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

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Introduction

- Uncertainty in deterministic reactor safety analysis calculations typically compares best estimate calculations with calculations in which one or more input parameters are changed from their best estimate values
  - If the probability distribution for an input parameter is known, the best estimate value would be set to the mean value
  - Uncertainty may be addressed by assigning pessimistic values to one or more of the uncertain input parameters
- In this work a Monte Carlo approach is examined
  - Previous Monte Carlo approaches (Vaurio and Mueller e.g.) have used response surfaces with selected stochastic input parameters as independent variables
  - Here, stochastic parameters are sampled and the safety analysis code rerun for each sampled set (each run is called a realization)
    - Importance measures can be used to assess the impact of each stochastic input parameter on output parameters
    - Estimates can be obtained for the probability that an output parameter falls within a selected range of values

Introduction (cont.)

- Analysis is carried out by coupling GoldSim with the MATWS safety analysis code
  - GoldSim is a transient simulation computer code developed and maintained by the GoldSim Technology Group
    - GoldSim provides for random sampling of stochastic parameters from a variety of probability distributions
    - GoldSim contains analysis tools for calculating importance measures and percentiles for transient results
  - MATWS is a simplified version of the SAS4A/SASSYS safety analysis code system for fast reactors
    - In the present application a single fuel pin is used to model the average behavior of the reactor that results from various accident initiators
    - Heat transfer from the reactor is represented by a single node along the direction of coolant flow through the core
    - Heat exchange modeled between the primary and intermediate coolant loops and from the intermediate coolant loop through a simplified representation of the steam generator
    - Transient response of the reactor core is modeled with point kinetics
  - MATWS is included in a dynamic link library (DLL) that can be accessed by GoldSim at run time

Reactor Model

- Analysis considers a metallic fueled, 840 MWth sodium cooled advanced burner fast reactor having an transuranic conversion ratio of approximately 0.5
  - The balance of plant is a simplified representation of the heat removal system for the PRISM Mod B reactor developed by Hill and Wigeland
    - Heat removal of up to 3.5% of nominal power through the vessel wall is modeled
    - Pump trips result in flow coastdowns with flow halving time of about 4 seconds in the primary coolant loop and 7 seconds in the intermediate coolant loop
    - Steam generator is modeled by tabular input
- Analysis considers unprotected (failure of reactor scram system) loss-of-heat-sink, loss-of-flow, and transient overpower accident sequences
  - ULOHS is initiated by the shutdown of heat removal through the steam generator
    - A loss-of-flow follows when the coolant inlet temperature reaches approximately 800 K
  - ULOF is initiated by flow coastdowns in the primary and intermediate coolant loops
    - Heat removal through the steam generator stops as a result of loss of intermediate loop flow
  - UTOP is initiated by the withdrawal of a single control rod
    - Steam generator is assumed to maintain constant outlet sodium temperature in the intermediate loop

Stochastic Parameters

- All stochastic parameters are assumed to be independent and to have normal probability distributions
  - Mean values are “best estimates”
  - Standard deviations were assigned values thought to be representative but have not been systematically evaluated
- Stochastic reactivity parameters included the coolant temperature coefficient, the Doppler coefficient, the fuel axial expansion coefficient, the radial core expansion coefficient, the control rod driveline expansion coefficient, and in the case of the UTOP, the control rod worth
- Stochastic system parameters are the rate at which heat removal declines to zero in the ULOHS and ULOF cases, the pump trip temperature in the case of the ULOHS, and the time required to fully withdraw the control rod in the UTOP case
- All results presented here are based on 10,000 independent samples of the stochastic parameters
  - The number of realizations required will depend on the purpose of the analysis and the time required to calculate a single realization

