An Integrated Approach for Characterization of Uncertainty in Complex Best Estimate Safety Assessment

Presented
By

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Acknowledgment

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- Ali Mosleh, Professor & Director of Center for Risk and Reliability, University of Maryland, College Park, MD
- This work was performed under a cooperative research agreement between the Center for Risk and Reliability at the University of Maryland and the US Nuclear Regulatory Commission during 2005-2007.

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Major Publications on this Approach

- Integrated Methodology for Thermal-Hydraulic Code Uncertainty Analysis with Application, M. Pourgolmohamad, M. Modarres, A. Mosleh, Nuclear Technology, Volume 165, Number 3 · March 2009 · Pages 333-359
- Methodology for the Use of Experimental Data to Enhance Model Uncertainty Assessment in Thermal Hydraulics Codes, M. Pourgolmohamad, A. Mosleh, M. Modarres, Reliability Engineering and System Safety, Reliability Engineering and System Safety 95 (2010) 77–86.
- Structured Treatment of Model Uncertainty in Complex Thermal-Hydraulics Codes; Technical Challenges, Prospective and Characterization, M. Pourgol-Mohamad, Ali Mosleh, M. Modarres, Nuclear Engineering and Design, Volume 241, Issue 1, January 2011, Pages 285-295.
- 10 other conference or workshop papers

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Motivation

- Our team is a PSA group interested in assessment of risks and use of risk information in safety regulations
- TH and other mechanistic codes are used in many PSA studies (Success criteria for safety systems such as ECCS, PTS studies, Fire Risks, etc.)
- USNRC revised ECCS licensing rules to allow the use of best estimate computer code plus uncertainty
- Assessment of uncertainties in PSAs are critical
- The approach has been developed in the context of applications in risk-informed and other PSA needs and applications

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Outline

- Scope of Research
- Overview on IMTHUA methodology
- Complexity and Structure of TH Codes
- IMTHUA Model Uncertainty Analysis
  - ✓ Single Model
  - ✓ Alternative Models
- Application of the Methodology to LOFT LBLOCA
- Steps Involved:
  - ✓ Input Phase
    - Modified PIRT
    - Code Models and Parameters
    - Inputs and Model Structure Uncertainty Quantification
  - ✓ Alternative Models
    - Dynamic Model Switching
    - Model Mixing
  - ✓ Output-Based Bayesian Updating
    - Approach
    - Data Availability and Treatment
      - Partially Relevant Data

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Scope

- Integrated Methodology for TH Uncertainty Analysis (IMTHUA)
  - ✓ Implements Promising Features from Existing Methodologies
  - ✓ Output Updating Using Bayesian Updating
- Use of all Available Information to Assess Uncertainties Related to
  - ✓ Boundary/Initial Conditions
  - ✓ Models, Sub-models and Corresponding Parameters
  - ✓ Output
- Assessment of Code Structure Uncertainty

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Sources of TH Uncertainty Analysis

Qualitative Phase
1. Qualification and Applicability study of TH Code a. Verification and Validation for Code and Calculations
2. Inputdeck and Nodalization Qualification
3. Data Accuracy and Applicability Assessment
4. Determination of Effects of Scale-up (Distortion Assessment)
5. Identification, Qualification, Ranking and Screening of Uncertainty Sources
Quantitative Phase
1. Uncertainty Characterization and assessment a. Models b. Parameters c. Dependency
2. Propagation of Uncertainties
3. Representation of Uncertainty Results a. Uncertainty Importance Assessment b. Interpretation of Results

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TH Code Structure and Complexities

- ✓ Limited user control over code structure
- ✓ Limited data and information about models, sub-models, and correlations, such as HTC
- ✓ Large number of interacting models and correlations (thousands)
- ✓ Dynamic aspects when only a small portion of the code models may be active during each time step, depending on the underlying simulation and system conditions
- ✓ Many horizontal and vertical flow regime phases in the code calculation, with fuzzy borders between them
- ✓ Inability to precisely solve field equations for specific configurations due to coarse average nodes
  - For example, choked flow model is called in TH codes calculation when the results of momentum equation calculation is unsatisfactory. The code calls for a choked flow model for velocity calculation and replaces it with the previous calculation. For better resolution, TH codes are recently coupled with CFD codes for more accurate calculations where needed.

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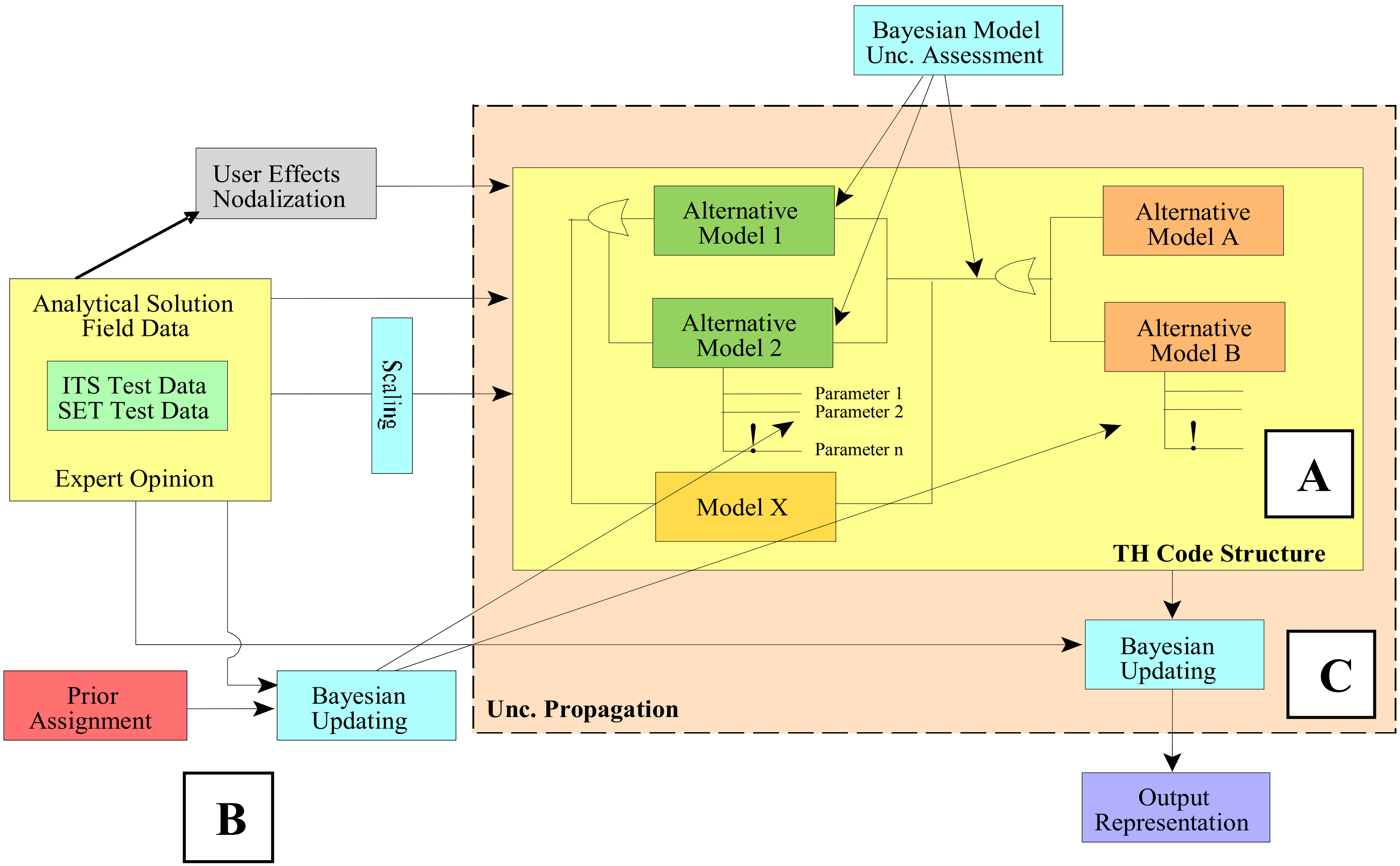
Overall Methodology Overview



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IMTHUA Methodology Overview (Cont.)

