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# Challenge of PWR new core design simulation: a focus on uncertainties due to nuclear data and reflector modelling

# Content

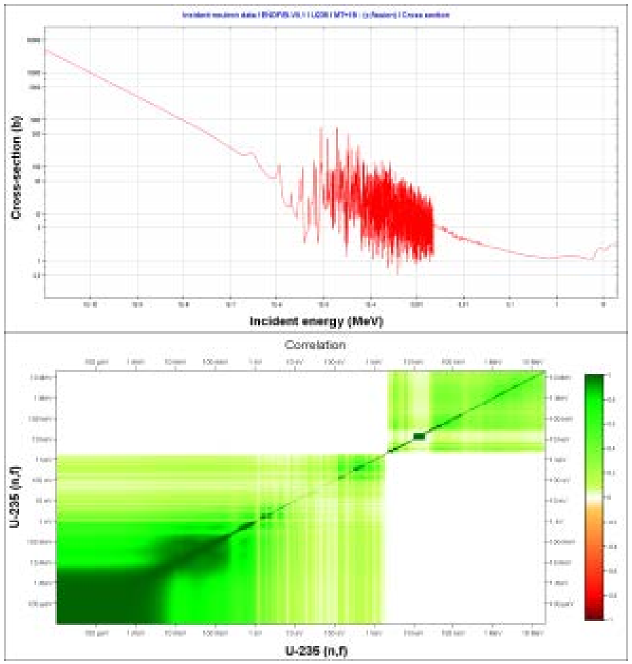
- Motivation
- Multi-scale approach in reactor physics
- Presentation of the analyzed cases
- Results analysis
- Conclusions

# Motivation

- Core power distribution plays a key role for the determination of several critical safety parameters (e.g. maximum fuel temperature, maximum cladding temperature or minimum DNB)
- Core power distribution is the result of a multi-scale / multi-physic* calculation approach
  - *In this study, constant thermo-hydraulic conditions were assumed
- At each level of this calculation sequence, different sources of uncertainty have an influence on the calculated power distribution
- Code-to-code comparison at the different levels as a method of validation

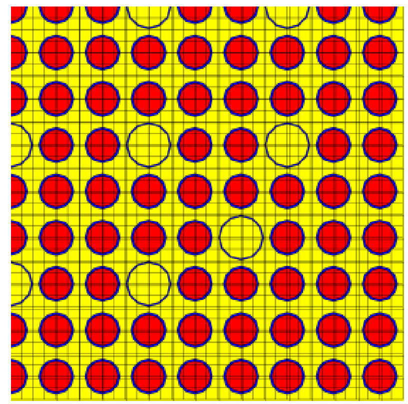
# Multi-scale approach in reactor physics

## First level: Microscopic Scale



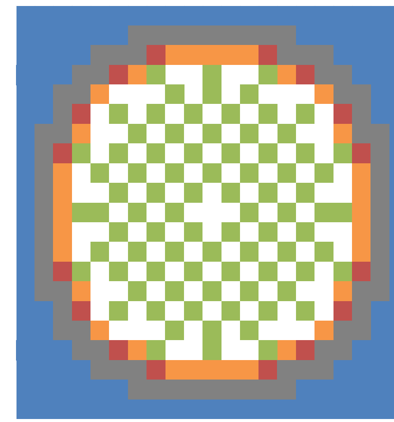

Nuclear data in multi-group form

## Second Level: Fuel Assembly Scale



Problem-dependent, homogenized 2-group cross sections

## Third Level: Core Scale



Nuclear Data:

- Cross-sections
- Angular-/Energy Distributions
- Covariances
- Etc.