Stochastic Parameters for ULOHS and ULOF Transients Based on EOEC Core

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

Stochastic Parameters for UTOP Transients Based on BOEC Core

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

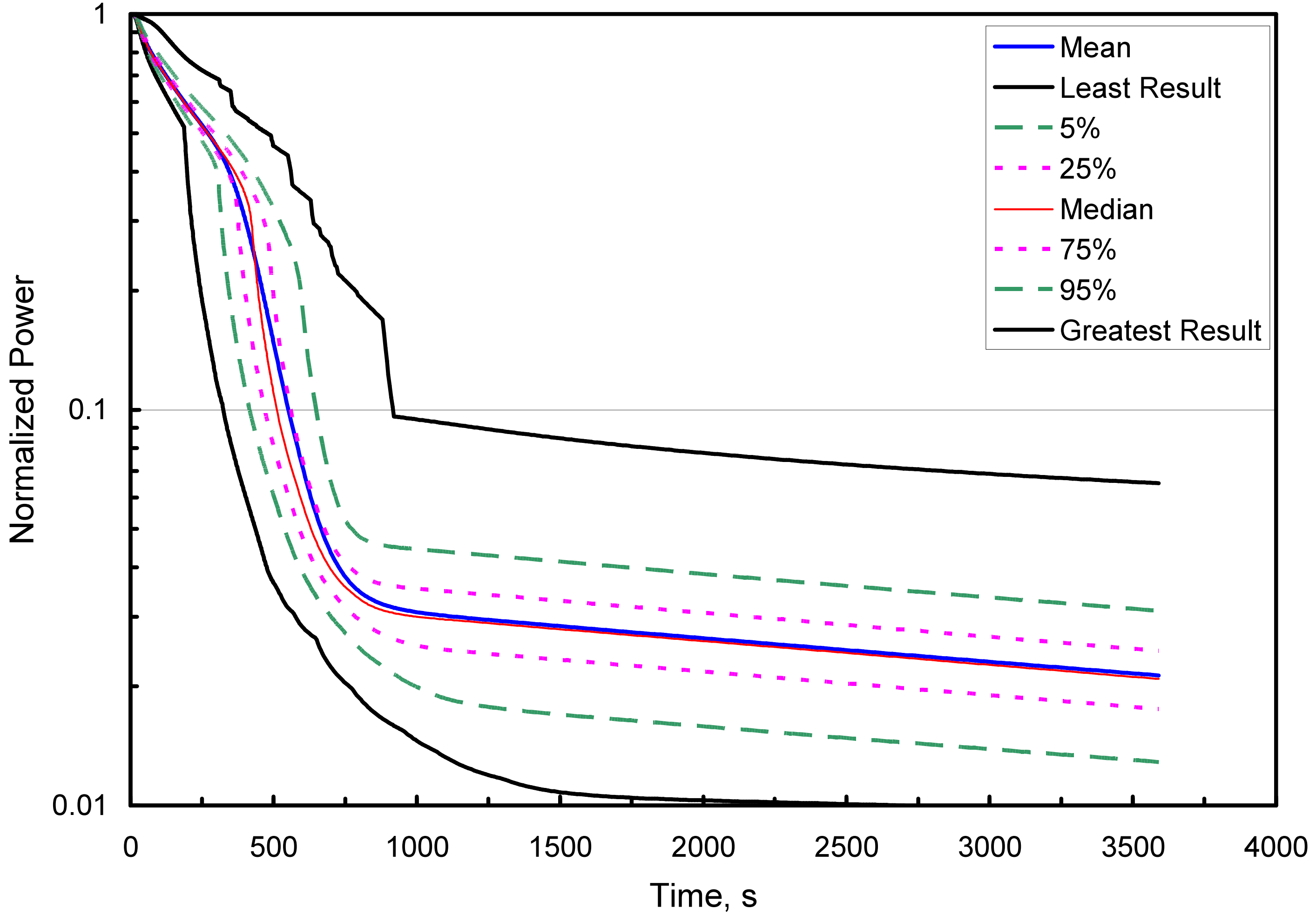
ULOHS Transient Results

- Percentile plots of normalized power and of various temperatures sometimes show abrupt changes in slope indicative of the fact that different realizations may determine a percentile boundary at different times
  - The ratio of the largest to smallest power is more than a factor of 10 as the transient time approaches one hour following initiation
    - Note that the largest and smallest values are not upper and lower bounds but the largest and smallest values among the 10,000 realizations
  - Largest and smallest fuel temperatures differ by as much as 200 K
- Frequency distributions for peak fuel and coolant temperatures can be used to estimate the probability of exceeding safety margins (e.g. coolant boiling or fuel melting)
  - Distributions resemble log-normal distributions but do not agree with log-normal distributions having the same means and standard deviations for the logarithms of temperature
  - Only 8 of the 10,000 realizations resulted in peak outlet coolant temperatures greater than the peak outlet coolant temperature found in the 2-sigma run

