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Heavy Reflector type EPR benchmarking

Anais Bresson¹, Michel Tommy-Martin¹, Isabelle Rupp², Faiza Sefta¹, Michal.Kostal³, Evzen.Losa³, Yuichi Mogami⁴, Yuta Takada⁴, Sylvie Ebalard⁵, Alix Janet⁵, Nicolas Chapoutier⁵, Cécile-Aline Gosmain¹

¹ EDF Lab Saclay, 7 blvd Gaspard Monge, 91120 Palaiseau

² EDF Lab Chatou, 6 Quai Watier, 78401 Chatou

³ Research Center Rez Ltd, Research Center Rez Ltd., 250 68 Husinec-Rez 130, Czech Republic

⁴ MHI, Japan, 1-1-1 Wadasakicho, Hyogo-ku, Kobe, Hyogo, 652-8585, Japan

⁵ FRAMATOME, Tour AREVA, 1, place Jean Millier, 92084 Paris la Défense cedex

Main authors : isabelle.rupp@edf.fr, cecile-aline.gosmain@edf.fr

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Abstract

As part of the EPR studies on the heavy reflector conducted by EDF, a neutronic and thermalhydraulic calculation benchmark was initiated between EDF (France), MHI (Japan) in the MAI (Material Ageing Institute) and CVR (Czech Rep.) and Framatome (formerly AREVA NP).

A previous similar benchmark between EDF and EPRI working with Westinghouse and Framatome had compared calculation results for a simplified PWR type internal structure¹. The analysis of the neutronic results in terms of calculated flux, dose and deposited energy showed that the methodologies were consistent despite some discrepancies in the neutronics results. Among the differences, the radial profiles of gamma heating were different with regard to the thickness of the component. This could have a significant effect for thicker components such as heavy reflectors. For the thermal hydraulics part, results showed a very good agreement in the case of an identical gamma heated field.

Given the large thickness of the EPR or WWER 1000 lower core internal component, the MAI project on Internals has examined more specifically the deposited energy profile and has set up a new benchmark based on a simplified heavy reflector geometry. Indeed, both Russian WWER 1000 and French EPR type of reactors have a heavy reflector and thus a substantial thickness of stainless steel. First of all, the objective for EDF, MHI, CVR and Framatome is to assess the neutronics loadings inside the vessel internals up to the vessel core. Then, using the same boundary conditions, EDF and MHI ran conjugate heat transfer calculations with their own numerical tools to determine the temperature of the internal structure. Two calculations have been performed, first with a common gamma heating rate and then with an in-house neutronic calculation. The objective of the first one was to evaluate the accuracy of the Computational Fluid Dynamics - Computational Heat Transfer (CFD-CHT). The second one has allowed an evaluation of the variation of the structure temperature induced by the gamma heating rate uncertainty. Thus, this work strengthens the complete participants' calculation chain from particle transport model to temperature evaluation inside the vessel.

The simplified geometry proposed for this benchmark seeks to combine both EPR and VVER1000 attributes. It has a double symmetry enabling the modelling of 1/4th of the heavy reflector and core barrel with three L-shaped assemblies. To cool down the structure, a flow goes up from the bottom to the top through 85 cooling holes. Flow rates, gamma heating rates and boundary conditions on the inner face of the baffle and outer face of the barrel are imposed.

The model, common to all participants, has enabled the comparison of a set of calculated values including neutron and gamma flux mainly in the thermal area of the spectrum, dose (in dpa) due to neutrons, gamma heating rates and finally, temperature of the structure and of the cooling fluid.

This paper presents comparison and first analysis of the participant's results.

¹ J Rashid, K. Kubischta, A Demma, T. Hardin, S. Anderson, F. Marx, T. McDonald, M. Snyder, D.Thomas, M. Tommy-Martin, I. Rupp, C. Pokor "Comparative Evaluation of Neutronics and Thermal Analysis Methodologies Utilized in the Functionality Analysis of Reactor Internals" – Fontevraud 8 2014.

1. Introduction

The Vessel Internals Project (2015-2019) of the Material Aging Institute has proposed a benchmark between EDF, MHI to compare neutronics and thermo-hydraulics simulations for heavy reflector component of WWER1000 or EPR designs. In 2016, Framatome and CVR (UJV group) have decided to join the benchmark.

A simplified geometry model with characteristics inspired by both WWER1000 and EPR designs has been proposed. The goal was to easily compare the same output results (neutron and gamma fluxes, DPA, gamma heating and temperature distribution in selected volumes) and to identify critical areas.

Since gamma heating energies calculated by neutronic codes are needed as input data by thermal-hydraulics codes, these two parts are chained.

The first part of the paper is devoted to the neutronics comparisons : all participants considered the same neutron and gamma sources as input and evaluated the score of interest including gamma heating energies. Those data were then considered in thermal-hydraulic calculations.

The second part is dedicated to CFD-CHT comparisons. In order to separate discrepancies due to neutronic from those due to thermal-hydraulic calculations, two different cases have been considered. In the first case, all participants used the gamma heating rates calculated by EDF while in the second case, the participants calculated their own gamma heating rates based on their own neutronic numerical tools (Figure 1).

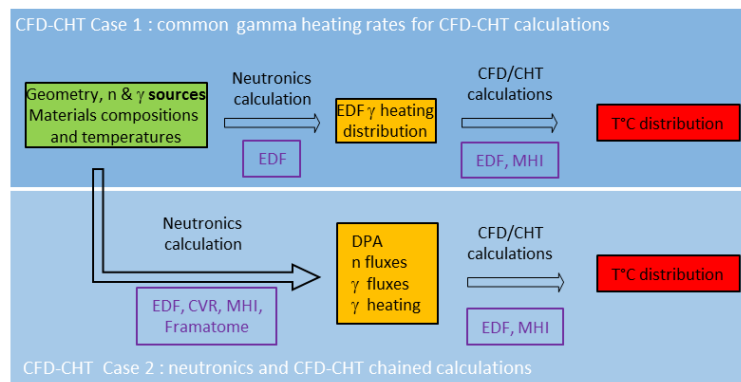


Figure 1 : Benchmark cases of calculations proposed

Neutronics calculations have been performed by all attendees, but only EDF and MHI have carried on the cases 1 and 2 up to the thermal hydraulic calculations.

