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Benchmark on Beam Interruptions in an Accelerator-driven System

Final Report on Phase I Calculations

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FOREWORD

Recognising a need to evaluate the thermal responses of accelerator-driven systems to a beam trip, the OECD/NEA Working Party on Scientific Issues in Partitioning and Transmutation (WPPT) is organising a series of benchmarks on beam interruptions in a lead-bismuth-cooled and MOX-fuelled accelerator-driven system. The series will range from the simple to the complex.

The present phase of the benchmark (Phase I) was designed to have the minimum phenomenological and computational complexity of models – without any degree of freedom – so as to obtain a particularly clean comparative assessment of the different computation methods. The benchmark sought the evaluation of temperature and power transients induced by beam interruptions of different durations.

This report summarises the comparative analysis of the ten sets of temperature and power variation results provided. In general, good agreement was observed among the results.

More complex calculation assumptions and computation methods will be addressed in the second phase of the benchmark, currently being defined, which will investigate fuel and coolant temperature variations under different power density conditions. In a third phase, the benchmark will be extended to cover irradiated fuel conditions.

Acknowledgements

The Secretariat expresses its sincere gratitude to the participants who were willing to devote their time and effort to this benchmark exercise.

Abstract

Transients induced by recovered beam interruptions of different durations in a MOX-fuelled and lead-bismuth-cooled 80 MWth prototypical system are investigated as a benchmark computational problem aimed at the comparative assessment of computation methods. A comprehensive comparison of ten contributions submitted by nine participants is presented in this final report. Generally, the differences in fuel and outlet coolant temperature trends among the ten sets of results provided can be physically neglected.

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Introduction

All the results of the first phase of benchmark calculations relevant to the *Beam Interruptions in a Lead-bismuth-cooled and MOX-fuelled XADS-type Accelerator-driven System* are presented and compared in this final report. It is useful to reiterate that the specification of this first phase of calculations was designed to have the minimum phenomenological and computational complexity of the models. Moreover, the benchmark specification defines a computational exercise without any degree of freedom, the goal being to obtain a particularly clean comparative assessment of the different computation methods used to evaluate power and temperature transients induced by beam interruptions of different duration. The benchmark specification is given as Appendix I. This final report demonstrates that, in this aim, Phase I of the benchmark has been successful. In fact, the differences among the ten sets of results provided by the nine participants can be physically neglected. In the near future, this good agreement will allow to further develop the benchmark with the aim of progressively investigating more complex calculation assumptions and computational methods. To this end, a second phase of beam interruption calculations which will consider the impact of different assumptions on the main benchmark results is presently being defined. Phase II calculations will also allow to investigate different fuel power density assumptions (not only relevant to an XADS-type average fuel pin, but also to an XADS-type hottest fuel pin and to a MYRRHA-type experimental ADS). Different fuel burn-up conditions (not only relevant to BOL fresh fuel, but also to EOC irradiated fuel) will be investigated in Phase III.

Returning to Phase I calculations, the above-mentioned specification simplifications were designed to have a minimum impact on the temperature variations in an XADS-type prototypical ADS charged by fresh fuel. Thus, Phase I results allow to evaluate (under BOL fuel conditions) both the average pin initial temperature distributions and the temperature variations induced by accelerator beam interruptions having different durations. After a short section devoted to the participants and the codes used, a subsequent section presents and compares results concerning the initial steady-state axial temperature distributions (common to all the considered beam interruption transients):

- The fuel centreline temperature (I1).
- The fuel surface temperature (I2).
- The clad surface temperature (I3).
- The coolant temperature (I4).

For each of the five beam interruption cases considered (1 s, 3 s, 6 s, 12 s and a definitive beam trip), time-dependent results are reported and compared:

- Fuel total power (normalised to its initial value) (T1).
- Fuel centreline temperature at the fuel zone mid-plane (height = 45.0 cm) (T2).
- Fuel surface temperature at the fuel zone mid-plane (height = 45.0 cm) (T3).
- Outlet coolant temperature (height = 90.0 cm) (T4).

Some concluding remarks close the present final report.

Participants, codes and some calculation conditions

Table 1 reports the names of the nine participants of Phase I calculations and the codes they used. As PSI solved the benchmark problems using two different calculation tools, a total of ten solutions have been calculated for both initial temperatures and the temperature variations induced by accelerator beam interruptions having different durations.

Table 1. Participant and code list

Participant	Institution (country)	Code used
Antonio D'Angelo	ENEA Casaccia (Italy)	TIESTE-MINOSSE
Gert Van den Eynde Baudouin Arien	SCK•CEN Mol (Belgium)	SITHER-PKS
Kazafumi Tsujimoto	JAERI Tokai (Japan)	EXCURS-M
Marcus Eriksson	Royal Institute of Technology, Stockholm (Sweden)	SASSYS/SAS4A
Michael Schikorr	FZK Karlsruhe (Germany)	SIM-ADS
Paul Coddington Konstantin Mikityuk	PSI (Switzerland)	TRAC-M
Paul Coddington Konstantin Mikityuk	PSI (Switzerland)	LOOP2
Pieter Wakker Jim Kuijper	NRG Petten (the Netherlands)	TRAC MOD
Ron Dagan Cornelis Broeders	FZK Karlsruhe (Germany)	SAS4ADS
Yonghee Kim	KAERI Daejon (Republic of Korea)	DESINUR

It is worthwhile to reiterate that the specification of the first phase of the benchmark concerns a simple model (single fuel channel thermal-hydraulics coupled with point kinetics) of the average fuel pin relevant to a lead-bismuth-cooled and MOX-fuelled XADS-type accelerator-driven prototypical system. In particular, the simple model geometry refers to the "fresh fuel" assumption corresponding to the BOL fuel condition. Irradiated fuel conditions are foreseen to be investigated in the near future.

