel, and no water rod	694	7/23/01	--
b7air0c_01a	.parm	Parameter output for 7x7 case with air fill gas, no channel, and no water rod	17	4/4/01	Assumption 3.27
b7air8c_01a	.out	Output for 7x7 case with air fill gas, 80-mil channel, and no water rod	649	7/23/01	--
b7air8c_01a	.parm	Parameter output for 7x7 case with air fill gas, 80-mil channel, and no water rod	17	4/4/01	Assumption 3.27
w7arg0c_01b	.out	Output for 7x7 case with argon fill gas, no channel, and water rod	1,569	7/23/01	--
w7arg0c_01b	.parm	Parameter output for 7x7 case with argon fill gas, no channel, and water rod	5	5/7/01	Text of Section 5.4.4
w7arg8c_01c	.out	Output for 7x7 case with argon fill gas, 80-mil channel, and water rod	1,325	7/23/01	--
w7arg8c_01c	.parm	Parameter output for 7x7 case with argon fill gas, 80-mil channel, and water rod	5	7/19/01	Text of Section 5.4.4
w7hel0c_01c	.out	Output for 7x7 case with helium fill gas, no channel, and water rod	1,564	7/23/01	--
w7hel0c_01c	.parm	Parameter output for 7x7 case with helium fill gas, no channel, and water rod	5	7/19/01	Text of Section 5.4.4
w7hel8c_01a	.out	Output for 7x7 case with helium fill gas, 80-mil channel, and water rod (incomplete, see next row)	1,293	7/23/01	--
w7hel8c_01a	.parm	Parameter output for 7x7 case with helium fill gas, 80-mil channel, and water rod (incomplete, see next row)	2	5/7/01	Text of Section 5.4.4
w7hel8c_supp	.out	Supplemental post-processing file for w7hel8c_01a.out (above)	19	7/23/01	--
w7hel8c_supp	.parm	Supplemental parameter output for w7hel8c_01a.parm (above). Contains complete parameter output.	5	5/7/01	Text of Section 5.4.4
w7nit0c_01b	.out	Output for 7x7 case with nitrogen fill gas, no channel, and water rod	1,568	7/23/01	--
w7nit0c_01b	.parm	Parameter output for 7x7 case with nitrogen fill gas, no channel, and water rod	5	5/7/01	Text of Section 5.4.4
w7nit8c_01c	.out	Output for 7x7 case with nitrogen fill gas, 80-mil channel, and water rod	1,322	7/23/01	--
w7nit8c_01c	.parm	Parameter output for 7x7 case with nitrogen fill gas, 80-mil channel, and water rod	5	7/19/01	Text of Section 5.4.4

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Filename	Ext.	Description	Size (kB)	Date	Results Used In
w8arg8c_01	.out	Output for 8x8 case with argon fill gas, 80-mil channel, and water rod	506	7/23/01	--
w8arg8c_01	.parm	Parameter output for 8x8 case with argon fill gas, 80-mil channel, and water rod	17	5/7/01	Table 81
w8hel0c_01	.out	Output for 8x8 case with helium fill gas, no channel, and water rod	530	7/23/01	--
w8hel0c_01	.parm	Parameter output for 8x8 case with helium fill gas, no channel, and water rod	17	5/7/01	Table 74
w8hel8c_01	.out	Output for 8x8 case with helium fill gas, 80-mil channel, and water rod	465	7/23/01	--
w8hel8c_01	.parm	Parameter output for 8x8 case with helium fill gas, 80-mil channel, and water rod	17	5/7/01	Table 75
w8nit0c_01	.out	Output for 8x8 case with nitrogen fill gas, no channel, and water rod	540	7/23/01	--
w8nit0c_01	.parm	Parameter output for 8x8 case with nitrogen fill gas, no channel, and water rod	17	5/7/01	Table 78
w8nit8c_01	.out	Output for 8x8 case with nitrogen fill gas, 80-mil channel, and water rod	505	7/23/01	--
w8nit8c_01	.parm	Parameter output for 8x8 case with nitrogen fill gas, 80-mil channel, and water rod	17	5/7/01	Table 79
w8vac0c_01	.out	Output for 8x8 case with vacuum fill condition, no channel, and water rod	582	7/23/01	--
w8vac0c_01	.parm	Parameter output for 8x8 case with vacuum fill condition, no channel, and water rod	17	5/7/01	Table 76
w8vac8c_01a	.out	Output for 8x8 case with vacuum fill condition, 80-mil channel, and water rod	556	7/23/01	--
w8vac8c_01a	.parm	Parameter output for 8x8 case with vacuum fill condition, 80-mil channel, and water rod	17	5/7/01	Table 77
b9arg0c_01	.out	Output for 9x9 case with argon fill gas, no channel, and no water rod	568	7/23/01	--
b9arg0c_01	.parm	Parameter output for 9x9 case with argon fill gas, no channel, and no water rod	17	4/5/01	Tables 70, 71, 129, 133, 176
b9arg8c_01a	.out	Output for 9x9 case with argon fill gas, 80-mil channel, and no water rod	614	7/23/01	--
b9arg8c_01a	.parm	Parameter output for 9x9 case with argon fill gas, 80-mil channel, and no water rod	17	4/5/01	Tables 72, 73, 130, 134, 177
b9hel0c_01	.out	Output for 9x9 case with helium fill gas, no channel, and no water rod	540	7/23/01	--
b9hel0c_01	.parm	Parameter output for 9x9 case with helium fill gas, no channel, and no water rod	17	4/5/01	Tables 28, 29, 123, 133, 176
b9hel8c_01a	.out	Output for 9x9 case with helium fill gas, 80-mil channel, and no water rod	550	7/23/01	--
b9hel8c_01a	.parm	Parameter output for 9x9 case with helium fill gas, 80-mil channel, and no water rod	17	4/5/01	Tables 22, 23, 124, 134, 177