Lattice Code:

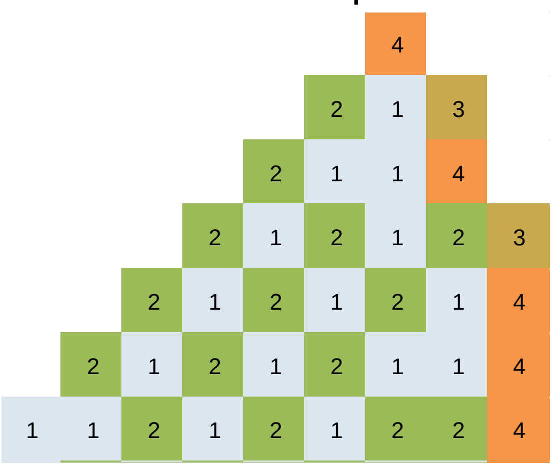
- NEWT
- DRAGON

Core Simulator:

- QUABOX/CUBBOX
- DONJON
- PARCS

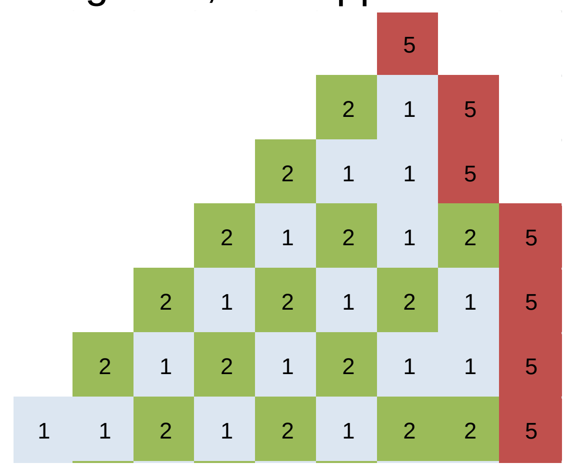
# Presentation of the analyzed cases

- Extracted from Exercise I-3 of the OECD/NEA UAM Benchmark
  (Benchmarks for **U**ncertainty **A**nalysis in **M**odelling for the Design, Operation and Safety Analysis of LWRs)
- Two ”*Gen-III*” type core loadings (UOX and MOX), surrounded with a massive steel reflector
- Fresh cores
- Conditions representative of hot full power state
  - Fuel temperature of 900 K ; moderator density of 0.7 g/cm$^3$ ; 1300 ppm of boron




UOX Core

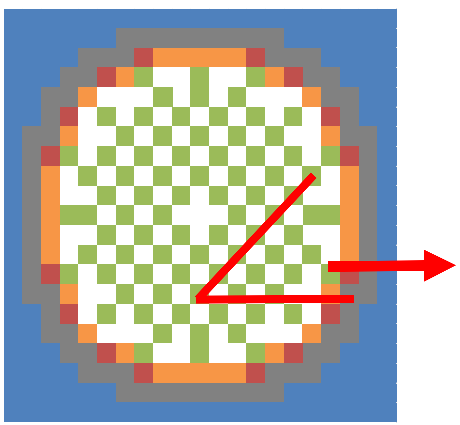
| | |
|---|---|
| 1 | UOX 2.1% |
| 2 | UOX 3.2% 20Gd |
| 3 | UOX 4.2% |
| 4 | UOX 4.2% 12Gd |
| 5 | MOX |




MOX Core

# Reference core power distribution

- A “reference” calculation is performed with the CSAS5 sequence of the SCALE 6.0 code system
  - Cross-section processing in the resolved / unresolved range to obtain a problem-dependent multigroup library
  - Transport calculation with the 3-D Monte Carlo Code KENO V.a
- Normalized power distributions (1/8 core symmetry):



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 1.08 | | |
| | | | | | 1.16 | 1.20 | 1.29 | |
| | | | | 1.00 | 1.12 | 1.27 | 1.31 | |
| | | | 0.86 | 0.92 | 1.02 | 1.12 | 1.07 | 1.11 |
| | | 0.78 | 0.80 | 0.87 | 0.93 | 1.03 | 1.11 | 1.11 |
| | 0.78 | 0.76 | 0.79 | 0.83 | 0.90 | 1.00 | 1.09 | 1.06 |
| 0.87 | 0.80 | 0.77 | 0.77 | 0.82 | 0.87 | 0.94 | 0.98 | 1.01 |

