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ORNL/TM-2001/20

SENSITIVITY OF VVER-1000 TRANSIENT THERMAL-HYDRAULIC CALCULATION RESULTS TO VARIATIONS IN MOX THERMAL PROPERTY VALUES

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ORNL-27 (4-00)

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Engineering Technology Division

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Date Published: April 2001

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vii
ABSTRACT	1
1. INTRODUCTION	1
2. NUCLEAR POWER PLANT MODEL	2
3. CALCULATION RESULTS	3
3.1 STEADY STATE CONDITIONS	3
3.2 FOUR-PUMP TRIP	7
3.3 PUMP LOCKED ROTOR	9
3.4 REGULATING ROD GROUP WITHDRAWAL	13
3.5 CONTROL ROD EJECTION	17
3.6 LARGE-BREAK LOCA	22
4. SUMMARY	25
5. CONCLUSIONS	26
REFERENCES	27

LIST OF FIGURES

Figure		Page
1	RELAP5 model of two loops of the primary system	2
2	RELAP5 model of two loops of the secondary system	3
3	Effect of specific heat variation on rod surface heat flux for four-pump trip event	4
4	Effect of fuel-to-cladding gap variation on rod surface heat flux for four-pump trip event	4
5	Effect of fuel conductivity variation on rod surface heat flux for four-pump trip event	5
6	Effect of fuel specific heat variation on rod temperature for four-pump trip event	5
7	Effect of fuel-to-cladding gap on rod temperatures for four-pump trip event	6
8	Effect of thermal conductivity on rod temperatures and centerline for four-pump trip event	6
9	Effect of fuel specific heat variation on CHFR for four-pump trip event	7
10	Effect of specific heat variation on rod surface heat flux for locked rotor event	9
11	Effect of fuel-to-cladding gap on rod surface heat flux for locked rotor event	10
12	Effect of fuel conductivity on rod surface heat flux for locked rotor event	10
13	Effect of fuel specific heat variation on fuel rod temperatures for locked rotor event	11
14	Effect of fuel-to-cladding gap on fuel rod temperatures for locked rotor event	11
15	Effect of fuel conductivity of fuel rod temperatures for locked rotor event	12
16	Effect of fuel specific heat on fuel rod surface heat flux for regulating rod group withdrawal event	13
17	Effect of fuel-to-cladding gap on fuel rod surface heat flux for regulating rod group withdrawal event	14
18	Effect of fuel conductivity on fuel rod surface heat flux for regulating rod group withdrawal event	14
19	Effect of fuel specific heat on CHFR for regulating rod group withdrawal event	15
20	Effect of fuel specific heat on fuel rod temperatures for regulating rod group withdrawal event	15
21	Effect of fuel-to-cladding gap on fuel rod temperatures for regulating rod group withdrawal event	16
22	Effect of fuel conductivity on fuel rod temperatures for regulating rod group withdrawal event	16
23	Effect of fuel specific heat on fuel rod surface heat flux for control rod ejection accident	17
24	Effect of fuel-to-cladding gap on fuel rod surface heat flux for control rod ejection accident	18
25	Effect of fuel conductivity variation on fuel rod heat flux for control rod ejection accident	19

26 Effect of fuel specific heat variation on fuel rod temperatures for control rod ejection accident 19
27 Effect of fuel-to-cladding gap on fuel rod temperatures for control rod ejection accident 20
28 Effect of fuel conductivity variation on fuel rod temperatures for control rod ejection accident 20
29 Effect of fuel specific heat on fuel enthalpy variation for control rod ejection accident 21
30 Effect of fuel specific heat variation on fuel rod heat flux for large-break LOCA 22
31 Effect of fuel-to-cladding gap on fuel rod heat flux for large-break LOCA 23
32 Effect of fuel conductivity variation on fuel rod heat flux for large-break LOCA 23
33 Effect of fuel specific heat on fuel rod temperature for large-break LOCA 24
34 Effect of fuel-to-cladding gap variation on fuel rod heat flux for large-break LOCA 24
35 Effect of fuel conductivity variation on fuel rod heat flux for large-break LOCA 25

LIST OF TABLES

Table		Page
1	Effect of fuel property and geometry variations for steady state conditions	7
2	Effect of fuel property and geometry variations for four-pump trip	8
3	Effect of fuel property and geometry variations for locked rotor	12
4	Effect of fuel property and geometry variations for group withdrawal	17
5	Effect of fuel property and geometry variations for control rod ejection	18
6	Effect of fuel property and geometry variations for LOCA	25

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ABSTRACT

Thermal-hydraulic analysis of Russian VVER-1000 reactors using mixed-oxide (MOX) fuel will be required before disposition of weapons-grade plutonium can begin in these reactors. This analysis is necessary to determine whether safety margins in the reactor remain sufficient after inserting MOX assemblies. Several limiting criteria are used to establish these margins. The criteria include fuel centerline and cladding surface temperature limits, the critical heat flux limit, fuel maximum enthalpy, Zirconium-water reaction limits, and cladding oxidation limits. The limiting conditions depend on the thermal properties of the fuel, such as fuel thermal conductivity and fuel specific heat, as well as other fuel-related parameters, such as fuel-to-cladding gap and fission product gas properties. These properties are well-established for uranium dioxide (UO_2) fuel, and values for UO_2 have been accepted in the licensing process. Although a significant amount of thermal property data is also available for MOX fuel, the database is not as extensive or as focused as that for UO_2 fuel; there is no recent licensing experience with this fuel in either Russia or the United States. The work presented here evaluates the impact of uncertainties in MOX thermal properties on the thermal-hydraulic results of several accident scenarios. The objective of this effort is to determine how sensitive transient calculations are to changes in fuel thermal properties. Five accident scenarios were evaluated: (1) a four main circulating pump trip event, (2) a locked main circulating pump rotor event, (3) an uncontrolled regulating rod group withdrawal, (4) a control rod ejection event, and (5) a large-break loss-of-coolant accident. For each scenario, two fuel properties and one fuel geometry parameter were varied parametrically to determine their impact on the accident response: fuel thermal conductivity, fuel specific heat, and fuel pellet-to-cladding gap. Results of these calculations indicate that variations of fuel thermal properties have only a limited impact on transient response and, therefore, a small impact on the thermal limits for the accident scenarios studied.

1. INTRODUCTION

An option for preventing the proliferation of weapons-grade plutonium is to burn it in a commercial power reactor. This option is being studied both in the United States and in Russia as one means of reducing the stockpile of weapons materials. Because mixed-oxide (MOX) fuel has never been licensed for use in commercial light-water reactors in either the United States or Russia, both countries presently have ongoing programs designed to allow the future use of this fuel in existing power reactors. A portion of these programs is designed to determine whether the safety of these reactors will be compromised by the introduction of MOX assemblies in the core. As a part of this safety evaluation, thermal-hydraulic analyses are required before any reactor will be licensed for operation using MOX fuel. Fuel thermal properties influence the results of these calculations because many of the limiting criteria used in the licensing process are dependent on

the fuel characteristics. The major limiting criteria are maximum fuel cladding surface and centerline temperature, the critical heat flux (CHF) limit (dependent on fuel rod surface heat flux), and fuel enthalpy limits. Each of these criteria is dependent on fuel-related variables such as fuel thermal conductivity (k), fuel specific heat (C_p), and fuel-to-cladding gap.

For uranium dioxide (UO_2) fuel, a significant data base of fuel thermal properties exists, and these have been accepted and used in the licensing process. A significant amount of thermal property data also exists for MOX fuel,[1] although significantly less than that for UO_2 fuel. Because this fuel has never been licensed for operation in a commercial power plant in either the United States or Russia, there are no "accepted" values in the licensing arena. The objective of this study is to determine how sensitive thermal-hydraulic calculational results are to uncertainties or variations in the fuel thermal properties and geometry. For this study, two fuel properties and one geometry variable were evaluated: fuel thermal conductivity, fuel specific heat, and fuel-to-cladding gap.

2. NUCLEAR POWER PLANT MODEL

Five transient events that have been previously selected to study the transient performance of a VVER-1000 reactor with MOX lead test assemblies (LTAs)[2] in the core were also used in this study. They were a four main circulation pump trip event, a locked main circulation pump rotor, a control rod group withdrawal, a control rod ejection event, and a large-break loss-of-coolant accident (LOCA). The three variables selected were each independently varied ±20% and the transient events run for each case. Thus, a total of seven transient calculations were performed for each event (including a "nominal" case for each event). For this study, three parameters were considered as performance indicators: fuel centerline temperature, cladding surface temperature, and fuel rod surface heat flux. These parameters were examined for one particular location in the reactor corresponding to the hot rod in the hot channel located in one of the MOX LTAs.

The RELAP5 model of the Balakovo 4 VVER-1000 nuclear power plant (NPP) used in these calculations was developed at the Kurchatov Institute. This model is presented in Ref. 3 and is shown schematically in Figs. 1 and 2. The core was divided into six volumes reflecting the average core, the hot assembly for UO_2 fuel, a single MOX assembly, the hot channel for UO_2 fuel, and two channels for MOX fuel (one with an average rod and one with a hot rod).

Because this model does not incorporate the final fuel and LTA design, the specific performance of the fuel (i.e., temperatures, heat flux levels, and CHF ratios) are not those that will

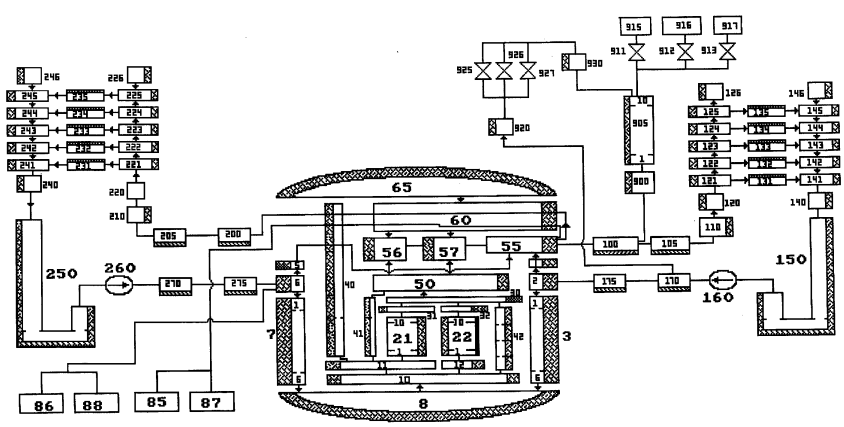

Fig. 1. RELAP5 model of two loops of the primary system.

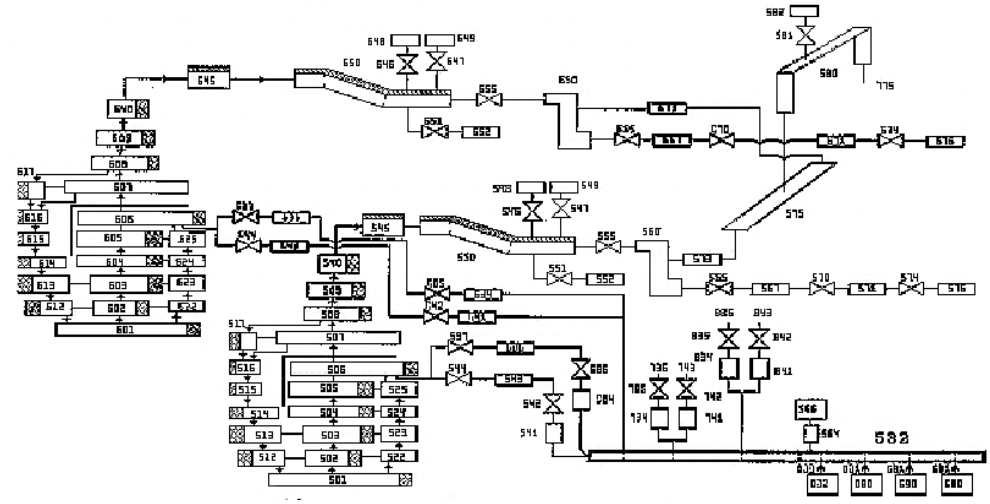

Fig. 2. RELAP5 model of two loops of the secondary system.

occur in the final reactor design. However, because this report focuses on differences in performance due to property variations, the fact that these values do not reflect what will actually occur in the final design should have little impact on the overall conclusions.

3. CALCULATION RESULTS

Calculations were performed for each of the five transients discussed previously. Results are presented as plots of heat flux (q”), centerline temperature (T_{cl}), and cladding temperature (T_{clad}) vs time with the variable of interest varied ±20% in each plot. The 20% variation was chosen somewhat arbitrarily; however, fuel properties are expected to vary significantly less than 20% (see Ref. 1). The results presented should therefore be conservative for independent variation of these properties. Each transient calculation will be discussed separately.