Filename	Ext.	Description	Size (kB)	Date	Results Used In
b9nit0c_01	.out	Output for 9x9 case with nitrogen fill gas, no channel, and no water rod	573	7/23/01	--
b9nit0c_01	.parm	Parameter output for 9x9 case with nitrogen fill gas, no channel, and no water rod	17	4/5/01	Tables 58, 59, 127, 133, 176
b9nit8c_01a	.out	Output for 9x9 case with nitrogen fill gas, 80-mil channel, and no water rod	577	7/23/01	--
b9nit8c_01a	.parm	Parameter output for 9x9 case with nitrogen fill gas, 80-mil channel, and no water rod	17	4/5/01	Tables 60, 61, 128, 134, 177
b9vac0c_01	.out	Output for 9x9 case with vacuum fill condition, no channel, and no water rod	544	7/23/01	--
b9vac0c_01	.parm	Parameter output for 9x9 case with vacuum fill condition, no channel, and no water rod	17	4/5/01	Tables 46, 47, 125, 133, 176
b9vac8c_01a	.out	Output for 9x9 case with vacuum fill condition, 80-mil channel, and no water rod	548	7/23/01	--
b9vac8c_01a	.parm	Parameter output for 9x9 case with vacuum fill condition, 80-mil channel, and no water rod	17	4/5/01	Tables 48, 49, 126, 134, 177
w9arg0c_01b	.out	Output for 9x9 case with argon fill gas, no channel, and water rod	486	7/23/01	--
w9arg0c_restart	.out	Output file for restart of w9arg0c_01b.out case (above), which was interrupted	3,181	7/23/01	--
w9arg0c_01b	.parm	Parameter output for 9x9 case with argon fill gas, no channel, and water rod	17	5/7/01	Table 88
w9arg8c_01	.out	Output for 9x9 case with argon fill gas, 80-mil channel, and water rod	711	7/23/01	--
w9arg8c_01	.parm	Parameter output for 9x9 case with argon fill gas, 80-mil channel, and water rod	17	5/7/01	Table 89
w9hel0c_01b	.out	Output for 9x9 case with helium fill gas, no channel, and water rod	837	7/23/01	--
w9hel0c_01b	.parm	Parameter output for 9x9 case with helium fill gas, no channel, and water rod	17	5/7/01	Table 82
w9hel8c_01d	.out	Output for 9x9 case with helium fill gas, 80-mil channel, and water rod	596	7/23/01	--
w9hel8c_01d	.parm	Parameter output for 9x9 case with helium fill gas, 80-mil channel, and water rod	17	5/7/01	Table 83
w9nit0c_01b	.out	Output for 9x9 case with nitrogen fill gas, no channel, and water rod	2,904	7/23/01	--
w9nit0c_01b	.parm	Parameter output for 9x9 case with nitrogen fill gas, no channel, and water rod	17	5/7/01	Table 86
w9nit8c_01d	.out	Output for 9x9 case with nitrogen fill gas, 80-mil channel, and water rod	624	7/23/01	--
w9nit8c_01d	.parm	Parameter output for 9x9 case with nitrogen fill gas, 80-mil channel, and water rod	17	5/7/01	Table 87
w9vac0c_01	.out	Output for 9x9 case with vacuum fill condition, no channel, and water rod	572	7/23/01	--

