PAUL SCHERRER INSTITUT

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Benchmark Exercise for Core Neutronics and Transient Behaviour

ESFR-SMART Spring School :: March 29, 2021

Outline

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 **S**odium **F**ast **R**eactor

Safety **M**easures **A**ssessment and **R**esearch **T**ools

It is based on the start-up core configuration of the French large Sodium cooled Fast Reactor Superphénix

Superphénix reactor

Largest ever operated liquid metal cooled Fast Reactor in the world (1986-1997)

Only ~4.5 years of operating, 7.9 billion kWh produced

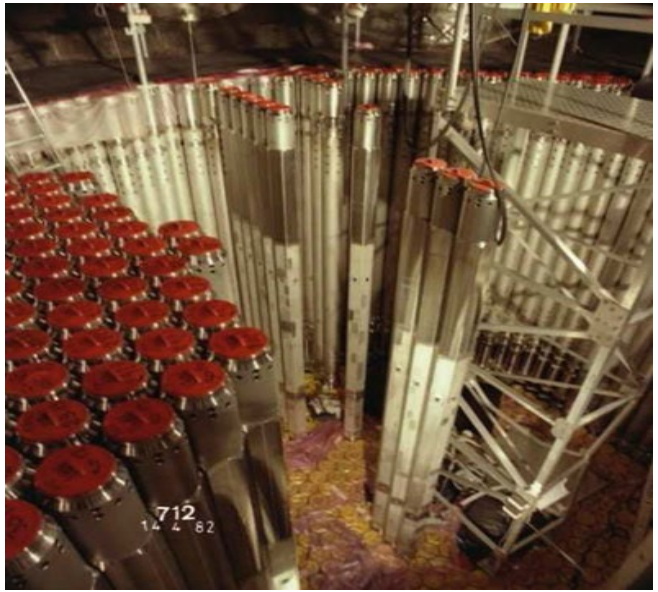
Two INES level 2 incidents:

- Leak of the storage drum (1987)
- Pollution of primary sodium (1990)

Thousands of experiments were conducted at start-up and operation

NERSA consortium logo

Superphénix reactor



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

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

(*) Differs from considered start-up core configuration

[1] Guidez, Joel, and Prele, Gerard, “Superphénix: Technical and Scientific Achievements”, Editions Atlantis Press, France, 2016.

Superphénix reactor

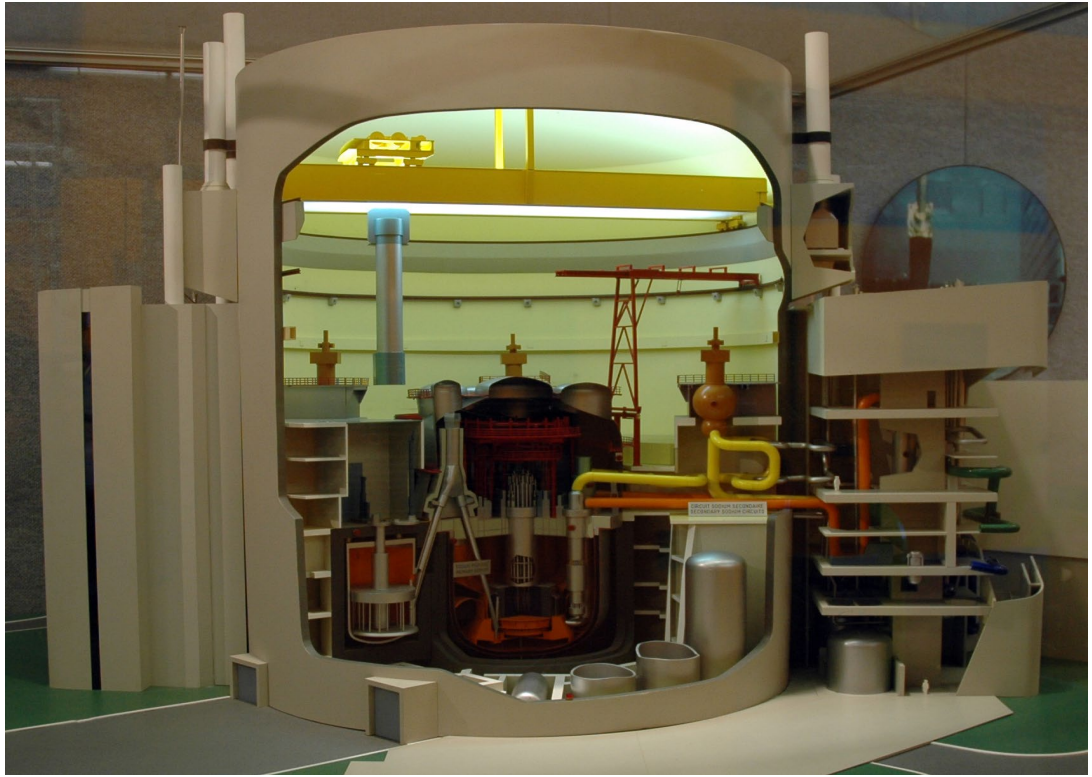


Photo of Superphénix reactor building mockup
(CEA-Cadarache, France)

Benchmark objectives

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

Development of core model

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:

[2] “Nuclear Science and Engineering”, Vol. 106, 1990.

[3] “Fast Reactor Database 2006 Update”, IAEA-TECDOC-1531, ISBN 92–0–114206–4, Vienna, 2006.

[4] “Superphenix Benchmark Used for Comparison of PNC and CEA Calculation Methods, and of JENDL-3.2 and CARNAVAL IV Nuclear Data”, O-Arai Engineering Center, Power Reactor and Nuclear Fuel Development Corporation, 1998.

Development of core model

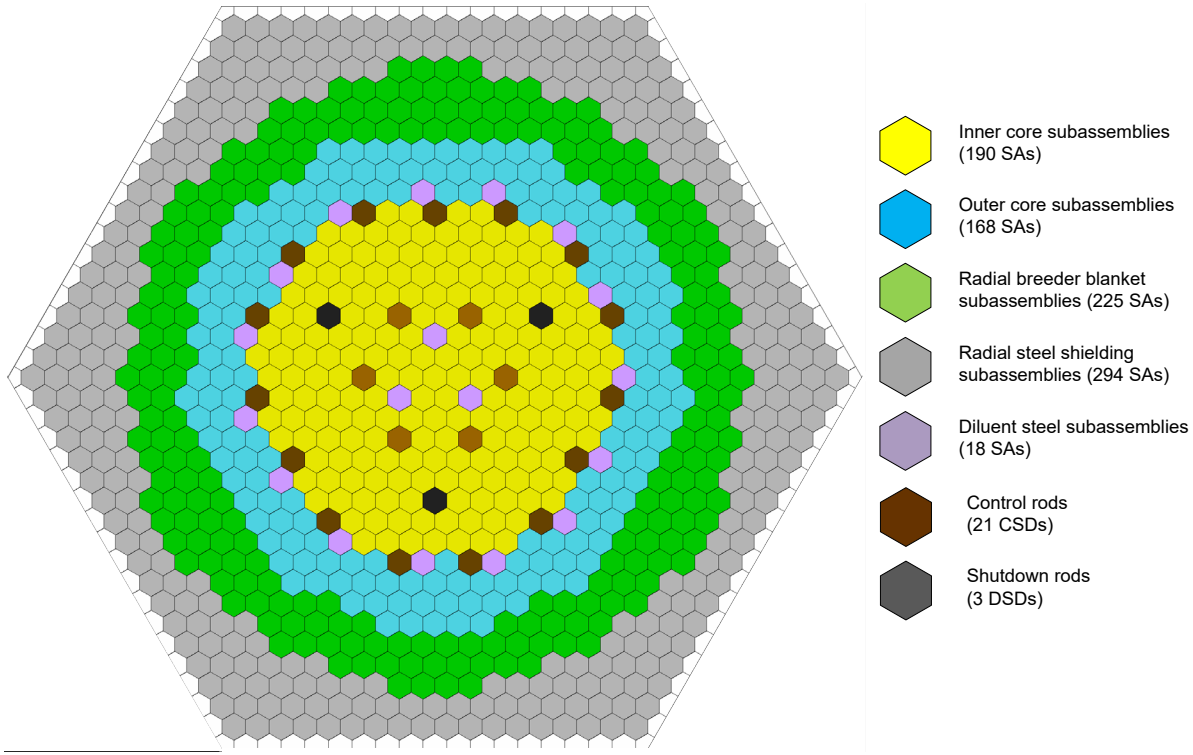
Choice of the core parameters and reference solution reported:

[5] A. Ponomarev, A. Bednarova, and K. Mikityuk, "New Sodium Fast Reactor Neutronics Benchmark", Proceeding of PHYSOR 2018: Reactor Physics Paving The Way Towards More Efficient Systems, Cancun, Mexico, 2018.

