Benchmark Exercise for Core Neutronics and Transient Behaviour

ESFR-SMART Spring School :: March 29, 2021
Superphénix reactor and benchmark objectives

Static neutronics phase:
• Development of the core model
• Overview of the benchmark specification
• Selected results on neutronic core performance

Transient phase:
• Simplified model for system codes
• Testing model for representation of core behavior
• Selected transient results
Superphénix reactor and benchmark objectives
Introduction

A new benchmark exercise performed within the ongoing EU Horizon-2020 ESFR-SMART project

**European Sodium Fast Reactor Safety Measures Assessment and Research Tools**

It is based on the start-up core configuration of the French large Sodium cooled Fast Reactor Superphénix
Largest ever operated liquid metal cooled Fast Reactor in the world (1986-1997)

Only ~4.5 years of operating, 7.9 billion kWh produced

Two INES level 2 incidents:
  • Leak of the storage drum (1987)
  • Pollution of primary sodium (1990)

Thousands of experiments were conducted at start-up and operation
Superphénix reactor

View of the SPX reactor core:
- Dummy fuel subassemblies
- Fertile SAs and neutron shielding


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal / electric power</td>
<td>MW</td>
<td>3000 / 1240</td>
</tr>
<tr>
<td>Average fissile / fertile fuel temperature</td>
<td>°C</td>
<td>1227 / 627</td>
</tr>
<tr>
<td>Primary sodium inlet / outlet temperature</td>
<td>°C</td>
<td>395 / 545</td>
</tr>
<tr>
<td>Fissile fuel</td>
<td>-</td>
<td>MOX</td>
</tr>
<tr>
<td>Pu content in the inner / outer subcore</td>
<td>%</td>
<td>16.0 / 19.7</td>
</tr>
<tr>
<td>Total mass of plutonium in the fissile core</td>
<td>kg</td>
<td>5780</td>
</tr>
<tr>
<td>Volume of the fissile core</td>
<td>m³</td>
<td>10.75</td>
</tr>
<tr>
<td>Equivalent diameter of the fissile core</td>
<td>m</td>
<td>3.70</td>
</tr>
<tr>
<td>Height of the fissile pellet stack</td>
<td>m</td>
<td>1.00</td>
</tr>
<tr>
<td>Height of the lower/upper breeder blanket</td>
<td>m</td>
<td>0.30 / 0.30</td>
</tr>
<tr>
<td>Height of the radial blanket fertile pellet stack</td>
<td>m</td>
<td>1.60</td>
</tr>
<tr>
<td>Number of subassemblies in the IC/OC</td>
<td>-</td>
<td>193* / 171*</td>
</tr>
<tr>
<td>Number of subassemblies in the RB</td>
<td>-</td>
<td>234*</td>
</tr>
<tr>
<td>Number of control rods (CSD/DSD)</td>
<td>-</td>
<td>21 / 3</td>
</tr>
<tr>
<td>Subassembly pitch in the diagrid</td>
<td>mm</td>
<td>179.0</td>
</tr>
</tbody>
</table>

(* ) Differs from considered start-up core configuration
Superphénix reactor

Photo of Superphénix reactor building mockup
(CEA-Cadarache, France)
Phase 1 – Static neutronics
   to validate static neutronics codes evaluating the core performance including comparison with experimental data on integral and local static parameters

Phase 2 – Transient
   to validate system codes simulating the start-up transients actuated during the commissioning phase at different power levels to study the dynamic response of the core to certain transient initiators and to evaluate reactivity feedback coefficients
Static neutronics phase
Core specification developed for neutronics analysis:

- “As fabricated” pin, fuel SA, CSD control rods design available
- Homogeneous/heterogeneous approaches for non-fuel zones
- Temperature expansion laws defined
- Fuel specification developed: initial core criticality of about 3700 pcm at 180°C reproduced (with JEFF-3.1.1)
- Criticality level at hot zero power (HZP) and hot full power (HFP) reproduced
- CSD rods worth reproduced

Data sources:

Development of core model

Choice of the core parameters and reference solution reported:


Model distributed as Serpent 2 input deck for different core configurations

Additional core configurations prepared in accord with definitions of reactivity effects
Superphenix start-up core subassemblies arrangement

- Outer core subassemblies (168 SAs)
- Radial breeder blanket subassemblies (225 SAs)
- Radial steel shielding subassemblies (294 SAs)
- Diluent steel subassemblies (18 SAs)
- Control rods (21 CSDs)
- Shutdown rods (3 DSDs)