3.1 STEADY STATE CONDITIONS

Each transient was initiated after 200 s of steady state operation. Therefore, the impact of changing the variables ±20% on steady state conditions can be examined by looking at the initial portion of each of the transient plots. Because steady state conditions are the same for each transient, results from the four-pump trip transient will be used to discuss the steady state results by looking at the plots between 100 and 200 s. Figures 3–5 show that changing the fuel specific heat, fuel-to-cladding gap, and fuel thermal conductivity by ±20% respectively, has no impact on the rod surface heat flux under steady state conditions. This is because under steady state conditions, with fuel rod heat generation constant, all of the heat must escape through the fuel rod surface, and there is no impact of these variables on the heat flux. Figure 6 shows the influence of fuel specific heat variation on rod surface and centerline temperatures. Because C_p only influences the amount of stored energy in the fuel, it does not impact either surface or centerline temperatures under steady state conditions. Figure 7 shows the effect of varying fuel-to-cladding gap on fuel rod temperatures. In this case, because increasing the gap increases the thermal resistance in the fuel rod, fuel centerline temperatures increase even under steady state conditions. However, because the rod surface heat flux does not change and the fluid conditions at the rod surface are the same, cladding (surface) temperatures are not impacted. Figure 8 shows that decreasing the

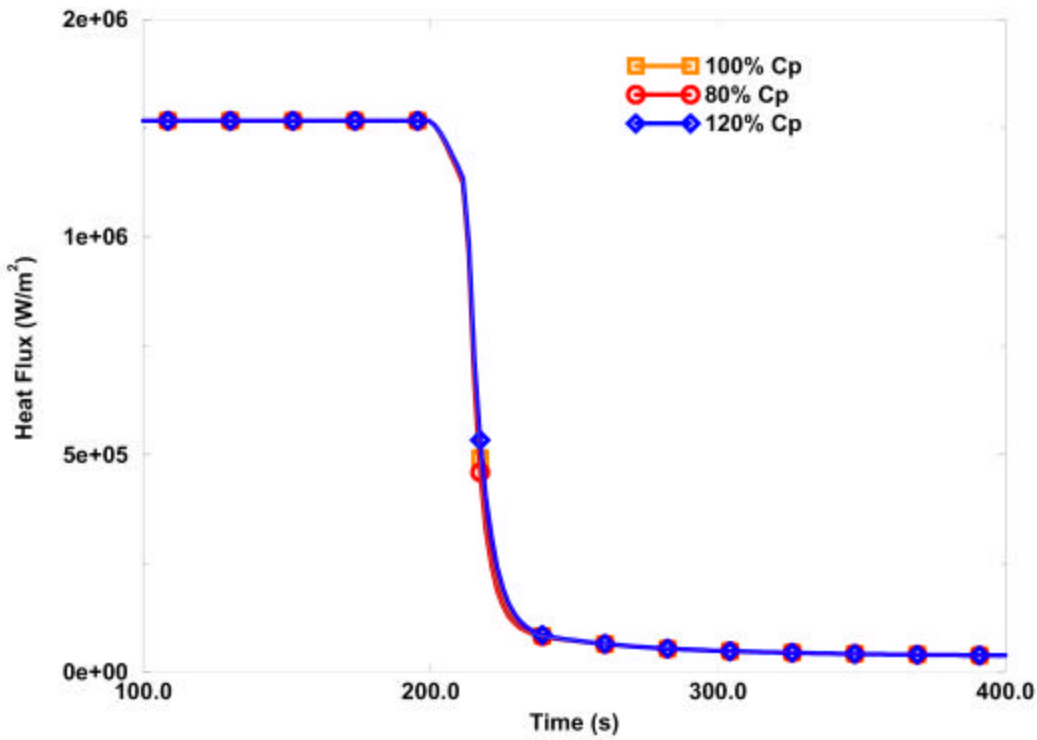

Fig. 3. Effect of specific heat variation on rod surface heat flux for four-pump trip event.

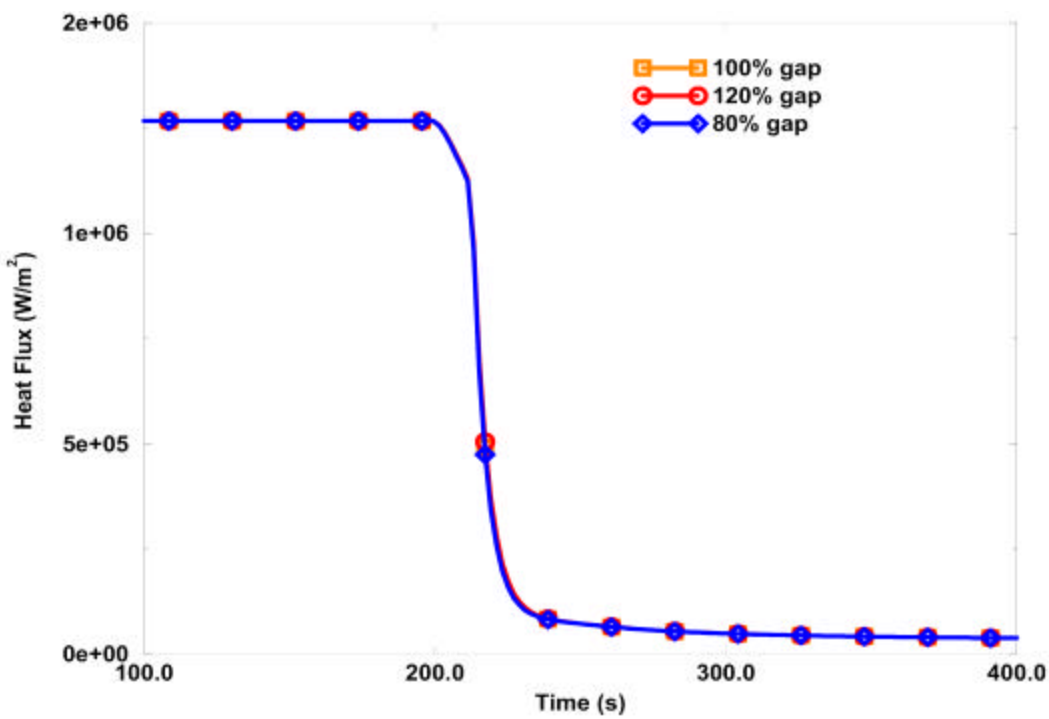

Fig. 4. Effect of fuel-to-cladding gap variation on rod surface heat flux for four-pump trip event.

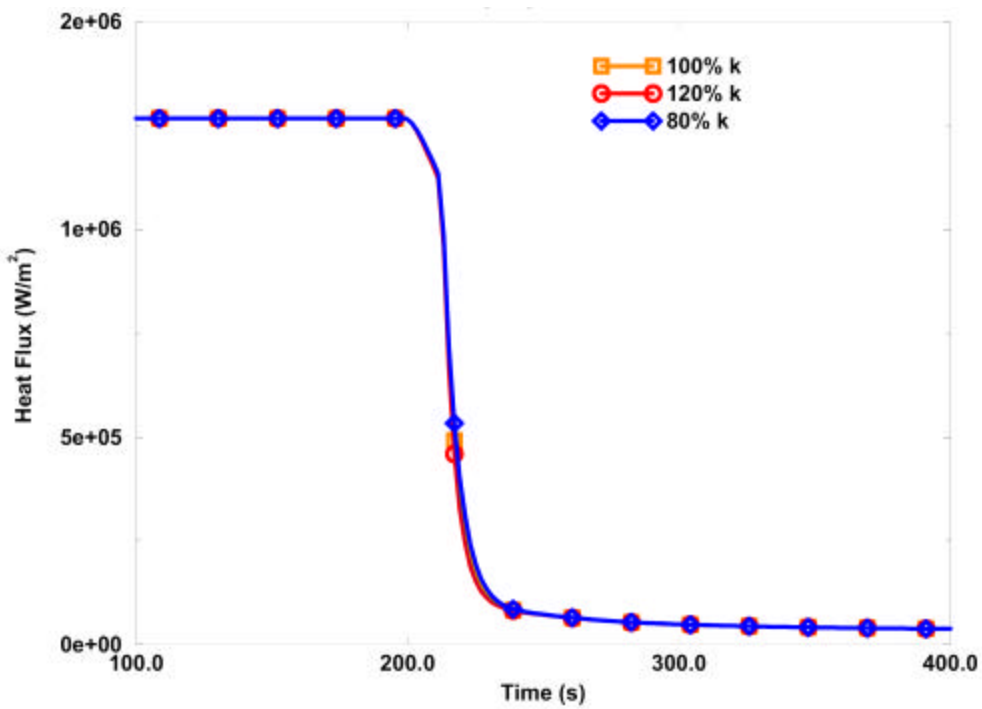

Fig. 5. Effect of fuel thermal conductivity variation on rod surface heat flux for four-pump trip event.

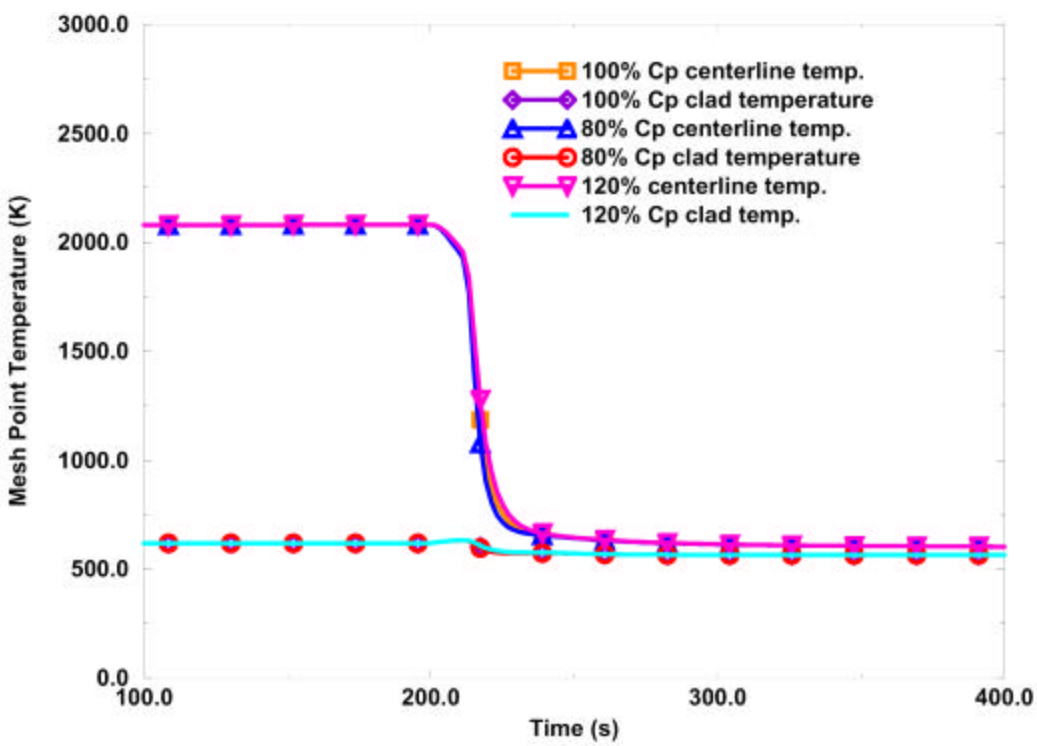

Fig. 6. Effect of fuel specific heat variation on rod temperature for four-pump trip event.

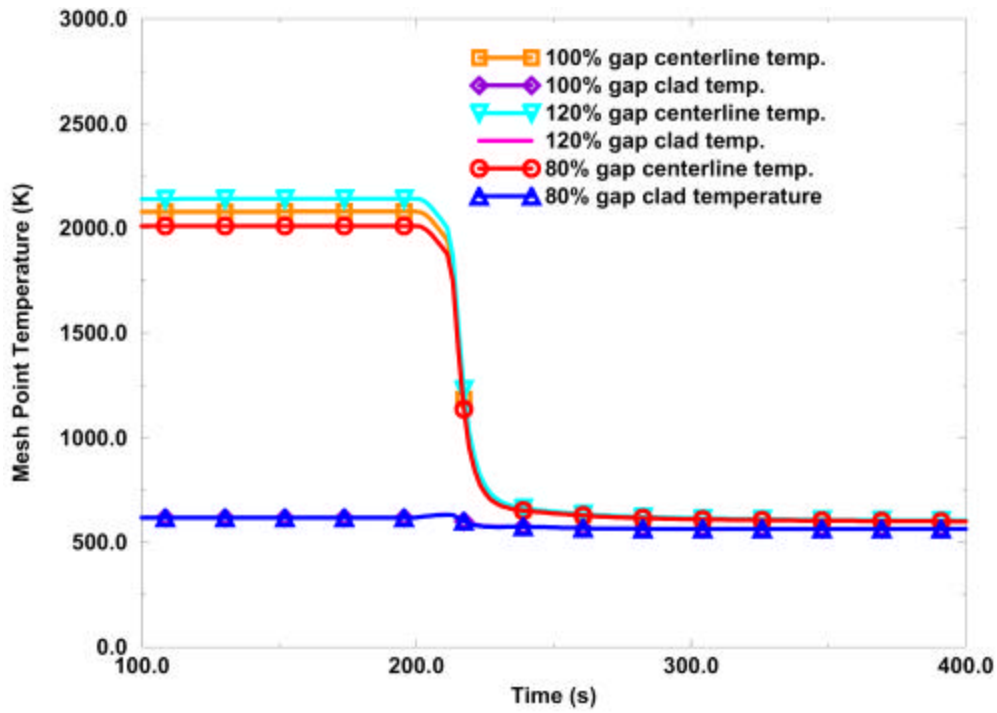

Fig. 7. Effect of fuel-to-cladding gap on rod temperatures for four-pump trip event.

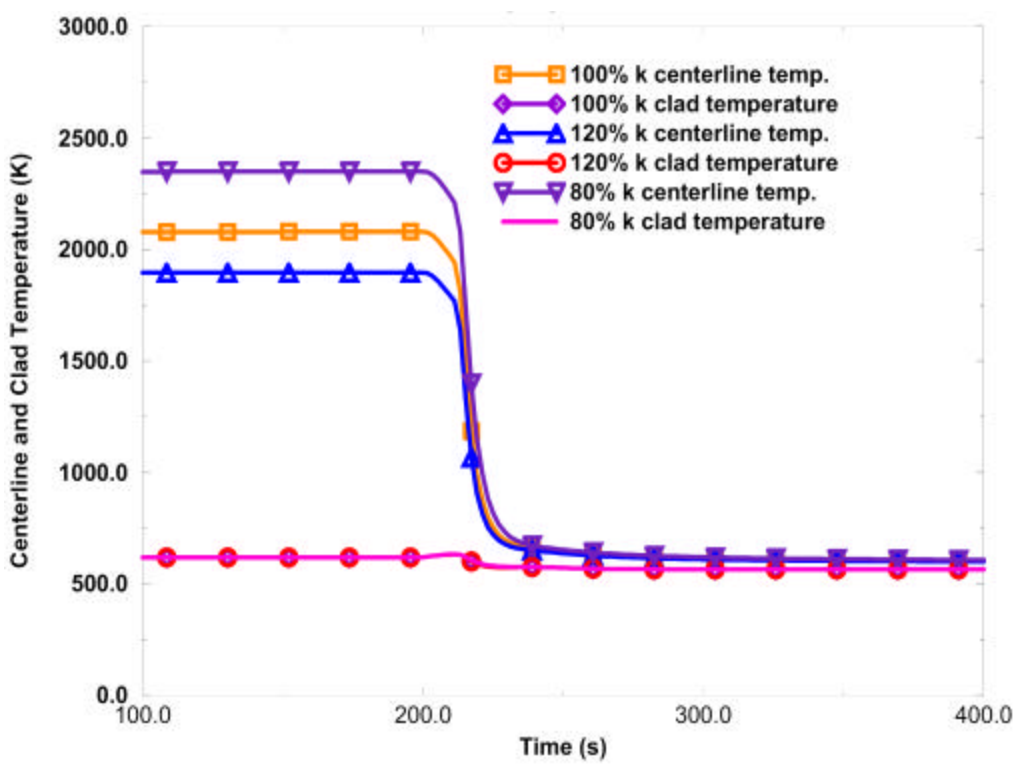

Fig. 8. Effect of fuel thermal conductivity on rod temperatures for four-pump trip event.

fuel thermal conductivity increases the fuel centerline temperatures under steady state conditions, but it has no influence on the cladding temperatures. Reasoning for this is the same as that discussed for the variation in fuel-to-cladding gap discussed previously. A summary of the variations under steady state conditions is shown in Table 1.