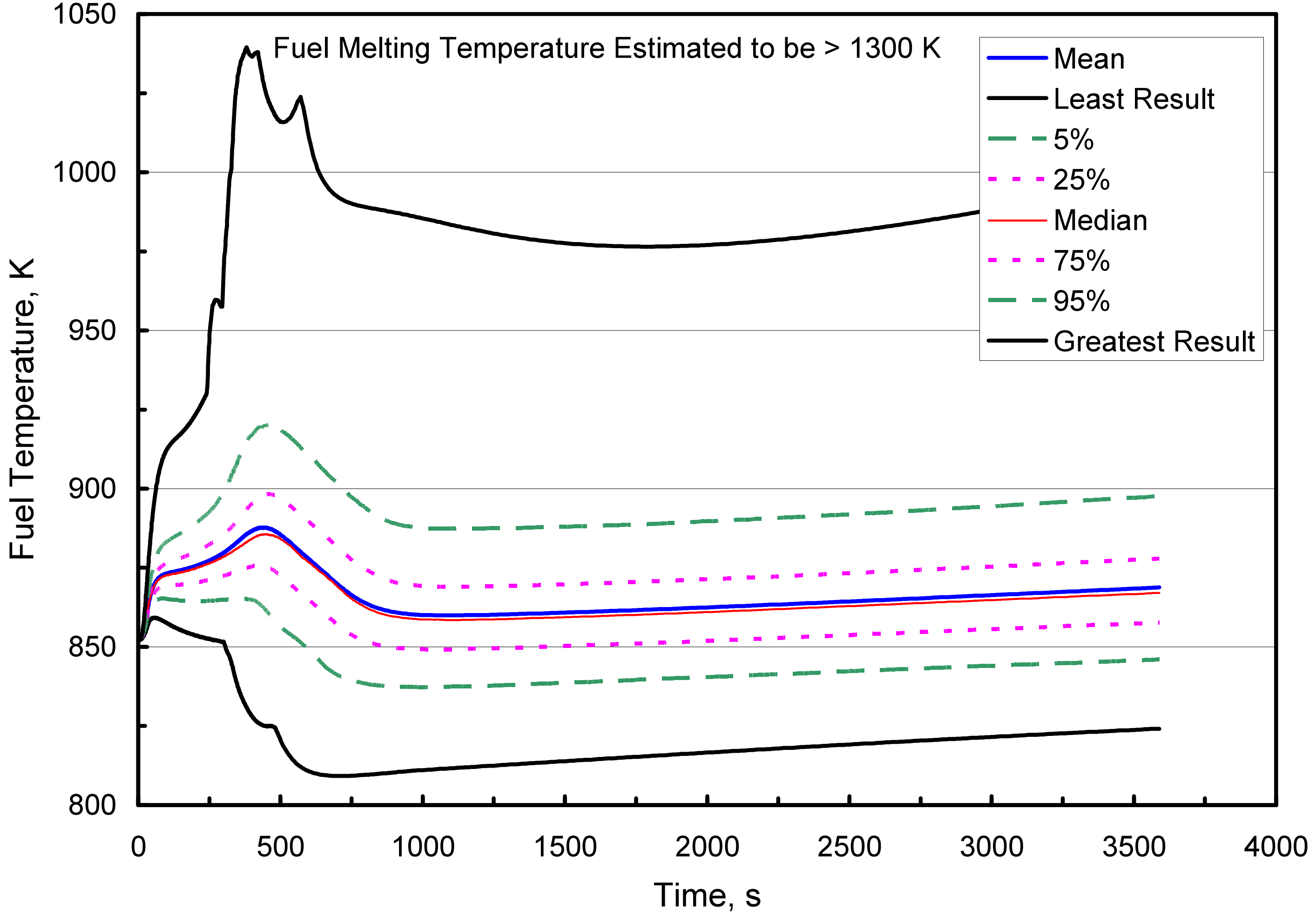
ULOHS Transient Results (cont.)

- Four importance measures were used to rank the impact of the stochastic input parameters on various outputs
  - All agreed that the three most important parameters for the outlet coolant temperature and the fuel temperature are in order of descending importance, radial core expansion, coolant temperature reactivity coefficient, fuel axial expansion reactivity coefficient
