Uncertainty Analysis for Unprotected Loss-of-Heat-Sink, Loss-of-Flow, and Transient-Overpower Events in Sodium-Cooled Fast Reactors

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Abstract. Reactor safety analyses often utilize a deterministic approach where in addition to performing best estimate calculations, uncertainty is accommodated by performing calculations with pessimistic values for input parameters that are important to safety. Here a stochastic approach is considered for explicitly including uncertainty in safety parameters by applying Monte Carlo sampling coupled with established deterministic reactor safety analysis tools. The Monte Carlo approach yields frequency distributions for reactor safety metrics (e.g., peak temperatures) that can be compared to performance limits, allowing for an improved determination of the safety margin and a clear determination of which safety parameters are most important to the transient response. Because the approach provides for the estimation of probabilities for violating safety boundaries it should be useful in a risk based regulatory environment. It has the advantage of not requiring any substantial rewriting of existing safety analyis computer codes.

1. Introduction

Typically, reactor safety analyses utilize deterministic calculations with "best estimate" input parameters and accomodate uncertainty by performing additional calculations using pessimistic values for input parameters that are important to safety. This paper considers a stochastic approach for explicitly including uncertainty in safety parameters by applying Monte Carlo sampling coupled with established deterministic reactor safety analysis tools. Similar analyses have been proposed in the past, but in these analyses a limited number of deterministic calculations were used to determine response surfaces for the outputs of interest. Then the response surfaces were coupled with Monte Carlo sampling[1]. Both the past and the current Monte Carlo approachs yield frequency distributions for reactor safety metrics (e.g., peak fuel or coolant temperatures). These can be compared to performance limits, providing an estimate of safety margins and a clear determination of which safety parameters affect the transient response.

The sensitivities of various output parameters to selected input parameters in unprotected combined loss of heat-sink and loss-of-flow (ULOHS), loss-of-flow (ULOF), and transient-overpower (UTOP) accidents are explored in this paper. Since the intent of the present study is to provide an illustration of the kind of results that can be obtained, the MATWS computer code[2], a simplified version of the SAS4A/SASSYS accident analysis code system[3], is used to model the accident sequences. Point kinetics is used to model the transient response of the reactor core. The approach taken can easily be modified to work with a more sophisticated safety analysis code, e.g. SAS4A/SASSYS. Because the modeling in SAS4A/SASSYS is more detailed, using this code would likely require more computer time, but for most cases, the additional time is not expected to be prohibitive. For this study, the

MATWS computer program is compiled as a subroutine in a dynamic link library (DLL) and the DLL coupled to the transient simulation computer code GoldSim[4]. Within the DLL the MATWS subroutine is called by a second subroutine which provides the coding required to pass information between MATWS and GoldSim. Random sampling of the stochastic input parameters is handled by GoldSim. In addition, GoldSim includes statistical analysis tools which can be used to assess the importance of the stochastic input parameters to results produced by MATWS.

2. Modeling

The present study considers an advanced burner fast reactor with metallic fuel operating at a power level of 840 MWth and having a conversion ratio (transuranic production rate/transuranic destruction rate) of approximately 0.5. Balance of plant modeling is the same as developed by Hill and Wigeland for the PRISM Mod B sodium cooled fast reactor[5]. It includes decay heat removal that depends on the reactor vessel temperature but that can remove up to 3.5% of nominal power. The reactor design is similar to the advanced burner reactor having a conversion ratio of 0.25, considered by Cahalan, Smith, Hill, and Dunn[6]. Reactivity coefficients used in the model were evaluated by Smith[7]. For the ULOHS and ULOF analysis, reactivity coefficients for an end of equilibrium cycle (EOEC) core were used. The reactivity coefficients used in ULOHS and ULOF analysis are listed in Table 1. Values for the coefficients are assumed to be mean values for a normal distribution. Uncertainties in the coefficients are represented by the standard deviations listed in the table. These standard deviations were assigned arbitrarily, but the values listed are thought to be representative of the magnitude of the uncertainty that would be obtained from a systematic analysis. In addition, the ULOHS calculations postulated that when the coolant inlet temperature reached a value of 800 K, pumps trip in both the primary and intermediate coolant loops begin to coast down. The trip temperature was assumed to be normally distributed with a mean value of 800 K and a standard deviation of 15 K. Also, the rate at which heat removal decreases to zero was assigned a normal probability distribution with a mean value of 0.05 s^{-1} and a standard deviation of 0.005 s^{-1}. Values for the pump trip temperature and the rate of heat removal decrease are also listed in Table 1. The MATWS model used here represents the reactor core by a single "average" fuel pin and heat transfer from the core is modeled by a single node along the direction of coolant flow. Within the node, heat transfer from fuel to cladding to coolant and to structure is explicitly modeled.

