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.
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


- 10 other conference or workshop papers
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.
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
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
## Sources of TH Uncertainty Analysis

<table>
<thead>
<tr>
<th>Qualitative Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Qualification and Applicability study of TH Code</td>
</tr>
<tr>
<td>a. Verification and Validation for Code and Calculations</td>
</tr>
<tr>
<td>2. Inputdeck and Nodalization Qualification</td>
</tr>
<tr>
<td>3. Data Accuracy and Applicability Assessment</td>
</tr>
<tr>
<td>4. Determination of Effects of Scale-up (Distortion Assessment)</td>
</tr>
<tr>
<td>5. Identification, Qualification, Ranking and Screening of Uncertainty Sources</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantitative Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Uncertainty Characterization and assessment</td>
</tr>
<tr>
<td>a. Models</td>
</tr>
<tr>
<td>b. Parameters</td>
</tr>
<tr>
<td>c. Dependency</td>
</tr>
<tr>
<td>2. Propagation of Uncertainties</td>
</tr>
<tr>
<td>3. Representation of Uncertainty Results</td>
</tr>
<tr>
<td>a. Uncertainty Importance Assessment</td>
</tr>
<tr>
<td>b. Interpretation of Results</td>
</tr>
</tbody>
</table>
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.
Overall Methodology Overview
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.
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.
Assessment & Propagation of Uncertainties in Models & Parameters

List of Important Parameters and Models → Distribution Assignment
- Maximum Entropy (MEA)
- Expert Judgment
- Bayesian Updating

Assemble Relevant Information & Data → Models and Parameters Dependency Quantification
- Expert Judgment
- Data

Parameter Uncertainty Importance Analysis Wrts the Phenomenon Model

Uncertainty Importance Of Input models and Parameters wrt Code Output → Outputs

Output Updating (2nd Level) → Output Uncertainty

Sampling Using Wilks Tolerance Criteria → Propagation of Uncertainty

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Model Output and Error Uncertainties

- Model output uncertainty
  - Sub Model or Code

- Model Error Uncertainty
  - TH Code
  - Relevant Experiments
  - Error Estimation
  - Reality
Summary of The Methodology

\[ \begin{align*}
X_1 & \quad \text{TH System} \\
X_2 & \quad \text{Code} \\
X_N & \\
Y_1 & \quad \text{Relevant Experiments} \\
Y_2 & \\
Y_M & \quad \text{Prior} \\
\end{align*} \]
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
Accounting for Model Error Uncertainty

- Scatter of Model Prediction vs. Experimental Measurement

- Result of Experiment, $X_e$

- Model Prediction, $X_m$

- $X_{m,i}$

- $X_i$

- $X_{e,i}$
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
## Multiplicative Error Model

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

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

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
- \( b_e, \sigma_e \) : Mean and SD of experimental error factor
- \( b_m, \sigma_m \) : Mean and SD of model error factor

Substituting (1) in (2):

\[ F_{e,i} X_{e,i} = F_{m,i} X_{m,i} \]

\[ \frac{X_{e,i}}{X_{m,i}} = \frac{F_{m,i}}{F_{e,i}} = F_{t,i} \]

Independency of \( F_m, F_e \)

\[ F_t \sim LN(b_m, b_e, \sqrt{\frac{2}{m} + \frac{2}{e}}) \]
Multiplicative Error: Bayesian Posterior

\[ f(b_m, m | X_{e,i}, X_{m,i}, b_e, e) = \frac{f_0(b_m, m) \cdot L(X_{e,i}, X_{m,i}, b_e, e | b_m, m)}{f_0(b_m, m) \cdot L(X_{e,i}, X_{m,i}, b_e, e | b_m, m) \int_{b_m} db_m d_m} \]

where:

\[ L(X_{e,i}, X_{m,i}, b_e, e | b_m, m) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}} \left( \frac{X_{e,i}}{X_{m,i}} \right)^{\frac{1}{2}} e^{-\frac{1}{2} \left( \frac{\ln\left( \frac{X_{e,i}}{X_{m,i}} \right) + (b_m - b_e)^2}{2 + \frac{2}{e}} \right)} \]

\[ f_0(b_m, m) : \quad \text{Prior Joint Distribution of Parameters} \]

\[ f(b_m, m | X_{e,i}, X_{m,i}, b_e, e) : \quad \text{Posterior Joint Distribution of Parameters} \]