Model distributed as Serpent 2 input deck for different core configurations

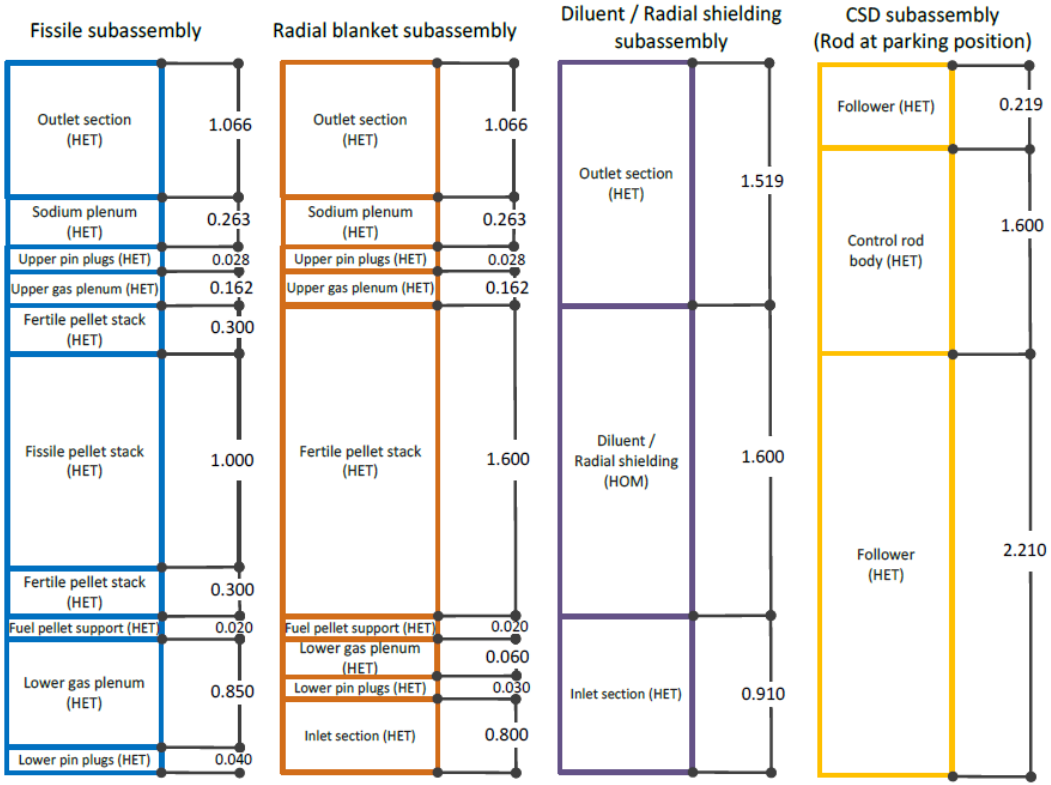
Additional core configurations prepared in accord with definitions of reactivity effects

Development of core model



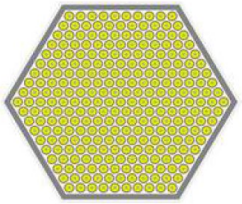
Superphenix start-up core subassemblies arrangement

Development of core model

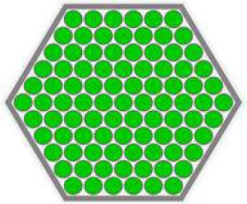


Subassemblies axial structure in Superphénix core model

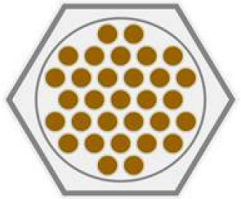
Cross section of geometry:



Fissile SA



Radial Breeder Blanket SA



Control rod (CSD)

Reference solution

Core criticality for different configurations (Serpent 2|JEFF311):

	Case	CSD insertion* [cm]	Temperature for XS / geometry [K]			Calculated		Measured reactivity [pcm]	C – E [pcm]
			Fissile	Fertile	Other	K-eff [-]	Reactivity [pcm]		
180°C →	1	0	453/453	453/453	453/453	1.03668	3538	3710	-170
400°C →	2	0	673/673	673/673	673/673	1.02886	2805	3079	-274
HFP →	3	0	1500/1500	900/900	673/673	1.01903	1867	2090	-223
Ref.HZP →	4	40	600/673	600/673	600/673	0.99893	-107	~0	-107

(*) From the top of fissile height

Reference solution

Isothermal temperature coefficient and its components:

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

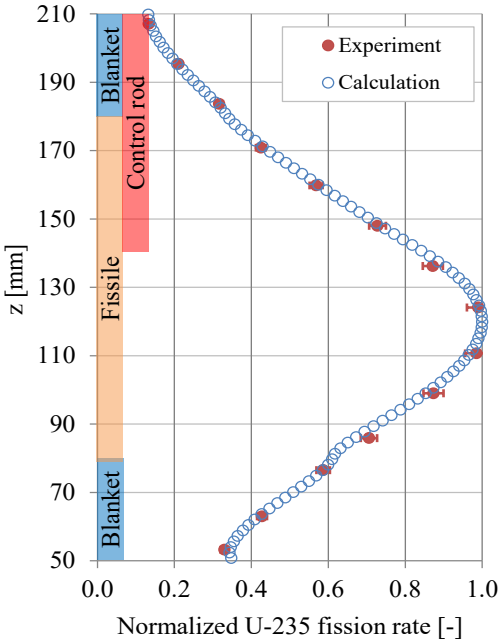
(*) Calculations do not consider inserted CRs and differential effect of CR movement due temperature expansion of the vessel and its inner structures

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

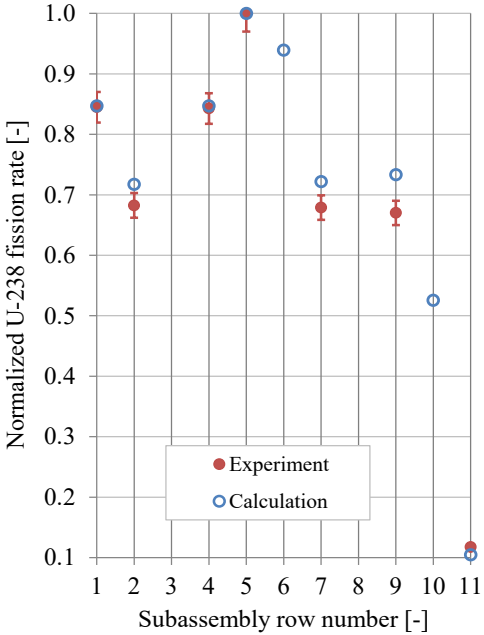
(***) Critical core configuration with CRs inserted by 40 cm

Reference solution

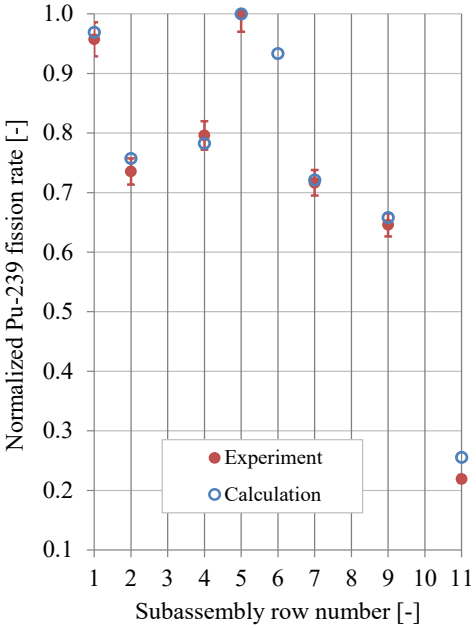
Reaction rates for HZP configuration compared to measured data:



(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

Benchmark results

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

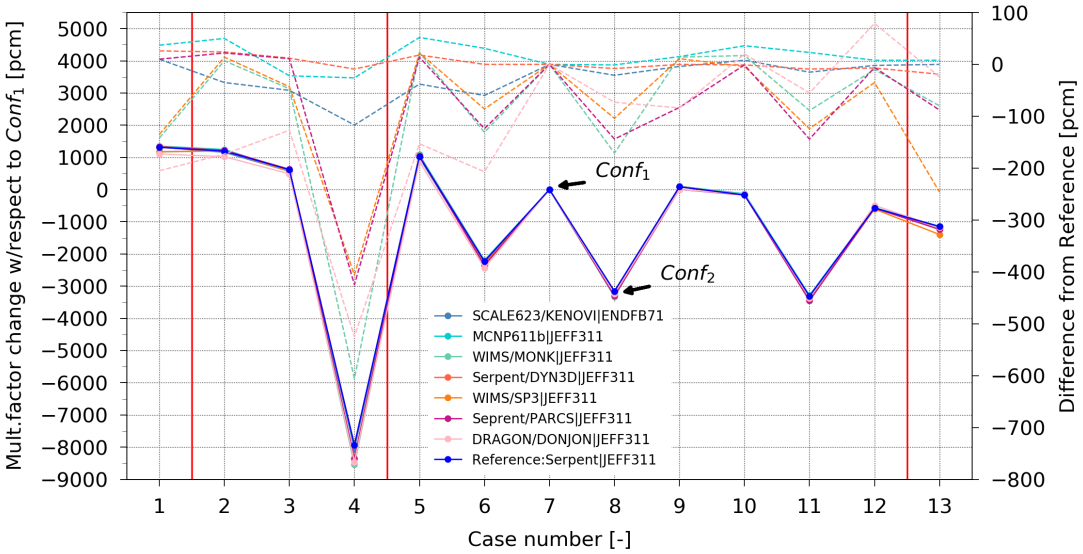
Benchmark results

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

Benchmark results

Multiplication factor data:

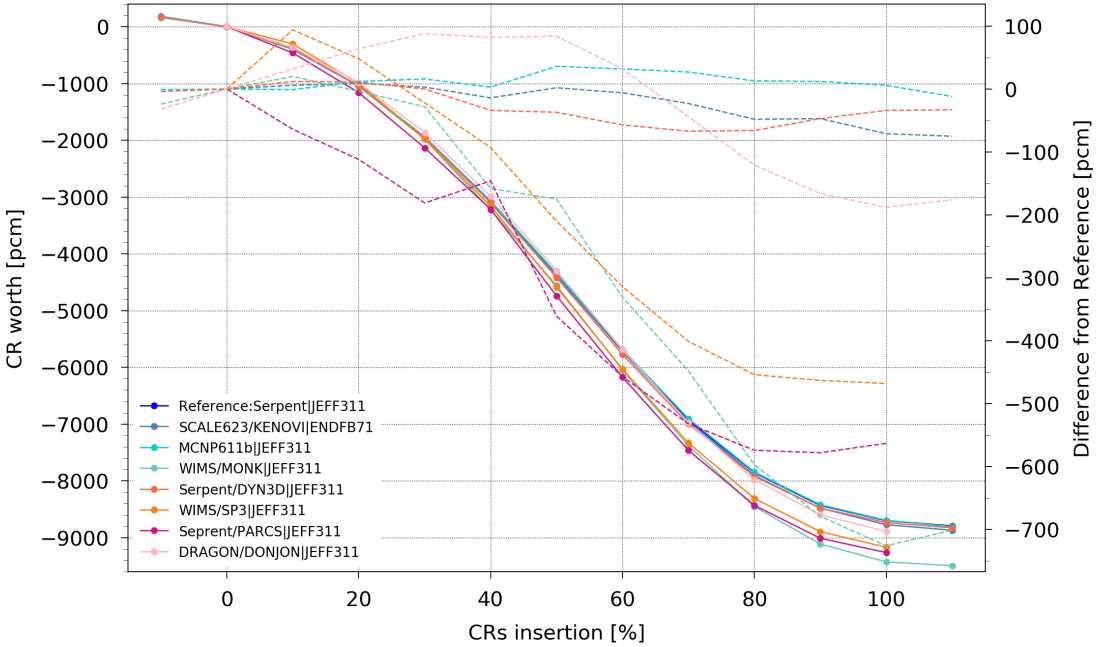


Case	CR insertion [cm]	XS temperature/Geometry [K] Fissile	Fertile	Others
1	0	300/293	300/293	300/293
2	0	300/453	300/453	300/453
3	0	453/453	453/453	453/453
4	100	453/453	453/453	453/453
5	0	300/673	300/673	300/673
6	40	300/673	300/673	300/673
7	0	600/673	600/673	600/673

Case	CR insertion [cm]	XS temperature/Geometry [K] Fissile	Fertile	Others
8	40	600/673	600/673	600/673
9	0	600/673	600/673	300/673
10	0	673/673	673/673	673/673
11	40	673/673	673/673	673/673
12	0	900/673	900/673	900/673
13	0	1500/1500	900/900	600/673

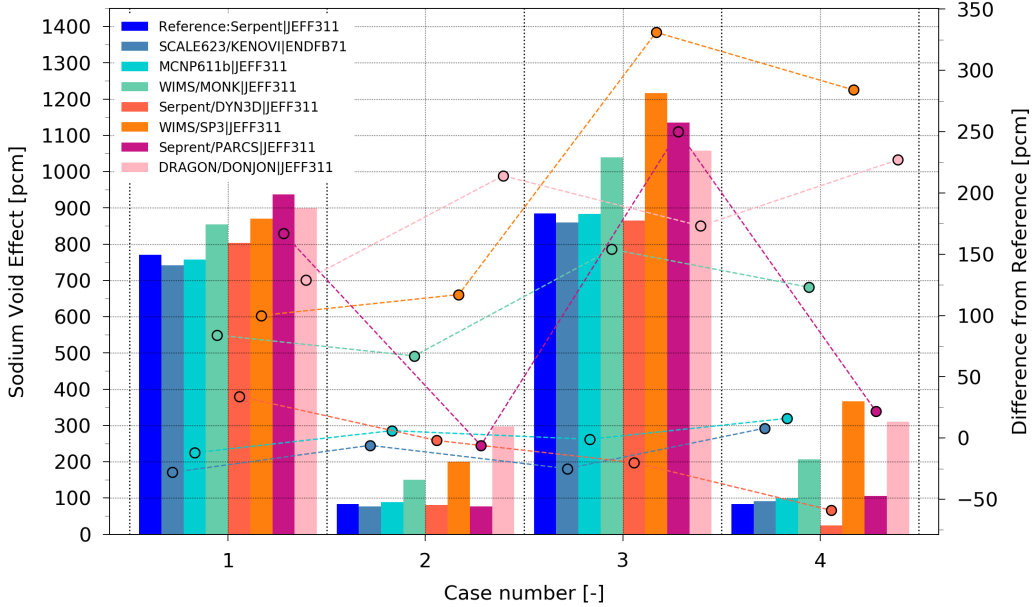
Benchmark results

Control rods worth curve:



Benchmark results

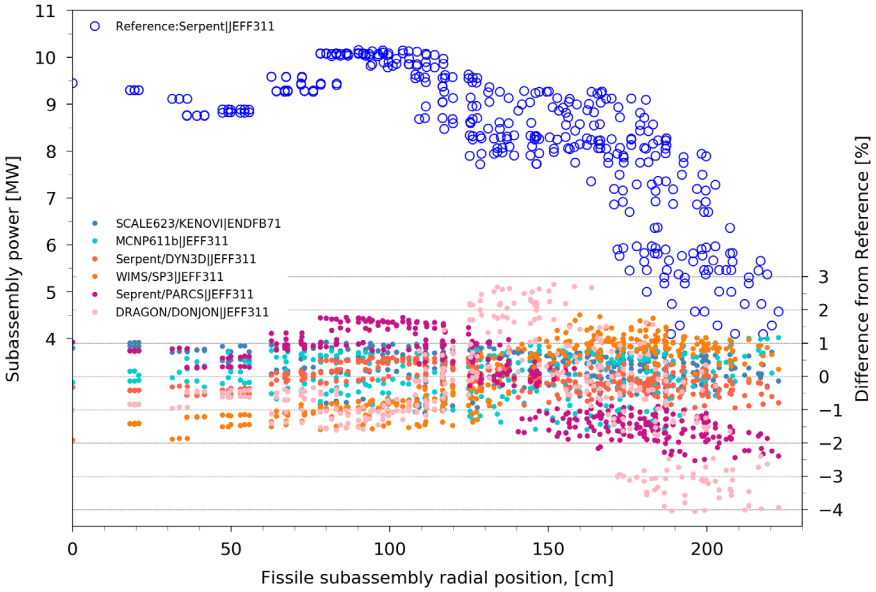
Sodium void effect:

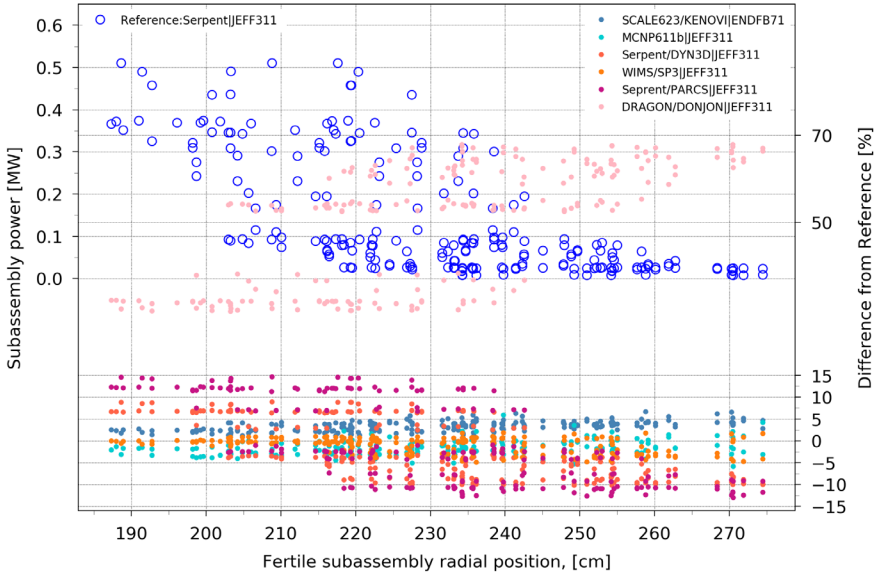


1 - Inner core, fissile height (CRs inserted by 40cm)
2 - Outer core, fissile height (CRs inserted by 40cm)
3 - Inner core, fissile height (CRs withdrawn)
4 - Outer core, fissile height (CRs withdrawn)

Benchmark results

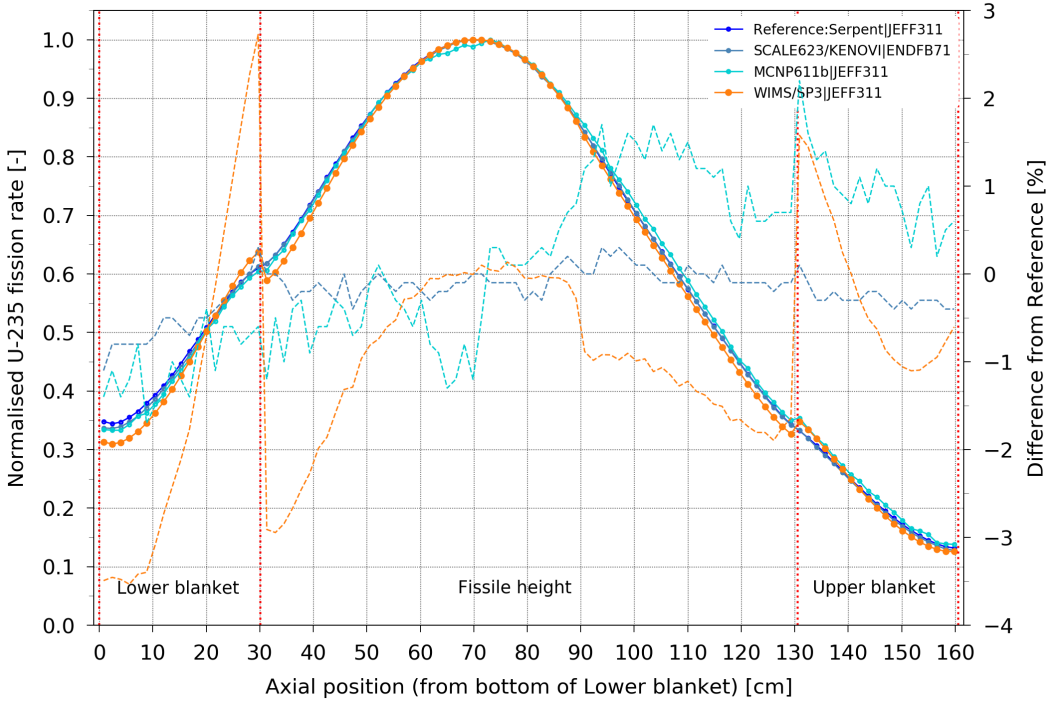
Subassembly power radial distributions:





Benchmark results

Axial profile of U-235 fission rate:



Benchmark results

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):

[6] Ponomarev, A., Mikityuk, K., Zhang, L., Nikitin, E., Fridman, E., Álvarez-Velarde, F., Romojaro Otero, P., Jiménez-Carrascosa, A., García-Herranz, N., Lindley, B., Davies, U., Seubert, A., and Henry, R., “SPX Benchmark Part I: Results of Static Neutronics,” Journal of Nuclear Engineering and Radiation Science, Spec. Vol. on EU ESFR-SMART project, October 2021.

Transient phase

Transient phase overview

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:

[7] M. Vanier, P. Bergeonneau, J. C. Gauthier, M. Jacob, J. De Antoni, E. Gesi, P. Peerani, and J. P. Adam, “Superphenix Reactivity Feedback and Coefficients”, Nuclear Science and Engineering, Vol. 106, pp. 30-36, 1990.

[8] Ph. Bergeonneau, M. Vanier, M. Favet, J. De Antoni, K. Essig, and J. P. Adam, ”An Analysis of the Dynamic Behavior of the Core”, Nuclear Science and Engineering, Vol. 106, pp. 18-29, 1990.

Transient phase overview

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:

[9] K. Mikityuk and M. Schikorr, “New Transient Analysis of the Superphénix Start-up Tests”, Proceedings of International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), Paris, France, March 4-7, 2013.

Development of transient model

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)

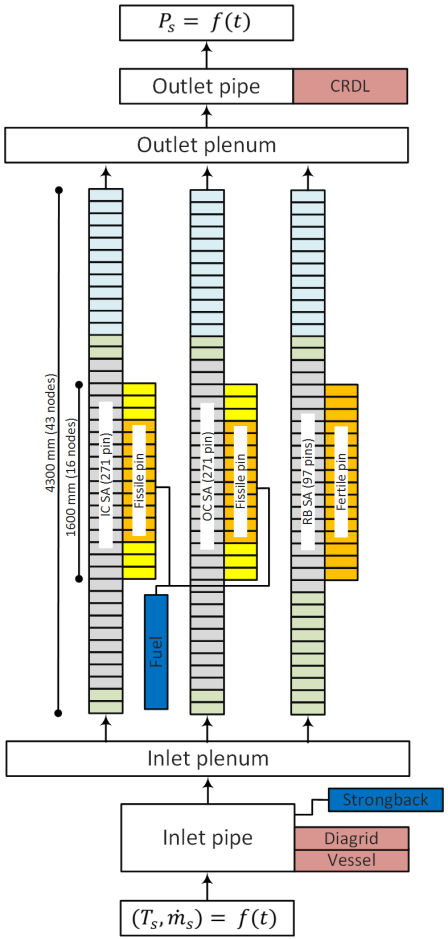
Point kinetics model

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



Benchmark specification

Point kinetics model reactivity:

$$\rho = \rho_{Doppler} + \rho_{Sodium} + \rho_{Fuel} + \rho_{Clad} + \rho_{Diagrid} + \rho_{CRdiff}$$

• 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)

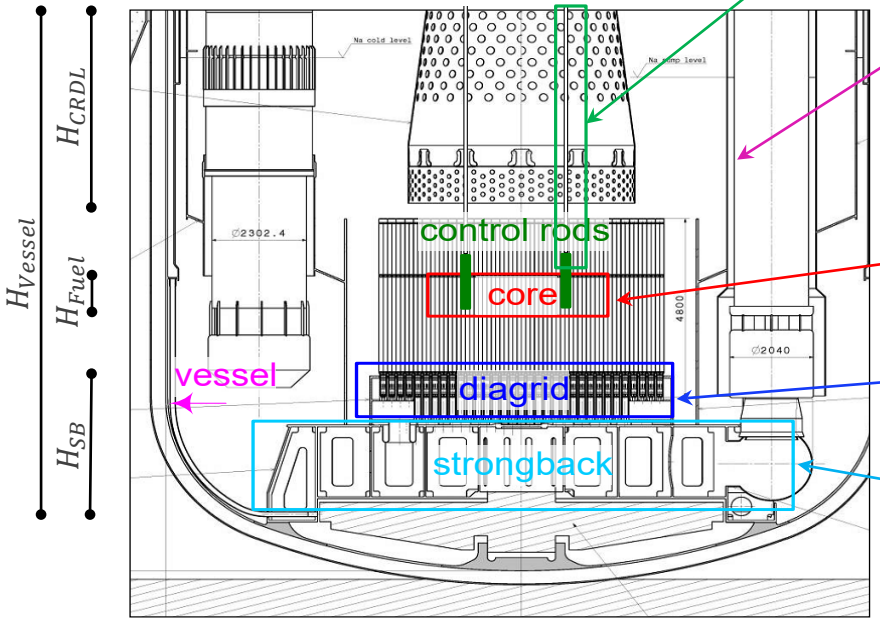
No axial profiles applied to global coefficients

Model details were studied additionally:

[10] A. Ponomarev and K. Mikityuk, ”Analysis of Hypothetical ULOF in Superphénix Start-up Core: Sensitivity to Modeling Details”, Proceedings of ICONE27, 2019.

Benchmark specification

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



Overview of primary vessel with its structures

CRDL (1D heat structure)	
Effective length, m	6.0
Inner radius, m	-
Outer radius, m	0.02
Thermal expansion coefficient, K^{-1}	$1.70 \cdot 10^{-5}$
Vessel (1D heat structure)	
Effective length, m	13.5
Inner radius, m	10.00
Outer radius, m	10.08
Thermal expansion coefficient, K^{-1}	$1.70 \cdot 10^{-5}$
Vessel reactivity effect delay, s	360
Fuel pellet stack	
Effective length, m	0.7
Thermal expansion coefficient, K^{-1}	$1.30 \cdot 10^{-5}$
Diagrid (1D heat structure)	
Slab thickness, m	0.008
Thermal expansion coefficient, K^{-1}	$1.73 \cdot 10^{-5}$
Strongback	
Effective length, m	4.0
Thermal expansion coefficient, K^{-1}	$1.73 \cdot 10^{-5}$
Strongback reactivity effect delay, s	100

Benchmark specification

CRs position effect modelling:

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

$$\rho_{CRdiff} = \delta_{CR} \cdot (\Delta H_{CRDL} + \Delta H_{Strongback} + \Delta H_{Vessel} + \Delta H_{Fuel}),$$

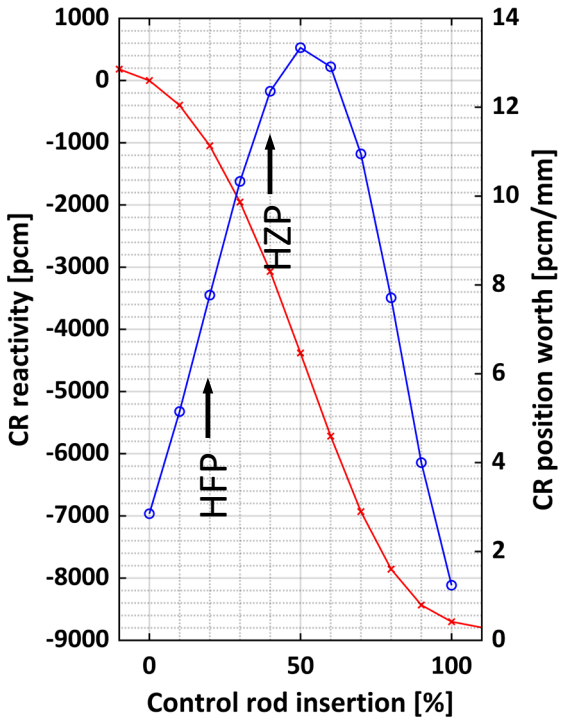
where

δ_{CR} - CRs position worth depending on power conditions [pcm/mm]

ΔH_i - CRs position change due to *i*-component's expansion [mm]