Table 1. Mean and standard deviations for the normally distributed parameters considered in the uncertainty analysis for ULOHS and ULOF transients for EOEC

Parameter	Mean	Standard Deviation
Rate of Heat Removal Decline, s^{-1}	0.05	0.005
Trip Temperature, K	800	15
Coolant Temperature Reactivity Feedback, $/K	0.00155	0.0002
Doppler Coefficient, $T\,dk/dT$	-0.00207	0.0003
Fuel Axial Expansion Reactivity Feedback, $/K	-0.00243	0.0006
Radial Core Expansion Reactivity Feedback, $/K	-0.00292	0.0006
Control Rod Driveline Expansion Reactivity Feedback, $/m	-45.1	4.5

Reactivity coefficients for the UTOP analysis were evaluated for a beginning of equilibrium cycle (BOEC) core. The mean values for the stochastic input parameters are listed in Table 2. Standard deviations for the various reactivity coefficients were left at the same values assigned to the corresponding coefficients for the EOEC core. In the UTOP analysis, a control rod is assumed to be withdrawn introducing reactivity at a constant rate. The reactivity worth and the time required to fully withdraw the rod were assigned normal probability distributions with the mean values and standard deviations listed in Table 2.

Table 2. Mean and standard deviations for the normally distributed parameters considered in the uncertainty analysis for a UTOP event for BOEC

Parameter	Mean	Standard Deviation
Time for Control Rod Withdrawal, s	22.3	2.23
Control Rod Worth, $	0.445	0.0445
Coolant Temperature Reactivity Feedback, $/K	0.00142	0.0002
Doppler Coefficient, $T\,dk/dT$	-0.00192	0.0003
Fuel Axial Expansion Reactivity Feedback, $/K	-0.00258	0.0006
Radial Core Expansion Reactivity Feedback, $/K	-0.00310	0.0006
Control Rod Driveline Expansion Reactivity Feedback, $/m	-53.5	4.5

In the calculational sequence, GoldSim produces several sets of input with each set containing an independent sample of all stochastic input parameters. MATWS calculations are carried out for each set. The result from each set is referred to as a realization. All the calculations considered in this report are based on 10,000 realizations and follow only the first hour of the transient. The number of samples required in a more complete analysis would depend on the purpose of the analysis. For example, initial calculations might consider many more stochastic input parameters and use fewer samples to identify the most important parameters. Then calculations with a larger number of samples might be carried out using a smaller set of stochastic input parameters. Rather than go through a more detailed screening process, the choice of stochastic parameters used in the current analysis was based on previous experience.

3. Analysis Results

3.1. ULOHS

This accident sequence is initiated by a loss of the ability to remove heat from the intermediate coolant loop. Heat removal in the MATWS model used here is specified by a table giving the heat removal rate as a function of time. The loss of heat removal is modeled by reducing the heat removal linearly to zero at a specified rate. Throughout the period while the heat removal rate is decreasing, the primary and intermediate coolant pumps continue to maintain the nominal flow. As the heat removal rate decreases, the coolant inlet temperature increases. When the inlet temperature reaches a value near 800 K, the pumps trip but the scram system fails. The pump trips initiate flow coastdowns in both the primary and intermediate coolant loops. Flow coastdowns are modeled by specifying the coolant flows in the primary and intermediate loops by means of tabular input. The flow halving time is about 4 seconds for the primary coolant loop and approximately 7 seconds for the intermediate loop.

The mean normalized power, greatest and least values, and the norrmalized power corresponding to various percentiles are shown in Fig. 1. At each time, the greatest and least values indicate the largest and smallest values of the normalized power among all the realizations evaluated, not the largest and smallest values that could ever occur. Similarly, the curve for a given percentile is, at a given time, the value below which that percentage of the realizations fall. The sharp curvature of some of the curves reflects the fact that different realizations determine the percentile boundary at different times. Pump trips occur in the transient as early as 182 seconds and as late as 890 seconds.

