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The Characteristics Method Applied to a MTR Whole Core Modeling

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The Jules Horowitz Reactor (JHR) is the future European Material Testing Reactor dedicated to technological irradiations. In order to guarantee a high level of performance of this MTR, the margins have to be evaluated with a great confidence as well as the flux and the nuclear heating inside the experimental devices placed in the core and in the reflector.

Therefore, the Nuclear Energy Division has developed a new calculation scheme based on a flux solver using the method of characteristics which has been recently implemented in the APOLLO2 transport code. This paper presents the validation of this calculation scheme in comparison with reference Monte Carlo results. The core geometry is described in detail. The XMAS 172-group library with P3 scattering was applied and lead to an excellent result agreement with an acceptable computation time.

KEYWORDS: Characteristics method, APOLLO2, Material Testing Reactor, calculation scheme

1. Introduction

The Jules Horowitz Reactor [1] is the future European Material Testing Reactor dedicated to technological irradiations. Due to its specific features a neutronics and thermalhydraulics simulation package named HORUS3D [2,3] (Horowitz Reactor simulation Unified System) has been developed to model the JHR core. HORUS3D/N (which corresponds to the neutronics part) is based on the APOLLO2 [4] and CRONOS2 [5] codes.

In order to estimate precisely the neutron flux (and then the nuclear heating) inside the devices, we need to develop a new calculation scheme. In most cases, the diffusion approximation is usually used to compute neutronics parameters (such as flux or reaction rates) on a 3D or 2D core with homogeneous regions. Unfortunately, we cannot get these parameters locally on each assembly with a fine precision. For that reason, we turned to the APOLLO2 transport code. This code recently offers a new flux solver based on the method of characteristics [6] using a general description of the geometry. This new method is interesting for several reasons:

- It allows us to describe exactly any type of geometry (like the complex JHR assemblies) via the graphical program SILENE. [7]
- With this method, we can also take into account any order of anisotropy. This feature is important to precisely compute the irradiation devices, in particular those placed in reflector.
- In addition, the APOLLO2 code allows us to perform depletion calculations.
- This is a very fast transport method in comparison with other flux solvers.

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Therefore this method is particularly adapted to model the JHR irradiation devices in a 2D core with a great confidence.

This paper presents the validation of this calculation scheme in comparison with reference Monte Carlo results.

2. JHR description

The reference JHR core configuration (Fig. 1) is composed of 46 assemblies arranged in a triangular lattice inside a rectangular aluminium matrix. Beryllium reflectors are found on two sides. The other two sides are left free in order to introduce mobile irradiation devices.

