UNCERTAINTY ANALYSIS METHODS FOR COUPLED NEUTRONICS--THE STATE OF THE ART, CRITICAL ISSUES AND NEEDS

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✓ Framework for Uncertainty in SYS-TH
✓ The Origin of Uncertainty
✓ The Approaches for Uncertainty
✓ Topics Relevant for Uncertainty Evaluation (TRUE)
✓ The CIAU Methodology
✓ The Extension to 3D NK-TH Analysis
✓ Conclusions
NEEDS FOR UNCERTAINTY

CONSISTENT APPLICATION OF A THERMOHYDRAULIC SYSTEM CODE

- CODE DEVELOPMENT & IMPROVEMENT (1)
- EXPERIMENTAL DATA (2)
- PROCEDURES FOR CODE USE (3)
- CODE USE (NPP) (5)
- CODE ASSESSMENT (4)
- UNCERTAINTY EVALUATION (6)
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.
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
PROPAGATION OF CODE INPUT “UNCERTAINTIES”

Multiple input (n)  Multiple output (m)

1 1

2 2

n m

- ‘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 $<<$ ‘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**
  - RANGE AND/OR PDF
  - n*

  1. RANGE AND/OR PDF → THERMALHYDRAULIC SYSTEM CODE
  2. 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
\( n \sim 10^5 \)

BIC         CODE                INPUT DECK

1
2
n

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

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

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

1
2
m

Predicted NPP transient scenario

UNCERTAINTY PROPAGATION
Multiple input (n)

1
2
n

1
2
m

THERMALHYDRAULIC SYSTEM CODE

ERROR BANDS

RELEVANT EXPERIMENTS

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
Multiple Input
\[ n \sim 10^5 \]

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

Relevant experimental data

BIC

CODE

INPUT DECK

1

2

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) ∆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.

Different nodalisations originate different ∆PCT
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 $\Delta$PCT 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

UNIP
Internal Report, 1999

for Uncertainty Evaluation

(exp) XXXX
“OLD” code* YYY
“INTERMEDIATE” code* ZZZZ
“NEW” code* VVVV

* 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.
SCENARIOS 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

- Upper Uncertainty Bound
- Lower Uncertainty Bound

Graph showing pressure (MPa) over time (s) with various uncertainty bands indicated.

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)
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

- NPP STATUS
- HYPERCUBE & TIME INTERVAL
- RELEVANT EXPERIMENTS
- "ERROR" DATABASE
- CODE APPLICATION RESULTS
- NPP UNCERTAINTY PREDICTION
- NPP CALCULATION

Error filling process → NPP STATUS → Error extraction process
The CIAU Method: the Engine

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

(°) Special methodology developed
The CIAU Method: the Flow-Diagram

- CIAU Development
  - Transient evolution & status approach
  - Qual. ITF and SETF data
  - Qual. Calc. Results
  - Data documentation for each status
    - Quantitative accuracy
    - Qualitative accuracy
    - Time accuracy
  - UMAE specific
  - Needed variables selection

- CIAU Application
  - Transient types and Hypercubes number
  - Scenario independence check
  - Uncertainty Calculation
    - Quantity Uncertainty Matrix (QUM)
    - Time Uncertainty Vector (TUV)
  - CIAU
    - ASM Transient Result
    - Possible stop of the process
    - Transient status characterization
    - Quantity Uncertainty
    - Scenario Uncertainty
    - Time Uncertainty
The CIAU Method: the Application

1) The Angra-2 DEGB licensing calculation

![Diagram showing Tclad (°C) with licensing limits and calculation bands.](image)
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
A 3D NK-TH RUN IMPLIES:

XSEC DERIVATION $\Rightarrow$ 3D NK $\Leftarrow$ TH

(A)               (B)   (C)   (D) (E) (F)

EACH OF THE STEPS (A) TO (F) CONSTITUTES
A SOURCE OF UNCERTAINTY

HEREAFTER KEY RECENT FINDINGS:

1) APPLICATION OF GRS METHOD – PARTIAL LOFW
2) FINDING FROM CRISUE-S EC PROJECT
3) CIAU-TN
A detailed description of the plant transient and results from analyses by coupled codes can be found in Mittag, 2000 and Mittag, 2001. During a test in the Balakovo-4 VVER-1000 (Russia), one of two working main steam generator feed water pumps was switched off at nominal power. Two seconds after the pump switch-off, the power control system responded by inserting the control rod group K1 from top to bottom within four seconds. As a result, the core power decreased down to about 63% of nominal power within 10 s. Also the control rod group K10 started moving in at a rate of 2 cm/s. The initial axial position was at 275 cm. The slow insertion of control rod group K10 down to an axial position of 140 cm resulted in a further power decrease to about 45% of nominal power. The reactor was stabilized at this level by the automatic power control. As all four main coolant pumps continued operating, the differences between the temperatures of the hot legs and the corresponding cold legs of the four primary loops decreased proportionally to the thermal power reduction, the temperatures in the loops stabilized at a new level. Initially, the primary pressure decreased, later on the primary pressure increased again, determined by the heat balance. The transient led to a strong decrease of the water level in the pressurizer (PRZ) in the early phase, then the level increased again to nominal values.
The Extension to 3D NK-TH Analysis

1) APPLICATION OF GRS METHOD – PARTIAL LOFW

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Range</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Magnitude of secondary pressure: correction factor *</td>
<td>0.9; 1.1</td>
<td>uniform</td>
</tr>
<tr>
<td>2</td>
<td>Total reactivity worth of control rod group K1</td>
<td>0.7; 1.0; 1.1</td>
<td>triangular</td>
</tr>
<tr>
<td>3</td>
<td>Total reactivity worth of control rod group K10</td>
<td>0.7; 1.0; 1.1</td>
<td>triangular</td>
</tr>
<tr>
<td>4</td>
<td>Shape of axial burn-up distribution**: correction factor</td>
<td>0.8; 1.0</td>
<td>uniform</td>
</tr>
<tr>
<td>5</td>
<td>Fuel temperature feedback: correction of the global core response</td>
<td>-0.2; 0; 0.2 (each 1/3)</td>
<td>discrete</td>
</tr>
<tr>
<td>6</td>
<td>Moderator density feedback: correction of the global core response</td>
<td>-0.2; 0; 0.2 (each 1/3)</td>
<td>discrete</td>
</tr>
<tr>
<td>7</td>
<td>Heaters in PRZ: heat-up time-constant [s]</td>
<td>2.0; 20.0</td>
<td>uniform</td>
</tr>
<tr>
<td>8</td>
<td>Heaters in PRZ: protection influence factor***</td>
<td>1; 2 (each 1/2)</td>
<td>discrete</td>
</tr>
<tr>
<td>9</td>
<td>Fuel rod gap heat transfer coefficient [W/m²K]</td>
<td>3000.0; 5000.0</td>
<td>uniform</td>
</tr>
<tr>
<td>10</td>
<td>Mass flow of the feed water</td>
<td>0.9; 1.1</td>
<td>uniform</td>
</tr>
<tr>
<td>11</td>
<td>Enthalpy of the feed water</td>
<td>0.9; 1.1</td>
<td>uniform</td>
</tr>
</tbody>
</table>
The Extension to 3D NK-TH Analysis

1) APPLICATION OF GRS METHOD – PARTIAL LOFW
The Extension to 3D NK-TH Analysis

1) APPLICATION OF GRS METHOD – PARTIAL LOFW
The Extension to 3D NK-TH Analysis

1) APPLICATION OF GRS METHOD – PARTIAL LOFW
1) APPLICATION OF GRS METHOD – PARTIAL LOFW
A variety of quantities of interest for the design and safety evaluation of LWR are the output of coupled 3-D neutron kinetics/thermal-hydraulics calculation. These range from the $k_{\text{eff}}$, to the boron concentration to reach criticality, to the worth of CR, to the transient pressure, the fuel temperature, the flow rate, the level (e.g. in the PRZ), the amount of radioactive liquid discharged from a relief valve (SRV or PORV). The identification of these quantities is connected with the transient type (e.g. ATWS or LBLOCA), with the application type, notably licensing or design analysis and is related to the duration of the transient. Each application is definitely associated with a set of quantities of interest. A minimum reasonable set of quantities of interest is defined below, making reference to a transient duration of the order of 100 s. The following quantities are selected and related point values are considered:
The Extension to 3D NK-TH Analysis

2) FINDING FROM CRISUE-SEC PROJECT

- [Quantity 1 and 2]. Peak pressure in RPV (UP location) and in PRZ (if applicable), related FWHM (if applicable) and time of occurrence.