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

\( X_m \) given as model prediction

\[ F_m \sim LN(b_m, m) \quad X \sim LN(\ln(X_m) + b_m, m) \]

\[ X = F_m X_m \]
Including Model Uncertainty

- When Both Model Output and Experimental Data Are Uncertain:

Model Prediction, $X_m$

Result of Experiment, $X_e$
Heat Flux Model Updating Using WinBugs

\[ f(b_{m,m} | X_{e,i}, X_{m,i}, b_{e,c}) : \text{Posterior Joint Distribution of Parameters} \]
Alternative Models Treatments

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

The time for Model Switch from 1-Φ to 2-Φ Choked Flow

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Model Mixing

- Inference requires careful assessment

Sub-Model A

\[ w_1 \times \text{Sub-Model B}_1 \]

\[ w_2 \times \text{Sub-Model B}_2 \]

CC SBLOCA Transient-CCFL Model Mixing

Mesh Point Temperature (K) vs. Time (s)
### TH Code Input Deck and User Options in Model Uncertainty

<table>
<thead>
<tr>
<th>User Domains</th>
<th>Impacts</th>
</tr>
</thead>
</table>
| **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 |
Input Deck and User Options (cont.)

![Graph showing cladding temperature at 2.01m against time for different scenarios.]
LOFT Application Test LB-1 Facility

<table>
<thead>
<tr>
<th>Item</th>
<th>LOFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel rod number</td>
<td>1300</td>
</tr>
<tr>
<td>Length (m)</td>
<td>1.68</td>
</tr>
<tr>
<td>Inlet flow area (m³)</td>
<td>0.16</td>
</tr>
<tr>
<td>Coolant volume (m³)</td>
<td>0.295</td>
</tr>
<tr>
<td>Maximum linear heat generation rate (kW/m)</td>
<td>39.4</td>
</tr>
<tr>
<td>Coolant temperature rise (K)</td>
<td>32.2</td>
</tr>
<tr>
<td>Power (MW)</td>
<td>36.7</td>
</tr>
<tr>
<td>Peaking factor</td>
<td>2.34</td>
</tr>
<tr>
<td>Power/coolant volume (MW/m³)</td>
<td>124.4</td>
</tr>
<tr>
<td>Core volume/system volume</td>
<td>0.038</td>
</tr>
<tr>
<td>Mass flux (Kg/s-m²)</td>
<td>1248.8</td>
</tr>
<tr>
<td>Core mass flow/system volume (Kg/s-m³)</td>
<td>25.6</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>LOFT measured initial conditions LB-1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Reactor Power (MW)</td>
</tr>
<tr>
<td>Low Pressure Scram Set Point (MPa)</td>
</tr>
<tr>
<td>Intact-loop Mass Flow (kg/s-m²)</td>
</tr>
<tr>
<td>Hot-leg Pressure (Mpa)</td>
</tr>
<tr>
<td>Hot-leg Temperature (°K)</td>
</tr>
<tr>
<td>Cold-leg Temperature (°K)</td>
</tr>
<tr>
<td>Pump Speed (rad/s)</td>
</tr>
<tr>
<td>Pressurizer Steam Volume (m³)</td>
</tr>
<tr>
<td>Pressurizer Liquid Volume (m)</td>
</tr>
<tr>
<td>Steam-generator Pressure (MPa)</td>
</tr>
<tr>
<td>Steam-generator Mass Flow (kg/s)</td>
</tr>
<tr>
<td>Accumulator Pressure (MPa)</td>
</tr>
<tr>
<td>Accumulator Temperature (°K)</td>
</tr>
<tr>
<td>Accumulator Initial Level (m)</td>
</tr>
<tr>
<td>Accumulator Level at End of Discharge (m)</td>
</tr>
<tr>
<td>Accumulator Liquid Level Change (m)</td>
</tr>
<tr>
<td>Accumulator Liquid Volume Discharged (m³)</td>
</tr>
<tr>
<td>Accumulator Initial Gas Volume (m³)</td>
</tr>
<tr>
<td>Accumulator Initial Gas/Liquid Fraction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LOFT Test LB-1 Sequence of Event Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
</tr>
<tr>
<td>Break initiated (s)</td>
</tr>
<tr>
<td>Reactor scrammed (s)</td>
</tr>
<tr>
<td>Primary-coolant pumps tripped (s)</td>
</tr>
<tr>
<td>Pressurizer emptied (s)</td>
</tr>
<tr>
<td>Accumulator A injection initiated (s)</td>
</tr>
<tr>
<td>Reflood Tripped On (s)</td>
</tr>
<tr>
<td>HPIS injection initiated (s)</td>
</tr>
<tr>
<td>LPIS injection initiated (s)</td>
</tr>
<tr>
<td>Maximum cladding temperature (°K)</td>
</tr>
</tbody>
</table>
# Code Models and Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
</table>
| Choked Flow        | 2-Phase Model Multiplier  
1-Phase model multiplier |
| Post CHF Heat      | Gap Conductance Model  
- Fuel Conductance Input Table in Inputdeck |
| Transfer           | Level Controller Card in the Inputdeck  
- Measurement Error 1.04 +/- 4 cm |
| 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_i  
Fuel and Cladding Thermal Conductivity |
| Entrainment        | Hydraulics Diameters (Hot Leg, Downcomer, etc) |
| Peaking Factor     | Radial |
| Accumulator        | Pressure  
Core Hydraulics Diameter |
| Steam Binding      | Accumulator Pressure  
Core Hydraulics Diameter  
- Entrainment in S.G. Inlet Plena  
- Entrainment in Upper Plenum  
- Pressure  
- Pump Head  
- Mass Flow  
- Pump Torque |
| Pump Two Phase     | Accumulator Pressure  
Core Hydraulics Diameter  
- Entrainment in S.G. Inlet Plena  
- Entrainment in Upper Plenum  
- Pressure  
- Pump Head  
- Mass Flow  
- Pump Torque |