Initial steady-state axial temperature distributions

Figure 1 shows the ten sets of steady-state axial temperature distributions calculated by different participants using various codes. In this figure, the highest temperature set (previously called I1) is relevant to the fuel centreline axial distribution. Results relevant to the fuel surface temperature (I2), the clad surface temperature (I3) and the coolant temperature (I4) are drawn at progressively lower temperatures in the same figure. The very good agreement among the different results appears evident. Even the two largest differences on fuel centreline temperature, relevant to the TRAC MOD (Pieter Wakker and Jim Kuijper, NRG Petten, the Netherlands) and to the SAS4ADS results (Ron Dagan and Cornelis Broeders, FZK Karlsruhe, Germany) are not significant (~ 1.5%). In fact they are both of the order of magnitude of 15 K and are relevant to a maximum fuel temperature value that is close to 1000 K. The relative differences concerning the other axial temperature distributions are even smaller.

Transient (time-dependent) results

Figure 2 shows the ten sets of time-dependent results relevant to the power transients induced by beam interruptions of different duration (1 s, 3 s, 6 s, 12 s) and by a definitive beam trip. The power trends are normalised to the initial (before the beam interruption) steady-state value (7 203.6 W for each fuel pin, or about 77.8 MW on the whole system fuel). The good agreement among the different results appear evident.

All the results agree on very fast power variations (drop at the beam interruption and rise at the possible beam recovery). These power level jumps will induce very large and fast variations of every neutron and gamma counter signals at each beam interruption [1,2].[1]

Due to the (conservative) assumption of no decay heat, the (common) result relevant to the relative power level on which the system drops just after the beam interruption (about 11% of the system initial power) must (and does) agree with the point kinetic analytical ("source jerk" method) value $1/(1-\rho/\beta)$. In Figure 3, which is an enlargement of the upper portion of Figure 2, the discrepancies on the power level reached just after the beam recovery are stressed. These variations are due to slight errors in reproducing the same feedback assumptions by means of the different codes. But the discrepancies do not have a significant impact on fuel and coolant temperature results (see the agreement among temperature result analysed hereafter). In fact, due to the assumption of a large (-8$) subcriticality level,[2] temperature results are not significantly sensitive to the neutron kinetics and to the feedback effects. In any case, Figure 3 shows that, just after beam recovery, there is a general increase in the power level the longer the duration of the beam interruption. This power increase, found in all the benchmark solutions, is the effect of greater decreases in fuel temperature for longer beam interruption durations (and of the corresponding larger system reactivity at beam recovery time). The power levels normalised to their initial value drawn in Figure 3 clearly show that, due to this effect, the fuel power level increases to values that can be larger (within 3%, for our XADS-type system in operational conditions and for the 12 s beam interruption duration) than the initial one.

Figure 4 shows the ten sets of time-dependent results relevant to the fuel centreline temperature at the fuel zone mid-plane (height = 45.0 cm). The general agreement among the different fuel temperature results appears evident. These results are of particular interest for evaluating possible cyclic thermal stresses of the oxide, which could be significant to induce fatigue in the fuel. For that reason, the corresponding values of fuel centreline temperature variations at the fuel zone mid-plane (height = 45.0 cm) are also listed in Table 2 for the various durations of beam interruption considered. Figure 4 shows the TRAC MOD results (Pieter Wakker and Jim Kuijper, NRG Petten, the Netherlands), which appear to be slightly overestimated, in particular for the asymptotic solutions (coherently with the steady-state results), but the corresponding discrepancy with the other solutions is not significant (always lower than 5%).

Table 2. Fuel temperature variations in an XADS-type prototypical system[3]

Beam interruption duration (s)	Fuel centreline temperature variation (K)
1	~ 70
3	~ 180
6	~ 300
12	~ 370

[1] Such large and fast counter signal variations would lead to the system scram in critical systems.
[2] This benchmark is devoted to beam interruptions under operational conditions.
[3] As per the benchmark specification, this evaluation is relevant to fresh fuel conditions.

Figures 5 and 6 show the ten sets of time-dependent results relevant to the fuel surface temperature at the fuel zone mid-plane (height = 45.0 cm) and to the outlet coolant temperature, respectively. Once again, the overall results are in good agreement. Outlet coolant temperature variations are of particular interest for evaluating possible cyclic thermal stresses of the above core structures and of the intermediate heat exchangers that could induce fatigue in those structures. For this reason, the corresponding evaluation of the outlet coolant temperature variation values are reported in Table 3 for different beam interruption durations.

Table 3. Outlet coolant temperature variations in an XADS-type prototypical system[4]

Beam interruption duration (s)	Fuel centreline temperature variation (K)
1	~ 13
3	~ 35
6	~ 60
12	~ 85

Concluding remarks

Beam interruptions in a lead-bismuth-cooled and MOX-fuelled XADS-type accelerator-driven system have been investigated in the framework of an OECD/NEA/WPPT computational benchmark first phase of calculations. The resulting average fuel pin initial temperature distributions and the transients of the power and the temperatures, induced by beam interruptions of different duration, have been reported and compared. Phase I of the benchmark aimed to produce a particularly clean comparative assessment of the different computation methods used to evaluate power and temperatures. In this context, the benchmark has been successful; results are practically independent of codes and methods. In fact, the temperature results show differences that are generally within ±3% and thus can be neglected from the physical point of view. In the near future, this positive result will allow to further develop the beam interruption benchmark, so as to enable the progressive investigation of more complex calculation assumptions and computational methods. To this end, a second phase of beam interruption calculations, which will investigate the impact of different assumptions on the main benchmark results, is presently being defined.

[4] As per the benchmark specification, this evaluation is relevant to fresh fuel conditions.

REFERENCES

[1] D'Angelo, A., M. Carta, G. Bianchini, "Preliminary Analysis of Neutronic Source Transients in a Small ADS Prototype", *Proc. of the 3rd Int. Conference on Accelerator-driven Transmutation Technologies and Applications*, Praga, Pruhonice (Czech Republic), 7-11 June 1999.

[2] D'Angelo, A., G. Bianchini, M. Carta, "Preliminary Analysis of Beam-trip and Beam-jump Events in an ADS Prototype", *Proc. of the Int. Conference on Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid (Spain), 27-30 Sept. 1999.