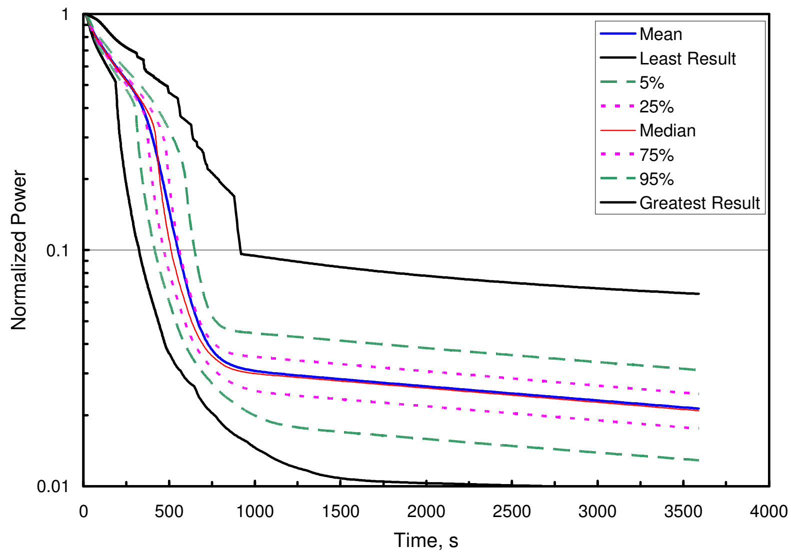

FIG. 1. Mean, percentiles and largest and smallest values for the normalized power in a ULOHS transient.

Fuel temperatures during the transient cover a range of more than 200 K as shown in Fig. 2. However, even the largest temperatures are well below the fuel melting temperature (estimated to be greater than 1300 K). Coolant outlet temperatures span a range of as much as 400 K. The largest temperature observed is within 25 K of the estimated coolant boiling temperature of 1250 K, but only one other of the 10,000 realizations produced a temperature within 100 K of the boiling temperature. Because the results calculated with this simplified model represent "average" conditions within the reactor core, they do suggest the possibility that the hottest subassemblies might experience coolant boiling on some realizations. The frequency distribution for the peak coolant temperature is shown in Fig. 3. For each histogram bar, the 99% confidence limits are estimated based on the assumption that the number of realizations in each temperature interval is binomially distibuted. These limits are indicated by horizontal lines above and below each histogram bar. For comparison, Fig. 3 shows a log-normal distribution having the same mean and standard deviation as computed from the logarithms of the temperatures used to construct the histogram. It is apparent that while the frequency distribution resembles a log-normal distribution, a log-normal distribution having the same mean and standard deviation falls within the 99% confidence limits only over relatively narrow temperature ranges.

In addition to the stochastic simulation described above, two deterministic simulations were carried out. For the first of these, the stochastic input parameters were set at their mean values as would be done in a "best estimate" simulation. The peak coolant outlet temperature was found to be 955 K, only about 3 K smaller that the arithmetic mean of the temperatures used to construct the histogram in Fig. 3. This result is shown as a vertical line along the abscissa of the graph in Fig. 3. In a second run, all stochastic parameters were set at their mean values plus two standard deviations. This calculation produced a peak outlet coolant temperature of 1101 K, shown as a vertical line closer to the right end of the abscissa of the graph in Fig. 3. Of the 10,000 realizations in the stochastic calculation described above, only eight realizations produced peak tempratures larger than this value. If one uses the a binomial distribution to estimate a 99% confidence limit for this value, only 15 realizations produced temperatures above the lower limit of the estimated confidence interval. This illustrates the conservative nature of the run with parameters set at the mean plus two standard deviations.

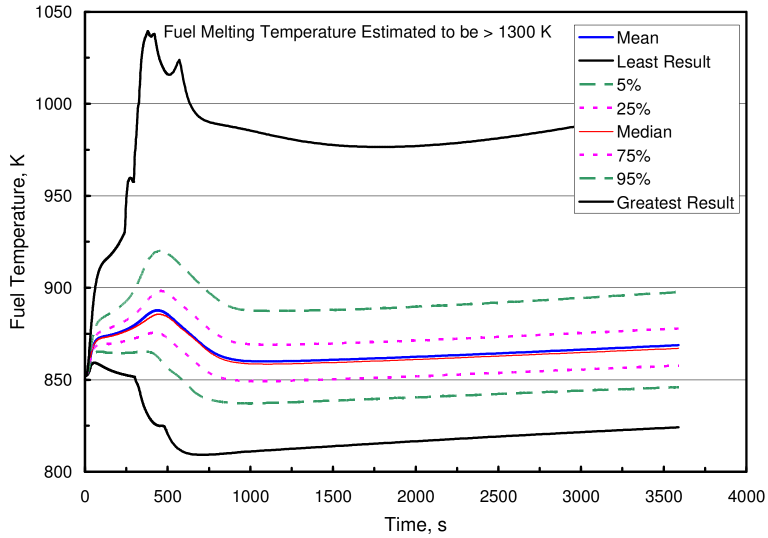

FIG. 2. Mean, percentiles and largest and smallest values for the fuel temperature in a ULOHS transient.