The outputs of interest are :

- **gamma and neutron fluxes** (47 & 22 groups for γ , 200, 47 & 3 groups for neutrons) to compare the ability of the codes to transport particles in successive absorbing media (steel/water/steel) ;
- **neutron and gamma heating energies** (deposited energy to be used as input data for TH calculations) allowing the evaluation of **temperature distributions** needed for mechanic codes to establish materials law.
- **Dpa** (displacement per atom integrated over a year) which are used to evaluate material ageing properties of internals and RPV steels.

2. Benchmark model and input data

a. Neutronic calculations

Geometry : The geometry model considered in this benchmark is a one fourth symmetry hypothetical heavy reflector and core barrel with three L-shaped assemblies. The following figure shows axial and radial slices with mesh naming schemes and water temperature distribution. The heavy baffle is composed of stainless steel with 85 EPR type water holes of 1.3cm diameter and 2 WWER type water holes of 7 cm diameter. The dimensions of internals considered in this model are similar to EPR reactor ones and are shown in Figure 2. The z axis origin is located at midplan of the baffle and assemblies.

Material composition : Baffle and barrel are composed of stainless steel (304) with a density of 7.85g/cm³, vessel of steel with a density of 7.80g/cm³, UO₂ fuel at 3.7% initial enrichment and a density of 10.41g/cm³, cladding in Zircaloy-4 with a density of 6.544g/cm³ and water with a density that varies from 0.7510g/cm³ at 560K to 0.6798g/cm³ at 593K. The boron concentration is fixed at 500ppm as a constant value.

Material properties

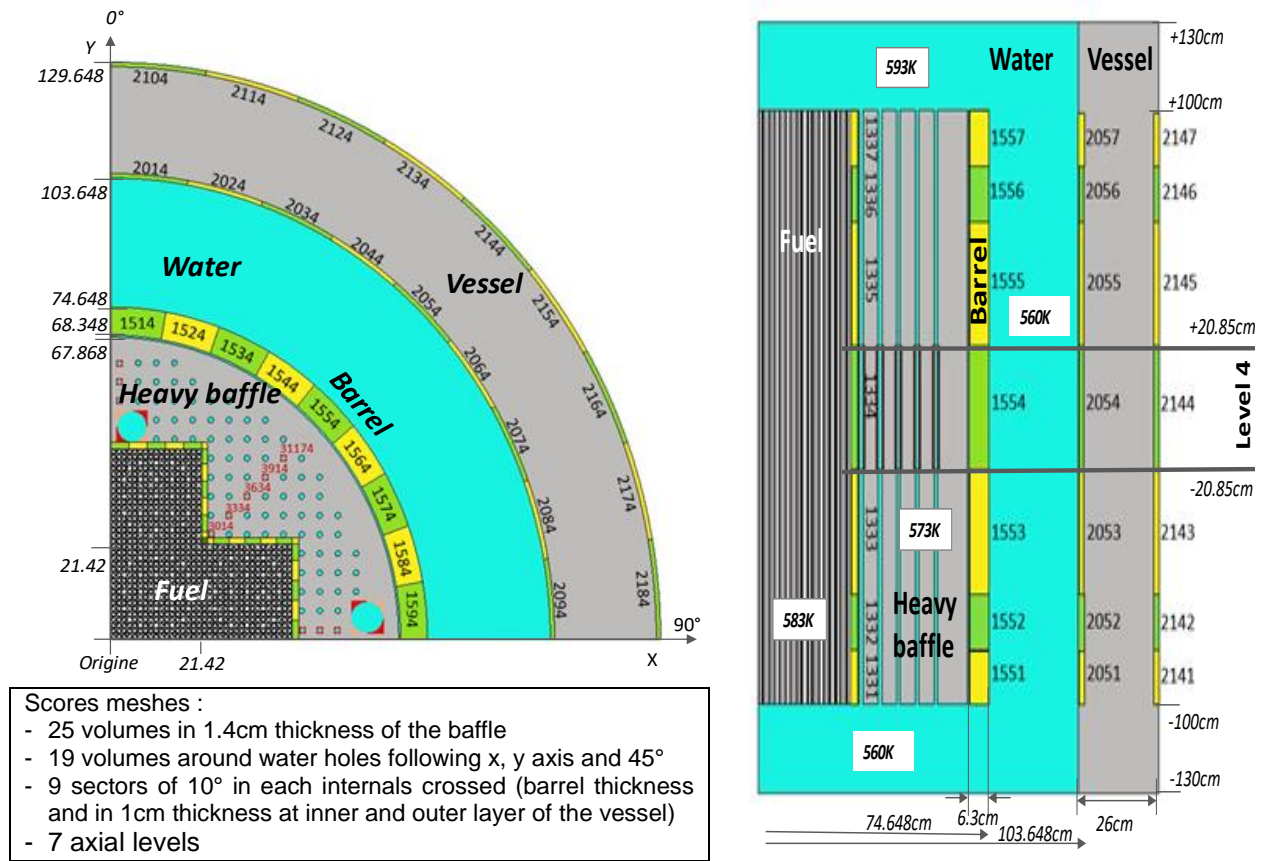


Figure 2 : Geometric configuration of the benchmark problem – Left : radial slice, Right : Axial slice with mesh naming schemes and water temperature distribution

Source term and power input conditions : The pin-by-pin radial power distribution, axial power distribution, isotopic fission fractions, isotopic energy released per fission, and isotopic neutrons emitted per fission were provided by EDF. The fission spectrum by isotope was determined with a Watt Function as depicted in the Figure 3, which also describes the core power distribution: assembly power ratio, the average power per assembly, and the average core power. The gamma spectra are depicted in Figure 4, and the evolution of fission ratios with burnup are shown in Table 1. Pin power factors were also specified for the three assemblies.

