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Risk-Informed Multi-Physics Best-Estimate Plus Uncertainties (BEPU): Demonstration of LOCA Scenario-Based Reflood Phenomena

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Risk-Informed Multi-Physics Best-Estimate Plus Uncertainties (BEPU): Demonstration of LOCA Scenario-Based Reflood Phenomena

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EXECUTIVE SUMMARY

The United States nuclear industry is facing a strong challenge to maintain regulatory required levels of safety while ensuring economic competitiveness to stay in business. Safety remains a key parameter for all aspects related to operation of light water reactor (LWR) nuclear power plants (NPPs) and can be achieved more economically by using a risk-informed ecosystem such as that being developed by the Risk-Informed Systems Analysis (RISA) Pathway under the United States (U.S.) Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program. The LWRS Program is promoting a wide range of research and development (R&D) activities with the goal to maximize both the safety and economically efficient performance of NPPs through improved scientific understanding, especially given that many plants are considering second license renewal.

The RISA Pathway has two main goals: 1) deployment of methodologies and technologies that enable better representation of safety margins and the factors that contribute to cost and safety, and 2) development of advanced applications that enable cost-effective plant operation.

This report summarizes Reactor Excursion and Leak Analysis Program 5 - 3D (RELAP5-3D) development activities for best-estimate plus uncertainty (BEPU) capability to support ongoing RISA Pathway pilot projects for risk-informed uncertainty quantification applications. Work scope includes: (1) improvement of perturbation model for selected closure laws and probability density functions (PDF) for the selected correlations; and (2) demonstration with loss of coolant accident (LOCA) scenario-based separate and integral effects.

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ACRONYMS

API	Application Programming Interface
BAF	bottom of active fuel
BEPU	best-estimate plus uncertainty
CCFL	counter-current flow limitation
CET	combined effect test
CFR	Code of Federal Regulations
CHF	critical heat flux
DBA	design basis accident
DNB	departure from nucleate boiling
ECCS	emergency core cooling system
FLECHT	Full-Length Emergency Core Heat Transfer
FOM	figure of merit
FY	fiscal year
HPC	high performing computing
HRA	Human Reliability Assessment
HUNTER	Human Unimodel for Nuclear Technology to Enhance Reliability
INL	Idaho National Laboratory
IET	integral effect test
ITF	Integral Test Facility
LBLOCA	Large Break Loss of Coolant Accident
LHS	Latin Hypercube Sampling
LOCA	loss of coolant accident
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
NPP	nuclear power plant
NRC	U. S. Nuclear Regulatory Commission
PCT	peak clad temperature
PDF	probability density function
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RAVEN	Risk Analysis Virtual ENvironment code
R&D	research and development
RELAP5-3D	Reactor Excursion and Leak Analysis Program 5 – 3D

RI-MP-BEPU	risk-informed multi-physics BEPU
RIMM	risk-informed margins management
RISA	Risk-Informed System Analysis
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SEASET	Separate Effects and System Effects Tests
SSC	systems, structures, and components
TH	thermal-hydraulic
TMI	Three Mile Island
UCSP	upper core support plate
UP	upper plenum
UQ	uncertainty quantification
U. S.	United States

1. INTRODUCTION

1.1 Background

Many ongoing pilot projects are aiming to use Reactor Excursion and Leak Analysis Program 5 – 3D (RELAP5-3D) for risk-informed analyses and uncertainty analyses. A particular interest is for the Risk-Informed Multi-Physics Best-Estimate Plus Uncertainties (RI-MP-BEPU) approach. The risk-informed analyses are covered by Risk Analysis Virtual ENvironment (RAVEN) and Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) software, which are used for various probabilistic risk assessment (PRA) applications. However, RELAP5-3D lacks the uncertainty analysis capabilities to perform a full Best-Estimate Plus Uncertainty (BEPU) analysis. The BEPU method requires the application of uncertainty quantification (UQ) methods, input parameter probability density functions (PDFs) determination, and propagation of these PDFs to RELAP5-3D. In addition, RELAP5-3D needs to provide UQ capable physics engine for a dynamic human reliability assessment (HRA) application.

The objectives of this activity are:

- Implement full RI-MP-BEPU analysis capability to RELAP5-3D
- Develop dynamic HRA control module for HUNTER
- Improve coupling with RAVEN to perform risk-informed analysis by using classical/dynamic PRA/HRA
- Demonstrate and benchmark RI-MP-BEPU and dynamic HRA capability through selected anticipated operation occurrence and design basis accident (DBA) scenarios
- Validation and verification of the developed RI-MP-BEPU model coupled with dynamic HRA
- Support existing and future industry pilot projects which plan to employ the RI-MP-BEPU and dynamic HRA model.

In FY-2020, RELAP5-3D was modified to apply basic PDF to quantify uncertainties in reflood phenomena during a loss of coolant accident (LOCA) [1]. The RELAP5-3D source code was reviewed to measure applicability of PDFs and relevant subroutines and modules were modified to receive PDFs from input deck cards. Code structure was also modified to allow direct uncertainty propagation by user without additional source code modification. RAVEN code was coupled to introduce a proper distribution of the uncertainties. A demonstration study was performed that showed the possibility of obtaining uncertainty bands and of assessing the importance of different models influencing the figure of merit (FOM) by performing statistical analyses.

During FY-2021, RELAP5-3D was fully modified to allow applying PDFs for separate and integral effects in LOCA safety analyses. Two Full-Length Emergency Core Heat Transfer – Separate Effects and System Effects Test (FLECHT-SEASET) results were used to set the range of uncertainties: 31701 and 31504. The range of uncertainties of major physical parameters were calculated and compared with experimental results and results from non-BEPU RELAP5-3D simulations. The updated RELAP5-3D version with UQ capability was disseminated to another RISA Pathway project, plant reload optimization, and was used for system-level analysis of LOCA and other demanding LWRS projects.

Another effort during FY-2021 was the development of a coupling framework for the dynamic HRA code HUNTER [2]. RAVEN was used to couple HUNTER and RELAP5-3D. A demonstration was performed for controlling trip signals of RELAP5-3D which represents a delay of operator actions during the accident.

1.2 Reflood Phenomena During Loss of Coolant Accident (LOCA)

Large break loss of coolant accidents (LBLOCAs) in a LWR can be described through three phases: blowdown, refill, and reflood followed by long-term cooling conditions. Description of each phase is as follows:

- **Blowdown**: the initial phase, occurring after the initial break and lasting approximately 30 seconds. The system pressure is decreasing very rapidly, causing primary coolant flashing out and a two-phase flow regime near the break. Cladding temperature increases during blowdown from normal operating conditions of approximately 325°C to approximately 550-800°C (~1000-1500°F). This phase is ending when the emergency core cooling system (ECCS) starts to inject.

- **Refill**: the second phase, lasting approximately 10 seconds. ECCS water starts to refill the reactor pressure vessel and the lower plenum water level starts to rise; the phase is ending when the lower plenum is full. During refill and reflood, cladding temperature varies because of the decay heat generation in fuel rods and heat removal by the two-phase flow through the core. Cladding temperature increases as long as heat removal is less than heat generation. Cladding temperature decreases when heat removal is greater than heat generation.
- **Reflood**: the third and final phase, lasting approximately 250 seconds. This phase starts when the water level in the lower plenum reaches the bottom of active fuel (BAF). Reflood from below allows a cooldown (quenching) of the overheated fuel rods. In some pressurized water reactors (PWR), combined water injection from top and bottom is also possible. During reflood, the coolant channels are experiencing post-critical heat flux (CHF) heat transfers, and the hot surfaces are cooled down as the liquid moves upward. Quenching/rewetting occurs when the liquid is in permanent contact with the fuel rod surface. Consequently, the heat transfer between fuel rods and coolant increased dramatically and the clad temperature decreased sharply as shown in Figure 1-1, thus, reflood quenching. The physics of quenching are complicated, and they strongly depend on the clad temperature. If the clad temperature is above the minimum stable film boiling temperature, cooling will happen through film boiling. However, if clad axial condition and precursor cooling reduce the clad temperature enough, transition and subcooled boiling will happen.

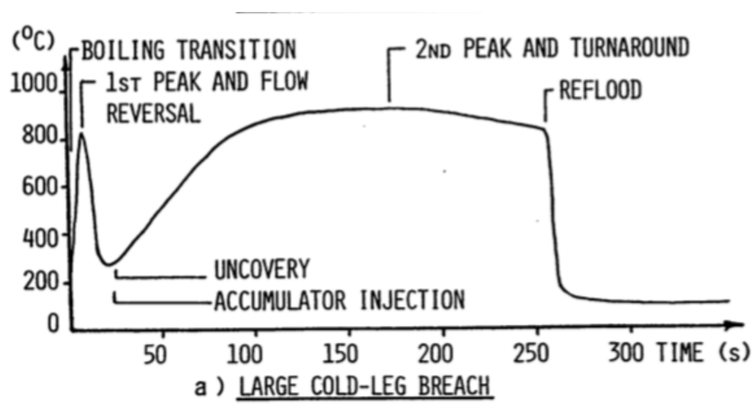

Figure 1-1. Peak cladding temperature (PCT) behavior LBLOCA phases in a PWR. [3]

ECCS is designed to inject water into the primary system and to recover or reflood the potentially uncovered core. Steam produced during the core quenching process creates pressure that is balanced against the hydraulic height difference between the core and the downcomer. The pressure differential is limited by the height of the cold leg.

As the reflood water enters the core, it is heated by the stored energy and decay power of the rods. Depending on the time during the transient and injection flow rate, the reflood water at the quench front can be subcooled or saturated, or the water can reach saturation below the quench front so that a two-phase mixture reaches the quench front. During the reflood, the hydraulic conditions on the fuel rod surfaces change completely from unwetted to wetted conditions within a few seconds. At the quench front, the stored energy of the rod is released over a relatively short distance in which the local axial temperature gradient can be as large as 500 K/cm. The transition boiling heat transfer regime exists during these few seconds. Correct modeling of the transition boiling is important in order to accurately predict the core reflood behavior.

Figure 1-1 also represents the importance of the reflood phase in the LBLOCA scenario, hence, correct analysis of reflood phenomena will provide accurate predictions of the final PCT which would allow a better definition of the safety margin (i.e., a difference between the predicted PCT and the maximum allowed PCT). Figure 1-2 shows the subcooled boiling region where the clad is experiencing film boiling with an inverted annular flow regime and dispersed droplet regime. The quenching front is then moving upward due to the cooldown provided by the liquid droplets, the steam, and the axial conduction. The main phenomena of reflood phase and its occurrence frequency are shown in Table 1-1.

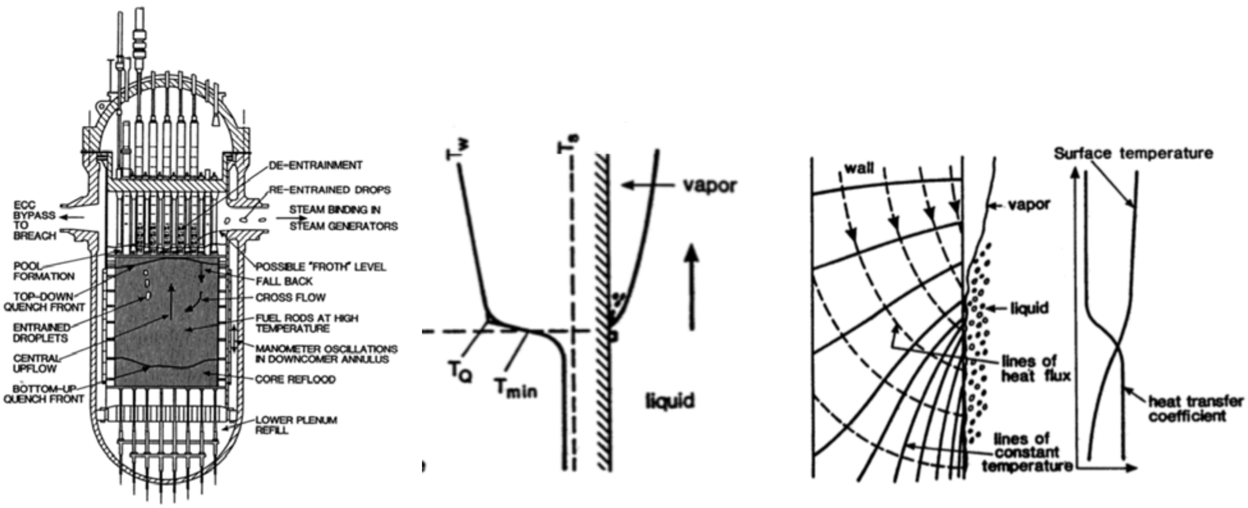

Figure 1-2. Schematic diagram of reflood phenomena in PWR core. [4]

Table 1-1. Phenomena occurring during the Reflood phase. [5]

Phenomena	Occurrence
Break Flow	Yes
Phase Separation (condition or transition)	Yes
Mixing and condensation during injection	Yes
Core wide void + flow distribution	Yes
ECC bypass and penetration	Partially
Counter-current flow limitation (CCFL) at the upper core support plate (UCSP)	Yes
Steam binding (liquid carryover, etc.)	Yes
Pool formation in upper plenum (UP)	Yes
Core heat transfer incl. departure from nucleate boiling (DNB), dry out, return to nucleate boiling	Yes
Quench front propagation	Yes
Entrainment (Core, UP)	Yes
De-entrainment (Core, UP)	Yes
1- and 2-phase pump behavior	Partially
Non-condensable gas effects	Partially

2. MODIFICATION OF RELAP5-3D

2.1 Code Architecture

RELAP5-3D is based on non-homogeneous and non-equilibrium model for a two-phase system using a semi-implicit or a nearly-implicit numerical scheme.

The source code is organized according to Figure 2-1.

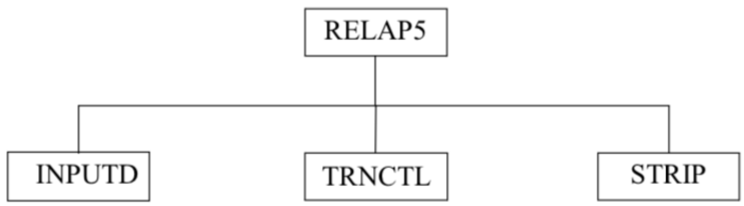

Figure 2-1. RELAP5-3D level structure.

It consists of an input block (INPUTD) that processes inputs, checks input data, and prepares required data block for all program options. The transient/steady-steady state block (TRNCTL) handles both steady state and transient options; the strip (STRIP) block controls the output data processing. The transient calculations are organized according to the modular structure shown in Figure 2-2.

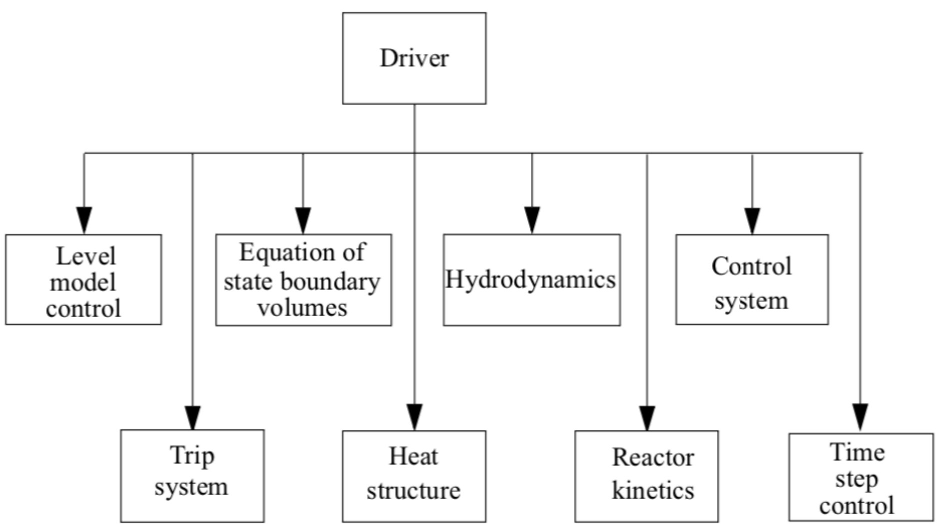

Figure 2-2. RELAP5-3D modular structures for transient calculations.

The relevant routines for the reflood analysis are being called by the hydrodynamics (subroutine HYDRO) and heat structures (subroutine HTADV) module.

2.2 Reflood Relevant Routines

Following list are the reflood relevant phenomena.

- Interfacial heat transfer
- Wall heat transfer
- Interfacial friction

In the RELAP5-3D source code, closure laws and correlations that are involved in a reflood phenomenon are as follows:

- Dispersed flow interphase heat transfer model for wet and dry walls
- Wall-to-fluid heat transfer model for transition and film boiling
- Junction interfacial drag coefficient

Related modules and subroutines source code were modified, and minor errors were corrected to allow perturbation of the main parameters of the models simulating the above phenomena. It is noted that details of the source code and their modification are not shown in this report due to export control.

Table 2-1 is the list of modified routines and modules to simulate the reflood phase. Names of routines/modules are not shown.

Table 2-1. RELAP5-3D routines for the selected reflood phenomena.

Phenomena	Modified Routine/Module
Interfacial heat transfer	Subroutine to compute interphase heat transfer.
Wall heat transfer	Subroutine to compute heat transfer coefficients for the non-reflood side boundary of the reflood model.
	Subroutine to compute reflood heat transfer coefficient using the pattern obtained in the above subroutine.
	Subroutine to compute the post-DNB forced convection heat transfer coefficient.
Interfacial friction	Subroutine to compute interphase drag.
	Subroutine to compute junction interphase drag term for bubbles and droplets.
	Subroutine to compute interphase friction coefficients in bubbly/slug flow.

Table 2-2 is the list of routine/module for data management (new variables declaration, array modifications). Names of routines/modules are not shown.

Table 2-2. RELAP5-3D modules modified for the BEPU reflood phenomena.

