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NGNP Parametric Fuel and Reactor Pressure Vessel Temperature Calculations

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ACRONYMS AND ABBREVIATIONS

GA	General Atomics
GT-MHR	Gas Turbine Modular Helium Reactor
LPCC	Low Pressure Conduction Cooldown
MHR	Modular Helium Reactor
NGNP	Next Generation Nuclear Plant
RCCS	Reactor Cavity Cooling System

1. SUMMARY

The Next Generation Nuclear Plant (NGNP) prototype design developed by the General Atomics (GA) team is designed to operate with a thermal power level of 600 MW and a coolant outlet temperature up to 950°C [GA 2007]. During the initial phase of NGNP operation, it may be desirable to operate the NGNP at less than rated power and/or with a reduced helium outlet temperature for extended periods, in order to monitor performance of the fuel, reactor vessel, and vessel internals before operation at full rated conditions.

This report describes parametric calculations of fuel and vessel temperatures for both normal operation and Low Pressure Conduction Cooldown (LPCC) events. The following parametric calculations were performed:

- For a fixed coolant outlet temperature of 950°C, the reactor thermal power was varied from 250 MW to 600 MW in increments of 50 MW.
- For a fixed reactor thermal power level of 600 MW, the coolant outlet temperature was varied from 750°C to 950°C in increments of 50°C.

Sensitivity to Coolant Inlet Temperature

For the GA NGNP design, coolant inlet temperatures ranging from 490°C to 590°C are being considered. In the absence of active vessel cooling, the vessel operating temperatures are determined in large measure by the design point selected for coolant inlet temperature [Richards 2008]. To avoid significant risks to the NGNP schedule, it is desirable for the NGNP reactor vessel to operate at peak temperatures below approximately 350°C, which would allow use of SA-508/533 steel for the reactor pressure vessel [Richards 2008]. This material has been used extensively for light water reactor pressure vessels. As discussed in [GA 2008], operation with an inlet temperature of 490°C and inlet flow routed through risers in the permanent side reflector offers the potential to reduce vessel operating temperatures to approximately 350°C without active vessel cooling.

As indicated in Eq. (1), for a fixed thermal power level Q, the product of core ΔT and total coolant mass flow rate $\dot{m}$ is constant. For NGNP, the outlet temperature is expected to be a fixed design requirement, and a decrease in inlet temperature will increase core ΔT and reduce $\dot{m}$. As indicated in Fig. 1-1, a 100°C decrease in inlet temperature results in an approximately 40°C increase in peak fuel temperature. Hence, one of the constraints on the inlet temperature is ensuring adequate coolant mass flow to maintain fuel operating temperatures at acceptable levels. The impact of higher core ΔT and lower $\dot{m}$ on peak fuel temperatures can be reduced if the core physics design is optimized to minimize power peaking factors, which helps to flatten the distribution of flow among the fuel columns [GA 2007]. In addition, the reactor internals design can be optimized to reduce bypass flow, which also helps to reduce fuel temperatures during normal operation [GA 2007].

$$Q = \dot{m}C_p\left(T_{out} - T_{in}\right) = \dot{m}C_p\Delta T \qquad (1)$$

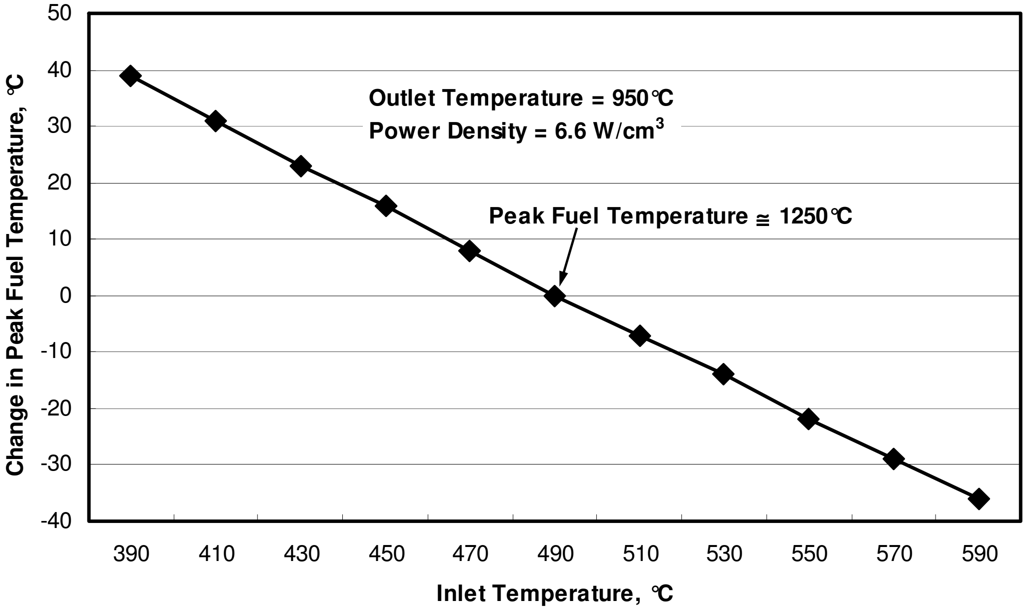

Figure 1-1. Effect of Coolant Inlet Temperature on Peak Fuel Temperature

For this study, two sets of parametric calculations were performed, corresponding to inlet temperatures of 490°C and 590°C.

Assumptions

During normal operation, the reactor internals design and/or an active vessel cooling system is assumed to maintain the peak vessel temperature at 350°C. For all cases, the maximum allowable core ΔT was assumed to be 460°C and the minimum allowable core ΔT was assumed to be 360°C. As discussed above, the constraint on maximum allowable core ΔT is imposed to ensure adequate cooling of the fuel elements. The constraint on minimum core ΔT is imposed to prevent excessive coolant velocities, which could result in unacceptably high coolant pressure drops and/or flow-induced vibrations. It is also assumed that the core physics design is optimized using a 3-zone axial shuffling scheme and the reactor internals design is optimized to limit the bypass flow fraction to 0.1. Both of these optimization measures are described in [GA 2007].

Results and Conclusions

Results for the two sets of parametric calculations are summarized in Tables 1-1 and 1-2. The calculations are described in more detail in Section 2 for normal operating conditions and in Section 3 for accident conditions. Based on these calculations, the following conclusions can be made:

1. For operation with a fixed core ΔT, the power-to-flow-rate ratio is constant [see Eq. (1)], and lowering the thermal power level results in only a modest reduction in peak fuel temperatures during normal operation. Peak fuel temperatures are reduced by about 85°C to 90°C as the thermal power level is dropped from 600 MW to 250 MW. This modest reduction results primarily from the slightly nonlinear relationship between the coolant velocity and local heat-transfer coefficient.[1]
2. Because the decay heat rate is proportional to thermal power level during normal operation, lowering the thermal power level results in a significant reduction in peak fuel temperatures during a LPCC event. Peak fuel temperatures are reduced by about 460°C to 470°C as the thermal power level is dropped from 600 MW to 250 MW.
3. For a fixed thermal power level, lowering the coolant outlet temperature by a given amount results in nearly the same reduction in peak fuel temperature during normal operation (e.g., lowering the coolant outlet temperature by 200°C results in lowering the peak fuel temperature by about 200°C.) This nearly one-to-one relationship results from peak fuel temperatures occurring near the bottom of the core during normal operation, where the coolant temperatures are the highest.
4. Lowering the coolant outlet temperature during normal operation results in only a small reduction in peak fuel temperatures during LPCC events, primarily because peak fuel temperatures occur near the axial midplane of the core during an LPCC event.
5. During LPCC events, vessel temperatures are determined largely by heat transfer to the Reactor Cavity Cooling System (RCCS), which occurs primarily by thermal radiation. Lowering the thermal power level or lowering the coolant outlet temperature results in only a small reduction in peak vessel temperature during these events.

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[1] For turbulent flow, the Nusselt number is proportional to Reynolds number to the 0.8 power.

