
UMD Approach TH Code Uncertainty* Assessment Application on LOFT LBLOCA Test Facility

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Questions (Discussed Internally Not for Presentation)

- Availability of Test Data
 - ✓ Practicality of Methodology Due to Lack of Sufficient Data
- Advantages Comparing Existing Methodologies
- Credibility of Distribution Fitting to Data from First Phase
- Questions of Probabilistic Framework for Uncertainty Quantification
- Structural Model Uncertainty
- Correct Representation/Interpretation of Output Results
- Conservative or Best Estimate or Mixed?



Outline*

- Scope of Research
- UMD methodology for uncertainty Analysis
 - ✓ Methodology Specification
 - ✓ Methodology Overview
- LOFT Test Facility-LBLOCA Application
 - ✓ Results
 - Input Based
 - Output Based
- Discussion



Scope of Research*

- An Integrated Methodology for TH Uncertainty Analysis
 - ✓ Implementation of the Best Features from Existing Methodologies
- Access and use all available information
 - ✓ About Boundary/Initial Conditions
 - ✓ Models, Sub-models and their Corresponding Parameters
 - ✓ Output
- More Effective Utilization of Data and Information
- Treat Code Structure Uncertainty
- Better Representation/Interpretation of Results



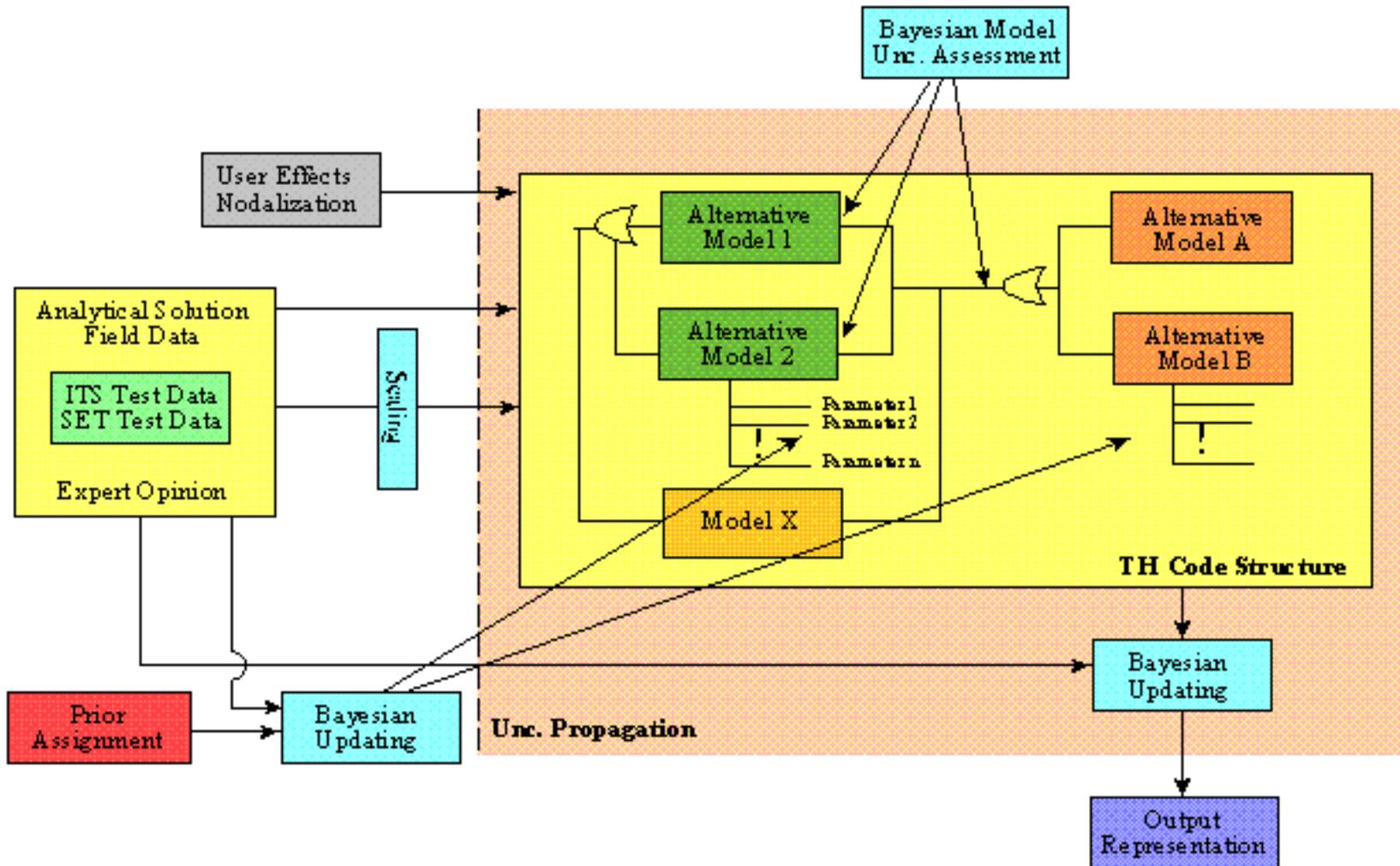
TH Uncertainty Analysis *

Comprehensive Uncertainty Range

- Comprehensive Uncertainty Distribution (Range) is defined the Range by Applying All Available Knowledge in more effective way
 - ✓ Qualification
 - Qualification and Applicability study of TH Code
 - Inputdeck and Nodalization Qualification
 - Data Accuracy and Applicability Assessment
 - Determination of Effects of Scale-up (Distortion Assessment)
 - Applicability of Available Test Data
 - Identification, Ranking and Screening of Uncertainty Sources
 - ✓ Quantification
 - Uncertainty Quantification of Models and Parameters
 - Dependency Consideration
 - Propagation of Uncertainties; Sufficient Statistics
 - Appropriate Representation of Uncertainty Ranges
 - Consideration for missing/screened out uncertainty sources



Overall Methodology Overview *



UMD Methodology Features

➤ Hybrid

- ✓ Quantification of Uncertainties with Data and Information for Inputs (Explicitly Considered)
- ✓ Quantification of Uncertainties for Model Structure (Explicitly Considered)
- ✓ Updating of Output Uncertainty with Independent Data and Information (implicitly Considered)

➤ Comprehensive in Treatment of Uncertainties

- ✓ More Effectively Identifying and Ranking Phenomena
- ✓ Considers Code as a White Box
- ✓ Explicit Consideration of Model Uncertainties with Quantification of Uncertainties in Parameters and Model Structure
- ✓ Systematic Assignment of Distribution
 - Maximum Entropy Approach Combined with Expert Judgment
 - Updating with Bayesian Method with New Experimental Data

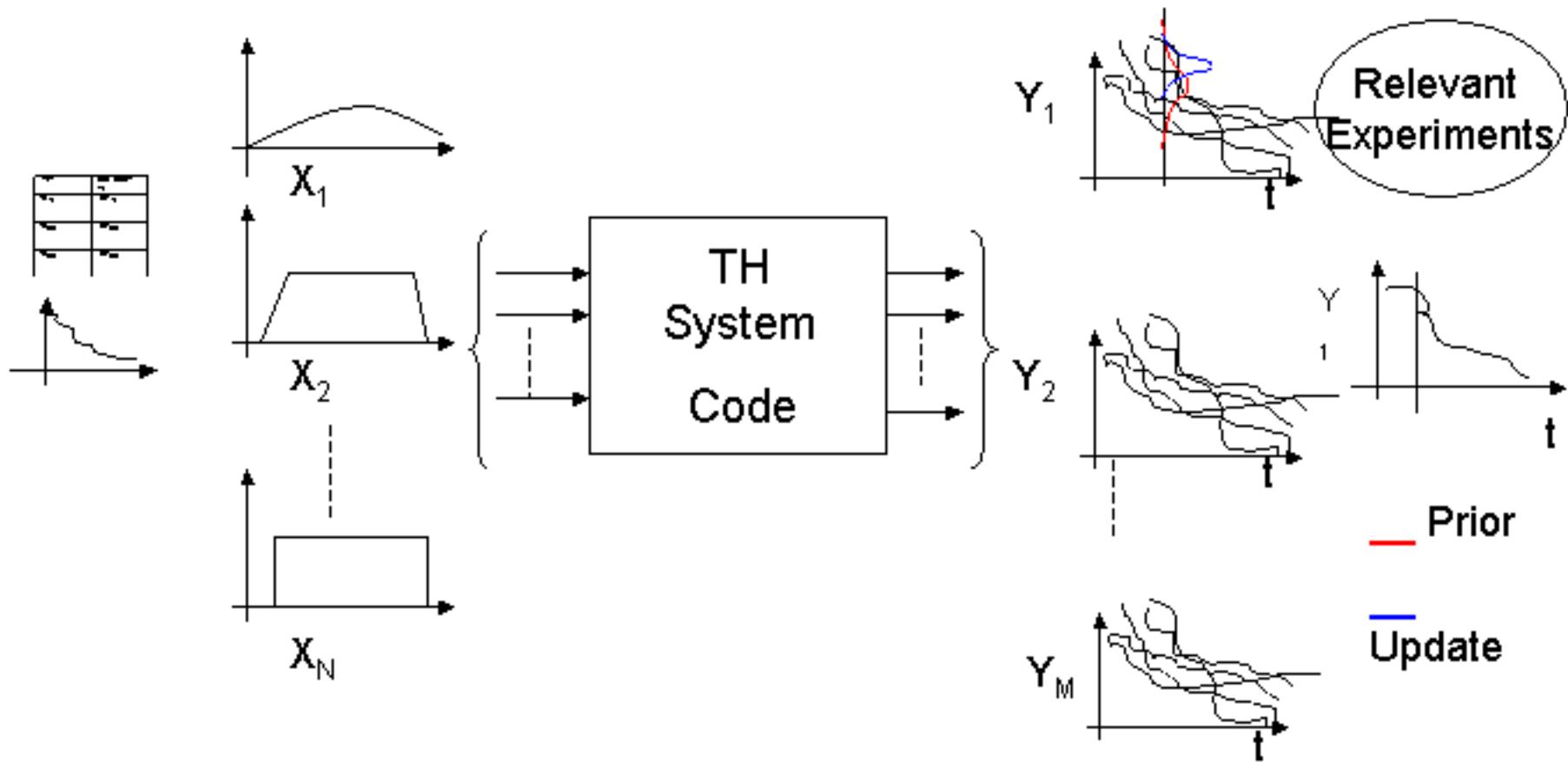


UMD Methodology Features (cont.)

- Efficient uncertainty propagation
 - ✓ Use of Wilks' tolerance limit criteria sampling
- Implicitly correcting output uncertainties to account for:
 - ✓ Errors of uncertain user
 - ✓ Numerical approximations
 - ✓ Unknown and not considered sources of uncertainties (Screened input and/or Incompleteness)
- Possibility of Incorporating and Automating on the Code

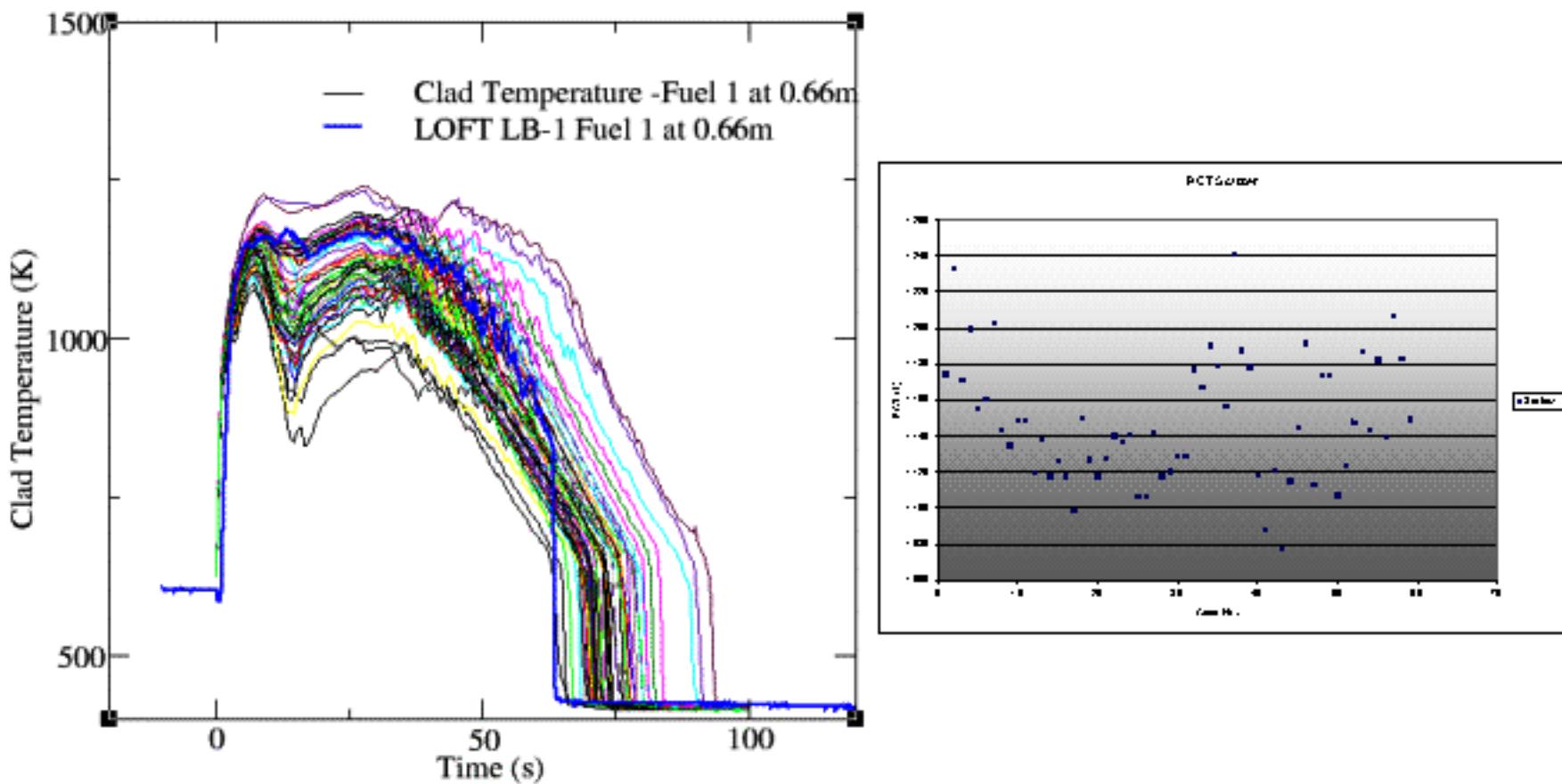


Summary of The Methodology

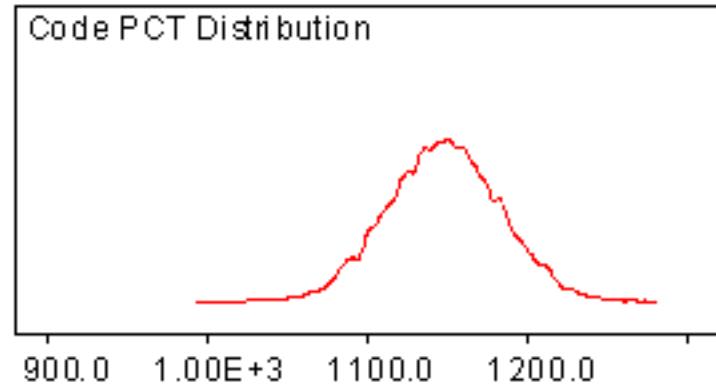
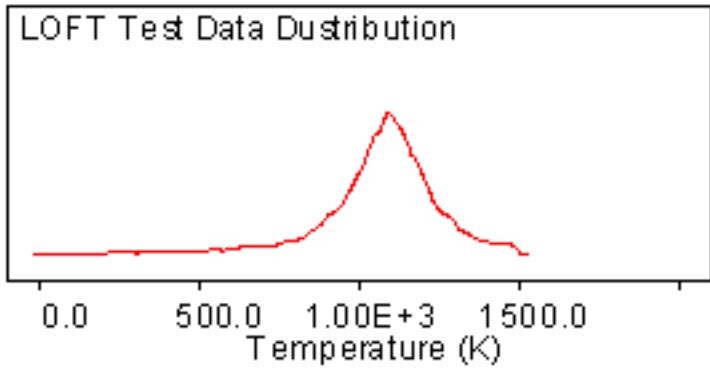
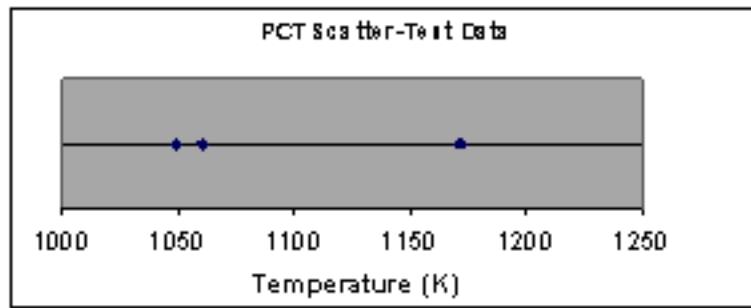
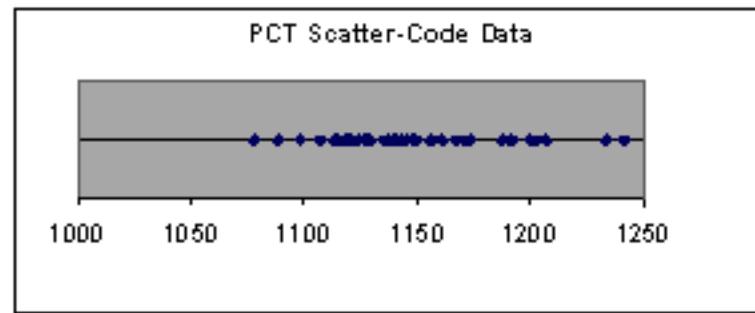