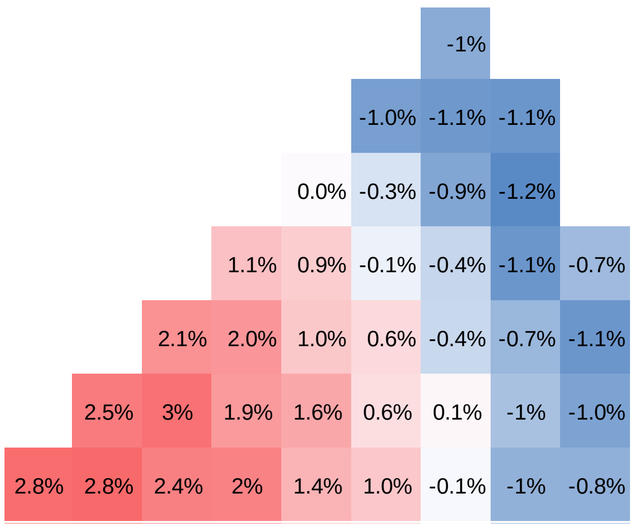
UOX Core

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 0.94 | | |
| | | | | | 1.05 | 0.97 | 0.86 | |
| | | | | 1.01 | 1.07 | 1.11 | 1.10 | |
| | | | 0.95 | 0.97 | 1.03 | 1.07 | 0.91 | 0.81 |
| | | 0.92 | 0.92 | 0.96 | 0.99 | 1.06 | 1.07 | 1.06 |
| | 0.95 | 0.92 | 0.92 | 0.94 | 0.99 | 1.08 | 1.14 | 1.14 |
| 1.08 | 0.99 | 0.93 | 0.92 | 0.94 | 0.98 | 1.03 | 1.05 | 1.12 |

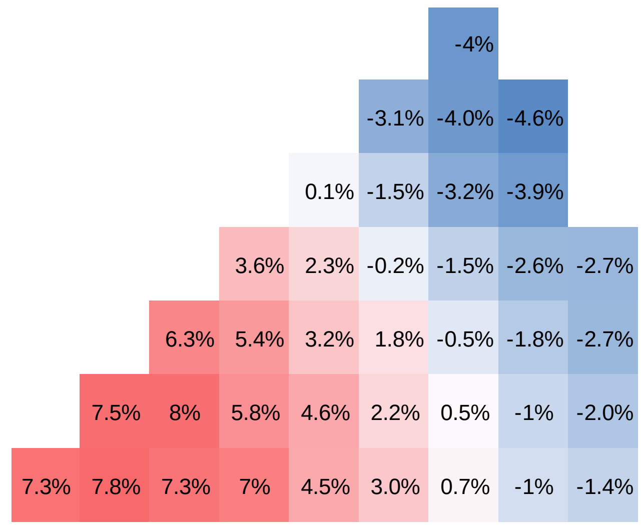
MOX Core

# Uncertainty from the microscopic scale (1/3)

- Effect of three nuclear data evaluations
  - American nuclear data evaluation, **ENDF/B-VII.0***,
  - European nuclear data evaluation, JEFF-3.1.1,
  - Older European nuclear data evaluation, JEF-2.2.