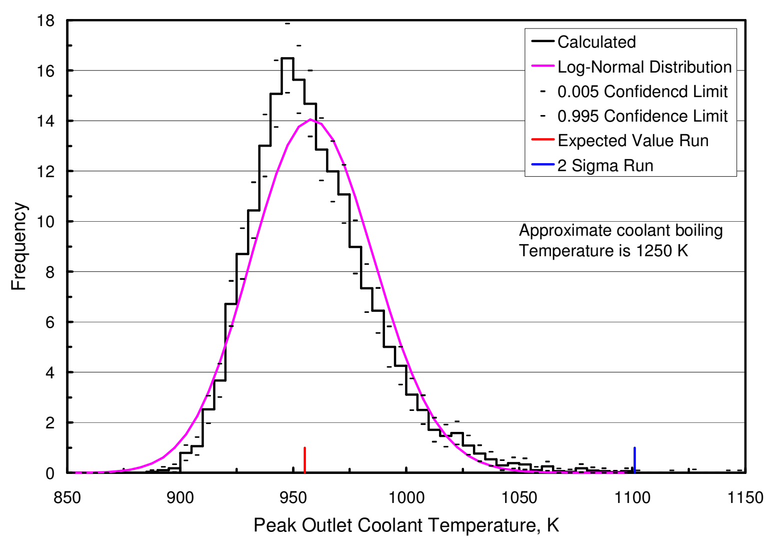

FIG. 3. Frequency distribution for the peak outlet coolant temperature in a ULOHS transient.

Several importance measures were calculated by GoldSim and used to rank the relative importance of the stochastic input parameters used in the calculations described above. These included correlation coefficients, standardized regression coefficients, and partial correlation coefficients. GoldSim provided a fourth importance measure by computing the variance of a particular output variable for given values of an input parameter and then computing the average value of the variances so determined. For the coolant outlet temperature, the first three of these importance measures ranked the stochastic input parameters in descending order of importance as 1) radial core expansion, 2) coolant temperature reactivity coefficient, 3) fuel axial expansion reactivity coefficient, 4) Doppler reactivity coefficient, 5) rate of heat removal decrease, 6) inlet coolant trip temperature, and 7) control rod expansion reactivity coefficient. The fourth measure modified the ranking for the last four of these paramters to 4) control rod expansion reactivity coefficient, 5) inlet coolant trip temperature, 6) Doppler reactivity coefficient, and 7) rate of heat removal decrease.

The importance measures calculated for the fuel temperature shows the same top three parameters as for the peak coolant temperature. However, the correlation coefficients, standardized regression coefficients, and partial correlation coefficients rank the remaining input parameters in descending order of importance as inlet coolant trip temperature, Doppler reactivity coefficient, rate of heat removal decrease, and control rod expansion reactivity coefficient while the fourth measure moves the control rod expansion reactivity coefficient ahead of the Doppler reactivity coefficient and the rate of heat removal decrease. The strong correlation between the peak fuel temperature and the radial core expansion is illustrated by the scatter plot shown in Fig. 4. In contrast, Fig. 5 shows the weak correlation between the peak fuel temperature and the Doppler coefficient.

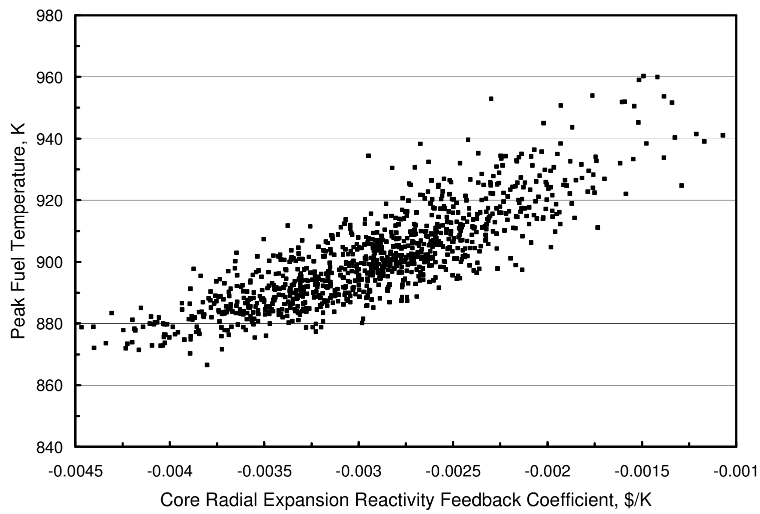

FIG. 4. Peak fuel temperature as function of the core radial expansion reactivity feedback coefficient for the first 1000 realizations in a ULOHS transient.