Table 1. Effect of fuel property and geometry variations for steady state conditions

	C_p			Gap			k		
	T_{cl} (°C)	T_{clad} (°C)	q" (%)	T_{cl} (°C)	T_{clad} (°C)	q" (%)	T_{cl} (°C)	T_{clad} (°C)	q" (%)
+20%	—	—	—	+62	—	—	–183	—	—
–20%	—	—	—	–68	—	—	+267	—	—

3.2 FOUR-PUMP TRIP

The four-pump trip event is classified as an operational occurrence, with these applicable limiting criteria: no departure from nucleate boiling (DNB) within the core and no fuel melt. Thus, appropriate indicators for this transient would be the fuel rod surface heat flux and fuel centerline temperature. The event was initiated by removing power from the four main coolant circulation pumps at 200 s. The reactor trips at 209 s due to high hot-leg coolant temperatures. Results of these calculations are presented in Figs. 3–9. Figure 3 presents the hot MOX fuel rod surface heat flux as a function of time with the fuel specific heat, C_p, treated parametrically. The results of these calculations indicate that the specific heat has only a very minor influence on the fuel rod surface flux in this transient. Higher fuel-specific heat values tend to increase the surface heat flux during the portion of the transient where the power is decreasing. Because fuel

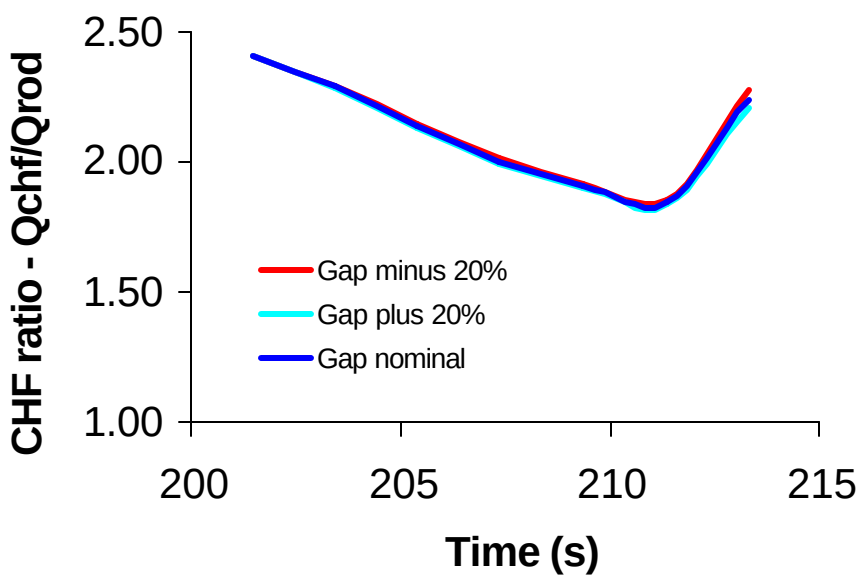

Fig. 9. Effect of fuel specific heat variation on CHFR for four-pump trip event.

temperatures are the same (Fig. 6) for all C_p values under steady state conditions, the total stored energy in the fuel must be higher for the higher C_p case. During the power decrease, the heat flux integrated over time must therefore be higher for the higher C_p results. Although this difference is small, this can be seen in Fig. 3. Figure 4 shows the influence of fuel-to-cladding gap on the fuel rod surface heat flux. Again the influence of this parameter is minimal with a larger gap causing a slightly higher heat flux during the rapid power decrease portion of the event. Larger gaps mean that the steady state operating temperature is higher (Fig. 7) than when smaller gaps exist. The stored energy in the rod is therefore higher, and the rod surface heat flux during the transient must increase as the rod gap increases. Figure 5 shows the impact of a variation in fuel thermal conductivity on the fuel rod surface heat flux. Here again, there is very little difference in the heat flux response during this transient. However, because lower conductivity means higher fuel steady state temperatures (as shown in Fig. 9) and higher initial stored energy, the calculation run with lower conductivity indicates a slightly higher surface heat flux during the rapid power decrease. Differences are between –7% and +8% for a ±20% variation in conductivity.

Although there are some slight differences in heat flux levels, the impact on the critical heat flux ratio (CHFR) is negligible. (CHFR is defined as the ratio of the critical heat flux as predicted by the Groeneveld table used in RELAP to the local fuel rod surface heat flux.) A plot of CHFR is presented in Fig. 9 for variation in fuel-to-cladding gap. CHFR is plotted only for those times in the transient when the fuel rod surface temperature is greater than the saturation temperature (a quirk of the RELAP code). Because the RELAP model used for these calculations incorporates preliminary neutronics parameters and power peaking factors, the CHFRs in these calculations are higher than those expected for the final core design.

Figure 6 shows both the fuel centerline temperature and the fuel cladding surface temperature as a function of time in the transient and presents C_p variation parametrically. Under steady state conditions (before 200 s), temperatures for all three C_p values are the same. After the power trips, during the rapid temperature transient, the fuel centerline temperatures are slightly higher for the case of 120% C_p (by about 91ºC) because the stored energy in the rod is higher for this case. Fuel cladding surface temperatures are not affected by fuel rod specific heat to any significant degree. Figure 7 is a similar plot with the fuel-to-cladding gap treated parametrically. Steady state fuel centerline temperatures are higher for a larger gap because the gap serves as an added resistance to heat flow from the rod. For similar times during the power reduction transient, centerline temperatures for the large gap case are slightly higher than those for the normal and small gap cases because of the higher temperatures and additional stored energy in the fuel rod under steady state conditions. The cladding-to-fuel gap does not impact cladding temperatures to any significant degree. Figure 8 shows centerline and cladding temperatures for three fuel thermal conductivity values. Lower fuel conductivity causes higher fuel centerline temperatures under steady state conditions and, therefore, slightly higher centerline temperatures during the transient due to added fuel stored energy, for the same reasons as discussed previously. Again, cladding temperatures are unaffected by changes in fuel thermal conductivity. A summary of results for the four-pump trip event is shown in Table 2.

Table 2. Effect of fuel property and geometry variations for four-pump trip

	C_p			**Gap**			**k**		
	T_{cl} (ºC)	**T_{clad} (ºC)**	**q" (%)**	**T_{cl} (ºC)**	**T_{clad} (ºC)**	**q" (%)**	**T_{cl} (ºC)**	**T_{clad} (ºC)**	**q" (%)**
+20%	+91	+5	+8	+17		+3	–115		–7
–20%	–109	–6	–7	–20		–4	+216		+8

3.3 PUMP LOCKED ROTOR

A rotor of a main circulation pump instantaneously locking is a design basis event; therefore, the acceptance criterion applicable to this event is that the cladding surface temperature must remain below 1200°C. In the simulation, the rotor of one main circulation pump was assumed to instantaneously lock at 200 s. The way that this event is modeled, the reactor does not trip. However, reactor power decreases approximately 15% due to coolant temperature feedback in the core (core exit temperature increases from about 594 K to about 601 K). Figures 10–12 show the hot MOX rod surface heat flux vs time for variations in C_p, fuel-to-cladding gap, and fuel conductivity, respectively. This event is so mild that varying these parameters has little impact on the rod surface heat flux. Figures 13–15 show fuel centerline and cladding temperatures as each of these parameters are varied. Conclusions about the impact of these parameters on the steady state temperatures are the same as those discussed previously. However, because the reactor does not scram and the power remains high, the temperatures simply follow the steady state trends throughout the transient: no changes in rod surface heat fluxes and cladding surface temperatures, while changes in fuel centerline temperatures are similar to those observed for steady-state conditions (for variations in fuel-to-cladding gap and fuel conductivity). Table 3 shows a summary of results for this event.

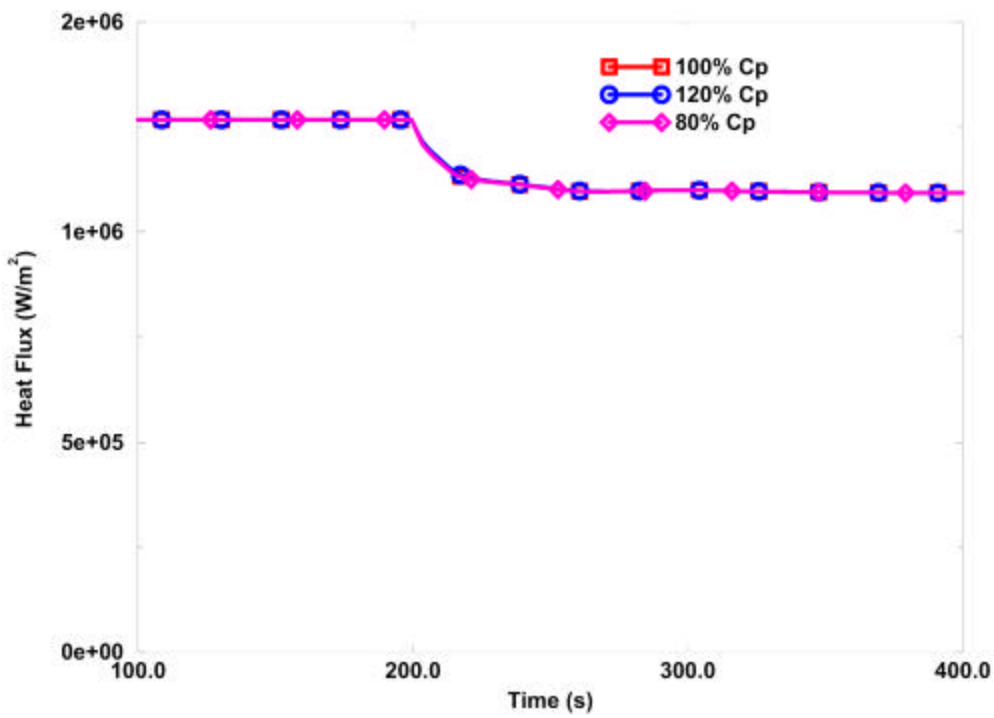

Fig. 10. Effect of specific heat variation on rod surface heat flux for locked rotor event.

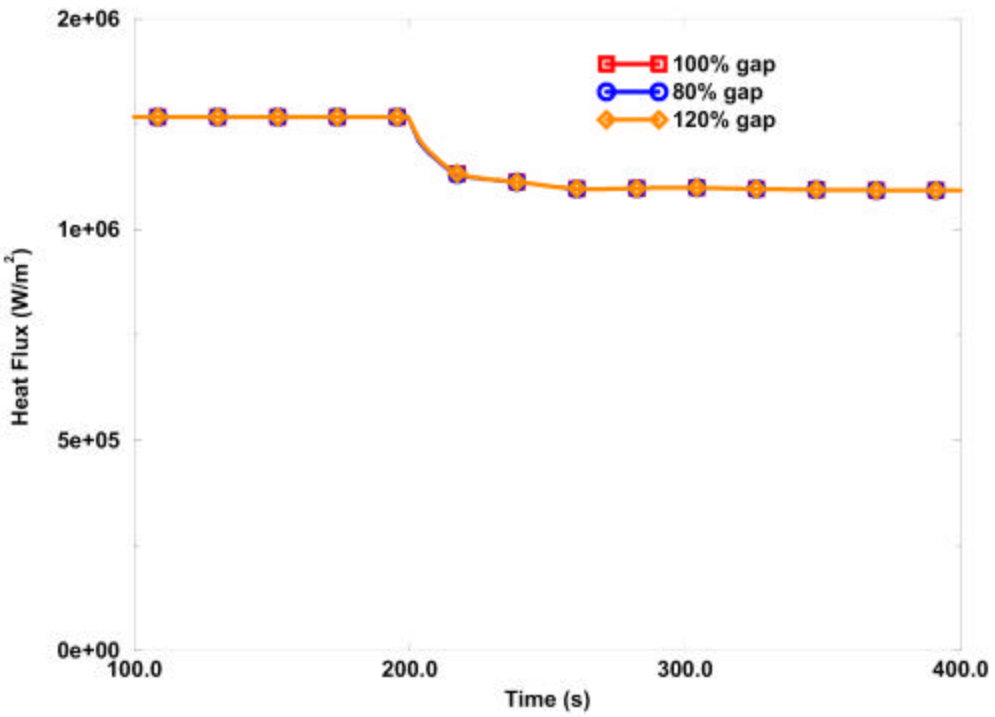

Fig. 11. Effect of fuel-to-cladding gap on rod surface heat flux for locked rotor event.