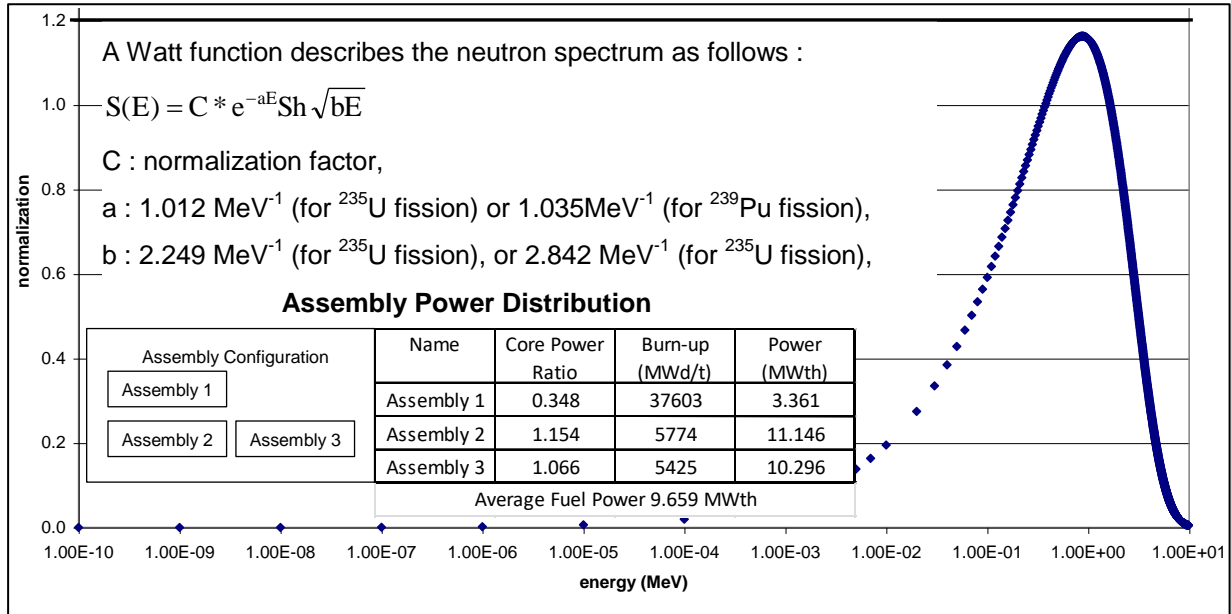


Figure 3 : Fission Spectra and Core Power Distribution

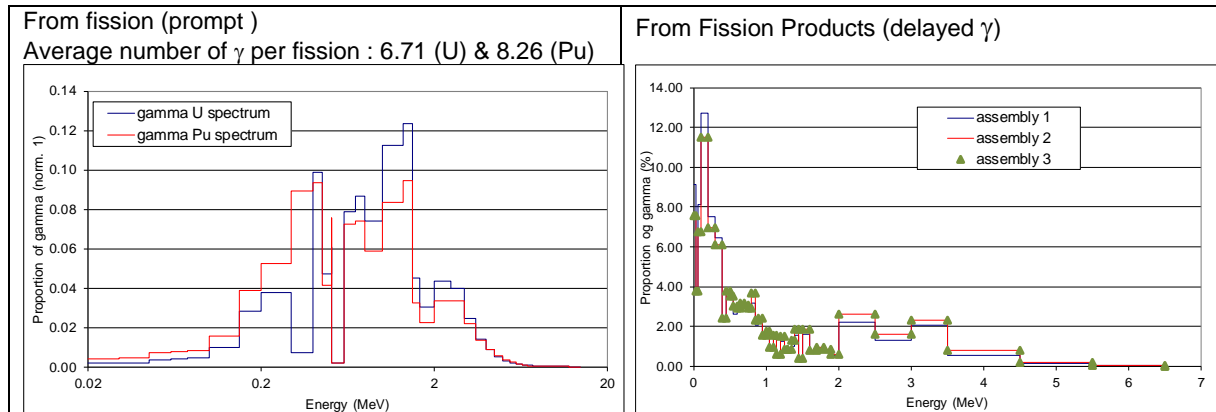


Figure 4 : Gamma Spectra

Table 1 : Fission fractions

assembly	burnup (MWd/t)	fission fractions (norm. 1)			
		U235	U238	Pu239	Pu241
1	37603	0.3317	0.0847	0.4563	0.1273
2	5774	0.7796	0.0666	0.1489	0.0048
3	5425	0.7879	0.0664	0.1415	0.0042

b. Thermal hydraulics and heat transfer calculations

Geometry used for CFD-CHT analysis consists in a hypothetical heavy reflector and fluid flow through the tubes (Figure 5). Dimensions are those used for the neutronic part (Figure 2).

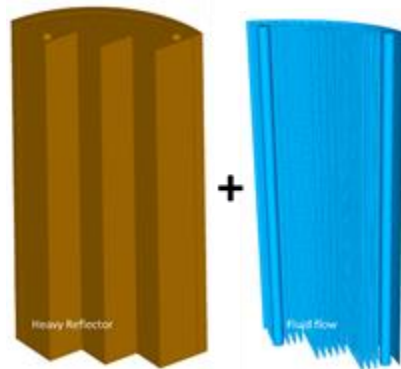


Figure 5 : Structural and fluid geometries for CFD-CHT analysis

Steel physical properties are function of the temperature (in °C) :

- Density x specific heat capacity ($J.m^{-3}/^{\circ}C$) $\rho C_p = (4.146 + 0.0002468 T + 8.908 \cdot 10^{-7} T^2) \cdot 10^6$
- Thermal conductivity ($W/m/^{\circ}C$) $\lambda = 15.64 + 0.0069 T + 10^{-5} T^2$

Values of fluid physical properties are those of water at a pressure of 155 bars and temperature of 294 °C :

- Density : $\rho = 739 \text{ kg.m}^{-3}$
- Specific Heat Capacity : $C_p = 5330 \text{ J/kg/K}$
- Thermal conductivity : $\lambda = 0.57 \text{ W/m/K}$
- Dynamic viscosity : $\mu = 9.09 \cdot 10^{-5} \text{ Pa.s}$

Boundary conditions are summarized in Figure 6. The surface at the upper core plate is assumed adiabatic. Heat transfer coefficients of other surfaces are determined by Computational Fluid Dynamics and Computational Heat Transfer (CFD/CHT) analysis.

