IAEA TECDOC – Uncertainty Evaluation in Best Estimate Safety Analysis for Nuclear Power Plants

APPROACH AND METHODS TO EVALUATE THE UNCERTAINTY IN SYS-TH CALCULATIONS

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CONTENT

✓ Framework for Uncertainty in SYS-TH
✓ The Origin of Uncertainty
✓ The Approaches for Uncertainty
✓ Topics Relevant for Uncertainty Evaluation (TRUE)
✓ The CIAU Methodology
✓ Conclusions
Framework for Uncertainty in SYS-TH

NEEDS FOR UNCERTAINTY

CONSISTENT APPLICATION OF A THERMOHYDRAULIC SYSTEM CODE

CODE DEVELOPMENT & IMPROVEMENT (1)

EXPERIMENTAL DATA (2)

PROCEDURES FOR CODE USE (3)

CODE ASSESSMENT (4)

CODE USE (NPP) (5)

UNCERTAINTY EVALUATION (6)
The Origin of Uncertainty

A) Balance (or conservation) equations are approximate:
   • Not all the interactions between steam and liquid are included;
   • Equations solved within cylindrical pipes (no geometric discontinuity): situation not common for NPP. Lacking info to be supplied by code user.

B) Presence of different fields of the same phase: e.g. liquid droplets and film. Only one velocity per phase is considered by codes.

C) Geometry averaging at a cross section scale: POROUS MEDIA APPROACH. Velocity profiles happen in the reality: OPEN MEDIA APPROACH (CFD LIKE).

D) Geometry averaging at a volume scale: only one velocity vector (each phase) is associated with a hydraulic mesh along its axis. Different velocity vectors may occur in the reality (inside LP, connection CL-DC)

E) Presence of large and small vortex or eddy. Energy and momentum dissipations not directly accounted.
   A large vortex may determine system behaviour (e.g. two-phase natural circulation between hot and cold fuel bundles).
F) The 2nd principle of thermodynamics is not necessarily fulfilled by codes.

G) The numerical solution is approximate. Approximate equations are solved by approximate numerical methods. The ‘amount’ of approximation is not documented.

H) Extensive use is made of empirical correlations:
   - Range of validity not fully specified;
   - Unavoidably used outside their range of validation;
   - Approximately implemented into the code;
   - Reference database affected by scatter and errors.

I) Paradox: ‘Steady State’ & ‘Fully Developed’ (SS & FD) flow approximation adopted. However all qualified correlations must be derived under SS & FD conditions. Almost in no region of the NPP those conditions apply.
J) State and material properties are approximate. Specifically true for derivatives of water properties.

K) Code User Effect (UE) exists. Two or more groups of users having available the same code and the same input information do not achieve the same results. UE due to:

- nodalization development;
- interpreting supplied information (usually incomplete);
- accepting a steady state performance of the nodalization;
- interpreting transient results, planning sensitivity studies, modifying (arbitrarily) the nodalization.

L) The computer/compiler installation affects the predictions of a code (computer/compiler effect). Very recent computers, compilers, and code releases did not improve the situation depicted a number of years ago.
M) Nodalization (N) effect exists. The N is the result of a wide range brainstorming process where user expertise, computer power and code manual play a role.

There is a number of required code input values that cannot be covered by logical recommendations: the user expertise needed to fix those may reveal inadequate.

N) Imperfect knowledge of Boundary and Initial Conditions (BIC). Some BIC values are unknown or known with approximation: the code user must add information.

O) Severe physical model deficiencies, which are unknown to the code user, cannot be excluded even in the latest versions of the advanced system codes. The achieved results may flyaway from reality in a way not understandable by the code user.
PRELIMINARY STATEMENTS FOR THE DESIGN OF AN UNCERTAINTY METHOD

- Uncertainty Origins (UO) from A) to J) embedded into the Code.
- Effects of UO from K) to M) can be made milder by following Procedures, possibly part of Code Manuals.
- UO N) and O) have to be carefully considered.
- Definitely, all UO have to be considered when developing an Uncertainty Method.

CURRENT SITUATION

- A Dozen Methods Available. Reviews Published.
The Approaches to Calculate Uncertainty

CLASSIFICATION ADOPTED HEREAFTER

- Difference between INPUT and OUTPUT PROPAGATION
  - PROPAGATION OF CODE INPUT “UNCERTAINTIES”
  - PROPAGATION OF CALCULATION OUTPUT “ERRORS”

- Alternative Classification
  - “PURELY” DETERMINISTIC METHOD
  - “PURELY” STATISTIC METHOD
  - USE OF STATISTICS