Function	Modified Routine/Module
Calculation support	Subroutine of auxiliary scratch arrays for use in various supporting calculations and functions throughout the program.
Transient control	Subroutine for the transient control module.
Heat structure quantity	Subroutine to hold heat structure quantities.
Heat transfer coefficient control	Subroutine to handle entire variables common to the heat transfer coefficient calculations.
Hydrodynamic junction control	Subroutine for hydrodynamic junction data (momentum cells).
Hydrodynamic volume control	Subroutine for hydrodynamic volumes data.
Hydrodynamic data control	Subroutine to control hydrodynamic systems, reference volume, its position coordinates, fluid type in the system, system name, system information flags, system thermodynamic property file name.

Table 2-3 is the list of modified input processing files for the input deck. Names of routines/modules are not shown.

Table 2-3. RELAP5-3D routines modified for BEPU input processing.

Function	Modified Routine/Module
Heat transfer boundary condition control	Subroutine to return left and right boundary conditions for a heat structure.
Component input control	Subroutine for control crosschecking of component input and the first pass of component initialization.
Loop control	Subroutine that prepares multiple loop tables, loading number of volumes, junctions and component per loop, and establishes the order for processing.
Heat structure data control	Subroutine for routine reading the heat structure component, modified for introducing the additional transition and film boiling coefficients.
Hydrodynamic optional card control	Subroutine for routine reading the optional hydrodynamic system cards that specify reference volume, its position coordinates, fluid type in the system, the system name, system information flags, and the system thermodynamic property file name. The subroutine was modified for introducing new cards for global perturbation of interfacial friction and heat transfer coefficients.
Pipe component data control	Subroutine to process pipe component data. Modified creating a new card for perturbation of wet and dry wall dispersed flow heat transfer coefficients.
Single junction data control	Subroutine for routine reading the single junction component, modified for testing perturbation of friction coefficient.

2.3 Input Deck Modifications

The analysis and the modification of the routines identified in the previous paragraph have led to the modification of the RELAP5-3D input deck. These modifications have the scope of allowing the user to perform perturbation of the selected reflood routines, thus allowing the forward propagation of the models' uncertainties through the code. Table 2-4 shows the input deck option update for the BEPU reflood analysis in RELAP5-3D.

Table 2-4. RELAP5-3D new input deck options for BEPU reflood analysis.

Card	Added words	Function
119	W3(R), W4(R)	added cards W3: system interfacial friction coefficient. Default is 1.0. W4: system interfacial heat transfer coefficient. Default is 1.0.
1CCCG800 or 1CCCG900	W1(I)	added option "6": introduce twenty-four words format for cards 1CCCG801 through 1CCCG899 (left boundary) or 1CCCG901 through 1CCCG999 (right boundary).
1CCCG801 through 1CCCG899 (left boundary) or	W1 to W19 are the same as the one for the option "4" (20 words format card) on card 1CCCG800 or 1CCCG900	Multipliers for "to liquid" and "to gas" heat transfer coefficients for transition and

Card	Added words	Function
1CCCG901 through 1CCCG999 (right boundary).	W20(R) Multiplier on transition boiling heat transfer coefficient – to liquid. The default value is 1.0. W21(R) Multiplier on transition boiling heat transfer coefficient – to gas. The default value is 1.0. W22(R) Multiplier on film boiling heat transfer coefficient – to liquid. The default value is 1.0. W23(R) Multiplier on film boiling heat transfer coefficient – to gas. The default value is 1.0. W24(I) Heat structure number.	film boiling.
CCC0004	W1(R): multiplier for interfacial heat transfer to the liquid-wet wall dispersed flow. The default value is 1.0. W2(R): multiplier for interfacial heat transfer to the vapor-wet wall dispersed flow. The default value is 1.0. W3(R): multiplier for interfacial heat transfer at the noncondensable gas-liquid interface - wet wall dispersed flow. The default value is 1.0. W4(R): multiplier for interfacial heat transfer to the liquid - dry wall dispersed flow. The default value is 1.0. W5(R): multiplier for interfacial heat transfer to the vapor - dry wall dispersed flow. The default value is 1.0. W6(R): multiplier for interfacial heat transfer at the noncondensable gas-liquid interface - dry wall dispersed flow. The default value is 1.0.	Added a new card for perturbing the interfacial heat coefficients for dry and wet wall conditions for pipe components.
CCC0110	W5(R): multiplier for the junction interphase friction. The default value is 1.0.	Added word for perturbing interfacial friction coefficient in a single junction component. For testing purposes.

3. UNCERTAINTY ANALYSIS OF REFLOOD PHENOMENA

Due to the complexity of the reflood phase phenomena, the uncertainty analysis of reflood phase needs experimental data from the combined effect test (CET) and integral effect test (IET), instead of the separate effect test (SET), from Integral Test Facilities (ITF). The FLECHT-SEASET facility is a dedicated experimental system for the reflood phenomena during a LOCA scenario. The basis of the proposed PDF is based on actual experimental data and associated uncertainty bands for the parameters of interest. Two test cases are used: Case 31504 (low flow), and Case 31701 (high flow) [6].

3.1 FLECHT-SEASET Reflood Experiments

The FLECHT-SEASET is a forced reflood experiment at a flooding rate of 24.6 mm/s (0.97 in./s) through the 161 electrically heated rod configuration which simulates a typical full-length 17×17 Westinghouse PWR core [6]. The bundle cross-section is shown in Figure 3-1. The goal of the experiment was to provide data on the PWR core reflood behavior following a hypothetical LOCA. The FLECHT-SEASET program examined following four generic PWR licensing issues which arose from the original core cooling hearings and the evaluation of the accident at the Three Mile Island Unit 2 (TMI-2) nuclear plant.

1. Heat transfer in blocked bundle arrays during reflood
2. Low flood/forced reflood heat transfer mechanisms
3. Steam cooling at low Reynolds numbers in rod bundles
4. Natural circulation cooling modes in single- and two-phase flow.

The facility design features for forced reflood experiment includes

- A cylindrical low mass bundle housing to minimize housing heat releases
- Housing differential pressure cells every 0.30 to obtain void fraction measurements along the heated length of the bundle
- Steam probes in each of 11 thimbles tubes to measure steam superheat radially and axially across the bundle
- 177 heater rod thermocouple computer channels
- Housing windows at the 0.91, 1.83, and 2.74 m elevations.

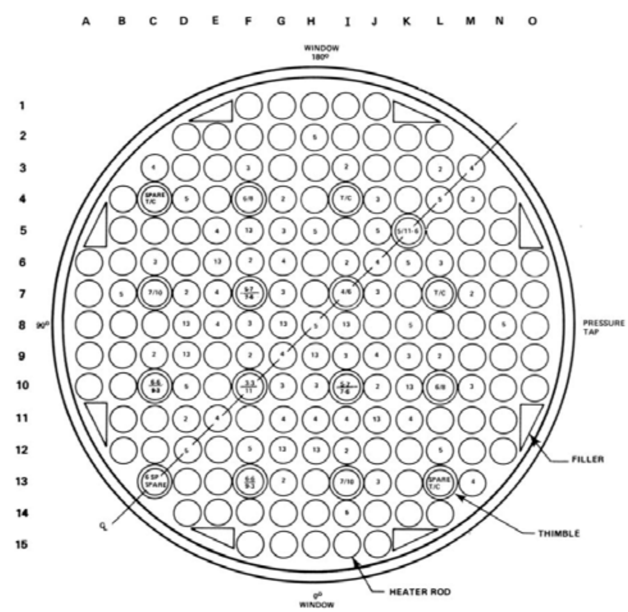

Figure 3-1. FLECHT-SEASET bundle cross-section.

The power to the heater rods decreased during the experiment following the American Nuclear Society plus 20 percent power decay curve 30 seconds after the LOCA initiation. The heater rods had a uniform radial power profile and a built-in modified cosine axial power profile with a peak-to-average power ratio of 1.66.

3.1.1 Test 31504

Test 31504 is low flow flooding rate of 25.6mm/s (0.97in/s) case. Test conditions are as follows.

- Initial clad temperature: 863°C (1585°F)
- Peak power: 2.3 kW/m (0.7 kW/ft)
- Upper plenum pressure: 0.28 MPa (40 psia)

- Injection rate, with lower planum full: 24.6 mm/s (0.97 in/s)
- Flooding water temperature entering lower planum: 51°C (123°F)
- Radial power distribution: uniform
- Axial power shape: cosine with 1.66 peak-to-average power ratio.

3.1.2 Test 31701

Test 31701 is high flow flooding rate of 155mm/s (61in/s) case. Test conditions are as follows.

- Initial clad temperature (1.83m elevation): 872°C (1601°F)
- Peak power: 2.3 kW/m (0.7 kW/ft)
- Upper plenum pressure: 0.28 MPa (40 psia)
- Injection rate, with lower planum full: 155 mm/s (6.1 in/s)
- Flooding water temperature entering lower planum: 53°C (127°F)
- Radial power distribution: uniform
- Axial power shape: cosine with 1.66 peak-to-average power ratio.

3.2 Uncertainty Analysis with RELAP5-3D/RAVEN

3.2.1 RELAP5-3D FLECHT-SEASET input deck

The RELAP5-3D nodalization of FLECHT-SEASET is based on a pipe (component 6) composed of 20 cells as shown in Figure 3-2. The measured fluid conditions for the upper lower zones were defined using time dependent volumes (component 5 and 7). The measured flow injection velocity was used to define the time-dependent junction (component 301) at the bottom of the pipe 6. This time dependent junction is modeling the connection between the lower plenum and the assembly. Decay heat was implemented inside the heat structure 61, which models the rod heaters. RELAP5-3D input deck is shown in Appendix D.

RAVEN is coupled to RELAP5-3D via an Application Programming Interface (API), which allows the analyst to perform input space sampling using Monte Carlo, Grid, or Latin Hypercube Sampling (LHS) schemes. RAVEN has the capability to run on High-Performance Computing (HPC) machines, which allows the parallel execution of serial runs. RAVEN was used in the RELAP5-3D uncertainty analysis method development [1].

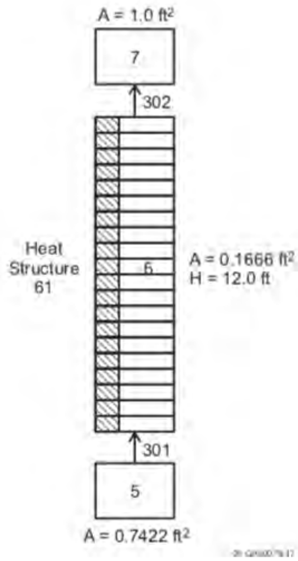

Figure 3-2. RELAP5-3D nodalization for the FLECHT-SEASET forced reflood experiment RAVEN Input Deck for RELAP5-3D PDF Control.

In this uncertainty analysis study, RAVEN was used as the simulation controller, input deck provider with propagation for the selected physical models (interfacial friction coefficient, interfacial heat transfer, post-DNB heat transfers), and postprocessor of RELAP5-3D. Figure 3-3 is the schematic diagram of the RAVEN and RELAP5-3D coupling. The RAVEN input decks for RELAP5-3D control and postprocess for uncertainty band are shown in Appendix A and B.

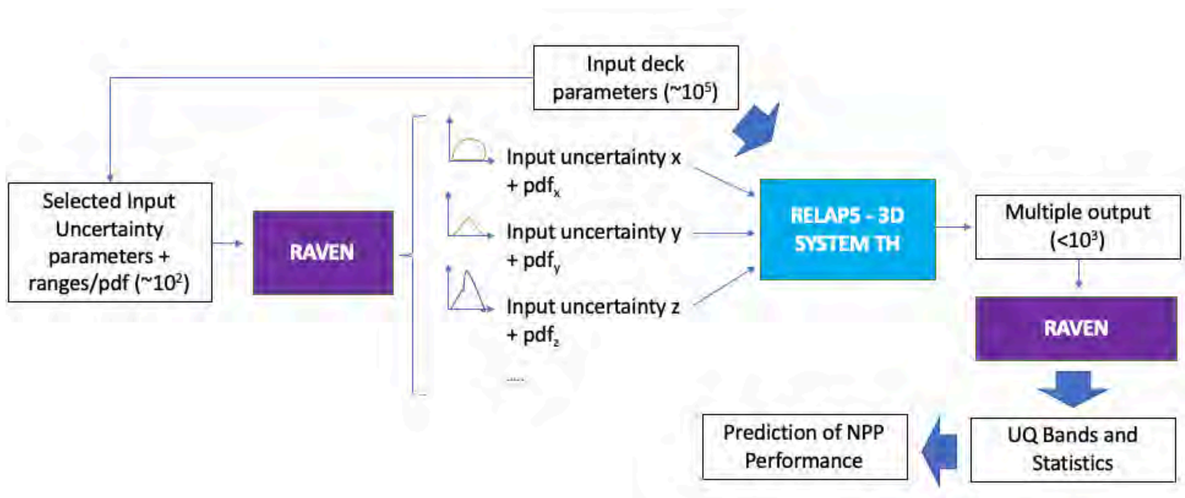

Figure 3-3. Schematic diagram of coupling of RELAP5-3D and RAVEN for uncertainty analysis. [1]

3.2.2 Application of Order-statistics Method

Order-statistics is a methodology of improving sampling robustness to allow more efficient sampling simulations.

Order-statistics, as the name suggests, organizes samples from the first (the minimum value) to the last (the maximum value). It is a method that implies no assumptions on the FOM PDF and an unlimited number of model uncertainties can be considered at the same time during the sampling process. As reported in [7], order-statistics are based on the use of Wilks` formula [8], which determines the minimum number of calculations:

$$\beta = 1 - \sum_{i=N-m+1}^{N} \frac{N!}{(N-i)!\,i!} \gamma^{i} (1-\gamma)^{N-i}$$

where γ is the percentile of the bounding value of the FOM, β is the confidence level, N is the number of calculation runs, m is the number of outputs in the γth quartile.

As it can be seen in Table 3-1, the number of code runs depends only on the percentage of the bounding value and on the desired confidence level. For example, for satisfying the United States Nuclear Regulatory Commission (U.S. NRC) requirement in 10 Code of Federal Regulation (CFR) 50.46 that there must be a high level of probability that the regulatory limits are not being exceeded, it is generally assumed that the determined code outputs bound 95% of the population (γ) with 95% confidence (β). Consequently, for m = 1, minimum of 59 calculations are required.

Table 3-1. Minimum number of runs using the Wilks formula for m=1. [8]

β/γ	**0.90**	**0.95**	**0.99**
0.90	22	45	230
0.95	29	59	299
0.99	44	90	459

Possible reduction of the conservatisms can be obtained by increasing the number of minimum calculations (N) and by increasing the number of outputs in the γth quartile (m). The results for a 95th percentile / 95% confidence for m ≥ 1 are given in Table 3-2.

Table 3-2. Minimum number of runs required, 95th percentile / 95% confidence, and $m \geq 1$.

m	N
1	59
2	93
3	124
4	153
10	311
20	548
100	2325

Using the upper and lower bounds, the uncertainty bands of the BEPU analysis results can be identified. In this case, a symmetrically two-sided formula [9] can be utilized to determine the number of simulations:

$$\Pr\left\{\left(CP(x_m) \leq \frac{1-\gamma}{2}\right) \cap \left(CP(x_M) \geq \frac{1+\gamma}{2}\right)\right\} = 1 + \gamma^N - 2\gamma^N \sum_{i=0}^{N} \frac{N!}{(N-i)!\,i!} \left(\frac{1-\gamma}{2\gamma}\right)^{i} \geq \beta$$

where CP is the cumulative probability, x_m is the minimum value, and x_m is the maximum value among the simulation results. Therefore, the number of simulations can be derived as 146 for the first order two-sided 95th percentile / 95% confidence level condition. In other words, the largest result is above the 95th percentile and the smallest result is below the 5th percentile with a confidence level of 95%. With regard to the sampling method, Monte Carlo sampling method can be used to sample the parameters from more complicated distributions.

3.2.3 Input Uncertainty Distribution

Table 3-3 is the minimum and maximum values of input uncertainty distribution from actual experiment data [6, 10, 11, 12, 13, 14]. Normal distribution was assumed for all the multipliers of the input parameters.

Table 3-3. Testing the Uncertainty Parameters (Test 31701 and 31504).

Parameter	Distribution	Multiplier (Min.)	Multiplier (Max.)
Interfacial junction coefficient	Uniform	0.7	3.5
Dry wall dispersed flow heat transfer coefficient of:			
Liquid	Uniform	0.5	1.2
Vapor	Uniform	0.5	1.2
Noncondensable	Uniform	0.5	1.2
Wet wall dispersed flow heat transfer coefficient of:			
Liquid	Uniform	0.5	1.2
Vapor	Uniform	0.5	1.2
Noncondensable	Uniform	0.5	1.2
Global interfacial heat transfer coefficient	Uniform	0.5	1.2
Transition boiling heat transfer of:			
Liquid	Uniform	0.7	1.3
Vapor	Uniform	0.7	1.3
Film boiling heat transfer of:			
Liquid	Uniform	0.7	1.3
Vapor	Uniform	0.7	1.3

3.2.4 Uncertainties in Reflood Phenomena

The calculation result of cladding and steam temperature with uncertainty band, uncertainty mean value, non-BEPU simulation, and experimental data are shown in Appendix C (Test 31504) and Appendix D (Test 31701). Following data presented to compare experiment, non-BEPU calculation and uncertainty band. Numbers in brackets are node numbers in RELAP5-3D nodalization of Figure 3-2.

- Core clad temperate at elevations of 0.62*m*(#4), 0.99*m*(#6), 1.23*m*(#7), 1.78*m*(#10), 2.46*m*(#14), 2.85m(#16), 3.08(#17), 3.38m(#19)
- Steam temperature at elevation of 1.23m(#7), 1.85m(#11), 2.46m(#14), 2.85m (#16), 3.08(#17), 3.54m(#20)
- Void fraction at elevation of 0.99m(#06), 1.54(#08), 1.78m (10#), 2.15m(#12), 2.46m(#13)
- Total bundle (steam) mass in the entire system.

4. CONCLUSIONS AND REMARKS

During FY-2020 and FY-2021, the LWRS RISA Pathway developed and demonstrated UQ capability by using RELAP5-3D and RAVEN codes with the basis of BEPU concept. The epistemic uncertainties, which are unavoidable but quantifiable, were the main interest of the project. These types of uncertainties are mainly generated from assumptions and approximation of physical models and numerical approaches during computer-based simulations. Since the RISA Pathway aims to improve safety margin to restore the economics of U.S.

nuclear power plants (NPPs), a correct understanding of system reliability and safety margin uncertainties are essential to the pathway goal.

