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EXPERIMENTAL VALIDATION OF THE NEW CODE PACKAGE APOLLO3-SFR AGAINST ZPPR-10A EXPERIMENT FOR CRITICAL AND VOIDED CONFIGURATIONS

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ABSTRACT

In order to accurately compute the ASTRID 4th generation Sodium Fast Reactor (SFR) prototype neutronic parameters, a new APOLLO3® deterministic code is under development at CEA. It will be part of the APOLLO3-SFR package (set of nuclear data, solvers from the code, calculation schemes) dedicated to fast reactor studies. In this paper, an experimental validation of this package is carried out with both ECCO and TDT-generated cross-sections libraries provided from ERANOS2 and APOLLO3-SFR respectively. To do so, experiments realized in the ZPPR reactor, dedicated to large sodium fast breeder reactors are reproduced according to the corresponding benchmark available in the IRPhE database. The new INCA neutronic interface, also developed at CEA, was used to easily process the whole calculation from ZPPR geometry description of the experiments to APOLLO3® computations. The results show satisfactory agreements for the critical model and sodium void effect experiments computed with the ECCO cross-section library and the TDT-generated one.

Key Words: **ASTRID, Fast critical assembly neutronic calculations, Experimental validation, Sodium void effect, APOLLO3®**

1. INTRODUCTION

Designing future Sodium Fast Reactors requires enhancing their operational performance and reducing the probability to go into core disruption. As a consequence of these constraints, these novel reactors exhibit rather unusual features compared to past designs, for example a rather large core with a flat shape, to reduce significantly the Sodium Void Effect. Therefore, the French studies related to the development of the 4th generation prototype fast neutron reactor called ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) require improved tools with accuracies meeting the design team requirements.

Concurrently to the ASTRID project, CEA and its industrial partners have launched a large program for developing a new generation of simulation tools facing the challenges of multiphysics coupling and high-performance computing on massively parallel computers.

In this context, the new APOLLO3® code [1], under development at CEA, will take over, after a commissioning period, the ERANOS2 [2] code, currently used for ASTRID neutronic conceptual design [3]. The APOLLO3® code will take advantage of new numerical developments for neutronic core reactor calculations and will be part of the new computational code package dedicated to Sodium Fast Reactor neutronics calculations and named APOLLO3-SFR.

A code package is defined as a tool consisting of nuclear data libraries, computer codes, as well as validated and qualified calculation schemes.
The transition from the old to the new codes generation is defined so as to meet the ASTRID development plans and will require the achievement of many tasks. One of these tasks is the VVUQ process, VVUQ standing for Verification, Validation and Uncertainty Quantification [4] applied to the APOLLO3-SFR package.
The flowchart presented in Figure 1 illustrates, in its left part, all the steps necessary to supply ASTRID Reactor designers the uncertainties that they can apply to their calculated neutronic key parameters, required in order to elaborate the Design and Safety Report (right part of the flowchart). If the margins for design are not adequate, a feedback between the users and the developers of the APOLLO3-SFR package is needed, leading potentially to new experiments, new developments in nuclear data, in neutronic calculation code or in increasing the accuracy of the calculation schemes.