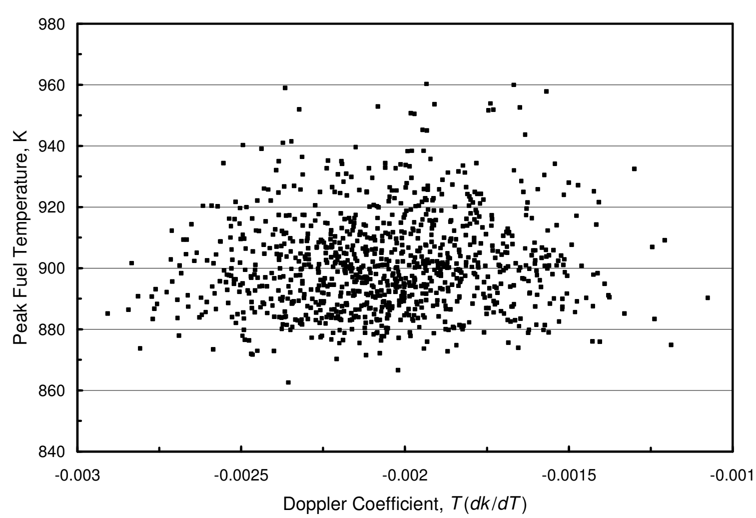

FIG. 5. Peak fuel temperature as function of the Doppler reactivity feedback coefficient for the first 1000 realizations in a ULOHS transient.

3.2. ULOF

Initiation of a ULOF occurs when pumps in both the primary and intermediate coolant loops begin a coastdown. It is postulated that the scram system fails so that the only mechanism for bringing the reactor power down from its nominal level is the reactivity feedbacks inherent to the reactor system. The coolant flow during the coastdown is determined by tabular input to the MATWS computer code. As in the latter part of the ULOHS, the flow halving times are approximately 4 and 7 seconds, respectively, for the primary and intermediate coolant loops. It is further postulated that the loss of flow in the primary and intermediate coolant loops is accompanied by a reduction in the flow of water in the steam generator so that heat removal from the intermediate loop is degraded. This reduction in heat removal is simulated by linearly reducing the rate of heat removal from the intermediate loop to zero over a period of about 20 seconds. As in the ULOHS case, the heat reduction rate is specified by means of tabular input to the MATWS code.

Largest and smallest values as well as the mean and selected percentile curves for the normalized power in a ULOF are shown in Fig. 6. The largest difference between largest and smallest values of the power is much smaller than in the case of the ULOHS, ranging up to only about a factor of 2.5. A similar plot for the coolant outlet temperature is shown in Fig. 7. The maximum difference, between the largest and smallest coolant outlet temperatures is 235 K. The margin to coolant boiling for the greatest result curve in Fig. 7 is about 130 K. One can expect that the subassemblies with the peak power-to-flow ratios will have coolant boiling margins smaller than this value.

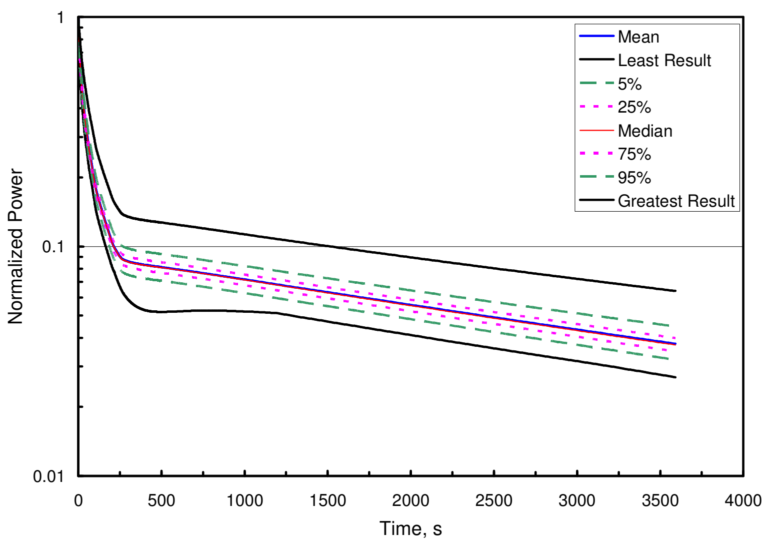

FIG. 6. Mean, percentiles and largest and smallest values for the normalized power in a ULOF transient.