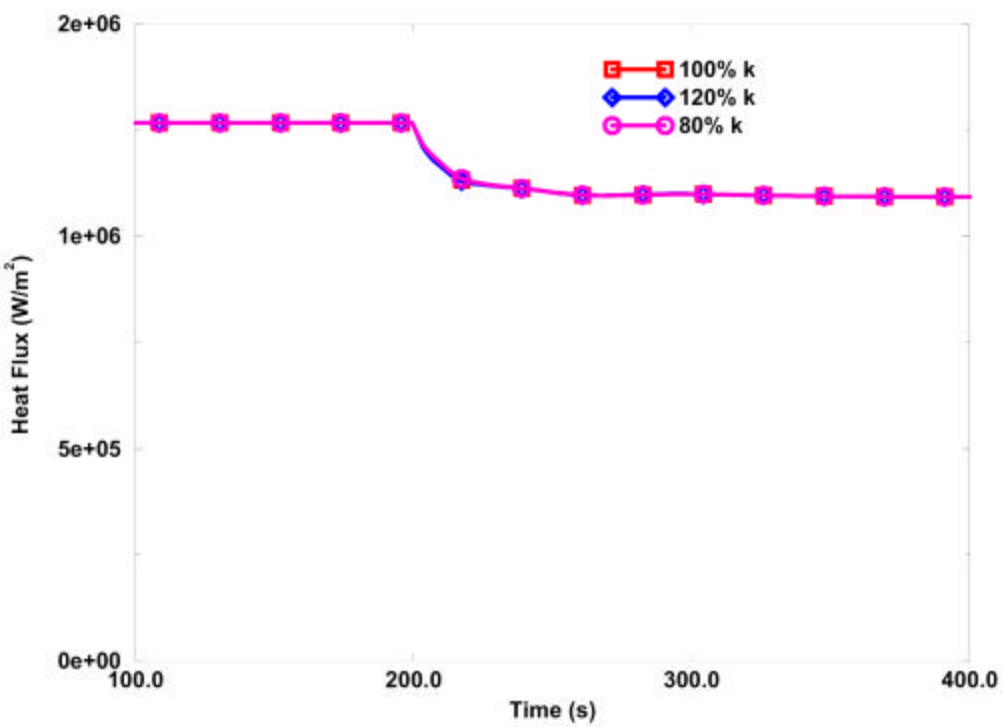

Fig. 12. Effect of fuel thermal conductivity on rod surface heat flux for locked rotor event.

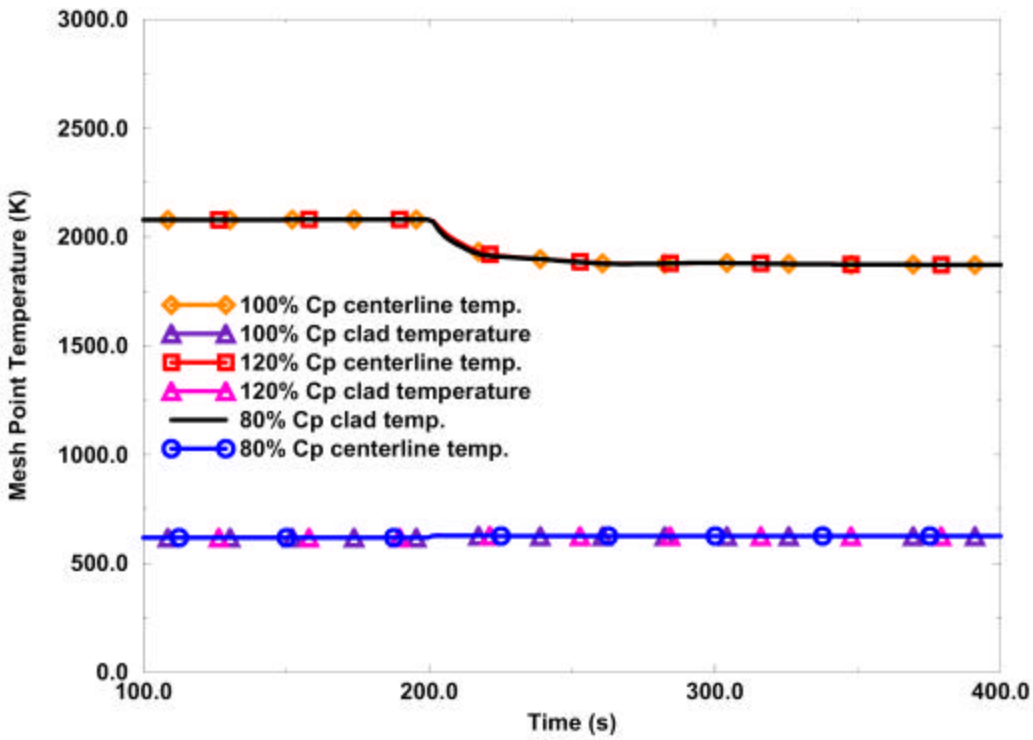

Fig. 13. Effect of fuel specific heat variation on fuel rod temperatures for locked rotor event.

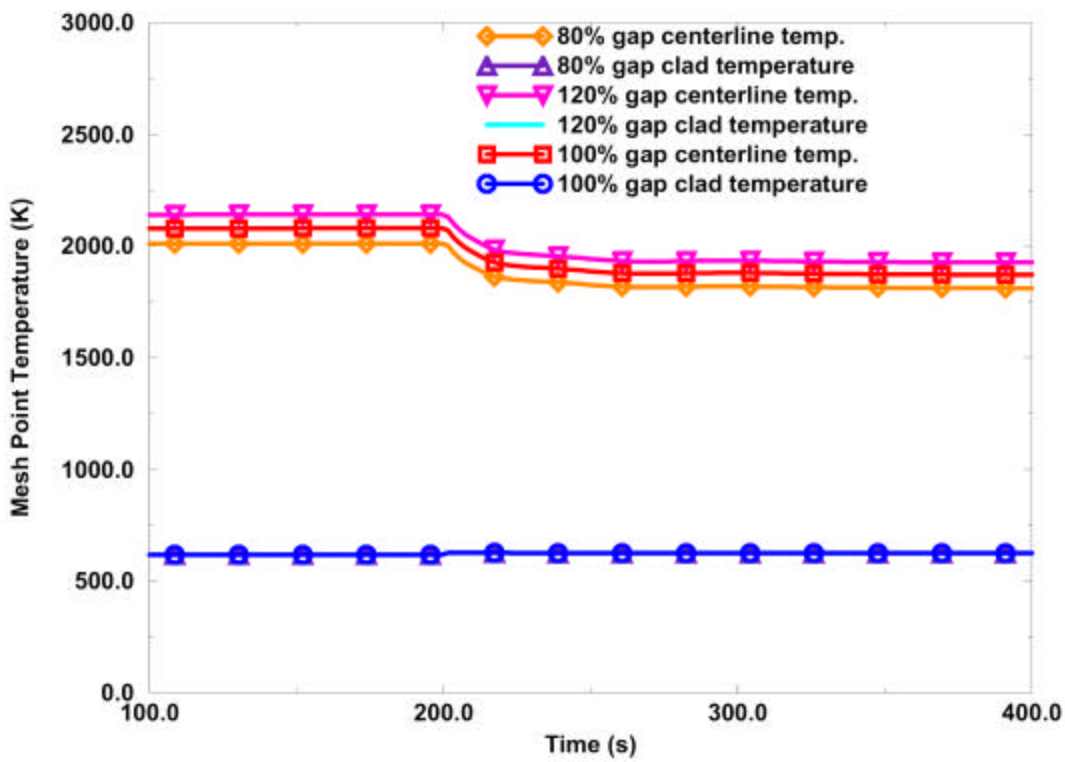

Fig. 14. Effect of fuel-to-cladding gap on fuel rod temperatures for locked rotor event.

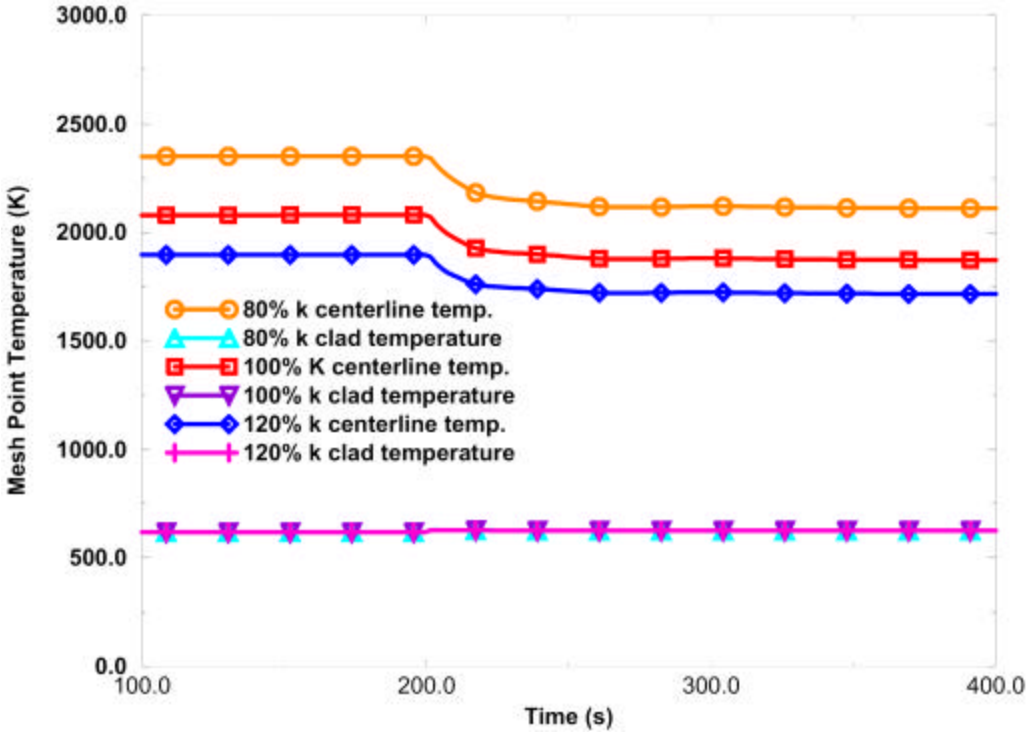

Fig. 15. Effect of fuel thermal conductivity of fuel rod temperatures for locked rotor event.

Table 3. Effect of fuel property and geometry variations for locked rotor

	C_p			Gap			k		
	T_{cl} (°C)	T_{clad} (°C)	q" (%)	T_{cl} (°C)	T_{clad} (°C)	q" (%)	T_{cl} (°C)	T_{clad} (°C)	q" (%)
+20%	—	—	—	+54	—	—	–160	—	—
–20%	—	—	—	–59	—	—	+240	—	—

3.4 REGULATING ROD GROUP WITHDRAWAL

The regulating rod group withdrawal event is considered an operational occurrence, and the acceptance criteria are therefore that no DNB occurs in the core and that there is no fuel melting in the core. The event is initiated by the withdrawal of the regulating rod group at 200 s. The core power increases until a reactor trip occurs at ~212 s on an overpower (107%) signal. Figure 16 shows the impact of a variation in fuel specific heat on this event. In this case, a slightly higher peak value of surface heat flux occurs for the 80% C_p value because under these conditions the fuel does not store as much energy as the rod power increases. After scram, the transient looks similar to that of the four main circulation pump trip case with the higher C_p case showing higher surface heat fluxes due to the additional stored energy in the rod under steady state conditions (indicated in summary table). Figure 17 shows that the effect of fuel-to-cladding gap has very little influence on the rod surface heat flux during this transient. Figure 18 shows the impact of fuel thermal conductivity variations, with similar conclusions as those discussed previously for C_p and fuel-cladding-gap variations for this event. Figure 19 shows CHFR during the period when the rod surface temperatures are above the saturation temperature. This ratio is presented for a variation in fuel specific heat because this parameter variation caused the largest change in the CHFR. As can be seen from Fig. 19, a variation of ±20% in fuel specific heat causes less than a ±1% change in the CHFR. Figure 20 shows both the fuel centerline and cladding surface temperatures vs time with C_p treated parametrically. In this case, lower fuel specific heat causes higher peak centerline temperatures because of the decreased ability of the fuel to store energy as the power increases compared to higher C_p cases. Cladding surface temperatures are virtually unaffected by variations in fuel specific heat. Figure 21 shows the impact of fuel cladding-to-gap. During the power increase portion of the transient, temperatures follow almost parallel paths for all of the gap conditions considered, while conclusions for the power reduction portion of the transient are similar to those of the four-pump trip transient. Figure 22 shows the effect of a

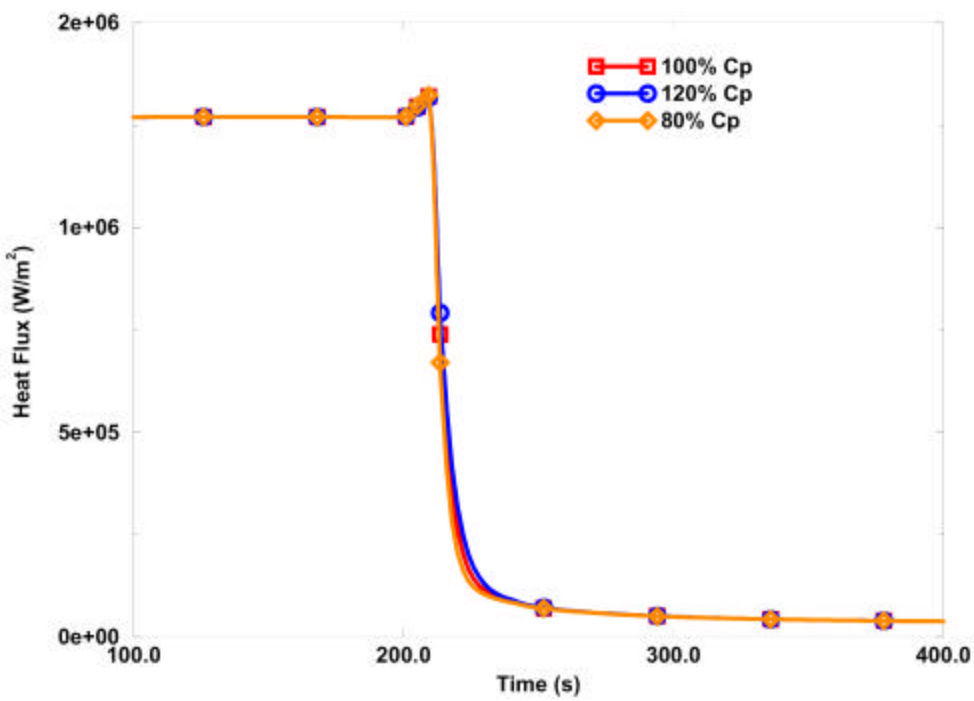

Fig. 16. Effect of fuel specific heat on fuel rod surface heat flux for regulating rod group withdrawal event.