- Treatment of the code structure uncertainty (the White-Box Approach): Step A. Key objective: Explicit quantification of uncertainties due to model form (structure) as well as model parameters.
- Applied both at the sub-model levels and also the entire TH code (Step C).
- Input parameter uncertainty quantification is performed via the Maximum Entropy and/or and expert judgment methods, depending on the availability and type of information (Step B).
- Hybrid of Input-Based and Output-Based Uncertainty Assessment (Step C) uncertainty analysis: Therefore IMTHUA is a two-step uncertainty quantification.

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IMTHUA Methodology Overview (Cont.)

- Modified PIRT: This is a two-step method that identifies and ranks phenomena based on their: (a) TH influence (using AHP), and (b) Uncertainty ranking based on an expert judgment procedure. See: Pourgol-Mohamad M, Modarres M., Mosleh A. Modified Phenomena Identification and Ranking Table (PIRT) For Uncertainty Analysis, Proceedings of 14th International Conference on Nuclear Engineering, July 17-20, 2005, Miami, Florida, USA.
- Uncertainty propagation through the use of Wilks' tolerance limits sampling criteria to reduce the number of Monte Carlo iterations for the required accuracy.

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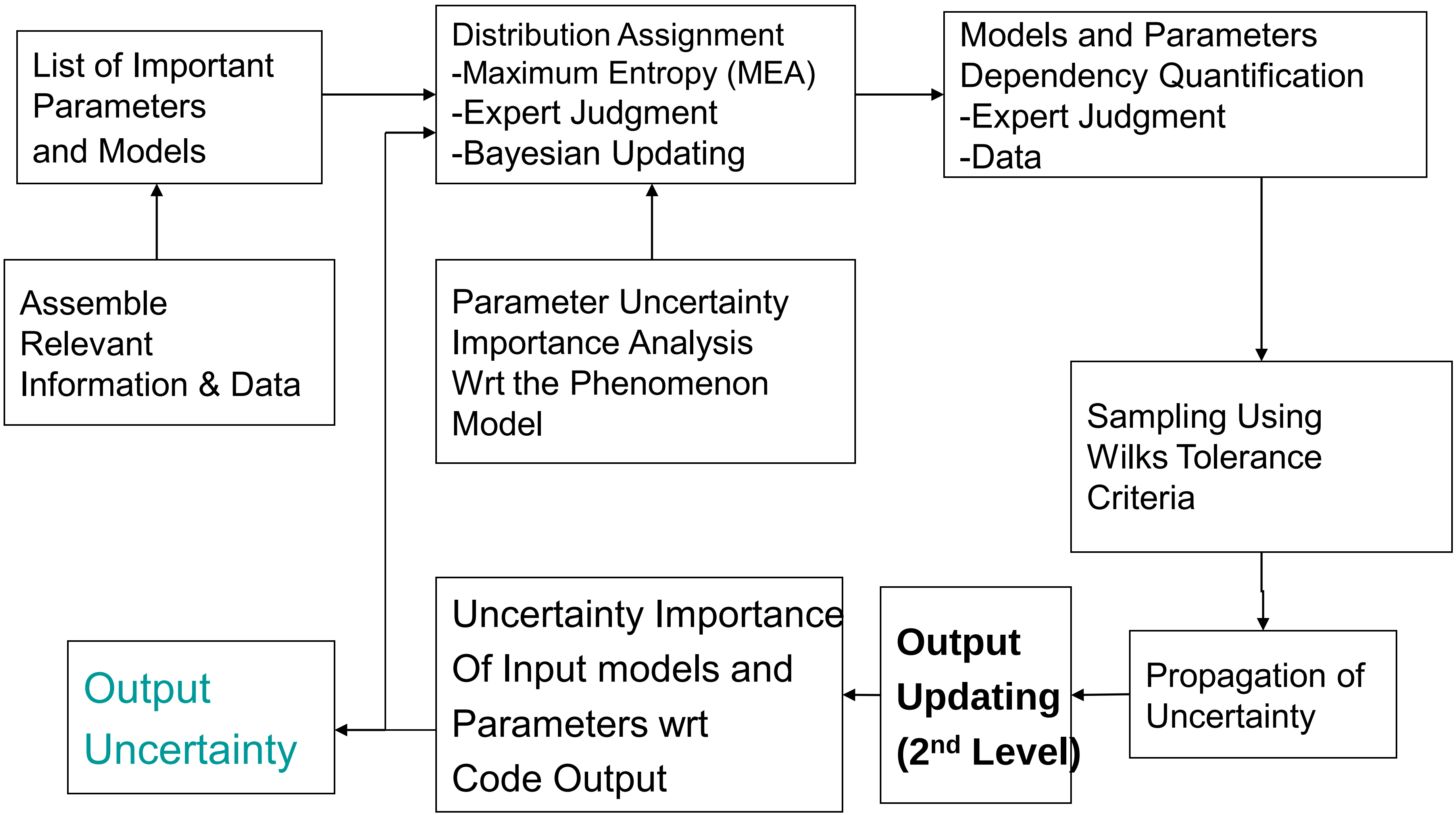
Assessment & Propagation of Uncertainties in Models & Parameters