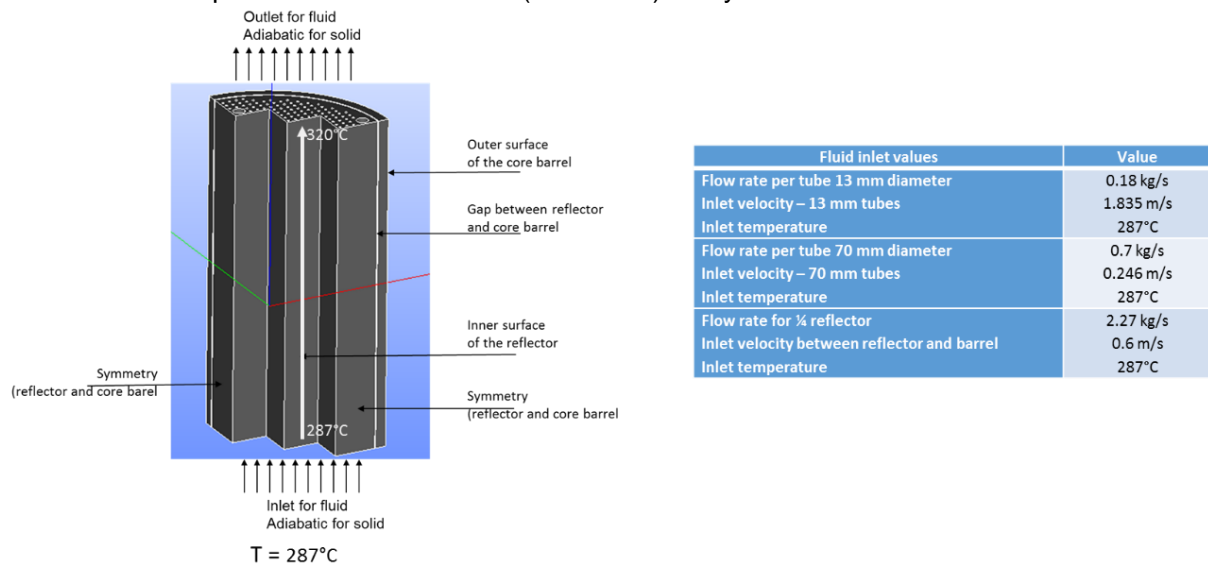


Figure 6 : Boundary conditions for CFD-CHT analysis

For the case 1 an additional input data is required : the common gamma heating deposit (Figure 12).

3. Methodologies

a. Neutronic calculations

Each participant has used its own methodology based on deterministic or stochastic codes and associated libraries for particles propagation and dpa calculations. Table 2 summarizes the tools used for neutronic calculations.

Table 2 : Methodologies and tools used in function of participant

Participants	Codes and version	Libraries ²	Libraries for DPA	Gamma heating conversion factor
EDF	TRIPOLI-4.10	JEFF3.1.2	IRDF-2002	KERMA ³ 2 separate calculations : - Fission and FP γ transport - n coupled with (n, γ) transport
CVR	MNCP6.1	ENDF B-VII.0		
FRAMATOME	MCNP5.1.60	ENDF/B-VII.1	ENDF/B-VII.1 IRDF-2002	
MHI	DORT ⁴	BUGLE-96 ⁵	ASTM-E693	NISTIR 5632

As indicated, only MHI uses a deterministic code. EDF, Framatome and CVR use stochastic codes with punctual libraries. It must be underlined that each participant has taken water temperature into account following its own methodology. Likewise each participant has considered or not variance reduction techniques.

FRAMATOME methodology : Dedicated and independent calculations are performed with MCNP5.1.60 code associated to ENDF/B-VII.1 library (provided by LANL) for each score in each scoring volume. This implies the use of variance reduction techniques only when necessary (initiated by a deterministic calculation via the CADIS methodology).

CVR methodology : CVR uses MCNP6.1 transport code associated to a reprocessed at given temperatures ENDF/B-VII.0 library. Source biasing and geometry splitting with Russian roulette variance reduction techniques is considered in their calculations.

EDF methodology : CEA transport code TRIPOLI4.10 is associated to JEFF3.1.2 library also provided by CEA. Energy and spatial meshes with automatic determination of biasing parameters are considered in EDF calculations with a detector located on the external surface of the vessel.

MHI methodology : DORT is used to calculate a two-dimensional radial flux in terms of (r, θ), and a two-dimensional axial flux in terms of (r, z); a three-dimensional solution was synthesized from the two, two-dimensional solutions. DORT calculations used BUGLE-96 as the cross-section library. BUGLE-96 library was generated from the nuclear data, ENDF/B-VI, and has a 47-neutron and 20-gamma group structure.

c. Thermal hydraulics and heat transfer calculations

EDF methodology : Conjugate heat transfer using CFD code *Code_Saturne* and thermal code SYRTHES is used. *Code_Saturne* is based on finite volumes method and SYRTHES on finite elements method. Local heat transfer coefficients between fluid and solid are calculated by the CFD code.

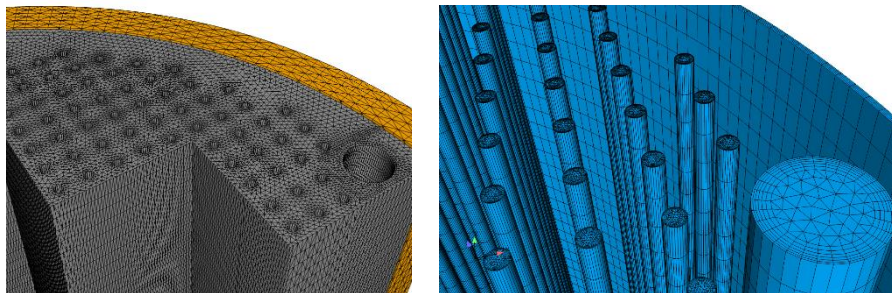


Figure 7 : EDF model – Structure : 4 million tetrahedra – Fluid 2 million hexahedra and prisms

MHI methodology : Calculation is performed by ABAQUS using a finite elements model for the structure and a 1D forced convection elements for the fluid flow. A Petukov's correlation equation is used to determine heat transfer coefficients between fluid and solid : 2000 W/M²K for 7mm diameter tubes, 14000 W/M²K for 13mm diameter tubes and 6000 W/M²K for the gap between reflector and barrel.