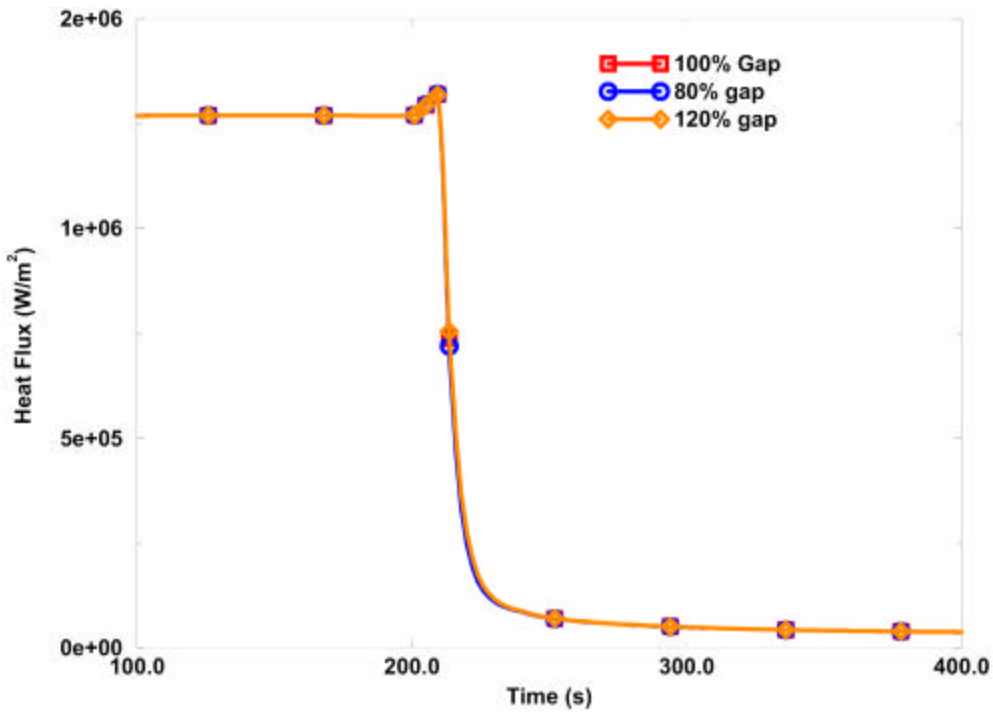

Fig. 17. Effect of fuel-to-cladding gap on fuel rod surface heat flux for regulating rod group withdrawal event.

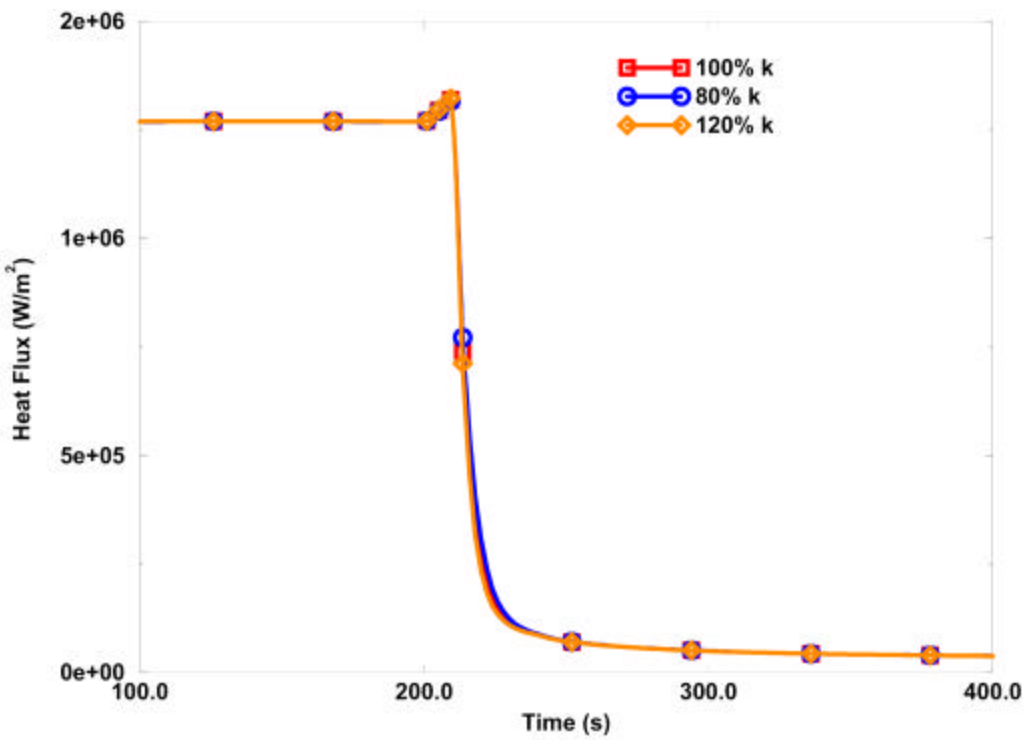

Fig. 18. Effect of fuel thermal conductivity on fuel rod surface heat flux for regulating rod group withdrawal event.

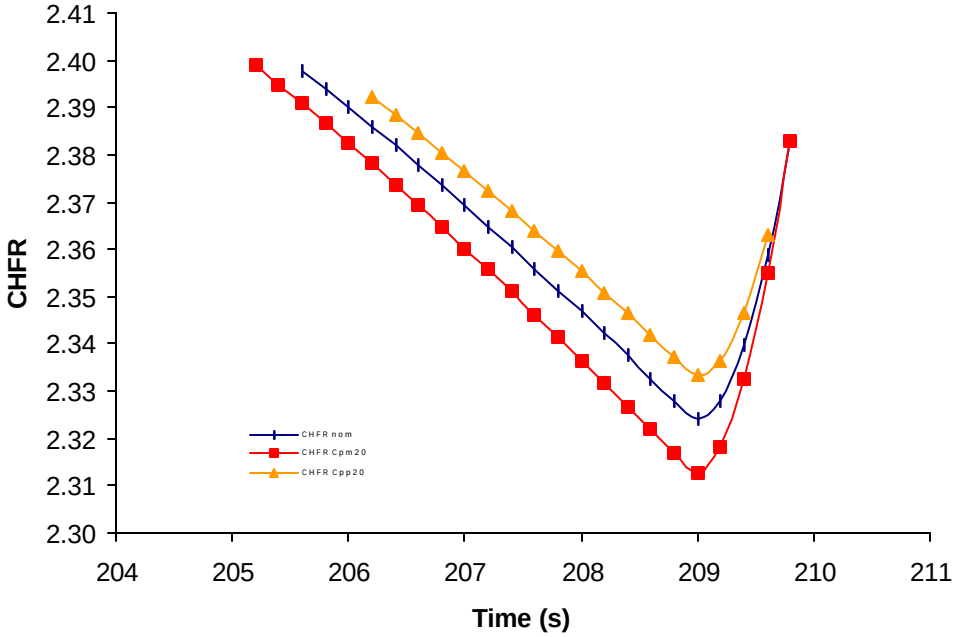

Fig. 19. Effect of fuel specific heat on CHFR for regulating rod group withdrawal event.

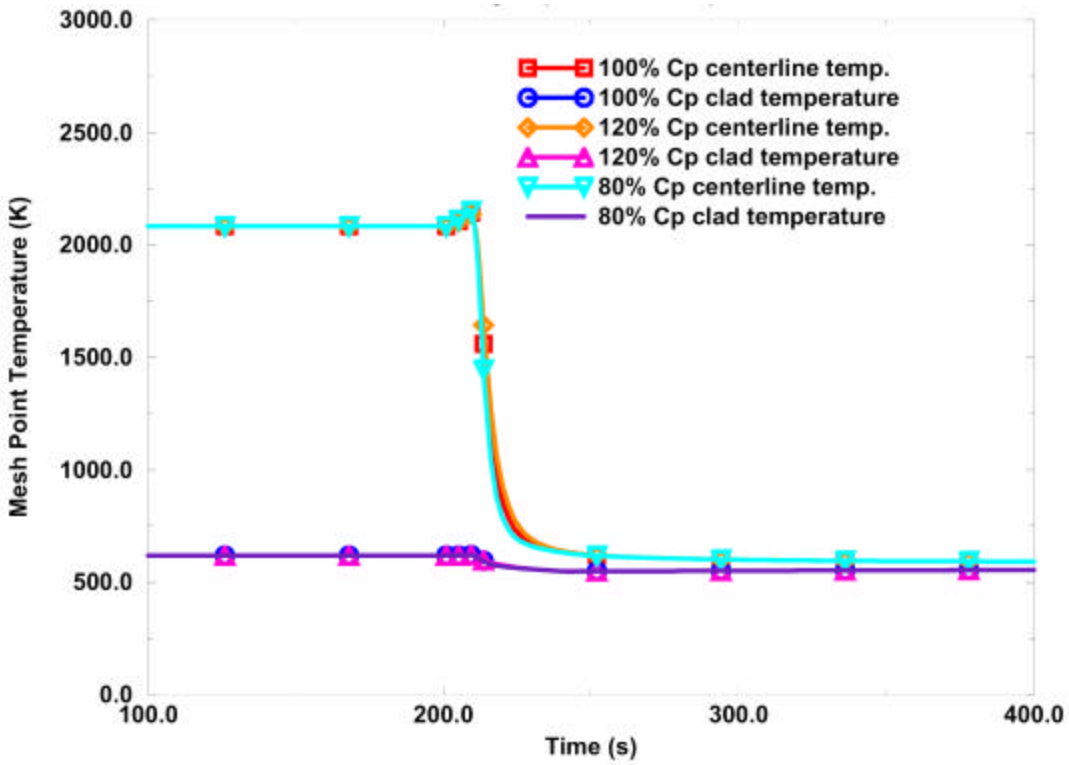

Fig. 20. Effect of fuel specific heat on fuel rod temperatures for regulating rod group withdrawal event.

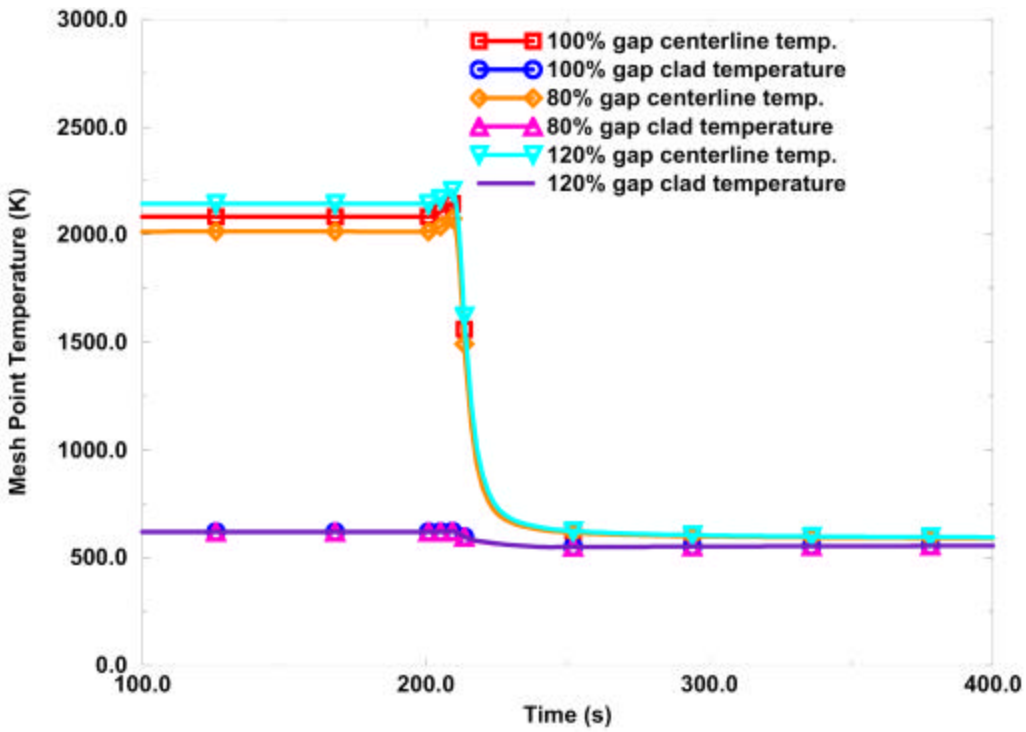

Fig. 21. Effect of fuel-to-cladding gap on fuel rod temperatures for regulating rod group withdrawal event.

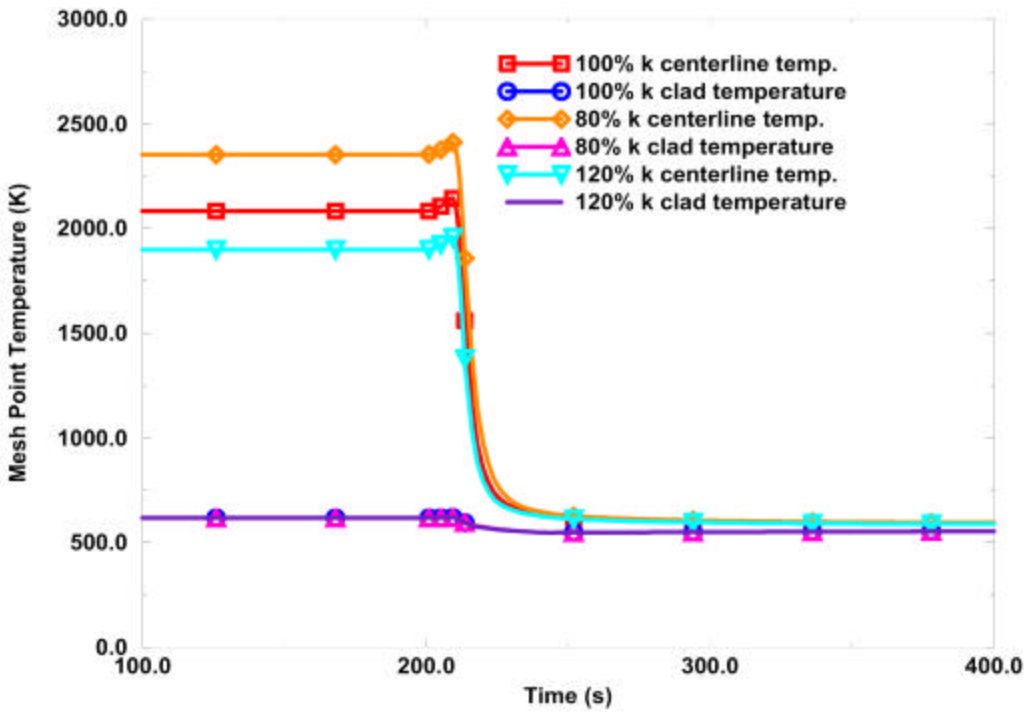

Fig. 22. Effect of fuel thermal conductivity on fuel rod temperatures for regulating rod group withdrawal event.

variation of fuel thermal conductivity, and the description is similar to that for the variation in fuel cladding-to-gap. A summary of results for the regulating rod group withdrawal event is presented in Table 4. In general, there are no changes in the surface heat fluxes and cladding temperatures when C_p, gap, and k are varied, and changes in centerline temperatures are similar to those observed under steady-state conditions.