FIGURES

Figure 1. Initial (steady-state) axial temperature distributions

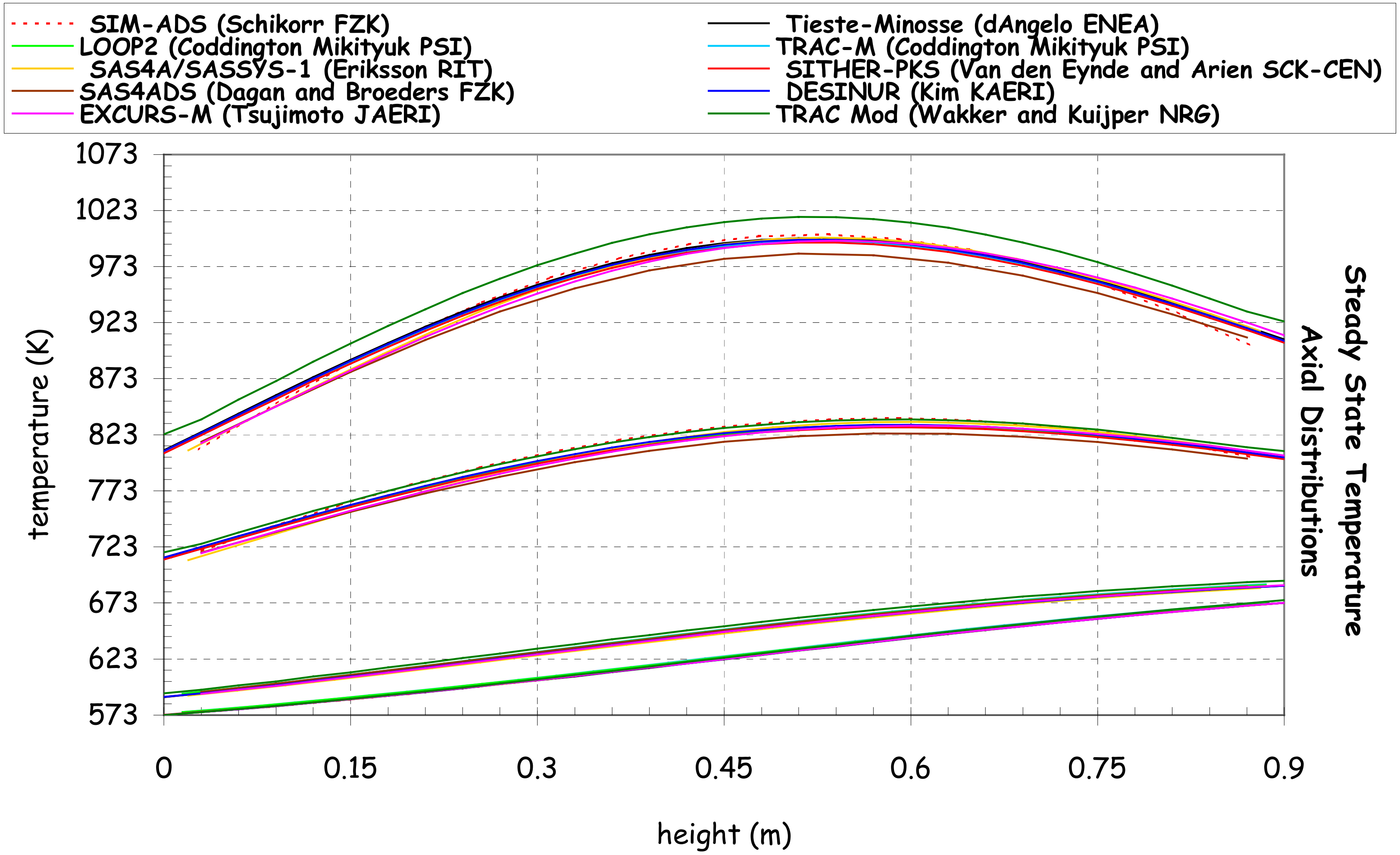


Figure 2. Power (normalised to the initial value) transients induced by beam interruptions of different duration: 1 s, 3 s, 6 s, 12 s and by a definitive beam trip