Inner core subassemblies (190 SAs)
Development of core model

Subassemblies axial structure in Superphénix core model

Cross section of geometry:
- Fissile SA
- Radial Breeder Blanket SA
- Control rod (CSD)
## Core criticality for different configurations (Serpent 2|JEFF311):

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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>453/453 453/453 453/453</td>
<td>1.03668</td>
<td>3538</td>
<td>3710</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>673/673 673/673 673/673</td>
<td>1.02886</td>
<td>2805</td>
<td>3079</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1500/1500 900/900 673/673</td>
<td>1.01903</td>
<td>1867</td>
<td>2090</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>600/673 600/673 600/673</td>
<td>0.99893</td>
<td>-107</td>
<td>~0</td>
</tr>
</tbody>
</table>

(*) From the top of fissile height

180°C → 180°C
400°C → 400°C
HFP → HFP
Ref.HZP → Ref.HZP
## Isothermal temperature coefficient and its components:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Benchmark*</th>
<th>Calculation CEA</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal temperature coefficient $K_{iso}$ (400–180°C) [pcm/°C]</td>
<td>3.34 (3.18**) (3.10***)</td>
<td>2.63 ± 0.53</td>
<td>2.87 ± 0.14</td>
</tr>
<tr>
<td>Expansion component $k$ [pcm/°C]</td>
<td>0.70</td>
<td>0.67 ± 0.23</td>
<td>0.74 ± 0.15</td>
</tr>
<tr>
<td>Doppler component $K_D$ [pcm]</td>
<td>1381 (1334***)</td>
<td>1086 ± 217</td>
<td>1180 ± 118</td>
</tr>
</tbody>
</table>

(*) Calculations do not consider inserted CRs and differential effect of CR movement due temperature expansion of the vessel and its inner structures

(**) Calculated value as sum of two individual components

(***) Critical core configuration with CRs inserted by 40 cm
Reaction rates for HZP configuration compared to measured data:

(a) Axial profile of U-235 fission rate

(b) Radial profile of U-238 fission rate in fissile region

(c) Radial profile of Pu-239 fission rate in upper breeder blanket
List of solutions* and participants in neutronics phase:

- Serpent 2|JEFF311 (PSI)
- SCALE623/KENO-VI|ENDFB71 (UPM)
- MCNP611|JEFF311 (CIEMAT)
- WIMS/MONK|JEFF311 (UCAM/WOOD)
- Serpent/DYN3D|JEFF311 (HZDR)
- WIMS/SP3|JEFF311 (UCAM/WOOD)
- Serpent/PARCS|JEFF311 (GRS)
- DRAGON/DONJON|JEFF311 (PSI)

*blue – Monte Carlo, red – deterministic and hybrid
Benchmark results

Expected benchmark results (provided as reference solution of Serpent 2):

- Criticality for 13 core configurations (from HZP to HFP, different CRs positions)
- CR worth curve
- Safety characteristics:
  - Fuel Doppler constant
  - Sodium density coefficient
  - Sodium void effect
  - Axial fuel expansion coefficient
  - Cladding expansion coefficient
  - Hexcan expansion coefficient
  - Diagrid plate expansion coefficient
- Power spatial distributions
- Fission reaction rates
- Kinetics parameters
Multiplication factor data:

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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>300/293</td>
<td>8</td>
<td>0</td>
<td>600/673</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>300/453</td>
<td>9</td>
<td>0</td>
<td>600/673</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>453/453</td>
<td>10</td>
<td>0</td>
<td>673/673</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>453/453</td>
<td>11</td>
<td>0</td>
<td>673/673</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>300/673</td>
<td>12</td>
<td>0</td>
<td>900/673</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>300/673</td>
<td>13</td>
<td>0</td>
<td>1500/1500</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>600/673</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Control rods worth curve:
Sodium void effect:

1 - Inner core, fissile height (CRs inserted by 40cm)
2 - Outer core, fissile height (CRs inserted by 40cm)
3 - Inner core, fissile height (CRs withdrawn)
4 - Outer core, fissile height (CRs withdrawn)
Subassembly power radial distributions:
Benchmark results

Axial profile of U-235 fission rate:
Outcomes of the neutronics phase:

• The benchmark became a successful exercise for code cross comparisons, essentially due to the detailed specification for all core configurations

• After few rounds of comparisons appropriate agreement observed in core criticality and reactivity effects for most of results, while some were excluded as not reliable