Table 4. Effect of fuel property and geometry variations for group withdrawal

	C_p			Gap			k		
	T_{cl} (ºC)	T_{clad} (ºC)	q" (%)	T_{cl} (ºC)	T_{clad} (ºC)	q" (%)	T_{cl} (ºC)	T_{clad} (ºC)	q" (%)
+20%	–6	—	21	+61	—	5	–181	—	–10
–20%	+8	—	–22	–70	—	–5	+268	—	18

3.5 CONTROL ROD EJECTION

The control rod ejection event is considered a design basis accident (DBA), and the acceptance criterion are that the fuel cladding surface temperature must remain below 1200ºC and that the fuel rod enthalpy must remain less than 840 J/g for irradiated fuel and less than 963 J/g for unirradiated fuel. In this event, the control rod guide cover is assumed to fail at 200 s; at the same time, the control rod is assumed to instantaneously be ejected with a reactivity insertion of 40 cents. A rapid power increase occurs with the overpower set point of 107% nominal being exceeded less than 0.5 s into the transient. An overpower of ~60% occurs before the control rod action can begin to reduce reactor power. Figure 23 shows the hot rod surface heat flux vs time

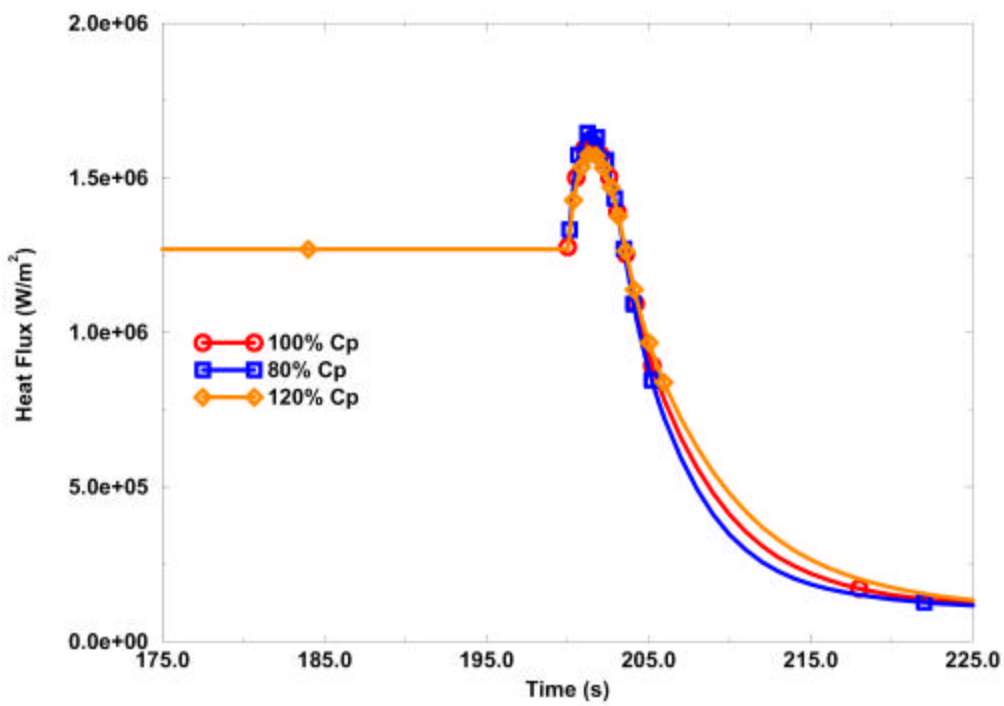

Fig. 23. Effect of fuel specific heat on fuel rod surface heat flux for control rod ejection accident.

for a fuel specific heat. During the power increase portion of the transient, the case with lower specific heat produces a higher surface heat flux (indicated in Table 5) because the fuel cannot store as much energy as for the case of a higher fuel specific heat. After reactor trip during the power reduction portion of the transient, because the total energy stored in rod for the higher specific heat case is larger, heat fluxes during the power reduction are higher with higher specific heat. The impact of gap variation on surface heat flux is shown in Fig. 24. The case with smaller gap, and therefore lower resistance to heat flow from the rod, shows higher peak heat fluxes (indicated in Table 5) and slightly lower heat flux from the rod surface as the power reduces. Figure 25 shows the impact of varying fuel thermal conductivity. Lower thermal conductivity tends to cause more of the overpower energy to be stored in the rod, which leads to lower peak surface heat fluxes (indicated in Table 5); higher fluxes occur during the power reduction portion of the transient. Fuel temperatures are shown in Figs. 26–28. The influence of fuel specific heat, shown in Fig. 26, is the same as in the case of the regulating rod group scenario; lower specific heat causes higher peak centerline temperatures (as indicated in the summary Table 5), but has little influence on the fuel cladding temperature. During the power decrease portion of the transient, higher C_p values cause higher centerline temperatures due to the higher initial stored energy

Table 5. Effect of fuel property and geometry variations for control rod ejection

	C_p				Gap				k			
	T_{cl} (°C)	T_{clad} (°C)	q" (%)	ÄH (J/kg)	T_{cl} (°C)	T_{clad} (°C)	q" (%)	ÄH (J/kg)	T_{cl} (°C)	T_{clad} (°C)	q" (%)	ÄH (J/kg)
+20%	–34	+3	–1	58,700	+47	+1	–3	68,700	–175	–2	+1	66,600
–20%	+44	–3	+2	75,900	–46	–2	+3	64,900	+245	+2	–2	66,300

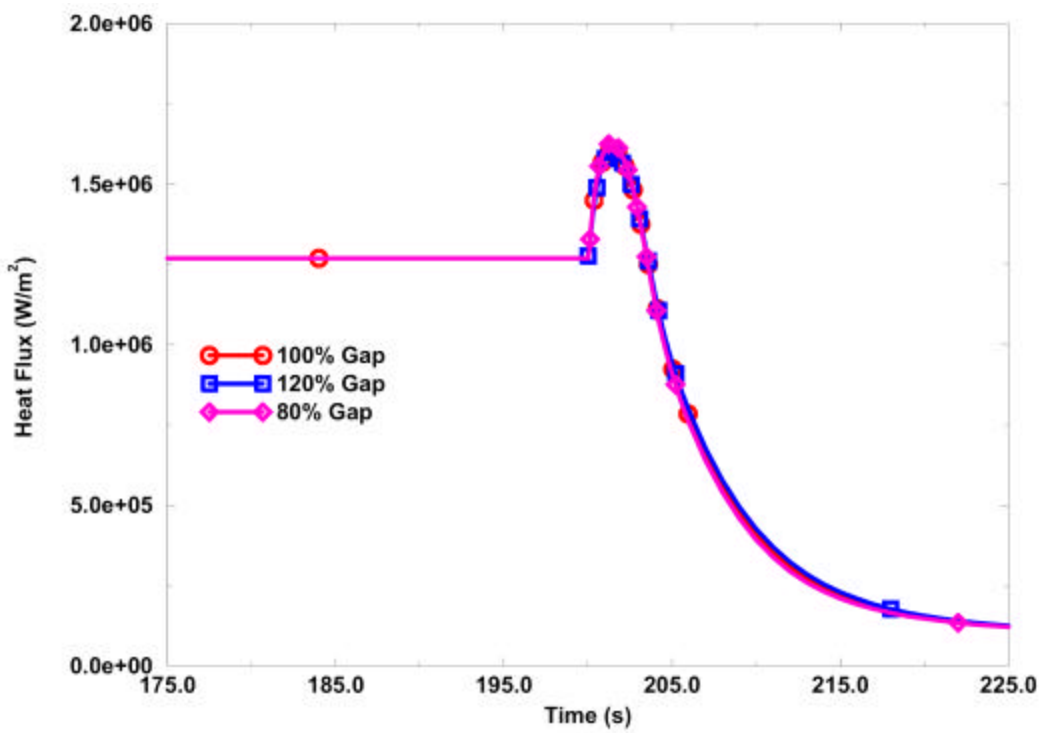

Fig. 24. Effect of fuel-to-cladding gap on fuel rod surface heat flux for control rod ejection accident.

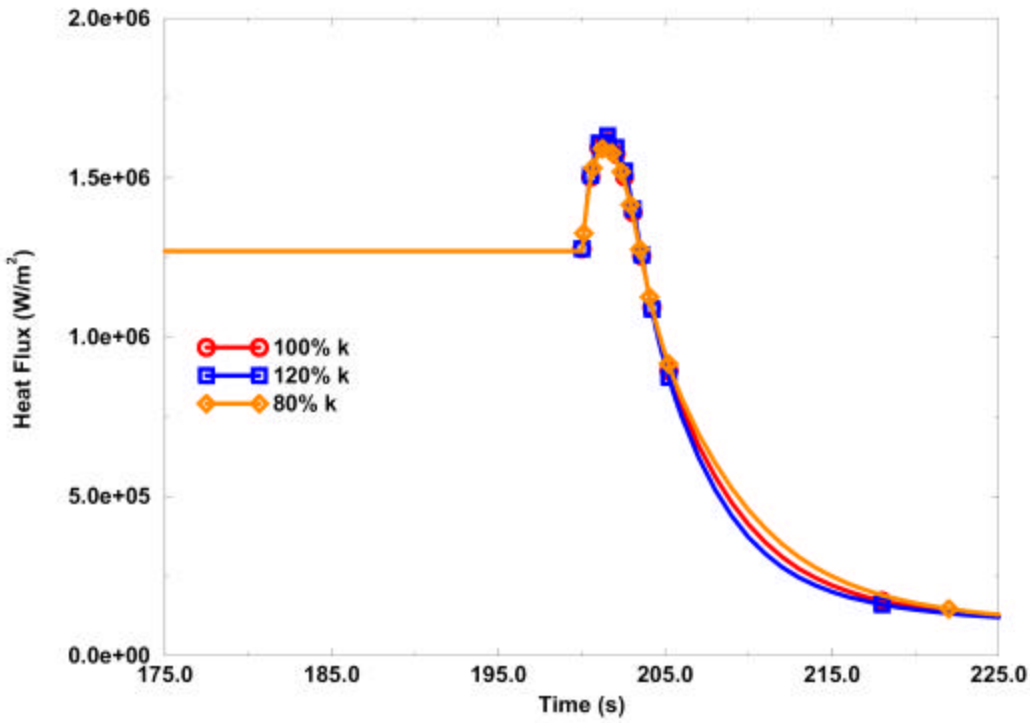

Fig. 25. Effect of fuel thermal conductivity variation on fuel rod heat flux for control rod ejection accident.

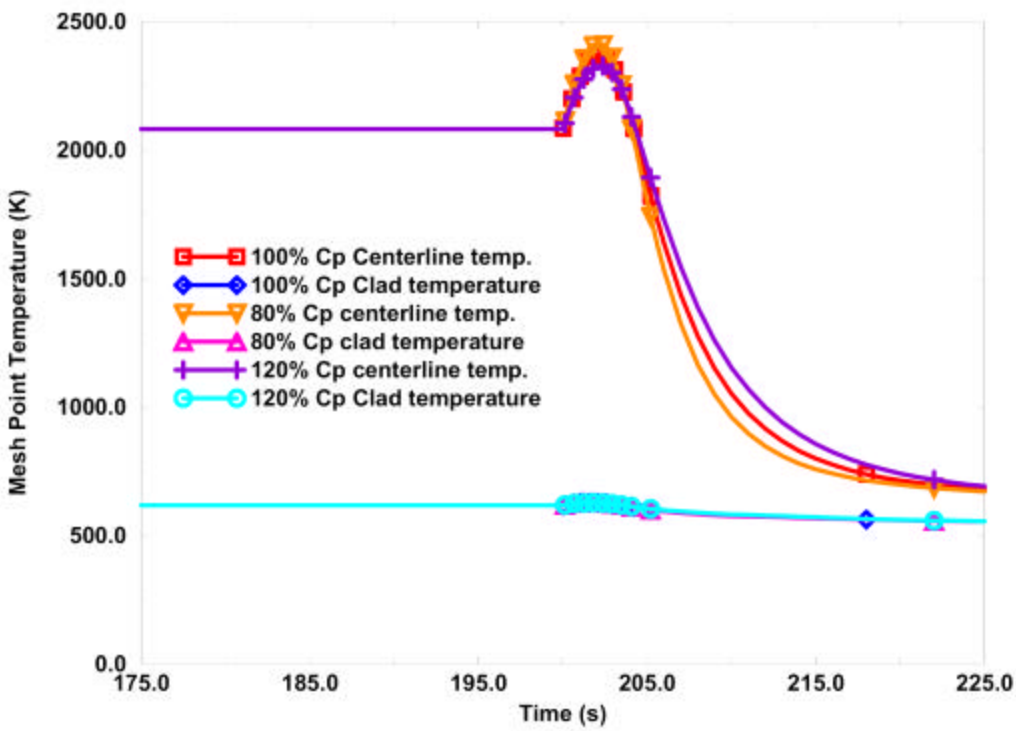

Fig. 26. Effect of fuel specific heat variation on fuel rod temperatures for control rod ejection accident.