Development of uncertainty analysis method was mostly devoted to the improvement of the RELAP5-3D source code to receive PDFs from coupled RAVEN code. The reflood phase during a LOCA scenario was selected for the uncertainty demonstration. By using Phenomena Identification Ranking Table, interfacial heat transfer, wall heat transfer, and interfacial friction models were identified as the main phenomena occurring in the reflood phase, and relevant subroutines and modules were modified to apply perturbation. The RELAP5-3D input and formatting subroutines and modules were also modified to allow RAVEN to control input parameters from the user select sampling method.

Two sets of FLECHET-SEASET experiment (31701 and 31504) data were used to define the minimum and maximum multiplier values for uncertainty propagation. Uncertainty bands are proposed for clad temperature, steam temperature, void fraction, and total mass. The uncertainty bands mostly covere both experiments and non-BEPU simulations, which explains the reason of the discrepancy between experiment and simulation data.

The BEPU method will be applied to various RISA Pathway projects:

- Enhanced resilience nuclear power plant to identify uncertainties in an accident scenario analysis while applying flexible operation strategy
- Analysis of uncertainties in DBAs in plant reloading optimization method development
- Uncertainty analysis of severe accidents at NPPs with digital instrumentation and controlling systems
- Uncertainty analysis in accident scenarios analyzed human cognitive model simulation tool development
- UQ in DBA analyses for accident tolerant fuel.

The BEPU method can also be combined with the multi-physics approach to consider feedback effects from different physical phenomena and simulation tools considered risk-informed approach. As shown in Figure 4-1, uncertainties in the multi-physics approach in neutronics, fuel performance, and thermal-hydraulic simulations can be quantified from an integral test facility or actual data from a NPP or another domain. The BEPU simulation will then extend to a risk-informed approach for comprehensive safety analyses. Other physics such as material science, natural hazard, and HRA can be included.

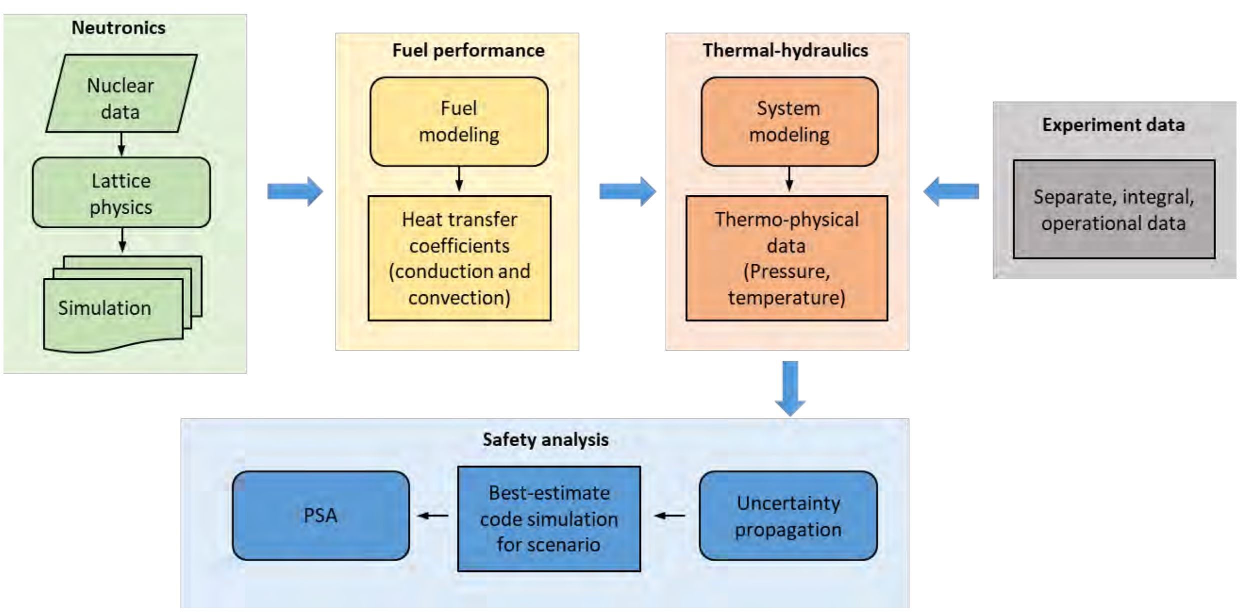

Figure 4-1. Schematic diagram of risk-informed multi-physics BEPU approach.

Another perspective of BEPU method will be applied to advanced nuclear system development. These reactors aim for enhanced safety and system reliability throughout the lifetime in all circumstances while minimizing the risk to the system and to the environment, but with maximum economic benefits to the owners/operators. However, these reactors use many kinds of passive features of autonomous and maintenance-free operation and the reliability and risk assessment of such passive systems became a major issue for licensing. For instance, it was reported that there are large uncertainties in natural circulation heat transfer systems especially with a liquid metal or heat pipe cooled passive system, and new regulatory guidelines are proposed based on system characteristics [15]. A new safety analysis approach is necessary considering both deterministic and probabilistic methodologies along with uncertainty analysis for verification of reliable plant operation.

5. REFERENCES

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APPEDIX A. RAVEN INPUT DECKS

Uncertainty Propagation

```
<?xml version="1.0" ?>
<Simulation>
  <RunInfo>
    <WorkingDir>FLECHT_LHS_4</WorkingDir>
    <RemoteRunCommand>raven_qsub_command.sh</RemoteRunCommand>
    <Sequence>Ptest_DummyStep</Sequence>
    <batchSize>153</batchSize>
    <mode>
    mpi
    <runQSUB/>
    </mode>
    <NumMPI>1</NumMPI>
    <clusterParameters>-P lwrs</clusterParameters>
    <expectedTime>00:15:00</expectedTime>
  </RunInfo>

  <Files>
    <Input name="flecht31701_A3.i" type="">flecht31701_A3.i</Input>
    <Input name="tpfh2o"           type="">tpfh2o</Input>
  </Files>

<Models>
    <Code name="MyRELAP" subType="Relap5">
      <executable>~/projects/raven/relap_BEPU/relap5.x</executable>
    </Code>
 </Models>

<Distributions>
    <Uniform name="PSTDNB">
      <upperBound>1.3</upperBound>
      <lowerBound>0.7</lowerBound>
    </Uniform>
    <Uniform name="FRICT_GLOBAL">
      <upperBound>3.5</upperBound>
      <lowerBound>0.7</lowerBound>
    </Uniform>
    <Uniform name="DISP">
      <upperBound>1.2</upperBound>
      <lowerBound>0.5</lowerBound>
    </Uniform>
</Distributions>

  <Samplers>
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      </variable>
      <variable name="1|0060004:1,1|0060004:2,1|0060004:3">
          <distribution>DISP</distribution>
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      </variable>
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          <grid type='CDF' construction='equal' steps='153' >0.0 1.0</grid>
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061908:20,1|10061908:21,1|10061909:20,1|10061909:21,1|10061910:20,1|10061910:21,1|10061911:20,1|1006191
1:21,1|10061912:20,1|10061912:21,1|10061913:20,1|10061913:21,1|10061914:20,1|10061914:21,1|10061915:20,
1|10061915:21,1|10061916:20,1|10061916:21,1|10061917:20,1|10061917:21,1|10061918:20,1|10061918:21,1|100
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          <distribution>PSTDNB</distribution>
          <grid type='CDF' construction='equal' steps='153' >0.0 1.0</grid>
      </variable>
    </Stratified>
```

```
  </Samplers>

  <Steps>
    <MultiRun name="Ptest_DummyStep" verbosity="debug"  re-seeding="1">
      <Input class="Files" type="">flecht31701_A3.i</Input>
      <Input class="Files" type="">tpfh2o</Input>
      <Model class="Models" type="Code">MyRELAP</Model>
      <Sampler class="Samplers" type="Stratified">LHS</Sampler>
      <Output  class="Databases" type="HDF5">DataB_REL5_1</Output>
    </MultiRun>
  </Steps>

  <Databases>
    <HDF5 name="DataB_REL5_1" readMode="overwrite"/>
  </Databases>

</Simulation>
```

Post-processing

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<?xml version="1.0" ?>
<Simulation verbosity="all">
  <RunInfo>
    <WorkingDir>.</WorkingDir>
    <Sequence>LOAD, SYNCRONIZE, STATICS</Sequence>
    <batchSize>1</batchSize>
  </RunInfo>

  <Models>
    <PostProcessor name="syncronizeHistorySet" subType="InterfacedPostProcessor">
      <method>HistorySetSync</method>
      <pivotParameter>time</pivotParameter>
      <extension>zeroed</extension>
      <syncMethod>grid</syncMethod>
      <numberOfSamples>10000</numberOfSamples>
    </PostProcessor>
    <PostProcessor name="alpha" subType="BasicStatistics">
      <expectedValue prefix="mean">httemp_61014_7</expectedValue>
      <percentile prefix="percentile">httemp_61014_7</percentile>
      <sigma prefix="sigma">httemp_61014_7</sigma>
      <maximum prefix="max">httemp_61014_7</maximum>
      <minimum prefix="min">httemp_61014_7</minimum>
      <pivotParameter>time</pivotParameter>
    </PostProcessor>

  </Models>

  <Files>
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  </Files>

  <Steps>
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      <Input class="Databases" type="HDF5">DataB_REL5_1</Input>
      <Output class="DataObjects" type="HistorySet">DATA_OUT</Output>
    </IOStep>
    <PostProcess name="SYNCRONIZE">
      <Input class="DataObjects" type="HistorySet">DATA_OUT</Input>
      <Model class="Models" type="PostProcessor">syncronizeHistorySet</Model>
      <Output class="DataObjects" type="HistorySet">HistorySetPostProcTestSyncronized</Output>
    </PostProcess>
    <PostProcess name="STATICS">
      <Input class="DataObjects" type="HistorySet">HistorySetPostProcTestSyncronized</Input>
      <Model class="Models" type="PostProcessor">alpha</Model>
      <Output class="DataObjects" type="HistorySet">alpha_basicStatPP</Output>
      <Output class="OutStreams" type="Print">alpha_basicStatPP_dump</Output>
    </PostProcess>
  </Steps>

  <Databases>
    <HDF5 name="DataB_REL5_1" readMode="read"/>
  </Databases>

  <DataObjects>
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0061905:20,1|10061905:21,1|10061906:20,1|10061906:21,1|10061907:20,1|10061907:21,1|10061908:20,1|100619
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      <Output>time, httemp_61014_7</Output>
    </HistorySet>
    <HistorySet name="HistorySetPostProcTestSyncronized">

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```

```
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          <Output>time, httemp_61014_7</Output>
        </PointSet>
        <HistorySet name="alpha_basicStatPP">
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            <pivotParameter>time</pivotParameter>
          </options>
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        </HistorySet>
      </DataObjects>

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          <type>csv</type>
        </Print>
        <Print name="chart2">
          <source>WILKSMAX</source>
          <type>csv</type>
        </Print>
        <Print name="alpha_basicStatPP_dump">
          <type>csv</type>
          <source>alpha_basicStatPP</source>
        </Print>
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                     max_httemp_61014_7,
                     min_httemp_61014_7</Group>
      </VariableGroups>

    </Simulation>
```