  - Three of the measures, based on various correlation parameters ranked the Doppler coefficient as fourth most important while the fourth measure ranked control rod driveline expansion as fourth most important
  - Scatter plots can be used to illustrate the relationship of various output parameters to individual input parameters

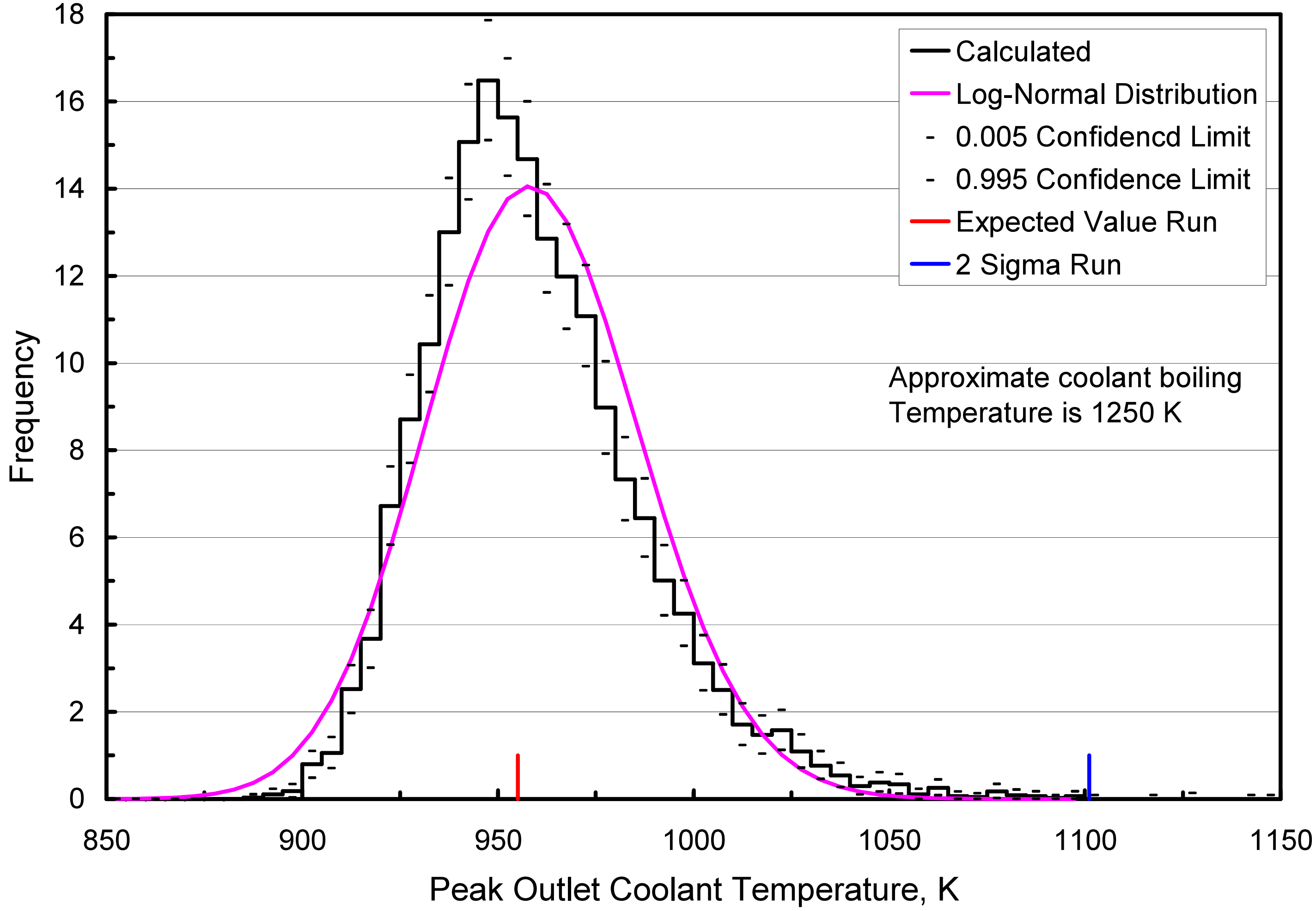
Mean, Greatest and Least Values, and Selected Percentile Curves for the Normalized Power in ULOHS Transient