Uncertainty Analysis LOFT LBLOCA

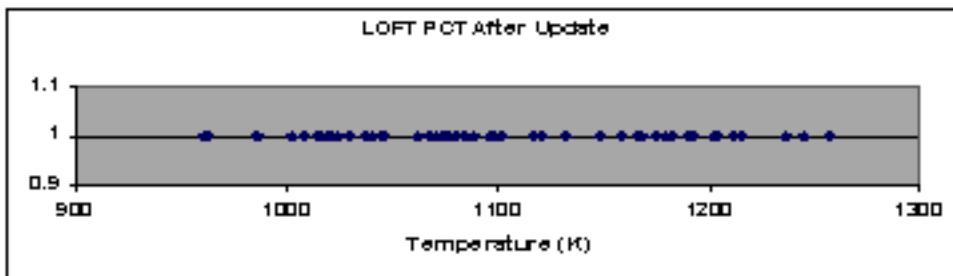
LOFT LOB-1 Uncertainty Analysis



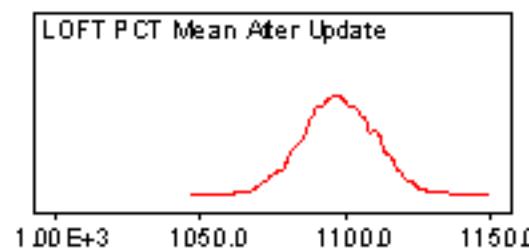
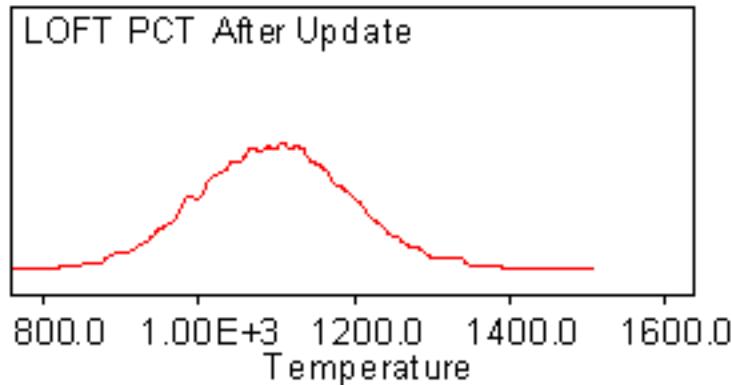
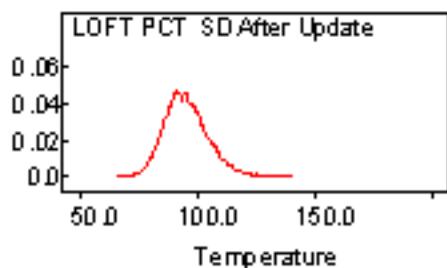
Output Updating Test Data



LOFT PCT After Update



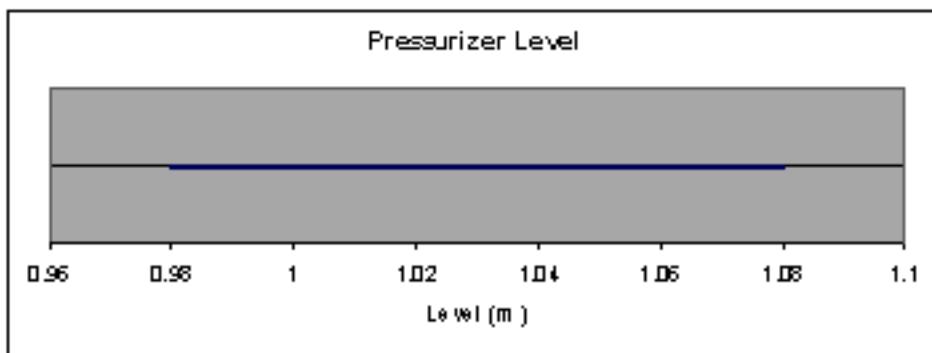
Node	Mean	SD	MC Error	2.50%	Median	97.50%
Code	1099	95.95	0.946	911.4	1099	1288
Code μ	1098	12.51	0.131	1073	1098	1122
Code σ	95.43	9.027	0.1073	79.57	94.75	115



Uncertainty Importance

► Pressurizer Level

Mean	1.03
SD	0.029



Node	Mean	SD
Code	1148	35.4

2-Sigma Importance	0.022444
4-Sigma Importance	0.05964
6-Sigma Importance	0.070076
Pressurizer Uncertainty	
Importance Measure	0.05072

Change in Uncertain Parameter	ΔPCT
Pressurizer Level + 1 Sigma	-0.2925
Pressurizer Level + 2 Sigma	-0.978
Pressurizer Level + 3 Sigma	-3.3408
Pressurizer level + 1 - Sigma	1.087
Pressurizer Level + 2- Sigma	3.2445
Pressurizer Level + 3- Sigma	4.1013



Discussion

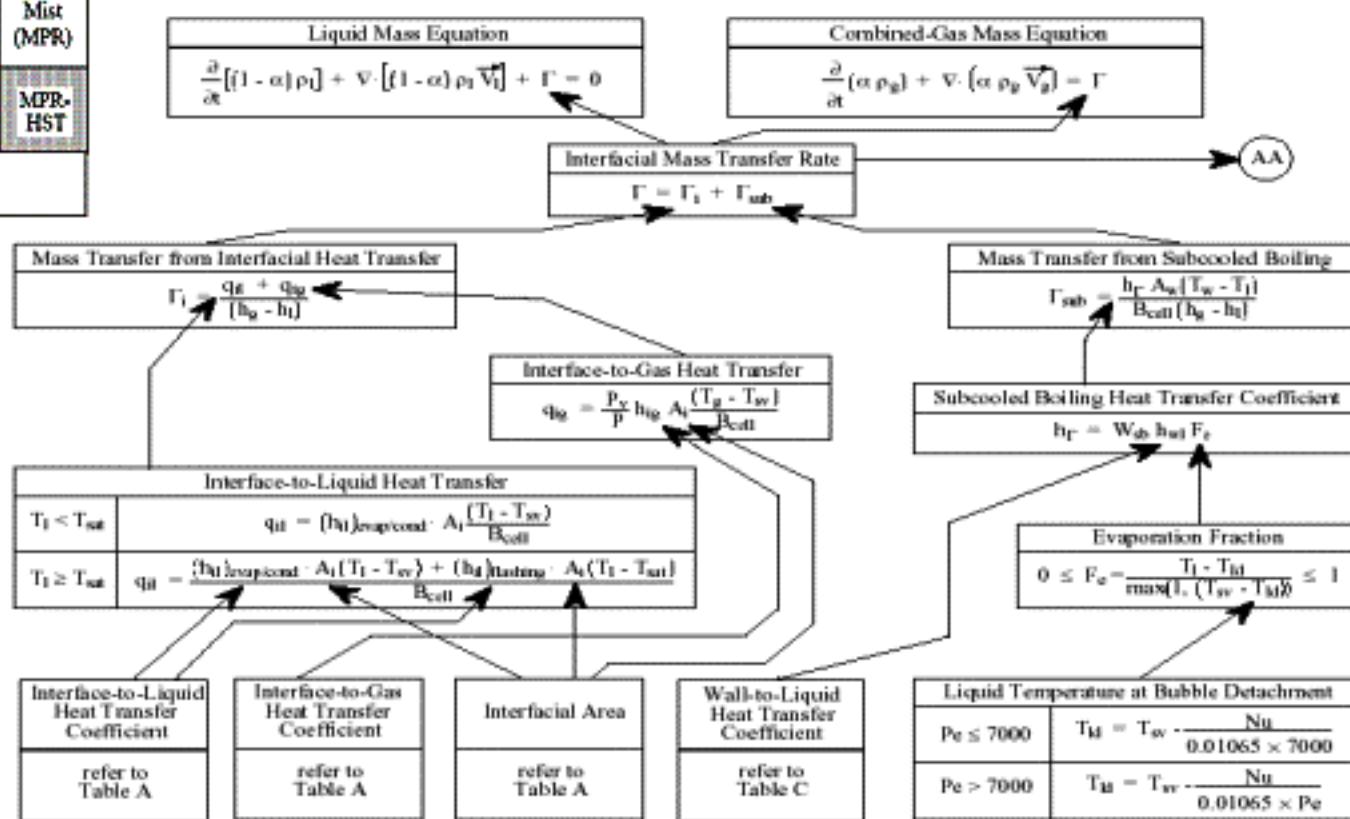
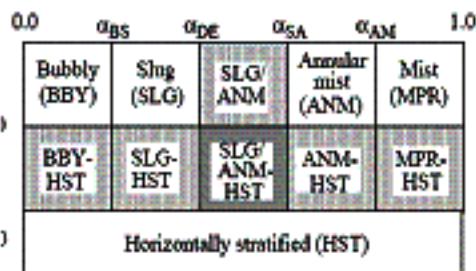


Code Structure



Code Structure (Example)

- Complex Configuration
- Many Dependent Parameters in Dynamic Environment



Code Model Uncertainties

- Plant Physical Description
 - ✓ Dimensions Uncertainties; Geometries
 - ✓ Code Input
 - Wall Surface Area, Cell Volume, Hydraulic Diameter, Power
 - ✓ Flow resistance; surface roughness
- Problem Boundary Condition
 - ✓ Break Location
 - ✓ Break Type (DEGB or Split)
 - ✓ Break Size (Small, Medium, or Large)
 - ✓ Offsite Power
 - ✓ Safety Injection Flow
 - ✓ Safety Injection Temperature
 - ✓ Safety Injection Delay
 - ✓ Containment Pressure
 - ✓ Rod Drop Time



Code Model Uncertainties (Cont.)

- Thermodynamic and Transport Fluid Properties
 - ✓ Density, Viscosity, Thermal conductivity , Internal energy
 - ✓ Enthalpy for the Liquid, Vapor, and Noncondensable components
 - ✓ Saturation properties for the Liquid and Vapor components
- Material Properties
 - ✓ Code Library; Temperature-Dependent properties
 - mixed Water (light and Heavy), Air, Nitrogen, Oxide Fuel, Zircaloy, stainless steel
- Local-Dependent (Closure Coefficients) Parameters
 - ✓ Interfacial Area (A_i); Interfacial Mass-Transfer Rate (Γ);
Interfacial Drag Coefficient (c_i); Wall Drag Coefficients (c_{wh} , c_{wg});
Interfacial Heat-transfer Coefficients (h_{ip} , h_{ig}); Heat-Transfer
Coefficient (h_{gl}); Wall Heat-Transfer Coefficients (h_{wh} , h_{wg})



CSAU/WCAB-TRAC

- Westinghouse Method is a Combination
- Focused on processes instead of parameters
 - ✓ Phenomena Based Models
 - ✓ Limited Focus on parameters (Initial/Boundary conditions +Dimension uncertainties)
- Methodology should be Best Estimate



Code Model Uncertainties (Westinghouse)

➤ Plant Initial Operating Conditions

✓ Reactor Power

- Initial Core Average Heat Rate
- Hot Rod Peak Linear Heat Rate
- Hot Rod Average Linear Heat Rate
- Hot Assembly Average Linear Heat Rate
- Hot Assembly Peak Linear Heat Rate
- Axial Power Distribution
- Low-Power Region Burnup
- Prior Operating History
- Moderator Temperature Coefficient
- Hot Full-Power Boron Concentration

✓ Fluid Condition

- Average Fluid Temperature
- RCS Pressure
- Loop Flowrate
- Upper Head Temperature
- Pressurizer Level
- Accumulator Water Temperature
- Accumulator Pressure
- Accumulator Water Volume
- Accumulator Line Resistance
- Accumulator Boron Concentration



Code Model Uncertainties

➤ Global Models

- ✓ Critical Flow
- ✓ Broken Cold-Leg Nozzle Resistance
- ✓ Broken Loop Pump Resistance
- ✓ Augmented KN
- ✓ Downcomer Condensation
- ✓ Upper Plenum Drain Distribution (Condensation, Interfacial Drag)

➤ Local Models

- ✓ Linear Heat Rate
- ✓ Fuel Conductivity before Burst
- ✓ Fuel Conductivity after Burst
- ✓ Packing Fraction due to Fuel Relocation
- ✓ Gap Conductance
- ✓ Rod Internal Pressure
- ✓ Cladding Burst Temperature
- ✓ Cladding Burst Strain
- ✓ Zirc-Water Reaction
- ✓ Blowdown Heatup HTC Multiplier
- ✓ Blowdown cooling HTC Multiplier
- ✓ Refill HTC Multiplier
- ✓ Reflood HTC Multiplier
- ✓ Minimum Film Boiling Temperature (Blowdown)



General Option Selection

➤ Volume-Related Options

- ✓ Thermal front tracking model
- ✓ Level model
- ✓ Water Packing Scheme
- ✓ Vertical Stratification Model
- ✓ Interphase Friction Model
 - normal pipe interphase friction model
 - rod bundle interphase friction model
- ✓ Wall Friction Calculation
- ✓ Phasic Non-equilibrium or equilibrium

➤ Junction-Related Options

- ✓ Energy correction
- ✓ COUNTERCURRENT flow limiting (CCFL) model
- ✓ Horizontal stratification vapor pullthrough/liquid entrainment model
- ✓ Choking (critical flow) model
- ✓ Operative area change
- ✓ Phasic velocity assumption
- ✓ Momentum flow



General Option Selection (Cont.)

➤ Initial Condition Options

- ✓ Volume Fluid State Initialization
- ✓ Junction Flow Initialization
- ✓ Heat Structure Initialization
- ✓ Control Variable Initialization
- ✓ Trip Initialization

➤ Boundary Condition Options

- ✓ Fluid pressure; PRZR, SG safety valves, and power-operated relief valves (PORVs), turbine
- ✓ Fluid temperature; safety injection, makeup, and main and auxiliary feedwater systems
- ✓ Fluid flow; safety injection (HP and LP injection), makeup, main and auxiliary feedwater systems, and for the main coolant system recirculation
- ✓ Heat Source; Core Power and Pressurizer Heaters
- ✓ Adiabatic Surface; Exterior of Insulated Piping
 - **Fluid State Boundary Conditions;** time-dependent volume (TMDPVOL)
 - **Fluid Flow Boundary Conditions;** time-dependent Junction (TMDPJUN)



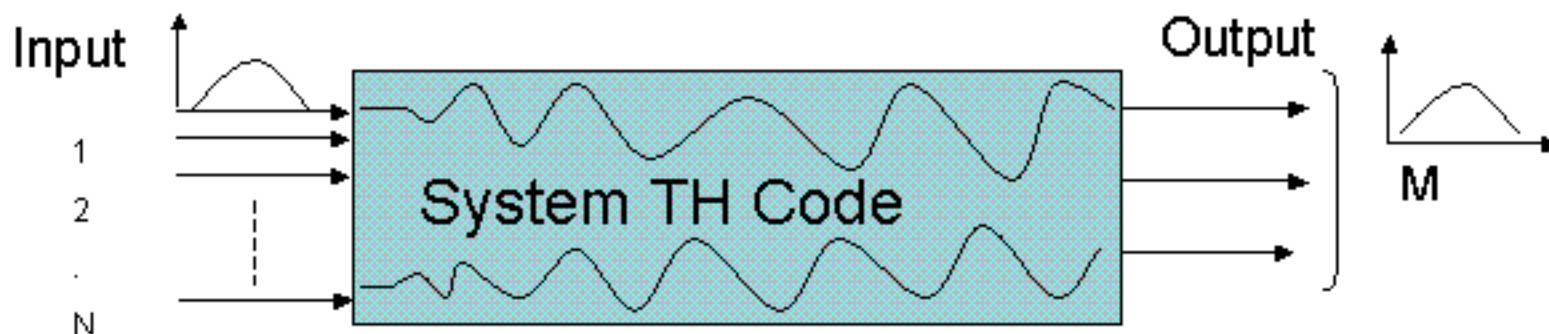
Existing Methodologies Overview and Comparison



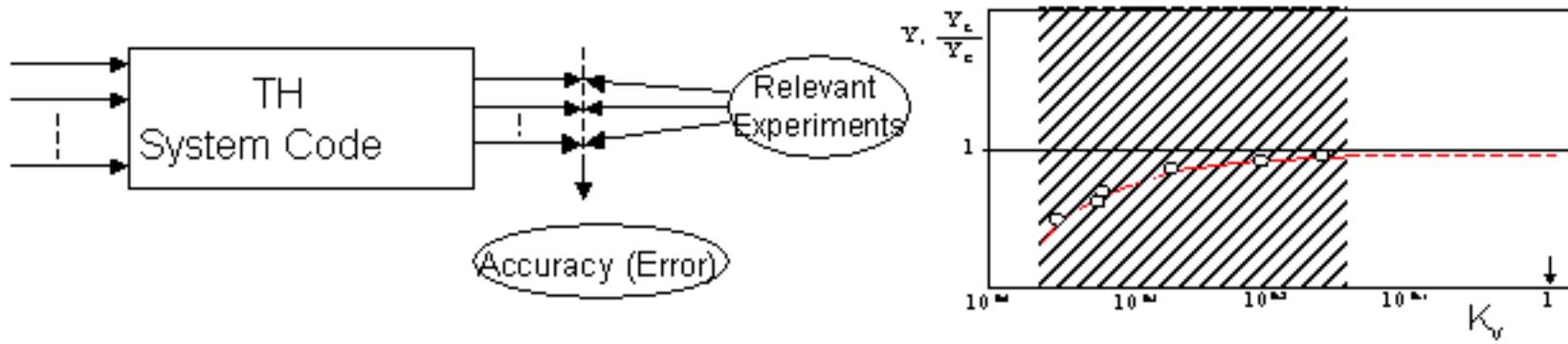
Existing TH Uncertainty Methodologies

Best Estimate Calculation +Uncertainty Analysis

➤ Input-Based Methodologies



➤ Output-Based Methodologies



Why Two Step Methodology?