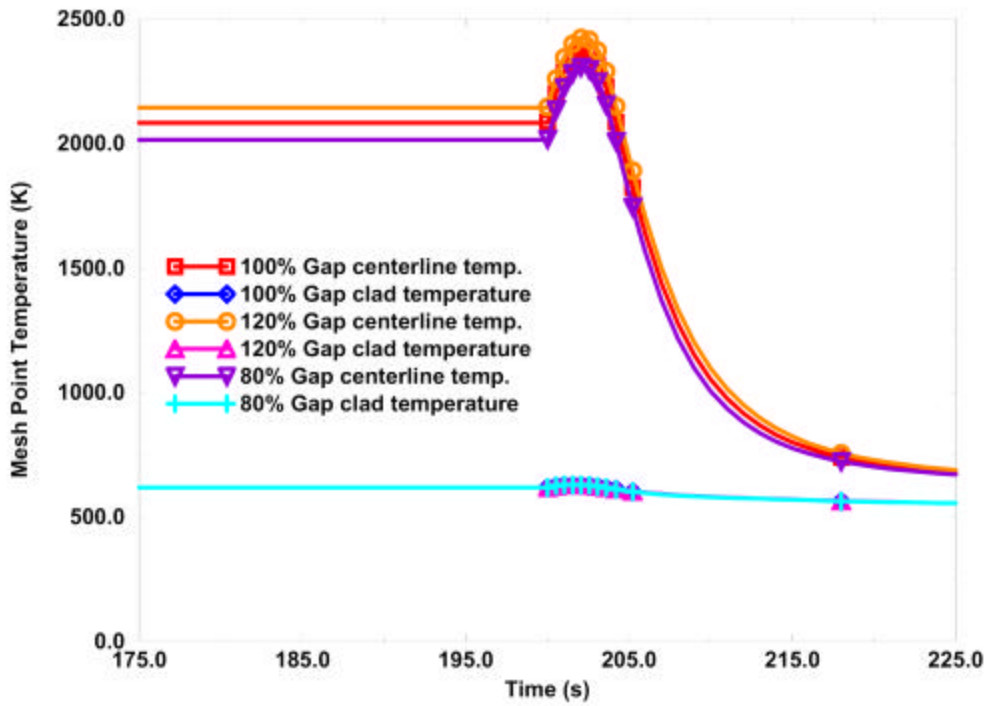

Fig. 27. Effect of fuel-to-cladding gap on fuel rod temperatures for control rod ejection accident.

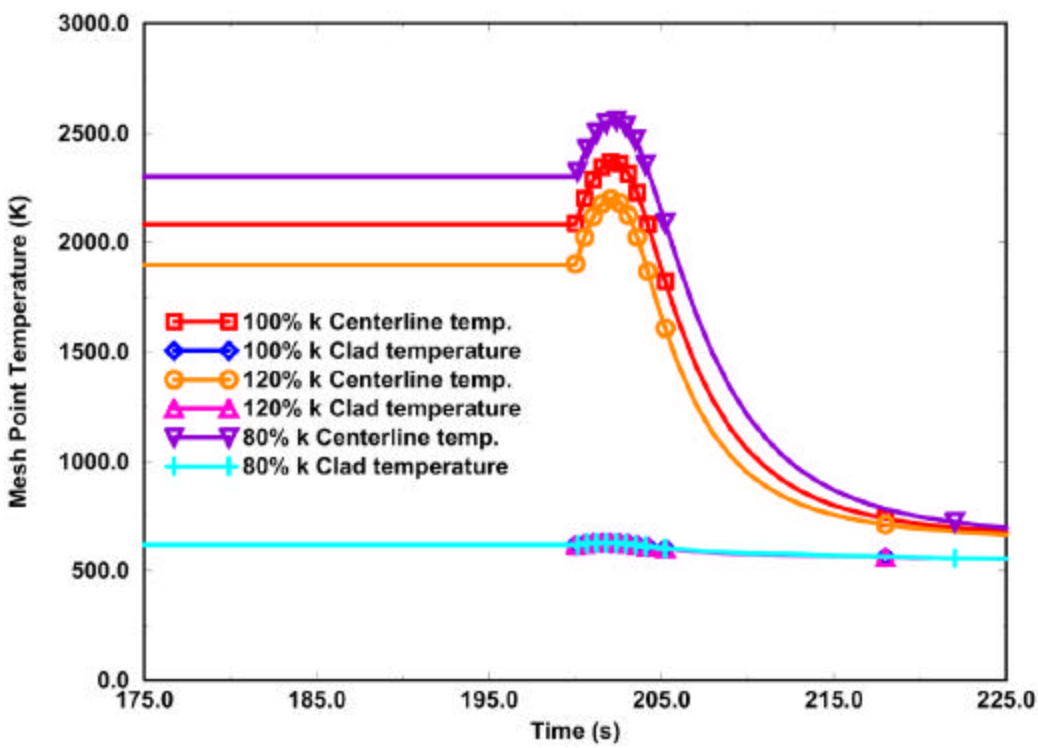

Fig. 28. Effect of fuel thermal conductivity variation on fuel rod temperatures for control rod ejection accident.

in the fuel. The influence of fuel-to-cladding gap is shown in Fig. 27. Larger gaps cause a higher peak temperature, but they have no significant influence on the fuel cladding temperature response. Figure 28 shows the influence of fuel thermal conductivity on fuel temperatures. Fuel centerline temperatures with differing fuel thermal conductivity follow an almost parallel path through the transient. Lower fuel thermal conductivity causes higher fuel centerline temperatures throughout the transient because the overall stored energy is larger under steady state conditions. Therefore, it takes longer to cool the fuel rod although the reactor scrams at the same time for all conductivity values.

The impact of fuel property variations on fuel enthalpy changes was also investigated. Figure 29 shows the effect of fuel specific heat variation (the property variation that caused the largest effect on enthalpy) on fuel enthalpy change during the transient. For each case, the steady state enthalpy condition was taken as the reference value. Only a small change in peak fuel enthalpy is noted. A 76,000-J/kg maximum difference in enthalpy is noted for a change in specific heat of –20%. A summary of results for the control rod ejection event is presented in Table 5.

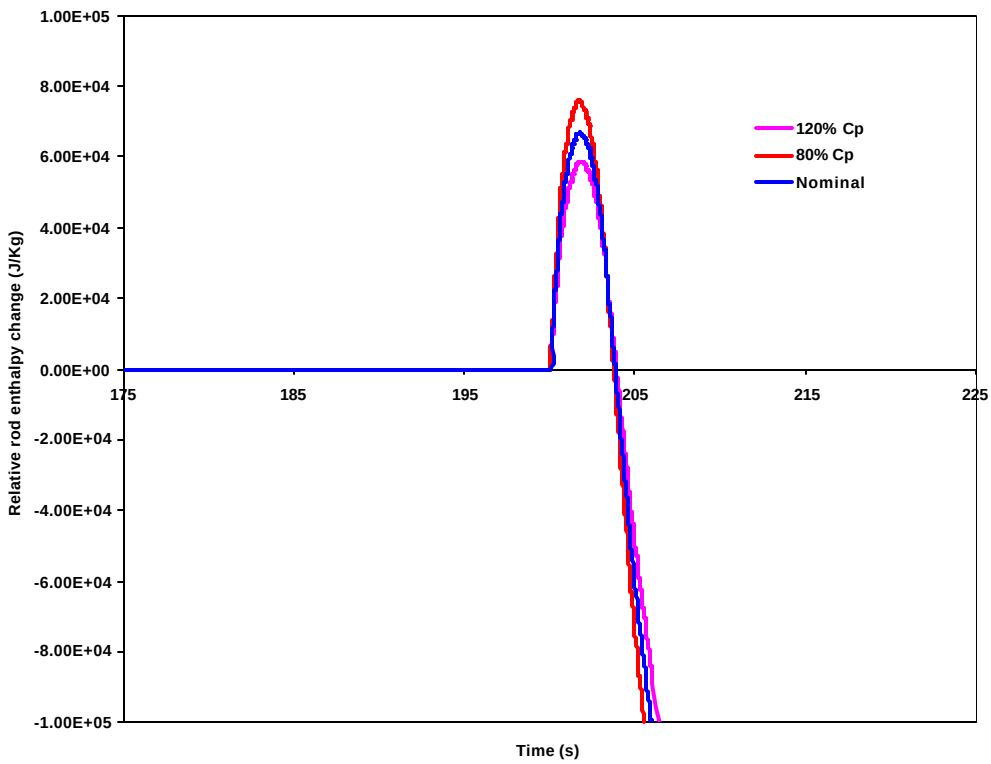

Fig. 29. Effect of fuel specific heat on fuel enthalpy variation for control rod ejection accident.

3.6 LARGE-BREAK LOCA

The large-break LOCA is a 100% instantaneous double-ended guillotine break of one of the primary circulation loop cold legs. It is classified as a DBA, and the acceptance criterion is that the fuel cladding temperatures remain below 1200°C. In the RELAP simulation, the break occurs

at 200 s. Control rod insertion begins less than 0.5 s after the break because of a low system pressure signal. In this event, the MOX rod followed as the indicator exceeds the CHF limit and goes through several temperature excursions as it alternately dries out and rewets throughout the transient at the axial level, which is followed in this study.

Figure 30 shows the rod surface heat flux as a function of time for a variation in fuel specific heat. Although this is a very complicated figure, in general, during the power decrease portion of the transient, high peak heat fluxes indicate wetting of the rod and therefore better heat transfer. For the low specific heat case, the fuel rod tends to rewet after CHF occurs and remains wetted throughout the remainder of the transient [also indicated by clad temperature plot (Fig. 33)]; the fuel rod in the higher specific heat cases tends to alternately wet and dryout throughout the simulation, resulting in higher rod temperatures as will be seen in following figures. The effect of fuel-to-cladding gap variation is shown in Fig. 31. Similar conclusions can be drawn from this figure, with the fuel tending to remain wet for lower fuel-to-cladding gaps. Figure 32 shows the influence of fuel thermal conductivity on fuel rod surface heat flux. Higher conductivity values tend to allow the rod to remain wet for longer periods in the transient. Fuel rod temperatures are shown in Figs. 33–35. Lower fuel specific heat tends to cause lower centerline and cladding temperatures as does lower fuel-to-cladding gap, while lower fuel thermal conductivity tends to cause higher fuel and cladding surface temperatures during this transient. A summary of results for the large-break LOCA event is presented in Table 6. Values shown in Table 6 for temperature variations are taken at the time of the initial peak in the fuel cladding temperature.

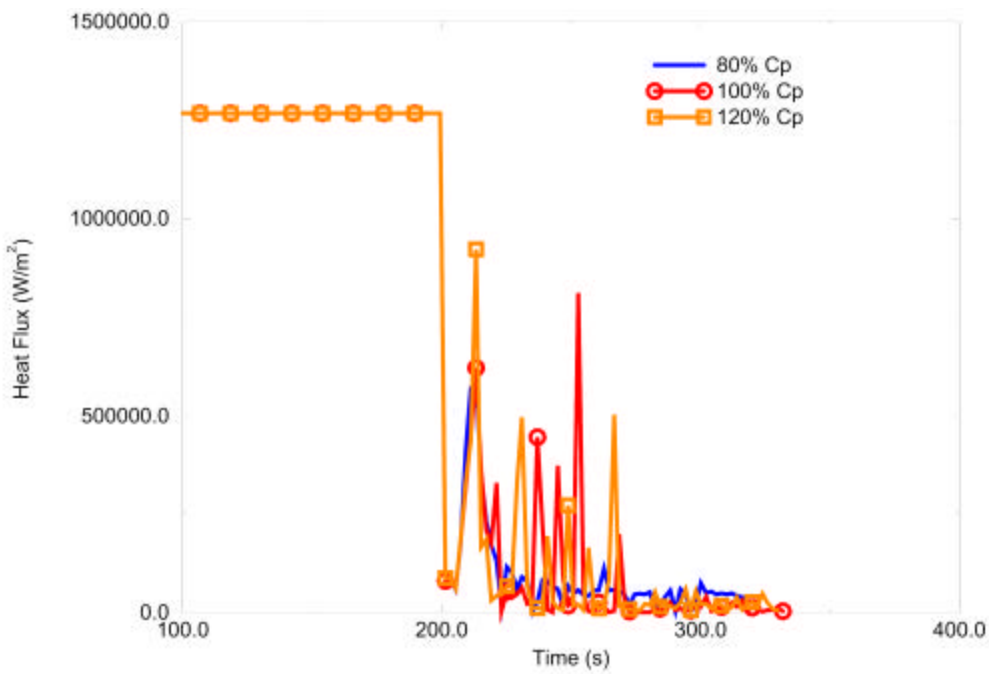

Fig. 30. Effect of fuel specific heat variation on fuel rod heat flux for large-break LOCA.

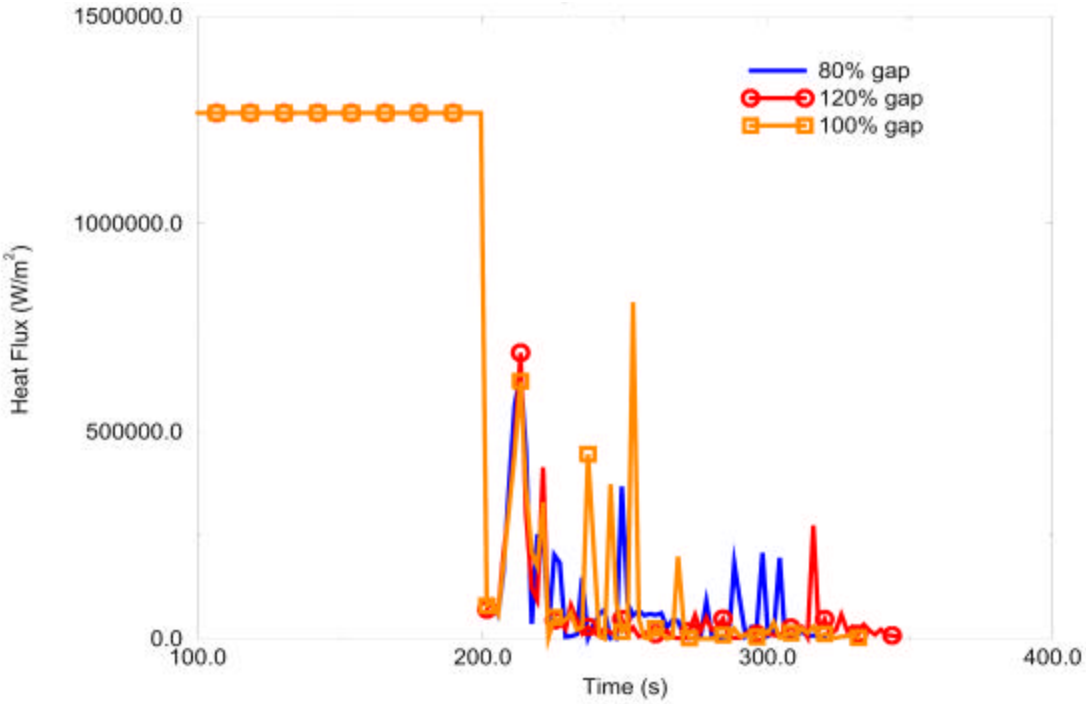

Fig. 31. Effect of fuel-to-cladding gap on fuel rod heat flux for large-break LOCA.