Table 1-1. Parametric Calculations Results Summary - 490°C Inlet Temperature

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
Reactor Power Level (MW_t)	600	550	500	450	400	350	300	250	600	600	600	600
Refueling Scheme	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling
Coolant Flow Rate (kg/s)	250.4	229.5	208.7	187.8	166.9	146.1	125.2	104.3	280.9	320	320	320
Bypass Flow Fraction	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Core Inlet Temp. (°C)	490	490	490	490	490	490	490	490	490	490	440	390
Core Outlet Temp. (°C)	950	950	950	950	950	950	950	950	900	850	800	750
Normal Operation (Poke Results)												
Avg. Outlet Temp. Fueled Region (°C)	983	983	983	983	983	983	983	983	930	876	826	776
Outlet Temp. Bypass Flow (°C)	649	649	649	649	649	649	649	649	631	614	564	514
Max. Coolant Temp. (°C)	1080	1080	1080	1080	1080	1080	1080	1080	1014	949	899	850
Max. Flow Fraction	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.04	1.04	1.04	1.04
Min. Flow Fraction	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.88	0.88	0.87
Max. Graphite Temp. (°C)	1158	1154	1149	1144	1138	1134	1130	1125	1091	1023	974	926
Avg. Graphite Temp. (°C)	833	830	827	824	821	818	816	811	799	765	716	666
Max. Fuel Temp. (°C)	1247	1235	1223	1210	1198	1185	1172	1158	1181	1114	1067	1019
Avg. Fuel Temp. (°C)	878	873	866	859	852	845	838	830	846	812	764	716
Max. Vessel Temp. (°C)	350	350	350	350	350	350	350	350	350	350	350	350
Core Inlet Pressure (psia)	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025
Core Pressure Drop (psid)	5.3	4.5	3.7	3	2.4	1.8	1.35	0.94	6.4	7.96	7.52	7.09
Accident Conditions (TAC2D Results)												
Max. Fuel Temp. (°C)	1571	1497	1421	1344	1263	1181	1121	1111	1564	1558	1545	1533
Max. Vessel Temp. (°C)	516	497	492	492	492	492	492	492	513	511	505	500

🟩	Inlet temperature determined by constraint on minimum allowable core ΔT of 360°C.
🟦	Max. vessel temperature during normal operation limited to 350°C through internals design and/or active vessel cooling.

Table 1-2. Parametric Calculations Results Summary - 590°C Inlet Temperature

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
Reactor Power Level (MW_t)	600	550	500	450	400	350	300	250	600	600	600	600
Refueling Scheme	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling	3-Zone Axial Shuffling
Coolant Flow Rate (kg/s)	320	293.3	266.7	240	213.3	186.7	160	133.3	320	320	320	320
Bypass Flow Fraction	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Core Inlet Temp. (°C)	590	590	590	590	590	590	590	590	540	490	440	390
Core Outlet Temp. (°C)	950	950	950	950	950	950	950	950	900	850	800	750
Normal Operation (Poke Results)												
Avg. Outlet Temp. Fueled Region (°C)	976	976	976	976	976	976	976	976	926	876	826	776
Outlet Temp. Bypass Flow (°C)	714	714	714	714	714	714	714	714	664	614	564	514
Max. Coolant Temp. (°C)	1048	1048	1048	1048	1048	1048	1048	1048	998	949	899	850
Max. Flow Fraction	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Min. Flow Fraction	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.87
Max. Graphite Temp. (°C)	1121	1117	1112	1108	1103	1098	1092	1088	1072	1023	974	926
Avg. Graphite Temp. (°C)	864	862	859	857	854	851	848	845	815	765	716	666
Max. Fuel Temp. (°C)	1210	1199	1187	1175	1163	1150	1138	1124	1162	1114	1067	1019
Avg. Fuel Temp. (°C)	910	904	897	891	885	878	871	864	861	812	764	716
Max. Vessel Temp. (°C)	350	350	350	350	350	350	350	350	350	350	350	350
Core Inlet Pressure (psia)	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025
Core Pressure Drop (psid)	8.8	7.5	6.2	5.1	4	3.1	2.3	1.6	8.4	7.96	7.52	7.09
Accident Conditions (TAC2D Results)												
Max. Fuel Temp. (°C)	1584	1511	1436	1360	1281	1201	1119	1112	1571	1558	1545	1533
Max. Vessel Temp. (°C)	522	503	502	502	502	502	502	502	516	511	505	500

🟩	Inlet temperature determined by constraint on minimum allowable core ΔT of 360°C.
🟦	Max. vessel temperature during normal operation limited to 350°C through internals design and/or active vessel cooling.

2. CALCULATIONS FOR NORMAL OPERATING CONDITIONS

Flow and temperature distributions were calculated using the POKE computer code [Kapernick 1993]. POKE performs a simplified thermal hydraulic analysis for a reactor configuration consisting of a number of regions, each containing parallel coolant channels that are connected to common inlet and outlet plenums. For the present analysis, individual columns were modeled as regions. Each column consists of an upper reflector, a fueled section, and a lower reflector. The code user specifies the number of axial nodes in the active core. For each region, POKE models an average coolant channel that is coupled to an adiabatic unit cell. Using the coolant-channel temperature as a boundary condition for convective heat transfer, two-dimensional heat-transfer calculations are performed at each axial location in each region to determine the moderator (graphite) and fuel temperatures. For the prismatic fuel block, the unit cell is a right-triangular element containing one-third of the area of a fuel compact and one-sixth the area of a coolant hole (see Figure 2-1). As indicated in Fig. 2-1, a small gap is modeled between the fuel compact and graphite moderator. Both conduction and radiation are assumed to occur across the gap.

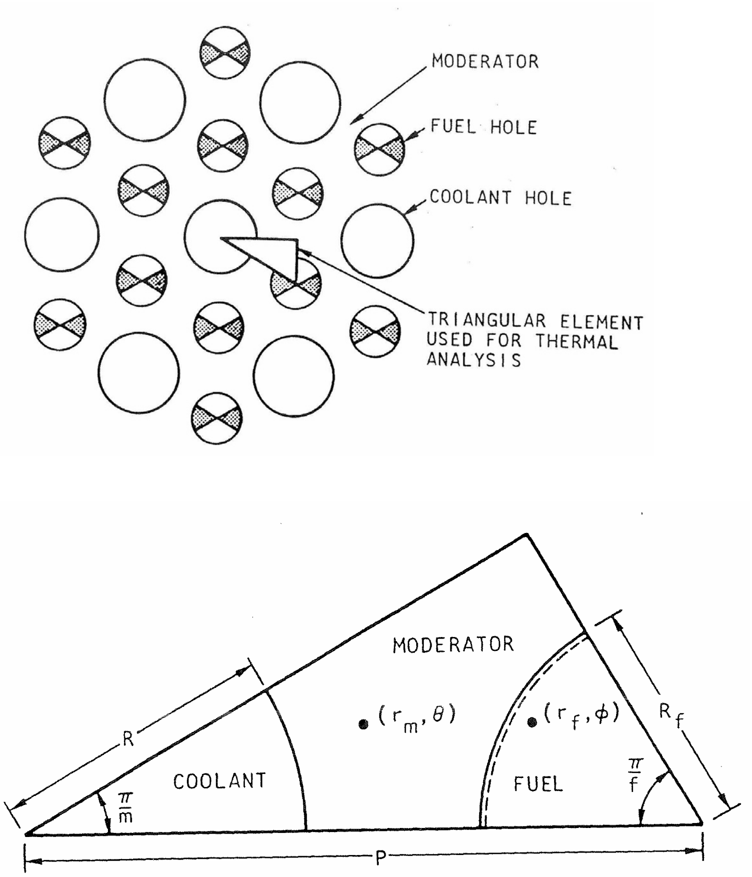

Figure 2-1. POKE Unit Cell Used for Thermal Analysis

Using calculated power distributions as input, POKE was used to calculate the flow distribution among the columns, and the temperatures of the coolant, graphite, and fuel at each axial location for each column. The coolant inlet temperature is assumed to persist over the length of the upper reflector and the column outlet temperature is assumed to persist over the length of the lower reflector. POKE also calculates the axial pressure distribution in each column and the overall pressure drop across the core.