APPENDIX B. RELAP5-3D INPUT DECK (CASE 31504)

```
=flecht-seaset developmental assessment case - test 31701
*deck flecht31701.i
*
* RELAP5-3D Developmental Assessment modifications by Paul Bayless, November 2008
*
*
* Modified by C. Parisi for DOE-LWRS/RISA/MP-BEPU Project, new Cards introduced in the input deck for Uncertainty propagation for
interfacial heat transfer, interfacial friction coefficient, transition and film boiling. August 2020.
*
* This deck was modified from that used in previous assessments (fs31701.i).
* The bundle hydraulic diameter was changed to 0.03191. This value was taken from Ken Carlson's MOD3.2 assessment deck for test 35557,
which has the same rod bundle. The junction hydraulic diameter is specified to be the same value. The heat structure heated diameter is
unchanged. The bundle volume flag was set to 1.
* Added reflood quantities to plot file and collapsed liquid level control variable.
* Semi-implicit solution scheme used.
*
0000100 new transnt
0000101 run
0000102 british  british
0000105      5.     6.
0000119 -1.0  fixed 1.0
0000201  80.0  1.0e-07   0.020        3     25    100    1000
0000202 120.0  1.0e-07   0.025        3     20    400    1600
0000203 160.0  1.0e-07   0.050        3     10    400    1600
0000301 httemp      6100407
0000302 httemp      6100607
0000303 httemp      6100707
0000304 httemp      6101007
0000305 httemp      6101407
0000306 httemp      6101607
0000307 httemp      6101707
0000308 voidg       006020000
0000309 voidg       006060000
0000310 voidg       006110000
0000311 voidg       006160000
0000312 voidg       006190000
20800001 zqbot      0061
20800002 zqtop      0061
*
***************************************************************
*                                                             *
*                    volume data cards                        *
*                                                             *
***************************************************************
*
*
* lower plenum (vol no. 1)
*
0050000   "low-pl"  tmdpvol
0050101   0.7422     1.57       0.0     0.0    90.0    1.57     0. 0. 0
0050200   3
0050201    200.00   40.0000  127.0
*
* junction no. 2  (lower plenum to core)
*
3010000   "jun  2"  tmdpjun
3010101   005000000  006000000  0.0
3010200   0
3010201 .500    .219  .219   0.000       5.000    .528    .528 0.
3010202 10.000  .522  .522   0.000      15.000    .520    .520 0.
3010203 20.000  .518  .518   0.000      25.000    .516    .516 0.
3010204 30.000  .515  .515   0.000      35.000    .515    .515 0.
3010205 40.000  .514  .514   0.000      45.000    .513    .513 0.
3010206 50.000  .514  .514   0.000      55.000    .514    .514 0.
3010207 60.000  .513  .513   0.000      65.000    .512    .512 0.
3010208 70.000  .512  .512   0.000      75.000    .512    .512 0.
3010209 80.000  .512  .512   0.000      85.000    .513    .513 0.
3010210 90.000  .512  .512   0.000      95.000    .514    .514 0.
3010211 100.000 .511  .511   0.000     105.000    .512    .512 0.
3010212 110.000 .511  .511   0.000     115.000    .511    .511 0.
3010213 120.000 .510  .510   0.000     125.000    .512    .512 0.
3010214 130.000 .511  .511   0.000     135.000    .512    .512 0.
3010215 140.000 .512  .512   0.000     145.000    .511    .511 0.
3010216 150.000 .512  .512   0.000     155.000    .513    .513 0.
3010217 160.000 .512  .512   0.000     165.500    .512    .512 0.
3010218 170.500 .511  .511   0.000     175.500    .511    .511 0.
3010219 180.500 .511  .511   0.000     185.500    .512    .512 0.
3010220 190.500 .512  .512   0.000     195.500   -.001   -.001 0.
3010221 201.000 -.001  -.001   0.000
*
* core (vol no. 2)
*
0060000   "core" pipe
0060001   20
0060004   1.0 1.0 1.0
+ 1.0 1.0 1.0
0060101   0.1666     20
0060301   0.6000     20
0060401   0.09996    20
0060601   90.0       20
*0060801   0.0        0.0386     20
0060801   0.0        0.03191    20
*0061001   00         20
```

```
0061001   100        20
0061101   0000       19
0061201   3          40.0112    478.00   0.0    0.0  0  1
0061202   3          40.0108    582.00   0.0    0.0  0  2
0061203   3          40.0104    686.15   0.0    0.0  0  3
0061204   3          40.0100    820.45   0.0    0.0  0  4
0061205   3          40.0096    1035.28  0.0    0.0  0  5
0061206   3          40.0092    1236.62  0.0    0.0  0  6
0061207   3          40.0088    1289.62  0.0    0.0  0  7
0061208   3          40.0084    1371.75  0.0    0.0  0  8
0061209   3          40.0080    1459.71  0.0    0.0  0  9
0061210   3          40.0076    1547.65  0.0    0.0  0  10
0061211   3          40.0072    1559.22  0.0    0.0  0  11
0061212   3          40.0068    1519.12  0.0    0.0  0  12
0061213   3          40.0064    1484.80  0.0    0.0  0  13
0061214   3          40.0060    1336.75  0.0    0.0  0  14
0061215   3          40.0056    1198.46  0.0    0.0  0  15
0061216   3          40.0052    1056.09  0.0    0.0  0  16
0061217   3          40.0048    868.73   0.0    0.0  0  17
0061218   3          40.0044    747.65   0.0    0.0  0  18
0061219   3          40.0040    653.78   0.0    0.0  0  19
0061220   3          40.0036    559.91   0.0    0.0  0  20
0061300   0
0061301   0.0        0.0        0.0     19
0061401   0.03191  1.  1.  1.  19
*
* upper plenum
*
0070000 "up-plen" tmdpvol
0070101   1.   1.   0.   0.   90.   1.   0.   0.   0
0070200   3
0070201     200.0   40.0     400.0
*
3020000  coretoup  sngljun
3020101   006010000  007000000  0.0     0.0    0.0     0100
3020110   0.         0.         1.      1.     1.3
3020201   1          0.0        0.0     0.0
*
***************************************************************
*                                                             *
*              heat slab structure                            *
*                                                             *
***************************************************************
*
*  core heater rods
*
10061000    20   7   2   0   0.   1    1   16
*
10061100    0           2
10061101    0.00396     1
10061102    0.00333     2
10061103    0.003105    4
10061104    0.00104     6
10061201    2           1
*
10061202    1           2
10061203    2           4
10061204    3           6
*
10061301    0.0         1
10061302    1.0         2
10061303    0.0         6
*
10061400    -1
10061401  478.00  478.00  478.00  478.00  478.00  478.00  478.00
10061402  582.00  582.00  582.00  582.00  582.00  582.00  582.00
10061403  686.15  686.15  686.15  686.15  686.15  686.15  686.15
10061404  820.45  820.45  820.45  820.45  820.45  820.45  820.45
10061405 1035.28 1035.28 1035.28 1035.28 1035.28 1035.28  1035.28
10061406 1236.62 1236.62 1236.62 1236.62 1236.62 1236.62  1236.62
10061407 1289.62 1289.62 1289.62 1289.62 1289.62 1289.62  1289.62
10061408 1371.75 1371.75 1371.75 1371.75 1371.75 1371.75  1371.75
10061409 1459.71 1459.71 1459.71 1459.71 1459.71 1459.71  1459.71
10061410 1547.65 1547.65 1547.65 1547.65 1547.65 1547.65  1547.65
10061411 1559.22 1559.22 1559.22 1559.22 1559.22 1559.22  1559.22
10061412 1519.12 1519.12 1519.12 1519.12 1519.12 1519.12  1519.12
10061413 1484.80 1484.80 1484.80 1484.80 1484.80 1484.80  1484.80
10061414 1336.75 1336.75 1336.75 1336.75 1336.75 1336.75  1336.75
10061415 1198.46 1198.46 1198.46 1198.46 1198.46 1198.46  1198.46
10061416 1056.09 1056.09 1056.09 1056.09 1056.09  1056.09  1056.0
10061417 868.73  868.73  868.73  868.73  868.73  868.73  868.73
10061418 747.65  747.65  747.65  747.65  747.65  747.65  747.65
10061419 653.78  653.78  653.78  653.78  653.78  653.78  653.78
10061420 559.91  559.91  559.91  559.91  559.91  559.91  559.91
*
10061501    0           0         0   0     0.0      20
*
10061601    006010000   10000     1   0     9.4584   20
*
10061701    100         0.0215    0   0    1
10061702    100         0.0215    0   0    2
10061703    100         0.0215    0   0    3
10061704    100         0.0340    0   0    4
10061705    100         0.0440    0   0    5
10061706    100         0.0555    0   0    6
10061707    100         0.0650    0   0    7
10061708    100         0.0745    0   0    8
```

```
10061709    100         0.0800    0   0    9
10061710    100         0.0830    0   0    10
10061711    100         0.0830    0   0    11
10061712    100         0.0800    0   0    12
10061713    100         0.0745    0   0    13
10061714    100         0.0650    0   0    14
10061715    100         0.0555    0   0    15
10061716    100         0.0440    0   0    16
10061717    100         0.0340    0   0    17
10061718    100         0.0215    0   0    18
10061719    100         0.0215    0   0    19
10061720    100         0.0215    0   0    20
*
*left
10061801   .1      .3   .3    0.     0.     0.      0.     1.  20
*      only the hydraulic diameter matters since chfcal is not
*           called when reflood is on.
*right
10061900   6
*                            elev  elev    k       k
*flags   htdiam elev el-rev grid-f grid-r gridk-f gridk-r apf  num
10061901  .03844  .3  11.7   .3     1.4      .1     .1     .43
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      1
10061902  .03844  .9  11.1   .9      .8      .1     .1     .43
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+ 1.0    1.0     2
10061903  .03844 1.5  10.5  1.5      .2      .1     .1     .43
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      3
10061904  .03844 2.1   9.9   .4     1.3      .1     .1     .68
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      4
10061905  .03844 2.7   9.3  1.0      .7      .1     .1     .88
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      5
10061906  .03844 3.3   8.7  1.6      .1      .1     .1    1.11
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      6
10061907  .03844 3.9   8.1   .5     1.2      .1     .1    1.30
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      7
10061908  .03844 4.5   7.5  1.1      .6      .1     .1    1.49
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      8
10061909  .03844 5.1   6.9  1.7     .04      .1     .1    1.60
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      9
10061910  .03844 5.7   6.3   .6     1.1      .1     .1    1.66
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+   1.0    1.0     10
10061911  .03844 6.3   5.7  1.2      .5      .1     .1    1.66
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      11
10061912  .03844 6.9   5.1   .1     1.6      .1     .1    1.60
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      12
10061913  .03844 7.5   4.5   .7     1.0      .1     .1    1.49
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      13
10061914  .03844 8.1   3.9  1.3      .4      .1     .1    1.30
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+   1.0    1.0     14
10061915  .03844 8.7   3.3   .2     1.6      .1     .1    1.11
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      15
10061916  .03844 9.3   2.7   .8     1.0      .1     .1     .88
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+   1.0    1.0     16
10061917  .03844 9.9   2.1  1.4      .4      .1     .1     .68
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+   1.0    1.0     17
10061918  .03844 10.5  1.5   .2     1.5      .1     .1     .43
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+   1.0    1.0     18
10061919  .03844 11.1   .9   .8      .9      .1     .1     .43
+          .0      1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0      1.0  1.0   1.0   1.0
+  1.0    1.0      19
```

```
10061920  .03844 11.7   .3  1.4      .3      .1     .1     .43
+         .0     1.1  1.0   1.0   1.0     1.0    1.0     1.0
+         1.0    1.0  1.0   1.0   1.0
+       1.0    1.0     20
*
*
*****************************************************
*     heat structure thermal property data          *
*****************************************************
*
*
20100100   tbl/fctn    1       1    * kanthac
20100200   tbl/fctn    1       1    * boron nitride
20100300   tbl/fctn    1       1    * stainless steel
*
*
*      thermal conductivity tables
*
* kanthac
*
20100101  0.0         .002694
20100102  1000.0      .003889
20100103  2000.0      .005083
20100104  4000.0      .007472
*
* boron nitride
*
20100201  100.0       .00408
20100202  400.0       .00406
20100203  600.0       .00396
20100204  800.0       .00390
20100205  1000.0      .00386
20100206  1200.0      .00381
20100207  1400.0      .00376
20100208  1600.0      .00371
20100209  1800.0      .00366
20100210  2000.0      .00361
20100220  4000.0      .00312
*
* stainless steel
*
*20100301  0.0         .002
20100302  70.0        .002415
20100303  400.0       .0028
20100304  600.0       .00303
20100305  800.0       .00327
20100306  1000.0      .0035
20100307  1200.0      .00373
20100308  1400.0      .00397
20100309  1600.0      .0042
20100310  1800.0      .00443
20100311  2000.0      .0046667
20100312  4000.0      .007
*
*
*     volumetric heat capacity
*
* kanthac
*
20100151  0.0         48.61
20100152  1200.       80.28
20100153  1400.0      124.88
20100154  1600.0      79.39
20100155  2200.0      82.51
*
* boron nitride
*
20100251   70.0       22.31
20100252  200.0       28.44
20100253  400.0       36.00
20100254  600.0       41.75
20100255  800.0       46.14
20100256  1000.0      49.47
20100257  1200.0      52.02
20100258  1400.0      53.95
20100259  1600.0      55.43
20100260  1800.0      56.55
20100261  2000.0      57.41
20100262  2400.0      58.56
*
* stainless steel
*
20100351  70.0        54.45
20100352  200.0       56.94
20100353  400.0       60.78
20100354  600.0       64.62
20100355  800.0       66.84
20100356  1000.0      69.06
20100357  1400.0      73.49
20100358  1800.0      77.93
20100359  2200.0      82.37
20100360  2400.0      84.59

*
**********************************
*          power table           *
**********************************
```

```
*
20210000  power
20210001     .5000     .8044             5.0000     .7870
20210002   10.0000     .7657            15.0000     .7492
20210003   20.0000     .7348            25.0000     .7222
20210004   30.0000     .7108            35.0000     .7028
20210005   40.0000     .6924            45.0000     .6835
20210006   50.0000     .6750            55.0000     .6685
20210007   60.0000     .6618            65.0000     .6547
20210008   70.0000     .6472            75.0000     .6409
20210009   80.0000     .6347            85.0000     .6284
20210010   90.0000     .6219            95.0000     .6163
20210011  100.0000     .6114           105.0000     .6065
20210012  110.0000     .6018           115.0000     .5965
20210013  120.0000     .5909           125.0000     .5865
20210014  130.0000     .0322           135.0000     .0027
20210015  140.0000     .0018           145.0000     .0017
20210016  150.0000     .0017           155.0000     .0017
20210017  160.0000     .0017           165.5000     .0015
20210018  170.5000     .0015           175.5000     .0017
20210019  180.5000     .0017           185.5000     .0015
20210020  190.5000     .0015           195.5000     .0017
*
**********************************
* control variables
**********************************
* collapsed liquid level
20500600  corelev  sum  1.0  0.0  0
20500601  0.0  0.6 voidf 6010000  0.6 voidf 6020000
20500602       0.6 voidf 6030000  0.6 voidf 6040000
20500603       0.6 voidf 6050000  0.6 voidf 6060000
20500604       0.6 voidf 6070000  0.6 voidf 6080000
20500605       0.6 voidf 6090000  0.6 voidf 6100000
20500606       0.6 voidf 6110000  0.6 voidf 6120000
20500607       0.6 voidf 6130000  0.6 voidf 6140000
20500608       0.6 voidf 6150000  0.6 voidf 6160000
20500609       0.6 voidf 6170000  0.6 voidf 6180000
20500610       0.6 voidf 6190000  0.6 voidf 6200000
*
*  end of problem
*.
```

APPENDIX C.

UNCERTAINTY ANALYSIS OF FLECHT-SEASET TEST 31504

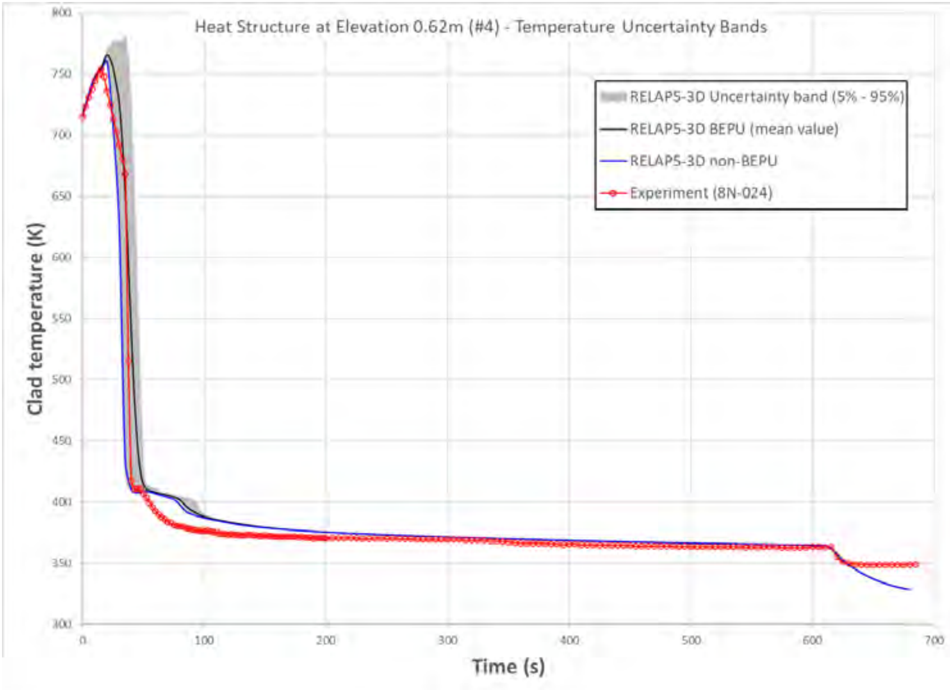

Figure C-1. FLECHT-SEASET clad temperature at elevation 0.62m (#4) (Test 31504).

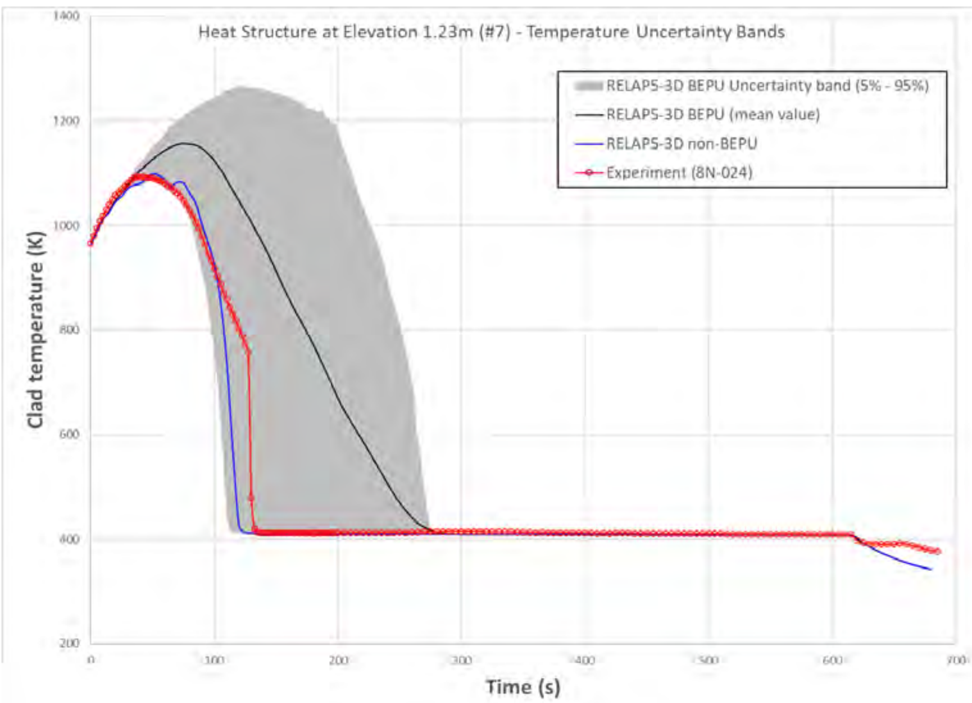

Figure C-2. FLECHT-SEASET clad temperature at elevation 1.23m (#07) (Test 31504).

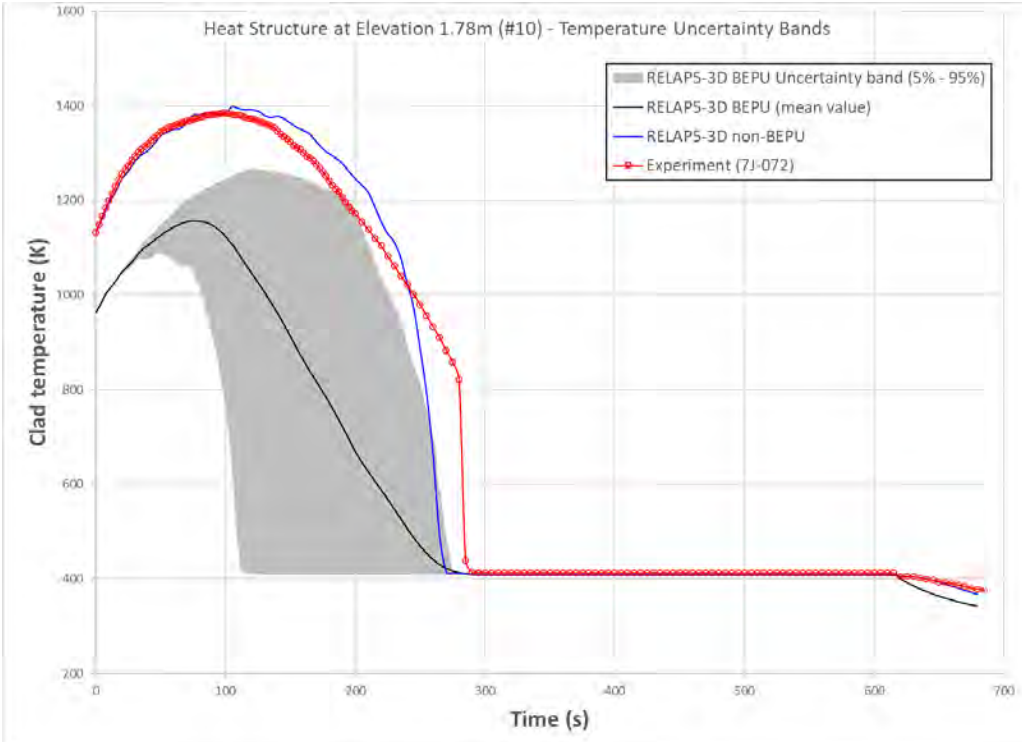

Figure C-3. FLECHT-SEASET clad temperature at elevation 1.78m (#10) (Test 31504).

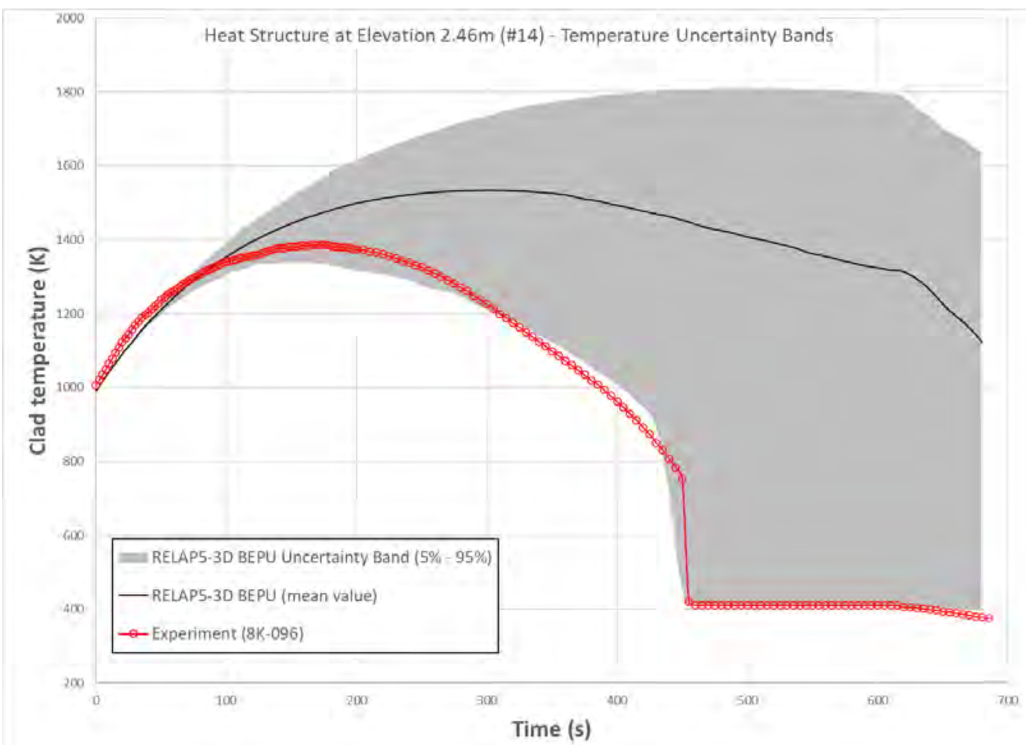

Figure C-4. FLECHT-SEASET clad temperature at elevation 2.46m (#14) (Test 31504).