- Existing Uncertainty Analysis Methodologies Either Input-driven or Output-driven Are Not Comprehensive
- **output-based methods**
 - ✓ Can Not Distinguish Uncertainty Contribution of the Individual Sources
 - ✓ Require Significant Amount of Experimental Data
 - ✓ Not Providing a Conceptual and Methodic Base for Generalization Beyond the Cases Studied (e.g., UMAE)
- **Input-based methods**
 - ✓ Initial Screening of Phenomena and Parameters
 - ✓ Intentionally Limiting the Scope (e.g., not considering "user effects")
 - Qualification is not Enough
 - ✓ Issue of Unknown Phenomena or Incomplete Spectrum of Alternative Models
 - E.g., 30 phenomena identified by Westinghouse/EPRI vs. 17 identified in the PIRT of original CSAU
- **Desirability a Hybrid Approach of an Input-driven “White Box” Approach Augmented with Output Correction and Uncertainty Assessment based on Experimental Results Relevant to Code Output.**



Comparison of Methodologies

		UMD	GRS	CSAU	UMAE	ASTRUM (W)
Input	Parameters	Use of Data & Judgment (Bayesian)	Expert Judgment (Data-informed)	Expert Judgment (Data-informed)	NA	Expert Judgment (Data-informed)
	Models	Expert Judgment Correction Factors/Bias Alternative Models	Expert Judgment Limited Alternative Models	Correction Factors	NA	Correction factors
	Restriction on the No. of Input Parameters	N	N	Y	NA	N
	Dependency Consideration	Y	N	N	NA	N
Propagation	Parameters	Statistical Tolerance Limit	95/95 Tolerance Limit	Response Surface	NA	95/95 Tolerance Limit
	Models	Statistical Tolerance Limit	95/95 Tolerance Limit	Response Surface	NA	95/95 Tolerance Limit
Output	Parameters	NA	NA	NA	NA	NA
	Models	Use of Integral Data Bayesian Framework	NA	NA	Accuracy Based Uncertainty	NA
	Consideration for Missed/Screened Out Models	Y	N	N	Y	N

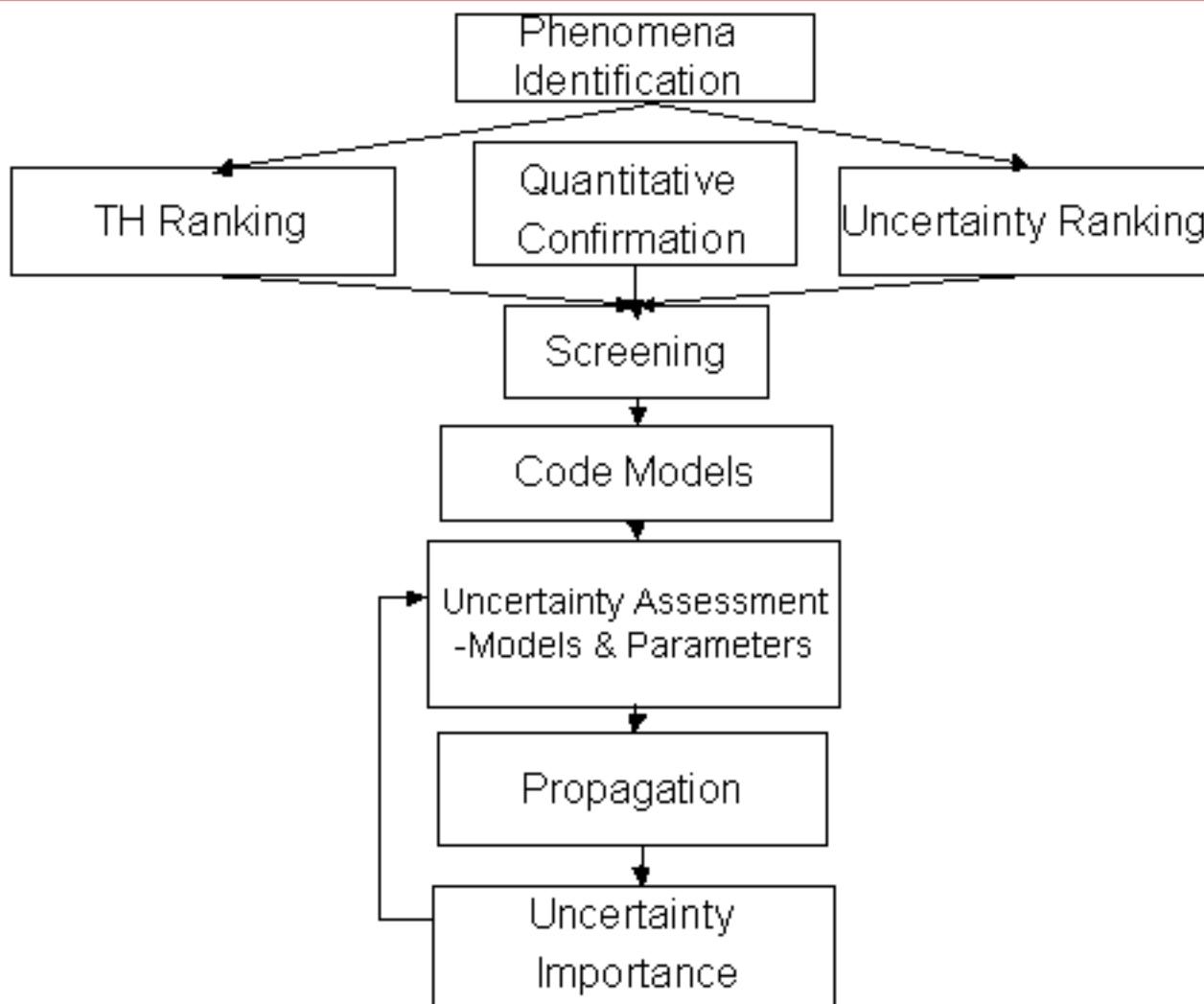


Methodology Flow Charts

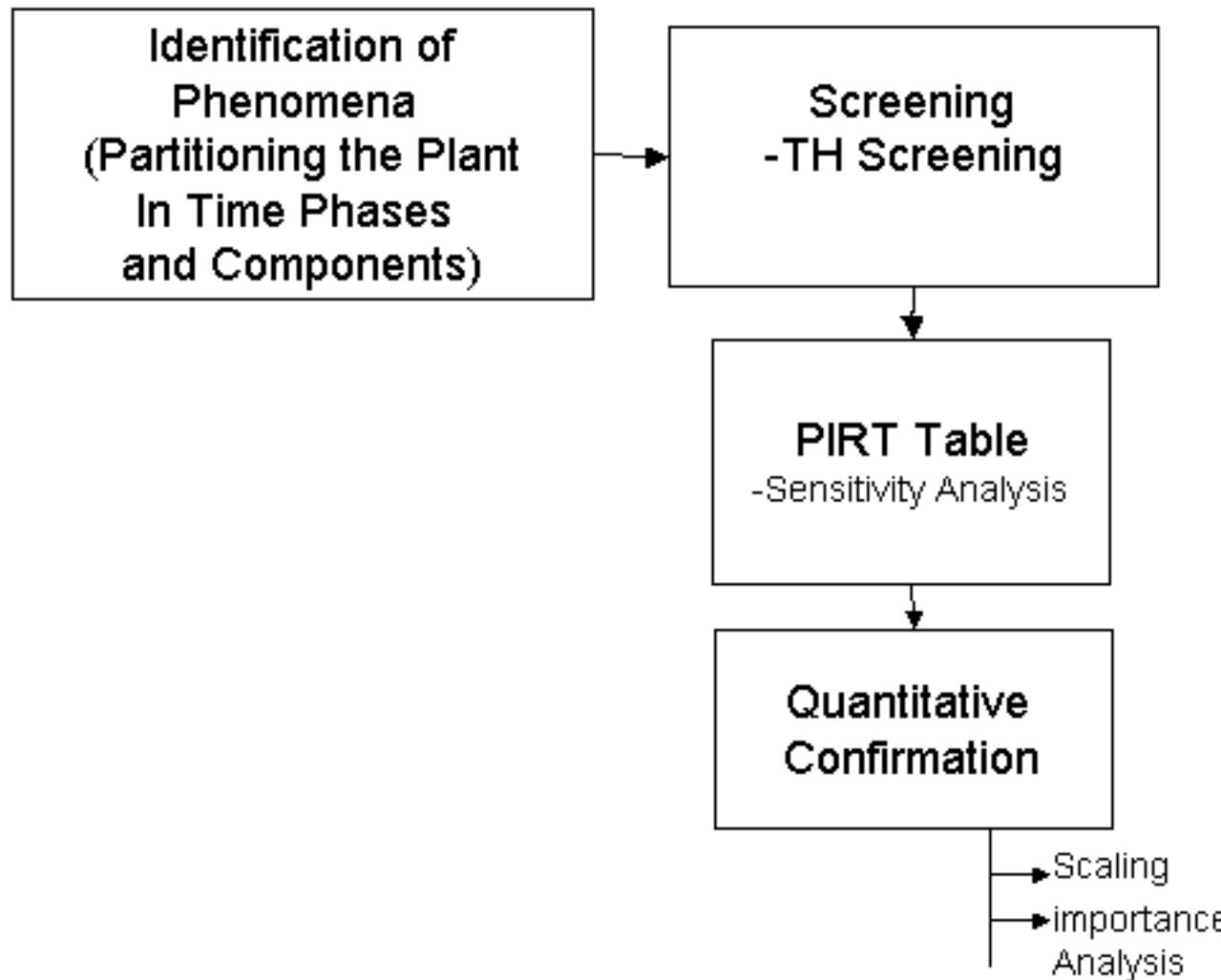


Uncertainty Analysis for TH Codes

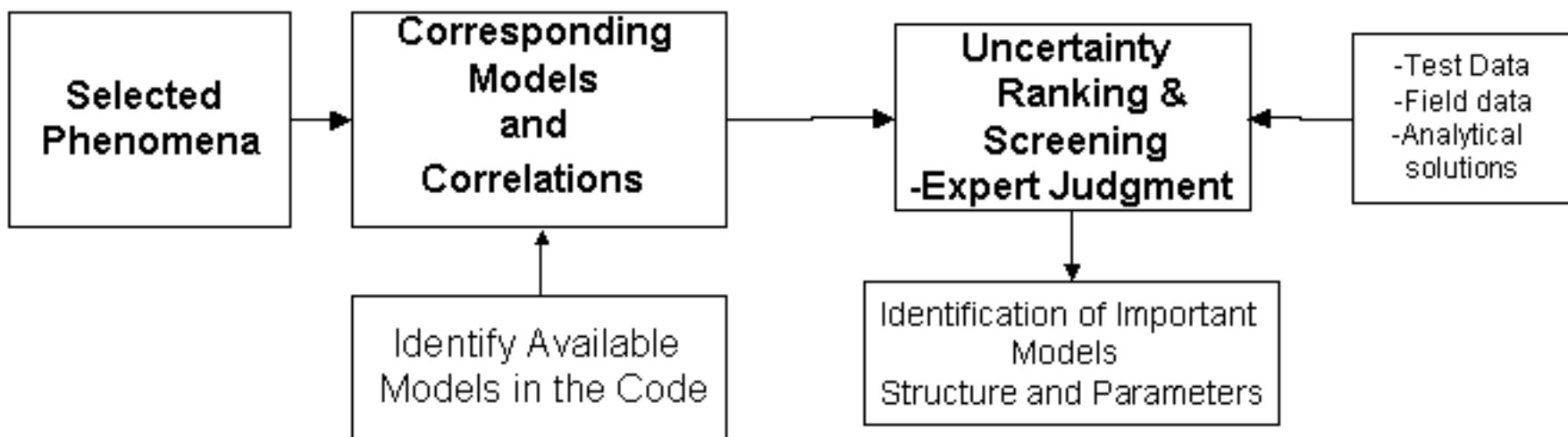
Input Phase



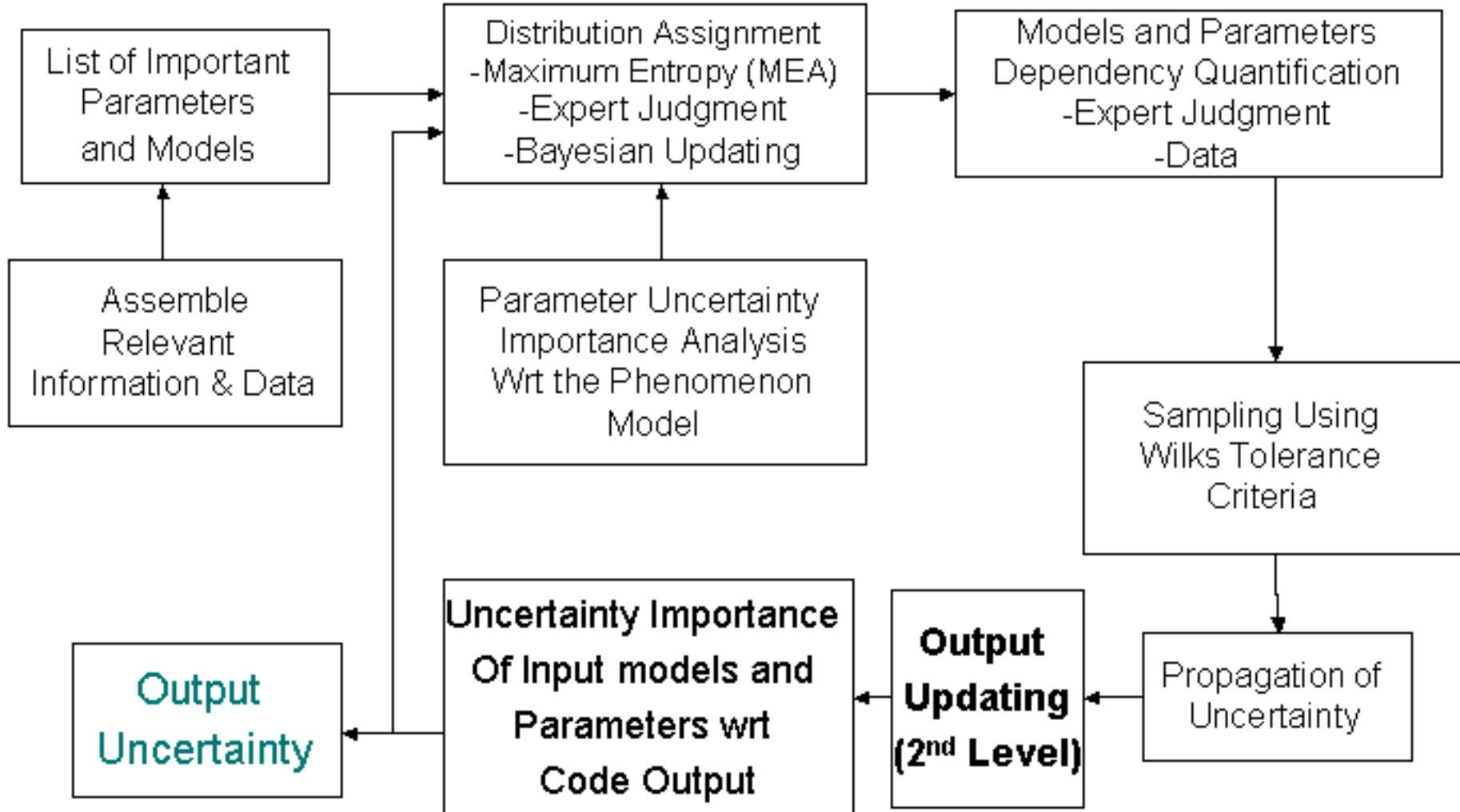
Phenomena Identification, Screening and Ranking



Uncertainty Ranking Code Models & Correlations



Assessment & Propagation of Uncertainties in Models & Parameters



Model Uncertainty



Model Uncertainty

- Alternative Models
 - ✓ User Input Options
 - ✓ Recommendations
- Uncertain Models
 - ✓ Model Parameters
 - ✓ Corrective Multipliers
 - ✓ Substitution Parameters
- Model Uncertainty Analysis
 - Alternative Model Structures
 - Weighting and Combining Models
 - Expert Judgment Elicitation



Model Uncertainties

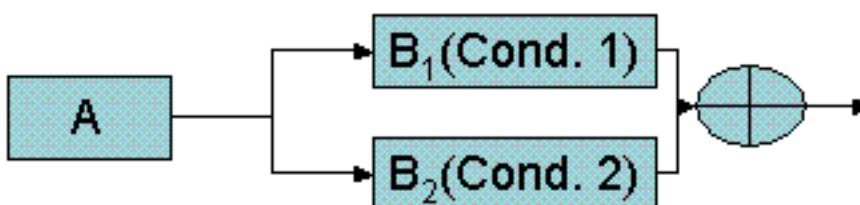
- Model Selection Logic
- Flow Regime Selection Logic
- Local parameters
 - ✓ Not considered for Code Output
 - ✓ Too many Parameter (Interim, Latent)
- Flow Regime Monitoring



Alternative Models; Code Automatic Switch

Case 1

- Case 1: Automatic Code Switching (Upon Satisfaction of Some Conditions)



Example: Flow Phase Change

Change from 1-Phase Choked flow to 2-Phase Choked Flow model
by changing in conditions



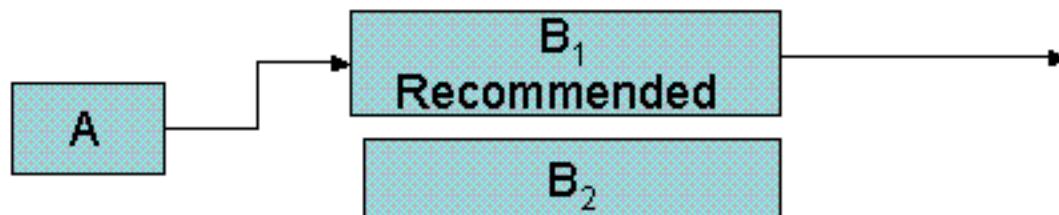
Alternative Models; Code Recommendation

Case 2

- Run the Code as Recommended

Example: User Choice

Operative area change: Abrupt Area Change vs. Smooth Area Change, or Partially Area Change