For normal operation calculations, the power distribution is based on the 3-zone axial fuel shuffling scheme described in [GA 2007] and developed by the Korea Atomic Energy Research Institute. This shuffling scheme flattens the radial/azimuthal (column-averaged) power distribution, which results in more uniform flow distributions among the fuel columns during normal operation and acceptable temperature distributions with a core inlet/outlet ΔT at the upper limit of 460°C and an outlet temperature of 950°C. Figure 2-2 shows the axial power distribution for this shuffling scheme.[2]

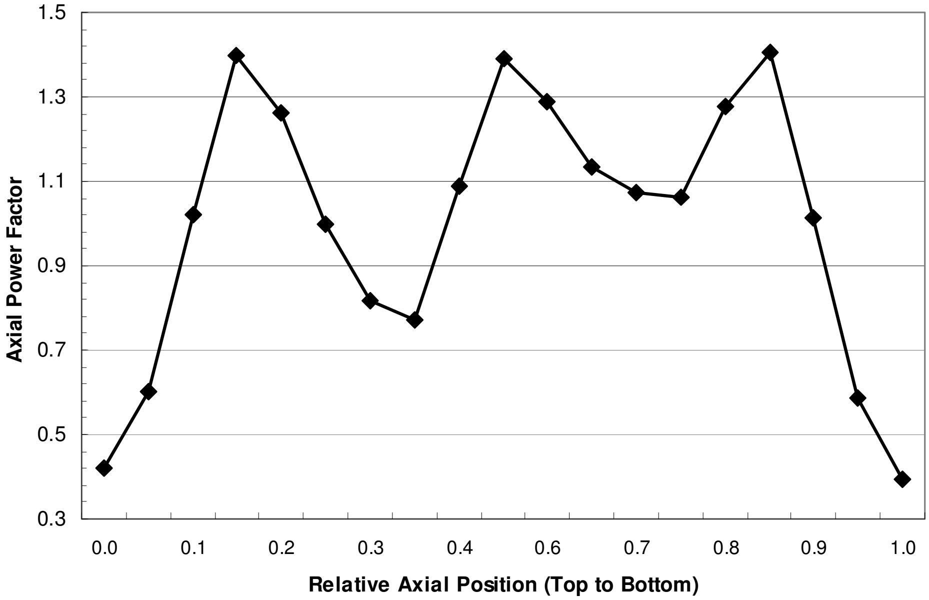

Figure 2-2. Axial Power Distribution Used for POKE Analyses

Sensitivity to Thermal Power Level

Figures 2-3 (490°C inlet temperature) and 2-4 (590°C inlet temperature) show the peak fuel temperature during normal operation as a function of thermal power level. For operation with a fixed core ΔT, the power-to-flow-rate ratio is constant [see Eq. (1)], and lowering the thermal power level results in only a modest reduction in peak fuel temperatures during normal operation. Peak fuel temperatures are reduced by about 85°C to 90°C as the thermal power

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[2] For the accident condition calculations described in Section 3, a more conservative power distribution based on conventional column refueling was used.

level is dropped from 600 MW to 250 MW. This modest reduction results primarily from the slightly nonlinear relationship between the coolant velocity and local heat-transfer coefficient. As discussed in Section 1, the maximum vessel temperature during normal operation is assumed to be limited to 350°C by means of reactor internals design and/or use of active vessel cooling.

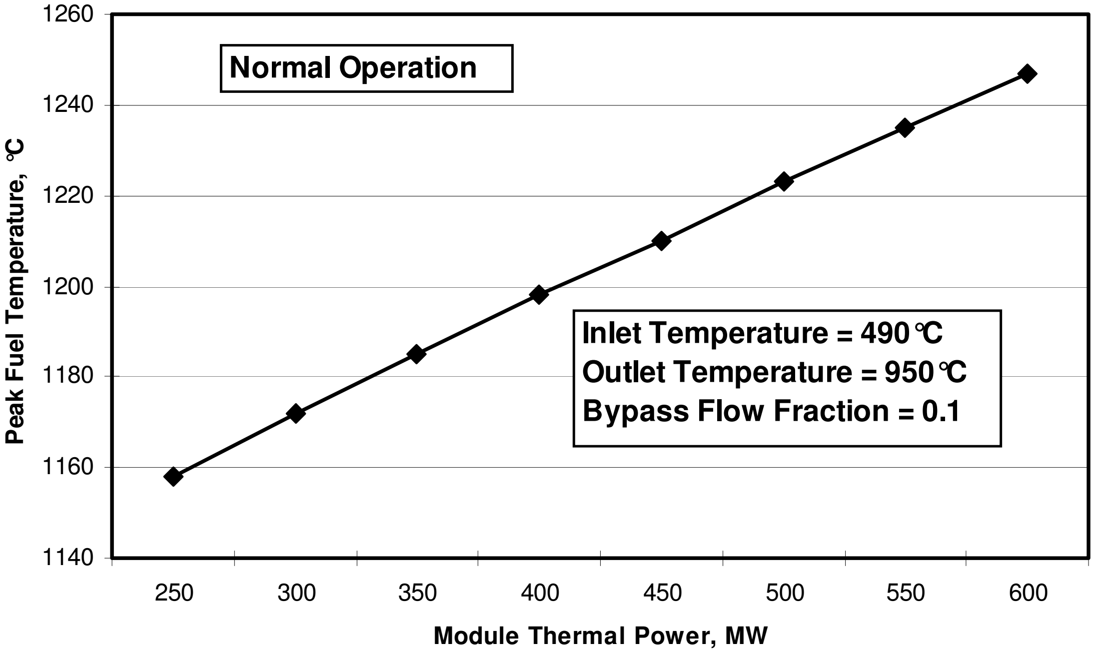

Figure 2-3. Sensitivity of Peak Fuel Temperature to Thermal Power Level (Normal Operation, 490°C inlet temperature)

Sensitivity to Coolant Outlet Temperature

Figures 2-5 (490°C inlet temperature) and 2-6 (590°C inlet temperature) show the peak fuel temperature during normal operation as a function of coolant outlet temperature at a fixed thermal power level of 600 MW. For a fixed thermal power level, lowering the coolant outlet temperature by a given amount results in nearly the same reduction in peak fuel temperature during normal operation, e.g., lowering the coolant outlet temperature by 200°C results in lowering the peak fuel temperature by about 200°C. This nearly one-to-one relationship results from peak fuel temperatures occurring near the bottom of the core during normal operation, where the coolant temperatures are the highest.