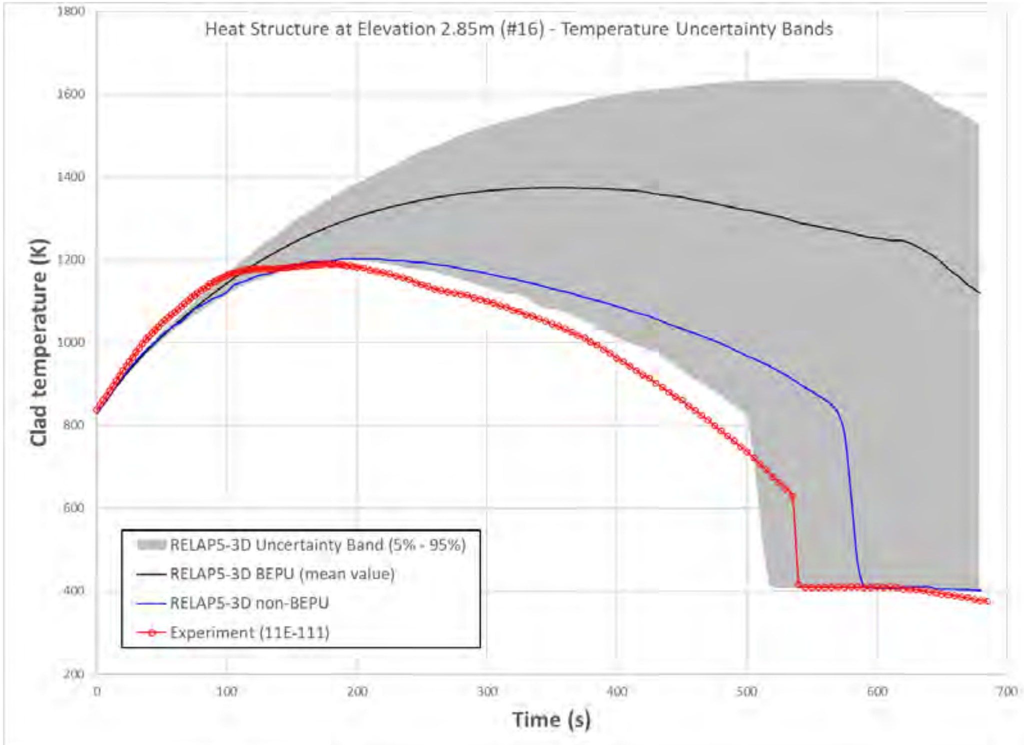

Figure C-5. FLECHT-SEASET clad temperature at elevation 2.85m (#16) (Test 31504).

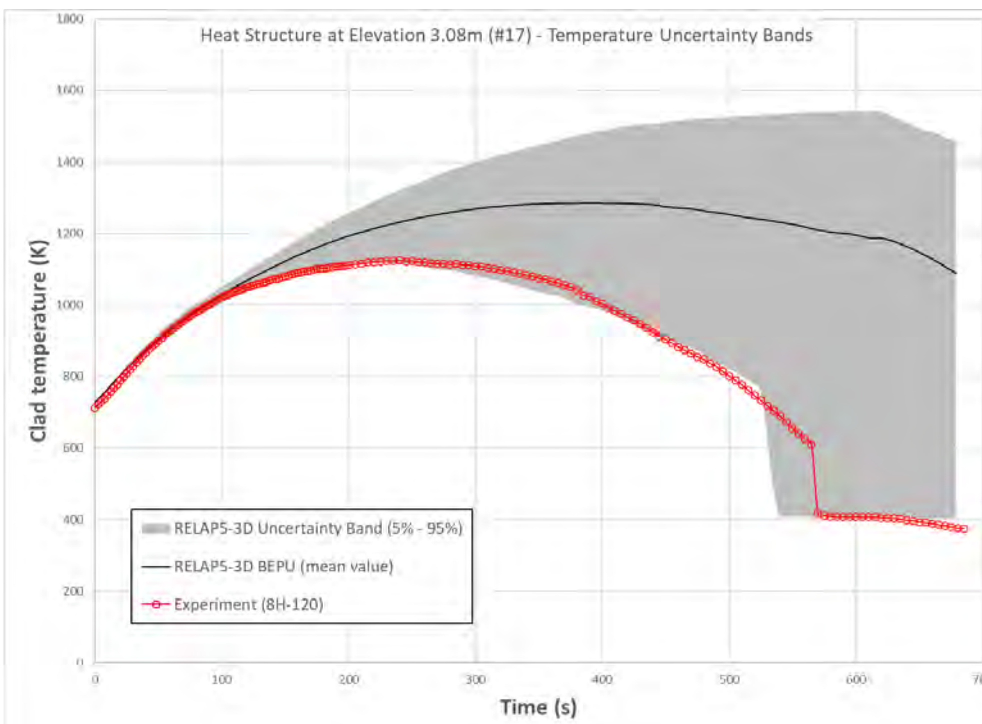

Figure C-6. FLECHT-SEASET clad temperature at elevation 3.08m (#17) (Test 31504).

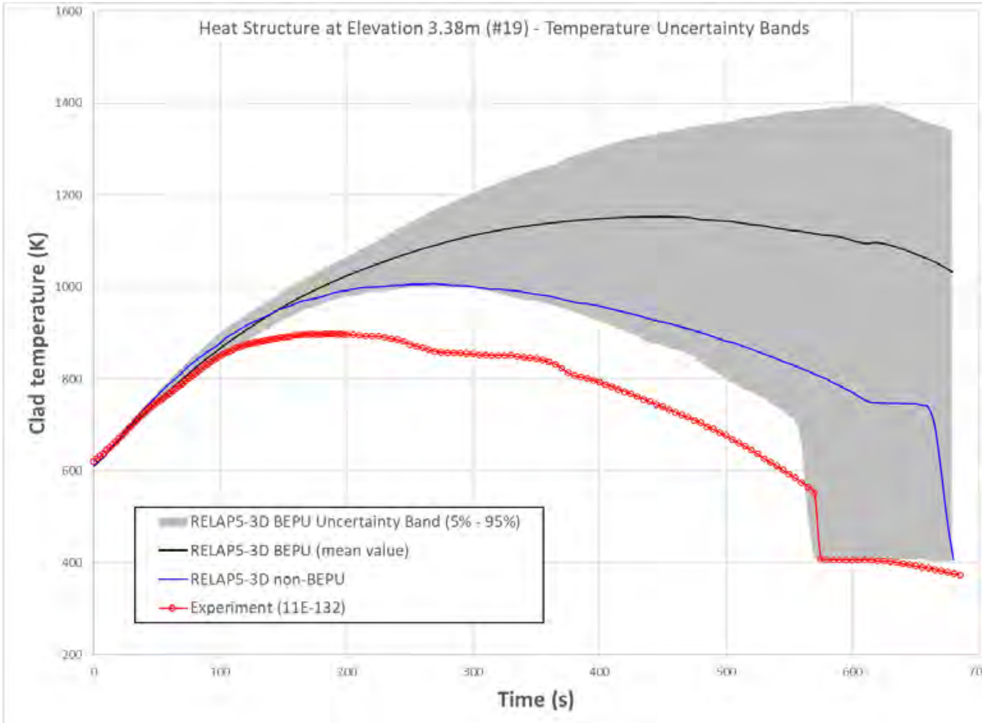

Figure C-7. FLECHT-SEASET clad temperature at elevation 3.38m (#19) (Test 31504).

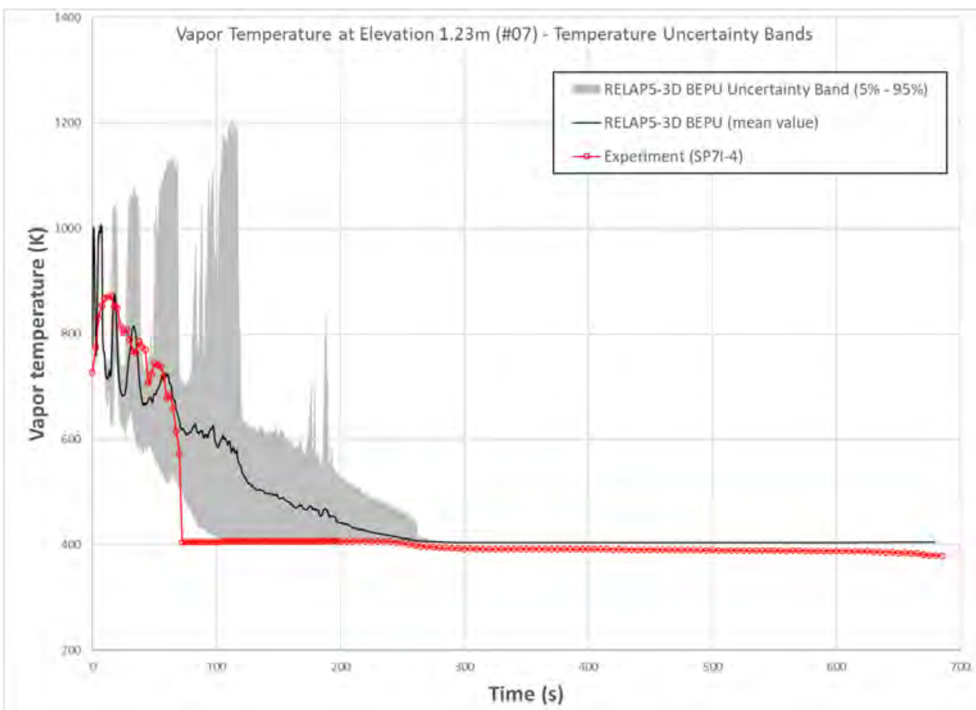

Figure C-8. FLECHT-SEASET vapor temperature at elevation 1.23m (#07) (Test 31504).

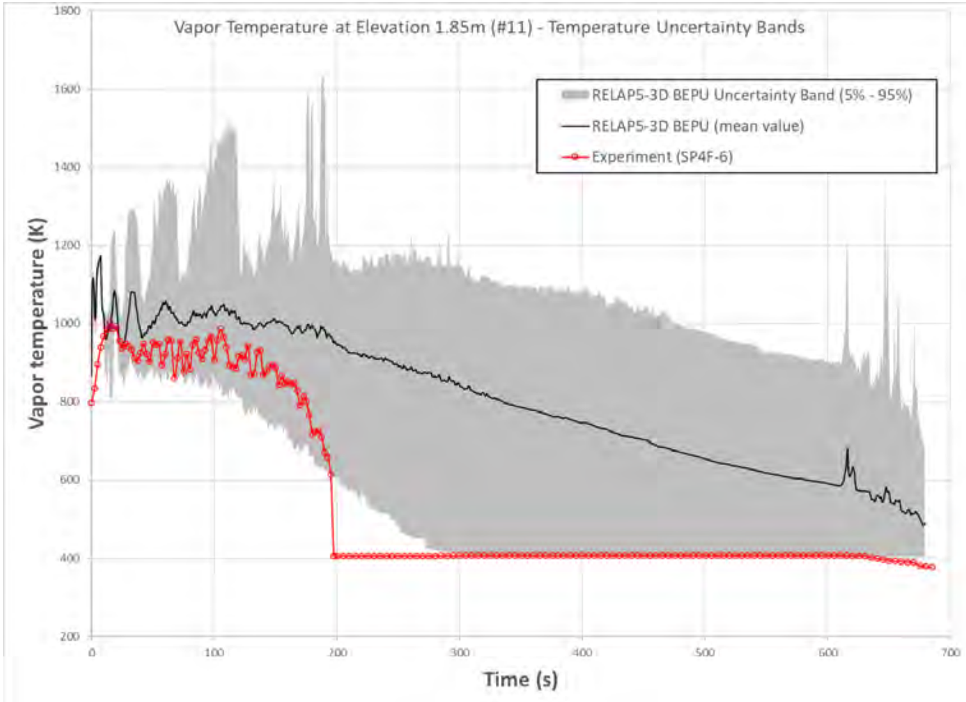

Figure C-9. FLECHT-SEASET vapor temperature at elevation 1.85m (#11) (Test 31504).

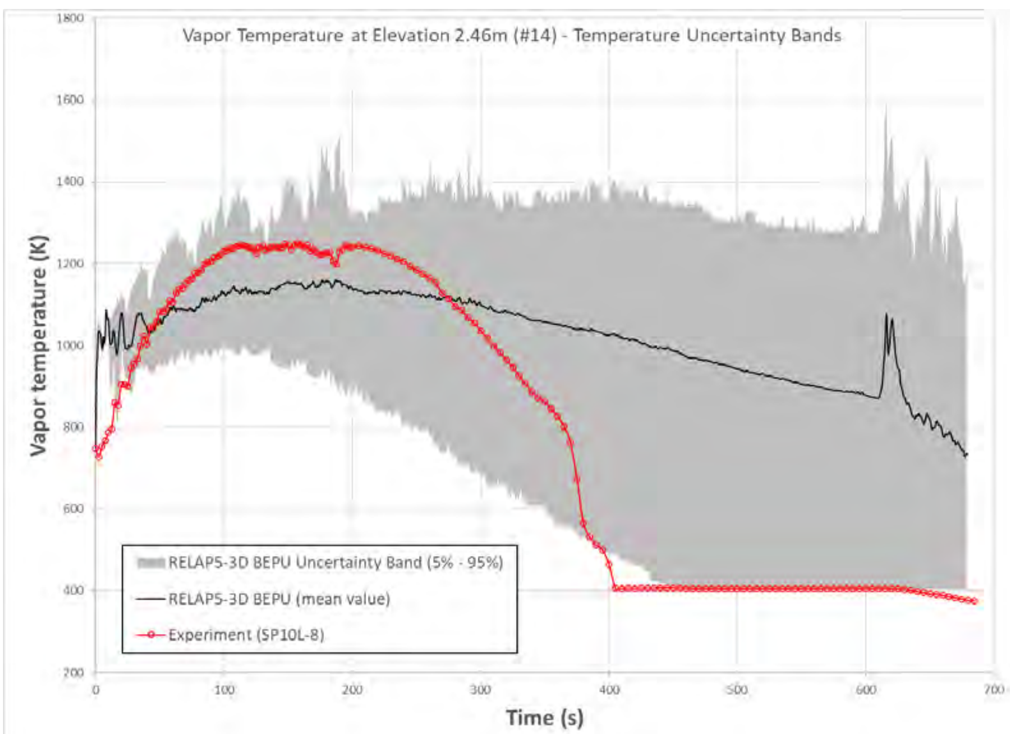

Figure C-10. FLECHT-SEASET vapor temperature at elevation 2.46m (#14) (Test 31504).

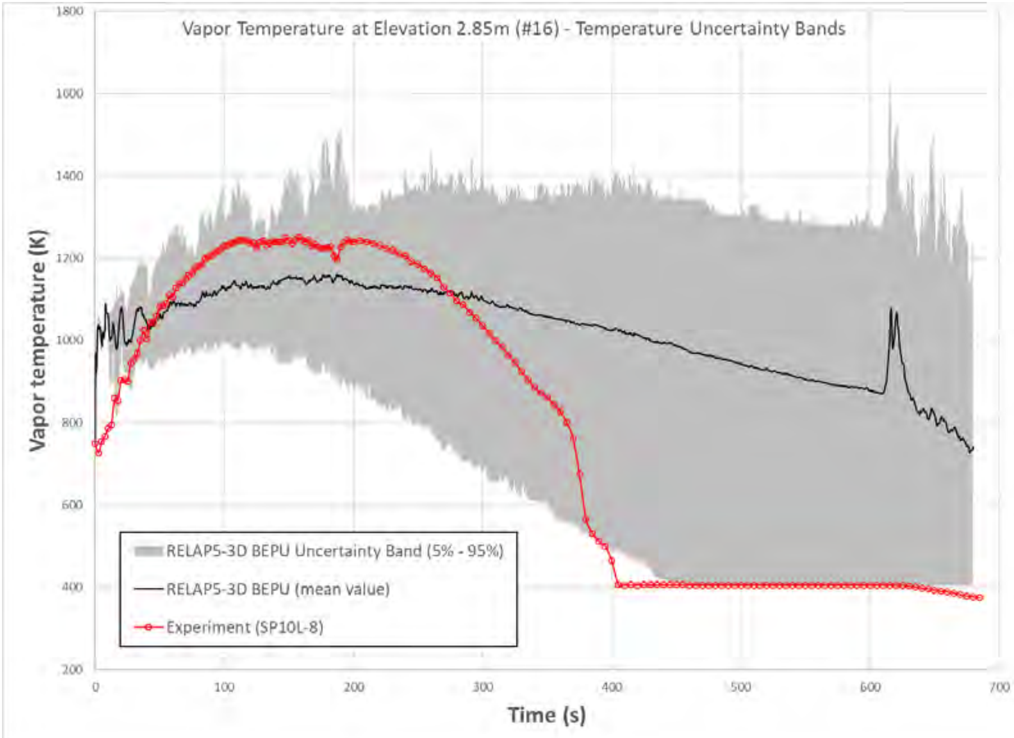

Figure C-11. FLECHT-SEASET vapor temperature at elevation 2.85m (#16) (Test 31504).