Discrepancy ENDF/B-VII.0 vs JEFF-3.1.1




Discrepancy ENDF/B-VII.0 vs JEF-2.2

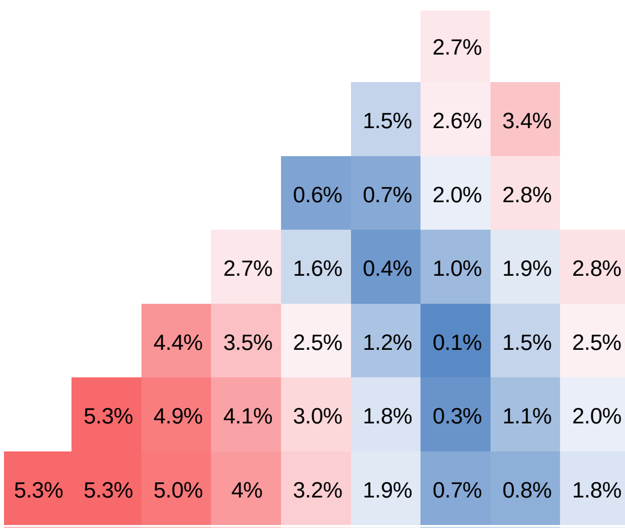
*Used in the following calculations

# Uncertainty from the microscopic scale (2/3)

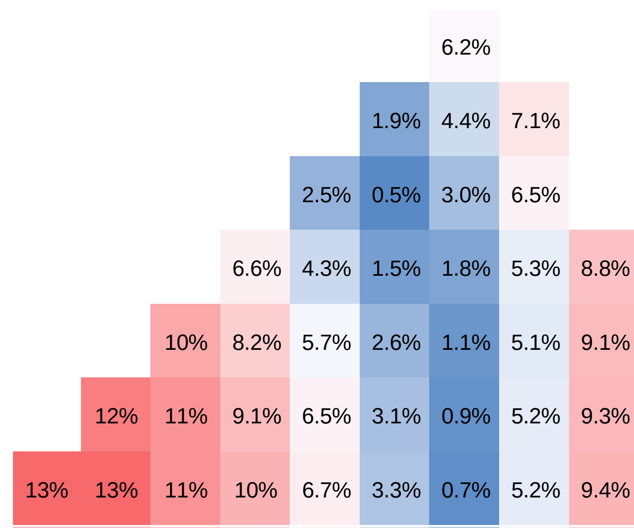
- Main idea of the GRS method
  - Many calculations (typically >> 100) are run for the same problem with varied input data
  - Variations are generated randomly from the probability distributions of the input parameters and correlations between them
  - Output quantities are statistically analyzed, uncertainty ranges and sensitivities are determined
  - The GRS SUSA package is traditionally being applied with uncertainties in thermo-hydraulic parameters, geometrical parameters, material parameters, … → moderate numbers of uncertain input quantities, small numbers of correlations
  - XSUSA: Applying the GRS method using nuclear data covariance files → huge numbers of uncertain input quantities, large numbers of correlations

# Uncertainty from the microscopic scale (3/3)

- Results from the XSUSA calculations
  - Maximum uncertainty in the center of the core
    - 5.3% in the UOX core
    - 13% in the MOX core




UOX Core




MOX Core

# Uncertainty from the assembly scale

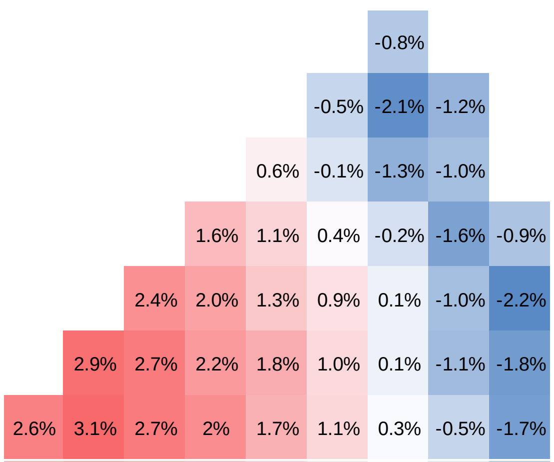
- Effect of different assembly calculation schemes
  - Same nuclear data (ENDF/B-VII.0)
  - Different lattice codes: NEWT and DRAGON
  - Same reflector properties (cross sections)
  - UOX Core

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 0.7% | | |
| | | | | | 0.9% | 0.8% | 0.7% | |
| | | | | 0.1% | 0.3% | 0.7% | 0.9% | |
| | | | -0.7% | -0.6% | 0.2% | 0.3% | 0.9% | 0.4% |
| | | -1.3% | -1.4% | -0.6% | -0.5% | 0.4% | 0.5% | 0.7% |
| | -1.6% | -1.8% | -1.2% | -1.2% | -0.3% | -0.1% | 0.4% | 0.6% |
| -1.8% | -1.9% | -1.5% | -2% | -0.9% | -0.8% | 0.1% | 0.6% | 0.4% |