A comparison of the frequency distribution for the peak fuel temperature and a log-normal distribution having the same mean and standard deviation for the logarithim of the temperature, shown in Fig. 8, indicates that the log-normal distribution is a poor representation for the probability density of the peak fuel temperature. The figure also shows the peak fuel temperatures obtained in a calculation with all stochastic parameters set at their mean values and in a second calculation with the parameters set a their mean values plus two standard deviations. In this case, only 13 of the 10,000 realizations produced peak temperatures greater than the peak temperature in the two-sigma run. This indicates once more the conservative nature of the two-sigma run.

The same importance measures applied to the coolant outlet temperature in the ULOHS case were applied to the ULOF case considered here. In agreement with the ULOHS case, these measures all agree that the two most important parameters that influence the peak coolant outlet temperature are the core radial expansion followed by the coolant temperature feedback, however, the measure for the core radial expansion is larger for the ULOF than for the ULOHS while the measure for the coolant temperature feedback is smaller in the ULOF than in the ULOHS. Note, that since heat removal through the steam generator is assumed to cease in both the ULOHS and the ULOF accident sequences, it was retained as a stochastic parameter in the ULOF case. The importance measures indicate that the behavior of the steam generator may be more important to the ULOF sequence in determining the peak outlet coolant temperature than to the ULOHS sequence.

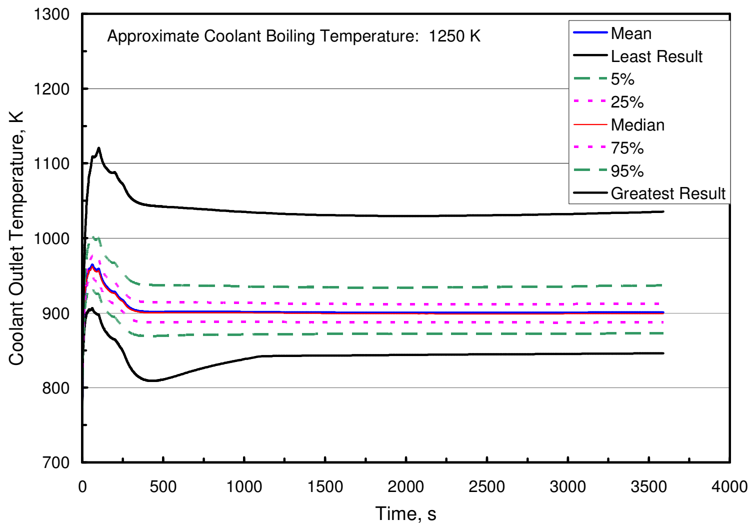

FIG. 7. Mean, percentiles and largest and smallest values for the coolant outlet temperature in a ULOF transient.

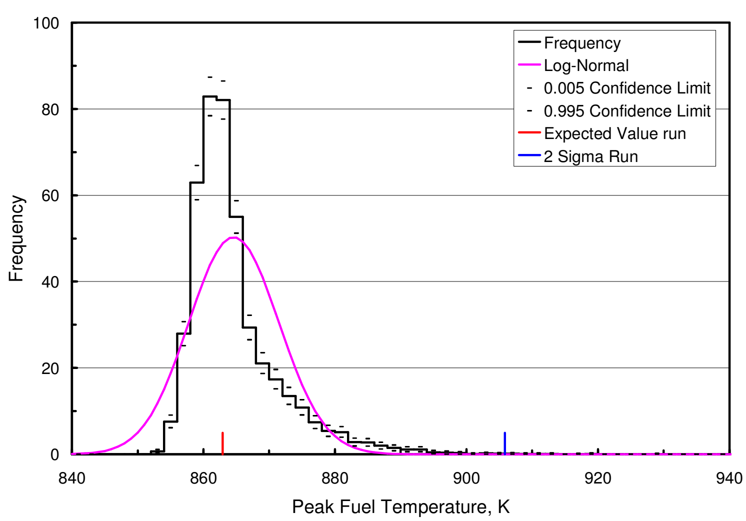

FIG. 8. Frequency distribution for the peak fuel temperature in a ULOF transient.