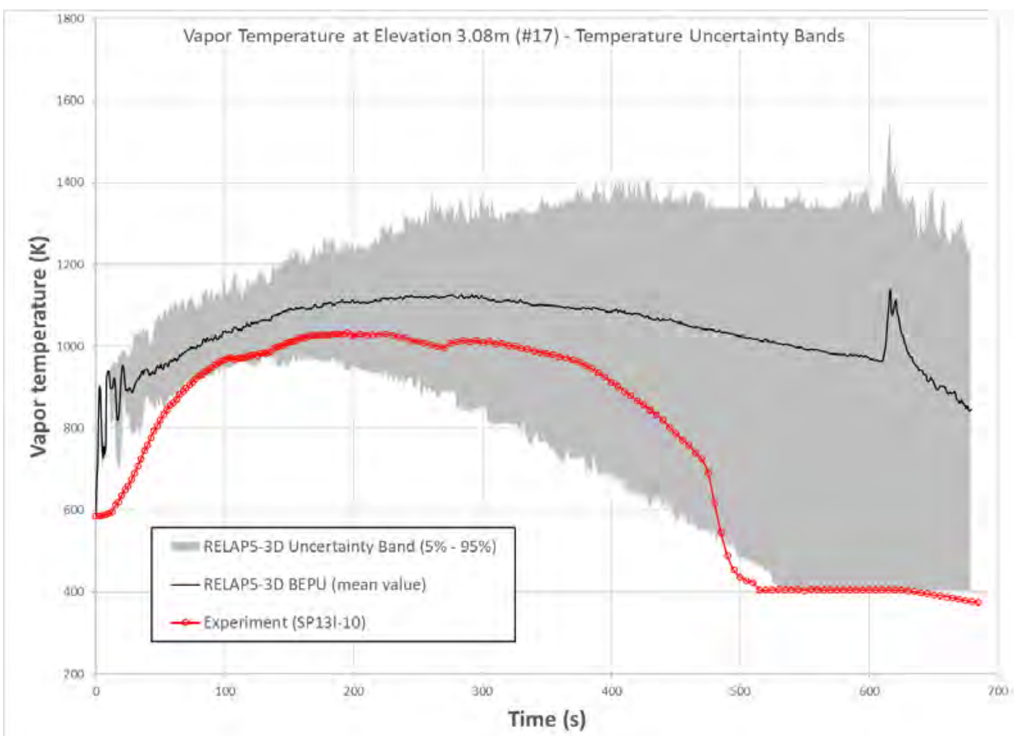

Figure C-12. FLECHT-SEASET vapor temperature at elevation 3.08m (#17) (Test 31504).

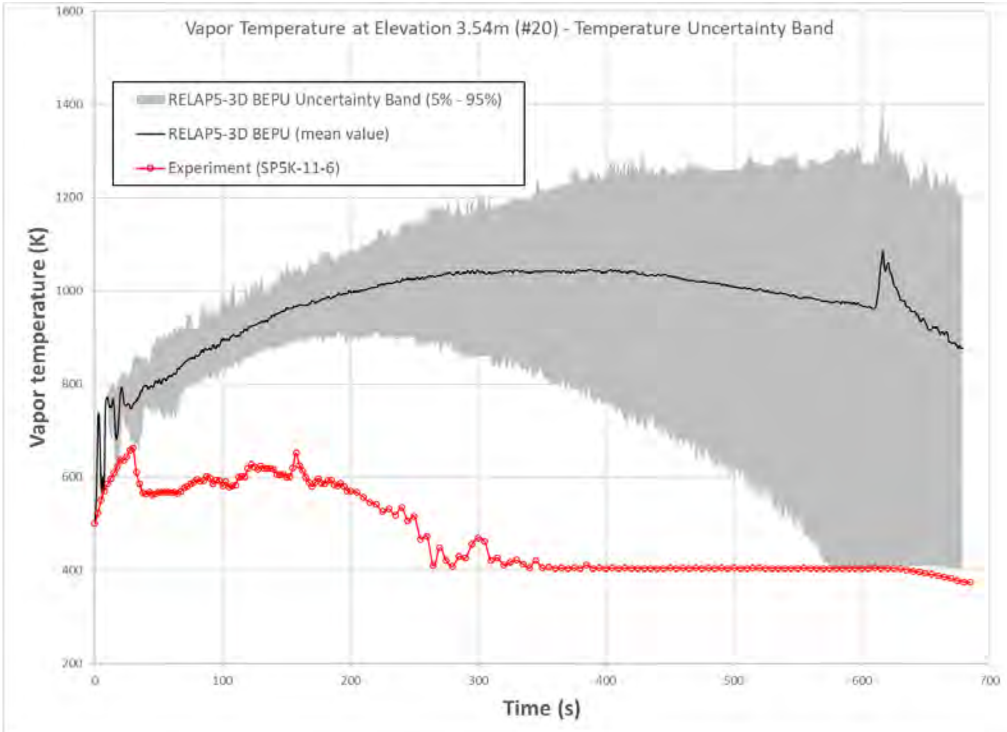

Figure C-13. FLECHT-SEASET vapor temperature at elevation 3.54m (#20) (Test 31504).

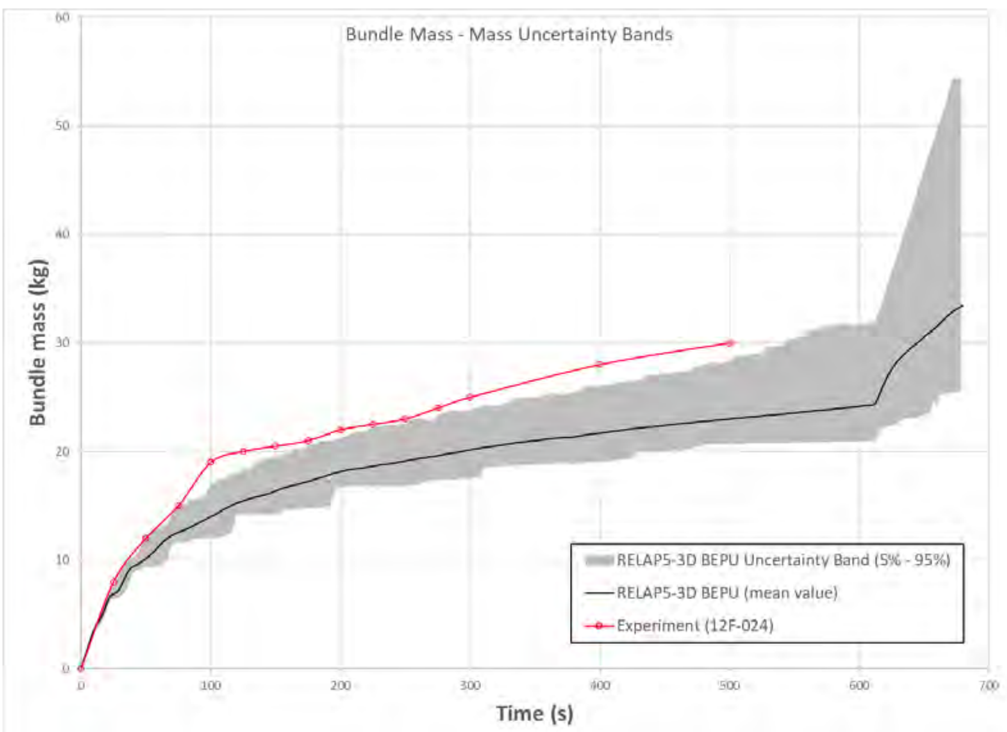

Figure C-14. FLECHT-SEASET bundle mass (Test 31504).

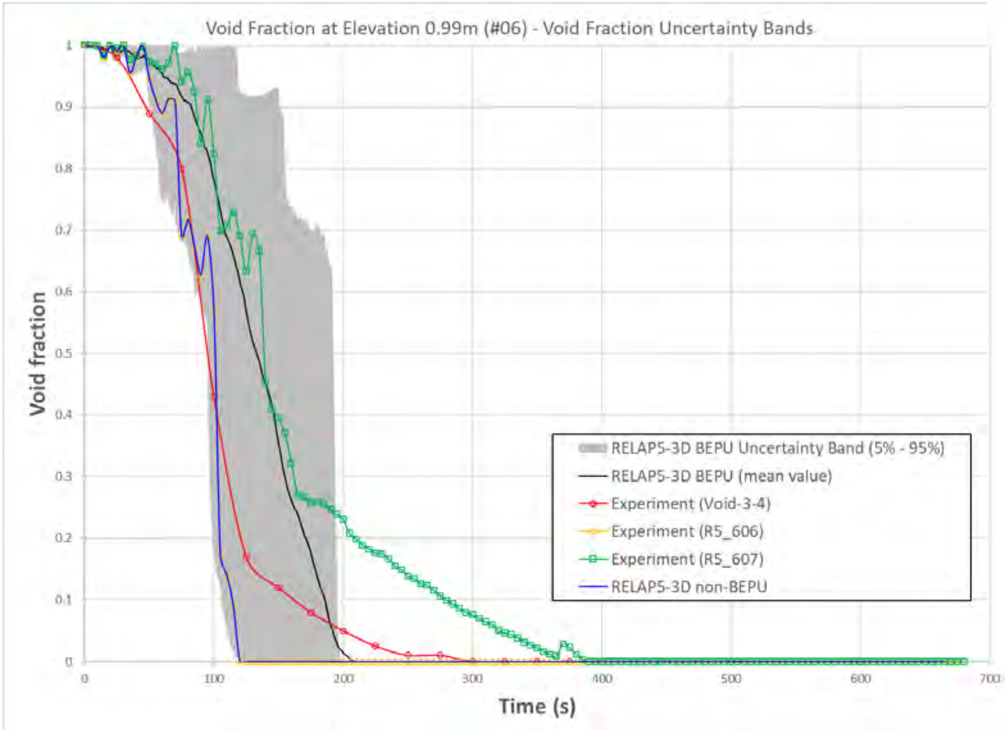

Figure C-15. FLECHT-SEASET void fraction at elevation 0.99m (#06) (Test 31504).

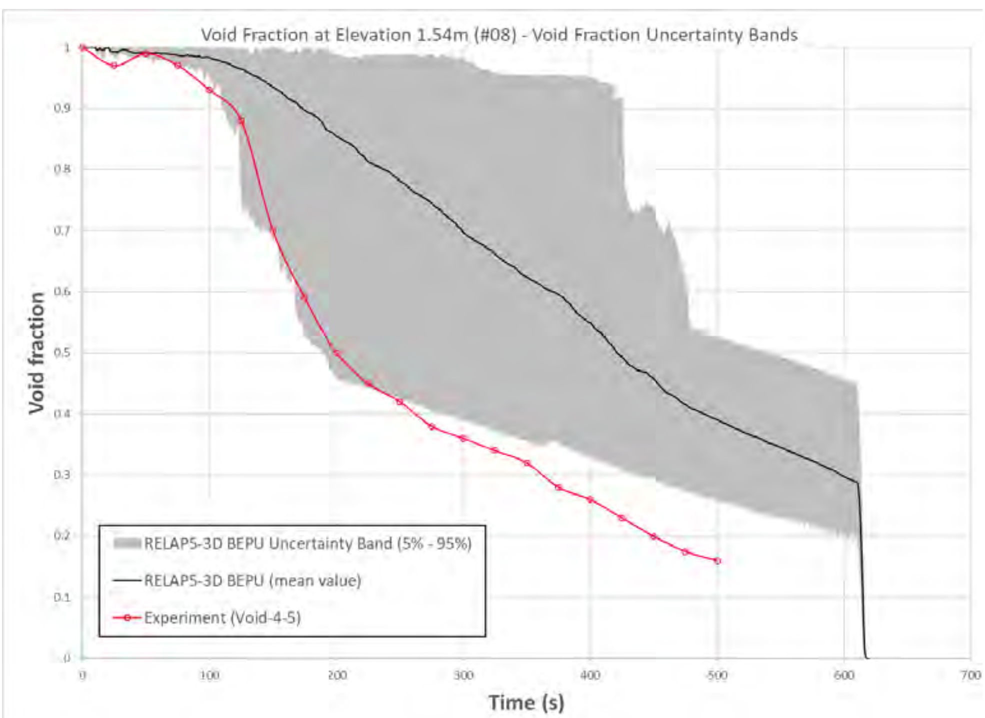

Figure C-16. FLECHT-SEASET void fraction at elevation 1.54m (#08) (Test 31504).

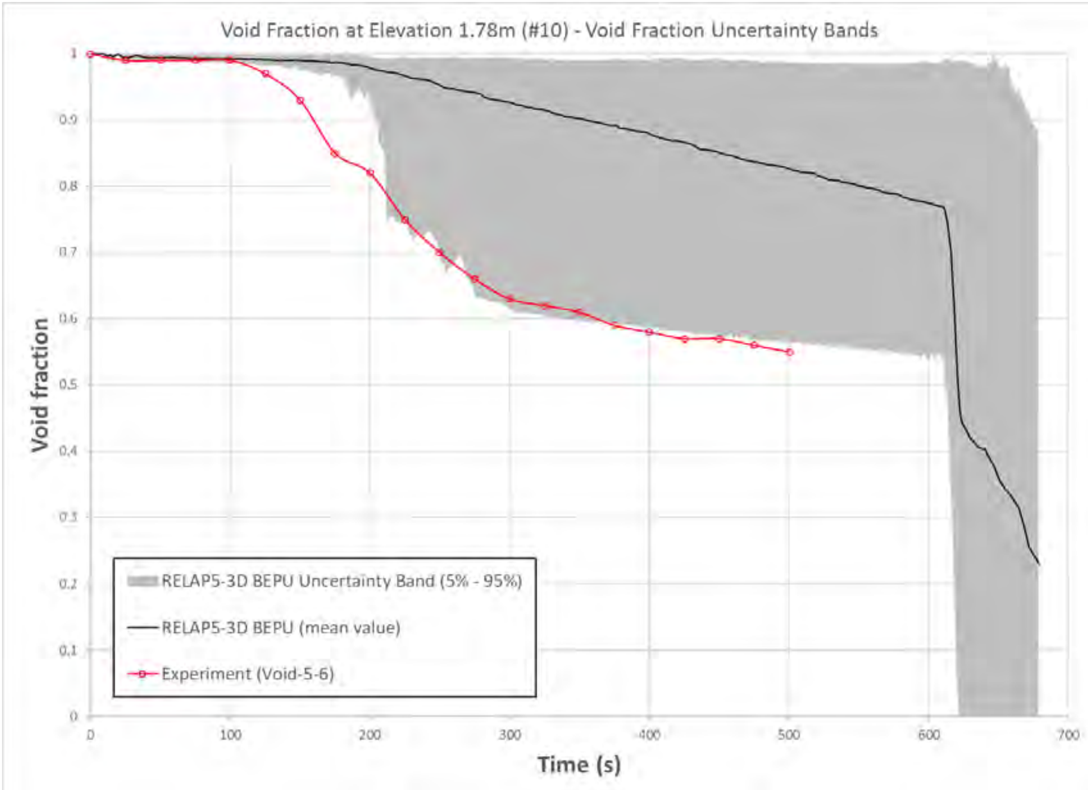

Figure C-17. FLECHT-SEASET void fraction at elevation 1.78m (#10) (Test 31504).

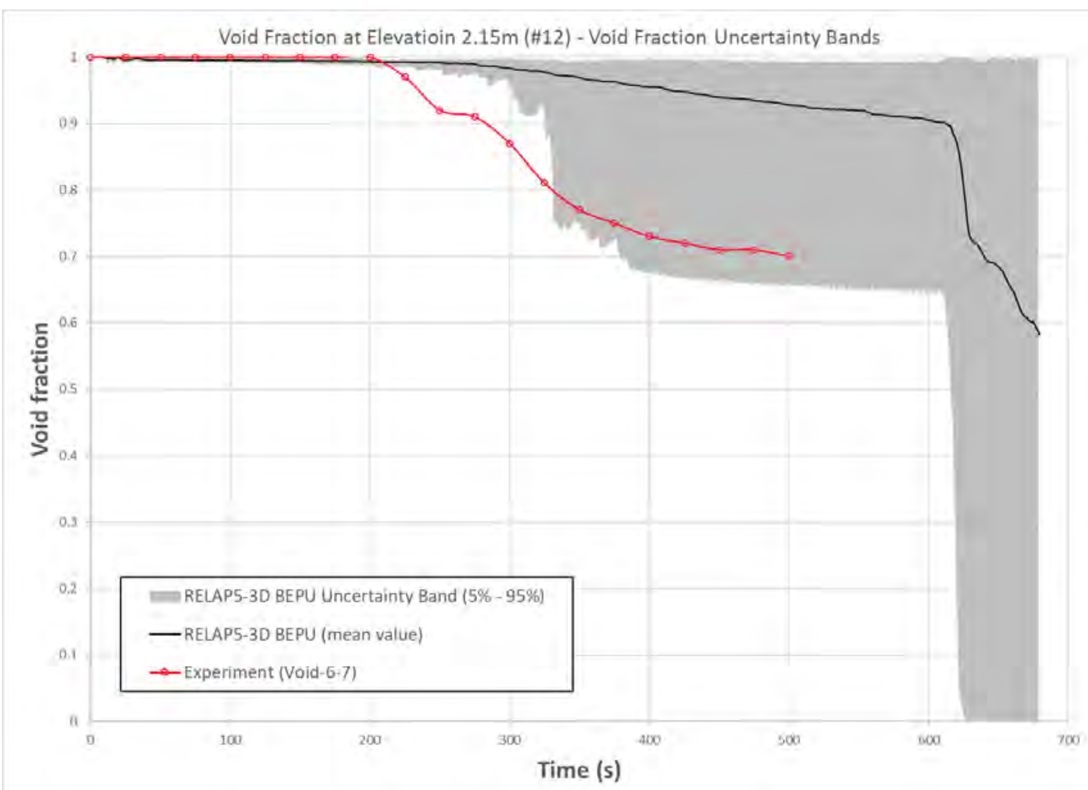

Figure C-18. FLECHT-SEASET void fraction at elevation 2.15m (#12) (Test 31504).