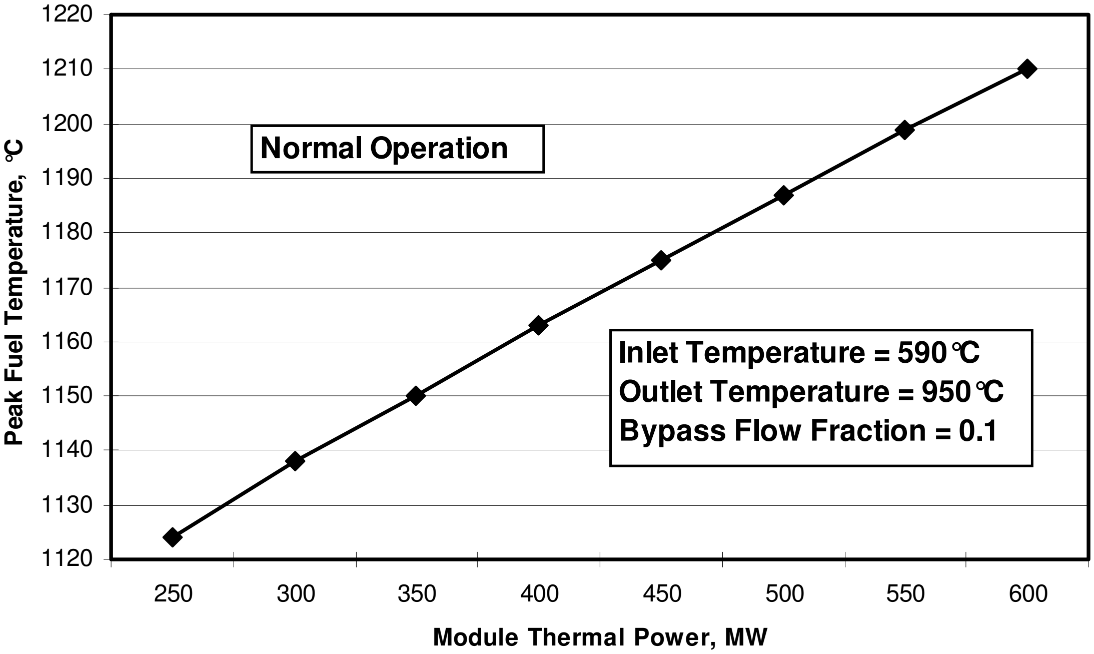

Figure 2-4. Sensitivity of Peak Fuel Temperature to Thermal Power Level (Normal Operation, 590°C inlet temperature)

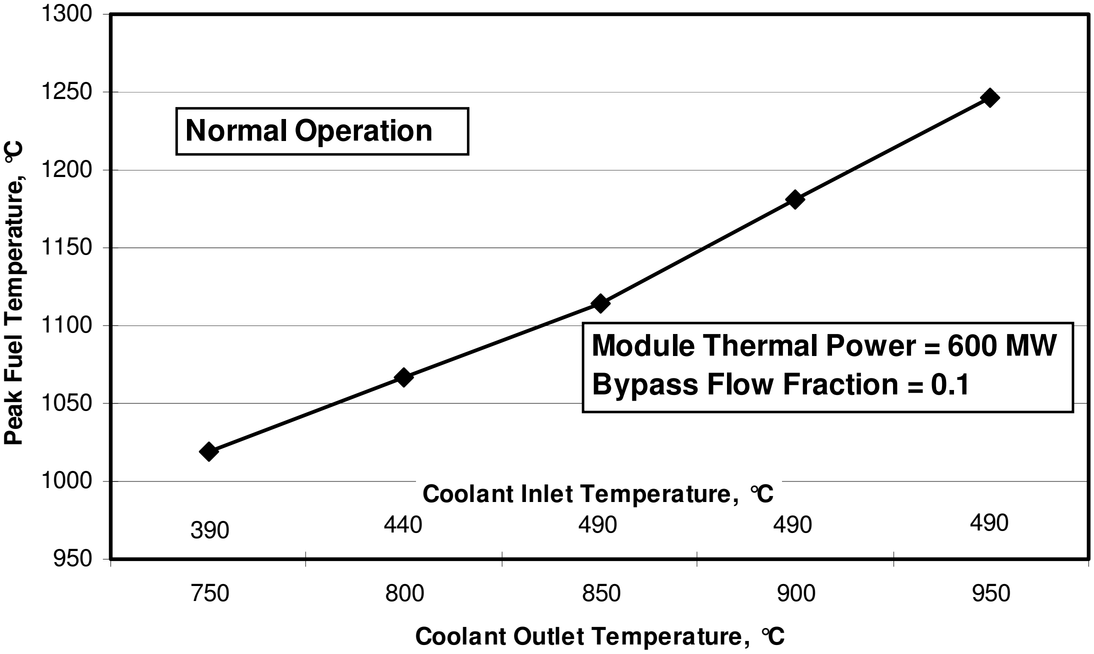

Figure 2-5. Sensitivity of Peak Fuel Temperature to Coolant Outlet Temperature (Normal Operation, 490°C inlet temperature)

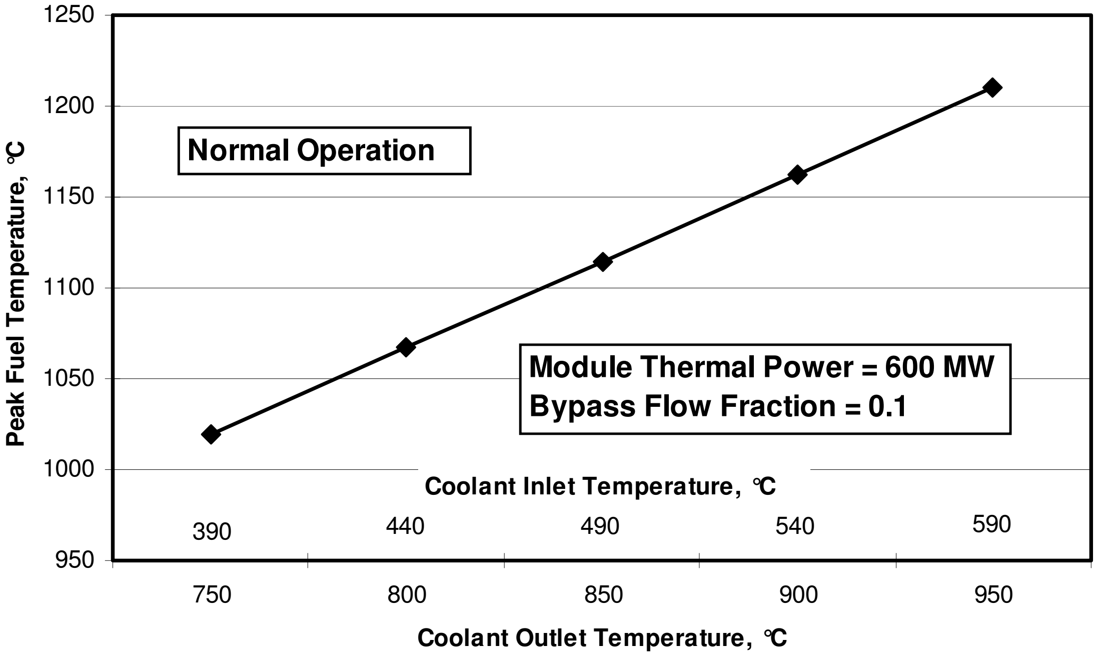

Figure 2-6. Sensitivity of Peak Fuel Temperature to Coolant Outlet Temperature (Normal Operation, 590°C inlet temperature)

3. CALCULATIONS FOR ACCIDENT CONDITIONS

Calculations for the LPCC events were performed using the TAC2D code [Boonstra 1976]. TAC2D is a legacy GA computer code that has been used for a wide variety of thermal analyses, including safety analyses to support Modular Helium Reactor (MHR) designs. For these calculations, a previous TAC2D model for the 600 MWt Gas Turbine Modular Helium Reactor (GT-MHR) design was used, with appropriate modifications to input parameters and initial conditions for the various parametric cases.

The baseline GT-MHR model includes the following features:

- 2-dimensional R-Z geometry model of the GT-MHR
- Thermal property data of all the internal materials including a thermal annealing model for graphite thermal conductivity
- Radial and axial power shape factors for the active core
- Fast neutron fluence data
- Decay heat data
- Steady-state temperature distribution for a GT-MHR operating with a reactor inlet/outlet temperatures of 490°C/850°C
- RCCS model with multi-dimensional radiation heat transfer

The R-Z model of the GT-MHR is composed of 91 radial and 153 axial grid lines, ranging from 0 to 23.4 m in the radial direction and 0 to 49.7 m in the axial direction. A total of 228 blocks were defined to specify the material types of for all components, including the reactor vessel, reactor internals, structural concrete, and surrounding earth. The geometry data and material properties of the GT-MHR were used without any modification for these parametric calculations. Other input parameters, including fast neutron fluence, decay heat, and initial temperature distribution were adjusted depending on the reactor power level, reactor inlet/outlet temperatures, and the results of POKE calculations for active core temperatures during normal operation.