Mean, Greatest and Least Values, and Selected Percentile Curves for the Fuel Temperature in ULOHS Transient



Frequency Distribution for the Peak Outlet Coolant Temperature with Log-Normal Approximation and Deterministic Calculations in ULOHS Transient



Approximate coolant boiling Temperature is 1250 K

Illustration of Strong Correlation Between Peak Fuel Temperature and Radial Core Expansion Reactivity Coefficient in ULOHS Transient

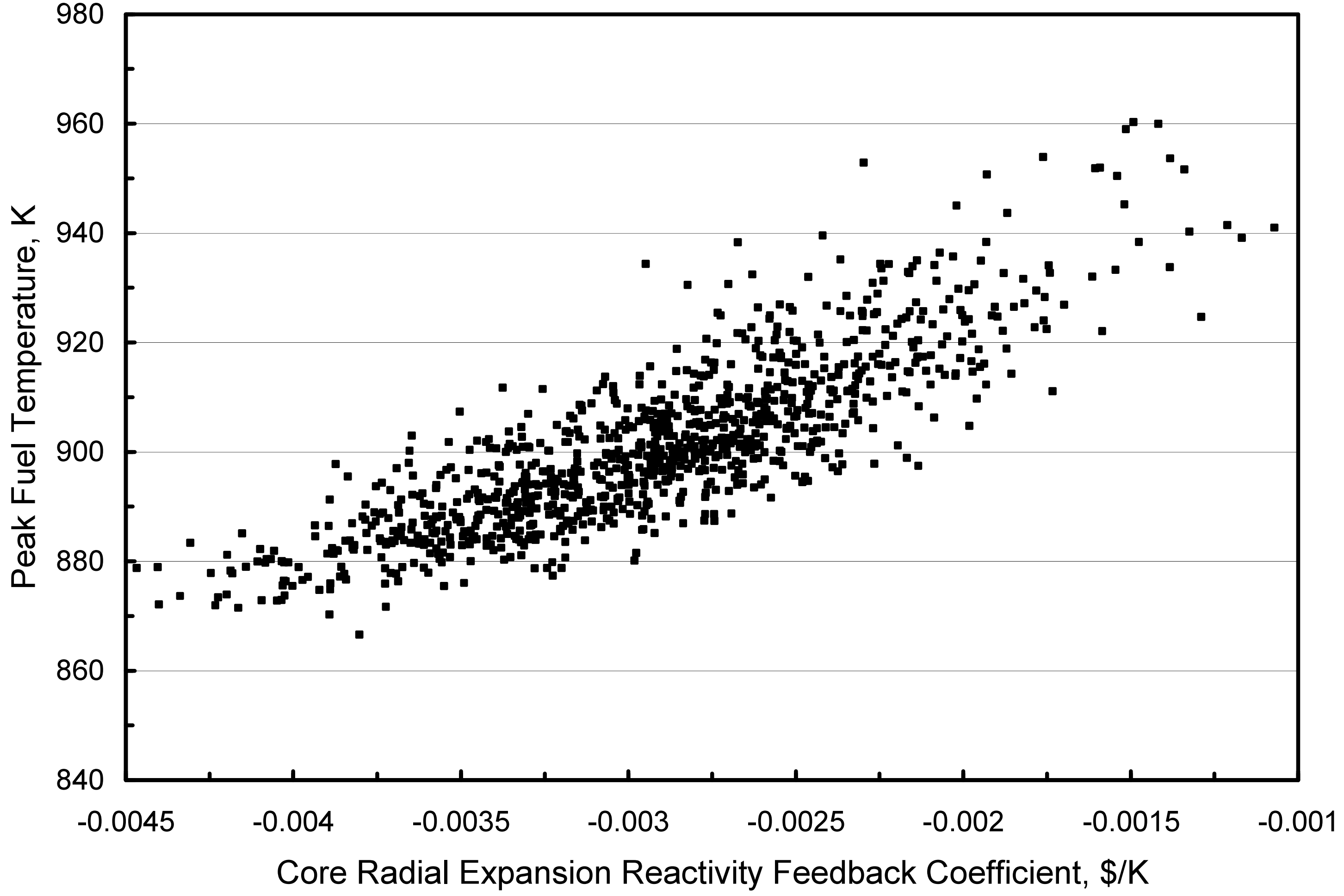
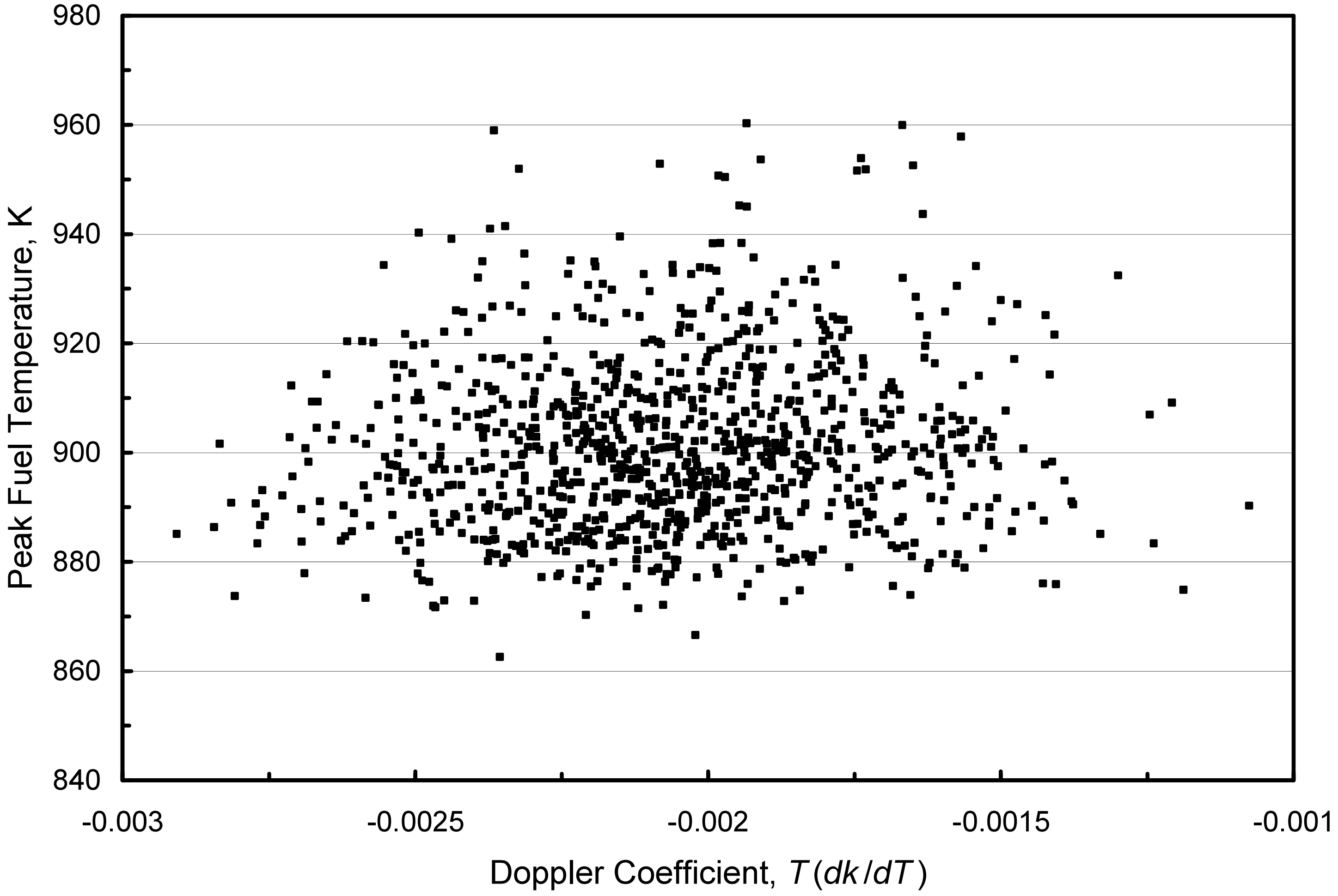