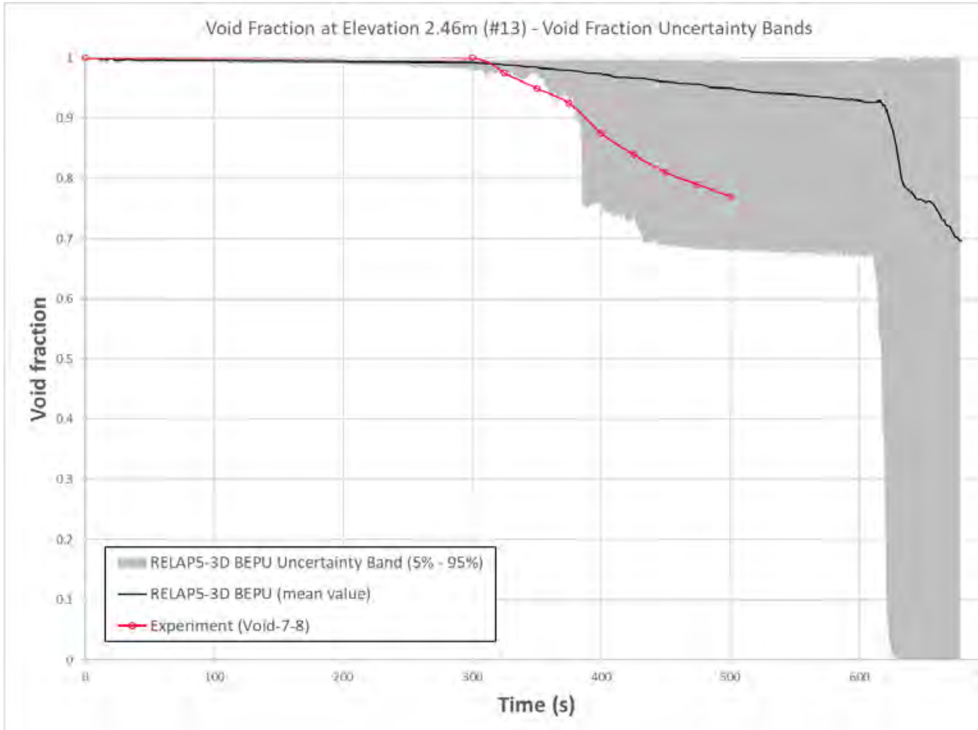

Figure C-19. FLECHT-SEASET void fraction at elevation 2.46m (#13) (Test 31504).

APPENDIX D.

UNCERTAINTY ANALYSIS OF FLECHT-SEASET TEST 31701

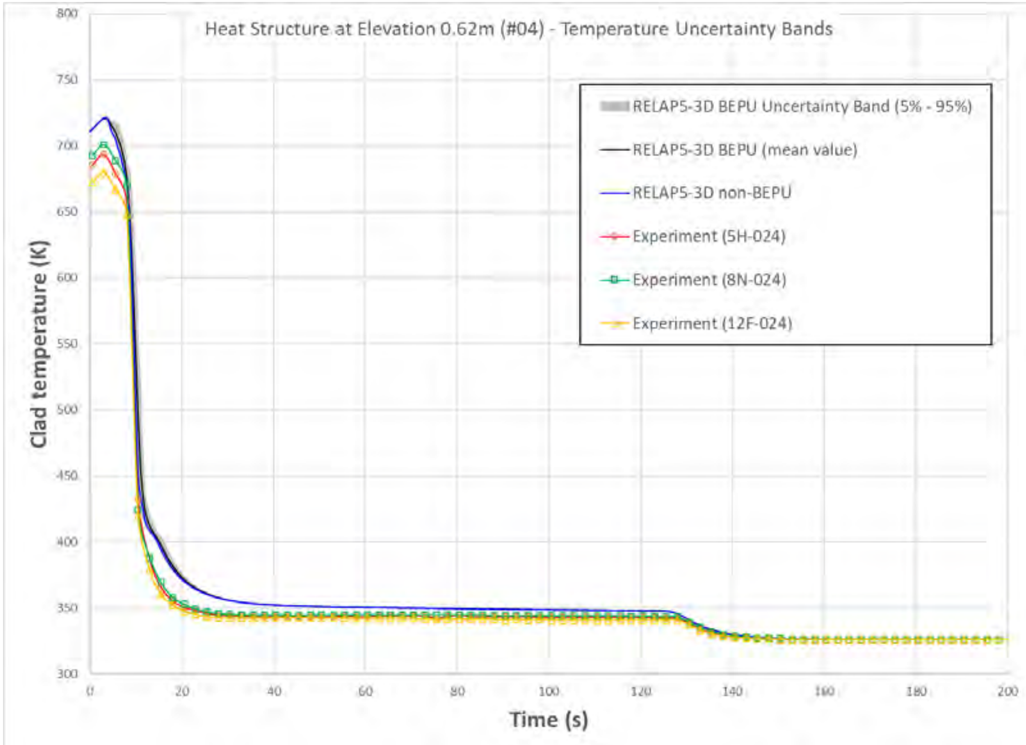

Figure D-1. FLECHT-SEASET clad temperature at elevation 0.62m (#04) (Test 31701).

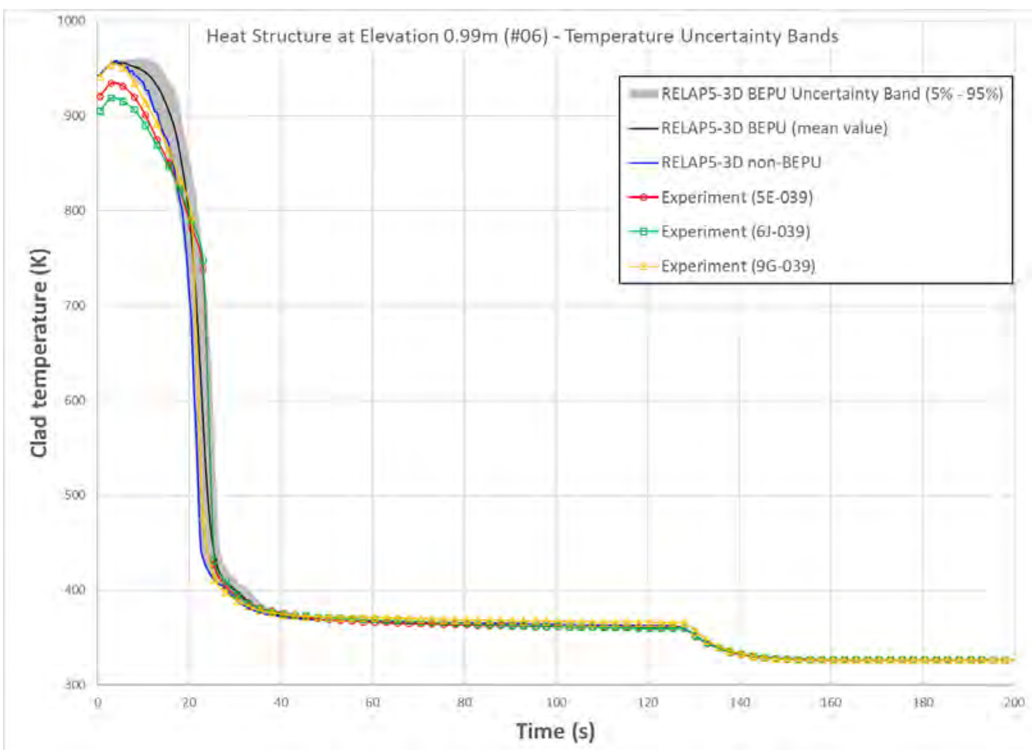

Figure D-2. FLECHT-SEASET clad temperature at elevation 0.99 m (#06) (Test 31701).

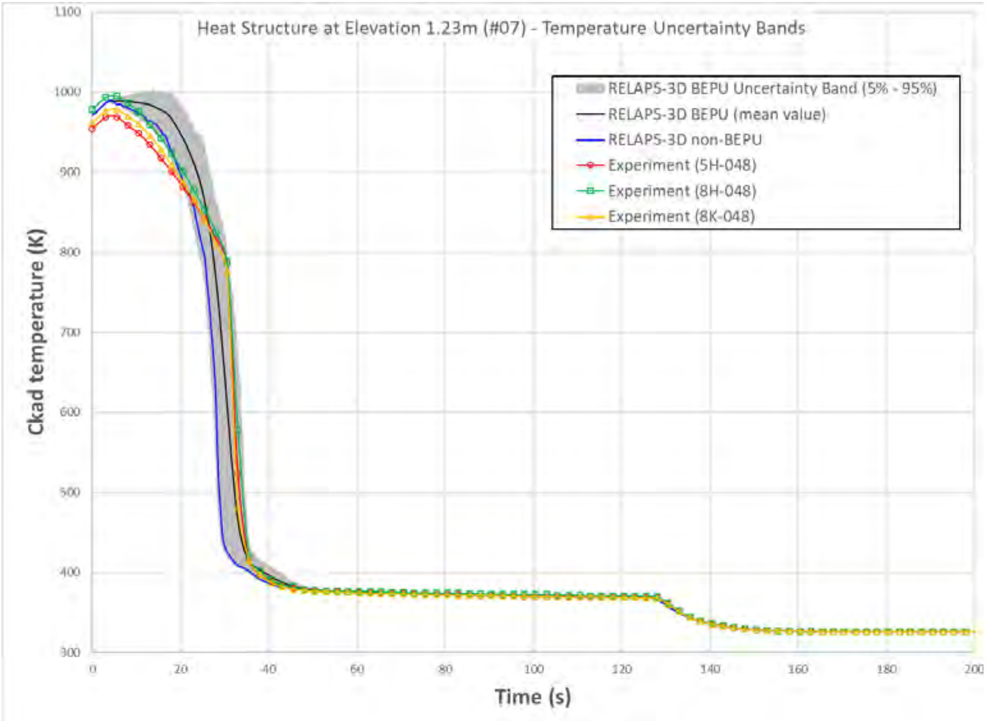

Figure D-3. FLECHT-SEASET clad temperature at elevation 1.23m (#07) (Test 31701).

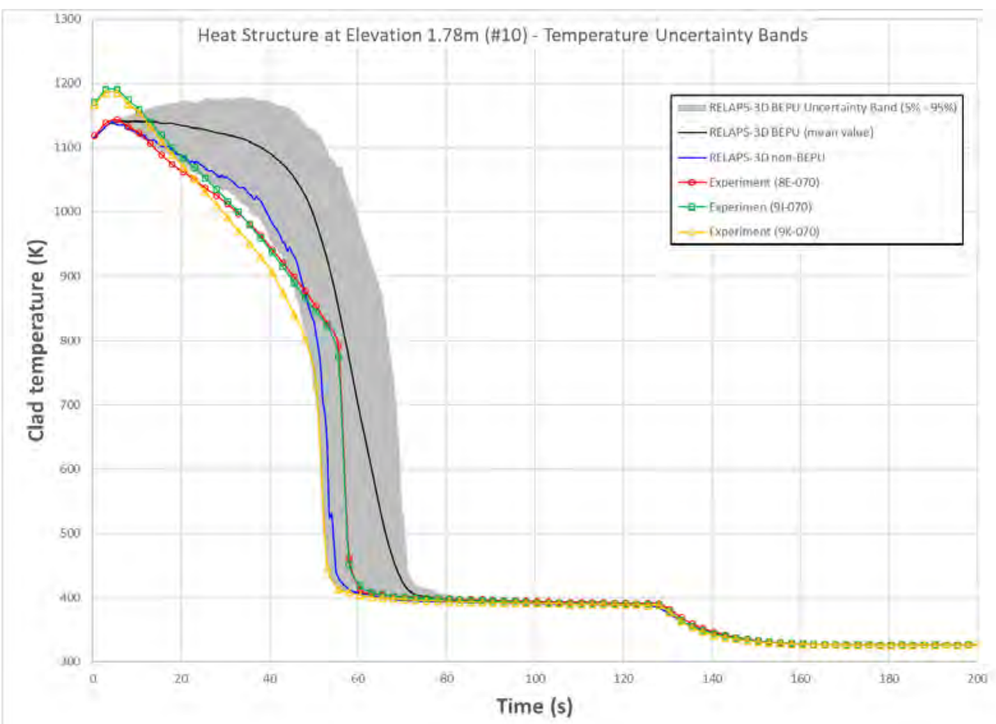

Figure D-4. FLECHT-SEASET clad temperature at elevation 1.78m (#10) (Test 31701).

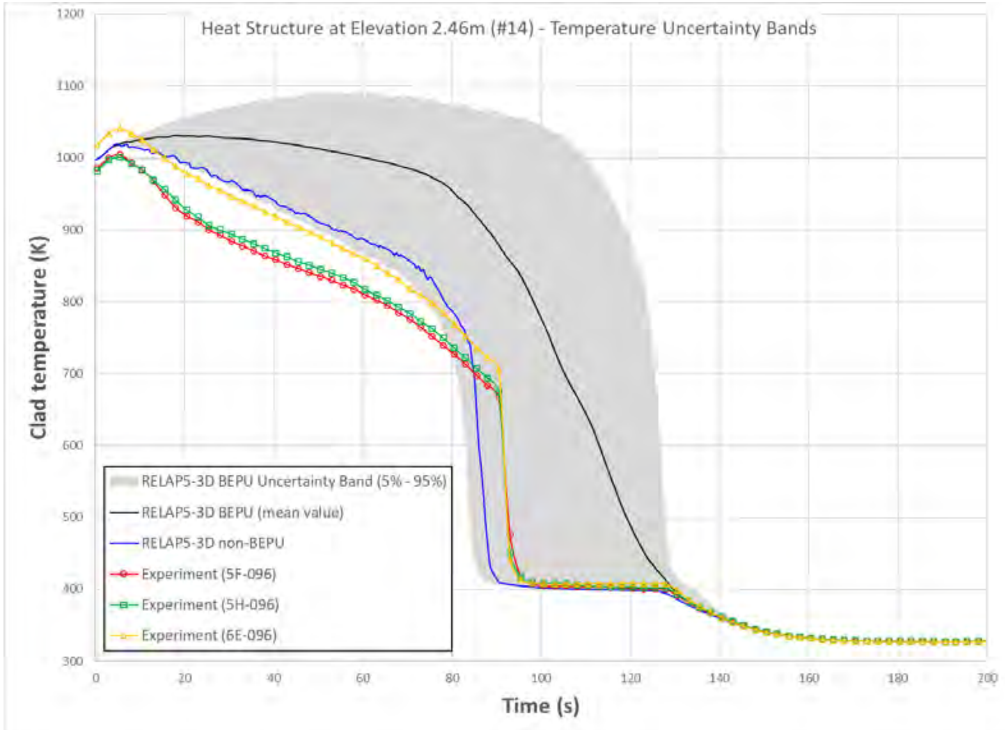

Figure D-5. FLECHT-SEASET clad temperature at elevation 2.46m (#14) (Test 31701).

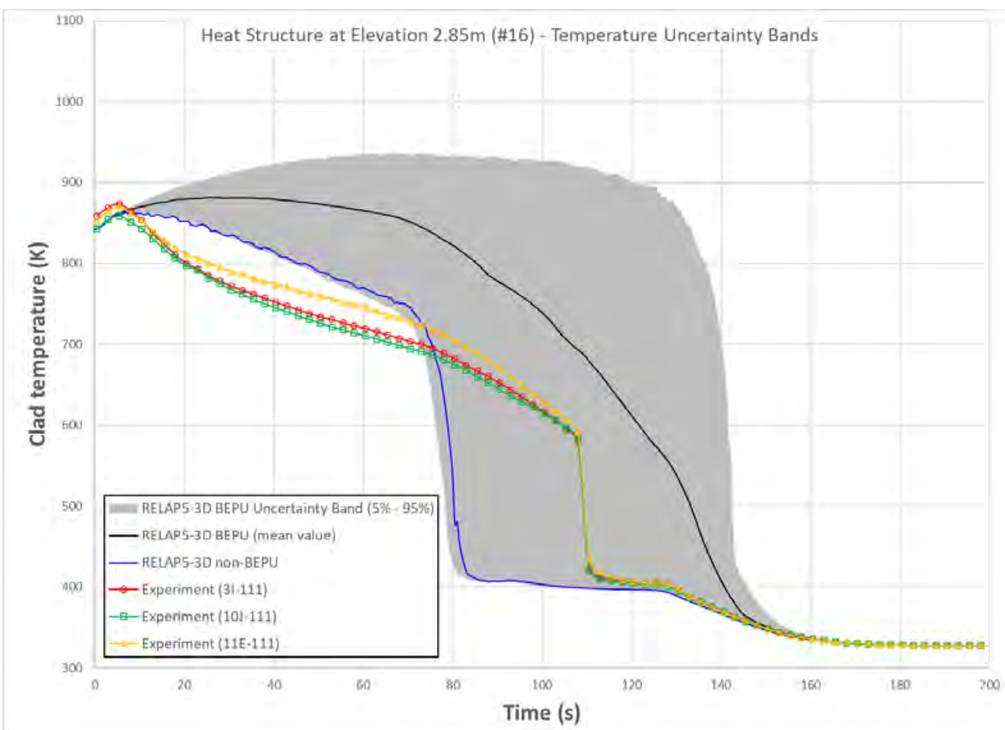

Figure D-6. FLECHT-SEASET clad temperature at elevation 2.85m (#16) (Test 31701).

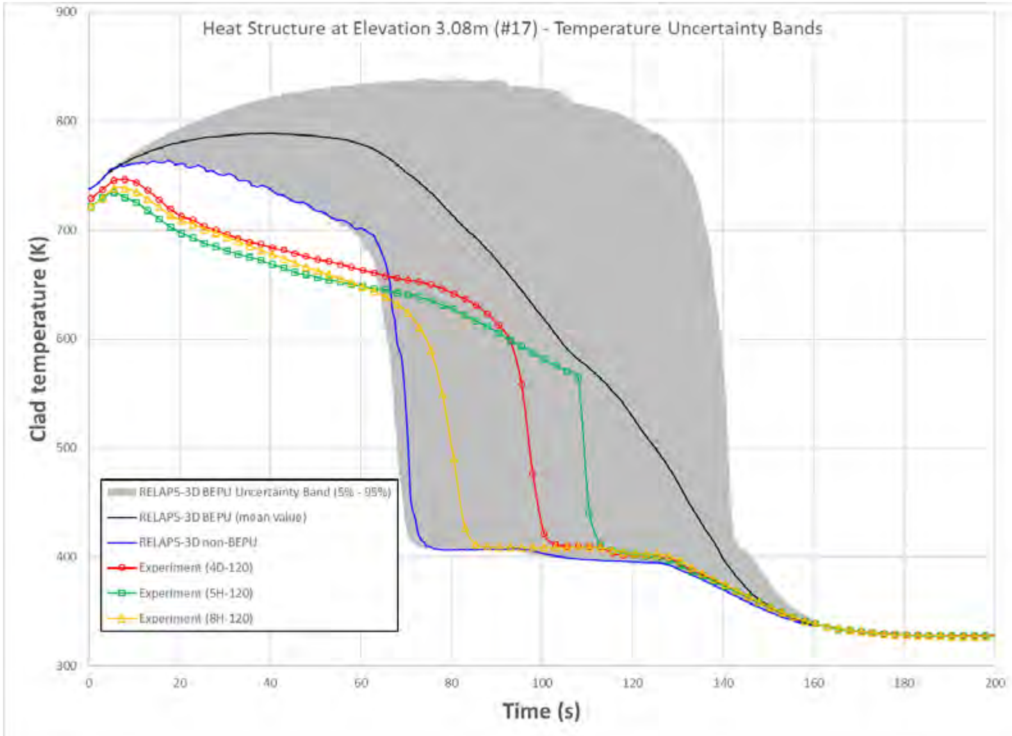

Figure D-7. FLECHT-SEASET clad temperature at elevation 3.08m (#17) (Test 31701).