Sample Distributions

**Parameter 3, Initial Pressurizer Pressure**

<table>
<thead>
<tr>
<th>Density Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.70</td>
</tr>
<tr>
<td></td>
<td>14.80</td>
</tr>
<tr>
<td></td>
<td>14.90</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
</tr>
<tr>
<td></td>
<td>15.10</td>
</tr>
<tr>
<td></td>
<td>15.20</td>
</tr>
<tr>
<td></td>
<td>15.30</td>
</tr>
<tr>
<td></td>
<td>14.70</td>
</tr>
<tr>
<td></td>
<td>14.80</td>
</tr>
<tr>
<td></td>
<td>14.90</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
</tr>
<tr>
<td></td>
<td>15.10</td>
</tr>
<tr>
<td></td>
<td>15.20</td>
</tr>
<tr>
<td></td>
<td>15.30</td>
</tr>
</tbody>
</table>

**Parameter 4, Fuel Conductivity Coefficient**

<table>
<thead>
<tr>
<th>Density Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
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<tr>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>1.10</td>
</tr>
</tbody>
</table>
LOFT LOB-1 Uncertainty Analysis

- Clad Temperature - Fuel 1 at 0.66m
- LOFT LB-1 Fuel 1 at 0.66m

PCT Scatter

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Output Updating
Code/ Test Data

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>SD</th>
<th>MC Error</th>
<th>2.50%</th>
<th>Median</th>
<th>97.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>1140.0</td>
<td>35.0</td>
<td>0.4</td>
<td>1071.0</td>
<td>1140.0</td>
<td>1208.0</td>
</tr>
<tr>
<td>Experiment</td>
<td>1120.0</td>
<td>70.0</td>
<td>0.8</td>
<td>981.6</td>
<td>1119.0</td>
<td>1256.0</td>
</tr>
</tbody>
</table>

Results from First 93 Code Uncertainty propagation

Code Calculation Before and After Updating

Mean = 1140.00

Mean = 1203.00

PDF

Peak Clad Temperature
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)