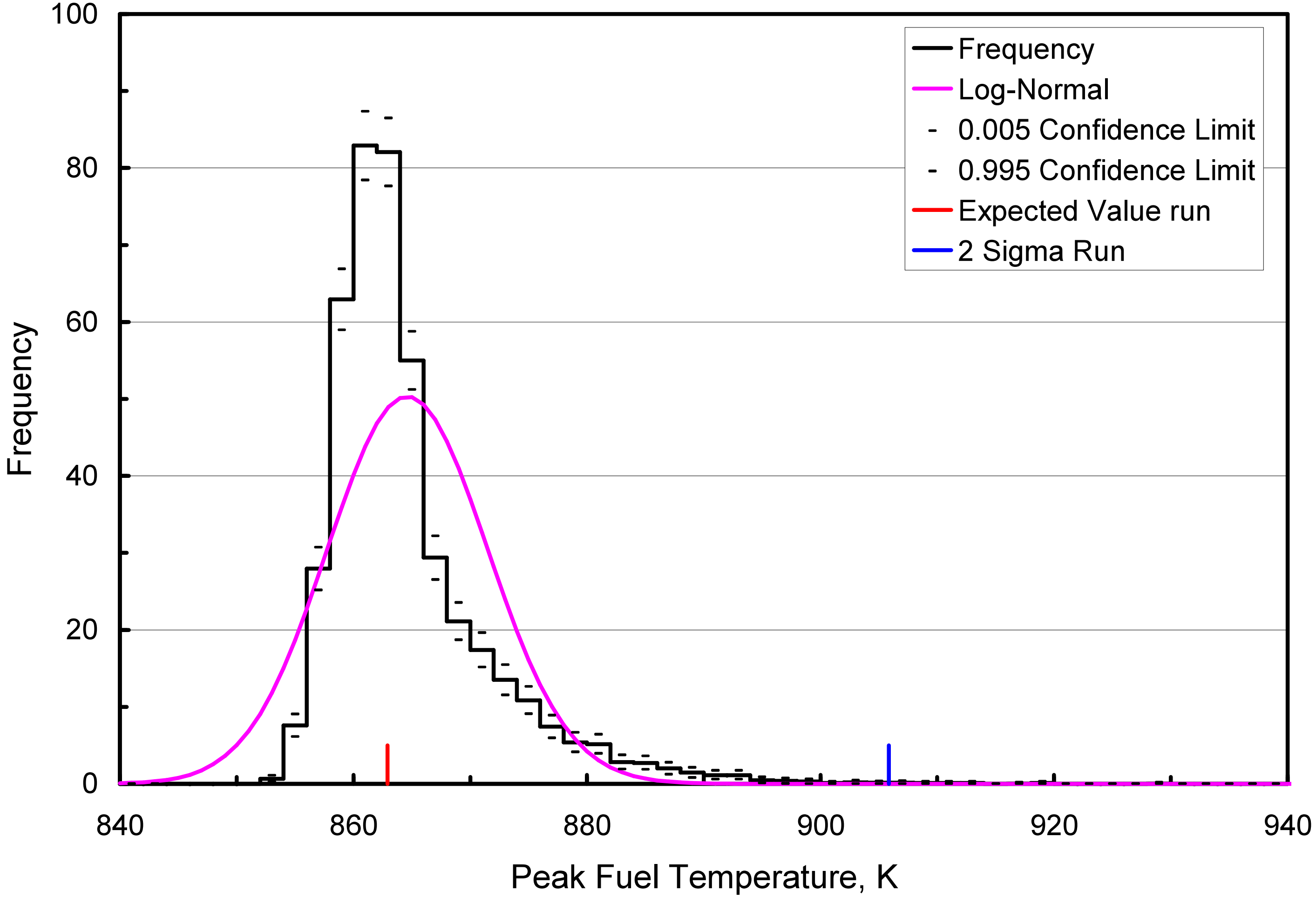
Illustration of Weak Correlation Between Peak Fuel Temperature and Doppler Reactivity Coefficient in ULOHS Transient



ULOF Transient Results

- Plots of the greatest and least values for the normalized power indicate the during the first hour of the transient the ratio of the greatest to the least power does not exceed 2.5
  - The difference between the greatest and least coolant outlet temperatures is 235 K
  - The smallest margin to coolant boiling is 130 K but assemblies with peak power-to-flow ratios will have smaller margins
- A log-normal probability distribution provides a poor approximation to the frequency distribution for the peak fuel temperature
  - A deterministic calculation with the input parameters set to their 2-sigma values again shows the very conservative value for the peak fuel and coolant outlet temperatures with only 13 of the 10,000 realizations producing peak fuel temperatures greater than the 2-sigma value
- Calculated importance measures indicate the most important parameter in determining the peak coolant outlet temperature is the radial core expansion coefficient, in agreement with the ULOHS results
  - Three of the importance measures indicate the possibility that the rate of decrease of heat removal through the steam generator may be more important to the ULOF outcome than to the ULOHS outcome