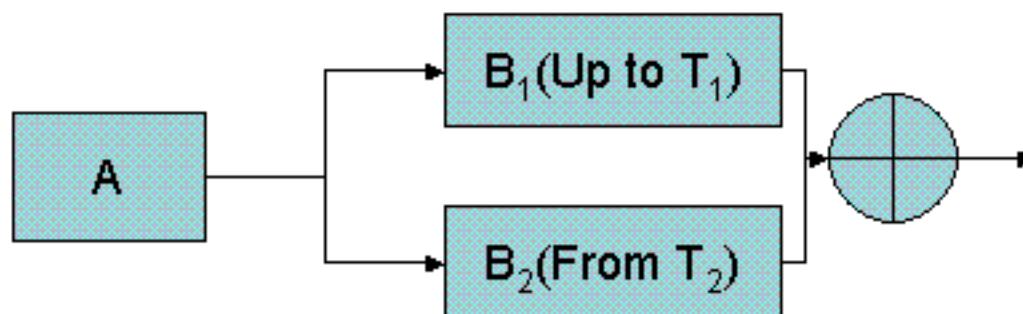
Two Different Data Set Different Structure



Alternative Models; User Choice

Case 3

- Change of Code Models by User in an Ongoing Run
 - Alternative Models in User Input
 - Some of them are not allowed by the Code

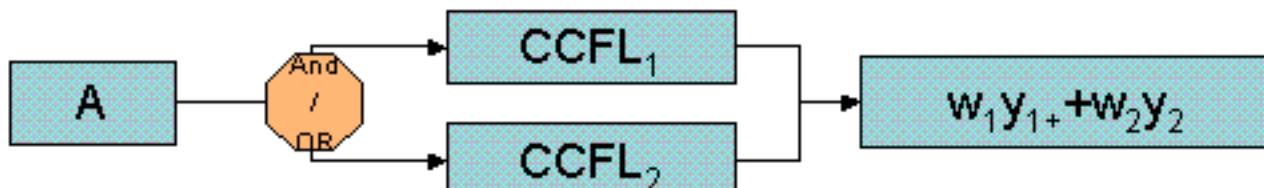


T₁: Change in Conditions (e.g., Boiling Curve)

or

T₁: Change of Model for its better Results

Alternative Models; Model Mixing Case 5



Same underlining Data but Different Model Structures

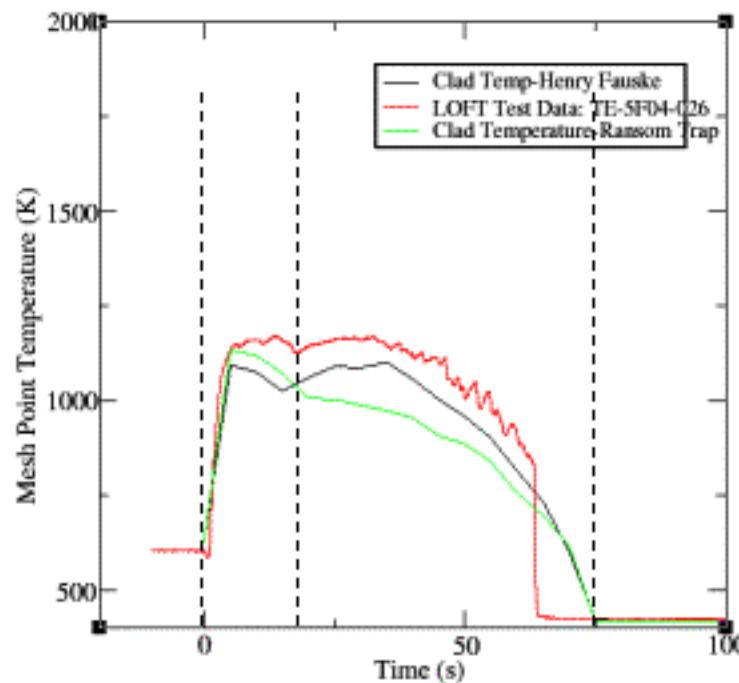
- CCFL Model: Wallis, Kutateladze and Bankoff correlation
 - $\beta = 0$ Wallis Correlation,
 - $\beta = 1$ Kutateladze Correlation
 - $0 < \beta < 1$, Bankoff Model as weighting of Wallis and Kutateladze Correlation
- Requested by User
- The coding checks if CCFL exists and if the liquid downflow exceeds the limit



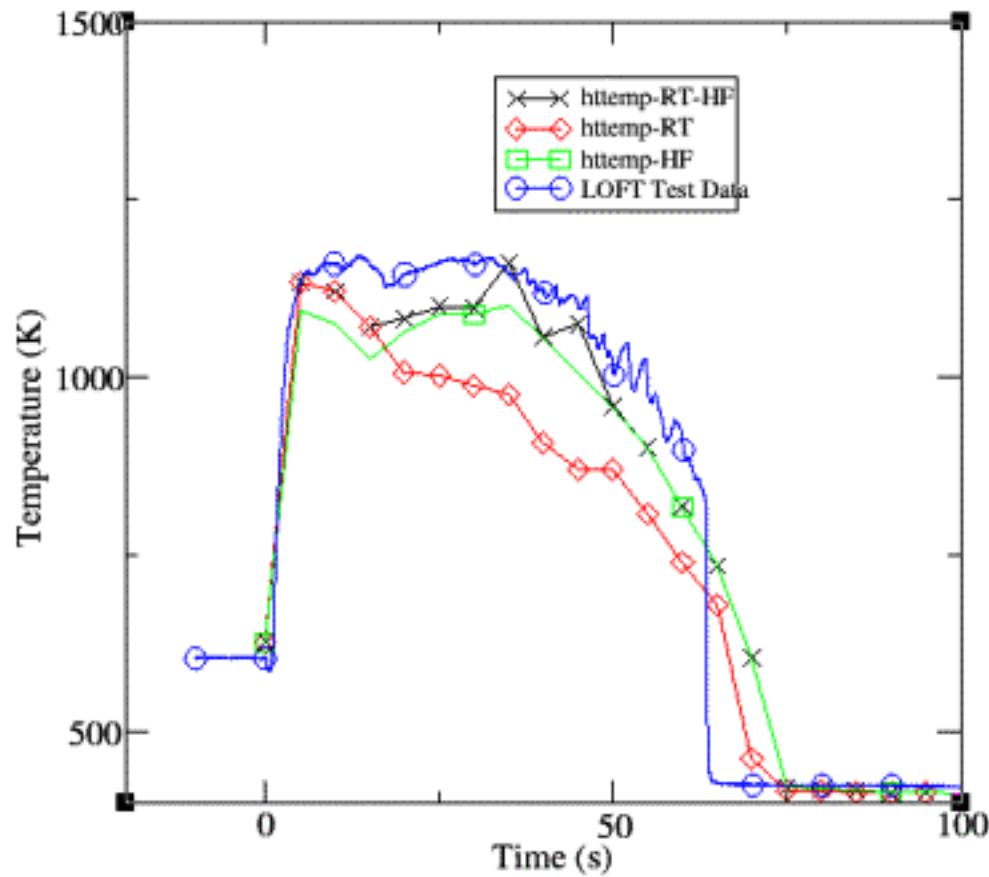
Alternative Models; Model Switch (cont.)

Case 5

- Code Capability to Switch between Alternative Models
 - ✓ Example; Henry-Fauske/Ransom Trap Models
- User Option (53)
- switch between the models based on problem time.
- switch between the models based on some physical conditions e.g., the void fraction of the upstream volume.



Model Switch



Alternative Models; MAX-MIN Case 6

- Selection of maximum or minimum of two model calculations

Example:

Code Selection:

Superheated Interfacial Heat Transfer Coefficients (h_{il} , h_{ig})

- ✓ Analytically Derived Correlation by Plesset and Zwick vs.
- ✓ Deduced correlation by Lee and Ryley from the observed data

Maximum Value produced by one of two correlations



PIRT



Real World, Complexities and Uncertainties

**System: Selected Part of The World
a NPP with its Surrounding Environment
Scenario**

Representative of interested Time-Dependent
Transient in limited time and location

**Phenomena Identification: Representatives
of Scenario in time phases in different
locations**

Phenomena, Process, Component Functions,
Behavior, Conditions, and Status

Too Many Phenomena

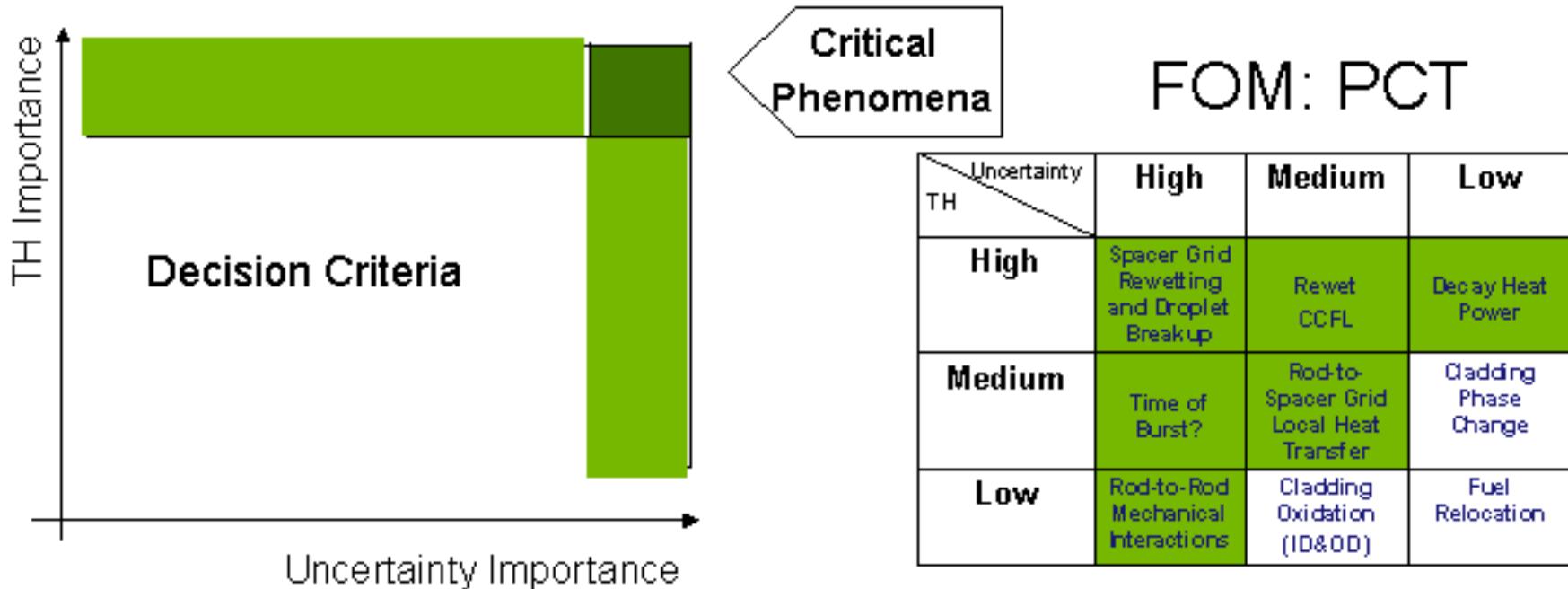
Different level of influence on FOM

Different level of Understanding

↓
PIRT Process



Modified PIRT



- Uncertainty Importance (in Form of Model Accuracy) is as important as TH Importance
 - ✓ TH importance is related to mean (nominal Value and Uncertainty Importance is related to deviation of the mean value)



Comparison LBLOCA PIRT

A Comparison

AREVA	Original CSAU	Westinghouse/EPRI
Dominant PIRT Parameters	Break Flow	Plant Initial Conditions
1.Break Flow	1.Mass Flow	1. RCS Average Fluid Temperature
2.Entrainment	Stored Energy an Fuel Response	2. RCS Pressure
3.Axial Power Distribution	1. Gap Conductance	3. Accumulator Fluid Temperature
4.Interfacial Heat Transfer	2. Peaking Factor	4. Accumulator Pressure
5.Core Multi-Dimnesional Flow	3. Fuel Conductivity	5. Accumulator Volume
6.ECCS Bypass	4. Fuel/ Fluid HT	6. Safety Injection Temperature
7.Steam Binding	5. Clad Conductivity	7.Accumulator Line Resistance
8.Spacer Effects	6. Fuel and Clad Heat Cap	Plant Initial Core Power Distribution
9.Cold Leg Condensation	7. Pellet Power Distribution	1.Nominal Hot Assembly Peaking Factor
10.Void Distribution	ECCS Bypass	2.Nominal Hot Assembly Average Relative Power
11.Accumulator Nitrogen Discharge	1. ECC Flow Deversion	3. Average relative power, lowerthird of core
12.Heat Transfer	Steam Binding	4. Average relative power, middle third of core
13.Upper Tie Plate CCFL	1. Liquid Mass Flow	5. Average relative power, outer edge of core
Treated Plant Parameters	2. Evaporation	Thermal-Hydraulics Physical Models
1.Core Power	3. Entrainment	1.Critical Flow Modeling (CF)
2.Pressurizer Pressure	4. De-entrainment	2. Broken Loop Resistance
3.Pressurizer Level	Pump 2-Phase Flow	3. Blowdown and reflood heattransfer
4.Accumulator Volume	1.Mass Flow	4. Minimum Film Boiling Temperature
5.Accumulator Pressure	2. Pressure	5. Condensation Modeling
6.Containment/Accumulator Temperature	3. Core Power	6. Break Type
7.Containment Volume	4. Dissolved Nitrogen	7. ECCS Bypass
8.Initial Flow Rate	5. Non-Condensable Gas Partial Pressure	8. Entrainment and Steam Binding
9.Initial Operating Temperature		9. Effect of Nitrogen Injection
10.Offsite Power Availability		(d) Hot Rod physical Models
11.Diesel Start		1. Local Hot Spot Peaking Factor
		2. Fuel Conductivity
		3. Gap Heat Transfer Coefficient
		4. Fuel Conductivity after Burst
		5. Fuel Density after Burst(Fuel Relocation)
		6. Cladding Reaction Rate
		7. Rod Internal Pressure
		8. Burst Temperature
		9. Burst Strain



Proposal for Comprehensive List of all Phenomena

- Development of Comprehensive Phenomena Matrix including all Phenomena, Process, Component Functions, Behavior, Conditions, and Status
 - ✓ Completion of Phenomena Matrix Initiated by OECD
 - ✓ A Pre-Processor for PIRT Developers



Modified PIRT Process

LOFT Application

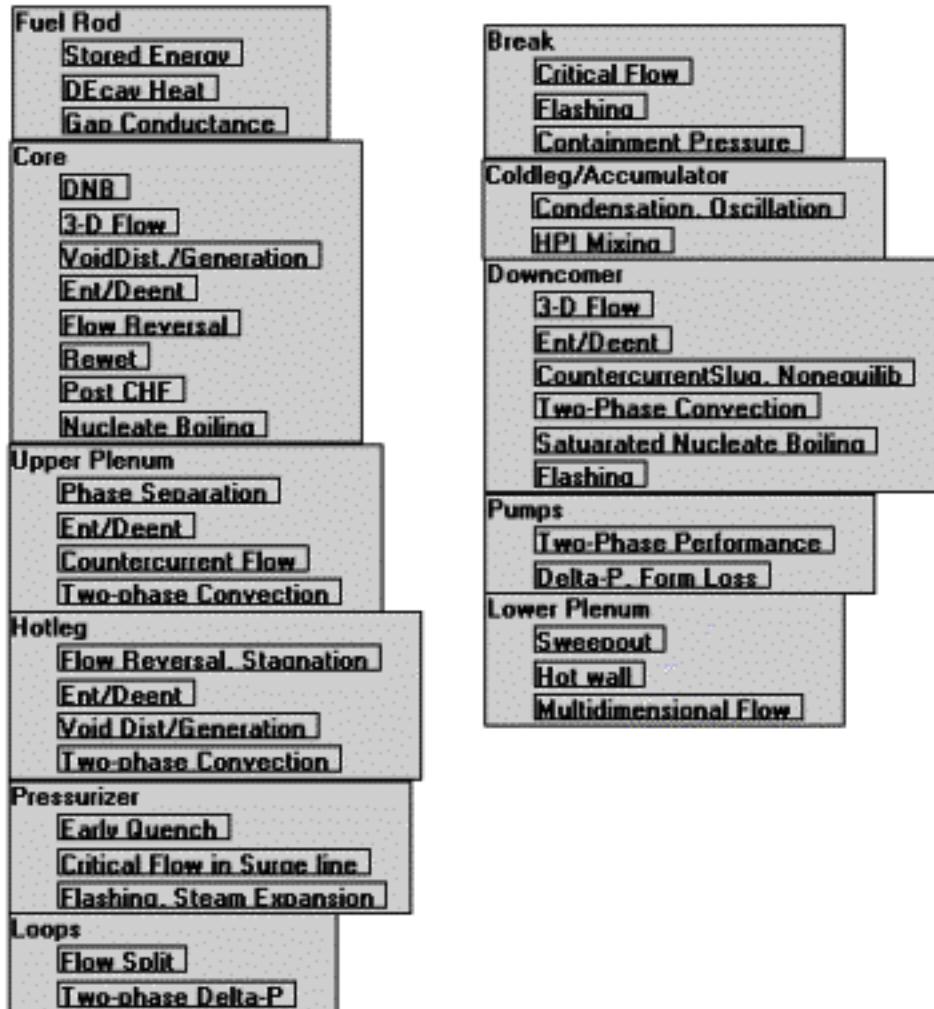
➤ TH/Uncertainty Process

- ✓ Identification:
 - Literature
 - Expert Judgment
 - Already Completed PIRTs
- ✓ TH Ranking
 - Analytical Hierarchical Process (AHP)
- ✓ Uncertainty Importance Assessment:
 - Degree of Credibility of the TH model(s)
 - Subjective Justification by Evaluating Available Information and Data from Experiments, and Code Predictions



Modified PIRT (cont.)