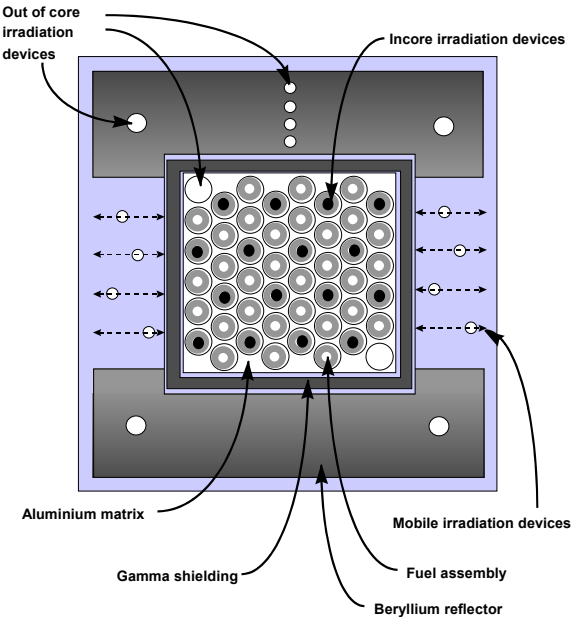


Fig. 1 : Cross-section of the JHR core

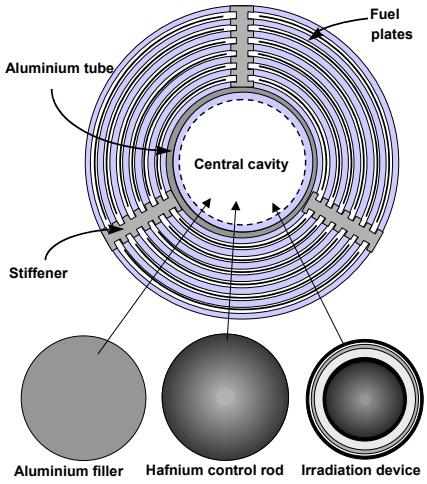


Fig. 2 : Cross-section of the JHR assembly

The JHR assembly (Fig.2) is composed of 3 groups of 6 cylindrical fuel plates maintained by 3 stiffeners. The fuel is composed of a dispersion of UMo powder in an aluminium matrix with an Uranium-235 enrichment less than 20%. The central cavity can host either an aluminium filler, a hafnium control rod or an irradiation test device.

3. APOLLO2 calculation scheme of the JHR devices

In this paragraph we will briefly describe the method of characteristics (MOC) as well as the main features of the APOLLO2 calculation scheme of the JHR experimental devices.

3.1 Method of characteristics

The MOC for unstructured meshes applies the discrete ordinate approximation to obtain a numerical iterative solution of the one group transport equation in a geometrical domain D of boundary ∂D:

$$\left.\begin{aligned} &(\Omega.\nabla + \Sigma)\psi^{(n)} = q, \quad x \in X, \\ &\psi^{(n)} = \beta\psi^{(n-1)} + \psi_0, \quad x \in \partial\_X, \end{aligned}\right\} \qquad (1)$$

where n denotes the iteration index, x=(r,Ω) stands for a generic point in phase space

$X = \{x; r \in D, \Omega \in (4\pi)\}$, Σ is the total cross section and

$$q = H\psi + S \tag{2}$$

is the emission density, where $(H\psi)(x) = \int_{(4\pi)} d\Omega' \Sigma_s(r, \Omega \cdot \Omega')\psi(r, \Omega')$ is the scattering operator, S the external source and ψ_0 an entering boundary flux.

In the method of characteristics the discrete ordinates scheme is used for the angular approximation, so that each integration over the angular variable is calculated as:

$$S_N = \{w_n, \Omega_n, n = 1, N\} \Rightarrow \frac{1}{4\pi} \int_{(4\pi)} f(\Omega) d\Omega \approx \sum_n w_n f(\Omega_n), \tag{3}$$

where w_n is the angular weight associated to direction Ω**.** In the classic Step Characteristics (SC) method the geometrical domain D is decomposed into a set of homogeneous regions $\{D_i, i = 1, N_{reg}\}$ on which we use the flat source approximation. As it is shown for example in [10] we can give the following representation to the collision term:

$$q(x) = \sum_i \theta_i(r) q_i(\Omega) = \sum_i \theta_i(r) \vec{A}(\Omega).\overrightarrow{q_i}, x \in X, \tag{4}$$

where θ_i is the characteristics function of homogeneous region D_i, $\vec{A}(\Omega)$ is a vector of spherical harmonics and

$$\vec{q}_i = \Sigma_{si} \vec{\phi}_i + \vec{S}_i \tag{4a}$$

is the average value of the emission density in region i. Here, Σ_{si} and $\vec{\phi}_i$ are, respectively, the scattering matrix and the vector of angular flux moments. In a multigroup setting, the external source S accounts for fissions and scattering from the other groups.

A set of parallel numerical trajectories is constructed for each angular direction in the angular quadrature formula (3) and an iterative solution of the transport equation is then obtained from boundary flux values by direct integration along each numerical trajectory. Over one of these trajectories, the flux can be expressed as:

$$\psi(x, \Omega) = e^{-\tau(x_{in}, x)} \psi(x_{in}, \Omega) + \int_{x_{in}}^{x} e^{-\tau(x', x)} q(x', \Omega) dx', \tag{5}$$

where x indicates the position along the trajectory, x_{in} is the entering point of the trajectory in the domain and $\tau(x', x)$ is the optical distance along the trajectory between point x and x'. In the SC method, equation (5) can be directly integrated, thanks to the flat source approximation, to give:

$$\psi_{out,i}^{(n)}(t) = e^{-\Sigma_i R_i(t)} \psi_{in,i}^{(n)}(t) + \underbrace{\frac{1 - e^{-\Sigma_i R_i(t)}}{\Sigma_i}}_{\beta(R_i)} q_i^{(n-1)}(\Omega), \tag{6}$$

where $R_i(t)$ is the length of the trajectory within the region i and Ω is the direction of trajectory t. Moreover $\psi_{out,,i}(t)$ and $\psi_{in,,i}(t)$ are respectively the fluxes exiting and entering region i along trajectory t. This equation is used to compute iteratively the angular flux across the cells along each trajectory.