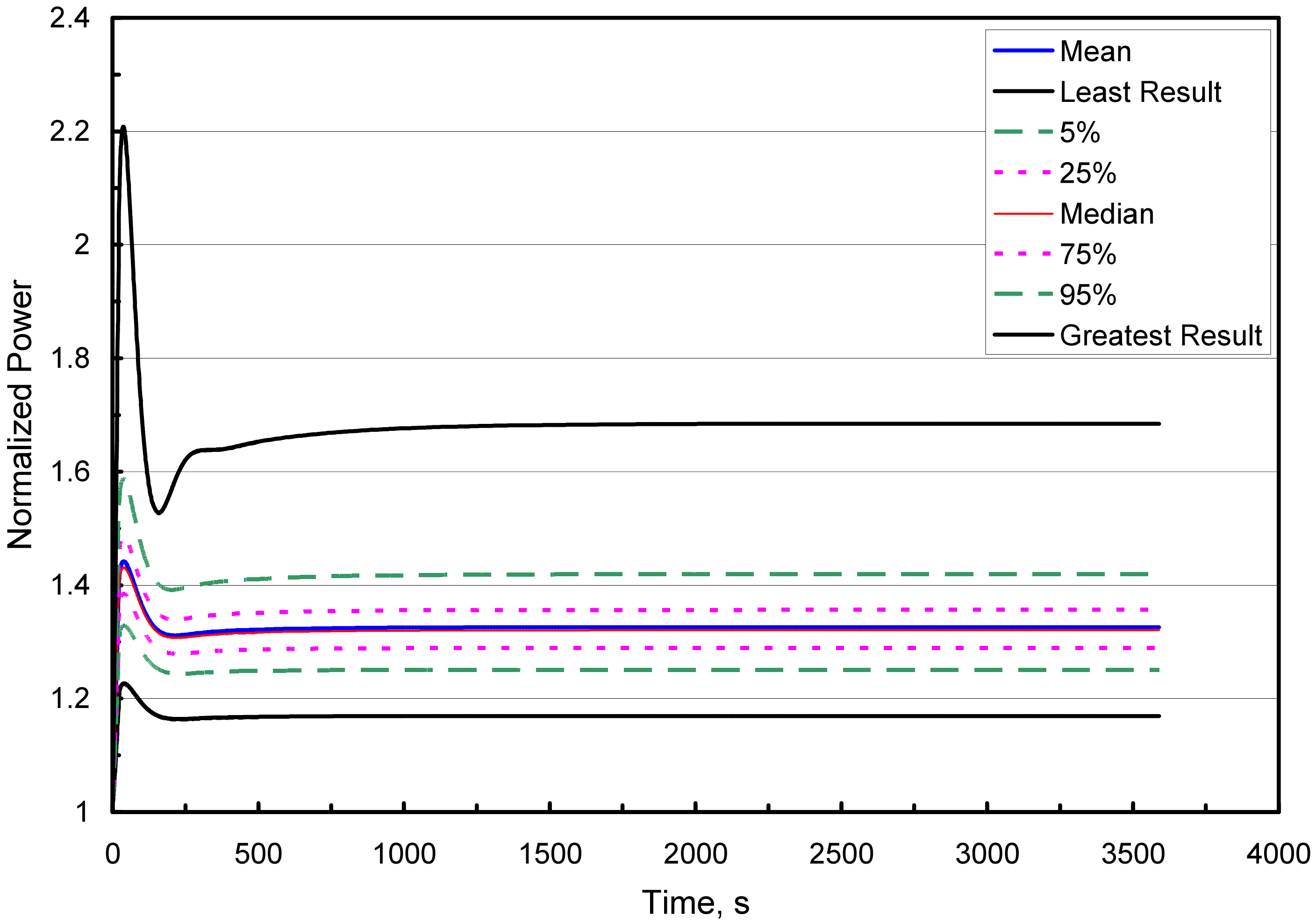
Frequency Distribution for the Peak Fuel Temperature with Log-Normal Approximation and Deterministic Calculations in ULOF Transient