Filename	Ext.	Description	Size (kB)	Date	Results Used In
w9vac0c_01	.parm	Parameter output for 9x9 case with vacuum fill condition, no channel, and water rod	17	5/7/01	Table 84
w9vac8c_01b	.out	Output for 9x9 case with vacuum fill condition, 80-mil channel, and water rod	616	7/23/01	--
w9vac8c_01b	.parm	Parameter output for 9x9 case with vacuum fill condition, 80-mil channel, and water rod	17	5/11/01	Table 85
h7stack_01	.out	Backcheck file for 7x7 cases, as referred to in Section 5.7 of the document. Parameter output files for each 7x7 case were read, and the peak cladding temperatures predicted with the effective thermal conductivity were backchecked against explicitly calculated values. This case created the eight files named h7*_01.parm, listed below in this table.	2,038	7/23/01	--
h7arg0c_01	.parm	Parameter output for backcheck of 7x7 case with argon fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 151
h7arg8c_01	.parm	Parameter output for backcheck of 7x7 case with argon fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 152
h7hel0c_01	.parm	Parameter output for backcheck of 7x7 case with helium fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 145
h7hel8c_01	.parm	Parameter output for backcheck of 7x7 case with a helium fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	13	4/27/01	Table 146
h7nit0c_01	.parm	Parameter output for backcheck of 7x7 case with nitrogen fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 149
h7nit8c_01	.parm	Parameter output for backcheck of 7x7 case with nitrogen fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 150
h7vac0c_01	.parm	Parameter output for backcheck of 7x7 case with vacuum fill condition, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 147
h7vac8c_01	.parm	Parameter output for backcheck of 7x7 case with vacuum fill condition, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 148

Filename	Ext.	Description	Size (kB)	Date	Results Used In
h8stack_02	.out	Backcheck file for 8x8 cases, as referred to in Section 5.7 of the document. Parameter output files for each 8x8 case were read, and the peak cladding temperatures predicted with the effective thermal conductivity were backchecked against explicitly calculated values. This case created the eight files named h8*_02.parm, listed below in this table.	2,010	7/23/01	--
h8arg0c_02	.parm	Parameter output for backcheck of 8x8 case with argon fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 159
h8arg8c_02	.parm	Parameter output for backcheck of 8x8 case with argon fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 160
h8hel0c_02	.parm	Parameter output for backcheck of 8x8 case with helium fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 153
h8hel8c_02	.parm	Parameter output for backcheck of 8x8 case with helium fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 154
h8nit0c_02	.parm	Parameter output for backcheck of 8x8 case with nitrogen fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 157
h8nit8c_02	.parm	Parameter output for backcheck of 8x8 case with nitrogen fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 158
h8vac0c_02	.parm	Parameter output for backcheck of 8x8 case with vacuum fill condition, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 155
h8vac8c_02	.parm	Parameter output for backcheck of 8x8 case with vacuum fill condition, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	21	4/27/01	Table 156
h9stack_02	.out	Backcheck file for 9x9 cases, as referred to in Section 5.7 of the document. Parameter output files for each 9x9 case were read, and the peak cladding temperatures predicted with the effective thermal conductivity were backchecked against explicitly calculated values. This case created the eight files named h9*_02.parm, listed below in this table.	2,056	7/23/01	--

Filename	Ext.	Description	Size (kB)	Date	Results Used In
h9arg0c_02	.parm	Parameter output for backcheck of 9x9 case with argon fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 167
h9arg8c_02	.parm	Parameter output for backcheck of 9x9 case with argon fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 168
h9hel0c_02	.parm	Parameter output for backcheck of 9x9 case with helium fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 161
h9hel8c_02	.parm	Parameter output for backcheck of 9x9 case with helium fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 162
h9nit0c_02	.parm	Parameter output for backcheck of 9x9 case with nitrogen fill gas, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 165
h9nit8c_02	.parm	Parameter output for backcheck of 9x9 case with nitrogen fill gas, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 166
h9vac0c_02	.parm	Parameter output for backcheck of 9x9 case with vacuum fill condition, no channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 163
h9vac8c_02	.parm	Parameter output for backcheck of 9x9 case with vacuum fill condition, 80-mil channel, and no water rod. Average temperature difference between predicted and calculated is reported in array TMDFAV.	25	4/27/01	Table 164
bench7_01	.out	Benchmark case of peak fuel temperatures predicted by effective thermal conductivity method against those measured in GE Morris Operation facility test. The difference between the two is output to the following four parameter files.	273	7/23/01	--
hel7b1	.parm	Parameter output for benchmark case against Run 11A of the GE Morris Operation facility test, at thermocouple position 2J – ID CZ346	1	7/23/01	Table 171
hel7b2	.parm	Parameter output for benchmark case against Run 10 of the GE Morris Operation facility test, at thermocouple position 2J – ID CZ346	1	7/23/01	Table 171
nit7b1	.parm	Parameter output for benchmark case against Run 7 of the GE Morris Operation facility test, at thermocouple position 2G – ID CZ246	1	7/23/01	Table 171
vac7b1	.parm	Parameter output for benchmark case against Run 6B of the GE Morris Operation facility test, at thermocouple position 2J – ID CZ346	1	7/23/01	Table 171