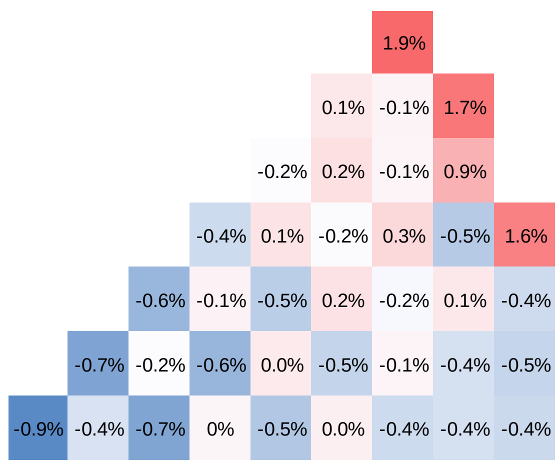
NEWT vs. DRAGON

# Uncertainty from the core scale (1/2)

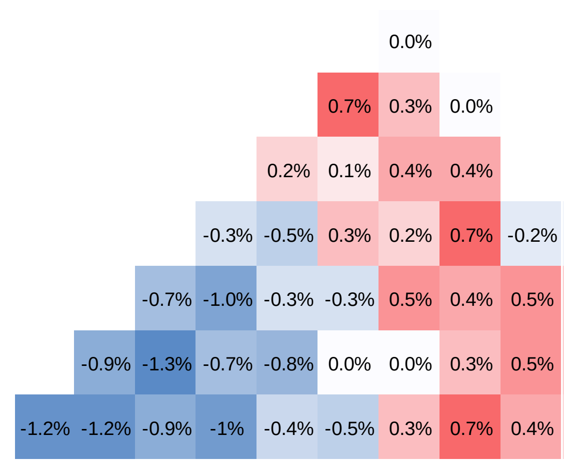
- Effect of different core simulators
  - QUABOX/CUBBOX (Q/C) – High-order polynomial flux expansion
  - PARCS – Analytic Nodal Method and Nodal Expansion Method
  - DONJON – Quadratic finite elements method
- UOX Core Results




PARCS (ANM) vs Q/C
(NEWT cross sections)




PARCS (NEM) vs Q/C
(NEWT cross sections)




PARCS (NEM) vs DONJON
(DRAGON cross sections)

# Uncertainty from the core scale (2/2)

- Effect of different core simulators
  - QUABOX/CUBBOX (Q/C) – High-order polynomial flux expansion
  - PARCS – Analytic Nodal Method and Nodal Expansion Method
- MOX Core Results

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | -2.6% | | |
| | | | | | -0.7% | 1.4% | -0.8% | |
| | | | | -0.7% | -0.5% | 0.9% | -2.0% | |
| | | | -0.7% | -0.8% | -0.6% | -0.3% | 1.7% | 0.5% |
| | | -0.9% | -1.0% | -0.6% | -0.5% | 0.0% | 1.6% | 1.6% |
| | -1.2% | -1.2% | -0.8% | -0.7% | -0.2% | 0.3% | 1.8% | 1.8% |
| -0.7% | -1.1% | -1.0% | -1% | -0.6% | -0.3% | 0.3% | 1.3% | 2.0% |

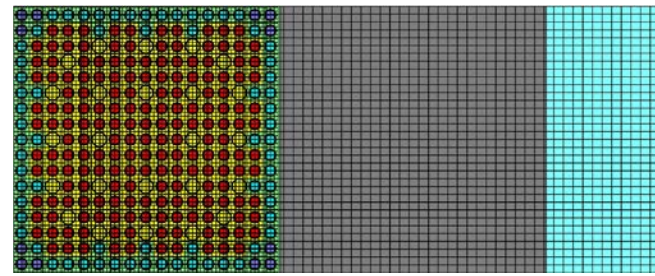
PARCS (ANM) vs Q/C
(NEWT cross sections)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | -3.0% | | |
| | | | | | -0.8% | -0.9% | -2.5% | |
| | | | | 0.1% | -0.6% | -0.3% | -2.2% | |
| | | | 0.6% | -0.1% | 0.1% | -0.6% | 0.3% | -1.2% |
| | | 1.0% | 0.2% | 0.7% | 0.0% | 0.3% | 0.1% | 0.2% |
| | 1.1% | 0.5% | 1.0% | 0.3% | 0.8% | 0.3% | 0.6% | 0.6% |
| 1.3% | 0.8% | 1.2% | 1% | 0.9% | 0.3% | 0.7% | 0.7% | 0.8% |

PARCS (NEM) vs Q/C
(NEWT cross sections)