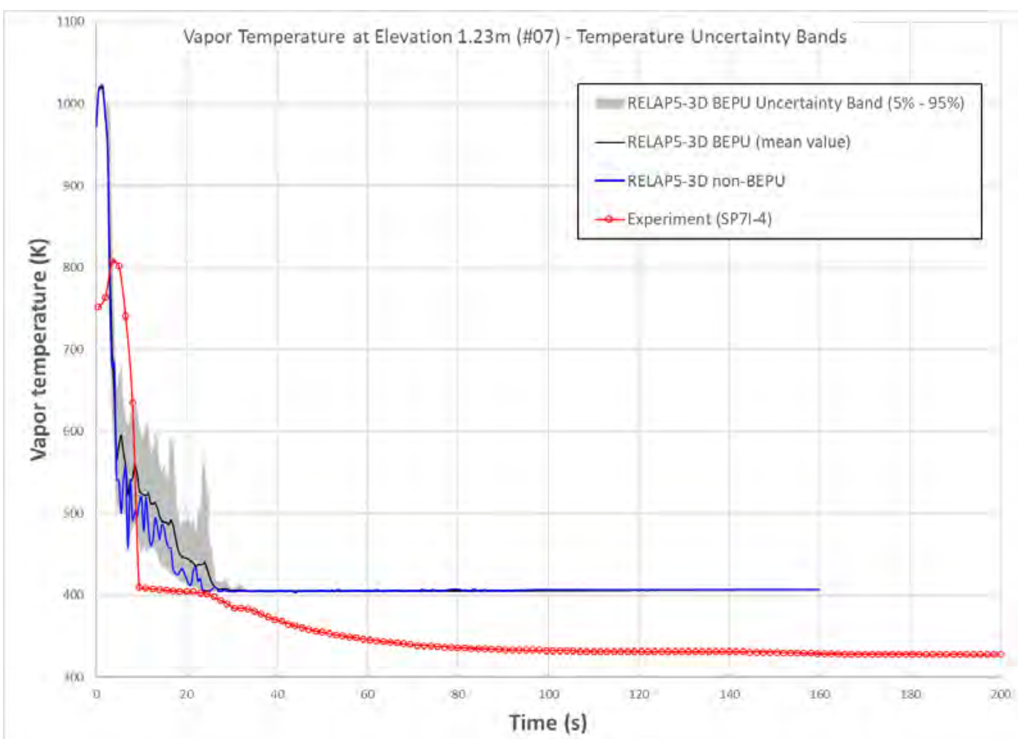

Figure D-8. FLECHT-SEASET vapor temperature at elevation 1.23m (#07) (Test 31701).

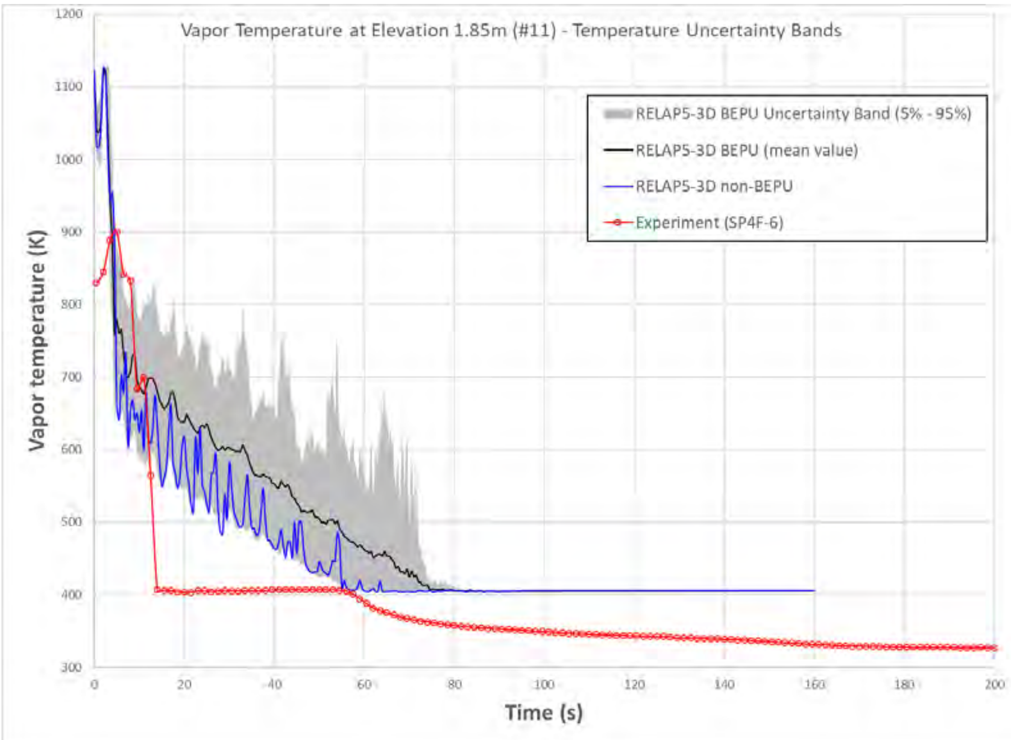

Figure D-9. FLECHT-SEASET vapor temperature at elevation 1.85m (#11) (Test 31701).

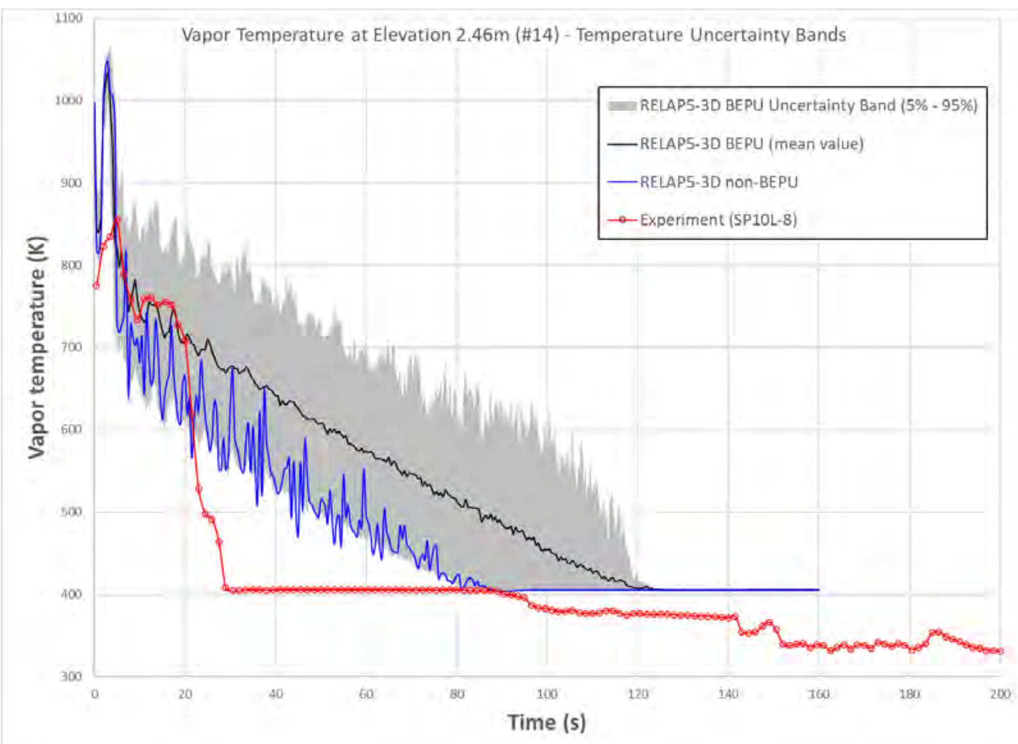

Figure D-10. FLECHT-SEASET vapor temperature at elevation 2.46m (#14) (Test 31701).

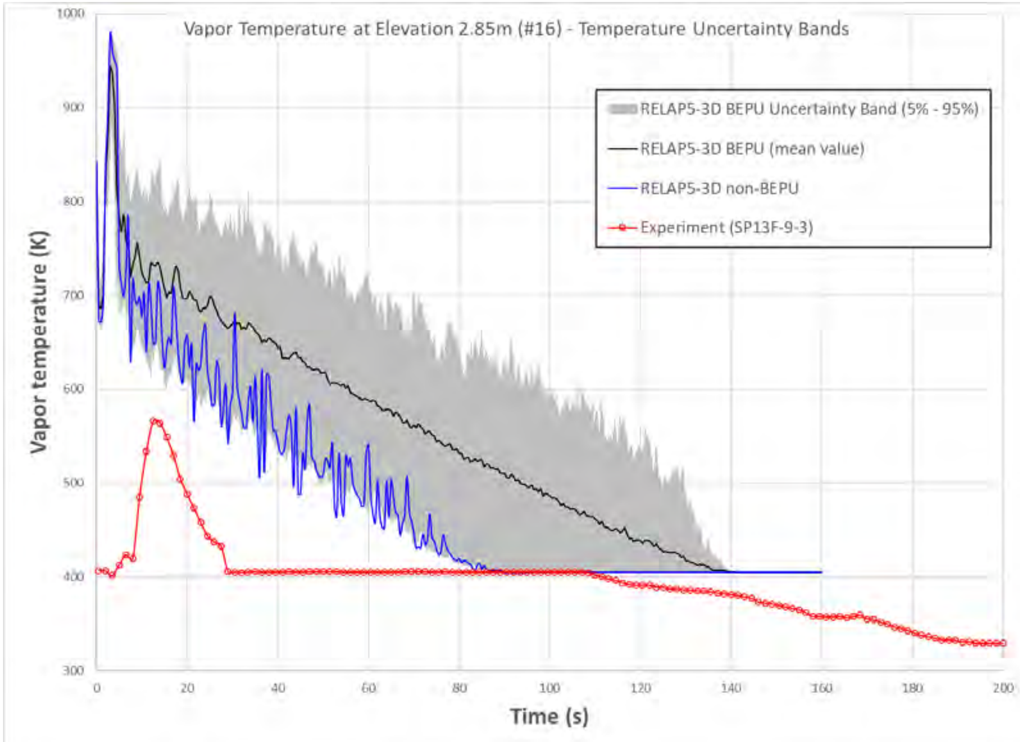

Figure D-11. FLECHT-SEASET vapor temperature at elevation 2.85m (#16) (Test 31701).

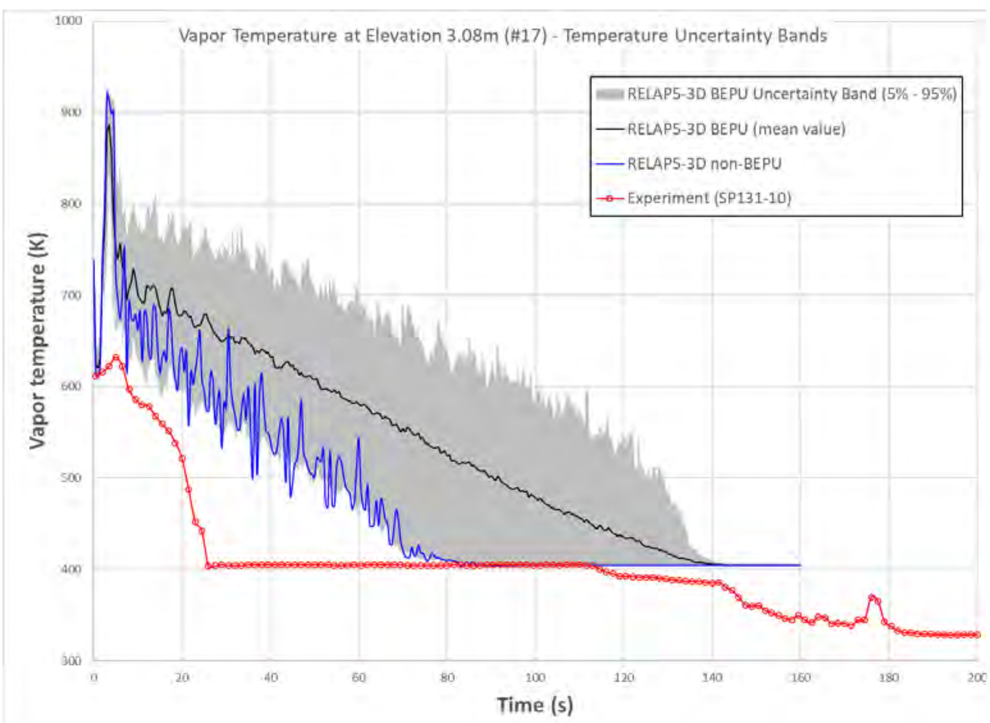

Figure D-12. FLECHT-SEASET vapor temperature at elevation 3.08m (#17) (Test 31701).

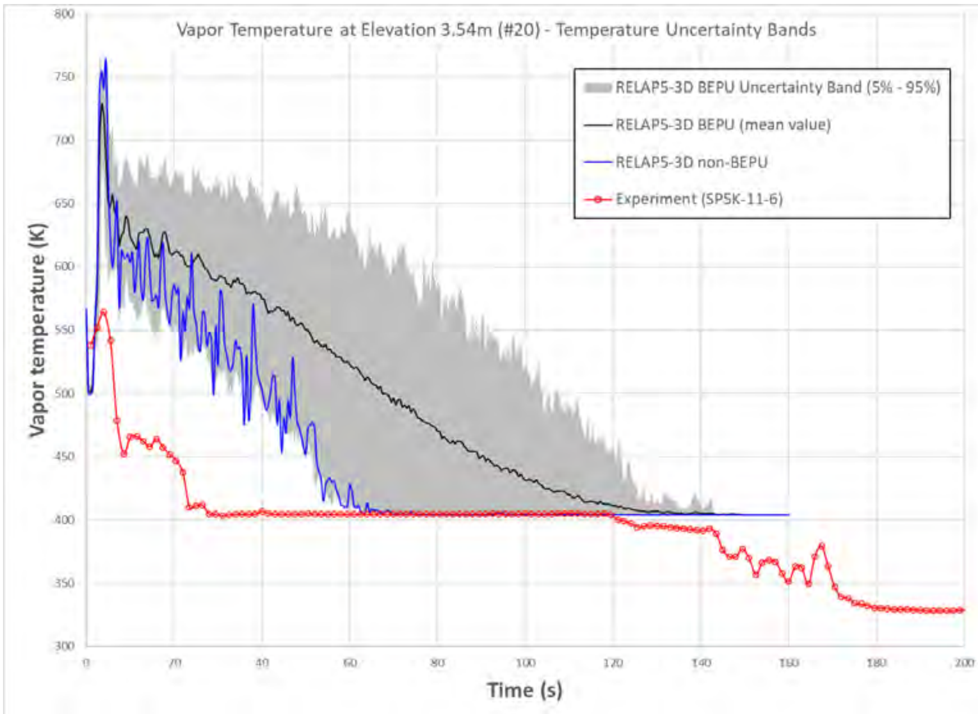

Figure D-13. FLECHT-SEASET vapor temperature at elevation 3.54m (#20) (Test 31701).

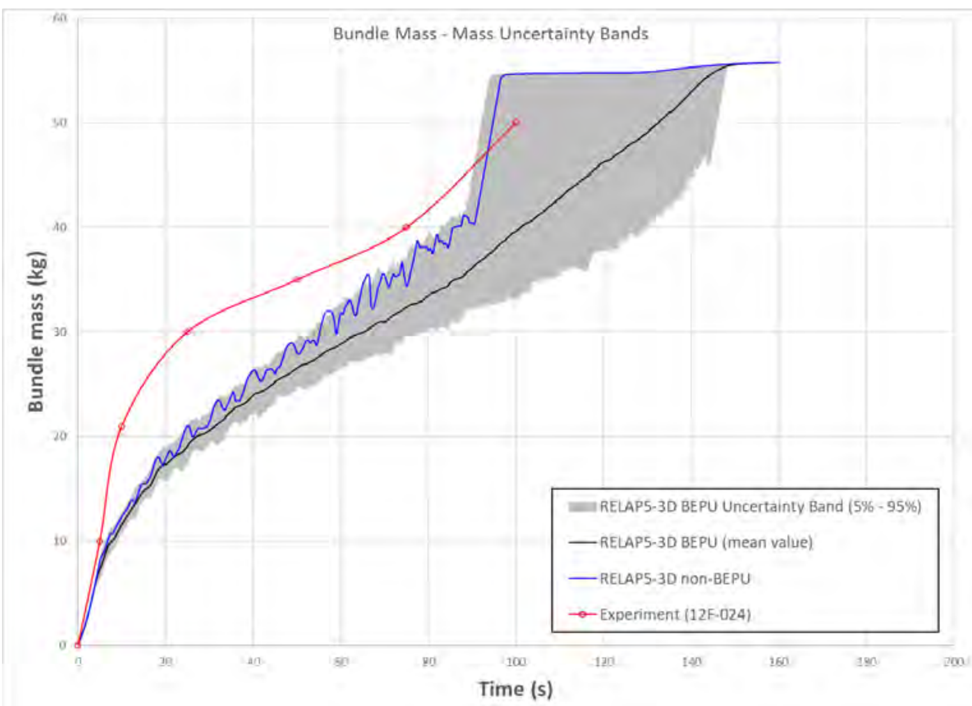

Figure D-14. FLECHT-SEASET bundle mass (Test 31701).