- [Quantity 3]. Peak total core power, related FWHM (if applicable) and time of occurrence.

- [Quantity 4]. CHF (or DNB) occurrence time.

- [Quantity 5]. PCT and time of occurrence.

- [Quantity 6]. Maximum fuel temperature (MFT) and time of occurrence.

- [Quantity 7]. Total thermal energy released to the fluid (TTEF) during the transient.

- [Quantity 8]. Maximum % of core, in terms of heat transfer area (HTA) of the active region where, at any time, rod surface temperature > 1 000 K occurs (CRHST = core region at high surface temperature).

- [Quantity 9]. Maximum % of core in terms of volume occupied by fuel pins in the active region where, at any time, fuel temperature > 3 000 K occurs (CRHFT = core region at high fuel temperature).
2) FINDING FROM CRISUE-S EC PROJECT

- [Quantity error, situation ‘a’]. For core power pulses characterised by FWHM < 0.1 s in the reference BE evaluation, the acceptable threshold error is 100% nominal power or 300% initial power of the considered system, which ever is smaller.

- [Quantity error, situation ‘b’]. For core power pulses characterised by FWHM ≥ 0.1 s in the reference BE evaluation, the acceptable threshold error is 20% nominal power or 100% initial power of the considered system, which ever is smaller.
2) FINDING FROM CRISUE-S EC PROJECT

- [Quantity error, situation ‘b’]. For PCT, the acceptable threshold error is 150 K (larger errors can be tolerated for BE prediction of PCT below 1 000 K).

- [Quantity error, situation ‘b’]. For MFT, the acceptable threshold error is 200 K.

- [Quantity error]. For TTEF the acceptable threshold error is 10% of energy released to the fluid in nominal conditions or 100% of energy released to the fluid at the actual initial power, during the considered transient duration, which ever is smaller.

- [Quantity error]. For CRHST the acceptable threshold error is 10% of core HTA.

- [Quantity error]. For CRHFT the acceptable threshold error is 10% of core pin volume.

- [Time error, situation ‘a’]. The acceptable time error that can be associated to the prediction of time of occurrence of Quantities 1 to 3 is 100% of the BE value.

- [Time error, situation ‘b’]. The acceptable time error that can be associated to the prediction of time of occurrence of Quantities 1 to 6 is 20% of the BE value.

- [Time error, situations ‘a’ and ‘b’]. The acceptable time error that can be associated to the prediction of FWHM for Quantities 1 to 3 is 20% of the BE value.
Acceptability thresholds for the quantities of interest

The definition of acceptability thresholds encounters the same difficulties mentioned earlier as concerns the quantities of interest. The dimension of the core, including the nominal power, the power generated per unit volume and various other nominal operating conditions (e.g. nominal pressure, set point for valves opening) may also affect the identification of thresholds of acceptance.

However, the errors that are acceptable (acceptability thresholds) for the identified quantities are defined here. In the present approach it is assumed that the overall error for a point-value quantity is the combination of two independent contributions: the quantity errors and the time error. Therefore, the predicted point-value quantity stays in a rectangle whose geometric centre is the BE prediction and whose edges are given by the “quantity” and the “time” error values [7].
3) CIAU-TN

- Extension of the CIAU Uncertainty Analysis to the (3D) Core Power → CIAU-TN
- CIAU-TN is based upon the same approach of CIAU for thermal-hydraulics codes
- Total Reactivity and core average exposure are ‘new’ driving quantities:

<table>
<thead>
<tr>
<th>Driving Quantities</th>
<th>(1) Upper Plenum Pressure (MPa)</th>
<th>(2) Primary Circuit Mass Inventory (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(3) Steam Generator Pressure (MPa)</th>
<th>(4) Cladding Temperature at 2/3 Core Height (K)</th>
<th>(5) Steam Generator Level (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(6) Core Power (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(7) Total Reactivity (k/k)</th>
<th>(8) Core Average Exposure (Gd/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypercube Limits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Core Power (%)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Total Reactivity (k/k)</td>
<td>Core Average Exposure (Gd/ft)</td>
</tr>
<tr>
<td>1</td>
<td>0.09 – 0.5</td>
<td>10 – 40</td>
<td>0.1 – 3.0</td>
<td>298 – 473</td>
<td>0 – 50</td>
<td>0.5 – 1.0</td>
<td>0.0070 – 0.0050</td>
<td>0 – 10</td>
</tr>
<tr>
<td>2</td>
<td>0.5 – 2.0</td>
<td>40 – 80</td>
<td>3.0 – 7.0</td>
<td>473 – 573</td>
<td>50 – 100</td>
<td>1.0 – 6.0</td>
<td>0.0050 – 0.0030</td>
<td>10 – 20</td>
</tr>
<tr>
<td>3</td>
<td>2.0 – 4.0</td>
<td>80 – 100</td>
<td>7.0 – 9.0</td>
<td>573 – 643</td>
<td>100 – 150</td>
<td>6.0 – 50</td>
<td>0.0030 – 0</td>
<td>20 – 30</td>
</tr>
<tr>
<td>4</td>
<td>4.0 – 5.0</td>
<td>100 – 120</td>
<td>-</td>
<td>643 – 973</td>
<td>-</td>
<td>50 – 100</td>
<td>0 – 0.010</td>
<td>30 – 40</td>
</tr>
<tr>
<td>5</td>
<td>5.0 – 7.0</td>
<td>-</td>
<td>-</td>
<td>973 – 1473</td>
<td>-</td>
<td>100 – 130</td>
<td>-0.010 – 0.100</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>7.0 – 9.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>130 – 300</td>
<td>-0.100 – -0.400</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>9.0 – 10.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300 – 1000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>10.0 – 15.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1000 – 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>15.0 – 18.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup> Percent of the initial nominal value.
The Extension to 3D NK-TH Analysis

3) CIAU-TN

- ‘NEW’ UNCERTAINTY VECTORS ARE INTRODUCED

  - **DTUV** (Detailed Time Uncertainty Vector) → *uncertainty on the time when the power peak occurs*
  - **DPUV** (Detailed Power Uncertainty Vector) → *uncertainty on the quantity of the Core Power*
  - **APFUV** (Axial Peaking Factors (Fz) Uncertainty Vector) → *uncertainty on the quantity of Fz*
  - **ZUV** (Axial (Z) Position Uncertainty Vector) → *uncertainty on axial position of the maximum value of Fz*
  - **RPFUV** (Radial Peaking Factors (Fr) Uncertainty Vector) → *uncertainty on the quantity of Fr*
  - **XUV, YUV** (Radial (X,Y) Position Uncertainty Vector) → *uncertainty on radial (x, y) position of the maximum value of Fr*

- ‘NEW’ OBJECT QUANTITIES

  - **CORE POWER HYSTORY**
  - **AXIAL PEAKING FACTORS DISTRIBUTION**
  - **AVERAGE RADIAL PEAKING FACTORS DISTRIBUTION**
The Extension to 3D NK-TH Analysis

3) CIAU-TN

STRUCTURES OF UNCERTAINTY MATRICES & VECTORS

VECTORS & MATRICES

1. TUV
   - Time
   - Primary Pressure
   - Mass Inventory
   - Rod Clad Temperature
   - Core Power
   - Total Reactivity
   - Core Average Exposure

2. QUM
   - Time
   - Primary Pressure
   - Mass Inventory
   - Rod Clad Temperature
   - Core Power
   - Total Reactivity
   - Core Average Exposure

3. DTUV
   - Time
   - Primary Pressure
   - Mass Inventory
   - Rod Clad Temperature
   - Core Power
   - Total Reactivity
   - Core Average Exposure

4. DPUV
   - Primary Pressure
   - Mass Inventory
   - Rod Clad Temperature
   - Core Power
   - Total Reactivity
   - Core Average Exposure

DRIVING QUANTITIES

OBJECT QUANTITIES

5. XUV
   - X position
   - Total Reactivity
   - Core Average Exposure

YUV
   - Y position
   - Total Reactivity
   - Core Average Exposure

ZUV
   - Z position
   - Total Reactivity
   - Core Average Exposure

6. APFUV
   - Axial Peak Factors
   - Distribution
   - Mass Inventory
   - Rod Clad Temperature
   - Core Power
   - Total Reactivity
   - Core Average Exposure