# Uncertainty from reflector modeling (1/2)

- Transport calculation
  - Reflector region computed with a transport code (NEWT)
  - With the flux obtained, homogenization is performed to obtain reflector cross sections



- Reflector "adjustment procedure":
  - A first core calculation is performed with these reflector cross sections, using deterministic tools (NEWT and Q/C)
  - A reference power distribution is obtained from another source (here Monte-Carlo, with KENO code)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 1.08 | | |
| | | | | | 1.16 | 1.20 | 1.29 | |
| | | | | 1.00 | 1.12 | 1.27 | 1.31 | |
| | | | 0.86 | 0.92 | 1.02 | 1.12 | 1.07 | 1.11 |
| | | 0.78 | 0.80 | 0.87 | 0.93 | 1.03 | 1.11 | 1.11 |
| | 0.78 | 0.76 | 0.79 | 0.83 | 0.90 | 1.00 | 1.09 | 1.06 |
| 0.87 | 0.80 | 0.77 | 0.77 | 0.82 | 0.87 | 0.94 | 0.98 | 1.01 |

Reference power distribution

# Uncertainty from reflector modeling (2/2)

- Reflector “adjustment procedure”
  - Discrepancy between the two calculations are computed
  - Transport-derived reflector cross sections are then adjusted in order to obtain the lowest discrepancies possible on power distribution between the reference KENO calculation and Q/C calculation (iterative process)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | -0.2% | | |
| | | | | | -1.1% | 3.8% | 2.3% | |
| | | | | -2.8% | 1.4% | 2.7% | 2.0% | |
| | | | -4.5% | -0.5% | -2.6% | 1.7% | 1.2% | 2.2% |
| | | -6.0% | -2.2% | -4.2% | 0.0% | -1.8% | 3.1% | 4.1% |
| | -7.1% | -3.5% | -5.8% | -1.6% | -3.4% | 1.3% | 3.1% | 3.6% |
| -4.6% | -4.4% | -6.7% | -3% | -4.9% | -0.1% | -1.5% | 0.7% | 3.9% |

KENO V.a vs Q/C **before** the adjustment procedure

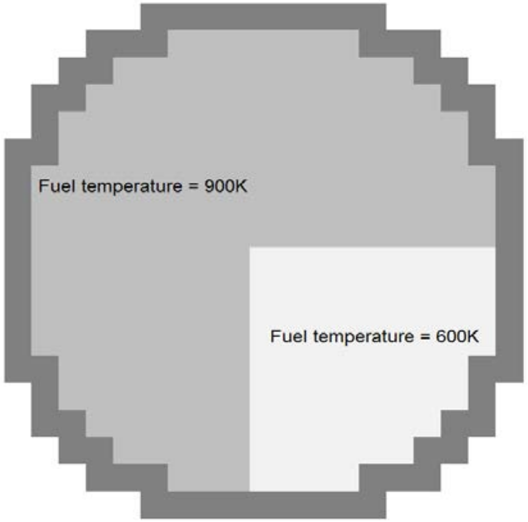
→

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | -2.4% | | |
| | | | | | -1.8% | 2.3% | -0.6% | |
| | | | | -2.1% | 1.3% | 1.8% | 0.1% | |
| | | | -2.5% | 0.9% | -2.0% | 1.2% | -0.3% | -0.7% |
| | | -2.8% | 0.5% | -2.4% | 0.9% | -1.9% | 1.9% | 1.5% |
| | -3.1% | 0.2% | -2.7% | 0.6% | -2.1% | 1.5% | 2.2% | 1.2% |
| -0.2% | -0.1% | -3.0% | 0% | -2.5% | 1.3% | -1.2% | -0.2% | 1.7% |

KENO V.a vs Q/C **after** the adjustment procedure

# Preliminary investigation on a hypothetic case (1/2)

- Are the adjusted reflector cross-sections applicable in an asymmetric state (e.g. during accidental transient)?
- Case description:
  - UOX core
  - Fuel temperature drop from 900K to 600K in one quarter of the core
  - Not realistic ***but***
  - Easy Monte-Carlo modelling



# Preliminary investigation on a hypothetic case (2/2)

- Discrepancy raise, compared to previous results of the nominal case
  - QUABOX/CUBBOX: 1%
  - PARCS: 2%
  - DONJON: 1%