Phenomena Identification-Blow-Down Phase



PIRT Results

Upper Plenum	Phase Separation	Ent./Deent.	2-Phase Convection	Countercurrent Flow
Phase Separation	1	3	1	9
Ent./Deent.	0.333	1	0.333	1
2-phase Convection	1	3	1	9
Countercurrent Flow	0.111	1	0.111	1

LOFT PIRT Development		Uncertainty Importance	TH Rank During Phase		
Component	Phenomena	Models	Blowdown	Refill	Reflood
Fuel Rod	Stored Energy	Low	0.735	0.532	0.068
	Decay Heat	Low	0.058	0.185	0.363
	Oxidation	Medium	*	0.097	0.319
	Gap Conductance	Medium	0.207	0.185	0.249
Core	Post-CHF heat Transfer	High	0.171	0.245	0.092
	Rewet	Medium	0.283	0.051	0.016
	Reflood Heat Transfer plus quench	High	*	*	0.199
	3-D flow	Medium	0.021	0.098	0.128
	Void generation/distribution	Low	0.105	0.178	0.132
	Entrainment/Deentrainment	Medium	0.032	0.082	0.102
	Nucleate Boiling	Medium	0.114	0.045	0.031
	Flow Reversal, Stagnation	Medium	0.082	0.043	0.016
	DNB	Low	0.191	0.048	0.023
	One-phase vapor natural convection	Low	*	0.201	0.202



Results (cont.)

After Quantitative Confirmation

Facility Operation Parameters
Initial Core Power
Pressurizer Pressure
Pressurizer Level
Accumulator Pressure
Accumulator Volume
Safety Injection Temperature
Containment Volume
Initial Flow Rate
Initial Operating Temperature
RCS Pressure
RCS Average Fluid Temperature

**PIRT
Results
+
Sensitivity
Analysis**

High Importance TH Phenomena
Critical Flow
Rewet
Entrainment/Deentrainment
Post-CHF Heat Transfer
Core 3-D Flow
Pump Two-Phase Flow
Non-Condensable Gases
Steam Binding
Conductive/ Convective Heat Transfer



Propagation



Uncertainty Propagation

- Tolerance limits:
 - *Non-parametric* : Nothing known about distribution except its continuousness
 - *Parametric* : know form of distribution but unknown values of some limited numbers of parameters
 - Tolerance limit provide an interval within which at least a proportion q of population lies with probability $1-\alpha$ or more that the stated interval does indeed “contain” the proportion of the population
 - Drawing random sample of size n , X_1, X_2, \dots, X_n ,
 - ✓ how large n should be so that we can be $1-\alpha$ (95%) sure that at least β (95%) of the population lies between specified limits
 - One-Sided vs. Two-Sided
 - Dependencies are considered for quantification
 - ✓ If judged to be potentially important
-



Tolerance Limit Basis

$$P\{T \in H_a\} = \int_{T_L}^{T_U} dG(T) = \gamma$$

➤ G(T): Unknown CDF of output variable T

➤ N times Code Runs $T_1, T_2, T_3, \dots, T_N$,

$$T_1 < T_2 < \dots < T_N$$

$$\beta = \sum_{j=0}^{s-1} \binom{N}{j} \gamma^j (1-\gamma)^{N-j}$$

In Case of Two-Sided Tolerance Limit,

$$\beta = 1 - \gamma^N - N(1 - \gamma) \gamma^{N-1}$$

93 Runs required for 95%|95% for the Single Output single variable



Statistical Aspects



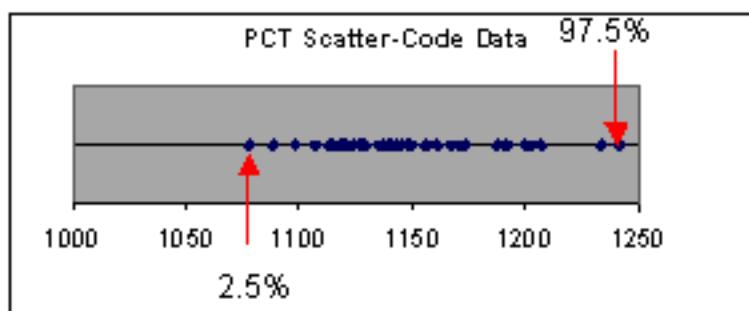
Output Updating

- A Bayesian Methodology Approach to Utilize Information and Data about Output
 - ✓ More Precise Results Distribution utilizing Experimental Data
- Statistical Proof for accuracy of Non-Paired Updating



Transient From Input phase to Out-Put Phase

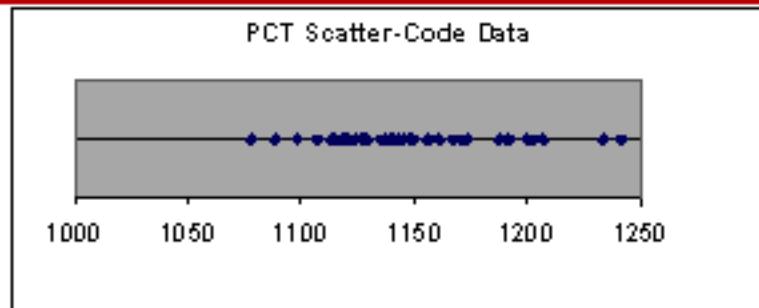
Method 1



- A distribution shape is assumed for the Data
 - ✓ Fits the Best to the Data
 - ✓ e.g., normal or lognormal distribution
- Coverage Area of the Distribution from Tolerance Interval is assigned to Distribution Quantiles Depends on Coverage
 - ✓ The smallest to 2.5% and the Largest to 97.5%
- Distribution Parameters Estimation From Quantiles



Transient From Input phase to Out-Put Phase Method 2



- Assumed Distribution Shape for the data
 - ✓ Fits the Best to the Data
 - ✓ (e.g., normal or lognormal distribution)
- Assumed Prior for Distributions Parameters
 - ✓ Wide Ranges
- Update Distribution of Parameters Utilizing Bayesian Theory

$$\pi(\mu, \sigma) = \frac{L(T_1, T_2, \dots, T_{59})\pi_0(\mu, \sigma)}{\iint_{\mu, \sigma} L(T_1, T_2, \dots, T_{59})\pi_0(\mu, \sigma)}$$



Uncertainty Importance



Uncertainty Importance

	X_1	X_2	X_3	X_4	X_N
$+1\sigma$	Out($X_1+1\sigma$)	Out($X_2+1\sigma$)			Out($X_N+1\sigma$)
$+2\sigma$	Out($X_1+2\sigma$)	Out($X_2+2\sigma$)			Out($X_N+2\sigma$)
$+3\sigma$.	.				
-1σ	.	.				
-2σ						
-3σ	Out($X_1-3\sigma$)	Out($X_2-3\sigma$)	...			Out($X_N-3\sigma$)
Importance Measure =	$\frac{\sigma_{out_1}}{\sigma_p}$					

➤ Importance measure may be defined in different ways



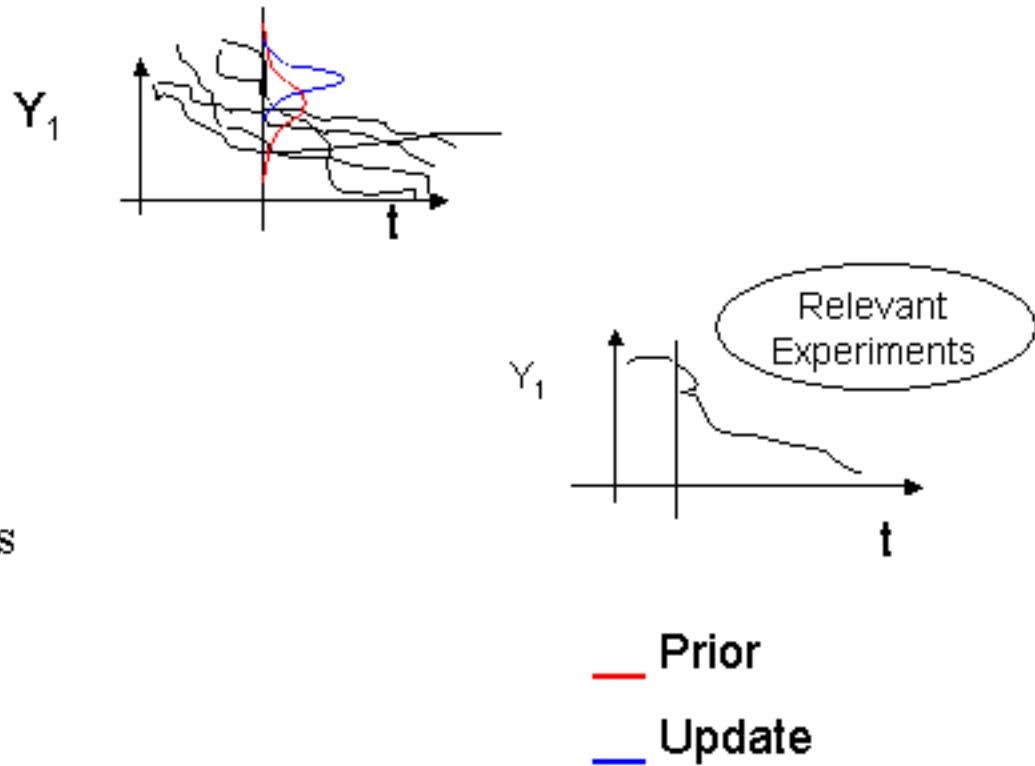
Output Updating



Implicit Consideration of Uncertainties

Second level: Output Updating

- Data and information about output (Usually integral test data) not used for input uncertainty characterization
- Bayesian updating for output is devised to perform updating



Missing Uncertainty Source Effect

- Screening by Expert Judgment
- Total 95%/95% uncertainty on considering existing parameters=350
- Uncorrelated Sources of uncertainties

$$\sigma_x^2 = \sum_{i=1}^n \sigma_i^2$$

- Effect of a missing (unmodeled parameter):

$$\sigma_{new} = 30$$

$$(\sigma_x^2 + \sigma_{n+1}^2)^{1/2} - \sigma_x = (350^2 + 30^2) - 350 = 1.28$$



Output Updating

- Independent Data Required
 - ✓ Data from Integrated test Facility
- The goal is building likelihood function of the available data
- Approaches
 - ✓ Paired Data
 - Equal Number of Experimental and Calculation Data
 - Association of Test Data $(T_1^D, T_2^D, \dots, T_n^D)$ with $(T_1^M, T_2^M, \dots, T_n^M)$
 - ✓ Independent Data
 - Unequal number of test and code data
 - Assumption of independency between test and code data
- Data can not be precisely paired in case of TH computational codes
 - ✓ Many Unknown BIC in Pairing Experiment and Calculation
 - ✓ Unequal Sizes of Experiment and Calculation Data
 - ✓ Due to Temporal Uncertainty in Magnitude and Timing, it is not Easy to Pair Data Points



Mathematical Basis

Data Availability and Applicability

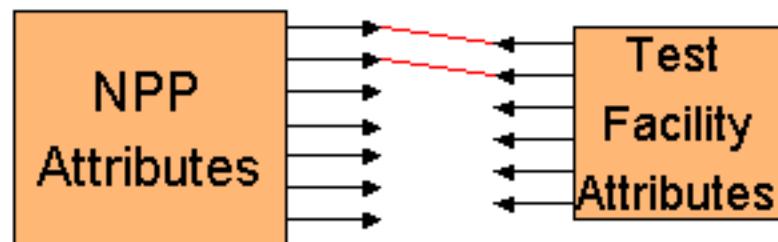
➤ Availability of Data

- ✓ Model Estimate from Code Calculation
- ✓ Experimental data set D such that $D=\{D_1, D_2, \dots, D_3\}$
- ✓ Confidence Factor φ

➤ Applicability of Data

➤ Attributes of Scenario Facility and Experimental Facilities,

- ✓ Distortion from Scaling (e.g., π group values)
- ✓ Location and Size of Break,
- ✓ Rate of power,
- ✓ Scaling Ratio of the Facilities,
- ✓ Involved Safety systems,
- ✓ Nuclear Core Configuration
- ✓ Others!



Binary Matching & Comparing Attributes



Mathematics Basis (cont.)

Data Applicability

➤ $0 \leq \varphi \leq 1$

Applicability Weight	
Value (φ)	Statement
0.00	Absolutely not Applicable
0.20	Strongly not Applicable
0.40	Moderately not Applicable
0.50	Slightly Applicable
0.60	Moderately Applicable
0.80	Strongly Applicable
1.00	Absolutely Applicable

$$\pi(T | IM, D) = \frac{[L(IM, D | T)]^\varphi \cdot \pi(T)}{\int_T [L(IM, D | T)]^\varphi \cdot \pi(T) dT}$$



Likelihood Adjustment Method Method 2

- Φ come from Source Data
- Assuming a Shape for Likelihood (e.g., Normal)
- Adjusting the Parameters (e.g., μ, σ)

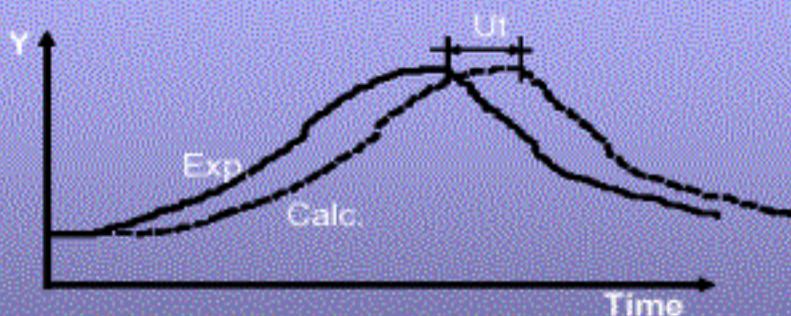
$$[L(IM, D | T)]^\varphi$$

$$L(IM, D | T) = [L(IM, D | \mu, \sigma)]^\varphi$$

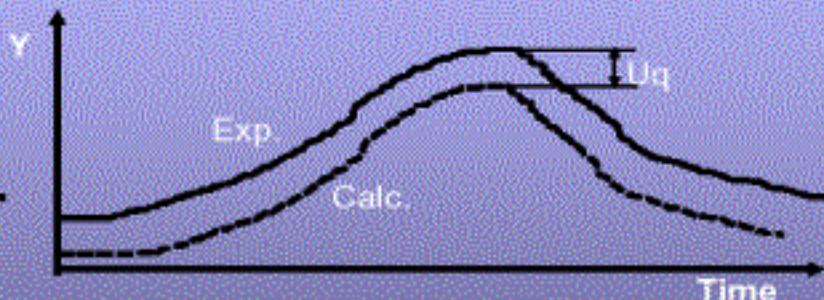


UMAE

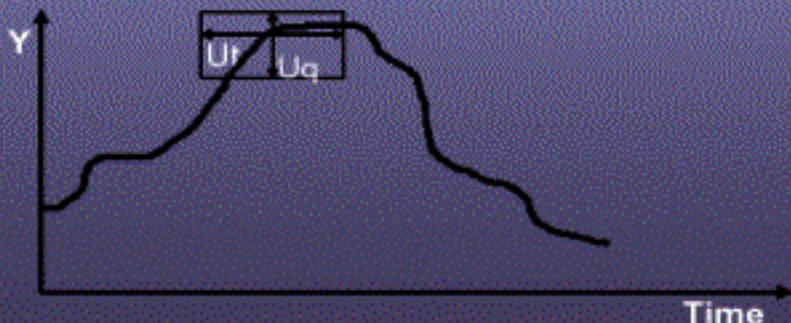
SEPARATION AND RECOMBINATION OF TIME ERROR AND QUANTITY ERROR



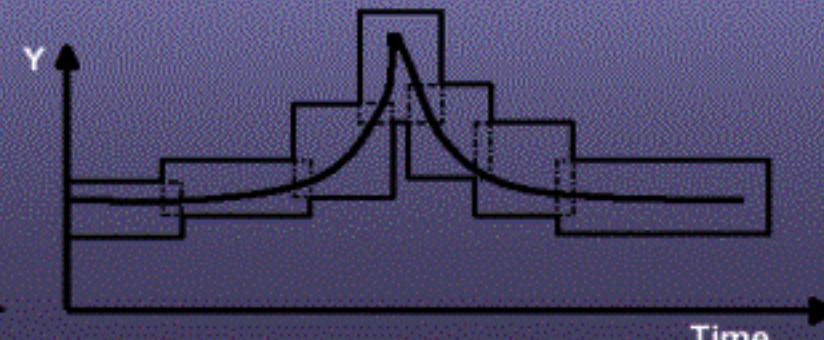
a) only Time Error is present



b) only Quantity Error is present



c) Combination of Errors



d) Derivation of Continuous Uncertainty Bands

9/41



Paired Data vs. Independent-Data

➤ Paired Data

- ✓ Possibility to construct Error distribution explicitly

$$Y_{n+1}^M \Rightarrow Y_{n+1}^M + \bar{E} + z.S_E$$

$$\bar{E} = \frac{1}{n} \sum_{j=1}^n E_j$$

$$S_E^2 = \frac{1}{n-1} \sum_{j=1}^n (E_j - \bar{E})^2$$

➤ Independent data

- BVN Distribution for data and code calculation
 - ✓ Test data and code result are not paired

$$Y_{m+1}^D \Rightarrow \bar{Y}_D + \frac{S_D}{S_M} (Y_{m+1}^M - \bar{Y}_M)$$

$$S_M^2 = \frac{1}{m-1} \sum_{j=1}^m (Y_j^M - \bar{Y}^M)^2$$

$$S_D^2 = \frac{1}{n-1} \sum_{j=1}^n (Y_j^D - \bar{Y}^D)^2$$

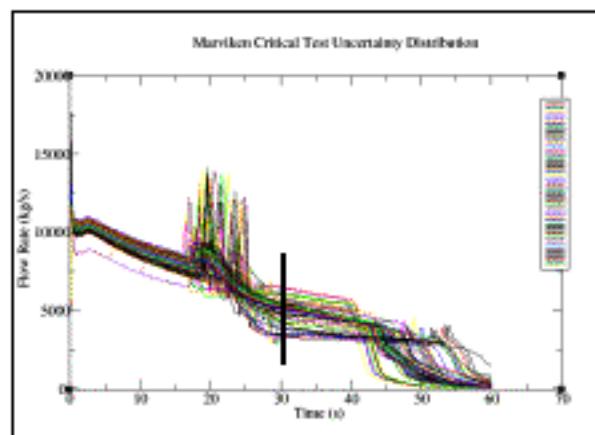
$$\bar{Y}^D = \frac{1}{n} \sum_{j=1}^n Y_j^D$$

$$\bar{Y}^M = \frac{1}{m} \sum_{j=1}^m Y_j^M$$



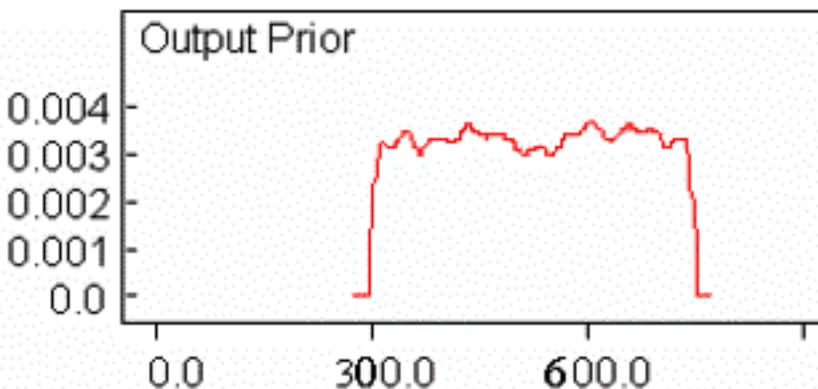
Marviken Test-Example (cont.)