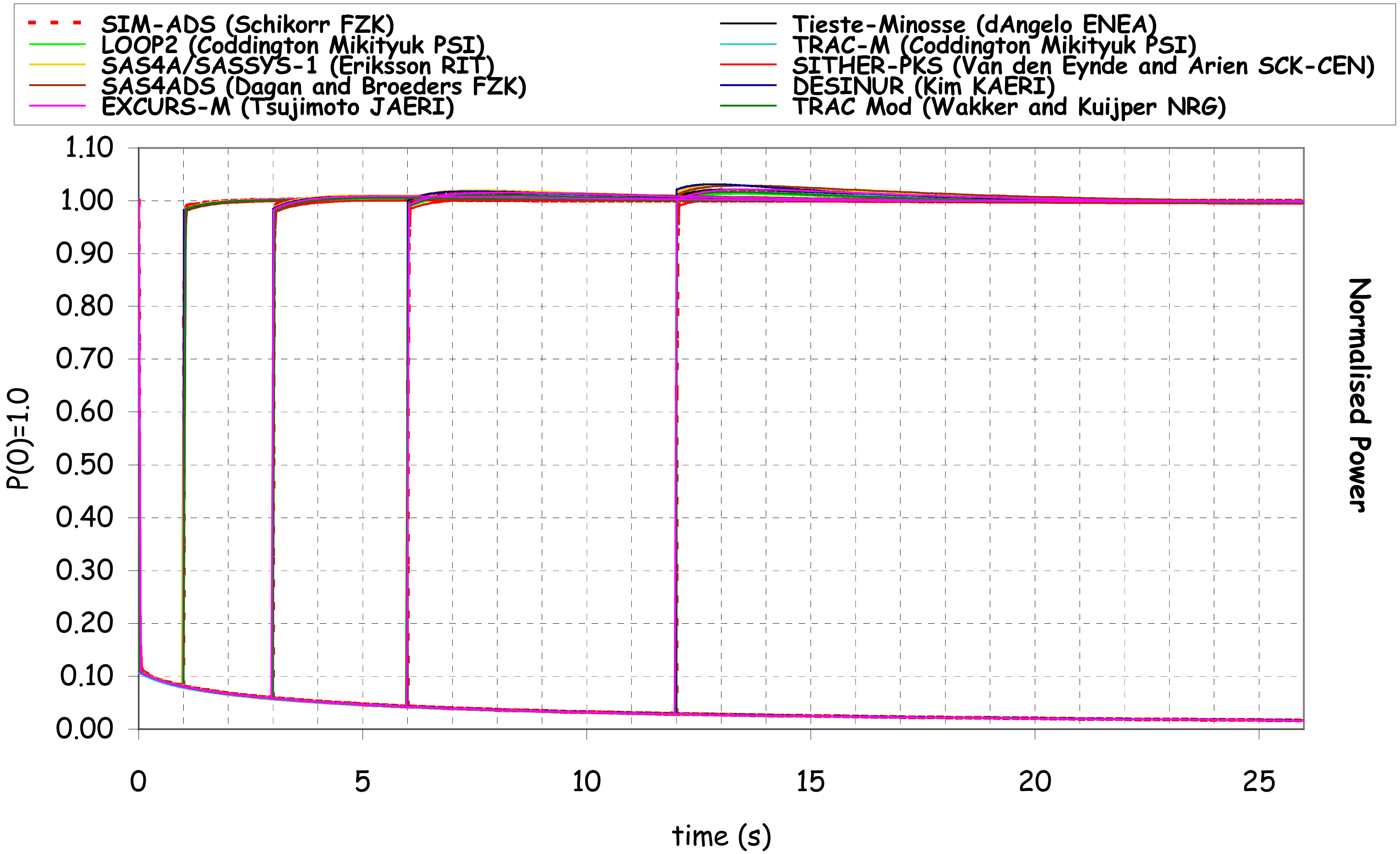


Figure 3. Enlargement of the upper part of Figure 2

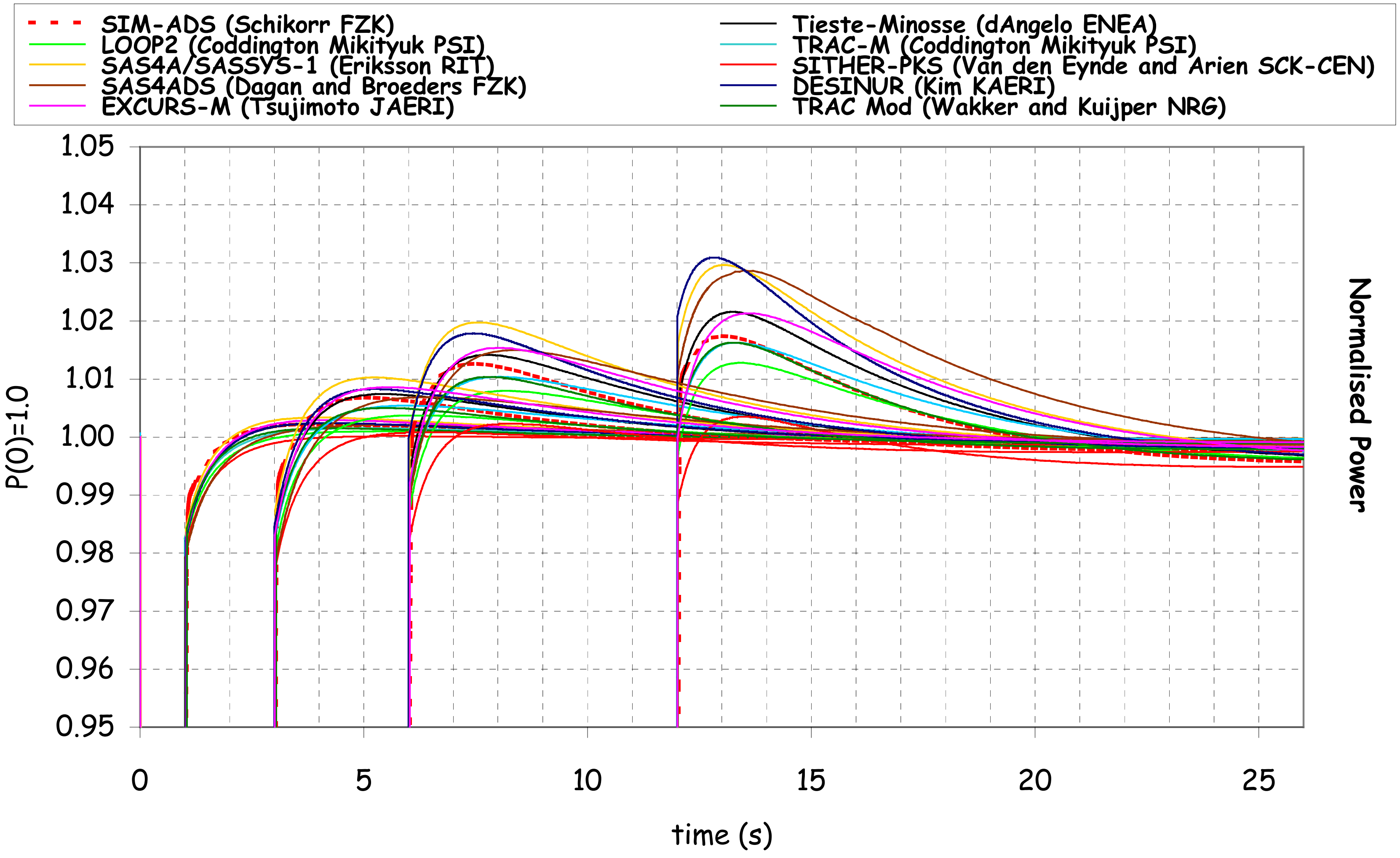


Figure 4. Fuel centreline temperature at the fuel zone mid-plane transients induced by beam interruptions of different duration: 1 s, 3 s, 6 s, 12 s and by a definitive beam trip