7. RPFUV
   - Radial Peak Factors
   - Distribution
   - Primary Pressure
   - Mass Inventory
   - Rod Clad Temperature
   - Core Power
   - Total Reactivity
   - Core Average Exposure
The Extension to 3D NK-TH Analysis

3) CIAU-TN: Simplified Diagram

EXP &/or REFERENCE DATA

CIAU METHODOLOGY

B.E. DATA

CIAU -TN

CIAU v2.0

TUV

QUM

UNCERTAINTY DATA

UNCERTAINTY BANDS

CIAU_3D

DTUV

DPUV

XUV–YUV–ZUV

APFUV-RPFUV

CORE POWER HISTORY

AXIAL PEAK FACTOR DISTRIBUTION

RADIAL PEAK FACTOR DISTRIBUTION

PRIMARY PRESSURE

ROD CLADDING TEMPERATURE

PRIMARY MASS

CORE POWER HISTORY

PRIMARY PRESSURE

ROD CLADDING TEMPERATURE

PRIMARY MASS

CORE POWER HISTORY
The Extension to 3D NK-TH Analysis

3) CIAU-TN

CIAU-TN DIAGRAM

CIAU_v2.0

ACCURACY CALCULATION & UNCERTAINTY EXTRAPOLATION

Detailed Core Power Uncertainty

Detailed Time Uncertainty

Detailed Accuracy Calculation & Detailed Uncertainty Extrapolation
(Time span corresponding to the core power peak)

Detailed Accuracy Calculation & Detailed Uncertainty Extrapolation for Axial & Radial Peak Factors Distribution

Input deck
Exp & Calc data

Core Power Quantity Uncertainty

Core Power Uncertainty in position of the core power peak

Time Uncertainty respect to core power peak

UBEP_v2.0

TRANSIENT STATUS CHARACTERIZATION

 CALC CODE RESULT

Uncertainty Bands
- Primary Pressure
- Mass Inventory
- Rod Clad Temperature
- Core Power

UBEP_N

TRANSIENT STATUS CHARACTERIZATION

Uncertainty Bands of the Core Power History

SNAP SHOTS

Uncertainty Bands of the Axial and Radial Peak Factors Distribution

UBEP_v2.0

TRANSIENT STATUS CHARACTERIZATION

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TRANSIENT STATUS CHARACTERIZATION

Uncertainty Bands of the Core Power History

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UBEP_v2.0

TRANSIENT STATUS CHARACTERIZATION

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- Primary Pressure
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- Rod Clad Temperature
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UBEP_N

TRANSIENT STATUS CHARACTERIZATION

Uncertainty Bands of the Core Power History

SNAP SHOTS

Uncertainty Bands of the Axial and Radial Peak Factors Distribution

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TRANSIENT STATUS CHARACTERIZATION

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Input deck
Exp & Calc data

Core Power Quantity Uncertainty

Core Power Uncertainty in position of the core power peak

Time Uncertainty respect to core power peak
The Extension to 3D NK-TH Analysis

CIAU-N TOOLS

SPATIAL ANALYSIS TOOL:

- 3D-AFE
- 3D-COLLECT
- 3D-DAST

TIME ANALYSIS TOOL:

- D-AFE
- D-COLLECT
- D-DAST
The Extension to 3D NK-TH Analysis

3) CIAU-TN

Detailed Comparison between Reference and Calculated Power Peak

Core Power (%)

Time (s)

Reference
Calculated

Core Power (%)

Time (s)

DTUV
DPUV

REFERENCE
CALCULATED

Axial Peak Factor Distribution

REFERENCE
CALCULATED

ZUV
APFUV

XUV - YUV
RPFUV
The Extension to 3D NK-TH Analysis

3) CIAU-TN

The graph shows the comparison between reference and calculated data over time. The key parameters include:

- Time (s) on the x-axis ranging from 0.00 to 5.00
- Core Power (%) on the y-axis ranging from 0.00 to 300.00

The graph highlights:

- Reference (blue line)
- Calculated (red line)

Key points:

- $\Delta t$ (time difference)
- $\Delta P$ (power difference)
- $t_P^R$ (reference time point)
- $t_P^C$ (calculated time point)

This graph is used to analyze the performance and accuracy of the Calculated data compared to the Reference data.
Detailed Comparison between Reference and Calculated Power Peak

Reference
Calculated

\( \Delta P \)