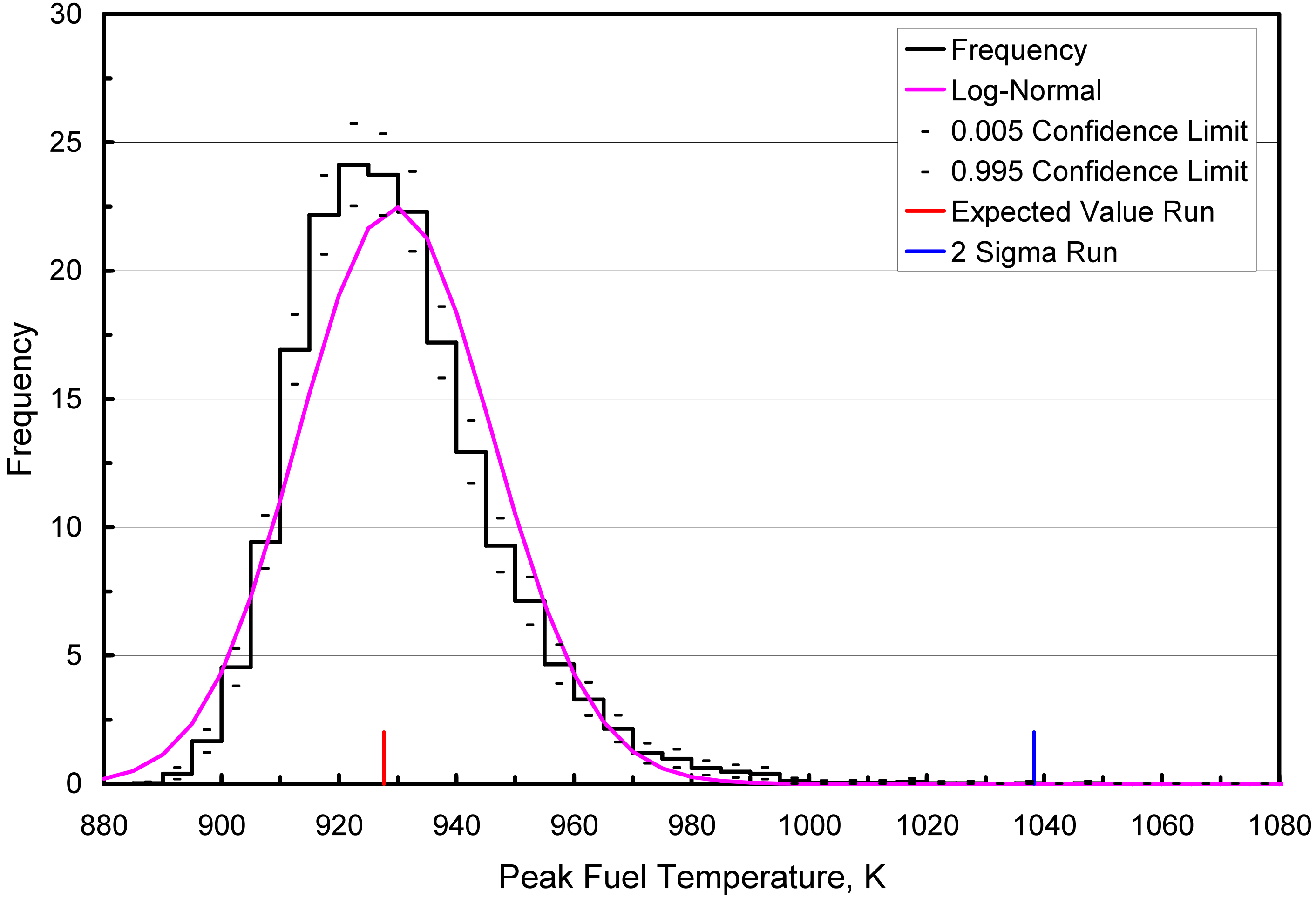
UTOP Transient Results

- Both the normalized power and the fuel temperature reach higher values than they reach in the ULOHS and ULOF transients
  - Coolant temperatures are lower than in the ULOHS and ULOF cases
  - The coolant inlet temperature increases by only about 20 K and is leveling off when the calculation is stopped about one hour into the transient
- The frequency distribution for the peak fuel temperature resembles a log-normal distribution but does not agree with a log-normal distribution having the same mean and standard deviation for the logarithm of the temperature
  - As in the ULOHS and the ULOF cases, a calculation with the stochastic input parameters set at their 2-sigma values provides a very conservative value for the peak temperature with only two of the 10,000 realizations producing peak temperatures greater than the 2-sigma result
- Importance measures indicate that the three most important input parameters in determining the peak fuel temperature are in descending order fuel axial expansion reactivity feedback, the worth of the control rod that is withdrawn, and the core radial expansion reactivity feedback

Mean, Greatest and Least Values, and Selected Percentile Curves for the Normalized Power in UTOP Transient



Frequency Distribution for the Peak Fuel Temperature with Log-Normal Approximation and Deterministic Calculations in UTOP Transient



Conclusions

- The Monte Carlo approach to uncertainty considered here can be used with safety analysis computer codes without any substantial rewriting of the codes
  - For illustrative purposes, stochastic input parameters were assumed to be independent and to have normal probability distributions with mean values set to “best estimates” and representative standard deviations
  - Future work should include a more rigorous determination of the appropriate probability distributions for the input parameters and of possible correlations among the parameters
- Analysis such as that considered in this work has potential usefulness in a risk based regulatory environment
  - Importance measures can be used to identify those input parameters most important in influencing various output parameters
  - The analysis provides a means of estimating probabilities that output falls within specified ranges or that safety margins such as coolant boiling or fuel melting are violated

Conclusions (cont.)

- Probability distributions for input parameters and probability distributions for output parameters are not of the same type
  - Normal probability distributions were used for input parameters while some output parameters had distributions that resembled log-normal distributions but with different means and standard deviations
  - A priori knowledge of output distributions could provide a means of estimating probabilities for performance parameters based parameters that could be estimated using a smaller number of realizations