Filename	Ext.	Description	Size (kB)	Date	Results Used In
h7mstk1_01	.out	Output for mesh density sensitivity test – 7x7 rod array with vacuum fill condition, 80-mil channel, and no water rod. Parameter output from this calculation is included below (h7vac22.parm et al., the last seven rows of this table)	2,141	7/23/01	--
h7vac22	.parm	Parameter output for mesh density sensitivity test – 2x2 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac44	.parm	Parameter output for mesh density sensitivity test – 4x4 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac66	.parm	Parameter output for mesh density sensitivity test – 6x6 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac88	.parm	Parameter output for mesh density sensitivity test – 8x8 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac10	.parm	Parameter output for mesh density sensitivity test – 10x10 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac12	.parm	Parameter output for mesh density sensitivity test – 12x12 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
h7vac14	.parm	Parameter output for mesh density sensitivity test – 14x14 element mesh. File created by h7mstk1_01.out case (above in this table)	25	5/9/01	Text of Section 5.7
emis_sens_test	.out	Output for case determining sensitivity of peak cladding temperatures in a 7x7 fuel assembly to basket wall emissivity variations	3,660	7/23/01	--

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/COM, 3 A516 Mild Steel Basket Structural Support
/COM, 4 UO2 Pellet SNF Uranium Oxide Pellet
/COM, 5 Zircaloy 4 SNF Cladding
/COM, 6 Oxidation Layer Stably Oxidized Zircaloy Surface
/COM, 7 Helium Canister Fill Gas
/COM, 8 Air Canister Fill Gas
/COM, 9 Nitrogen Canister Fill Gas
/COM, 10 Argon Canister Fill Gas
/COM, 15 Alloy 22 Carbon Steel Canister Shell
/COM, 18 AL 6061 Thermal Shunts
/COM, 19 Neutronit A 978 Absorber Plates
/COM, *****
/COM, **      Density: DENS (kg/m^3) **
/COM, **      Emissivity EMIS **
/COM, **      Conductivity: KXX (W/mK) **
/COM, **      Specific Heat: C (J/kgK) **
/COM, *****
/COM,
/COM, DEFINE CONSTANT DENSITIES
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MPDATA,DENS, 4, 1, .10970E+05, !!!!!REF10
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MPDATA,DENS, 6, 1, .65600E+04, !!!!!REF11
MPDATA,DENS, 7, 1, 0.1626E+00, !!!!!REF8
MPDATA,DENS, 8, 1, 1.1774E+00, !!!!!REF8
MPDATA,DENS, 9, 1, 1.1389E+00, !!!!!REF8
MPDATA,DENS, 10, 1, 1.6243E+00, !!!!!REF8
MPDATA,DENS, 15, 1, 0.8690E+04, !!!!!REF4
MPDATA,DENS, 18, 1, 0.2713E+04, !!!!!REF3 (Section II, Table NF-2)
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MPDATA,EMIS, 3, 1, .80000E+00, !!!!!REF7
MPDATA,EMIS, 4, 1, .79000E+00, !!!!!REF12
MPDATA,EMIS, 5, 1, .80600E+00, !!!!!REF12
MPDATA,EMIS, 6, 1, .80600E+00, !!!!!REF12
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MPDATA,  C, 6, 1, .33000E+03,          !!!!!REF10
MPDATA,  C, 19, 1, .50000E+03,          !!!!!REF5
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Attachment IV Images