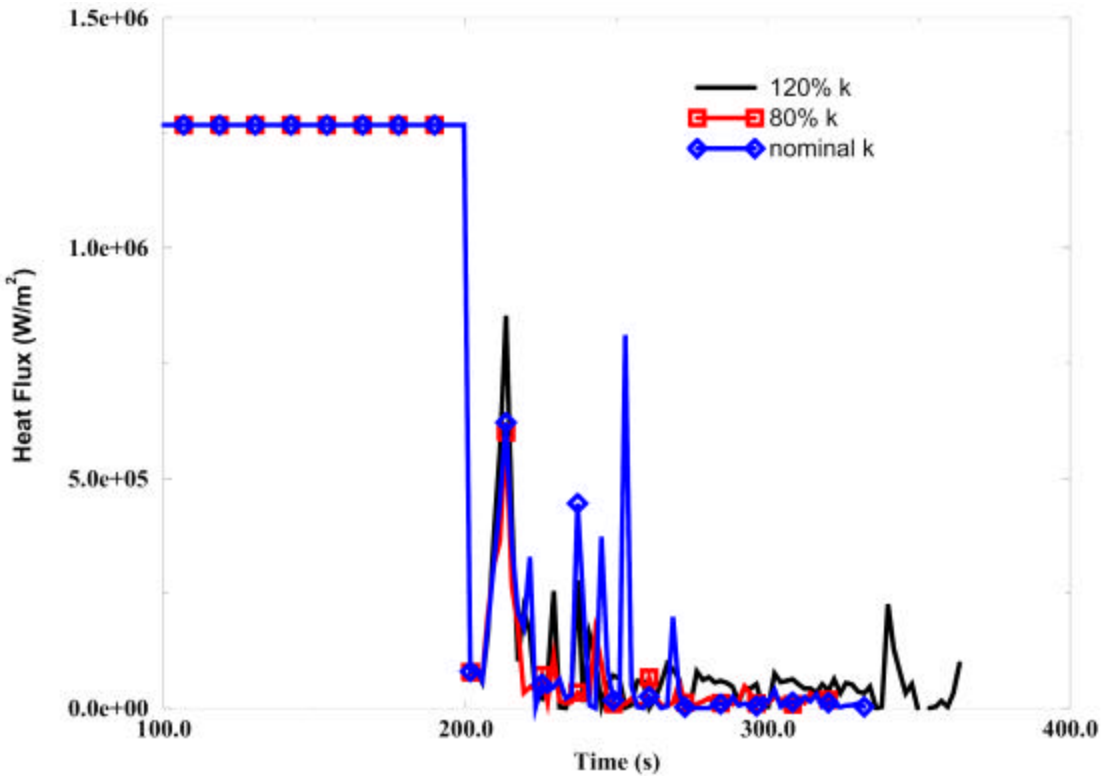

Fig. 32. Effect of fuel thermal conductivity variation on fuel rod heat flux for large-break LOCA.

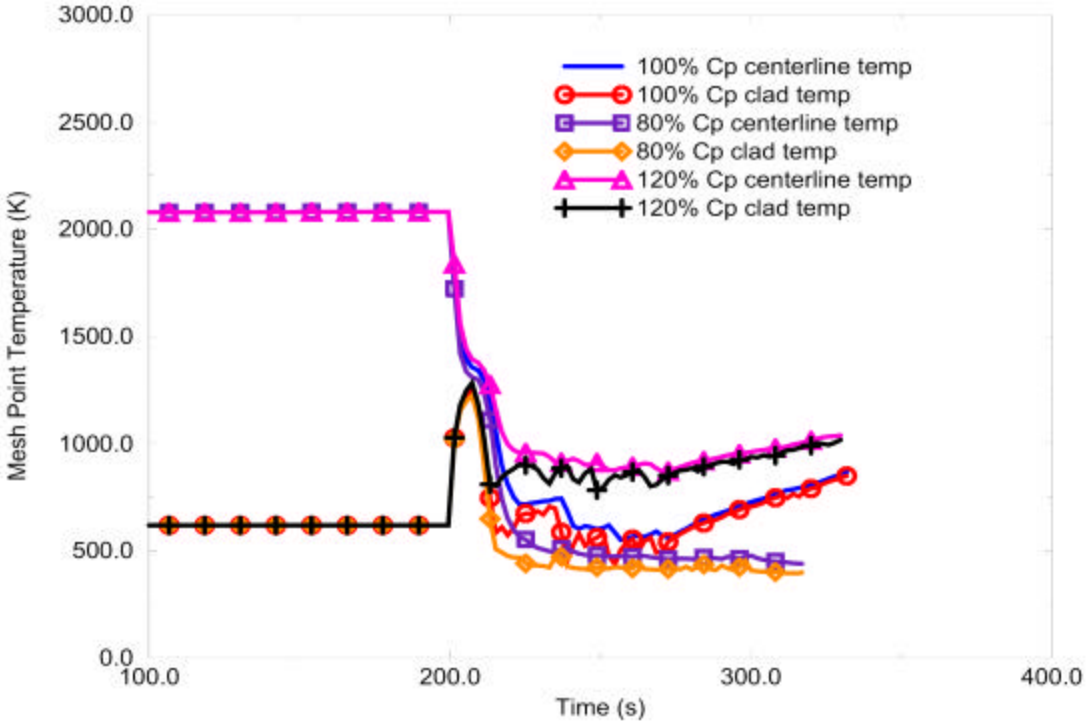

Fig. 33. Effect of fuel specific heat on fuel rod temperature for large-break LOCA.

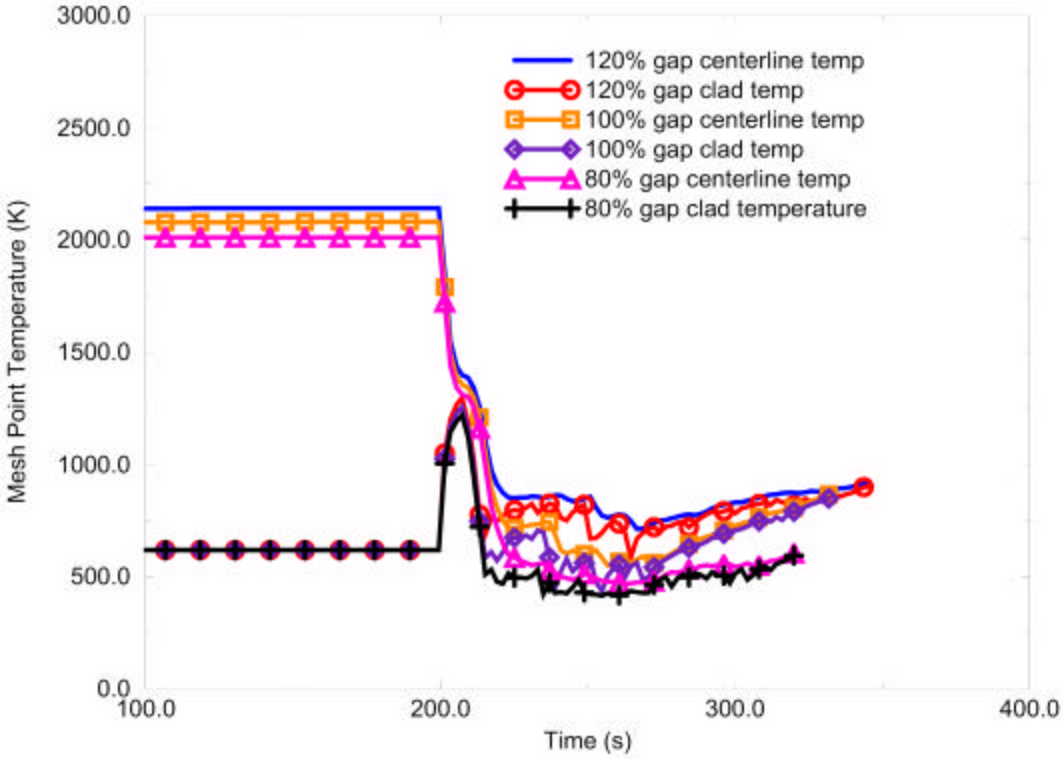

Fig. 34. Effect of fuel-to-cladding gap variation on fuel rod heat flux for large-break LOCA.

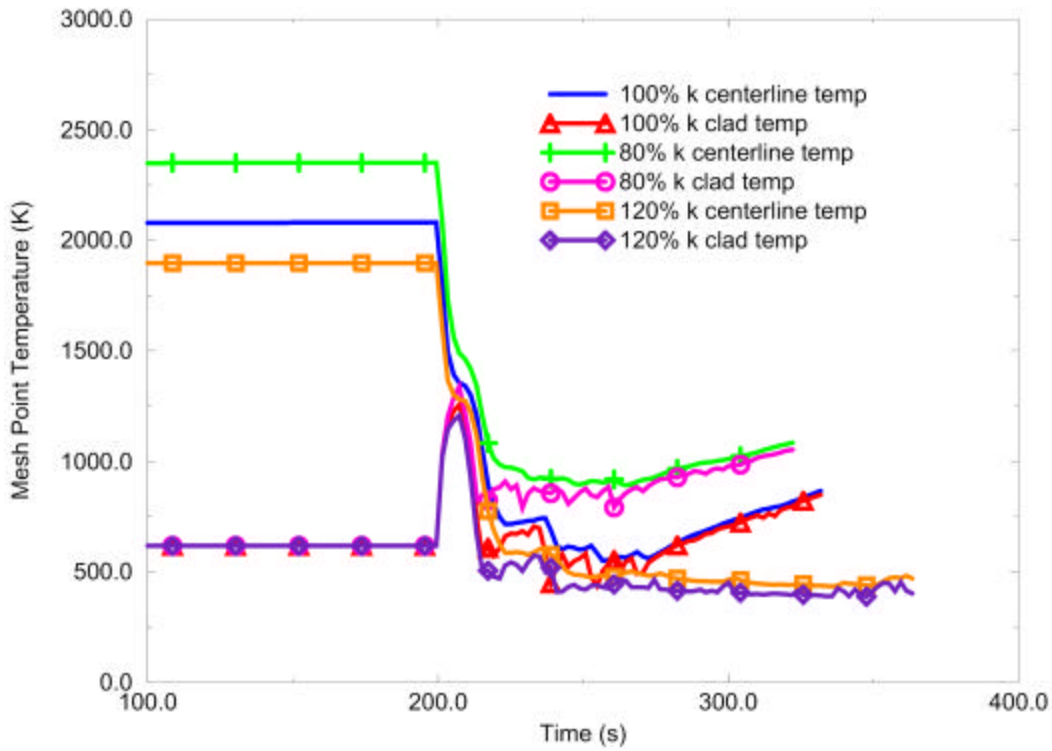

Fig. 35. Effect of fuel thermal conductivity variation on fuel rod heat flux for large-break LOCA.

Table 6. Effect of fuel property and geometry variations for LOCA

	C_p			Gap			k		
	T_{cl} (°C)	T_{clad} (°C)	q" (%)	T_{cl} (°C)	T_{clad} (°C)	q" (%)	T_{cl} (°C)	T_{clad} (°C)	q" (%)
+20%	+40	+28	+47	+45	+43	–13	–69	–46	+6
–20%	–44	–31	–27	–42	–36	–21	+139	+81	–25

4. SUMMARY

Tables 1–6 show a summary of the impact of fuel property and geometry variations (for the hottest MOX rod) for steady state conditions and for each of the transients studied. The biggest impact on fuel centerline temperatures is observed for the steady state results, with a maximum increase in centerline temperature of 267°C with a decrease in fuel thermal conductivity of 20%. Variations in fuel specific heat have no impact on any of the parameters followed under steady state conditions. Lower fuel conductivity and larger fuel-to-cladding gaps tend to increase the fuel centerline temperature but have no influence on cladding surface temperatures or heat fluxes under steady state conditions. Higher fuel specific heat implies higher stored energy (for the same fuel temperature) and the capability to store more energy under transient conditions. Therefore, it tends to slow down both the temperature increase during transients where the fuel power is

increasing and the temperature decrease during transients where the fuel power is decreasing. Larger fuel-to-cladding gaps tend to cause slightly higher heat fluxes during the initial portion of transient events; however, the effect is very small for the transients studied. The slightly higher fluxes are primarily a result of larger gaps that cause higher fuel temperatures under steady state conditions; therefore, they cause the fuel to have higher stored energy. At longer times in the transient, this effect is not as significant. For the transients, the effect of lower fuel thermal conductivity causes similar trends in the rod surface heat flux as a larger fuel-to-cladding gap, for the same reasons. Transient fuel temperatures for both fuel-to-cladding gap and fuel thermal conductivity variations tend to follow the steady state behavior. Higher gap and lower thermal conductivity both tend to cause higher fuel centerline temperatures, but they have little effect on cladding temperatures for the events studied. The maximum increase in heat flux values occurs during the LOCA where an increase of approximately 47% is noted after scram of the reactor for an increase in specific heat of 20% (looking only at the first heat flux peak after scram). Although this appears to be a large increase, it occurs very rapidly after the reactor scrams and only lasts a few seconds; therefore, it does not significantly influence fuel rod centerline temperatures. The maximum clad temperature increase is only 81ºC for a decrease in fuel conductivity of 20%. This maximum also occurs for the LOCA event after scram.

5. CONCLUSIONS

A series of calculations have been performed using the RELAP5 code to evaluate the influence of MOX fuel property variations or uncertainties on calculational results. Five transients were examined; they were chosen to be representative of the range of accidents that must be analyzed for VVER-1000 safety analysis. The RELAP model of the Balakovo 4 NPP included a single MOX fuel bundle, which represented an LTA in the core. The hot rod within this bundle was chosen as an indicator of MOX fuel performance, and its temperature and heat flux history was followed throughout each transient. The MOX fuel thermal conductivity, specific heat, and fuel-to-cladding gap were varied ±20% from their nominal values, and transients were run for each case.

Results of these calculations indicate that fuel property variations of the magnitude studied here have only a minor effect on the fuel performance, and they would therefore have only a very minor influence on core safety margins.

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3. V. K. Ivanov, "RELAP 5 Input Deck Development to Perform Computer Modeling of the Accident Regimes and Transient for VVER-1000 Reactors," Russian Research Center "Kurchatov Institute," 1998 (to be published).

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