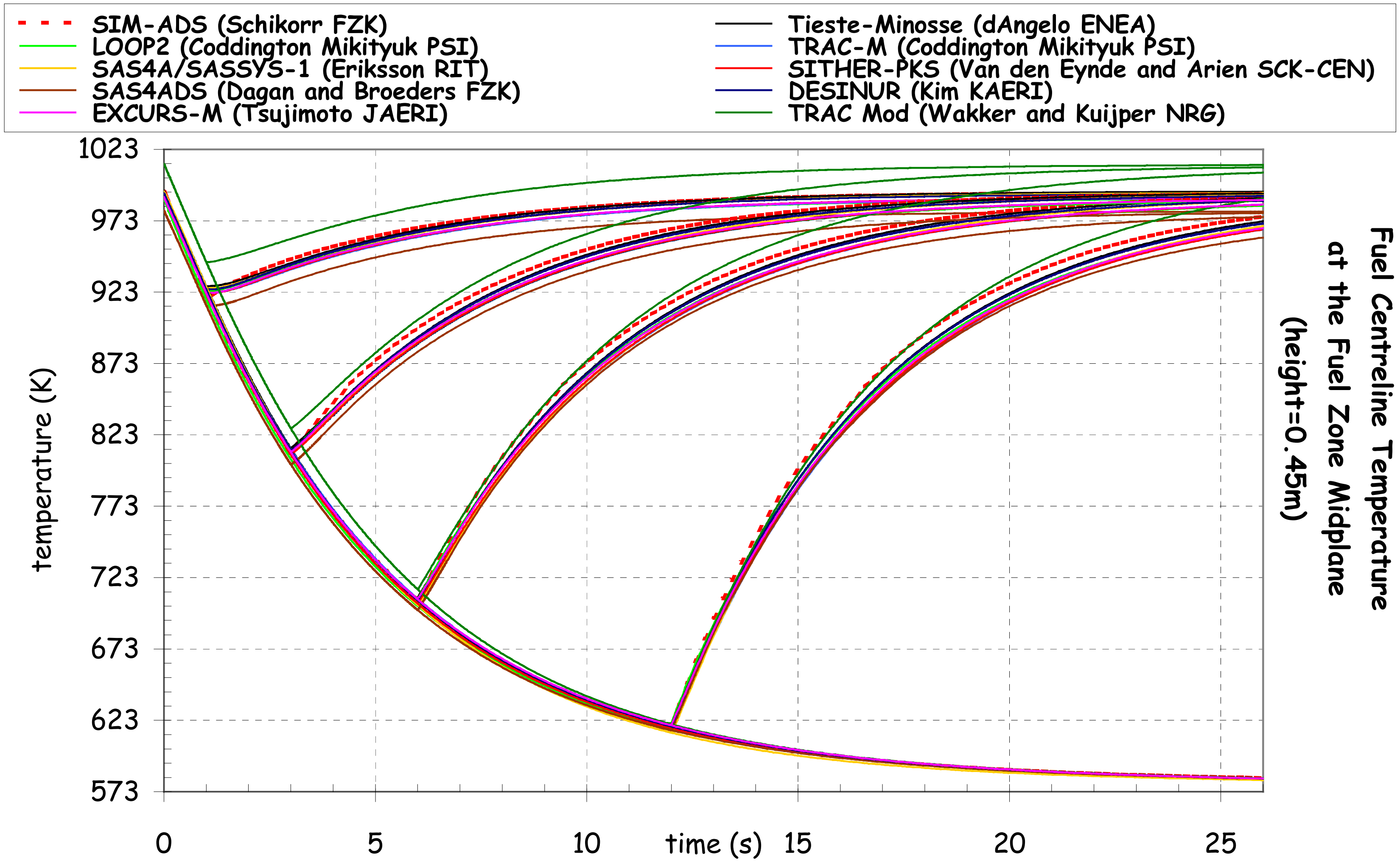


Figure 5. Fuel surface temperature at the fuel zone mid-plane transients induced by beam interruptions of different duration: 1 s, 3 s, 6 s, 12 s and by a definitive beam trip