\( \Delta t_1 \)

\( \Delta t_2 \)

DTUV
DPUV

The Extension to 3D NK-TH Analysis

3) CIAU-TN
The Extension to 3D NK-TH Analysis

3) CIAU-TN

Axial Peak Factor Distribution

REFERENCE
CALCULATED

$\Delta F_z$

$\Delta Z$

$\tau_p^C$

$\tau_p^R$

ZUV
APFUV
The Extension to 3D NK-TH Analysis

3) CIAU-TN

Average Radial Peak Factor Distribution

REFERENCE
CALCULATED

Cell Position

XUV - YUV
RPFUV
The Extension to 3D NK-TH Analysis

3) CIAU-TN

X - POSITION UNCERTAINTY VECTOR (XUV)

Y - POSITION UNCERTAINTY VECTOR (YUV)

X - POSITION ERROR
(XUV x x) / 100

Y - POSITION ERROR
(YUV x y) / 100
The Extension to 3D NK-TH Analysis

3) CIAU-TN

TOTAL CORE POWER

- UPI (RELAP5/PARCS)
- REFERENCE
- UPPER BAND
- LOWER BAND

\[ \Delta E_P = 22.34\% \]
\[ \Delta t_P = 14.05\% \]
\[ \Delta(\int Pdt) = 77.58\% \]
The Extension to 3D NK-TH Analysis

3) CIAU-TN

TOTAL CORE POWER

- UPI (RELAP5/PARCS)
- REFERENCE
- UPPER BAND
- LOWER BAND

UNCERTAINTY RECTANGLE IN CORRESPONDENCE OF THE POWER PEAK

ΔE_p = 22.34 %
Δt_p = 14.05 %
The Extension to 3D NK-TH Analysis

TOTAL CORE POWER: 3D Representation of the Error

3) CIAU-TN

![3D Representation of the Error](image)
The Extension to 3D NK-TH Analysis

3) CIAU-TN

AXIAL PEAK FACTORS DISTRIBUTION

(UII (RELAP5/PARCS)
REFERENCE
UPPER BAND
LOWER BAND)

\[(\Delta U)_{AVG} = 11.68\%\]
The Extension to 3D NK-TH Analysis

3) CIAU-TN

RADIAL PEAK FACTORS DISTRIBUTION

\[(\Delta U)_{AVG} = 25.35 \%\]
The Extension to 3D NK-TH Analysis

3) CIAU-TN

RADIAL PEAK FACTORS DISTRIBUTION

Y-Cell Position (X = 19)

UPI (RELAP5/PARCS)
REFERENCE
UPPER BAND
LOWER BAND
The Extension to 3D NK-TH Analysis

3) CIAU-TN

**TOTAL CORE POWER**

- **First Peak:**
  - Quantity Uncertainty = 16.1%
  - Time Uncertainty = 32.7%

- **Second Peak:**
  - Quantity Uncertainty = 35.8%
  - Time Uncertainty = 22.3%

- **Energy Released to the fuel:**
  - Uncertainty = 60.4%
CONCLUSIONS 1 OF 2

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

✓ APPROACHES TO QUANTIFY UNCERTAINTY
   PROPAGATION OF CODE INPUT UNCERTAINTY & PROPAGATION OF CODE OUTPUT ERROR HAVE BEEN DISTINGUISHED

✓ TOPICS TO BE CONSIDERED FOR UNCERTAINTY
   METHOD DEVELOPMENT & APPLICATION (TRUE).

✓ CIAU METHODOLOGY OUTLINED.
   • THE IDEA
   • THE ENGINE
   • THE RESULTS FROM APPLICATION2
UNCERTAINTY METHODS ARE MATURE FOR INDUSTRIAL APPLICATION IN THE AREA OF SYS-TH AND DBA

KEY DEVELOPMENTS OUTLINED IN THE AREA OF COUPLED 3D NK-TH APPLICATIONS: DEMONSTRATION OF MATURITY NOT ACHIEVED

INTERNATIONAL ACTIVITIES IN PROGRESS:

A) OECD-CSNI BEMUSE PROJECT.

B) IAEA TECDOC TO BE ISSUED & TM BE+UNC (PISA SEPT. 2005).

C) EC NURESIM PROJECT – VALIDATION OF METHOD PROPOSED BY DAN CACUCI.