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | -0.4% | 1.8% | 2.5% | 3.6% | 3.2% | 3.3% | 0.7% | | | | | |
| | | | -1.5% | -0.6% | -0.8% | 1.9% | 3.2% | 1.2% | 3.8% | 3.8% | 1.5% | 2.2% | 1.6% | | | |
| | | -2.9% | 1.1% | 0.7% | 0.4% | -2.2% | 2.2% | -0.4% | 2.7% | -0.4% | 2.9% | 3.3% | 4.1% | -0.4% | | |
| | -1.3% | 1.8% | -2.5% | 0.8% | -2.8% | 0.2% | -2.7% | 1.3% | -1.9% | 2.0% | -0.4% | 2.7% | -0.5% | 3.5% | 0.4% | |
| | 0.1% | 1.8% | 1.4% | -2.0% | 0.5% | -3.0% | -0.1% | -2.6% | 0.8% | -2.0% | 1.7% | -1.1% | 2.4% | 2.8% | 0.5% | |
| 0.8% | 0.8% | 1.9% | -1.5% | 1.8% | -2.2% | 0.1% | -3.4% | 0.1% | -2.9% | 0.7% | -2.2% | 1.5% | -1.3% | 2.0% | 0.4% | 0.8% |
| 2.6% | 3.2% | -1.4% | 1.9% | -1.6% | 1.1% | -3.1% | -0.2% | -3.8% | -0.4% | -2.8% | 0.3% | -2.4% | 1.2% | -1.8% | 2.3% | 1.8% |
| 2.6% | 3.0% | 1.9% | -1.6% | 1.4% | -2.3% | -0.1% | -3.8% | -1.0% | -3.7% | -0.5% | -3.4% | -0.1% | -2.8% | 0.9% | 1.9% | 0.9% |
| 3.1% | 0.7% | -0.5% | 2.0% | -2.0% | 0.5% | -3.3% | -0.8% | -1.0% | -1.1% | -3.8% | -0.8% | -3.8% | -0.1% | -2.2% | -1.1% | 1.0% |
| 3.1% | 3.6% | 2.5% | -1.5% | 1.3% | -2.6% | -0.4% | -4.0% | -1.3% | -4.1% | -0.9% | -3.9% | -0.9% | -3.6% | 0.0% | 0.9% | 0.2% |
| 3.2% | 3.4% | -0.8% | 1.8% | -1.9% | 0.7% | -2.9% | -0.7% | -4.1% | -1.0% | -3.9% | -0.7% | -3.7% | -0.2% | -3.1% | 0.9% | 0.3% |
| 0.7% | 1.5% | 2.6% | -1.0% | 1.5% | -2.3% | 0.4% | -3.2% | -0.5% | -3.4% | -0.5% | -3.4% | -0.2% | -3.0% | 0.2% | -1.3% | -1.8% |
| | 1.8% | 3.2% | 2.6% | -1.4% | 1.6% | -2.2% | 0.4% | -2.9% | 0.1% | -2.9% | 0.1% | -2.9% | 0.4% | 0.9% | -0.6% | |
| | 0.7% | 3.7% | -0.7% | 2.5% | -0.8% | 2.1% | -1.8% | 1.2% | -2.3% | 0.8% | -2.3% | 0.8% | -2.2% | 1.8% | -1.0% | |
| | | -1.1% | 3.7% | 3.3% | 3.1% | -0.4% | 2.5% | -0.6% | 1.8% | -1.7% | 1.5% | 1.9% | 2.2% | -2.4% | | |
| | | | 0.9% | 1.5% | 1.8% | 4.0% | 3.8% | 0.7% | 2.9% | 2.6% | 0.3% | 0.6% | -0.3% | | | |
| | | | | | 1.9% | 3.5% | 3.1% | 3.0% | 2.3% | 2.3% | -0.1% | | | | | |