Sensitivity to Thermal Power Level

Figures 3-1 (490°C inlet temperature) and 3-2 (590°C inlet temperature) show the peak fuel temperature during an LPCC event as a function of thermal power level. Because the decay heat rate is proportional to thermal power level during normal operation, lowering the thermal power level results in a significant reduction in peak fuel temperatures during a LPCC event. Peak fuel temperatures are reduced by about 460°C to 470°C as the thermal power level is dropped from 600 MW to 250 MW. The change in slope below a power level of 300 MWt is probably the result of reduced annealing of the graphite thermal conductivity at lower temperatures.

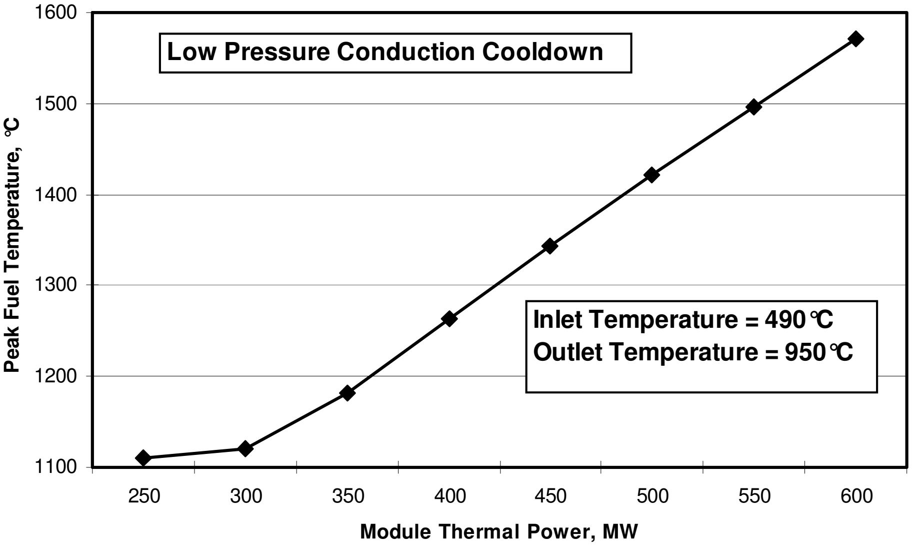

Figure 3-1. Sensitivity of Peak Fuel Temperature to Thermal Power Level (LPCC Event, 490°C inlet temperature)

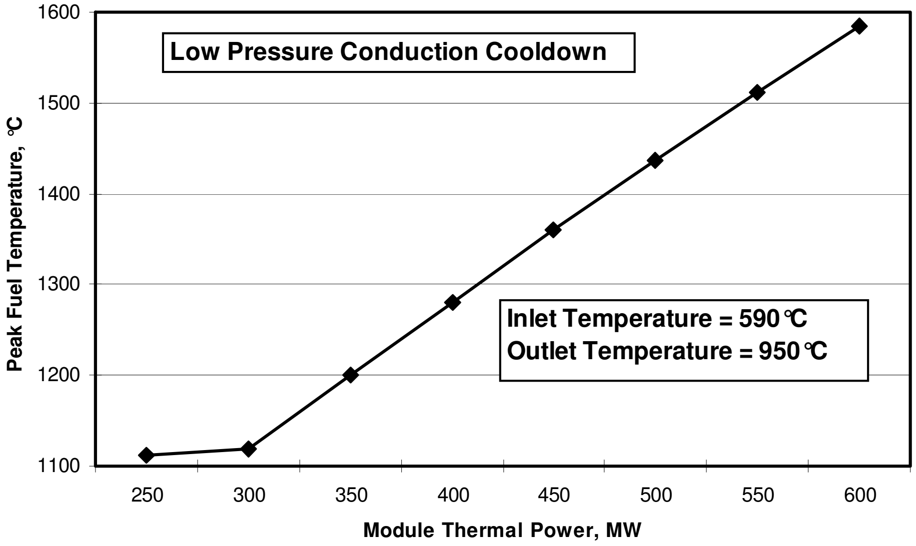

Figure 3-2. Sensitivity of Peak Fuel Temperature to Thermal Power Level (LPCC Event, 590°C inlet temperature)

Figures 3-3 (490°C inlet temperature) and 3-4 (590°C inlet temperature) show the peak vessel temperature during an LPCC event as a function of thermal power level. During LPCC events, vessel temperatures are determined largely by heat transfer to the Reactor Cavity Cooling System (RCCS), which occurs primarily by thermal radiation. Lowering the thermal power level results in only a relatively small reduction in peak vessel temperature during these events. At power levels below about 500 MWt, the peak vessel temperatures occur early in the transient and are approximately the same (see Figs. 3-13 and 3-15).

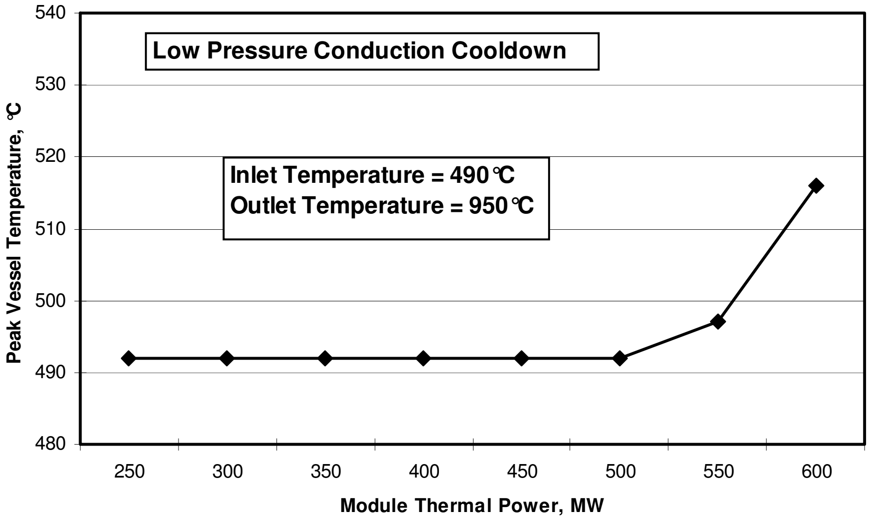

Figure 3-3. Sensitivity of Peak Vessel Temperature to Thermal Power Level (LPCC Event, 490°C inlet temperature)

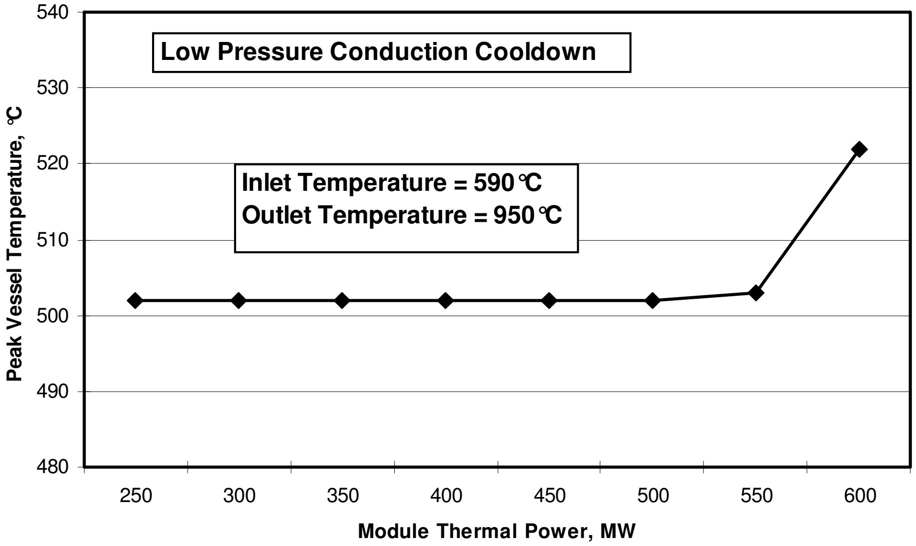

Figure 3-4. Sensitivity of Peak Vessel Temperature to Thermal Power Level (LPCC Event, 590°C inlet temperature)

Sensitivity to Coolant Outlet Temperature

Figures 3-5 (490°C inlet temperature) and 3-6 (590°C inlet temperature) show the peak fuel temperature during an LPCC event as a function of coolant outlet temperature at a fixed thermal power level of 600 MW. Lowering the coolant outlet temperature during normal operation results in only a small reduction in peak fuel temperatures during LPCC events, primarily because peak fuel temperatures occur near the axial midplane of the core during an LPCC event.