- Corresponding reference structure features proposed

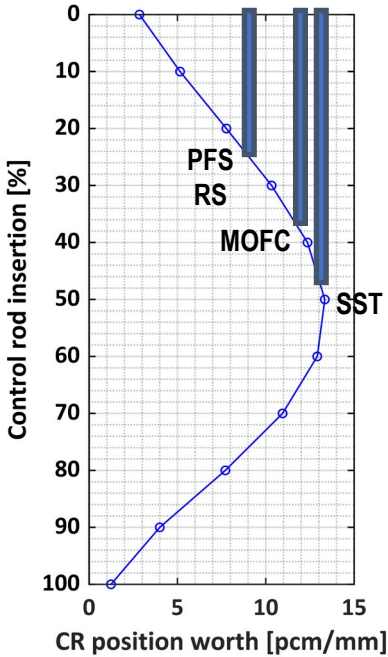
Alternative approach: using coefficients in pcm/°C



Benchmark specification

Definition of transients initial conditions:

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



CR worth curve calculated with Serpent 2 and CR position in transients

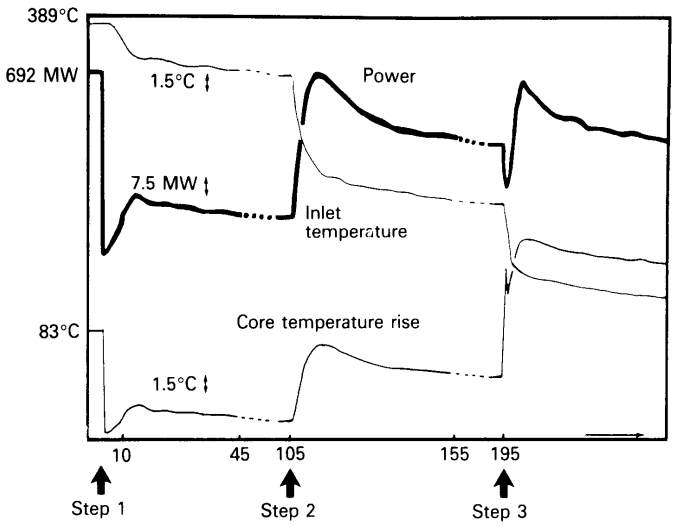
Model check on experimental data

Transient model testing:

- Prediction of reactivity from cold to HFP core state
- Reproducing experimentally evaluated feedback coefficients using transient simulations:

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

3-step procedure, from [7]:



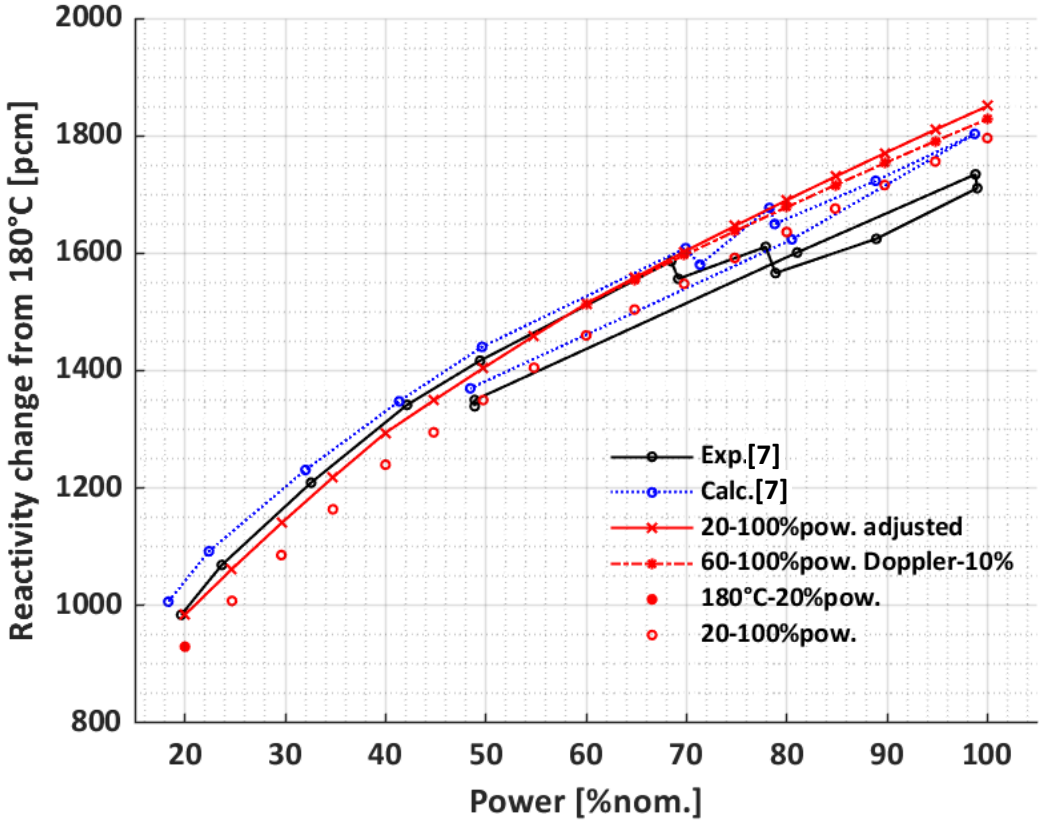
Data source:

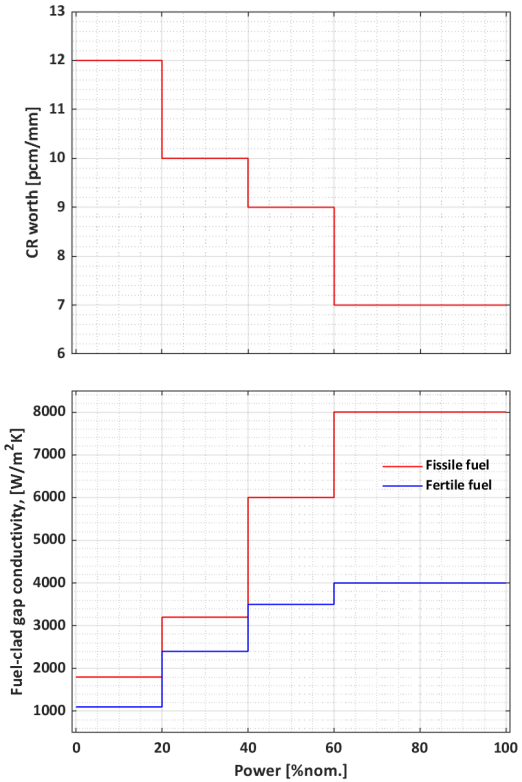
[7] M. Vanier, et.al., “Superphénix Reactivity Feedback and Coefficients”, Nuclear Science and Engineering, Vol. 106, pp. 30-36, 1990.

Results reported (paper accepted):

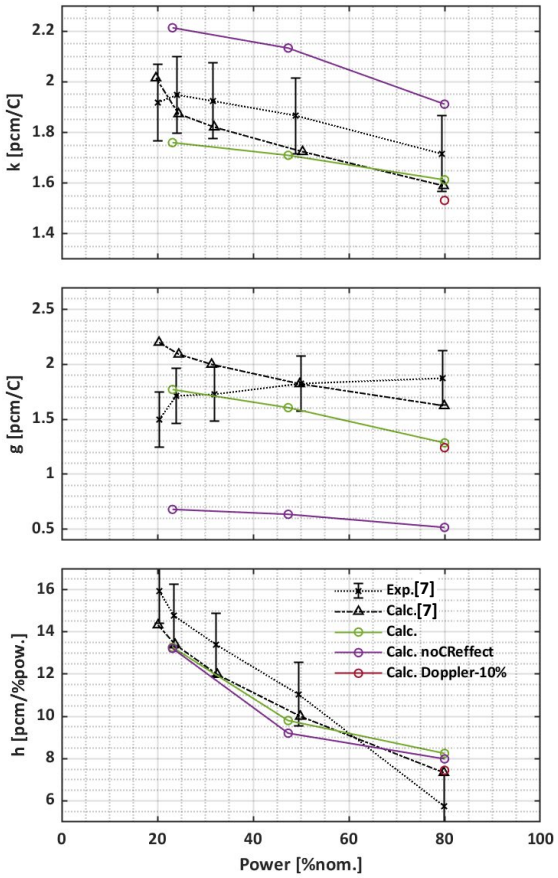
[11] A. Ponomarev and K. Mikityuk, “Modelling of Reactivity Effects and Transient Behaviour of Large Sodium Fast Reactor”, Journal of Nuclear Engineering and Radiation Science, Spec. Vol. on EU ESFR-SMART project, October 2021.