Prior Distributions



➤ M=101 & N=3

- Truncated Normal Distribution for Test data and Code Data
- Uniform Prior distribution for parameters

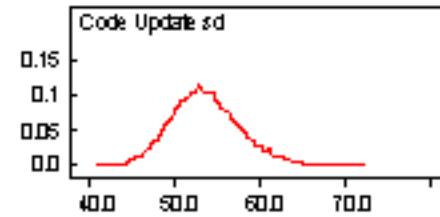
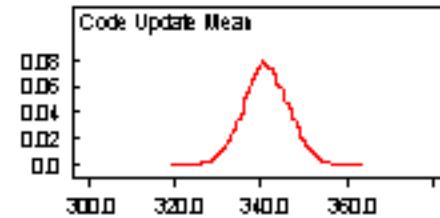
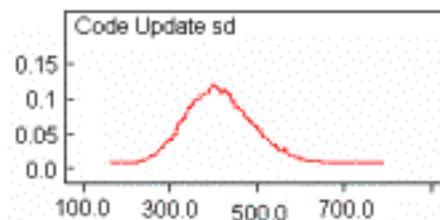
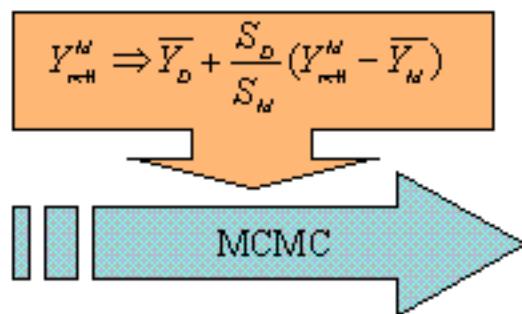
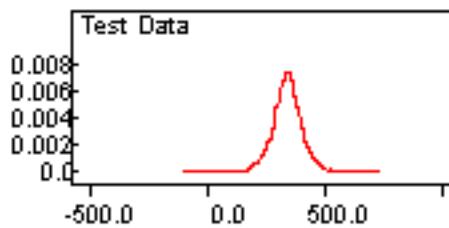
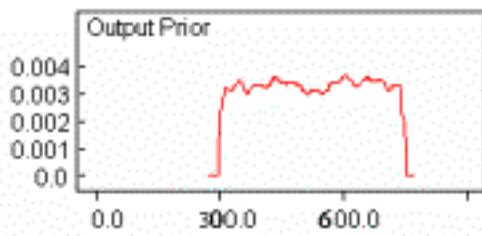


Node	Mean	SD	MC Error	5.00%	Median	95.00%
Code	526.8	5.7	0.9373	310.9	526.8	735.3



Marviken Facility Application- An Example (cont.)

Code Output Update



node	mean	sd	MC error	5.00%	median	95.00%
Code	335.9	12.83	0.1252	314.9	335.7	357
expr	340.7	67.12	0.723	231.5	340.9	449.5
4(Test)	341.3	33.44	0.3131	286.6	340.9	397.2
4(Code)	336.1	1.277	0.01439	334	336.1	338.2
*(Test)	53.53	21.47	0.301	23.48	50.26	92.9
*(Code)	12.87	0.9026	0.009175	11.31	12.63	14.25

node	mean	sd	MC error	5.00%	median	95.00%
code	341.2	54.22	0.3723	252.6	341.1	430.1
meanp	341.1	5.326	0.03598	332.3	341	350
sigmap	53.62	3.836	0.02857	47.66	53.39	60.28



Parameters Quantification



Parameters Quantification

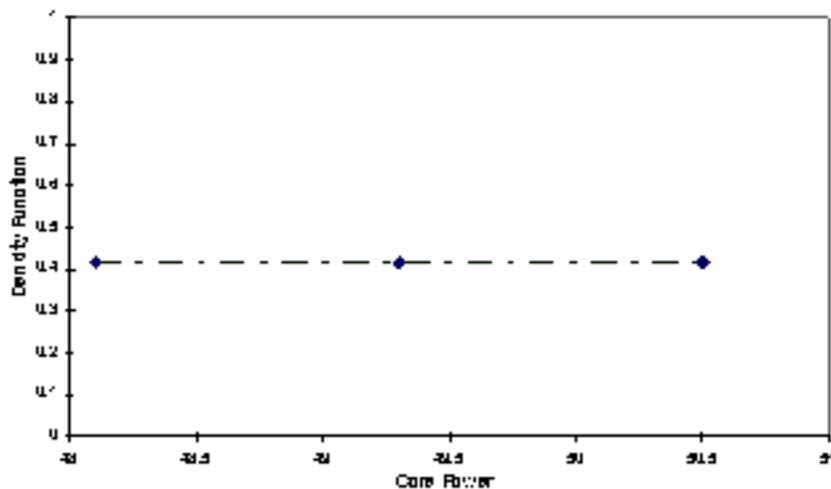
- Applicable Data Collection and Evaluation
 - ✓ Applicability Study
- Prior Distribution Quantification
 - ✓ Maximum Entropy, or Constrained ME Approach
 - ✓ Expert Justification
- Prior Update
 - ✓ The ME-Based Prior Distributions Update with Available Experts Opinion
 - ✓ Updating the Resulting Posterior Distributions with Experimental Data if Available



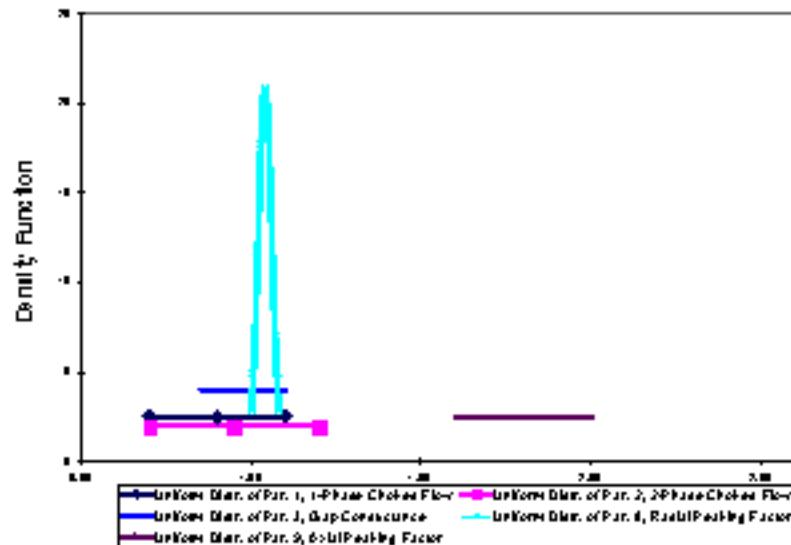
Parameters Distributions

An Example

LOFT Uncertainty Analysis-UMD
Uniform Distr. on Par. d. Core Power



LOFT Uncertainty Analysis-UMD



Parameters & Sampling

=====

DISTRIBUTIONS OF THE PARAMETERS

=====

PARAMETER NO. 1 : UNIFORM DISTRIBUTION
BETWEEN 7.0000E-01 AND 1.1000E+00

PARAMETER NO. 2 : UNIFORM DISTRIBUTION
BETWEEN 7.0000E-01 AND 1.2000E+00

PARAMETER NO. 3 : UNIFORM DISTRIBUTION
BETWEEN 8.5000E-01 AND 1.1000E+00

PARAMETER NO. 4 : NORMAL DISTRIBUTION
WITH MY= 1.0000E+00, SIGMA= 1.0000E01
TRUNCATED AT ITS
1.59E+01 % AND 8.41E+01 % QUANTILES

Index	Par. 1	Par. 2	Par. 3	Par. 4	Par. 5	Par. 6	Par. 7	Par. 8	Par. 9
1	0.73	0.89	0.86	1.00	1.05	1.02	1.78	2.42	15.04
2	1.07	0.71	0.89	1.03	1.05	1.02	1.60	2.35	15.04
3	0.76	0.91	1.06	1.04	1.05	0.97	1.87	2.24	14.93
4	0.78	1.20	1.08	0.95	1.07	1.01	1.86	2.51	14.82
5	0.85	0.75	0.94	0.98	1.03	1.00	1.84	2.38	14.77
6	1.04	0.87	0.87	0.93	1.02	1.09	1.73	2.47	14.72
7	0.96	0.74	0.89	1.01	1.01	1.03	1.81	2.21	15.02
8	0.83	0.91	1.04	0.99	1.03	1.03	1.80	2.14	14.85
9	1.03	0.79	0.97	0.99	1.06	1.07	1.86	2.12	14.76
10	0.96	1.04	0.99	1.00	1.04	0.95	1.86	2.39	14.95
11	1.08	0.81	0.89	1.04	1.02	1.06	1.92	2.15	14.76
12	1.08	0.72	0.89	0.93	1.03	0.94	1.82	2.13	14.89
13	0.90	1.10	1.00	1.08	1.06	0.97	1.80	2.30	14.94
14	0.91	0.75	0.92	1.08	1.06	1.10	1.97	2.48	14.77
15	1.09	0.75	1.09	0.98	1.06	1.02	1.74	2.33	14.75
16	0.80	0.91	0.93	1.07	1.05	0.92	1.84	2.33	14.88
17	0.72	1.03	0.90	1.10	1.03	0.93	1.72	2.58	14.81
18	0.93	0.95	1.02	0.93	1.04	0.97	1.89	2.31	14.81
19				1.04	1.07	0.94	1.95	2.17	15.01

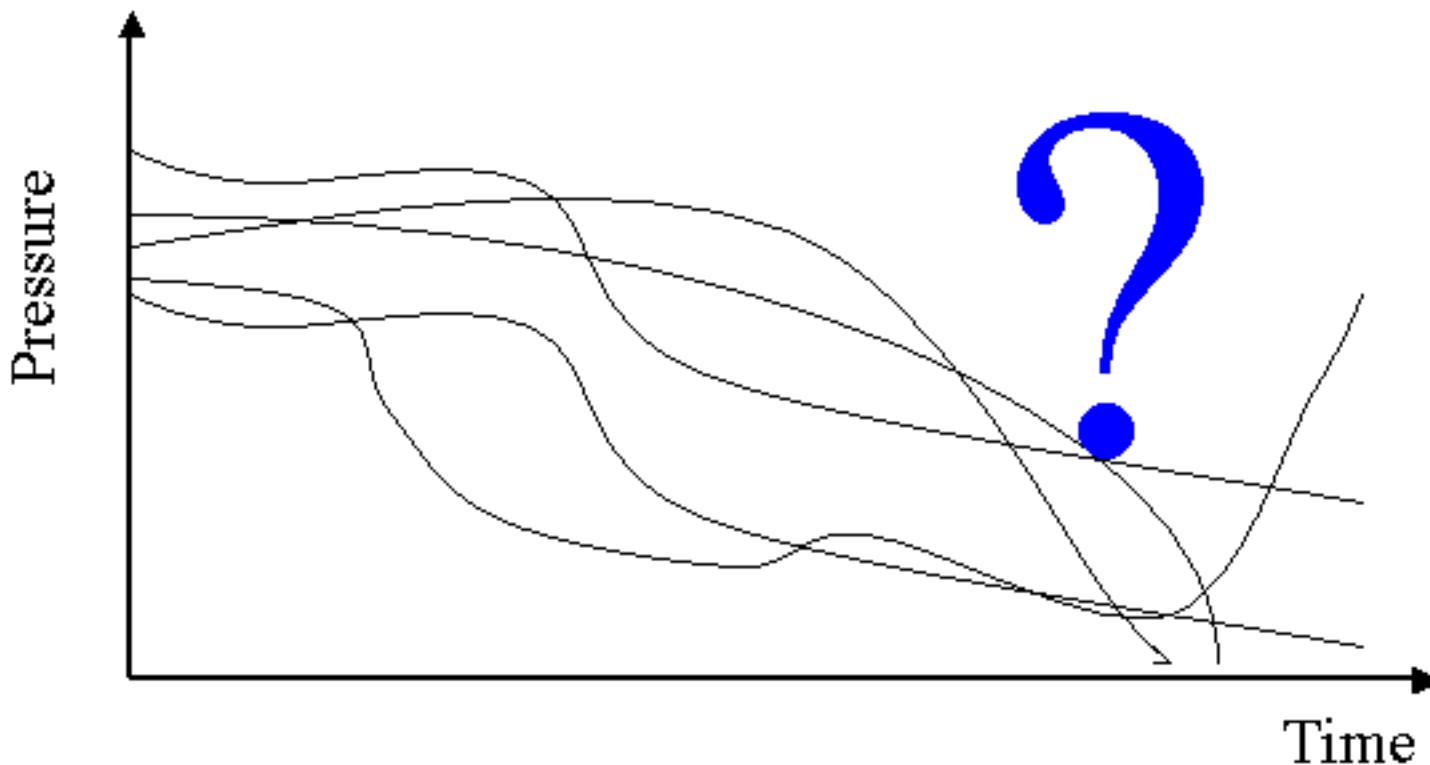


Physical/Statistical Representation/Interpretation



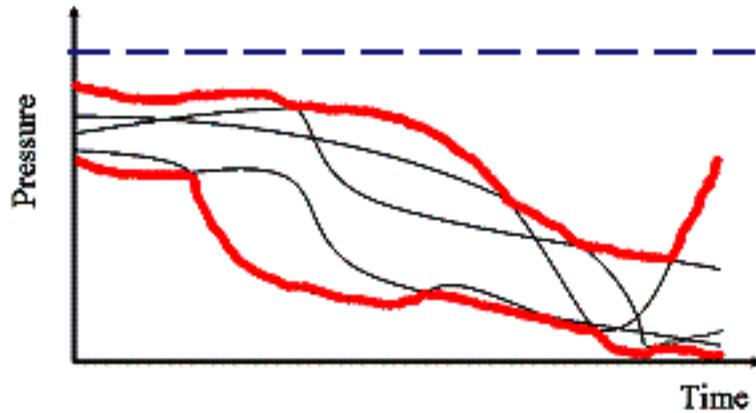
End Results Discussion

Correct Representation/Interpretation of Results



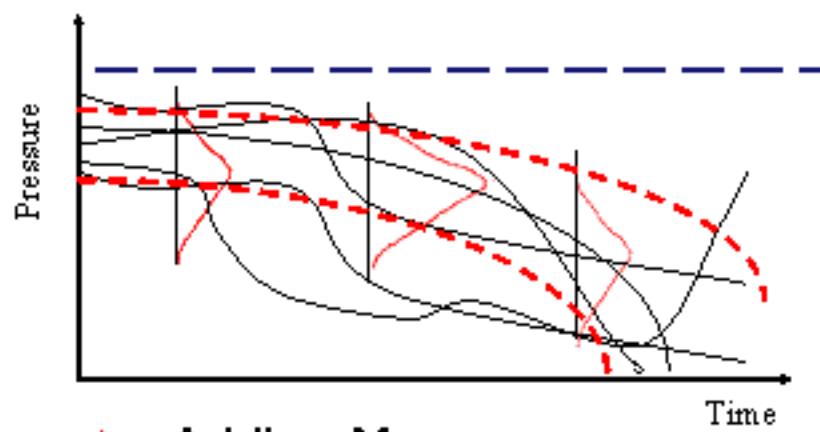
Correct Representation/Interpretation of Results (cont.)