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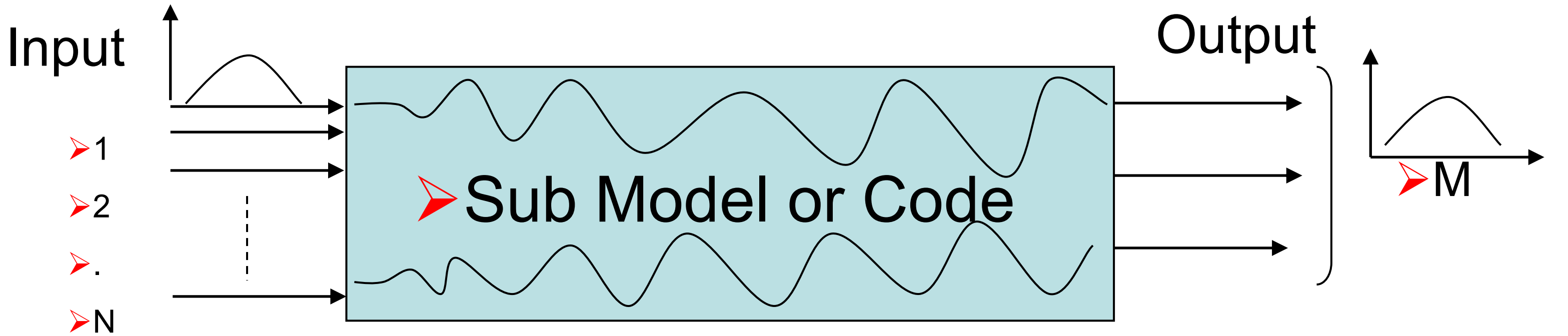
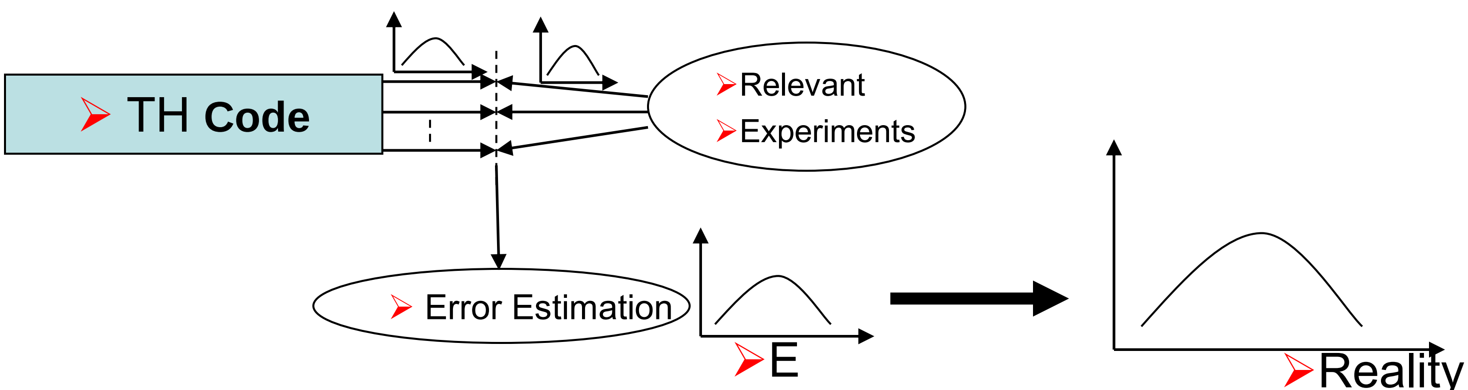
Model Output and Error Uncertainties

- Model output uncertainty



- Model Error Uncertainty



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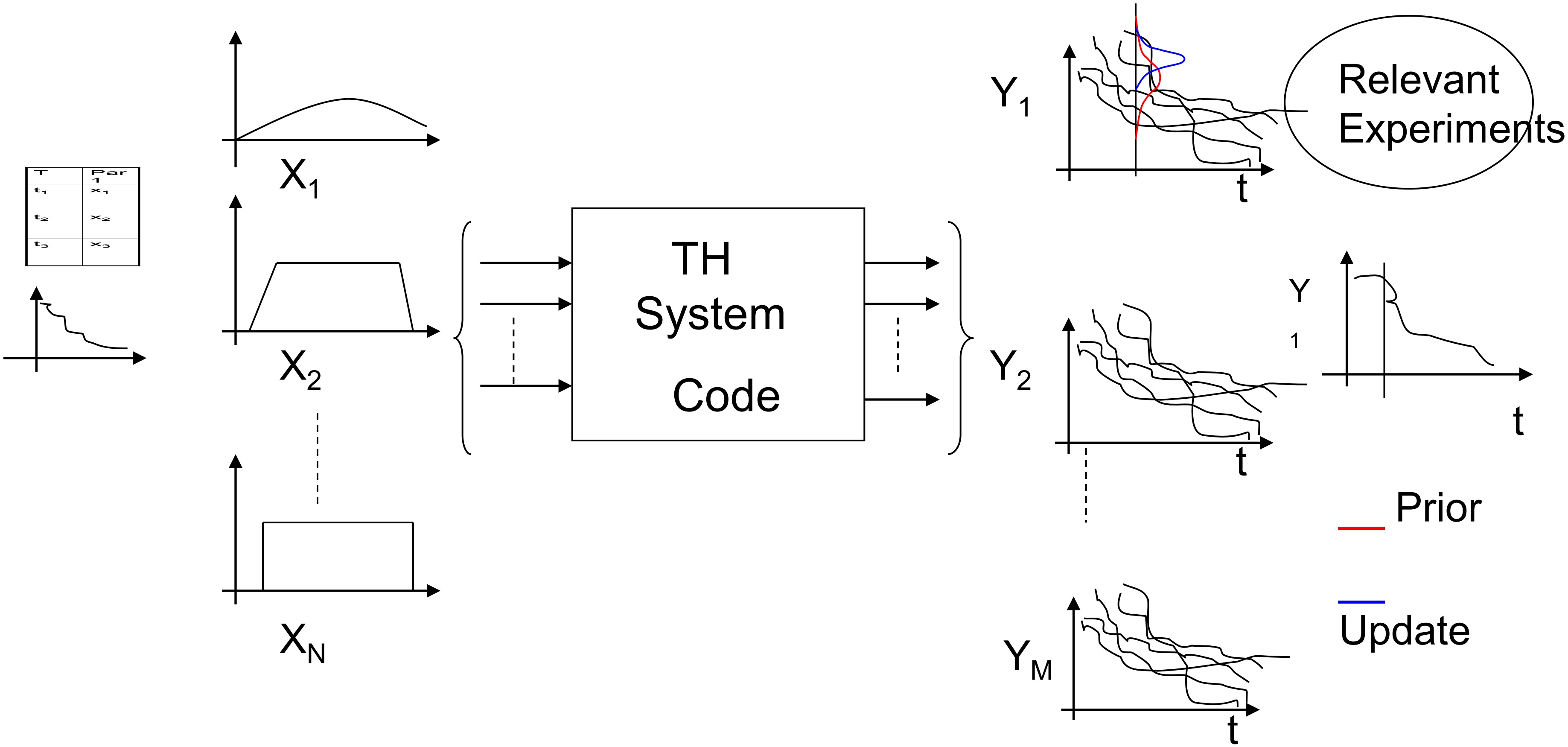
Summary of The Methodology



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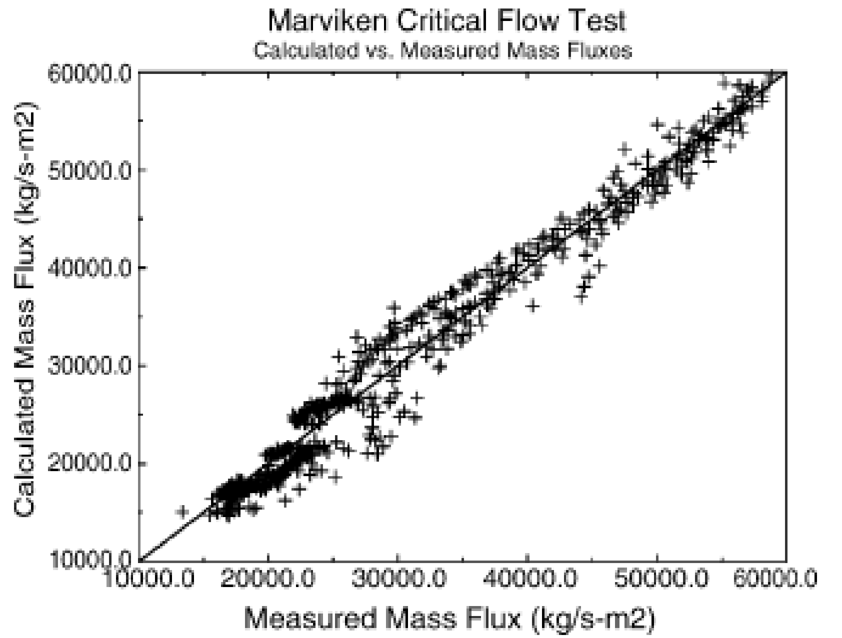
Singe Model Uncertainty Treatment