Prediction of core reactivity





Reproducing feedback coefficients

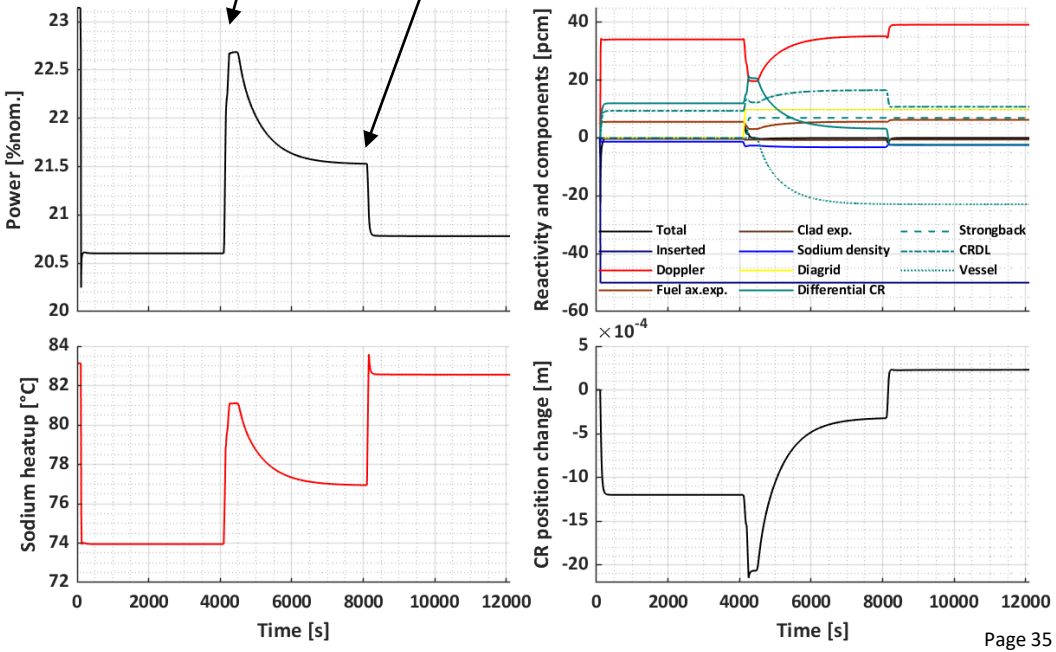


Three-step calculation experiment at 692 MW:

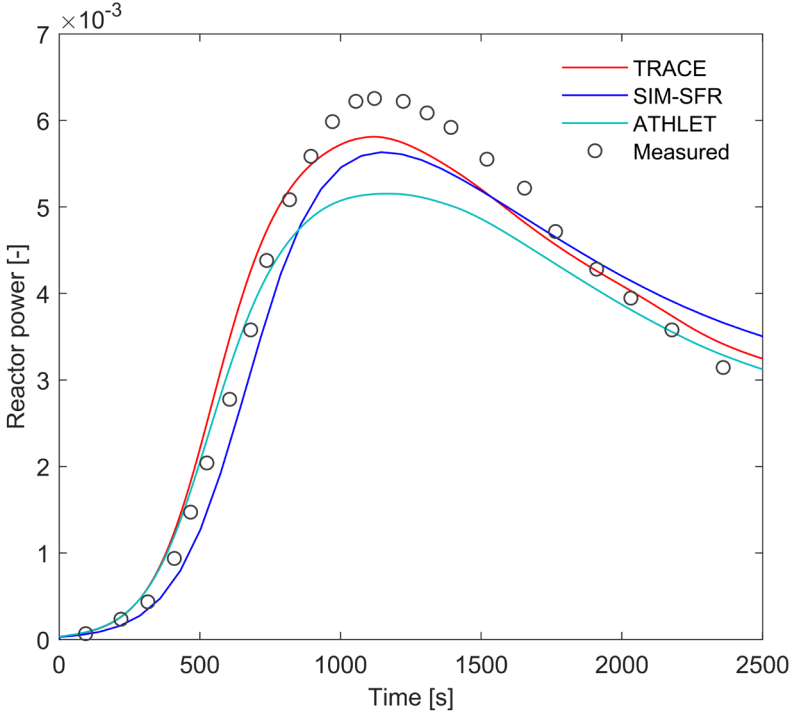
Step 1: Reactivity insertion of -50 pcm

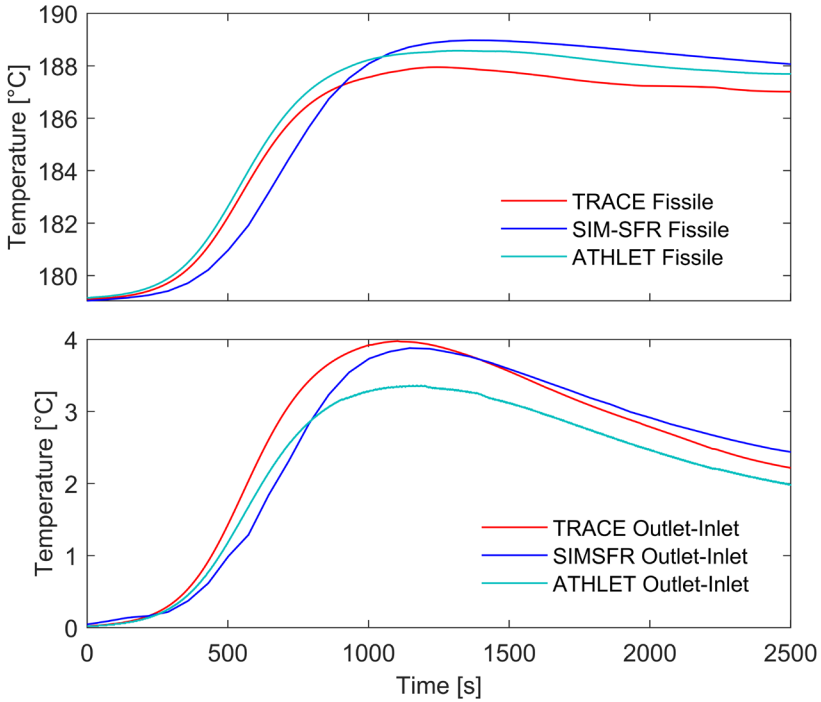
Step 2: Inlet temperature decrease by 10°C

Step 3: Primary mass flow decrease by 10%

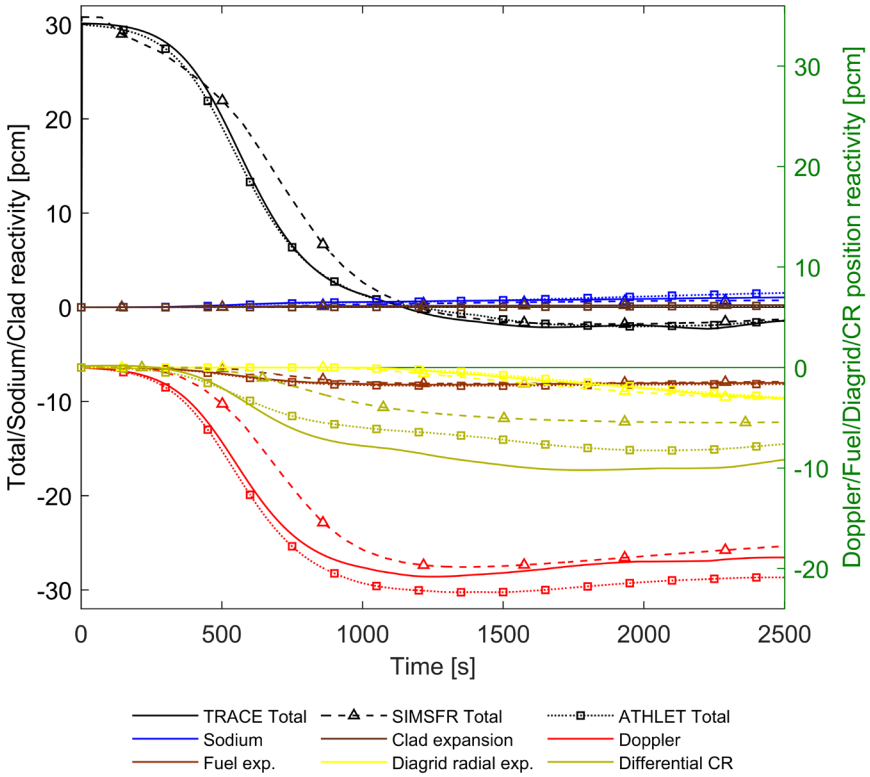


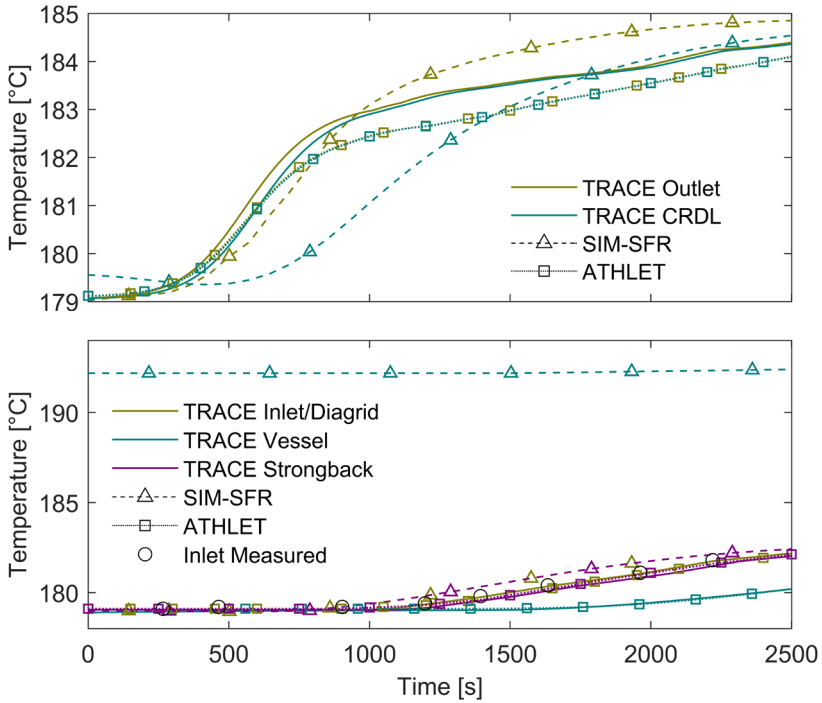
Transient results
SST: +30 pcm reactivity insertion at HZP