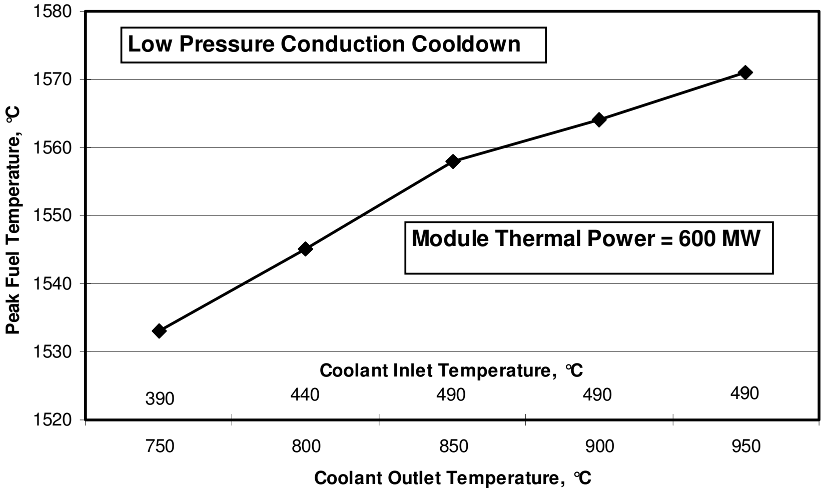

Figure 3-5. Sensitivity of Peak Fuel Temperature to Coolant Outlet Temperature (LPCC Event, 490°C inlet temperature)

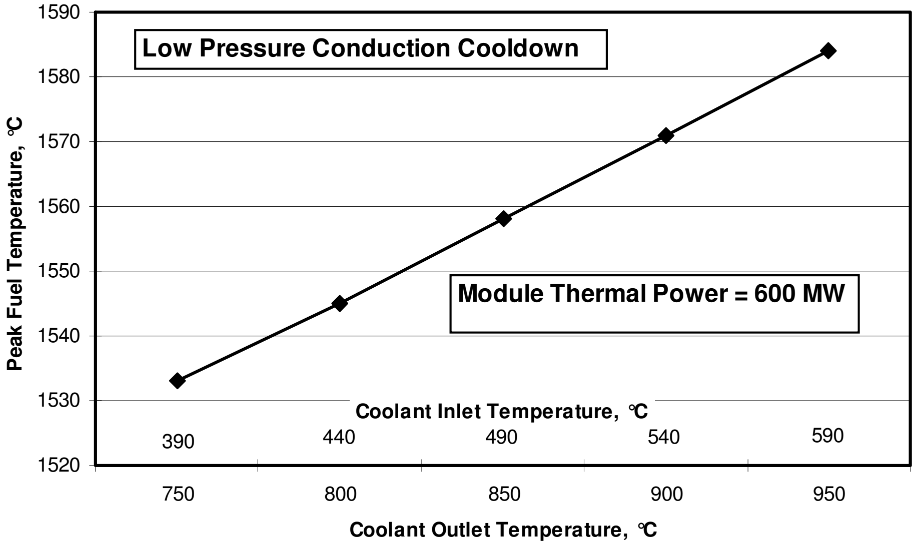

Figure 3-6. Sensitivity of Peak Fuel Temperature to Coolant Outlet Temperature (LPCC Event, 590°C inlet temperature)

Figures 3-7 (490°C inlet temperature) and 3-8 (590°C inlet temperature) show the peak vessel temperature during an LPCC event as a function of coolant outlet temperature. During LPCC events, vessel temperatures are determined largely by heat transfer to the Reactor Cavity Cooling System (RCCS), which occurs primarily by thermal radiation. Lowering the coolant outlet temperature results in only a small reduction in peak vessel temperature during these events.

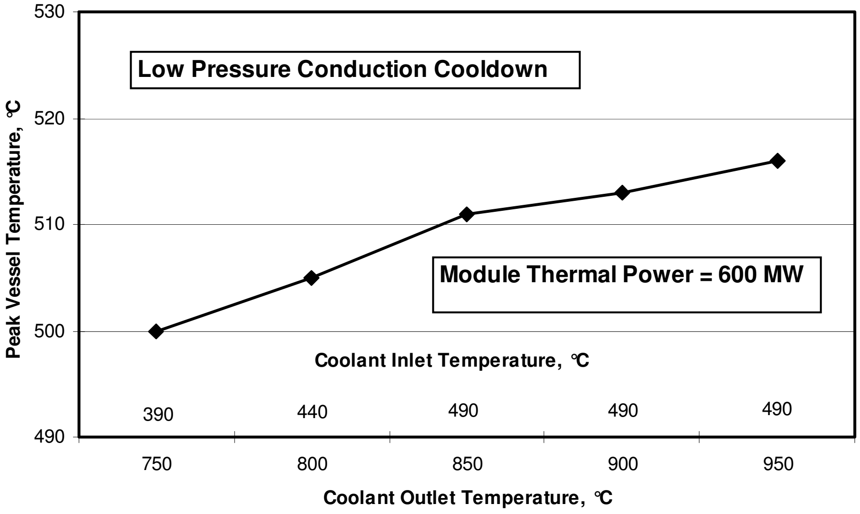

Figure 3-7. Sensitivity of Peak Vessel Temperature to Coolant Outlet Temperature (LPCC Event, 490°C inlet temperature)

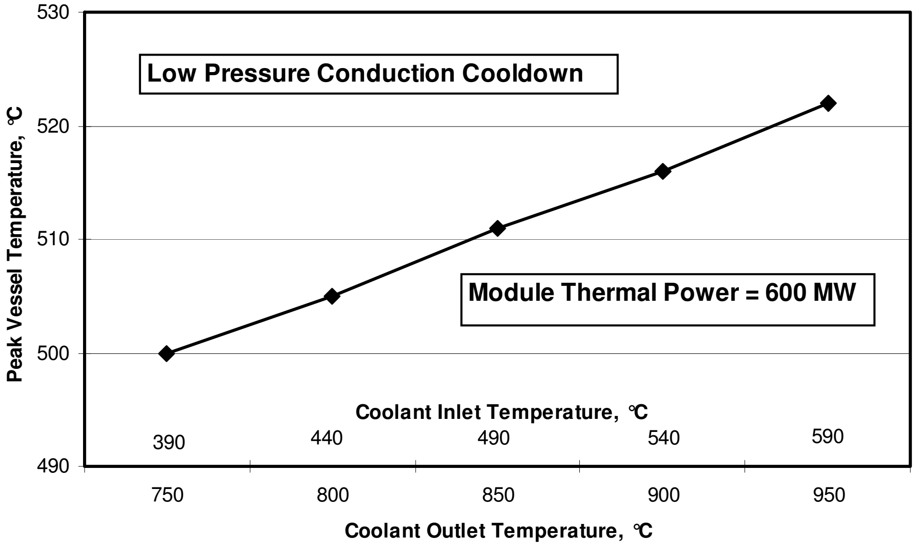

Figure 3-8. Sensitivity of Peak Vessel Temperature to Coolant Outlet Temperature (LPCC Event, 590°C inlet temperature)

Transient Plots

Transient plots for the parametric cases are shown in Figs. 3-9 through 3-16.