- Multiplicative Error
- Bias Consideration
- Uncertainty Treatment for Code Structure

$$R_{in} = \frac{\text{Measured Flow Rate}}{\text{Predicted Flow Rate}}$$



✓ E.g., TRAC natural choking model has an average bias of 1.2

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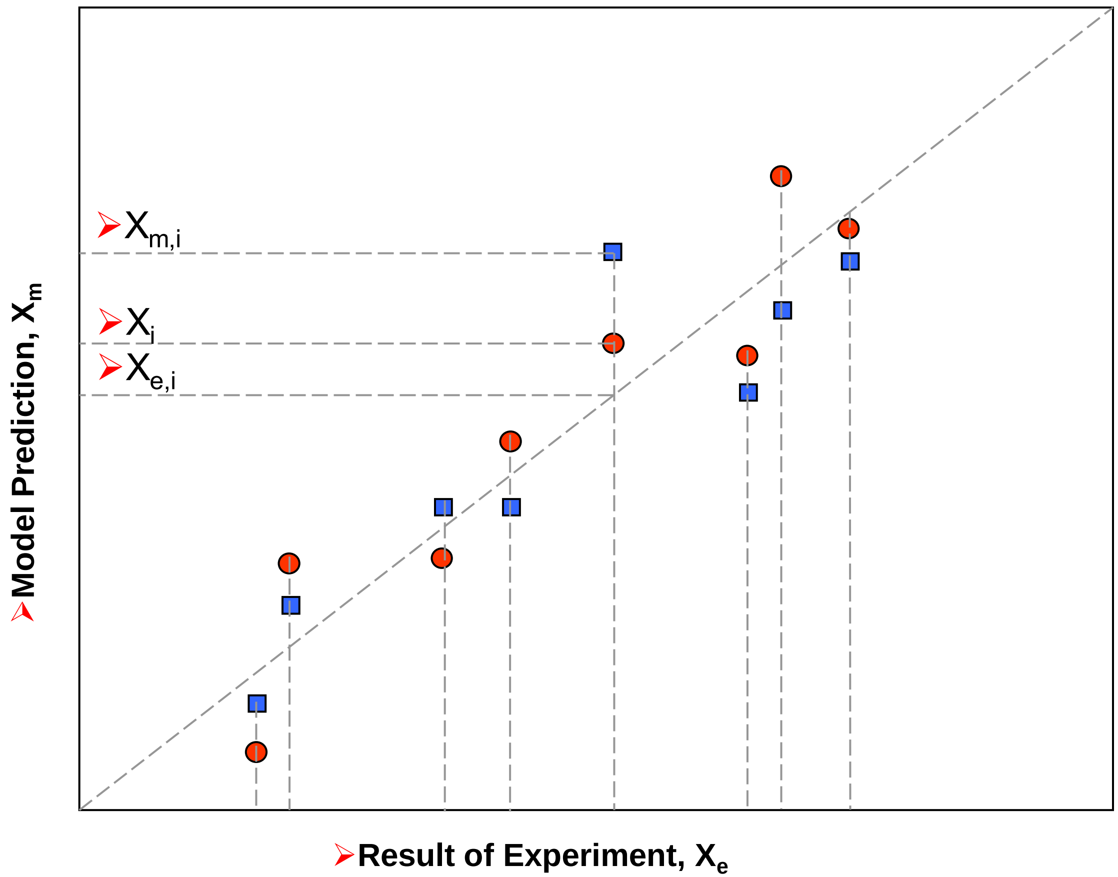
Accounting for Model Error Uncertainty

- Scatter of Model Prediction vs. Experimental Measurement



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Multiplicative Error: Approach and Assumptions

- The model prediction (output), result of experiment and real value of interest have the same sign (all positive or all negative)
- The ratio of real value and experimental results is a random variable with lognormal distribution for which the 95% confidence bounds are known (Experimental Accuracy)
- The ratio of real value and model prediction (output) is a random variable with lognormal distribution with parameters to be determined
- The ratio of model predictions and results of experiment is a function of the two random variables introduced earlier. The distribution of this random variable is lognormal and will be used to represent the likelihood of data
- The distribution of real quantity of interest given a model prediction will be a lognormal distribution

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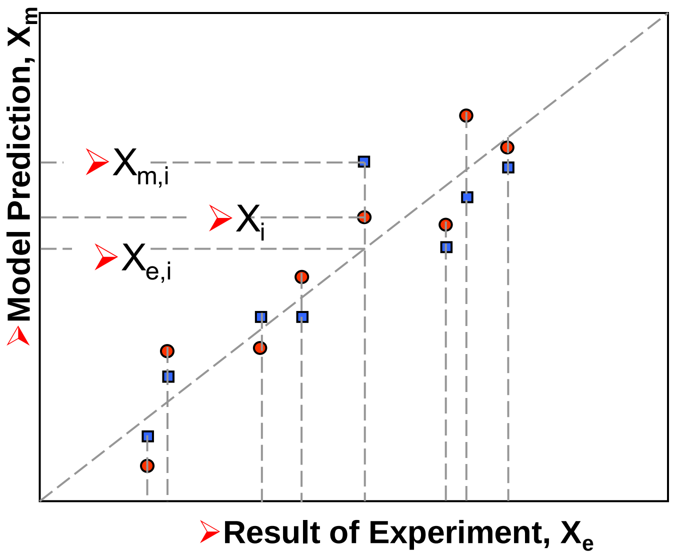
Multiplicative Error Model



$$\frac{X_i}{X_{e,i}} = F_{e,i} \quad ; \quad F_e \sim LN(b_e, \sigma_e) \qquad (1)$$

$$\frac{X_i}{X_{m,i}} = F_{m,i} \quad ; \quad F_m \sim LN(b_m, \sigma_m) \qquad (2)$$

where:

X : Real Quantity

X_e : Result of experiment

X_m : Model prediction

F_e : The error factor for experimental data

F_m : The error factor for model predictions

b_e, σ_e : Mean and SD of experimental error factor

b_m, σ_m : Mean and SD of model error factor

Substituting (1) in (2):

$$\left.\begin{aligned} & F_{e,i}X_{e,i} = F_{m,i}X_{m,i} \\ & \frac{X_{e,i}}{X_{m,i}} = \frac{F_{m,i}}{F_{e,i}} = F_{t,i} \\ & \text{Independency of } F_m, F_e \end{aligned}\right\} \Rightarrow F_t \sim LN\left(b_m - b_e, \sqrt{\sigma_m^2 + \sigma_e^2}\right)$$

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Multiplicative Error: Bayesian Posterior

$$f(\beta_m,\sigma_m \mid X_{e,i},X_{m,i},\beta_e,\sigma_e) = \frac{f_0(\beta_m,\sigma_m)\times L(X_{e,i},X_{m,i},\beta_e,\sigma_e \mid \beta_m,\sigma_m)}{\int_{\sigma_m}\int_{\beta_m} f_0(\beta_m,\sigma_m)\times L(X_{e,i},X_{m,i},\beta_e,\sigma_e \mid \beta_m,\sigma_m)\,d\beta_m\,d\sigma_m}$$

$where:$

$$L(X_{e,i},X_{m,i},\beta_e,\sigma_e \mid \beta_m,\sigma_m) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\left(\frac{X_{e,i}}{X_{m,i}}\right)\sqrt{\sigma_m^2+\sigma_e^2}}\, e^{-\frac{1}{2}\times\frac{\left[\ln\left(\frac{X_{e,i}}{X_{m,i}}\right)-(\beta_m-\beta_e)\right]^2}{\sigma_m^2+\sigma_e^2}}$$