² Each participant is responsible for the library considered and the way it had been processed.

³ KERMA : Kinetics Energy Release in MAtter

⁴ Maximum order of scattering P3 -Maximum number of direction quadrature S8

⁵ BUGLE-96 is a multigroup library based on ENDF/B-VI punctual data

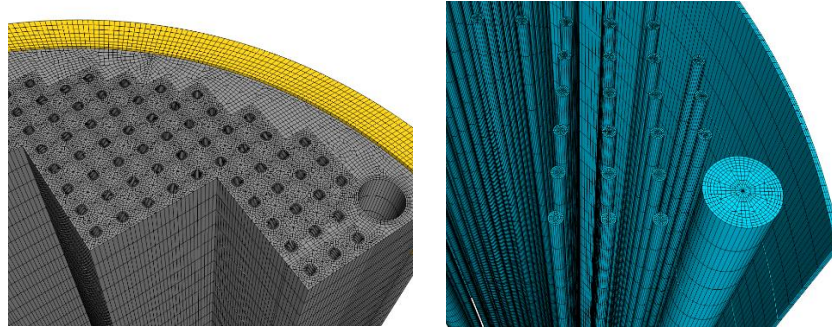


Figure 8 : MHI model – 1.1 million elements

4. Results

a. Neutronic results

Due to a large amount of scoring volumes defined, the authors have chosen to focus on the comparison of all participants' results in internals (baffle and barrel) and at mid plan of the core. Statistical errors associated to stochastic values are inferior to 1% (at 1σ) whatever the code considered. Since this benchmark is based on a hypothetical simplified model, the results couldn't be compared to reference measurements. To analyze the simulation results it was therefore necessary to choose an arbitrary reference which for this paper will be EDF TRIPOLI4.10/JEFF3.1.2 results

Total neutron flux : Figure 9 presents the deviation of total neutron flux to the chosen reference.

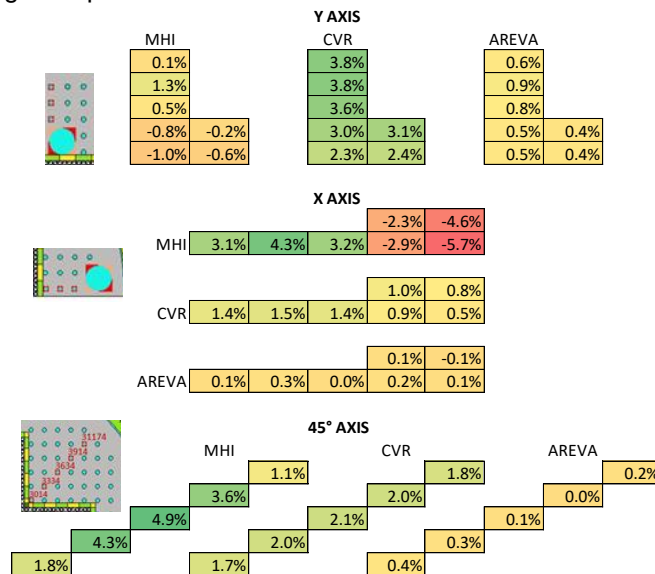


Figure 9 : Total neutron flux – deviation to EDF results (at the inner layer of the baffle on the left – at the barrel on the right – surrounding water holes in the baffle below)

One can notice the good agreement between participants' results on total neutron flux with low discrepancies at the inner layer of the baffle and in volumes surrounding water holes in the baffle ($< \pm 4\%$) and far below 20% at the barrel. The higher deviation at the barrel is observed with MHI results obtained with a deterministic method (between -5 and -11%) when discrepancies between stochastic methods are limited to 3%.

DPA : Depicted below the deviation of participants' dpa results to EDF results considered as reference. At inner layer of the baffle, a good agreement on DPA score ($< 10\%$) between participants' results is observed although different dpa response functions are considered. At the barrel, discrepancies are lower than 20% and reduced to 10% when FRAMATOME considers the same IRDF2002 response functions as EDF and CVR instead of the continuous-energy damage cross section from ENDFB7.1 for iron. Having similar DPA evaluation while using the same response function is consistent with the fact that the neutron flux were in a good agreement on the barrel. The larger discrepancy is then obtained

with MHI dpa results, since a deviation between CVR, FRAMATOME and EDF results is maintained lower to $\pm 2\%$.

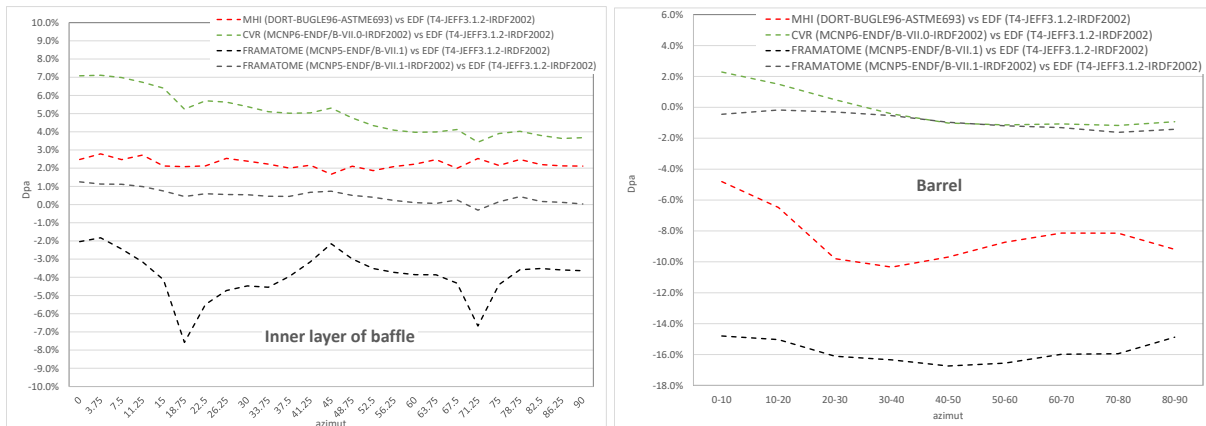


Figure 10 : DPA – deviation to EDF results (at the inner layer of the baffle on the left – at the barrel on the right)

Deposited Energy :

Figure 11 presents deviation of participants' deposited energy calculations to EDF results. One can notice discrepancies below 20% and a tendency of EDF results to underestimate deposited energy whatever the scoring volume considered. The highest discrepancies are observed with MHI results at inner layer of the baffle (around 15%) and tend to decrease when crossing the heavy thickness of the barrel to be limited to less than 10% at the barrel. Stochastic based results are consistent with deviation largely inferior to 10% from the inner layer of the baffle to the barrel.