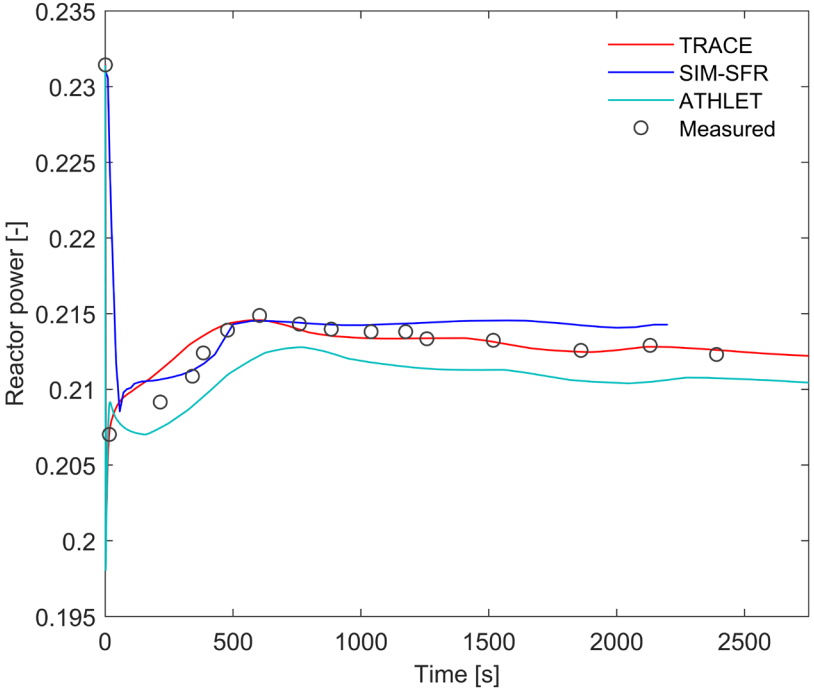


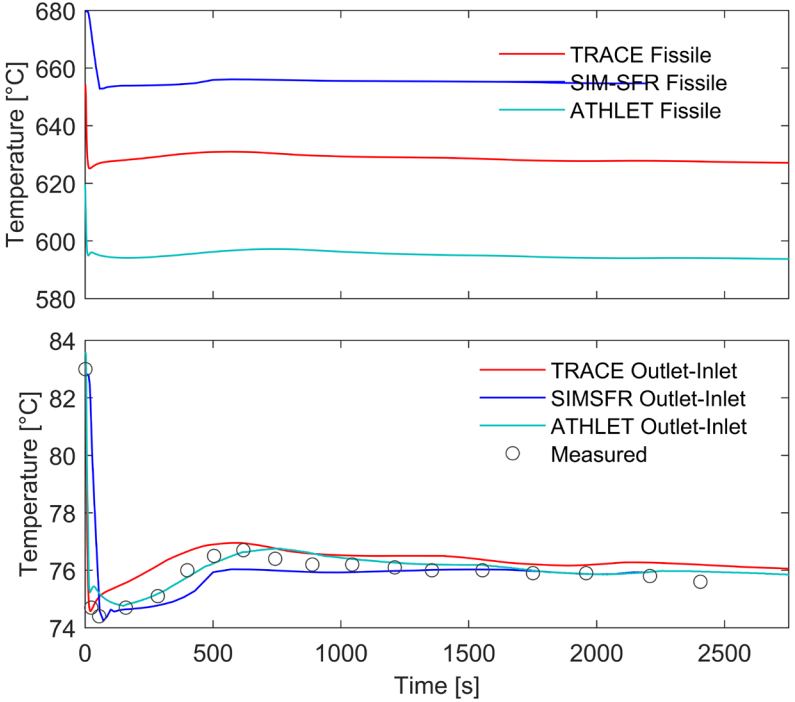
Transient results
SST: +30 pcm reactivity insertion at HZP



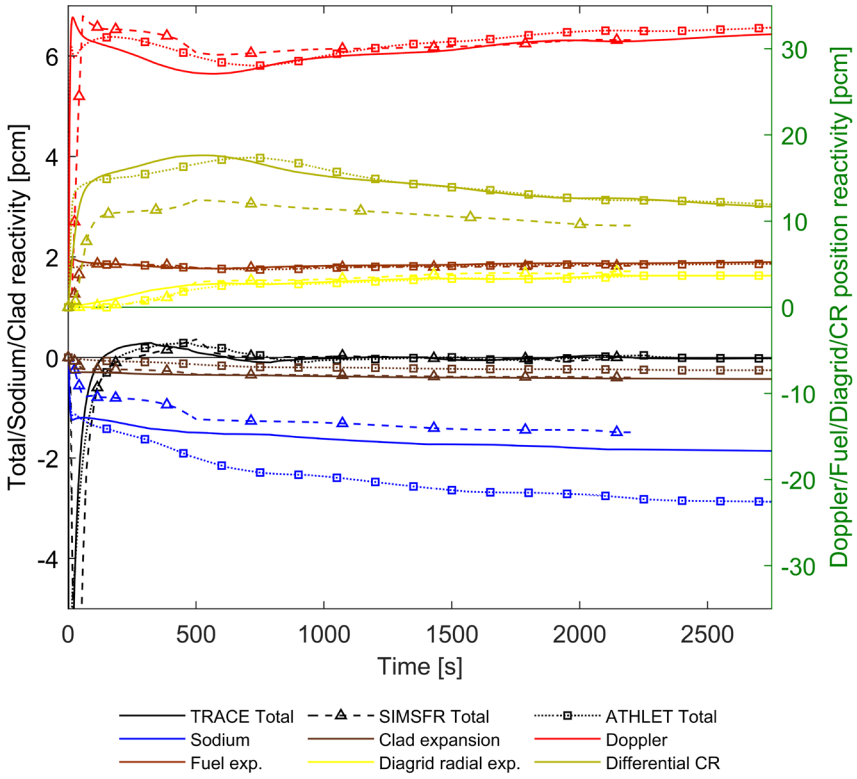


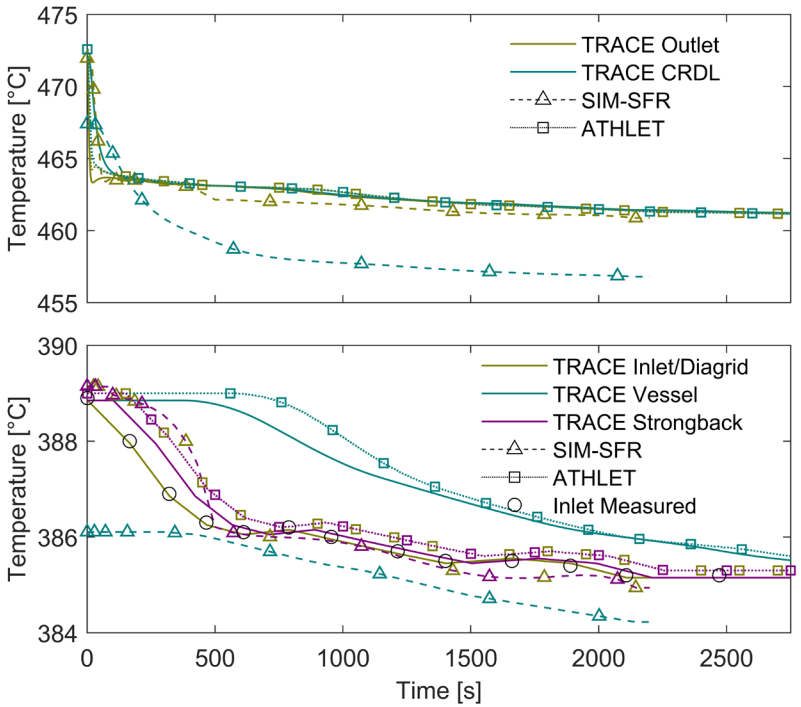
Transient results
MOFC1: -50 pcm reactivity insertion at 692MWth