Fuel Assembly Array Size ^a	Fill Gas	Channel Size	Fig. #	Fuel Assembly Array Size ^a	Fill Gas	Channel Size	Fig. #
Finite Element Mesh Images				7x7-WR	argon	none	IV-38
7x7	--	80-mil	IV-1	7x7-WR	argon	80-mil	IV-39
7x7	--	100-mil	IV-2	7x7-WR	helium	none	IV-40
7x7	--	120-mil	IV-3	7x7-WR	helium	80-mil	IV-41
8x8	--	80-mil	IV-4	7x7-WR	nitrogen	none	IV-42
9x9	--	80-mil	IV-5	7x7-WR	nitrogen	80-mil	IV-43
7x7-WR	--	80-mil	IV-6	7x7-WR	vacuum	none	IV-44
8x8-WR	--	80-mil	IV-7	7x7-WR	vacuum	80-mil	IV-45
9x9-WR	--	80-mil	IV-8	8x8-WR	argon	none	IV-46
Homogeneous mesh ^b	--	--	IV-9	8x8-WR	argon	80-mil	IV-47
Temperature Result Contour Plots (For Case of 600 W/assembly, 25°C Basket Temperature)				8x8-WR	helium	none	IV-48
7x7	argon	none	IV-10	8x8-WR	helium	80-mil	IV-49
7x7	argon	80-mil	IV-11	8x8-WR	nitrogen	none	IV-50
7x7	helium	none	IV-12	8x8-WR	nitrogen	80-mil	IV-51
7x7	helium	80-mil	IV-13	8x8-WR	vacuum	none	IV-52
7x7	helium	100-mil	IV-14	8x8-WR	vacuum	80-mil	IV-53
7x7	helium	120-mil	IV-15	9x9-WR	argon	none	IV-54
7x7	nitrogen	none	IV-16	9x9-WR	argon	80-mil	IV-55
7x7	nitrogen	80-mil	IV-17	9x9-WR	helium	none	IV-56
7x7	vacuum	none	IV-18	9x9-WR	helium	80-mil	IV-57
7x7	vacuum	80-mil	IV-19	9x9-WR	nitrogen	none	IV-58
7x7	vacuum	100-mil	IV-20	9x9-WR	nitrogen	80-mil	IV-59
7x7	vacuum	120-mil	IV-21	9x9-WR	vacuum	none	IV-60
8x8	argon	none	IV-22	9x9-WR	vacuum	80-mil	IV-61
8x8	argon	80-mil	IV-23				
8x8	helium	none	IV-24				
8x8	helium	80-mil	IV-25				
8x8	nitrogen	none	IV-26				
8x8	nitrogen	80-mil	IV-27				
8x8	vacuum	none	IV-28				
8x8	vacuum	80-mil	IV-29				
9x9	argon	none	IV-30				
9x9	argon	80-mil	IV-31				
9x9	helium	none	IV-32				
9x9	helium	80-mil	IV-33				
9x9	nitrogen	none	IV-34				
9x9	nitrogen	80-mil	IV-35				
9x9	vacuum	none	IV-36				
9x9	vacuum	80-mil	IV-37				

^a WR – assembly array with water rod^b Used in backcheck

Figure IV-1. Finite Element Mesh, 7x7 GE-2 BWR Fuel Assembly w/ 80-mil Channel

Figure IV-2. Finite Element Mesh, 7x7 GE-2 BWR Fuel Assembly w/ 100-mil Channel

Figure IV-3. Finite Element Mesh, 7x7 GE-2 BWR Fuel Assembly w/ 120-mil Channel

Figure IV-4. Finite Element Mesh, 8x8 GE-5 BWR Fuel Assembly w/ 80-mil Channel

Figure IV-5. Finite Element Mesh, 9x9 ANF-JP BWR Fuel Assembly w/ 80-mil Channel

Figure IV-6. Finite Element Mesh, 7x7 ANF BWR Fuel Assembly w/ Water Rod

Figure IV-7. Finite Element Mesh, 8x8 GE-9 BWR Fuel Assembly w/ Water Rod

Figure IV-8. Finite Element Mesh, 9x9 ANF-9X BWR Fuel Assembly w/ Water Rod

Figure IV-9. Finite Element Mesh, Homogeneous Mesh Used for Backcheck

Figure IV-10. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Argon w/ No Channel

Figure IV-11. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Argon w/ 80-mil Channel

Figure IV-12. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Helium w/ No Channel

Figure IV-13. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Helium w/ 80-mil Channel

Figure IV-14. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Helium w/ 100-mil Channel

Figure IV-15. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Helium w/ 120-mil Channel

Figure IV-16. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Nitrogen w/ No Channel

Figure IV-17. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Nitrogen w/ 80-mil Channel

Figure IV-18. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Vacuum w/ No Channel

Figure IV-19. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Vacuum w/ 80-mil Channel

Figure IV-20. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Vacuum w/ 100-mil Channel