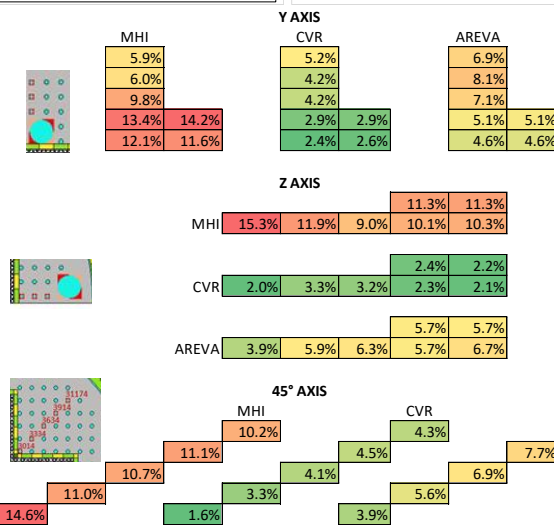
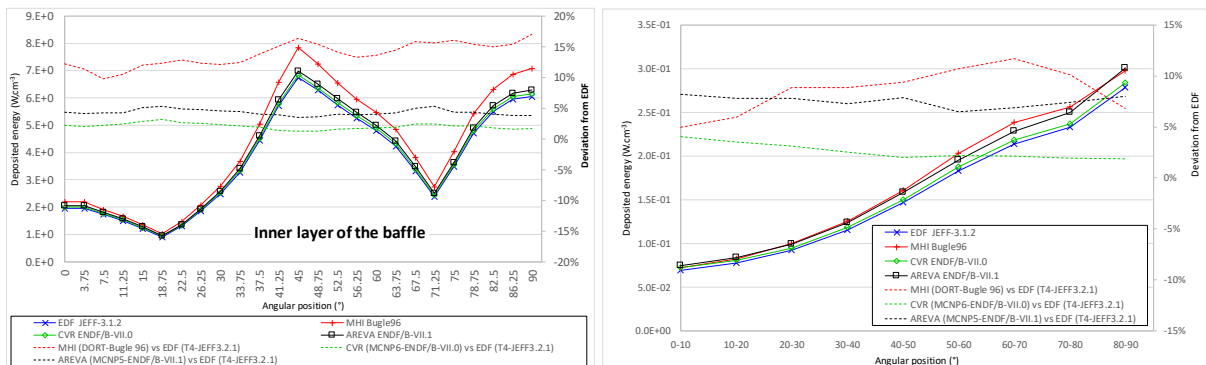


Figure 11 : Deposited energy – deviation to EDF results (at the inner layer of the baffle on the left – at the barrel on the right – surrounding water holes in the baffle below)

Conclusion of neutronics calculations

The results of this benchmark implying an EPR like heavy baffle confirm the consistent trends observed during the previous benchmark, [ref. 1], with noticeable lower deviations (systematically inferior to 20%) on total neutron fluxes, dpa and deposited energies at the inner layer of the baffle, around water holes and at the barrel. The major discrepancies are observed with the MHI deterministic methodology calculations (up to 15% on deposited energy) when the highest deviations between stochastic codes calculations are limited to less than 10% (when considered the IRDF2002 response function for dpa scores).

Several iterations between participants on assumptions and input data may explain the noticeable improvement of discrepancies compared to the previous benchmark.

b. Thermal results – Case 1

Only MHI and EDF achieved the CFD-CHT calculation for this case. We remind that for that case, gamma heating rates are the same both for MHI and EDF. The aim is to compare CFD-CHT methodologies and results independently from neutronics uncertainties.

To facilitate the use of input data files for the participants, EDF has set the deposited energy field on a regular grid (Figure 12, middle frame).

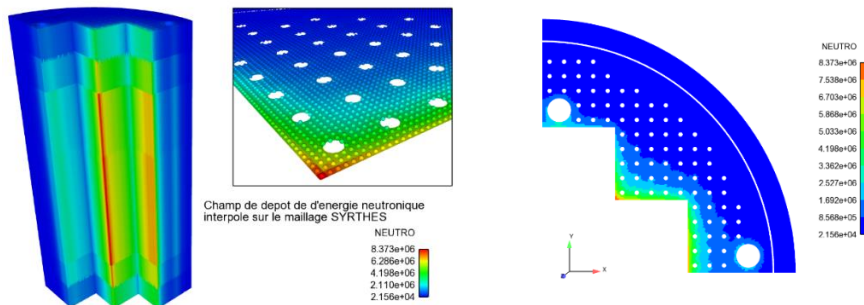


Figure 12 : Gamma heating rates used as input data by both MHI and EDF (on the right : middle plane z=0)