The updating of the flux moments is made via the angular flux:

$$\vec{\phi}_i^{(n)} = \sum_n w_n \vec{A}(\Omega_n)\psi_i^{(n)}(\Omega_n),$$

where $\psi_i^{(n)}(\Omega_n)$ are the cell mean angular fluxes that are defined by the cell balance equation:

$$\Sigma_i \psi_i^{(n)}(\Omega_n) = q_i^{(n-1)}(\Omega_n) - \frac{1}{V_i} \sum_{t//\Omega, t\cap i} w_\perp(t)\left[\psi_{out,i}^{(n)} - \psi_{in,i}^{(n)}(t)\right]. \qquad (7)$$

Here V_i is the volume of the cell and the sum in t is done for all trajectories with direction Ω that intersect cell i. The $w_\perp$ is the spatial integration weight, geometrically representing the area affected to the trajectory. We avoid, in this brief discussion, to discuss the treatment of boundary conditions that can be found in [11].

3.2 Calculation scheme

The purpose of this study is to calculate with a high level of precision the experimental devices into the JHR core by using the APOLLO2 code and the method of characteristics.

For that reason, we used as few simplifications as possible. Here are the main features of the calculation scheme:

- A completely detailed geometry has been used without any spatial homogeneization:

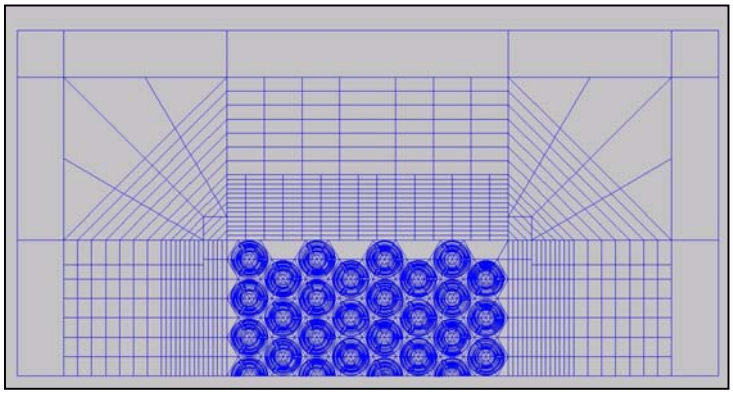


Fig. 3 APOLLO2 detailed core geometry

We defined a half core where each fuel assembly is completely described (the symmetry has been added to reduce the calculation time for the tests). This core geometry involves about 8000 meshes. In this configuration (Fig. 3), we placed in the middle of the core a fuel assembly containing an irradiation device.

- The APOLLO2 calculations are performed with the 172-group library. [9]
- The self-shielding calculation on heavy resonant isotopes is first carried out on a simplified assembly geometry (1D cylindrical assembly). The self-shielded cross sections are then redistributed for each assembly inside the core.
- The MOC integration parameters have been chosen in order to obtain accurate results (Δr=spacing between parallel trajectories=0.05 cm, N_φ=number of angles in $(0,\pi)$=12, N_ψ=number of polar directions=3).

The validation of this APOLLO2 calculation scheme is based on comparisons with the Monte Carlo code TRIPOLI4. [8]

4. Validation

Two configurations have been considered to validate the calculation scheme: a first

validation on an assembly and a global validation on the core.

4.1 Reference calculation

The reference calculations were performed with the Monte Carlo code TRIPOLI4 without any simplifications. All geometry details have been represented and pointwise cross sections have been used. One hundred millions of neutrons are simulated in order to get small statistical uncertainties.