3.3. UTOP

A UTOP accident sequence initiates when a control rod begins to move out of the reactor core. By assumption this event fails to initiate a reactor scram and the coolant pumps continue to maintain the nominal flow through the primary and intermediate coolant loops. In addition, the steam generator is assumed to maintain a constant sodium outlet temperature in the intermediate coolant loop. Figure 9 shows the normalized reactor power for this transient. As in previous plots of the normalized power, the figure shows the mean, greatest and least results, and curves for various percentiles. When the control rod begins to move out of the core, the reactor power increases and continues to increase until after the rod is fully withdrawn. Then the various reactivity feedback mechanisms act to adjust the reactivity back to zero, however, when this is accomplished, the reactor power achieves a steady state at a level higher than nominal. Mean, percentile, and greatest and least result plots are shown for the fuel temperature in Fig. 10. Both the normalized power and the fuel temperature reach higher levels than in the ULOHS and the ULOF transients, but the coolant temperatures remain lower. During the first hour or so, the coolant inlet temperature rises at most only about 20 K and is leveling off when the calculation was stopped. During the ULOHS transient, the coolant inlet temperature rose as much as 200 K and in the ULOF by as much as 100 K.

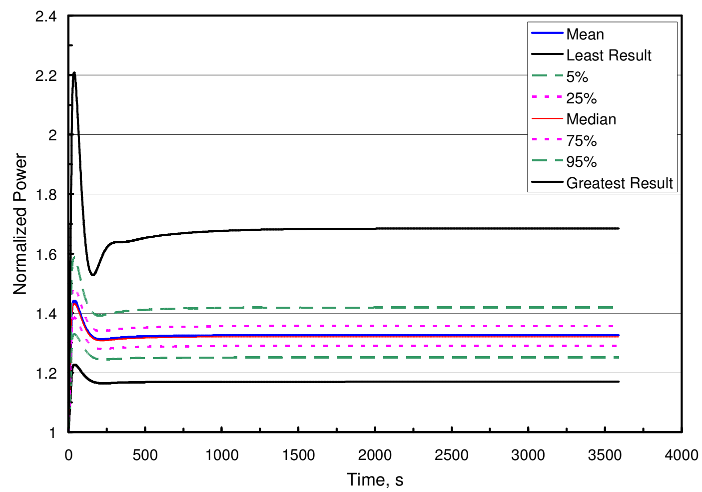

FIG. 9. Mean, percentiles and largest and smallest values for the normalized power in a UTOP transient.

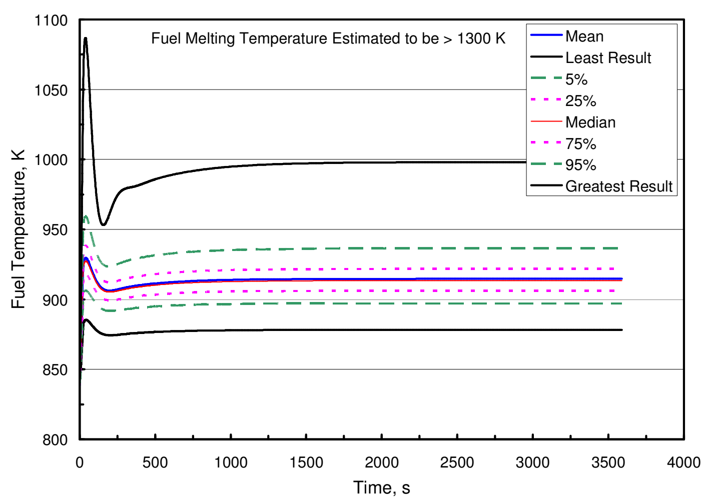

FIG. 10. Mean, percentiles and largest and smallest values for the fuel temperature in a UTOP transient.

The frequency distribution for the peak fuel temperature is shown in Fig. 11. As was the case for similar plots for peak temperatures in the ULOHS and ULOF cases, a log-normal distribution having the same mean and standard deviation as the logarithms of the temperature used to construct the histogram lies outside the 99% confidence intervals over most of the temperature range shown in the plot. The peak temperatures obtained in calculations with the stochastic parameters set at their mean values and at their mean values plus two standard deviations are indicated on the plot. Just as in the earlier cases, the plot indicates the conservative nature of the two-sigma result. Only two realizations produced peak fuel temperatures greater than in the two-sigma case.