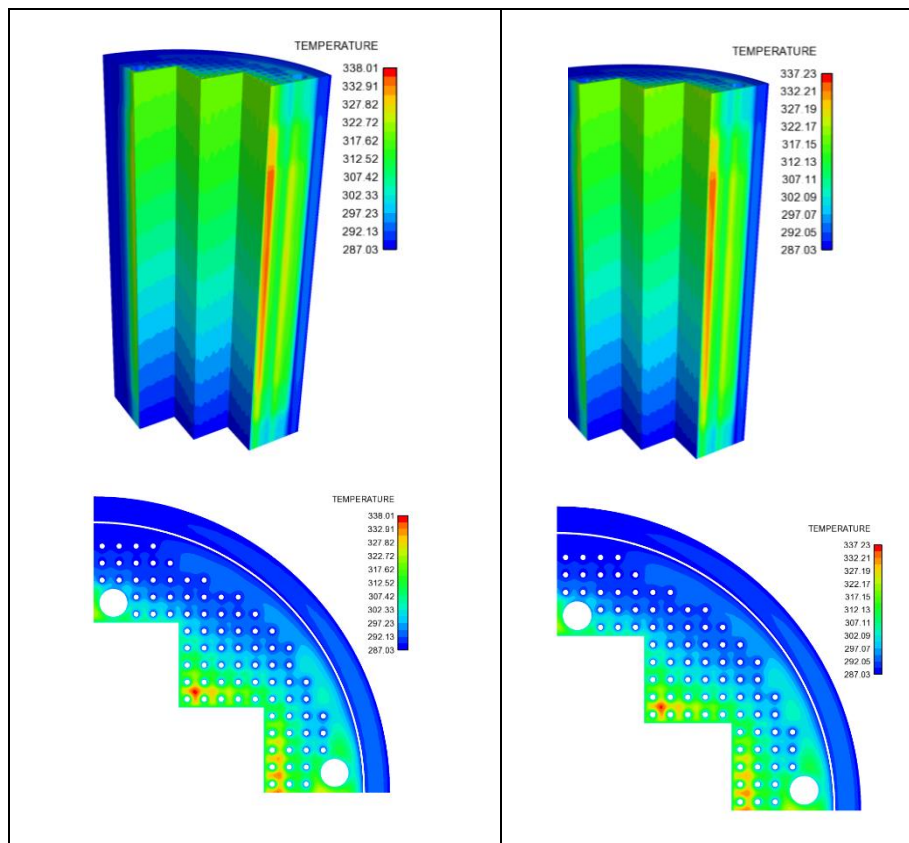


Figure 13 : Temperature in the structure (3D and mid plane z=0) - Left : EDF, right : MHI

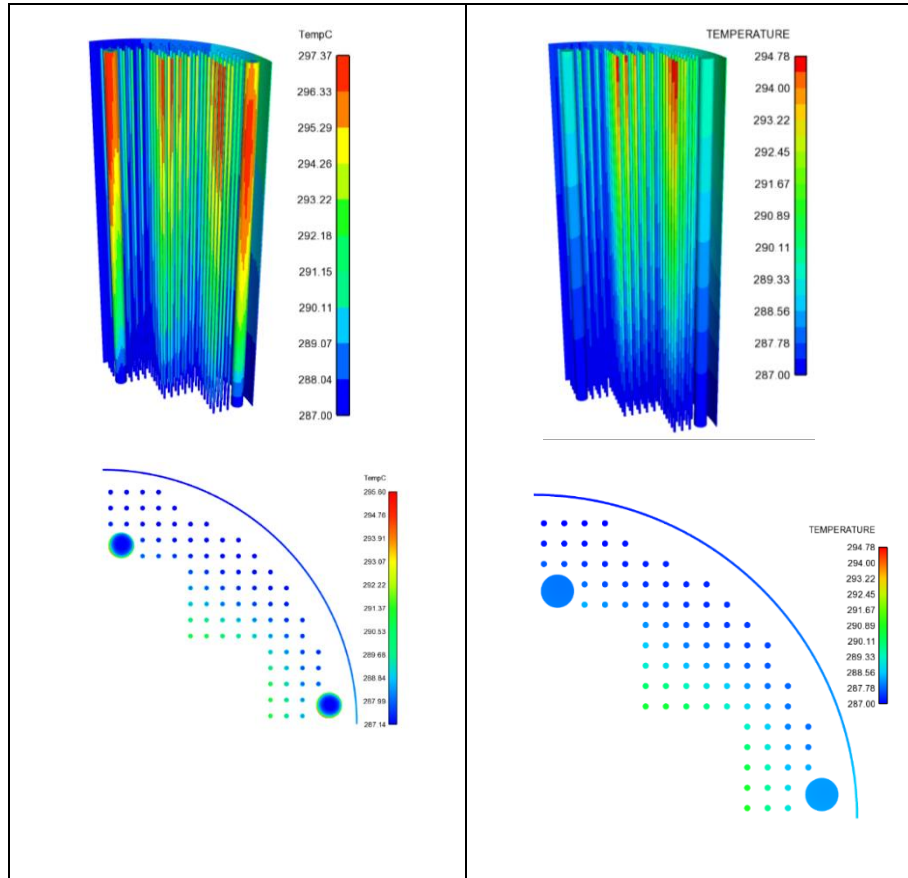


Figure 14 : Temperature in the fluid – (3D and mid plane z=0) - Left : EDF, right : MHI

Conclusion for the case 1

Even if methodologies for fluid and solid coupling are different between EDF and MHI, good agreement is found for temperatures in the structure (Figure 13). Temperature fields are very similar and results show a difference less than 1°C for the maximum temperature in the structure.

Using conjugate heat transfer between fluid and solid, fluid temperature is more detailed in the EDF calculation but correlations used by MHI are well adapted and finally both methodologies for heat exchange lead to a good representation of the impact of the cooling tubes on the structure temperature. The temperature difference in the fluid is less than 3°C (Figure 14). In fact, for the temperature in the structure, the major factors in the simulation are the gamma heating rates, which are identical in this case 1.

c. Thermal results – Case 2

Only MHI and EDF achieved the CFD-CHT calculation for this case. We remind that for that case, using common neutron and gamma sources, both MHI and EDF performed all the steps of the simulation, from gamma heating rates calculation to CFD-CHT calculation. The aim is to compare thermal results and specifically the effect of variations of the gamma heating field on the temperature.

Using a new version of neutronics libraries and following its traditional methodology (ie. working with deposited energy by volume), EDF calculated new gamma heating rates. For its part, MHI used its own softwares to calculate the deposited energy. Both are presented in Figure 15.