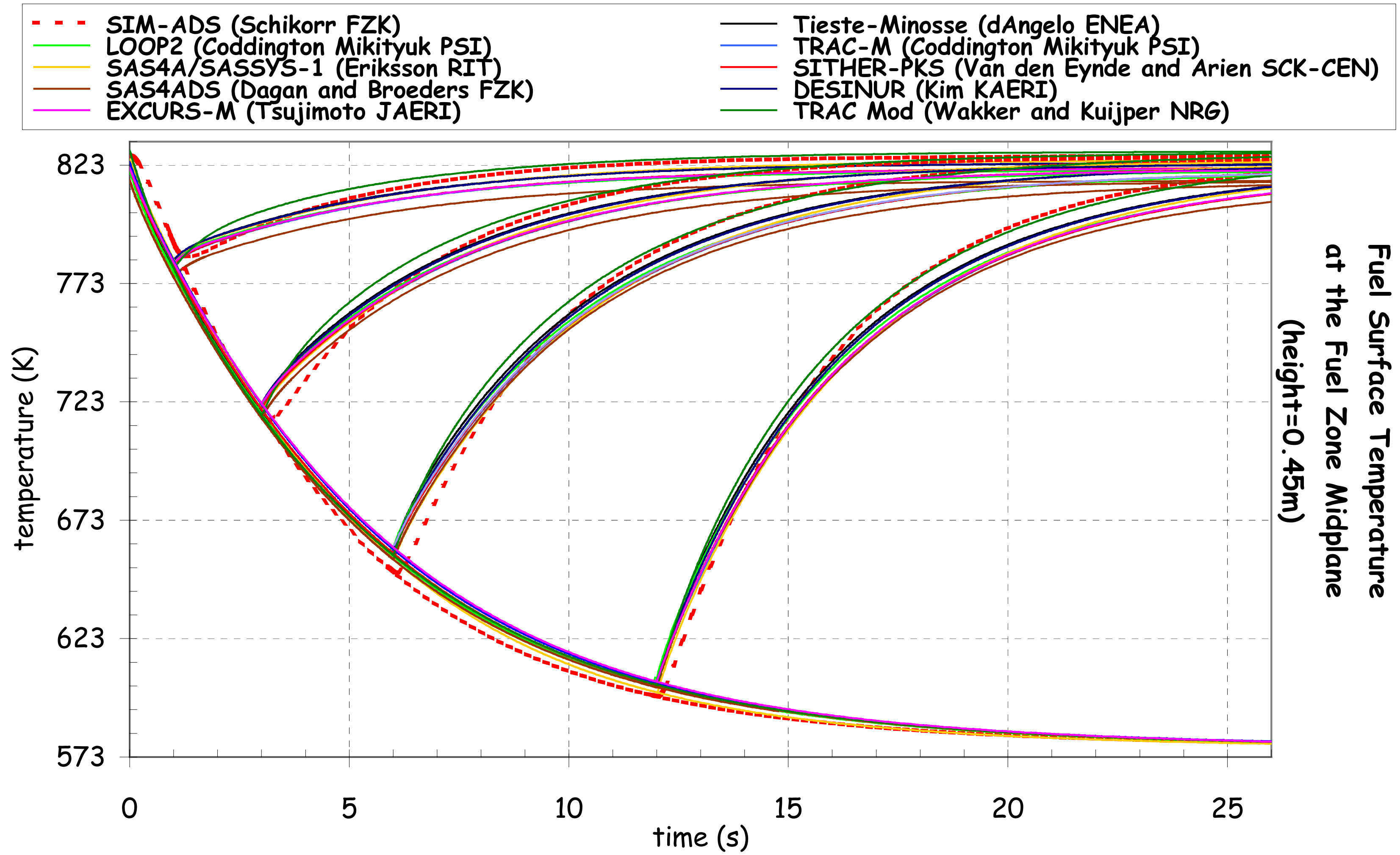
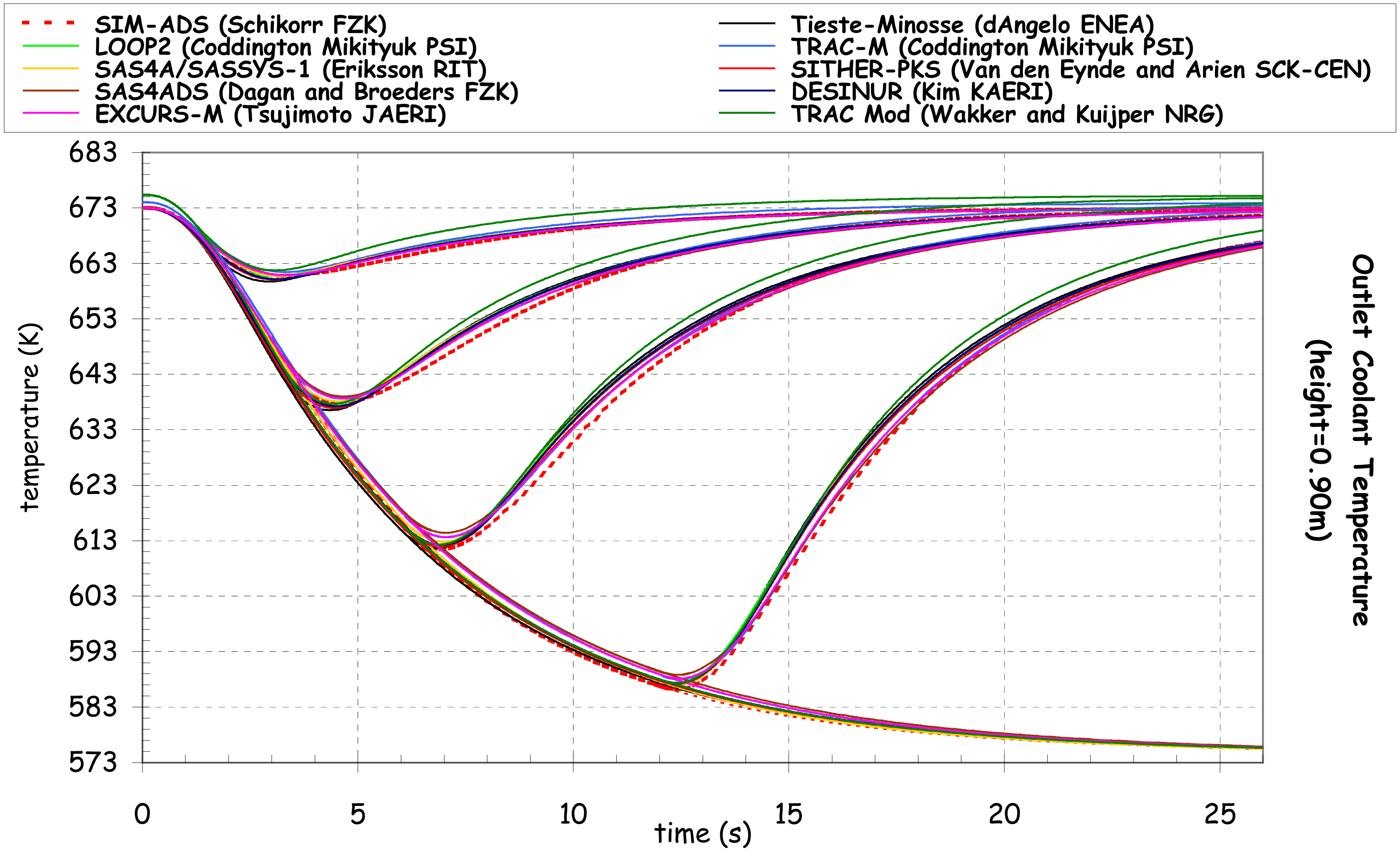


Figure 6. Outlet coolant temperature at the fuel zone mid-plane transients induced by beam interruptions of different duration: 1 s, 3 s, 6 s, 12 s and by a definitive beam trip



Appendix

BEAM INTERRUPTIONS IN A LEAD-BISMUTH-COOLED AND MOX-FUELLED ACCELERATOR-DRIVEN SYSTEM

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Abstract

This specification is proposed for a computational problem that aims to investigate the outlet core coolant temperature behaviours induced by beam interruptions of varying duration in an XADS-type system. In order to define the common application for the proposed computational benchmark, fuel channel geometry, power data, material properties, heat transfer correlations and the point kinetics are provided.