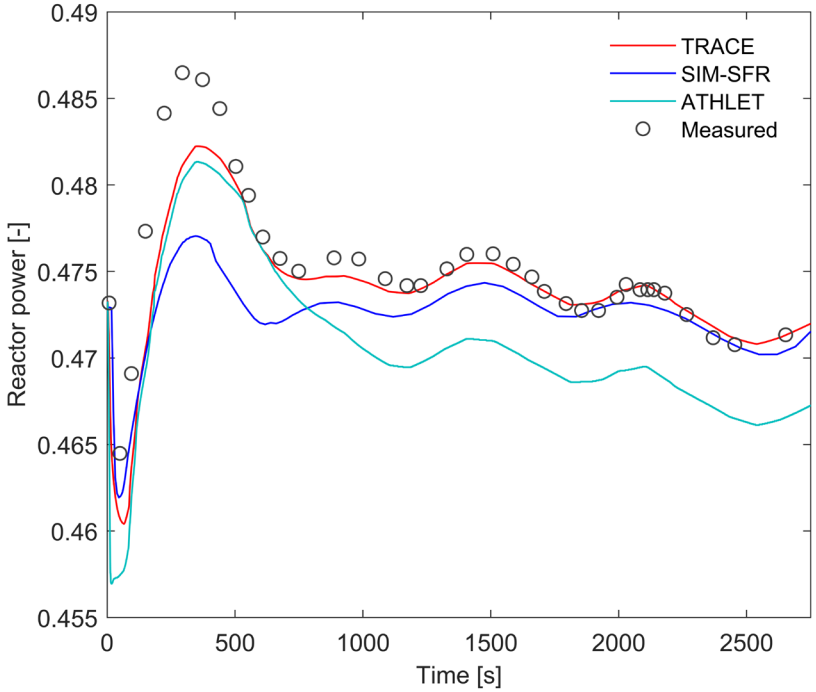


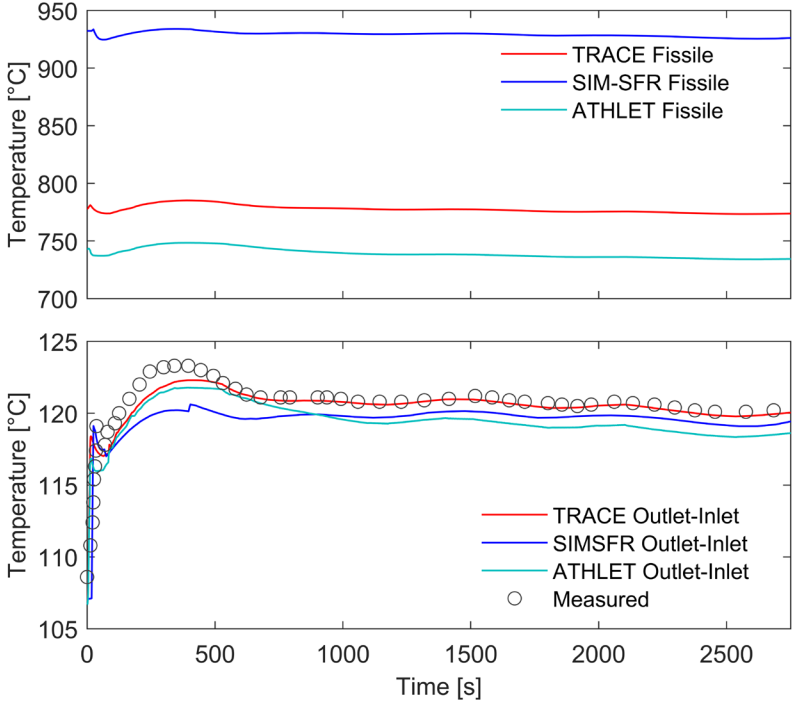
Transient results
MOFC1: -50 pcm reactivity insertion at 692MWth



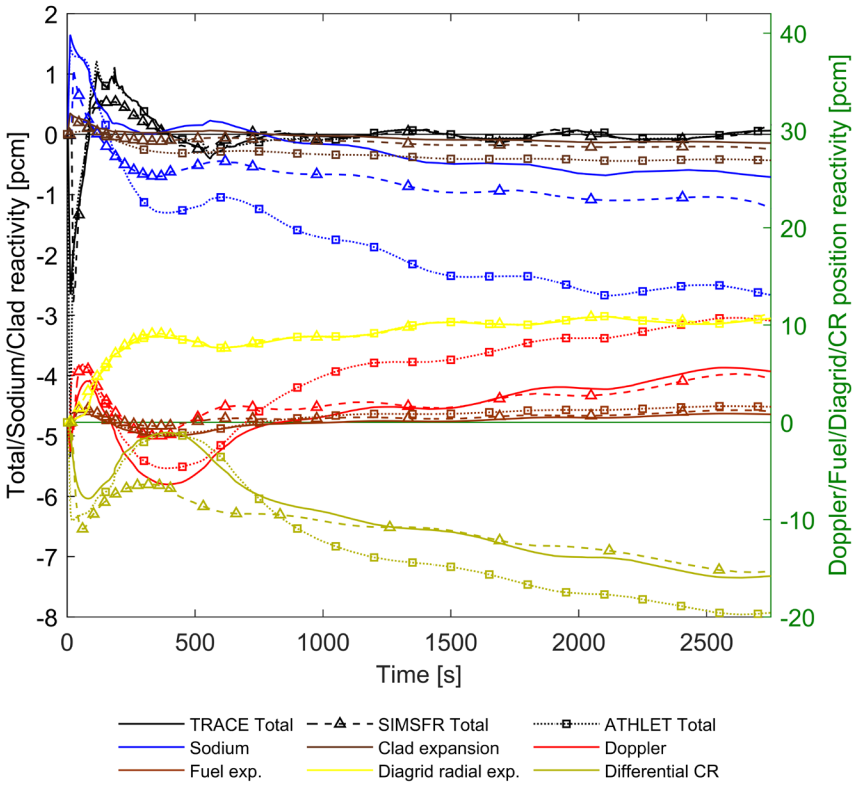


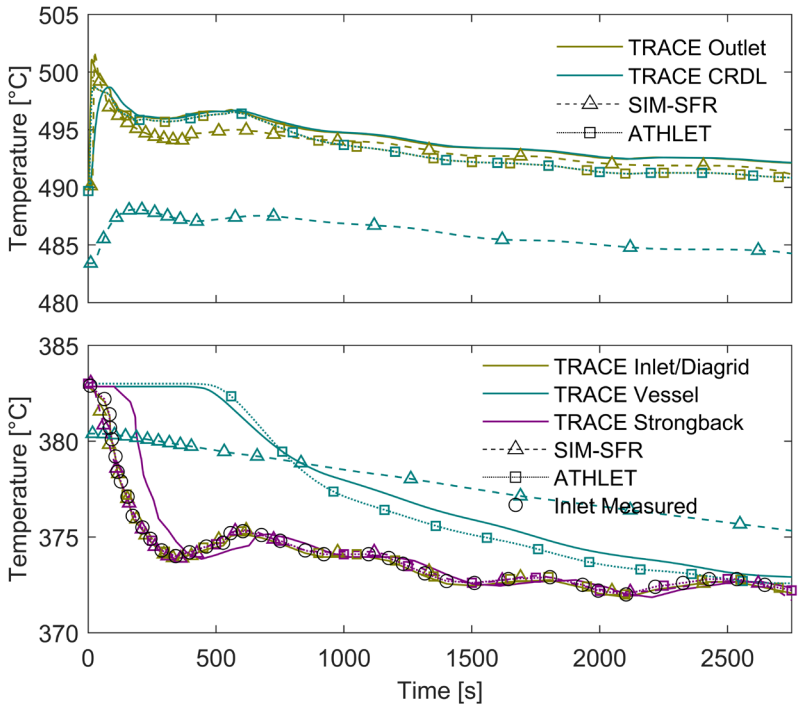
Transient results
PFS: -10% primary mass flow at 1415 MWth



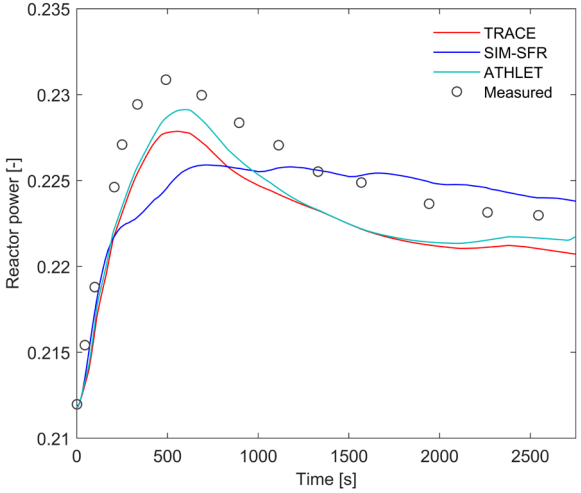


Transient results
PFS: -10% primary mass flow at 1415 MWth

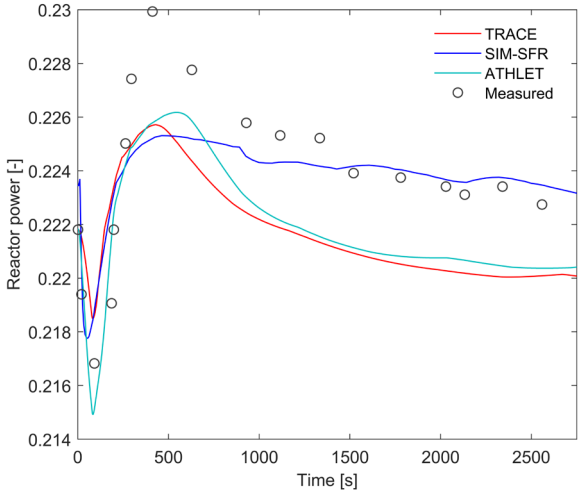




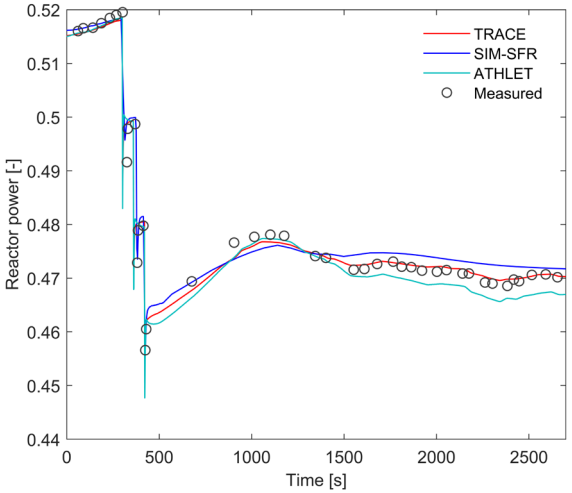
Transient results



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

Transient results

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):

[12] A. Ponomarev, K. Mikityuk, E. Bubelis, M. Schikorr, E. Fridman, and V. Di Nora, ”SPX Benchmark Part II: Transient Results”, Journal of Nuclear Engineering and Radiation Science, Spec. Vol. on EU ESFR-SMART project, October 2021.

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The work has been prepared within EU Project ESFR-SMART which has received funding from the EURATOM Research and Training Program 2014-2018 under the Grant Agreement No. 754501

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Wir schaffen Wissen – heute für morgen

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

- **PSI**
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- **UCAM/Jacobs**
- **HZDR**
- **GRS**
- **KIT**

Thank you!