$f_0(\beta_m,\sigma_m)$: Prior Joint Distirbution of Parameters

$f(\beta_m,\sigma_m \mid X_{e,i},X_{m,i},\beta_e,\sigma_e)$: Posterior Joint Distirbution of Parameters

Given a model prediction such as X_m the distribution of the real value X will be:

$$\left.\begin{array}{l} X_m \text{ given as model prediction} \\ F_m \sim LN(\beta_m,\sigma_m) \\ X = F_m X_m \end{array}\right\} \Rightarrow X \sim LN\left(\ln(X_m)+\beta_m,\sigma_m\right)$$

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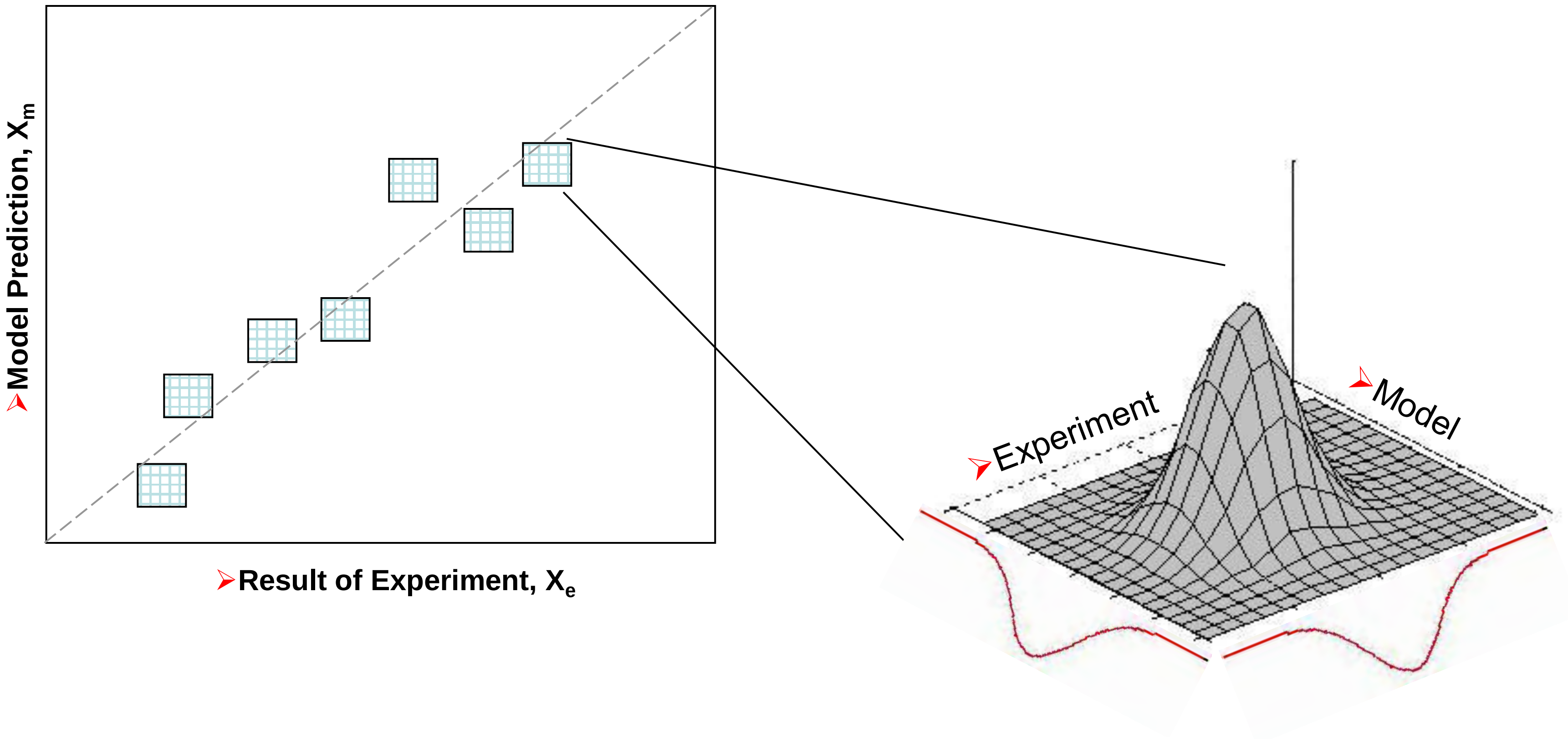
Including Model Unceratinty

- **When Both Model Output and Experimental Data Are Uncertain:**



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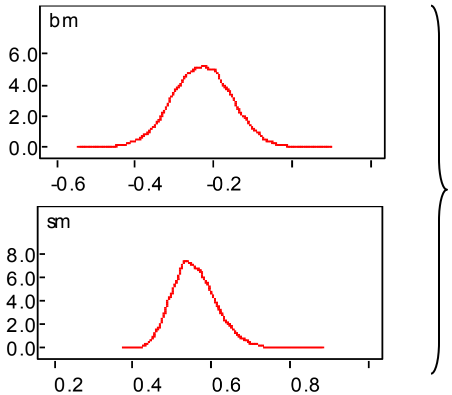
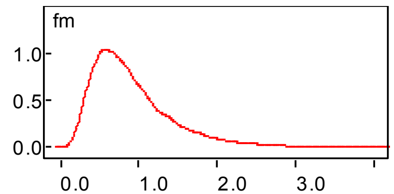
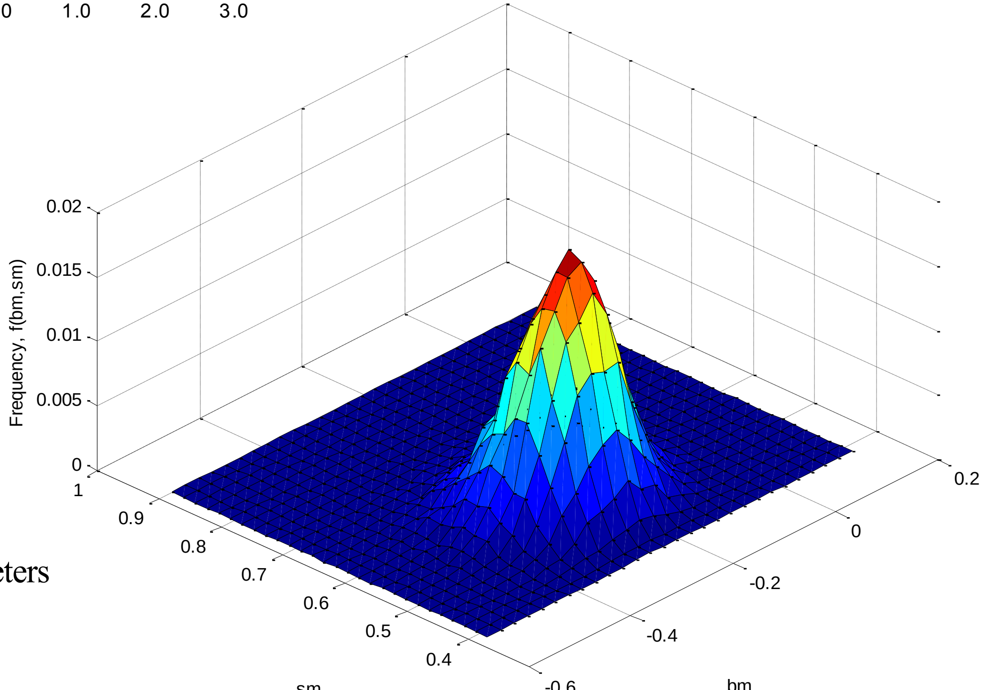
Heat Flux Model Updating Using WinBugs