4.2 Validation on an assembly containing a CHOUCA experimental device

The geometry of a JHR assembly containing a CHOUCA irradiation device is as follows:

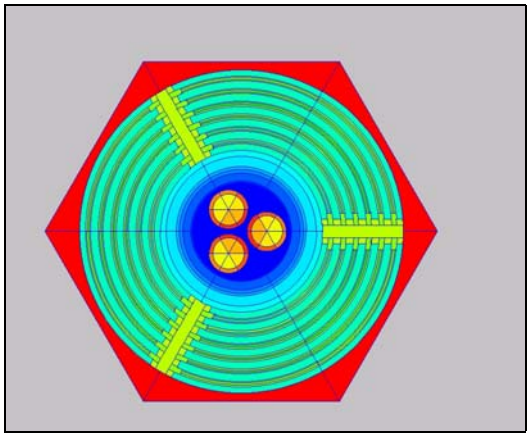


Fig. 4 APOLLO2 assembly geometry (CHOUCA)

The central cavity is composed of three steel cylindrical devices cooled by a NaK solution. For the calculation, each device is split into three sectors.

In order to avoid compensation effects, the results are compared not only on the multiplication factor k_∞ but also on the well-known 6-factor formula ($k_\infty = \chi_{n,2n} \times \varepsilon_{even} \times \varepsilon_{odd} \times p \times f \times \eta$) composed of the (n,2n) factor $\chi_{n,2n}$, the fast fission factor ε_{even}, the odd fast fission factor ε_{odd}, the resonance escape probability p, the thermal utilization factor f and the thermal fission factor η.

We also add the comparison of the flux in the cylindrical devices for each sector as integrated on a 2-group energy mesh. Finally, in our tables, we show also the results obtained with the collision probability method (P_{ij}) with HORUS3D/N.

Results obtained with APOLLO2 and TRIPOLI4 calculations are summarized in Tables 1 and 2:

	APOLLO2 (MOC)	APOLLO2 (exact 2D P_{ij})
K_∞	131	110
$\chi_{n,2n}$	8	7
ε_{even}	-12	-13
ε_{odd}	-36	-38
p	-122	-117
f	302	279
η	-2	-2

Table 1 APOLLO2 6 factor discrepancies (in pcm) with TRIPOLI4 results

Experimental devices		APOLLO2 (MOC)	APOLLO2 (exact 2D P_{ij})
Sector #1	Fast group	0.1	0.1
	Thermal group	-1.6	-1.8
Sector #2	Fast group	0.1	0.1
	Thermal group	-1.2	-1.5
Sector #3	Fast group	0.4	0.5
	Thermal group	-1	-1.4

Table 2 APOLLO2 flux discrepancies (in %) with TRIPOLI4 results

The TRIPOLI4 simulation uncertainties of all the results do not exceed 0.2%.

We can clearly observe the very satisfactory results obtained with MOC in comparison with TRIPOLI4. The multiplication factor is calculated with MOC with a discrepancy of about 130 pcm and the relative discrepancies on the device flux are less than 1.6%. We can also notice that both "exact 2D P_{ij}" and MOC results are very close.

In terms of CPU time, the MOC calculation of this JHR assembly is about 3 times faster than the "exact 2D P_{ij}". This feature is very interesting for depletion calculations.

4.3 Validation on a 2D JHR core

The APOLLO2 calculation scheme described in paragraph 3.2 was then applied to the JHR core. The results have been compared on the absorption rate, as integrated on the 2-group energy mesh and homogenized on the following regions: the fuel assemblies, one sixth of assembly near the assembly containing experimental devices and the three sectors of the cylindrical devices. The comparison of the APOLLO2 results with the TRIPOLI4 reference is presented in the following tables:

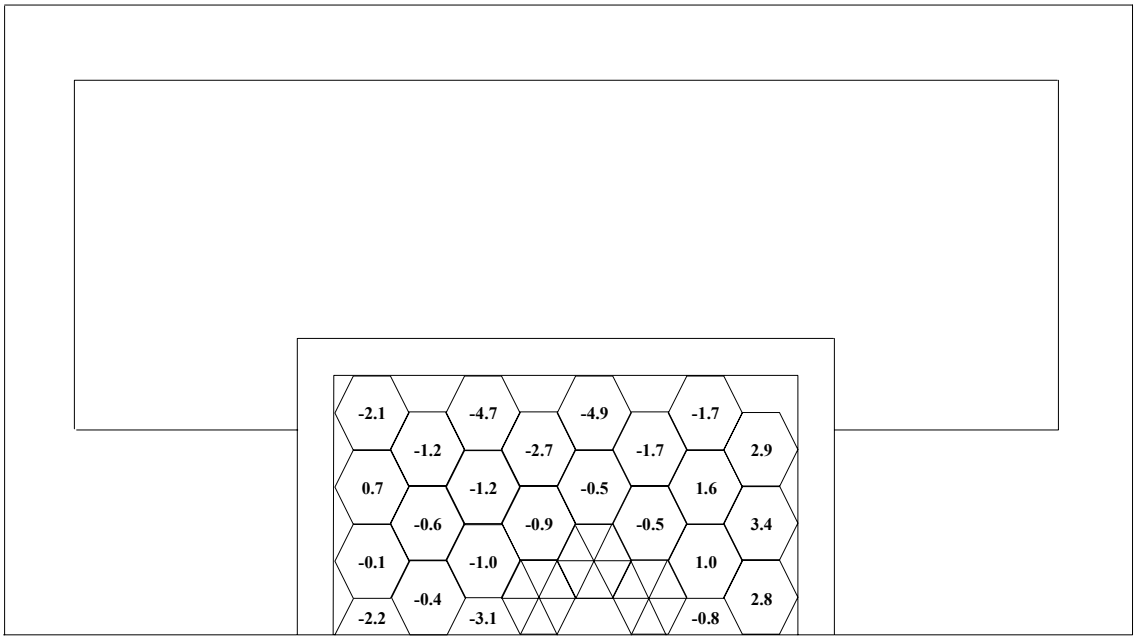
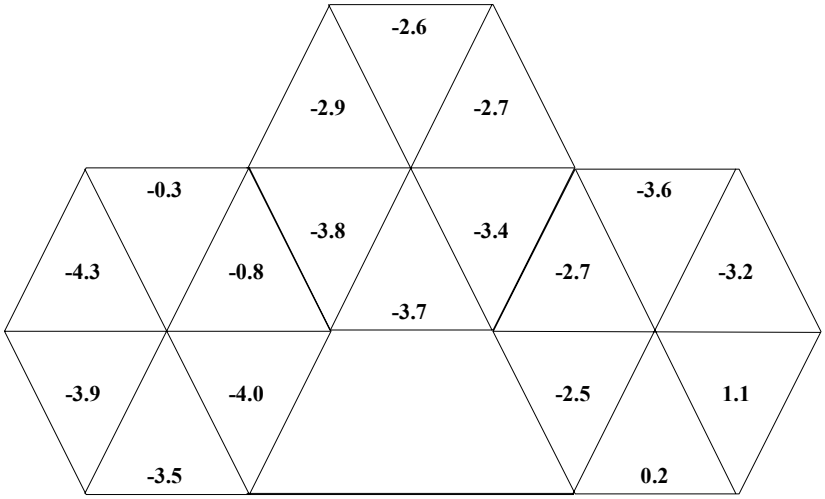


Table 3 APOLLO2 thermal absorption rate discrepancies (in %) with TRIPOLI4 results on the core



Experimental devices	APOLLO2 (MOC)
Sector #1	-5.4
Sector #2	-5.0
Sector #3	-5.4

Table 4 APOLLO2 thermal absorption rate discrepancies (in %) with TRIPOLI4 results on the central assemblies and the experimental devices

As shown on Tables 3 and 4, we can notice that the global results obtained on the homogenised fuel assemblies are very close to the TRIPOLI4 results (with average discrepancies of about 3%) and do not exceed 5%. With regard to the fine results determined on the experimental devices, we can observe a good agreement between APOLLO2 and TRIPOLI4 calculations with a maximum discrepancy of 5.4%.

With regard to the CPU time, the APOLLO2 calculation of this JHR core (corresponding to about 8000 spatial meshes and 172 energy groups) only takes about 9 hours on a 2 GHz-PC. This calculation time could be greatly reduced (while maintaining a high level of precision) by using a few group energy mesh (e.g. the 20-group mesh used for some reactor studies).

5. Conclusion

In this paper, we show that the APOLLO2 transport code using the method of characteristics has the capability of performing reference calculations of a 2D JHR core containing irradiation devices. The validation of the APOLLO2 calculation scheme was successfully carried out by comparison with the Monte Carlo code TRIPOLI4.

The very satisfactory results obtained with the characteristics method in terms of precision and calculation time allow us to envisage a 2D JHR core calculation taking account the fuel depletion. This can be carried out by the current improvement of the method as well as the use for instance of a reduced number of energy groups.

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