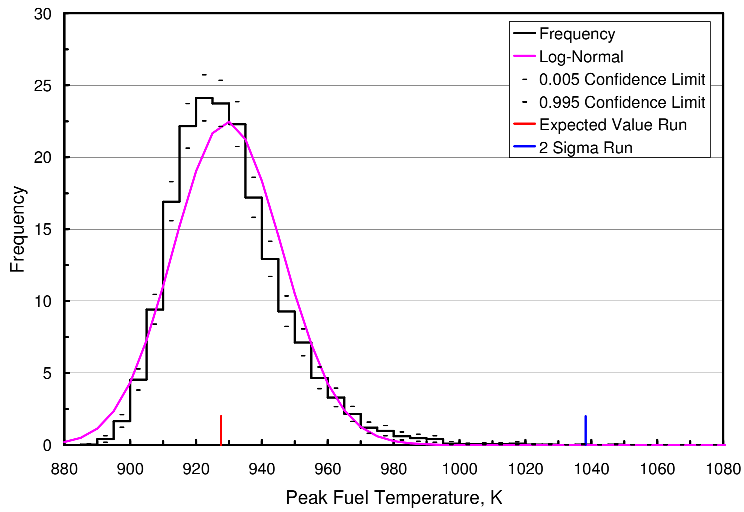

FIG. 11. Frequency distribution for the peak fuel temperature in a UTOP transient.

The importance measure considered in the ULOHS and ULOF cases were also applied in the UTOP case. These measures indicate that the three most important parameters that influence the peak fuel temperature are, in descending order, fuel axial expansion reactivity feedback, the worth of the control rod that is withdrawn, and the radial expansion reactivity feedback. All measures except the fourth measure indicate that the fourth most important parameter is the Doppler coefficient. The fourth measure indicates that the fourth most important parameter is the coolant temperature feedback. Table 2 indicates that the Doppler coefficient is considerably smaller than fuel axial expansion coefficient. This accounts for it reduced importance in this case.

4. Conclusions

A study has been completed to demonstrate the potential utility a probabilistic approach to examining the impact of input parameter uncertainty on various outputs from reactor safety analysis calculations. As discussed in Section 2, standard deviations for the normal probability distributions were assigned arbitrarily since systematic evaluations were not available. The values selected are thought to be representative of the kind of values that would result from a more rigorous evaluation. This probabilistic approach has the advantage that it does not require any substantial rewriting of the safety analysis code used to model the accident sequences. All that is required is a means of generating samples of the stochastic input parameters along with an interface subroutine to provide the sampled values of the these parameters to the safety analysis code and to collect the results from the transient calculation for each sampled set for further analysis. While a relatively small set of stochastic parameters were considered in the analysis presented here, a much larger set can easily be accomodated. Note also that in the present analysis, the input parameters were assumed to be independent. Future work should determine the appropriate probability distributions for the stochastic input and develop an understanding of correlations that might exist among these parameters and take the correlations into account in the sampling process.

The approach to uncertainty considered here not only provides an indication of the range of possible values of various outputs such as the reactor power and fuel and coolant temperatures, but it also provides a means of estimating the probability of achieving results in various parts of the range as well as of achieving results outside the range. For example, the frequency distributions obtained for the peak fuel temperature and the peak outlet coolant temperature provide a means of estimating probability distributions for the margin to fuel melting or coolant boiling. In addition, it is possible to quantify the relative importance of various uncertain input parameters to uncertainty in accident outcomes. Because the approach provides for the estimation of probabilities for violating safety boundaries it is of potential usefulness in a risk based regulatory environment.

In future work it will be desirable to use a higher fidelity reactor safety code, such as SAS4A/SASSYS. Use of such a code will require more computer time and while the additional computer time is not expected to prohibit calculations such as those considered here it is likely to provide incentive to perform calculations with a smaller number of realizations. If one knew a priori, for example, that the distributions of output parameters were normal or log-normal, then in the stochastic analysis it would be sufficient to obtain reasonable estimates of the mean and standard deviation and this might be achievable with a relatively small number or realizations. For some of the cases considered here the frequency distributions for the peak fuel temperature and the peak coolant outlet temperature appear to resemble a log-normal distribution. In these cases, the log-normal distribution might provide a fairly reasonable approximation to the frequency distribution by requiring the log-normal distribution to have the mean and standard deviation calculated for the logarithm of the temperature. It should be noted however, that in no case did the log-normal distribution fall within estimated 99% confidence limits for more than a small portion of the temperature range and that in the case of the peak fuel temperature in a ULOF transient, the log-normal distribution was a very poor approximation the to calculated frequency distribution. The results shown here indicate clearly that even though all input parameters were assumed to have normal probability distributions, the resulting output parameters were not normally distributed.

ACKNOWLEDGEMENTS

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