- Physical Representation/
Interpretation



- Interpretation of Events
Causing Different Behavior in
the Trend

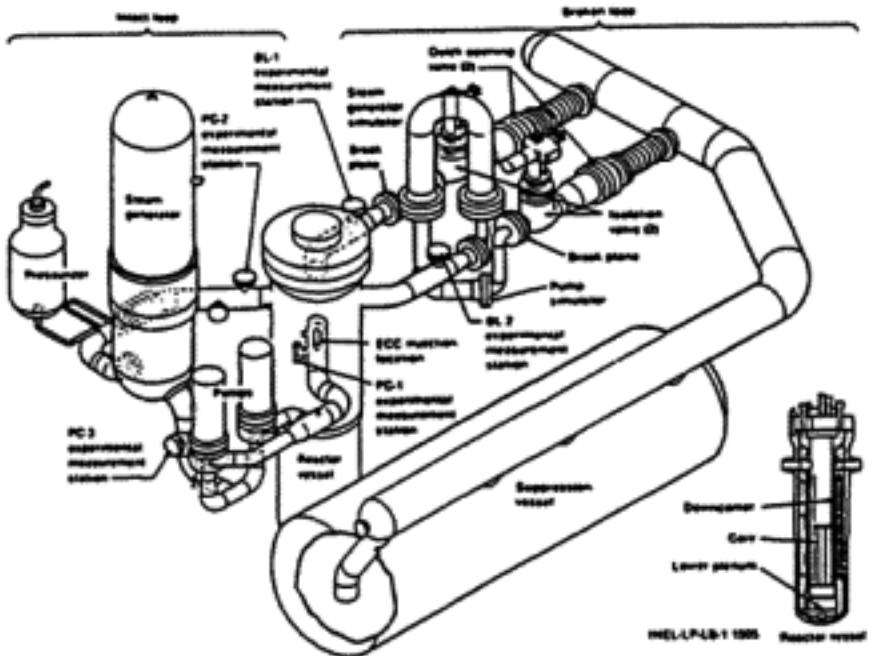
- Statistical Representation/
Interpretation



- Adding More
Uncertainty on the Tails
- Predictions on Future
Behavior



LOFT Application Test LB-1 Facility



<i>Item</i>	<i>LOFT</i>
Fuel rod number	1300
Length (m)	1.68
Inlet flow area (m ²)	0.16
Coolant volume (m ³)	0.295
Maximum linear heat generation rate (kW/m)	39.4
Coolant temperature rise (K)	32.2
Power (MW)	36.7
Peaking factor	2.34
Power/coolant volume (MW/m ³)	124.4
Core volume/system volume	0.038
Mass flux (kg/s-m ²)	1248.8
Core mass flow/system volume (kg/s-m ³)	25.6



Initial Conditions and Scenario Sequence of Time

➤ Scenario Specification

- ✓ High Power Fuel Assembly
- ✓ 200% Cold Leg Break Test
- ✓ Higher Reactor Power (49.3 MW) and Loop Flow
- ✓ Inactivated High Pressure Injection
- ✓ Intact Loop Pumps with Fly Wheel
Disconnected Fly Wheel at Pump Trip

LOFT measured initial conditions LB-1	
Parameter	LB-1
Reactor Power (MW)	49.3
Low Pressure Scram Set Point (MPa)	14.5
Intact-loop Mass Flow(kg/s-m ²)	305.8
Hot-leg Pressure (Mpa)	14.77
Hot-leg Temperature (°F)	586.1
Cold-leg Temperature (°F)	556.6
Pump Speed (rad/s)	209
Pressurizer Steam Volume (m ³)	0.38
Pressurizer Liquid Volume (m)	0.55
Steam-generator Pressure (MPa)	5.53
Steam-generator Mass Flow(kg/s)	25.4
Accumulator Pressure (MPa)	4.21
Accumulator Temperature (°F)	305
Accumulator Initial Level (m)	2.31
Accumulator Level at End of Discharge (m)	1.75
Accumulator Liquid Level Change (m)	0.56
Accumulator Liquid Volume Discharged (m ³)	0.76
Accumulator Initial Gas Volume (m ³)	0.65
Accumulator Initial Gas/Liquid Fraction	0.85

LOFT Test LB-1 Sequence of Event Timing		
Event	Measured	Code Results
Break initiated (s)	0	0
Reactor scrammed (s)	0.13	0.13
Primary-coolant pumps tripped (s)	0.63	0.63
Pressurizer emptied (s)	Instrument failure	15.5
Accumulator A injection initiated (s)	17.4	14
Relood Tripped On (s)	NA	0
HPIS injection initiated (s)	NA	NA
LPIS injection initiated (s)	24.8	24.8
Maximum cladding temperature (°F)	1170	1050



Parameters

- Choked Flow (Measured Flow Rate/Predicted Flow Rate)
 - ✓ 1-Phase model multiplier
 - ✓ 2-Phase Model Multiplier
- Post-CHF Heat Transfer
 - ✓ Gap Conductance Model
 - ✓ Fuel Conductance Input Table in Inputdeck
- Pressurizer Level
 - ✓ Level Controller card in the Inputdeck
 - Measurement Error 1.04 +/- 4 cm
- Core Power
 - ✓ Power table
 - Measurement error 49.3 Mw_t +/- 1.3 Mw_t



Parameters (cont.)

- Entrainment
 - ✓ CCFL Hydraulics Diameters (Hot Leg, Downcomer, ...)
 - ✓ Steam Binding (Core Hydraulics Diameter)
- Peaking Factor
 - ✓ Radial
 - ✓ Axial
- Accumulator
 - ✓ Pressure
- Core Hydraulics Diameter (Steam Binding)
- Pump Two-Phase Flow
 - ✓ Mass Flow
 - ✓ Pressure



Test Data Matrix



Test Data Matrix Utilized Data

Test Facility \	1	2	3	4	5	6
LOFT	L2-3	L2-5	LP-LB-1	L3-1	L3-7	
Marviken	22	24	20			
ISP	2,5,8,9, 11, 27,38	13,17,12				
UPTF						
Flecht-Seaset						
TPTF						



LOFT Simulation

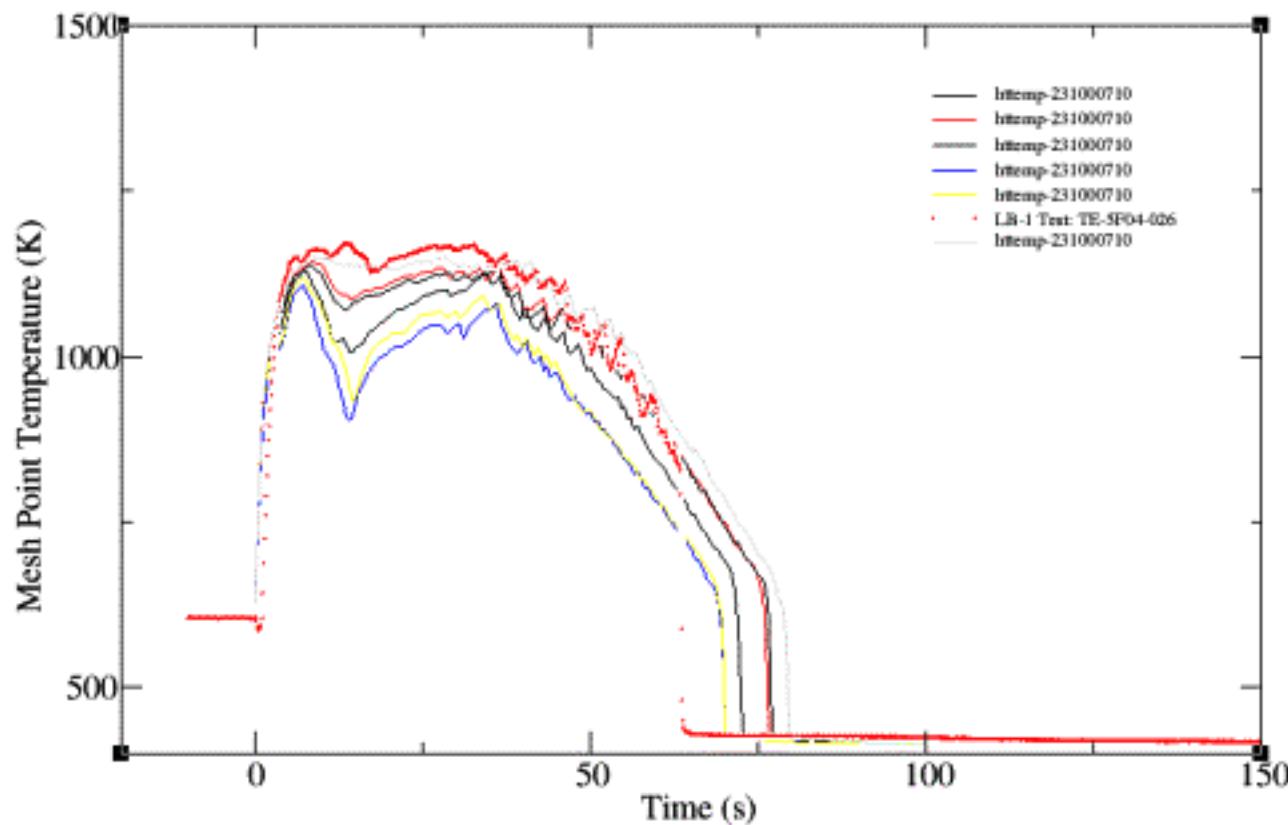
- LOFT Data was used (Non-Blind Simulation)
- Parameters Variability are not concerned
 - ✓ Accumulator Pressure, Temperature and Level