$f(b_m, s_m \mid X_{e,i}, X_{m,i}, b_e, s_e)$: Posterior Joint Distirbution of Parameters

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Alternative Models Treatments

- Dynamic Model Switching
- Recommended Code Option
- Change of Code Models by User in Same Run
- Model Mixing
- Model Maximization/Minimization

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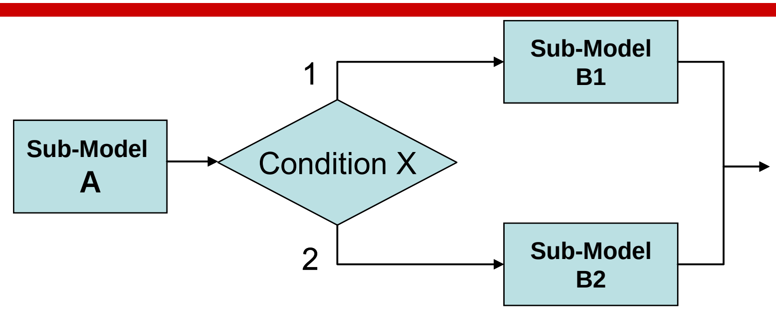
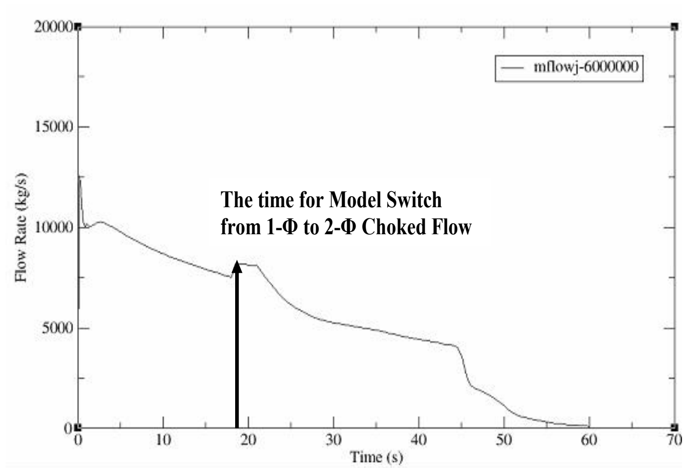
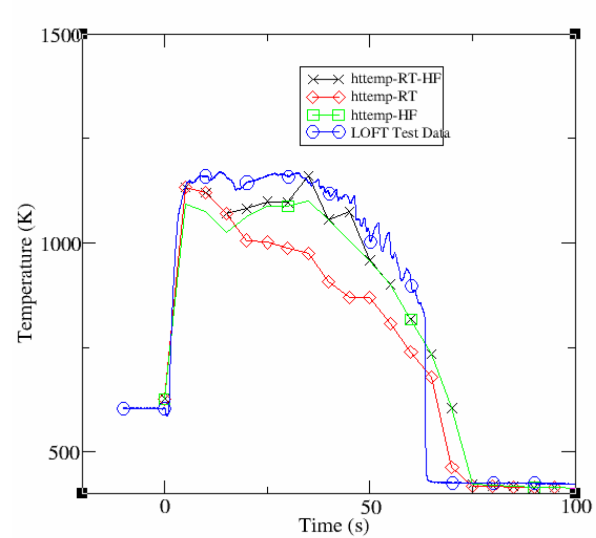
Dynamic Model Switching







- Model Switch from 1-Φ Choked Flow to 2- Φ Choked Flow-Marviken Blowdown
- Model Switch by Code or User for Henry-Fauske and Henry-Trap Choked Flow Model

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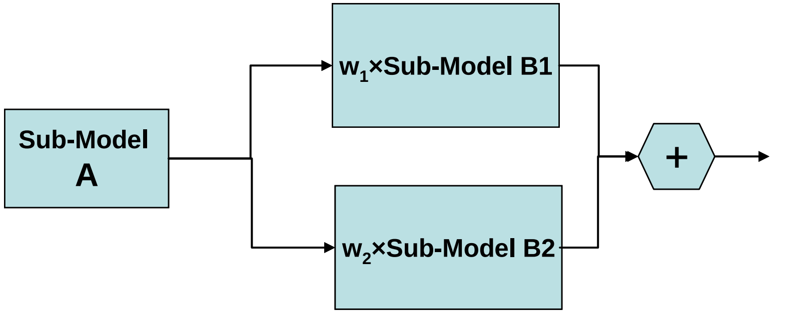
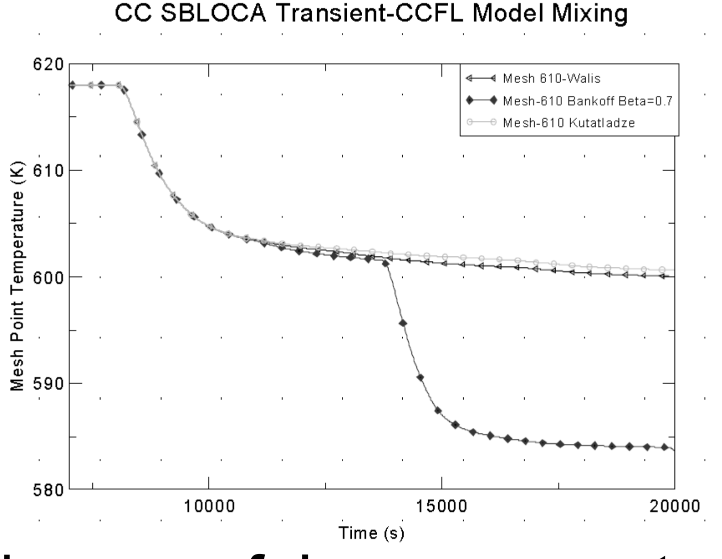
Model Mixing





- Inference requires careful assessment

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TH Code Input Deck and User Options in Model Uncertainty

User Domains	Impacts
System Nodalization	-Node Size -Component Selection -Node Numbers
Code Options	-Input parameters related to specific system characteristics -Input parameters needed for specific system components -Specification of initial and boundary conditions -Specification of state and transport property data -Selection of parameters determining time step size -Choice between engineering or alternative models, e.g., critical flow models -The efficiency of separators -Two-phase flow characteristics of main coolant pumps -Pressure loss coefficient for pipes, pipe connections, valves, etc.
Code Source Adjustments	-Multipliers -Choice between engineering or alternative models, e.g., critical flow models in a specific time -Numerical scheme