KENO V.a vs. QUABOX/CUBBOX

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 0.34 | 0.35 | 0.36 | 0.37 | 0.42 | 0.47 | 0.51 | | | | | |
| | | | 0.37 | 0.39 | 0.33 | 0.36 | 0.37 | 0.37 | 0.44 | 0.49 | 0.51 | 0.68 | 0.70 | | | |
| | | 0.31 | 0.35 | 0.38 | 0.35 | 0.35 | 0.36 | 0.37 | 0.43 | 0.48 | 0.57 | 0.70 | 0.70 | 0.68 | | |
| | 0.37 | 0.35 | 0.34 | 0.35 | 0.34 | 0.34 | 0.36 | 0.38 | 0.43 | 0.49 | 0.57 | 0.68 | 0.75 | 0.83 | 0.94 | |
| | 0.38 | 0.38 | 0.34 | 0.33 | 0.33 | 0.34 | 0.37 | 0.41 | 0.45 | 0.52 | 0.59 | 0.69 | 0.82 | 0.98 | 1.06 | |
| 0.34 | 0.32 | 0.35 | 0.33 | 0.32 | 0.34 | 0.36 | 0.41 | 0.45 | 0.51 | 0.57 | 0.65 | 0.74 | 0.87 | 1.00 | 1.00 | 1.10 |
| 0.35 | 0.36 | 0.34 | 0.33 | 0.34 | 0.36 | 0.41 | 0.46 | 0.54 | 0.59 | 0.67 | 0.74 | 0.85 | 0.96 | 1.11 | 1.23 | 1.25 |
| 0.36 | 0.37 | 0.36 | 0.35 | 0.36 | 0.40 | 0.46 | 0.56 | 0.68 | 0.74 | 0.80 | 0.90 | 1.01 | 1.15 | 1.31 | 1.44 | 1.43 |
| 0.37 | 0.37 | 0.37 | 0.38 | 0.40 | 0.45 | 0.53 | 0.67 | 0.87 | 0.92 | 0.99 | 1.10 | 1.25 | 1.39 | 1.53 | 1.62 | 1.66 |
| 0.42 | 0.44 | 0.43 | 0.43 | 0.45 | 0.51 | 0.59 | 0.74 | 0.92 | 1.04 | 1.16 | 1.32 | 1.48 | 1.68 | 1.92 | 2.11 | 2.06 |
| 0.47 | 0.49 | 0.49 | 0.49 | 0.52 | 0.57 | 0.67 | 0.80 | 0.99 | 1.16 | 1.34 | 1.53 | 1.75 | 1.97 | 2.20 | 2.38 | 2.38 |
| 0.51 | 0.51 | 0.57 | 0.58 | 0.59 | 0.65 | 0.74 | 0.90 | 1.09 | 1.31 | 1.52 | 1.77 | 2.02 | 2.33 | 2.59 | 2.45 | 2.53 |
| | 0.68 | 0.70 | 0.68 | 0.69 | 0.74 | 0.85 | 1.00 | 1.23 | 1.47 | 1.74 | 2.01 | 2.32 | 2.69 | 3.07 | 3.16 | |
| | 0.71 | 0.70 | 0.75 | 0.82 | 0.87 | 0.95 | 1.13 | 1.37 | 1.66 | 1.95 | 2.31 | 2.68 | 2.84 | 2.96 | 3.18 | |
| | | 0.68 | 0.83 | 0.97 | 0.99 | 1.09 | 1.29 | 1.50 | 1.88 | 2.17 | 2.56 | 3.04 | 2.95 | 2.68 | | |
| | | | 0.93 | 1.05 | 0.99 | 1.21 | 1.42 | 1.59 | 2.07 | 2.34 | 2.42 | 3.13 | 3.16 | | | |
| | | | | | 1.08 | 1.23 | 1.40 | 1.63 | 2.02 | 2.33 | 2.48 | | | | | |

Power distribution UOX Core, KENO V.a

# Conclusions

- Uncertainty in the basic nuclear data is one of the main source of uncertainty in the resulting core power distribution
  → especially when MOX assemblies are present

- The use of the various lattice codes introduces small discrepancies on the core power distribution

- The influence of the different numerical methods of the core simulators is also small

- Reflector cross sections are usually obtained through an « adjustment » procedure
  - This procedure is necessary in order to conserve the flux gradient and reaction rates at core periphery
  - Ongoing work on prediction accuracy of power distribution in asymmetric situations
  - In a very simple case, the discrepancy increase was a couple of percents