Introduction

Transients induced by recovered beam interruptions in a MOX-fuelled and lead-bismuth-cooled, 80 MWth XADS-type system, are proposed as a computational benchmark problem for the comparative assessment of computation methods. The present proposal is made in the frame of a NEA benchmark series for simulation of coupled thermal, fluid dynamics and reactor kinetics transients in accelerator-driven subcritical nuclear reactors. Also this benchmark proposal is designed to have, at least at the present stage, the minimum phenomenological and computational complexity. For this reason, the benchmark specification does not define the detailed geometry, material properties and correlations to investigate fuel or neutronics of an XADS-type system. Nevertheless, the simplifications have been designed to have minimum impact on the main benchmark results, the outlet core coolant temperature trends induced by accelerator beam interruptions having very different durations (1 s, 3 s, 6 s, 12 s and a definitive beam trip). Besides the outlet core coolant temperature, in order to facilitate the result analysis, some few additional results are requested from the benchmark participants.

I. Fuel channel geometry and power data

The 80 MWth[1] lead-bismuth-cooled XADS core is foreseen to charge 120 MOX fuel hexagonal assemblies, each one containing 90 active pins. The following simplified fuel element channel geometry[2] is assumed for the present benchmark in an XADS-type system.

Table 1. Fuel pin channel geometry

Fuel zone height	0.90 m
Inner fuel radius (inner hole radius)	0.9×10^{-3} m
Outer fuel radius	3.57×10^{-3} m
Inner clad radius	3.685×10^{-3} m
Outer clad radius	4.25×10^{-3} m
Coolant flow area	9.89×10^{-5} m^2
Coolant inlet temperature	573.0 K
Fuel pin total power (initial value)	7 203.6 W
Coolant outlet temperature (initial value)	673.0 K

The coolant movement in the XADS design is driven by the lead-bismuth natural convection and by pumps at the same time. When the pumps are working, forced convection prevails on the lead-bismuth natural convection. Though the lead-bismuth flow rate variations due to the natural convection are essential to mitigate transients in which the coolant temperature tends to rise abnormally, it has a minor impact on the transients induced by beam trips [1]. Therefore, the corresponding mass flow rate variations during the beam interruption transients are ignored in the present benchmark proposal. Similarly, for the sake of simplicity, the inlet coolant temperature is also considered constant and equal to the initial value [2]. The channel model described above is given presuming that the coolant will be treated with a single lumped radial node and multiple axial nodes. Besides the data of Table 1, the pin pitch = 13.406×10^{-3} m value is also necessary to define the clad-coolant heat exchange by means of a Nusselt number correlation (see Section III).

For the sake of simplicity, the heat decay power is ignored at this first stage of the benchmark. This assumption is conservative: it leads to outlet coolant temperature variations that are only some few degrees higher than those relevant to the XADS-type system conditions after a long working time.

The total fuel power variations are to be evaluated approximately by point kinetics. The constant axial power shape to be adopted with the simplified fuel element channel geometry of Table 1 is reported in Table 2. Table 2 contains linear power values (kW/m) on a regular grid (step = 3 cm) that, if needed, can be converted to the power produced within each mesh segment assuming a linear variation between couples of close data in Table 2.

For any fixed axial mesh segment, the radial power density distribution is assumed to be constant inside the fuel (but obviously zero in the central hole). The oxide-fuel axial conductivity can be ignored. An adiabatic boundary condition is assumed on the outer surface of the fuel channel.

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[1] The thermal power produced in fuel elements is about 77.8 MW.

[2] Obtained taking into account only the fuel zone and forcing the geometry to solve an axial heterogeneity between MOX active fuel zone (87 cm) and UO_2 blanket zones (3 cm).

Table 2. Linear power axial distribution

	Axial mesh boundaries (m)	Power wasted in the fuel (kW/m)
31	0.90	5.956
30	0.87	6.293
29	0.84	6.625
28	0.81	6.950
27	0.78	7.265
26	0.75	7.565
25	0.72	7.847
24	0.69	8.109
23	0.66	8.347
22	0.63	8.559
21	0.60	8.742
20	0.57	8.895
19	0.54	9.015
18	0.51	9.103
17	0.48	9.155
16	0.45	9.173
15	0.42	9.155
14	0.39	9.103
13	0.36	9.015
12	0.33	8.895
11	0.30	8.742
10	0.27	8.559
9	0.24	8.347
8	0.21	8.109
7	0.18	7.847
6	0.15	7.565
5	0.12	7.265
4	0.09	6.950
3	0.06	6.625
2	0.03	6.293
1	0.00	5.956

II. Material properties

(*T is the temperature in K.*)

Coolant conductivity (W/K × m) [3]	$k_{Coolant} = 3.9021 + 0.0123 \times T$
Coolant density (Kg/m^3) [3]	$\rho_{Coolant} = 11112 - 1.375 \times T$
Coolant specific heat (J/K × Kg) [3]	$C_{Coolant} = 146.5$
Coolant viscosity (Kg/m × sec)[3] [3]	$\mu_{Coolant} = 5.73 \times 10^{-3} - 8.92 \times 10^{-6} \times T + 4.71 \times 10^{-9} \times T^2$
Clad conductivity (W/K × m) [3]	$k_{Clad} = 15.4767 + T \times 3.448 \times 10^{-3}$
Clad density (Kg/m^3)	$\rho_{Clad} = 7924$
Clad specific heat (J/K × Kg) [3]	$C_{Clad} = 620$
Fuel conductivity (W/K × m) [4]	$k_{Fuel} = \frac{1}{0.042 + T \times 2.71 \times 10^{-4}} + T^3 \times 6.9 \times 10^{-11}$
Fuel density (Kg/m^3)	$\rho_{Fuel} = 10354$
Fuel specific heat (UO_2, PuO_2) (J/K × Kg) [5]	$C_{UO_2} = 81.825 + 0.78695 \times T - 1.1552 \times 10^{-3} \times T^2 + 9.9037 \times 10^{-7} \times T^3 - 5.1982 \times 10^{-10} \times T^4 + 1.5241 \times 10^{-13} \times T^5 - 1.7906 \times 10^{-17} \times T^6$ $C_{PuO_2} = \frac{-4.9236 \times 10^6}{T^2} + 240.89 + 0.32556 \times T - 3.5398 \times 10^{-4} \times T^2 + 1.512 \times 10^{-7} \times T^3 - 1.9707 \times 10^{-11} \times T^4$
Fuel mixture specific heat (J/K × Kg)	$C_{Fuel} = \frac{214.65 \times C_{UO2} + 55.56 \times C_{PuO2}}{270.21}$ $\left(\frac{\text{Weight } PuO_2}{\text{Weight } (PuO_2 + UO_2)} \approx 20.5\% \right)$

[3] Though the coolant viscosity is not needed at the present stage of the benchmark.