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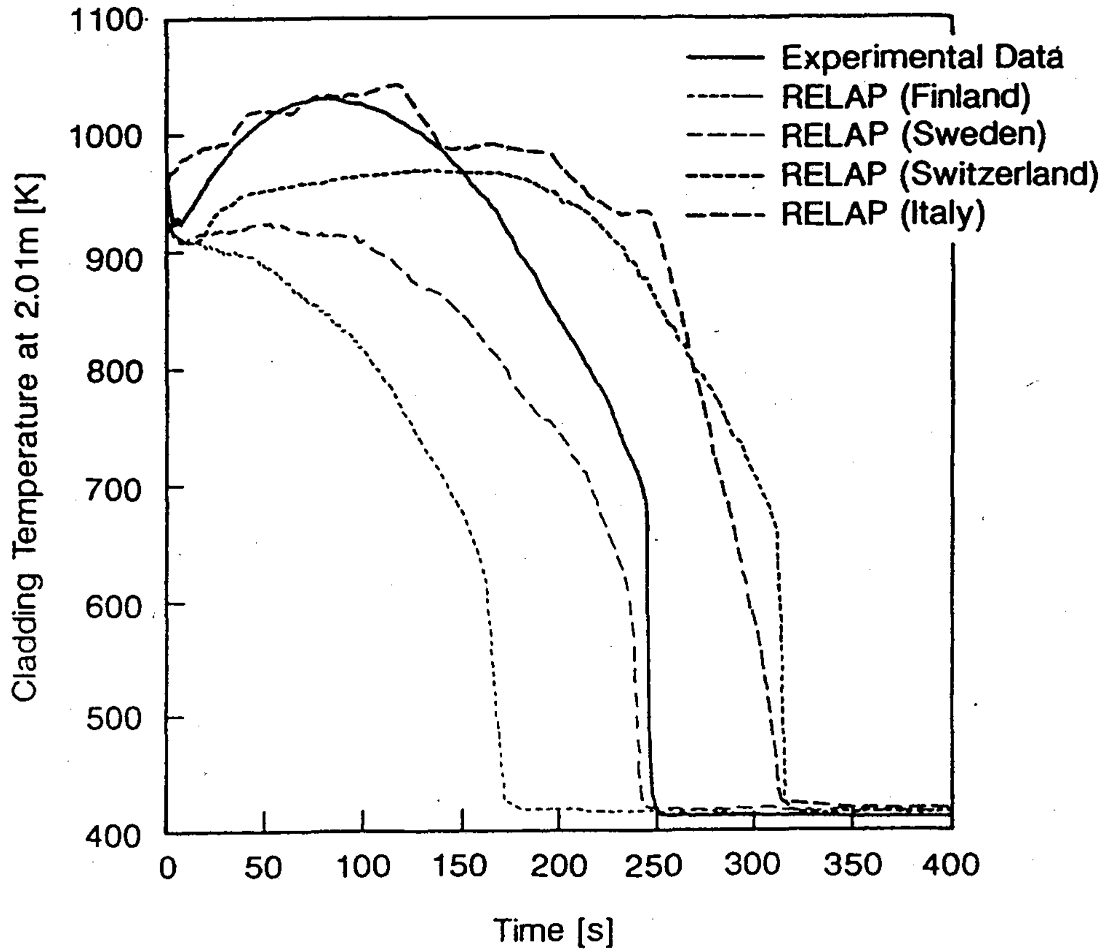
Input Deck and User Options (cont.)



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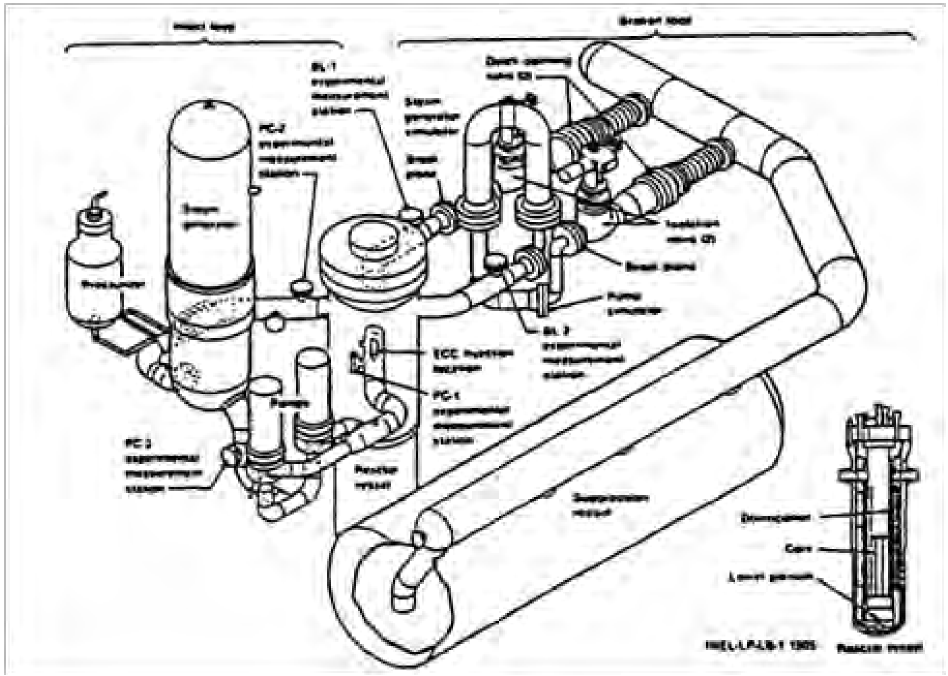
LOFT Application Test LB-1 Facility



Item	*LOFT*
Fuel rod number	1300
Length (m)	1.68
Inlet flow area (m3)	0.16
Coolant volume (m3)	0.295
laximum 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/m3)	124.4
Core volume/system volume	0.038
Mass flux (Kg/s-m2)	1248.8
Core mass flow/system volume (Kg/s-m3)	25.6

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Initial Conditions and Scenario Sequence of Time

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-m2)	***305.8***
Hot-leg Pressure (Mpa)	***14.77***
Hot-leg Temperature (°K)	***586.1***
Cold-leg Temperature (°K)	***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 (°K)	***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***

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 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***
Reflood Tripped On (s)	***NA***	***0***
HPIS injection initiated (s)	***NA***	***NA***
LPIS injection initiated (s)	***24.8***	***24.8***
Maximum cladding temperature (°K)	***1170***	***1050***

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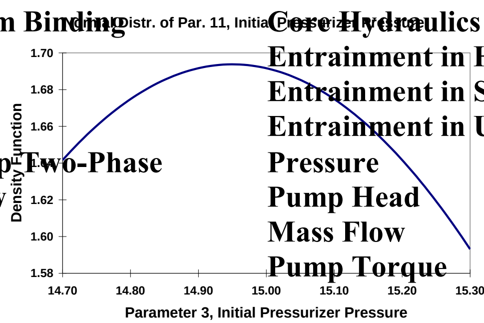
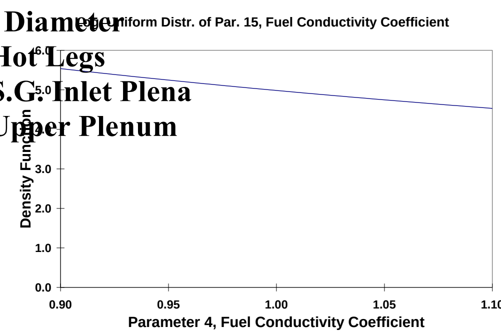
Code Models and Parameters

Choked Flow	**2-Phase Model Multiplier** **1-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 Mwt+/-1.3 MW_t **Fuel and Cladding Thermal Conductivity**
Entrainment	**Hydraulics Diameters (Hot Leg, Downcomer, etc)**
Peaking Factor	**Radial**
Accumulator	**Pressure**
Steam Binding	**Core Hydraulics Diameter** **Entrainment in Hot Legs** **Entrainment in S.G. Inlet Plena** **Entrainment in Upper Plenum**
Pump Two-Phase Flow	**Pressure** **Pump Head** **Mass Flow** **Pump Torque**