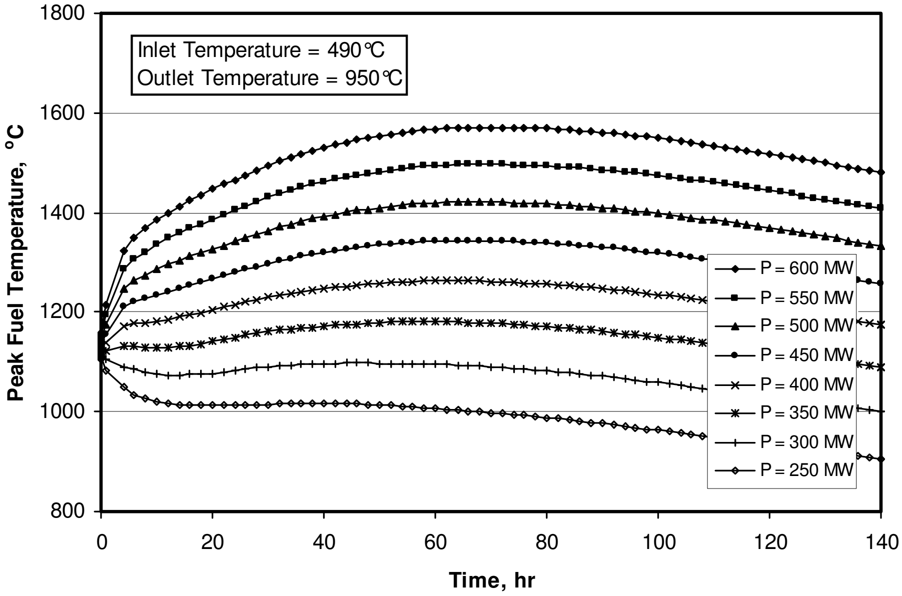

Figure 3-9. Transient Plot - Sensitivity of Peak Fuel Temperature to Thermal Power Level (LPCC Event, 490°C inlet temperature)

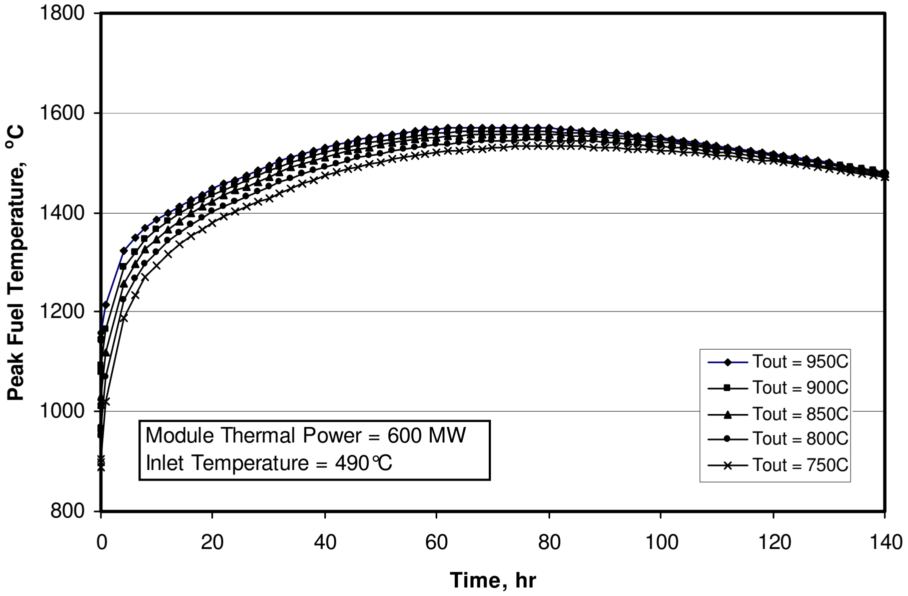

Figure 3-10. Transient Plot - Sensitivity of Peak Fuel Temperature to Coolant Outlet Temperature (LPCC Event, 490℃ inlet temperature)

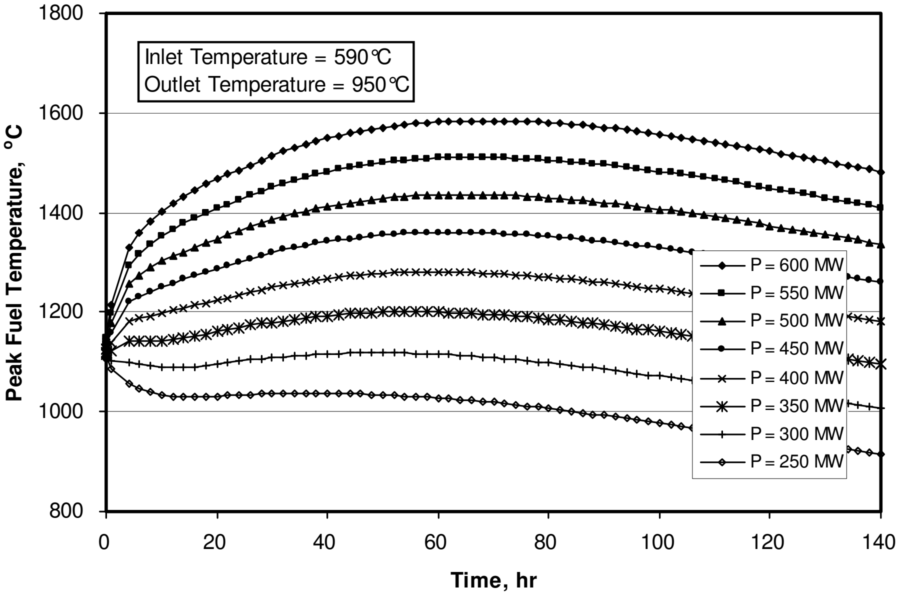

Figure 3-11. Transient Plot - Sensitivity of Peak Fuel Temperature to Thermal Power Level (LPCC Event, 590℃ inlet temperature)

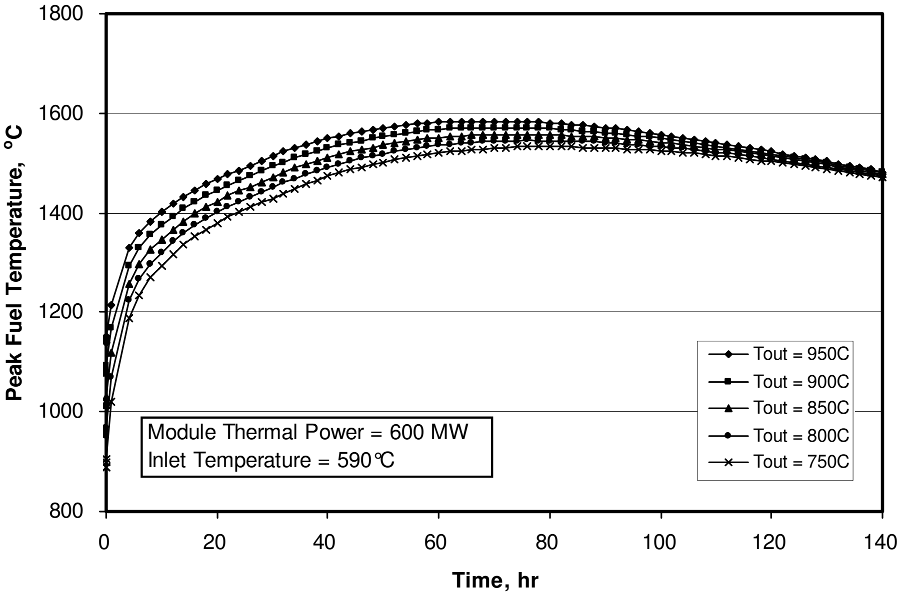

Figure 3-12. Transient Plot - Sensitivity of Peak Fuel Temperature to Coolant Outlet Temperature (LPCC Event, 590°C inlet temperature)