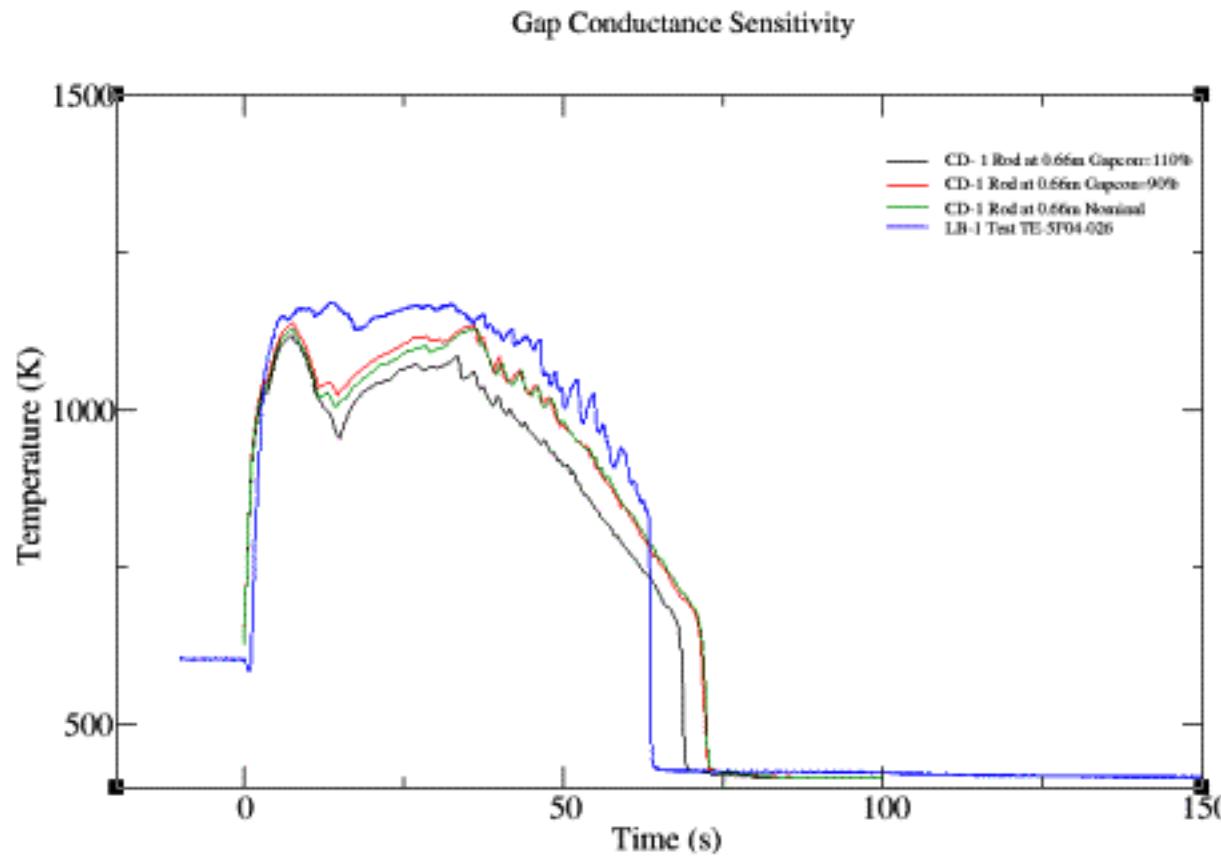
LOFT Sensitivity Analysis



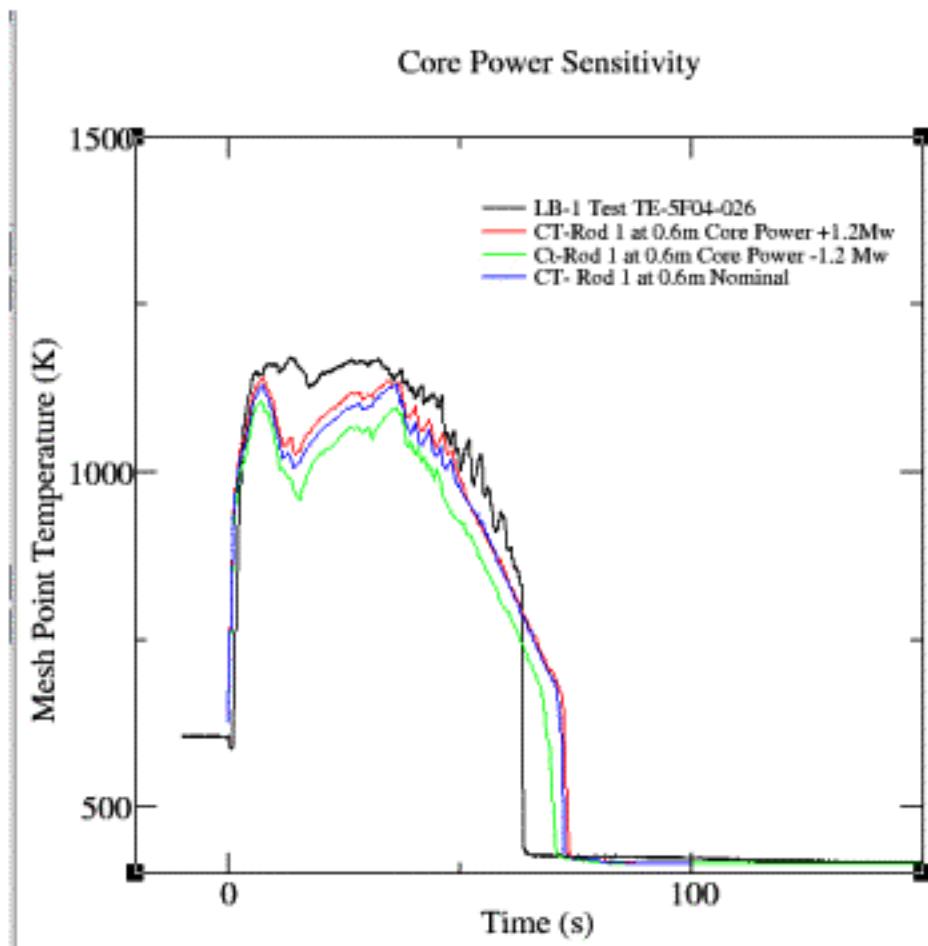
Cladding Temperature Rod 1 at 0.66m



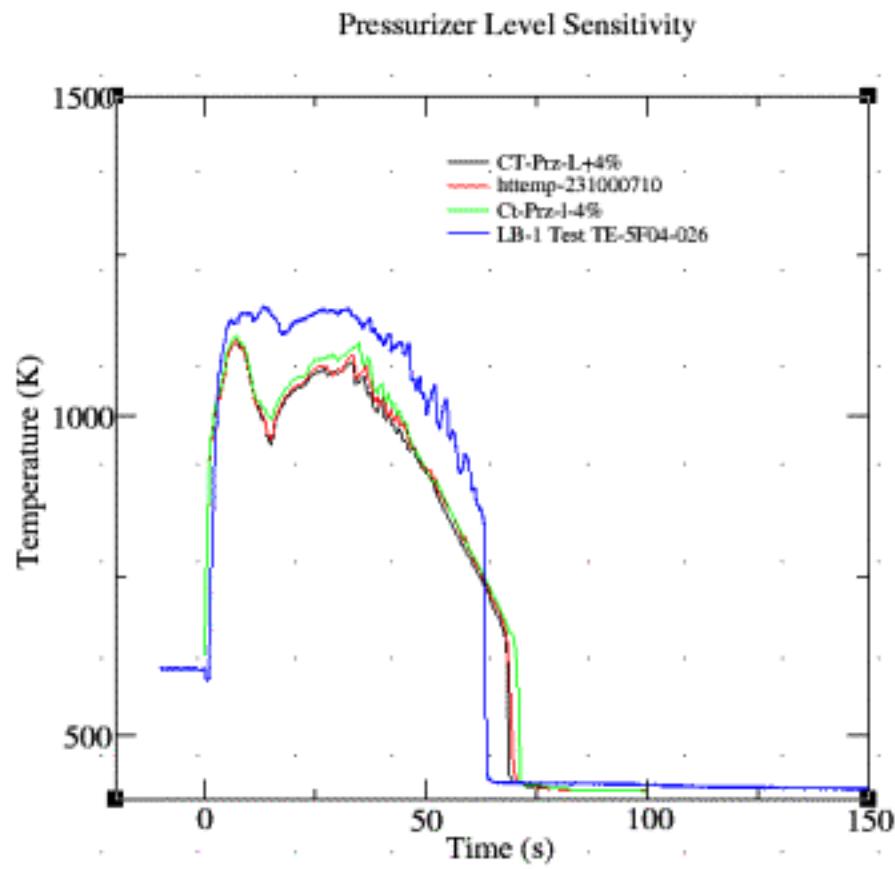
Gap Conductance Sensitivity



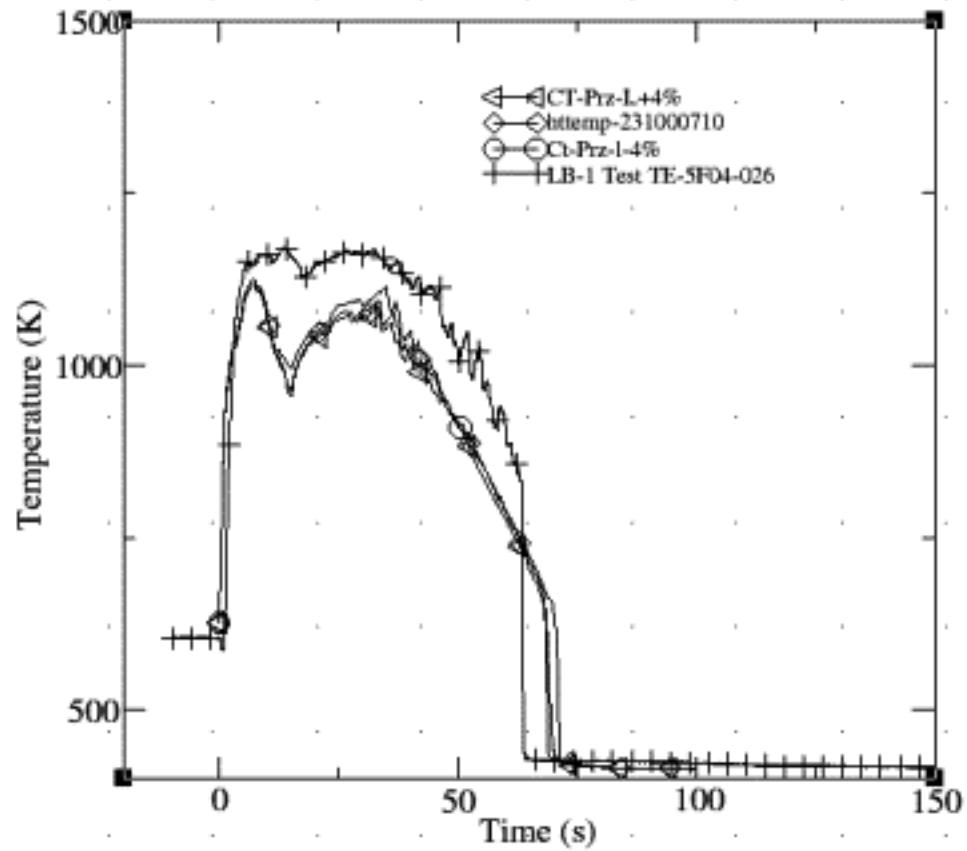
Core Power Sensitivity



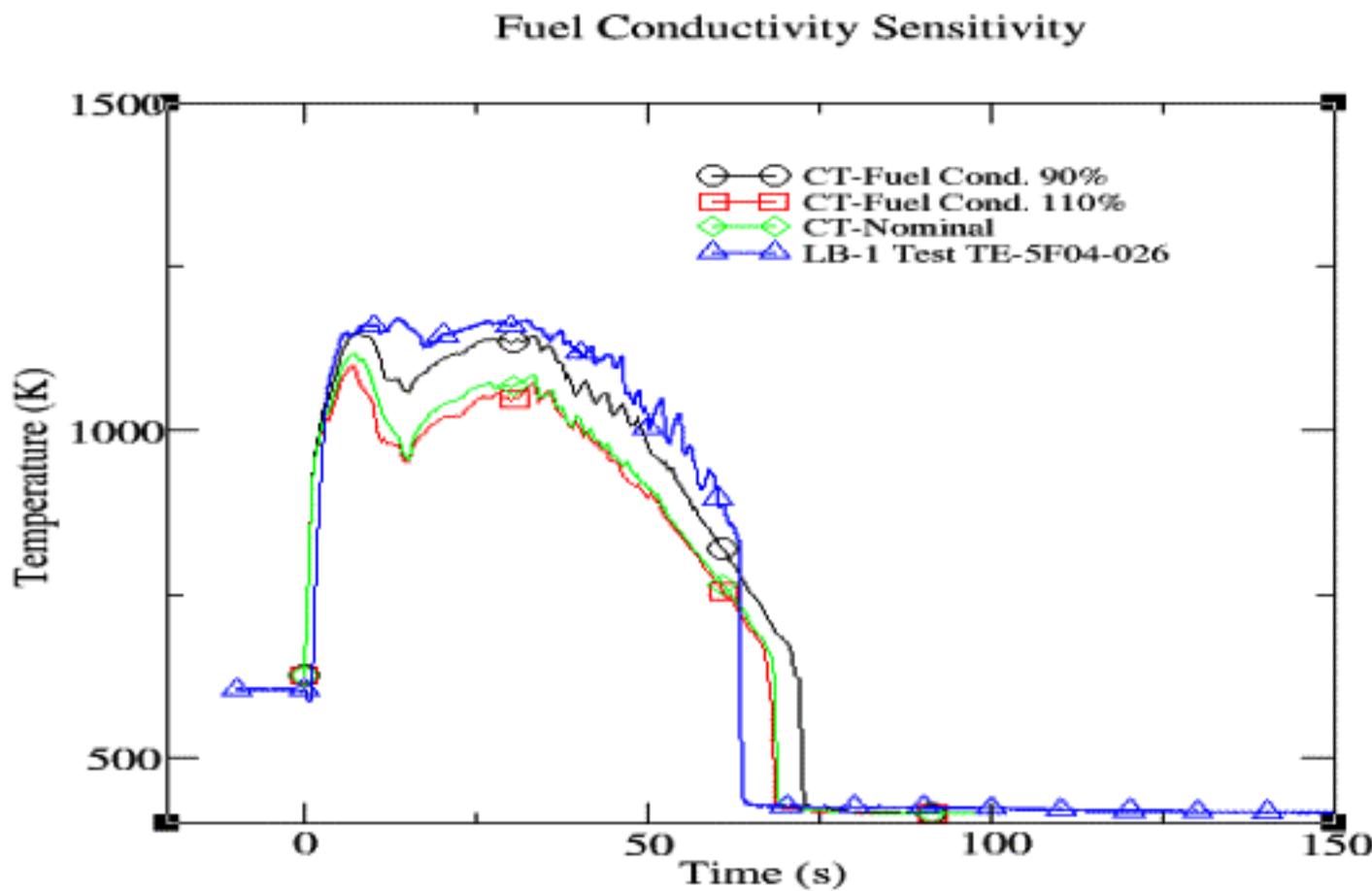
Pressurizer Level Sensitivity



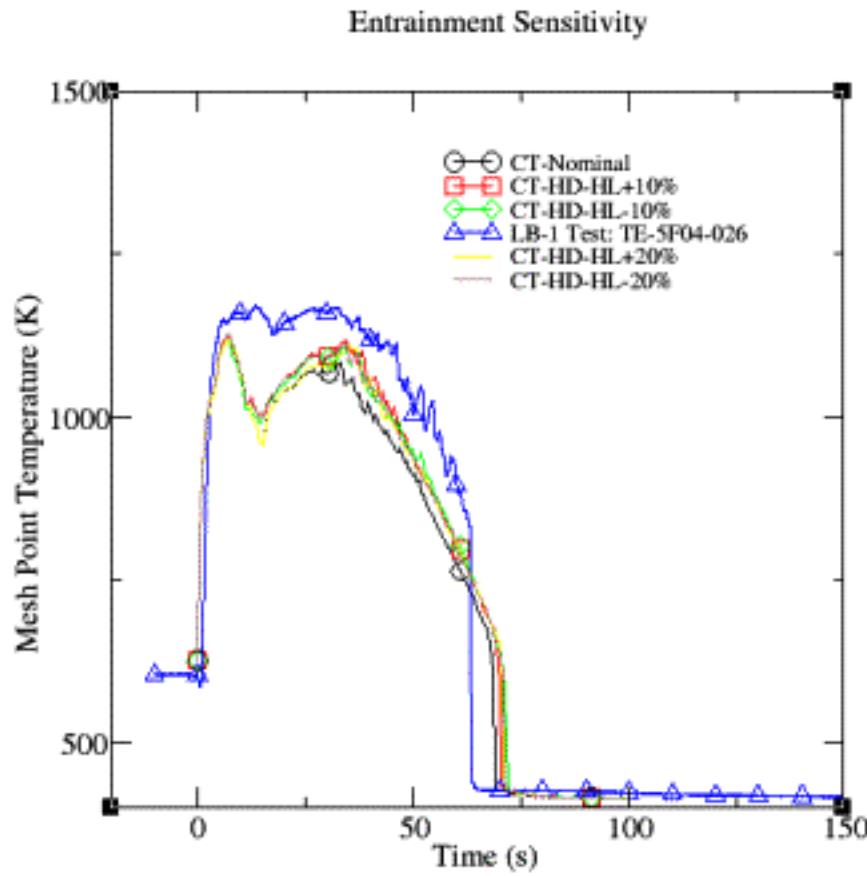
Pressurizer Level Sensitivity



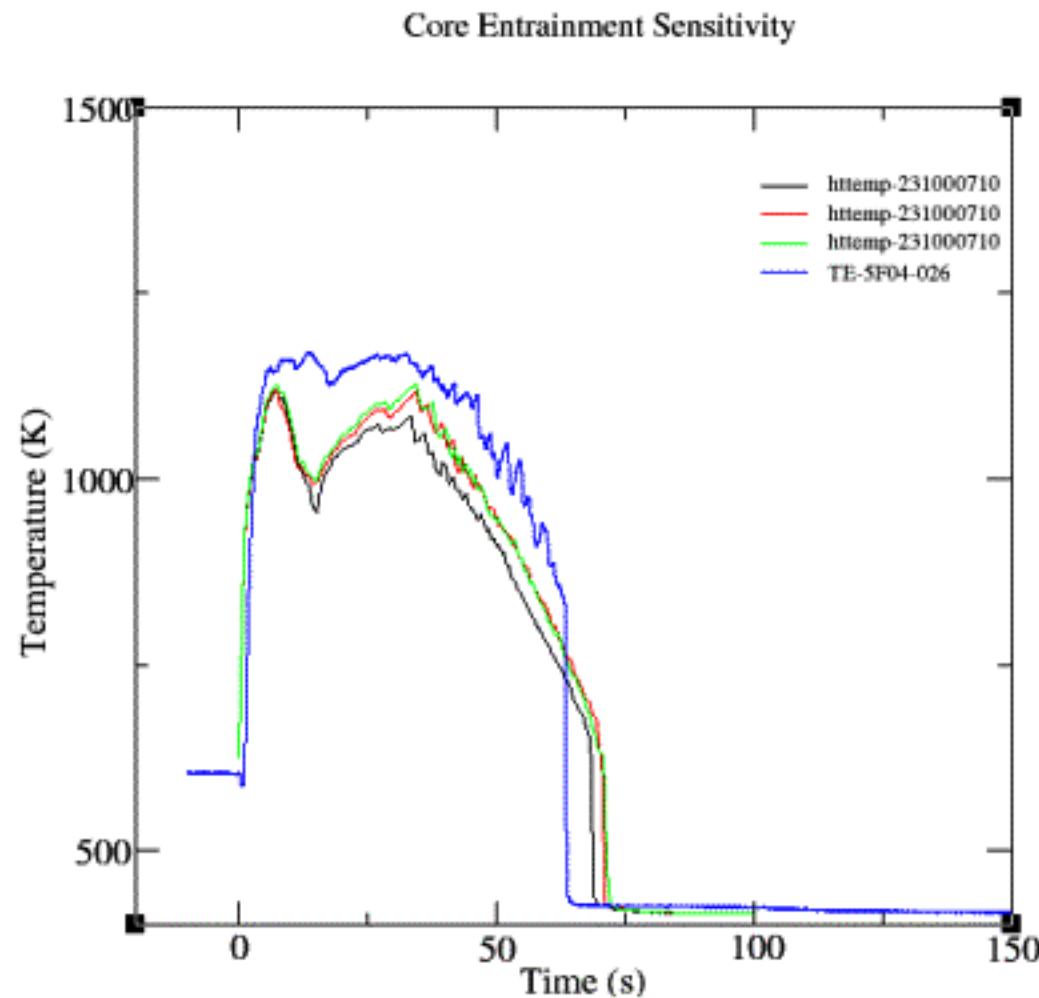
Fuel Conductivity Sensitivity



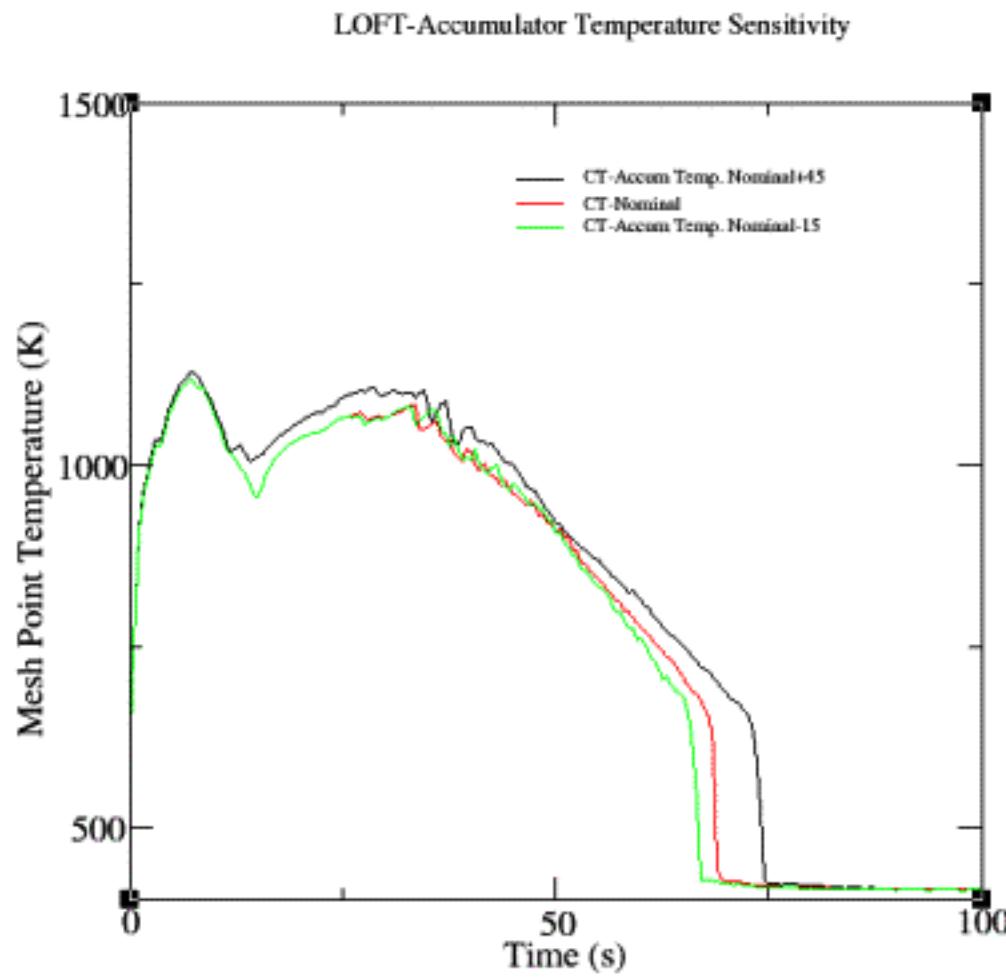
Entrainment



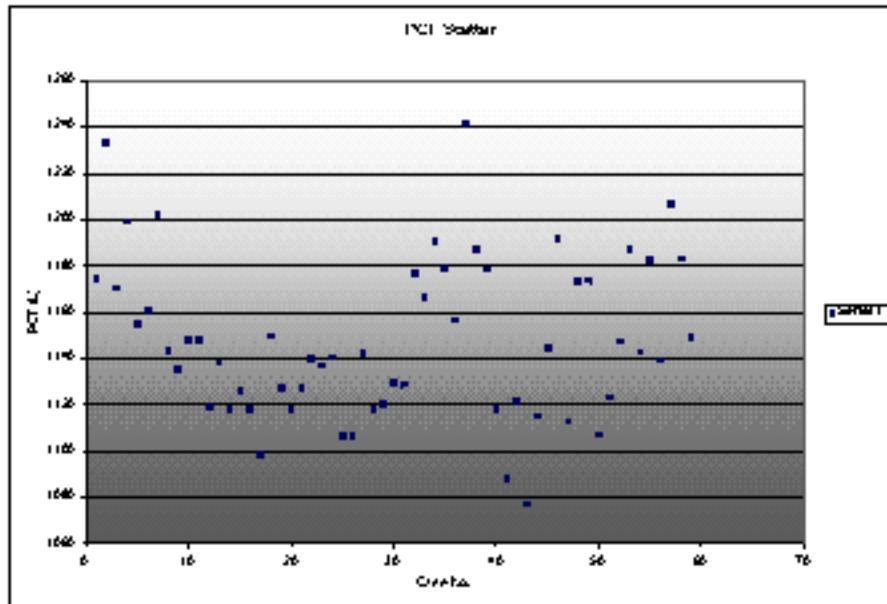
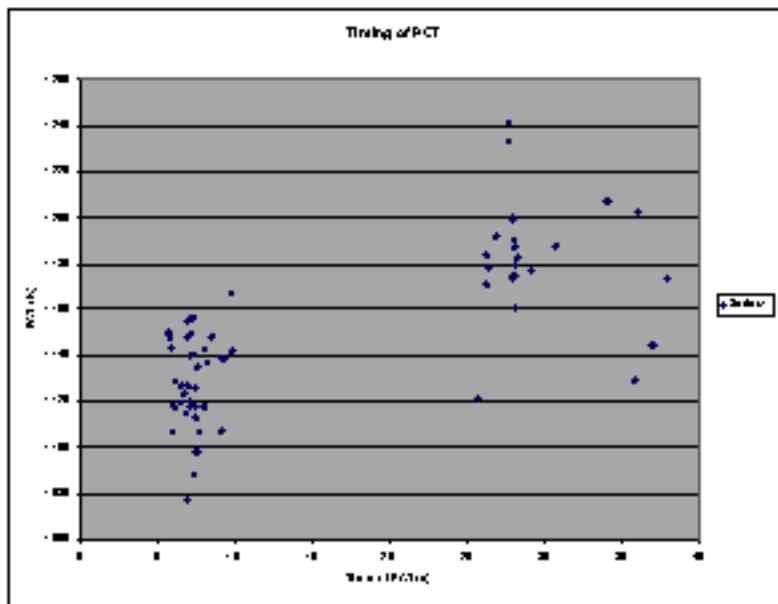
Core Entrainment Sensitivity



Accumulator Temperature Sensitivity



Timing of and Scatter of PCT



Data and Information



Data

- Analytical Solutions
- Field data (Nuclear Power Plant Operation)
 - ✓ Initial Conditions
- Scale-Down Facilities
 - ✓ Integrated Effect Tests Facilities (IET)
 - About Phenomena
 - ✓ Separate Effects Test Facilities (SET)