III. Heat transfer correlations

1) *Clad-coolant heat exchange coefficient* (W/(K × m^2)) [4]:

$$h = \frac{Nu \times k_{Coolant}}{D}$$

where h is the heat exchange coefficient, Nu is the Nusselt number (see below), D is the hydraulic diameter which is equal to (4 × S)/W, $k_{Coolant}$ is the coolant conductivity, S is the coolant flow area and W is the wetted perimeter = 2π r_p.

The Nusselt number is evaluated as [4]:

$$Nu = 4 + 0.16\left(\frac{p}{2r_p}\right)^5 + 0.33\left(\frac{p}{2r_p}\right)^{3.8}\left(\frac{Pe}{100}\right)^{0.86}$$

where Pe is the Peclet number = $\frac{\rho_{Coolant} \times V \times D \times C_p}{k_{Coolant}}$, $\rho_{Coolant}$ is the coolant density, V is the coolant velocity, C_p is the coolant specific heat, p is the pin pitch and r_p is the outer clad radius.

2) *Fuel-clad* (W/(K × m^2)):

The fuel-clad gap is assumed to be open and filled by helium. Under these hypotheses the (approximated) heat exchange coefficient is [6]:

$$h_{gap} = \frac{3.623 \times 10^{-3} \times T_{gap}{}^{0.66}}{R_{gap}}$$

where T_{gap} is the gap filling gas temperature $\frac{T_{ex\_fuel} + T_{in\_clad}}{2}$ (T_{ex_fuel} is the outer fuel temperature, T_{in_clad} is the inner clad temperature) and R_{gap} is the gap size.

IV. Point kinetics

The effective delayed neutron fraction is assumed to be equal to 350 pcm. At full power, the system is assumed to be about 8 $ sub critical (i.e. the effective multiplication factor K_{eff} = 0.97276).

The average neutron generation time, $\Lambda = 4.2 \times 10^{-7}$ s

Table 3. Delayed neutron emission group data

Group, i	Fraction, β_i	Decay constant, λ_i s^{-1}
1	8.6×10^{-5}	0.0129
2	7.30×10^{-4}	0.0313
3	6.55×10^{-4}	0.1346
4	1.267×10^{-3}	0.3443
5	5.80×10^{-4}	1.3764
6	1.82×10^{-4}	3.7425
Total	350×10^{-5}	

A. *A non-linear fuel temperature feedback (reactivity) effect is assumed*:

$$Re\,activity_{Fuel\_feedback}(t) = \left[\overline{T}_{Fuel}(t) - \overline{T}_{Fuel}(0)\right]\frac{A_D}{\overline{T}_{Fuel}(t)}$$

where A_D is a constant coefficient: A_D = -700 pcm (-2 $) and $\overline{T}_{Fuel}$ is a fuel-effective temperature.[4]

B. *A linear coolant density feedback (reactivity) effect is assumed*:

$$Re\,activity_{Coolant\_feedback}(t) = \left[\overline{T}_{Coolant}(t) - \overline{T}_{Coolant}(0)\right]B_V$$

where B_V is a constant coefficient: B_V = -1.2 pcm/K (-3.43×10^{-3} $/K) and $\overline{T}_{Coolant}$ a coolant effective temperature obtained weighting linearly (on the axial mesh size only) the different mesh segment $\overline{T}_{Coolant}(z)$ values.

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[4] $\overline{T}_{Fuel}$ can be simply calculated weighting linearly (on the axial mesh size only) the following different mesh segment $T_{Fuel}(z)$ effective-value approximation: $\overline{T}_{Fuel}(z) = 0.3 \times T_{Fuel\_Centre}(z) + 0.7 \times T_{Fuel\_Boundary}(z)$.

V. Beam interruptions and calculation result definition

It is assumed that the external neutron source, that initially keeps up the amplitude factor of point kinetics to be constant (steady state conditions), drops suddenly to zero at one millisecond. Five benchmark problems are proposed: beam interruptions of 1 s, 3 s, 6 s, 12 s duration, and a definitive beam trip. In order to model the four recovered beam interruptions, the external neutron source is assumed to be suddenly reset to the initial value at: 1.001 s, 3.001 s, 6.001 s, 12.001 s, respectively.

The coolant temperature at the top of the fuel channel (height = 90 cm) is the main result requested from the present benchmark participants. Results have to be calculated at the initial conditions and for 26 s after the beam interruption time (from 0 s to 26.001 s).

Some additional results are also requested to facilitate the result analysis in the case of significant discrepancies. These concern: the fuel pin total power normalised to its initial value (that practically, in our assumption of no decay heat, is the amplitude factor of point kinetics), the temperature distributions in the fuel channel at the equilibrium initial conditions, and time-dependent temperatures in a few representative positions.

Namely, it is requested to report the following set (common to all the requested transients) of initial steady state computed results:

1) Axial distribution of the fuel centreline temperature.

2) Axial distribution of the fuel surface temperature.

3) Axial distribution of the clad surface temperature.

4) Axial distribution of the coolant temperature.

It is also requested to report from time equal to 0 s to time equal to 26.001 s the following set of time-dependent calculation results relevant to each of the five proposed benchmarks:

1) Fuel pin total power normalised to its initial value.

2) Fuel centreline temperature at the fuel zone mid-plane (height = 45.0 cm).

3) Fuel surface temperature at the fuel zone mid-plane (height = 45.0 cm).

4) Coolant temperature at the top of the fuel channel (height = 90 cm).

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