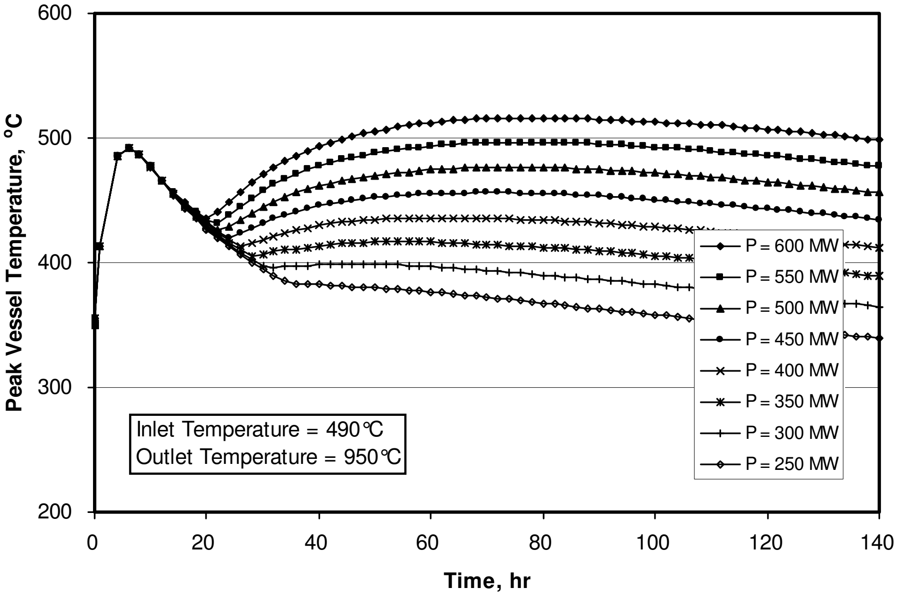

Figure 3-13. Transient Plot - Sensitivity of Peak Vessel Temperature to Thermal Power Level (LPCC Event, 490°C inlet temperature)

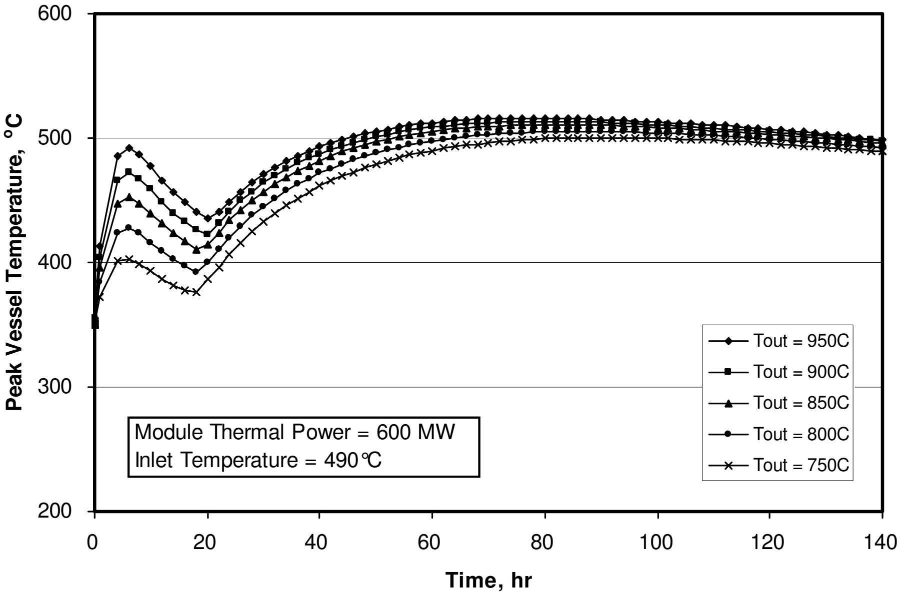

Figure 3-14. Transient Plot - Sensitivity of Peak Vessel Temperature to Coolant Outlet Temperature (LPCC Event, 490°C inlet temperature)

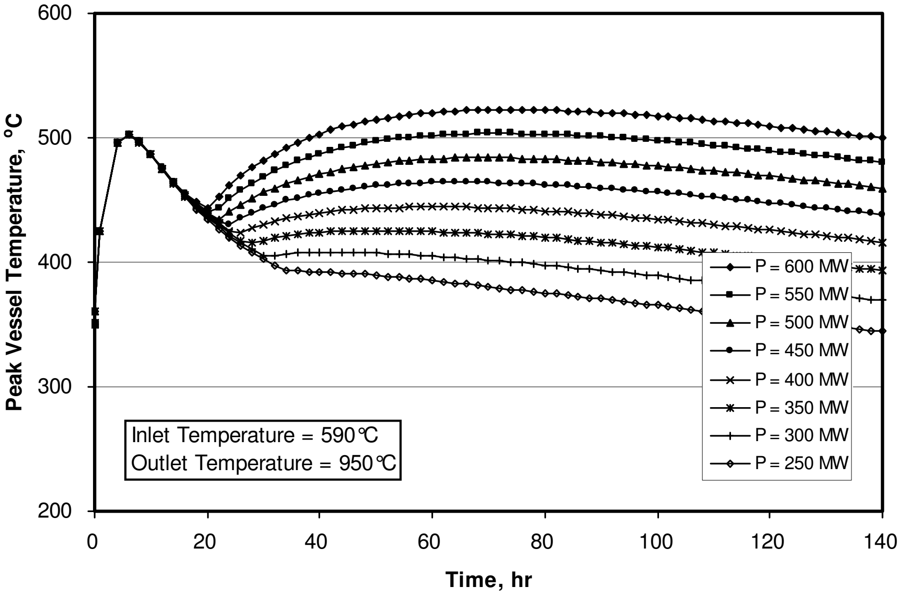

Figure 3-15. Transient Plot - Sensitivity of Peak Vessel Temperature to Thermal Power Level (LPCC Event, 590°C inlet temperature)

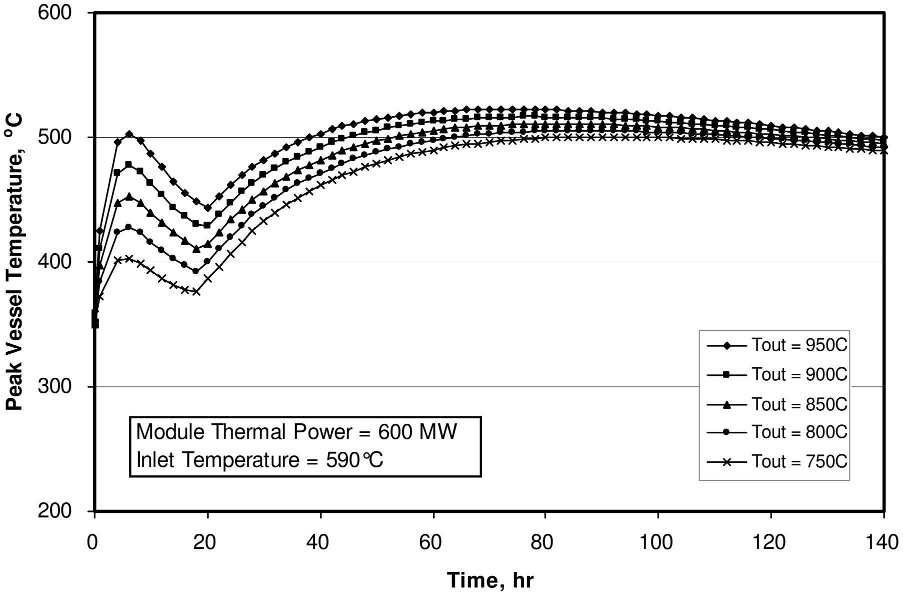

Figure 3-16. Transient Plot - Sensitivity of Vessel Fuel Temperature to Coolant Outlet Temperature (LPCC Event, 590°C inlet temperature)

4. REFERENCES

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