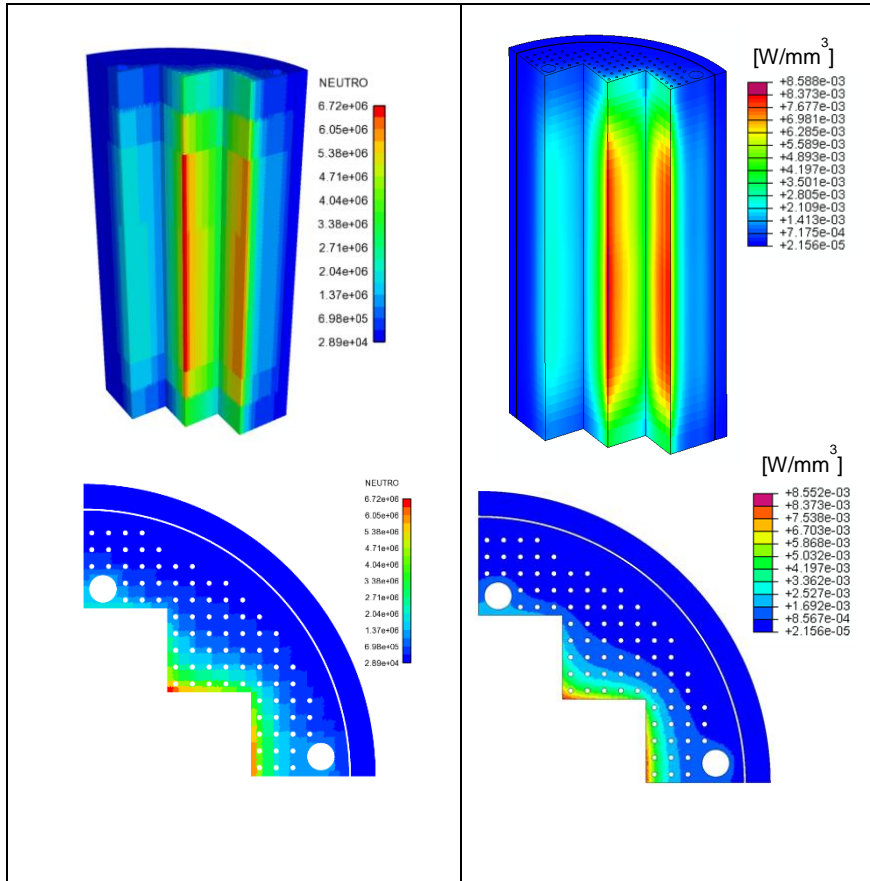


Figure 15 : Gamma heating rates - Left : EDF (W/m³) , right : MHI (W/mm³)

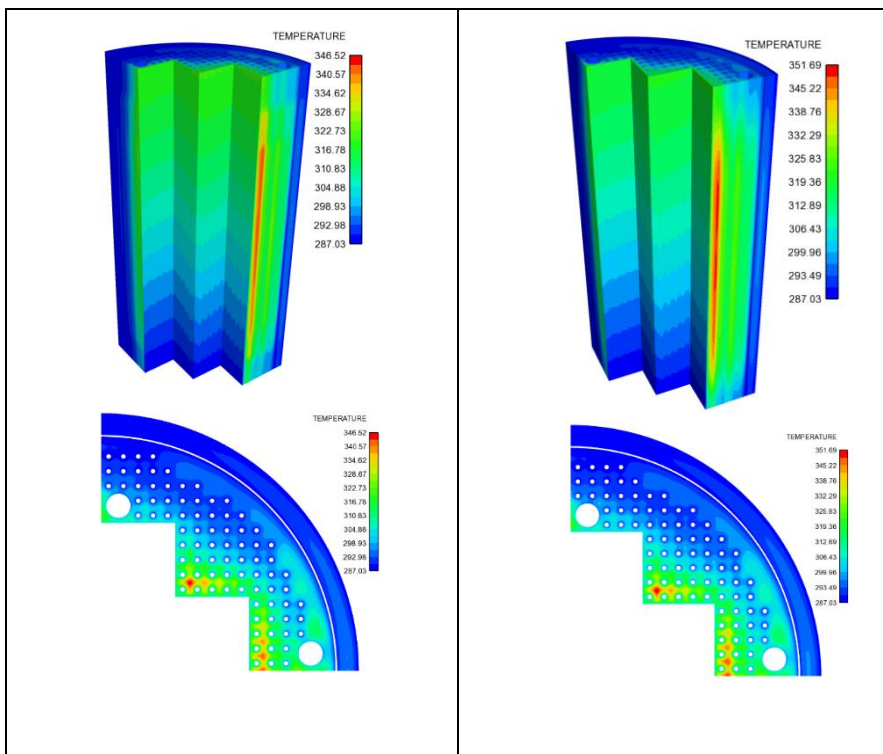


Figure 16 : Temperature in structure (3D and mid plane) - Left : EDF, right : MHI

Conclusion of the case 2

When EDF and MHI used their own gamma heating fields, results for the CFD-CHT calculations vary more : discrepancies between maximum temperature in the structure reached 5°C (346.5°C for EDF and 351.7°C for MHI). As the methodology has been validated by the case 1, it shows that temperatures in the structure are directly correlated to the deposited energy. Moreover, some other studies showed that it exists a linear correlation between gamma heating rates and temperature when not being close from boundary conditions.

Then, considering that neutronics calculations have shown some discrepancies in the deposited energy around 10% between EDF and MHI (Figure 11), and that temperature increase is around 40.5°C in EDF's calculation, we can give an evaluation of discrepancies on thermal field around 4°C; which is confirmed by MHI's calculation.

It has to be noticed that the final discrepancy between EDF and MHI final maximum temperature is quite reasonable in the context of material damage evaluation.

Conclusion of thermal calculations

This benchmark validates the approaches used both by EDF and MHI concerning CFD-CHT calculations for heavy reflector type geometry. It shows also the impact of neutronics uncertainties on the structural temperature field. Maximum temperature in the structure is directly influenced by the deposited energy level and we have to be particularly careful when considering uncertainties around neutronics calculations.

References

- [ref. 1] J Rashid, K. Kubischta, A Demma, T. Hardin, S. Anderson, F. Marx, T. McDonald, M. Snyder, D.Thomas, M. Tommy-Martin, I. Rupp, C. Pokor "Comparative Evaluation of Neutronics and Thermal Analysis Methodologies Utilized in the Functionality Analysis of Reactor Internals" – Fontevraud 8 2014.