Figure IV-21. Solution Plot, 7x7 GE-2 BWR Fuel Assembly in Vacuum w/ 120-mil Channel

Figure IV-22. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Argon w/ No Channel

Figure IV-23. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Argon w/ 80-mil Channel

Figure IV-24. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Helium w/ No Channel

Figure IV-25. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Helium w/ 80-mil Channel

Figure IV-26. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Nitrogen w/ No Channel

Figure IV-27. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Nitrogen w/ 80-mil Channel

Figure IV-28. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Vacuum w/ No Channel

Figure IV-29. Solution Plot, 8x8 GE-5 BWR Fuel Assembly in Vacuum w/ 80-mil Channel

Figure IV-30. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Argon w/ No Channel

Figure IV-31. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Argon w/ 80-mil Channel

Figure IV-32. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Helium w/ No Channel

Figure IV-33.. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Helium w/ 80-mil Channel

Figure IV-34. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Nitrogen w/ No Channel

Figure IV-35. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Nitrogen w/ 80-mil Channel

Figure IV-36. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Vacuum w/ No Channel

Figure IV-37. Solution Plot, 9x9 ANF-JP BWR Fuel Assembly in Vacuum w/ 80-mil Channel

Figure IV-38. Solution Plot, 7x7 ANF BWR Fuel Assy. in Argon w/ No Channel & Water Rod

Figure IV-39. Solution Plot, 7x7 ANF BWR Fuel Assy. in Argon w/ 80-mil Channel & Water Rod

Figure IV-40. Solution Plot, 7x7 ANF BWR Fuel Assy. in Helium w/ No Channel & Water Rod

Figure IV-41. Solution Plot, 7x7 ANF BWR Fuel Assy. in Helium w/ 80-mil Channel & Water Rod

Figure IV-42. Solution Plot, 7x7 ANF BWR Fuel Assy. in Nitrogen w/ No Channel & Water Rod

Figure IV-43. Sol. Plot, 7x7 ANF BWR Fuel Assy. in Nitrogen w/ 80-mil Channel & Water Rod

Figure IV-44. Solution Plot, 7x7 ANF BWR Fuel Assy. in Vacuum w/ No Channel & Water Rod

Figure IV-45. Sol. Plot, 7x7 ANF BWR Fuel Assy. in Vacuum w/ 80-mil Channel & Water Rod

Figure IV-46. Solution Plot, 8x8 GE-9 BWR Fuel Assy. in Argon w/ No Channel & Water Rod

Figure IV-47. Solution Plot, 8x8 GE-9 BWR Fuel Assy. in Argon w/ 80-mil Channel & Water Rod

Figure IV-48. Solution Plot, 8x8 GE-9 BWR Fuel Assy. in Helium w/ No Channel & Water Rod

Figure IV-49. Solution Plot, 8x8 GE-9 BWR Fuel Assy. in Helium w/ 80-mil Channel & Water Rod

Figure IV-50. Solution Plot, 8x8 GE-9 BWR Fuel Assy. in Nitrogen w/ No Channel & Water Rod

Figure IV-51. Sol. Plot, 8x8 GE-9 BWR Fuel Assy. in Nitrogen w/ 80-mil Channel & Water Rod

Figure IV-52. Solution Plot, 8x8 GE-9 BWR Fuel Assy. in Vacuum w/ No Channel & Water Rod

Figure IV-53. Sol. Plot, 8x8 GE-9 BWR Fuel Assy. in Vacuum w/ 80-mil Channel & Water Rod

Figure IV-54. Solution Plot, 9x9 ANF-9X BWR Fuel Assy. in Argon w/ No Channel & Water Rod

Figure IV-55. Sol. Plot, 9x9 ANF-9X BWR Fuel Assy. in Argon w/ 80-mil Channel & Water Rod

Figure IV-56. Solution Plot, 9x9 ANF-9X BWR Fuel Assy. in Helium w/ No Channel & Water Rod

Figure IV-57. Sol. Plot, 9x9 ANF-9X BWR Fuel Assy. in Helium w/ 80-mil Channel & Water Rod

Figure IV-58. Sol. Plot, 9x9 ANF-9X BWR Fuel Assy. in Nitrogen w/ No Channel & Water Rod

Figure IV-59. Sol. Plot, 9x9 ANF-9X BWR Fuel Assy. in Nitrogen w/ 80-mil Channel & Water Rod

Figure IV-60. Sol. Plot, 9x9 ANF-9X BWR Fuel Assy. in Vacuum w/ No Channel & Water Rod

Figure IV-61. Sol. Plot, 9x9 ANF-9X BWR Fuel Assy. in Vacuum w/ 80-mil Channel & Water Rod

10/9/01

Analytical Calculation for Heat Generation within the SNF Cladding

This attachment discusses the conservatism of Assumption 3.20, that all of the spent nuclear fuel heat is produced within the UO_2 pellet. Consider the cross section of the spent fuel rod in Figure VI-1 below.