COMBINATIONS OF THE VARIOUS APPROACHES CAN BE PURSUED
THE APPROACHES TO CALCULATE UNCERTAINTY

**PROPAGATION OF CODE INPUT “UNCERTAINTIES”**

Multiple input (n) → THERMALHYDRAULIC

Multiple output (m) → SYSTEM CODE

- ‘n’ can be as large as $10^5$
- the dimension of ‘m’ is not a main concern

**THE PROPAGATION OF CODE INPUT UNCERTAINTIES IMPLIES THAT**

- ‘n∗’ must be selected with ‘n∗’ of the order of $10^2$ and $\ll \ ‘n’$
- range of variations and/or Probability Distribution Function (PDF) must be assigned to each of the ‘n∗’ parameters
The Approaches to Calculate Uncertainty

PROPAGATION OF CODE INPUT “UNCERTAINTIES”

PATH FOR UNCERTAINTY EVALUATION

Input Uncertainty

1

2

n*

RANGE AND/OR PDF

THERMALHYDRAULIC SYSTEM CODE

ERROR BANDS

Output Uncertainty

DRAWBACKS:

➢ Engineering judgment needed to select:

  • ‘n*’ starting from ‘n’
  • range and/or PDF for each ‘n*’

➢ The error propagation occurs through the code that, by definition, is an ‘imperfect’ tool
THE PROPAGATION OF INPUT UNCERTAINTIES

Multiple Input
\(n \sim 10^5\)

Selection of input uncertain parameters
\(n^* < 10^2\)

ID of range & PDF per each \(n^*\)

Multiple Output
\(m \sim 10^3\) (typical, uninfluent)

Predicted NPP transient scenario

UNCERTAINTY PROPAGATION
The Approaches to Calculate Uncertainty

**PROPAGATION OF CALCULATION OUTPUT “ERRORS”**

**PATH FOR UNCERTAINTY EVALUATION**

Multiple input (n)

- 1
- 2
- n

**THERMALHYDRAULIC SYSTEM CODE**

Multiple output (m)

- 1
- 2
- m

**RELEVANT EXPERIMENTS**

**ERROR BANDS**

**DRAWBACKS:**

- The process of ‘extrapolation’ of output errors is not based upon fundamental principles
- It is impossible to distinguish contributions to the output error bands
THE PROPAGATION OF OUTPUT UNCERTAINTIES

Multiple Input

\[ n \sim 10^5 \]

Multiple Output

\[ m \sim 10^3 \]

(typical, uninfluential)

Relevant experimental data

BIC

CODE

INPUT DECK

1

2

\[ \cdots \]

1

2

\[ \cdots \]

\[ n \]

\[ m \]

Accuracy quantification & criteria for accuracy extrapolation

Predicted NPP transient scenario

UNCERTAINTY PROPAGATION
1) NODALISATION CHOICES
Results from the LBLOCA DEGB DBA Angra-2 analysis: different input decks (nodalisation user choices) produce different effects upon relevant code output parameter, i.e. $\Delta PCT$

2) CODE VERSIONS
Results from the SBLOCA BDBA UMS transient analysis: different code versions (same developer) have a strong impact in the prediction of a relevant uncertainty parameter, i.e. PCT

3) BIFURCATIONS
Results from a bifurcation study related to the SBLOCA BDBA UMS transient analysis. This study is possible with the availability of the Code with Capability of Internal Assessment of Uncertainty (CIAU).
Topics Relevant for Uncertainty Evaluation (TRUE)

NODALISATION CHOICES

UNIPI
Internal Report, 2001

PCT obtained with the same code-version and different RPV-UP noding
Two problems detected:

a) Reference PCT affected by nodalisation (choices)
b) \( \Delta \text{PCT} \) strongly affected by nodalisation (i.e., a given input uncertain parameter is relevant or not depending upon the selected nodalisation (see the diagram below))

The conclusion at item b) is also applicable to different codes.
LESSON LEARNED

THE PROCESS OF PROPAGATING UNCERTAINTY THROUGH THE CODE (propagation of code input uncertainty) IS AFFECTED BY THE CODE AND BY THE NODALISATION:

AN ASSIGNED INPUT UNCERTAIN PARAMETER MAY AFFECT ΔPCT IN ONE DIRECTION OR IN ANOTHER DEPENDING UPON THE STRUCTURE OF THE INPUT DECK (AND OF THE CODE).
After the closure of the Uncertainty Method Study (UMS) and after report /4/ was issued University of Pisa performed comparison calculations of experiment LSTF-SB-CL-18 using different versions of the RELAP 5 code, i.e. MOD 2, MOD 3.2 and MOD 3.2.2. Mod2 was used by the University of Pisa, and MOD 3.2 by AEA Technology as well as ENUSA in this study. It turned out that MOD 3.2 calculated a 170 K higher peak clad temperature compared with MOD 2 and MOD 3.2.2 (using the same input deck). This may contribute to the relative high upper limit of the uncertainty ranges calculated by AEAT and ENUSA. This is also in agreement with the AEAT peak clad temperature of 787 K at 300 s for their reference calculation using nominal values for the input parameters (without calculating the first heat-up). The measured peak is 610 K at 500 s.
Topics Relevant for Uncertainty Evaluation (TRUE)