Sample Distributions

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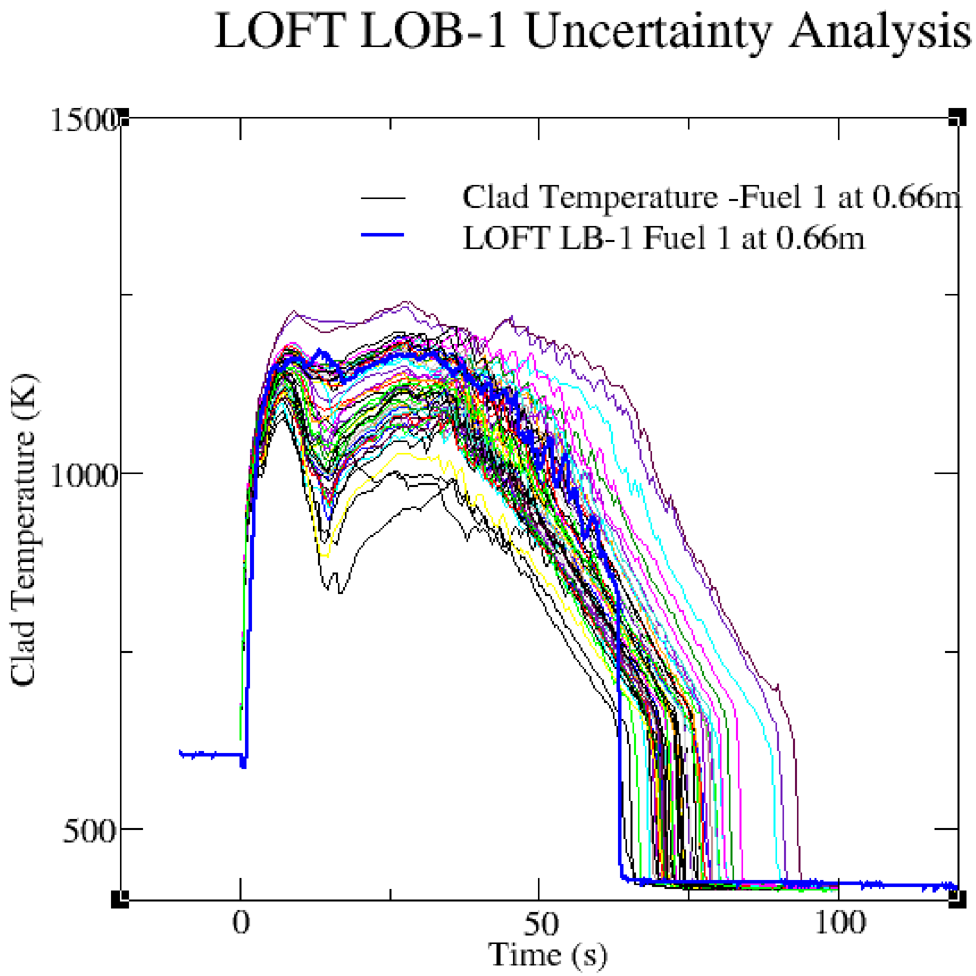
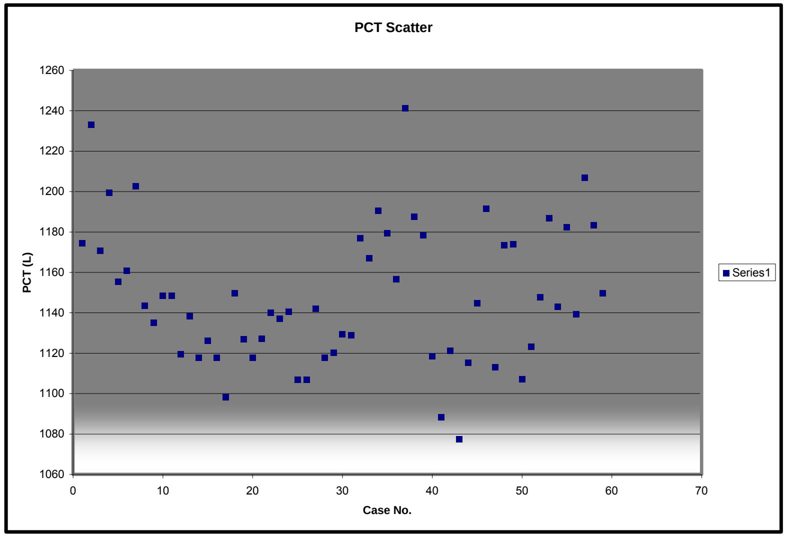
Uncertainty Propagation-Modified PIRT LOFT LBLOCA





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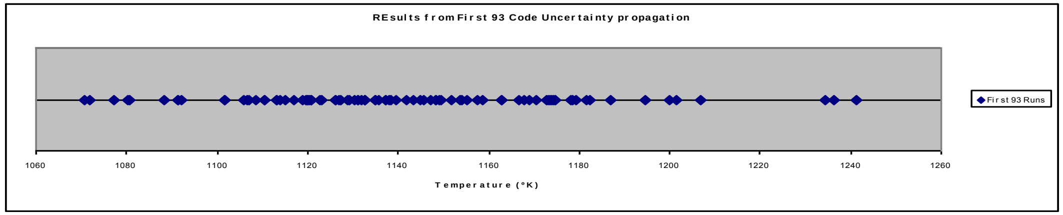
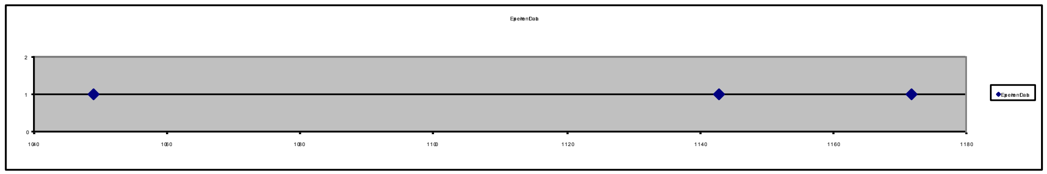
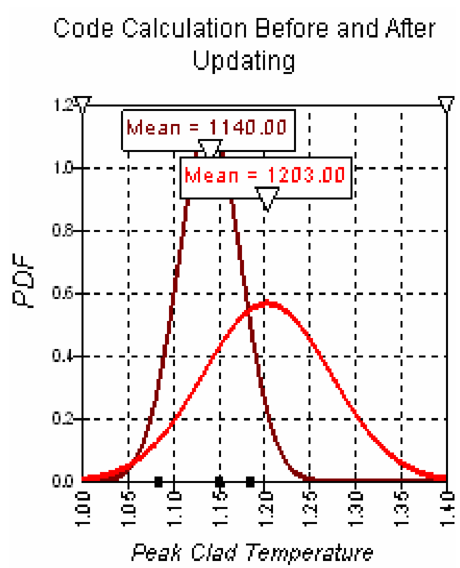
Output Updating

Code/ Test Data







Data	Mean	SD	MC Error	2.50%	Median	97.50%
Code	1140.0	35.0	0.4	1071.0	1140.0	1208.0
Experiment	1120.0	70.0	0.8	981.6	1119.0	1256.0

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Concluding Remarks

- Utilization of most available data and information to include important sources of uncertainty
- Structure of models and sub-models important contributor to final result
- Depending on different conditions and availability of information and data different strategies for treating several classes of model (code structure) uncertainties proposed
- Treatment of cases involving alternative models.
- A Bayesian updating proposed for single model structure uncertainty assessment, while other techniques such as mixing, switching, maximization /minimization were proposed for alternative models.
- Output Bayesian updating proposed to account for User Errors, Numerical Approximations, Unknown and Not Considered Sources of Uncertainties (Screened input and/or Incompleteness)

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