Figure VI-1. Cross section of spent fuel rod

The peak cladding temperature will be compared for the following three cases:

- Case 1. Heat is produced in the UO_2 pellet only (Assumption 3.20)
- Case 2. Heat is produced in the cladding only, with no heat in the pellet (an extreme case)
- Case 3. Heat generation is distributed through the pellet and the cladding

The following assumptions apply to this analysis:

- The total heat production of the rod is a constant (Q)
- All cases have the same cladding surface temperature (T_c boundary condition)
- In all cases, the peak cladding temperature will occur at T_p
- There is no gap between the pellet and the cladding
- Conductivities of the pellet and cladding are constant
- A unit length of $L = 1$ is assumed.

Case 1 – Heat is Produced in the UO_2 Pellet Only

For this case the temperature distribution within the cladding is given by Equation 3.26 of a standard heat transfer text (p. 91, Ref. 22) which is solved for heat transfer rate in Equation 3.27 and repeated here:

$$q_r = \frac{2\pi L k_c (T_p - T_c)}{\ln(r_c / r_p)}$$

Equation VI-1

Substituting $L = 1$ and $Q = q_r$ (the heat produced in the pellet) and solving for $(T_p - T_c)$ results in:

$$\Delta T_1 = (T_p - T_c) = \frac{Q \ln(r_c / r_p)}{2\pi k_c} \quad \text{Equation VI-2}$$

The term ΔT_1 determines the peak cladding temperature if the boundary condition T_c is known.

Case 2 – Heat is Produced in the Cladding Only, with No Heat in the Pellet

For this case the temperature distribution within the cladding is given by Equation 3.51 of a standard heat transfer text (p. 106, Ref. 22):

$$T(r) = -\frac{\dot{q}}{4k_c} r^2 + C_1 \ln r + C_2 \quad \text{Equation VI-3}$$

To find C_1 and C_2 we need to solve two boundary conditions:

$$\left. \frac{dT}{dr} \right|_{r=r_p} = 0 = -\frac{\dot{q}}{2k_c} r_p + \frac{C_1}{r_p} \Rightarrow C_1 = \frac{\dot{q}}{2k_c} r_p^2 \quad \text{Equation VI-4}$$

$$T(r_c) = T_c = -\frac{\dot{q}}{4k_c} r_c^2 + C_1 \ln r_c + C_2 \Rightarrow C_2 = \frac{\dot{q}}{4k_c} r_c^2 - \frac{\dot{q}}{2k_c} r_p^2 \ln r_c + T_c \quad \text{Equation VI-5}$$

Substituting C_1 and C_2 into Equation VI-3 and evaluating $T(r)$ for $r = r_p$ gives:

$$\begin{aligned} T_p = T(r_p) &= -\frac{\dot{q}}{4k_c} r_p^2 + \frac{\dot{q}}{2k_c} r_p^2 \ln r_p + \frac{\dot{q}}{4k_c} r_c^2 - \frac{\dot{q}}{2k_c} r_p^2 \ln r_c + T_c \\ &= \frac{\dot{q} r_p^2}{4k_c} \left[-1 + 2 \ln(r_p / r_c) + (r_c / r_p)^2 \right] + T_c \end{aligned} \quad \text{Equation VI-6}$$

Further substituting $q' = Q/(\pi(r_c^2 - r_p^2))$ with $L = 1$ and solving for $(T_p - T_c)$ results in:

$$\Delta T_2 = (T_p - T_c) = \frac{Q r_p^2}{4\pi k_c (r_c^2 - r_p^2)} \left[-1 + 2 \ln(r_p / r_c) + (r_c / r_p)^2 \right] \quad \text{Equation VI-7}$$

Case 3 – Heat Generation is Distributed Through the Pellet and the Cladding

Before proceeding with the temperature distribution of Case 3, it may be possible to bound Case 3 by comparing the results of Cases 1 and 2. The ratio of temperature drops from Cases 1 and 2 can be written as:

$$\frac{\Delta T_1}{\Delta T_2} = \frac{\frac{Q \ln(r_c / r_p)}{2\pi k_c}}{\frac{Q r_p^2}{4\pi k_c (r_c^2 - r_p^2)} \left[-1 + 2 \ln(r_p / r_c) + (r_c / r_p)^2 \right]}$$