CODE VERSIONS/SAME INPUT DECK

UNIPI
Internal Report, 1999

* All ‘frozen’ code versions
Topics Relevant for Uncertainty Evaluation (TRUE)

CODE VERSIONS/SAME INPUT DECK

UNIPI
Internal Report, 1999

LESSON LEARNED

CODE VERSIONS (HIGHLY EVALUATED AND QUALIFIED SYS-TH CODE), WITH THE SAME INPUT DECK, HAVE STRONG IMPACT UPON RESULTS AND AFFECT UNCERTAINTY PREDICTION

THEREFORE, ‘DIRECT’ SPECIFIC CODE QUALIFICATION NEEDED FOR UNCERTAINTY EVALUATION
Topics Relevant for Uncertainty Evaluation (TRUE)

BIFURCATIONS

UNIP1 Paper, 2000

SCENAR1OS CAN BE IMAGINED WHERE BIFURCATIONS BRING THE TRANSIENT EVOLUTION FAR FROM THE BEST-ESTIMATE DETERMINISTIC PREDICTION, THUS INVALIDATING THE CONNECTED UNCERTAINTY EVALUATION.

THEREFORE, A BIFURCATION ANALYSIS MAY REVEAL NECESSARY.

STARTING POINTS FOR THE BIFURCATION ANALYSIS ARE:

- THE IDENTIFICATION OF TYPE ONE AND OF TYPE TWO BIFURCATIONS
- THE KNOWLEDGE OF THE UNCERTAINTY CHARACTERIZING THE PARAMETERS WHICH AFFECT THE BIFURCATION.
(Simplified) ‘Tree’ of uncertainty bands resulting from the bifurcation study:

Primary System Pressure

Topics Relevant for Uncertainty Evaluation (TRUE)
Topics Relevant for Uncertainty Evaluation (TRUE)

BIFURCATIONS

UNIPI

Paper, 2000

Standard CIAU application to UMS

Bifurcation CIAU boundaries for UMS

UMS results obtained

By AEAT (and ENUSA)
Topics Relevant for Uncertainty Evaluation (TRUE)

BIFURCATIONS

UNIPI
Paper, 2000

LESSON LEARNED

BIFURCATION STUDY IS POSSIBLE

BIFURCATION STUDY PRODUCES (as expected)
WIDER UNCERTAINTY BANDS (as related to the
standard uncertainty study)

THE UMS AEAT (extreme) RESULT IS (basically)
REPRODUCED BY THE CIAU BIFURCATION STUDY
The CIAU Method: the Idea

Error filling process

NPP STATUS

Error extraction process

NPP CALCULATION

HYPERCUBE & TIME INTERVAL

RELEVANT EXPERIMENTS

“ERROR” DATABASE

CODE APPLICATION RESULTS

NPP UNCERTAINTY PREDICTION
The CIAU Method: the Engine

The UMAE methodology is the Engine and the Qualification Tool to run the CIAU idea

(°) Special methodology developed
1) The Angra-2 DEGB licensing calculation
The CIAU Method: the Application

2) The Kozloduy-3 200 mm break to show similarity of code results.
3) The Kozloduy-3 500 mm DEGB – support for demonstrating DBA

- **Lower Uncertainty Limit**: 1945 K (PCT in hot rod for code run 6 in Tab. 7-2)
- **Reference Value**: 1422 K (PCT in hot rod from ref. [7])
- **Upper Uncertainty Limit**: 350 s (all rod quenched from ref. [7])
- **BE calc & Lower and Upper Unc. Bands**: >700 s (all rod quenched for code run 6 in Tab. 7-2) – VALUE OUT OF SCALE

- **‘Driven’ conservatism**
- **‘Rigorous’ conservatism**

**Licensing Threshold**
CONCLUSIONS

✓ UNCERTAINTY ORIGINS IN TH-SYS CLASSIFIED.
   • “USER EFFECT” AND “CV+J” APPROACH ARE IMPORTANT SOURCES OF UNCERTAINTY.

✓ APPROACHES FOR UNCERTAINTY IDENTIFIED.
   • PROPAGATION OF CODE INPUT UNCERTAINTY & PROPAGATION OF CODE OUTPUT ERROR HAVE BEEN DISTINGUISHED

✓ TOPICS EMPHASIZED FOR UNCERTAINTY METHOD DEVELOPMENT & APPLICATION (TRUE).

✓ MATURE UNCERTAINTY METHODS EXIST FOR DBA AND TH-SYS (ROLE OF 3D NK).
   NEED TO SPREAD THE TECHNOLOGY

✓ CIAU METHODOLOGY HAS BEEN OUTLINED.
   • THE IDEA
   • THE ENGINE
   • THE RESULTS FROM APPLICATIONS