• The reactivity set for transient phase developed based on Serpent 2 results

Results reported (paper accepted):

Transient phase
Six selected operational transients:

- **MOFC1**: -50 pcm reactivity insertion at 692 MWth [7]
- **MOFC2**: +10% secondary mass flowrate increase at 692 MWth [7]
- **MOFC3**: -10% primary mass flowrate reduction at 666 MWth [7]
- **PFS**: -10% primary mass flowrate reduction at 1415 MWth [8]
- **RS**: -74 pcm stepwise reactivity insertion at 1542 MWth [8]
- **SST**: +30 pcm reactivity insertion at hot zero power (HZP) [8]

Data sources:


System codes: TRACE (PSI), SIM-SFR (KIT), ATHLET (HZDR)

Simplified primary circuit representation with few-channel approach

Peculiarity of the study: modelling of in-reactor structures thermal expansion and corresponding reactivity feedbacks (vessel wall, diagrid plate, core support structure (strongback), control rod drive lines (CRDL))

Similar approach has been applied with TRACE and SIM-SFR in the past:

Simplified three-channel model: IC-, OC- and RB-average SA

Individual transient boundary conditions

Axial sections of SA:
• Inlet section with flow gagging valve
• Pin bundle with associated pin heat structure
• Upper flow transition section
• Outlet shielding section (steel sleeve)

Point kinetics model

Vessel wall, diagrid plate, CRDL associated heat structures

Simplified models for strongback and fuel axial expansion

Assumptions for uncertain parameters:
• Pellet-clad gap conductance
• CR position worth
Point kinetics model reactivity:

\[
\rho = \rho_{\text{Doppler}} + \rho_{\text{Sodium}} + \rho_{\text{Fuel}} + \rho_{\text{Clad}} + \rho_{\text{Diagrid}} + \rho_{\text{CRdiff}}
\]

- Doppler constant (IC/OC/LAB/UAB/RB) [pcm] -1135 (-757/-257/-54/-19/-28)
- Sodium density coefficient (IC/OC) [pcm/(kg/m^3)] 0.992 (0.904/0.096)
- Fuel expansion coefficient (IC/OC) [pcm/°C] -0.192 (-0.108/-0.084)
- Clad expansion coefficient [pcm/°C] 0.05
- Diagrid radial expansion [pcm/°C] -0.992
- CRs position worth [pcm/mm] 7.0 - 14.0 (depending on position)

No axial profiles applied to global coefficients

Model details were studied additionally:

Representation of in-reactor structures for calculation of reactivity feedbacks (due to CR position change):

**CRDL (1D heat structure)**
- Effective length, m: 6.0
- Inner radius, m: -
- Outer radius, m: 0.02
- Thermal expansion coefficient, $K^{-1}$: $1.70 \times 10^{-5}$

**Vessel (1D heat structure)**
- Effective length, m: 13.5
- Inner radius, m: 10.00
- Outer radius, m: 10.08
- Thermal expansion coefficient, $K^{-1}$: $1.70 \times 10^{-5}$
- Vessel reactivity effect delay, s: 360

**Fuel pellet stack**
- Effective length, m: 0.7
- Thermal expansion coefficient, $K^{-1}$: $1.30 \times 10^{-5}$

**Diagrid (1D heat structure)**
- Slab thickness, m: 0.008
- Thermal expansion coefficient, $K^{-1}$: $1.73 \times 10^{-5}$

**Strongback**
- Effective length, m: 4.0
- Thermal expansion coefficient, $K^{-1}$: $1.73 \times 10^{-5}$
- Strongback reactivity effect delay, s: 100
CRs position effect modelling:

- Derived using the CRs position worth on the curve and differential CRs position change:

\[
\rho_{CR\text{diff}} = \delta_{CR} \cdot (\Delta H_{CRDL} + \Delta H_{Strongback} + \Delta H_{Vessel} + \Delta H_{Fuel}),
\]

where

- \(\delta_{CR}\) - CRs position worth depending on power conditions [pcm/mm]
- \(\Delta H_i\) - CRs position change due to \(i\)-component’s expansion [mm]