Equation VI-8

Cancelling terms and then substituting typical fuel rod cladding radii of $r_c = 7.15$ mm and $r_p = 6.3372$ mm (fuel rod radius assumed equal to cladding inner radius from Table 12) results in the following:

$$\frac{\Delta T_1}{\Delta T_2} = \frac{2 \ln(r_c / r_p) (r_c^2 - r_p^2)}{r_p^2 \left[-1 + 2 \ln(r_p / r_c) \right] + r_c^2}$$

Equation VI-9

This demonstrates that when all of the heat is produced in the pellet, the cladding temperature drop from surface to peak is roughly twice what it would be in the extreme case of all heat being produced in the cladding. It can be surmised then that all cases between Cases 1 and 2 (heat distributed over both pellet and cladding) will be bounded (with respect to maximum cladding temperature) by the case of all heat being produced in the pellet. This supports Assumption 3.20.

To complete the discussion, the governing equation for temperature distribution within the cladding for Case 3 is the same as for Case 2 and is provided above as Equation VI-3. For Case 3, the boundary conditions (to find C_1 and C_2) are slightly different as written below:

$$\left. \frac{dT}{dr} \right|_{r=r_p} = \frac{-Q_p}{2\pi r_p L k_c} = -\frac{\dot{q}}{2k_c} r_p + \frac{C_1}{r_p} \quad \Rightarrow \quad C_1 = \frac{\dot{q} r_p^2}{2k_c} - \frac{Q_p}{2\pi k_c}$$

Equation VI-10

$$T(r_c) = T_c = -\frac{\dot{q}}{4k_c} r_c^2 + C_1 \ln r_c + C_2 \quad \Rightarrow \quad C_2 = \frac{\dot{q} r_c^2}{4k_c} - \frac{\dot{q} r_p^2}{2k_c} \ln r_c + T_c$$

Equation VI-11

Substituting C_1 and C_2 into Equation VI-3 and evaluating $T(r)$ for $r = r_p$ gives:

$$\begin{aligned}
 T_p = T(r_p) &= -\frac{\dot{q}r_p^2}{4k_c} + \frac{\dot{q}r_p^2}{2k_c} \ln r_p - \frac{Q_p}{2\pi k_c} \ln r_p + \frac{\dot{q}r_c^2}{4k_c} - \frac{\dot{q}r_p^2}{2k_c} \ln r_c + \frac{Q_p}{2\pi k_c} \ln r_c + T_c \\
 &= \frac{Q_p \ln(r_c/r_p)}{2\pi k_c} + \frac{\dot{q}r_p^2}{4k_c} \left[-1 + 2 \ln(r_p/r_c) + (r_c/r_p)^2 \right] + T_c
 \end{aligned}$$

Equation VI-12

Further substituting $q' = Q/(\pi(r_c^2 - r_p^2))$ with $L = 1$ and solving for $(T_p - T_c)$ results in:

$$\Delta T_3 = (T_p - T_c) = \frac{Q_p \ln(r_c/r_p)}{2\pi k_c} + \frac{Q_c r_p^2}{4\pi k_c (r_c^2 - r_p^2)} \left[-1 + 2 \ln(r_p/r_c) + (r_c/r_p)^2 \right]$$

Equation VI-13

Finally substituting $Q_p = Q - Q_c$ results in the following:

$$\Delta T_3 = \frac{Q \ln(r_c/r_p)}{2\pi k_c} + \frac{Q_c}{4\pi k_c} \left(\frac{r_p^2}{r_c^2 - r_p^2} \left[-1 + 2 \ln(r_p/r_c) + (r_c/r_p)^2 \right] - 2 \ln(r_c/r_p) \right)$$

Equation VI-14

Like the solution in Equation VI-9, if typical fuel rod cladding radii of $r_c = 7.15$ mm and $r_p = 6.3372$ mm are used to evaluate the coefficient of the second term above, the following results:

$$\Delta T_3 = \frac{Q \ln(r_c/r_p)}{2\pi k_c} - 0.1255 \frac{Q_c}{4\pi k_c}$$

Equation VI-15

The first term of Equation VI-15 is equivalent to Equation VI-2 where heat is produced in the pellet only. In Equation VI-15, the temperature drop is reduced from that of Case 1 for any positive Q_c (heat produced in the cladding). Therefore, the highest cladding temperatures occur when all of the heat is produced in the pellet, supporting Assumption 3.20.