- Corresponding reference structure features proposed

Alternative approach: using coefficients in pcm/°C
### Benchmark specification

**Definition of transients initial conditions:**

<table>
<thead>
<tr>
<th></th>
<th>MOFC1</th>
<th>MOFC2</th>
<th>MOFC3</th>
<th>PFS</th>
<th>RS</th>
<th>SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power, W</td>
<td>6.920E+08</td>
<td>6.333E+08</td>
<td>6.632E+08</td>
<td>1.415E+09</td>
<td>1.540E+09</td>
<td>8.500E+04</td>
</tr>
<tr>
<td>IC average pin power, W</td>
<td>7.868E+03</td>
<td>7.200E+03</td>
<td>7.540E+03</td>
<td>1.609E+04</td>
<td>1.751E+04</td>
<td>9.664E-01</td>
</tr>
<tr>
<td>OC average pin power, W</td>
<td>6.139E+03</td>
<td>5.618E+03</td>
<td>5.884E+03</td>
<td>1.255E+04</td>
<td>1.366E+04</td>
<td>7.541E-01</td>
</tr>
<tr>
<td>RB average pin power, W</td>
<td>3.603E+02</td>
<td>3.298E+02</td>
<td>3.453E+02</td>
<td>7.368E+02</td>
<td>8.019E+02</td>
<td>4.426E-02</td>
</tr>
<tr>
<td>Fissile gap conductance, W·m⁻²·K⁻¹</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
<td>6000</td>
<td>6000</td>
<td>1800</td>
</tr>
<tr>
<td>Fertile gap conductance, W·m⁻²·K⁻¹</td>
<td>2400</td>
<td>2400</td>
<td>2400</td>
<td>3500</td>
<td>5000</td>
<td>1100</td>
</tr>
<tr>
<td>Initial core inlet temperature, °C</td>
<td>389.0</td>
<td>384.9</td>
<td>374.2</td>
<td>383.0</td>
<td>399.7</td>
<td>179.0</td>
</tr>
<tr>
<td>Initial flowrate, t/s</td>
<td>6300</td>
<td>6360</td>
<td>6300</td>
<td>10400</td>
<td>10400</td>
<td>3200</td>
</tr>
<tr>
<td>CR position worth, pcm/mm</td>
<td>12.0</td>
<td>12.0</td>
<td>12.0</td>
<td>9.0</td>
<td>9.0</td>
<td>14.0</td>
</tr>
</tbody>
</table>

**CR worth curve calculated with Serpent 2 and CR position in transients**
Transient model testing:
  - Prediction of reactivity from cold to HFP core state
  - Reproducing experimentally evaluated feedback coefficients using transient simulations:

$$k = \frac{\partial \rho}{\partial T_i} \text{ (pcm/°C)}$$
$$g = \frac{\partial \rho}{\partial \Delta T} \text{ (pcm/°C)}$$
$$h = \frac{\partial \rho}{\partial P} \text{ (pcm/% nominal power)}$$
$$k \cdot dT_i + g \cdot d\Delta T + h \cdot dP = d\rho_{CR}$$

Data source:

Results reported (paper accepted):
Prediction of core reactivity
Reproducing feedback coefficients

Three-step calculation experiment at 692 MW:
Step 1: Reactivity insertion of -50 pcm
Step 2: Inlet temperature decrease by 10°C
Step 3: Primary mass flow decrease by 10%
Transient results
SST: +30 pcm reactivity insertion at HZP
Transient results
SST: +30 pcm reactivity insertion at HZP
Transient results
MOFC1: -50 pcm reactivity insertion at 692MWth
Transient results
MOFC1: -50 pcm reactivity insertion at 692MWth
Transient results
PFS: -10% primary mass flow at 1415 MWth
Transient results
PFS: -10% primary mass flow at 1415 MWth
Transient results

- **MOFC2**: +10% secondary mass flowrate increase at 692 MWth
- **MOFC3**: -10% primary mass flowrate reduction at 666 MWth
- **RS**: -74 pcm stepwise reactivity insertion at 1542 MWth
Outcomes of the transient phase:

- Model developed allows simulation of core behavior in wide range of conditions
- Reasonably good agreement observed for all results
- Features specified for improving of the modelling (i.e. dynamic fuel pin model, accuracy of experimental data, information on CR curtains positions...)
- Basis for further studies (i.e. modelling detailed flow paths and structures in the primary system, spatial kinetics...)
- Approach on modelling reactivity effects, i.e. CR differential effect, used in modelling of ESFR-SMART core

Results reported (paper submitted for review):

Acknowledgments and funding:

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My thanks go to all partners who contributed to the work:

PSI
UPM
CIEMAT
UCAM/Jacobs
HZDR
GRS
KIT
Thank you!