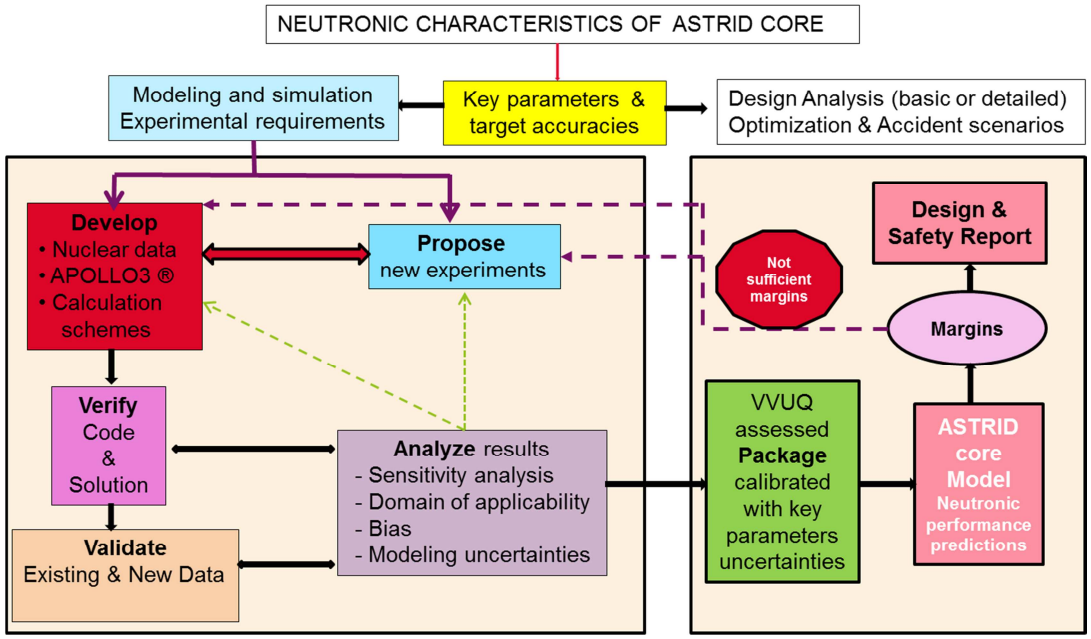

Figure 1. Verification, Validation and Uncertainty Quantification process

The work presented in this paper deals with the experimental validation step, also called qualification, and corresponds to the comparison of the global package results against experimental results from integral measurements. This qualification work is performed to demonstrate the accuracy of the new APOLLO3-SFR package. From this qualification process, calculation biases and associated uncertainties will be finally derived.
Even though the experimental validation of APOLLO3-SFR will be mainly based on experiments done in the French MASURCA facility, a fast mock-up reactor located at CEA Cadarache, the International Reactor Physics Evaluation (IRPhE) database [5] contains also appropriate experimental sets to be used for the experimental validation, particularly for the validation of the Sodium Void Effect calculation.
The objective of the paper is to present the beginning of the experimental validation carried out making a comparison between the APOLLO3-SFR package calculations and experimental results proposed by the ZPPR-LMFR-EXP-001 benchmark [6] taken from the IRPhE database.

2. PRESENTATION OF THE APOLLO3-SFR PACKAGE

The APOLLO3-SFR package is composed of several neutron cross section libraries, derived from the JEFF-3.1.1 nuclear data evaluated files [7], with 1968-groups and 172-groups structure. They are obtained by processing the general purpose files of each evaluation with the GALILEE [8] system which is the CEA nuclear data processing system for transport, depletion and shielding codes. Probability tables are also included for the main resonant nuclides.

The deterministic neutron transport code used in our package is the APOLLO3® code which contains, among others, cell/lattice and core solvers briefly described hereafter:

- IDT [9]: a 1D/2D/3D solver base on the Sn discrete ordinates method and finite differences, nodal or short characteristic methods for the spatial variable
- TDT-MOC [10-11]: a 2D/3D solver based on long characteristic method which enables the treatment of general unstructured geometries
- Minos [12]: a 2D/3D SPn solver based on a mixed dual finite elements (Ravier-Thomas) method allowing the treatment of regular Cartesian/hexagonal geometries
- Minaret [13]: a 2D/3D Sn/SPn solver based on the discrete ordinates method and Galerkin discontinuous finite elements dealing with unstructured Cartesian/hexagonal geometries
- Pastis [14] is 2D/3D Pn solver based on a variational nodal (and response matrix) method for the spatial treatment (using Legendre polynomial expansion of the flux).

Innovative calculation schemes using these JEFF-3.1.1 nuclear data and the new methods offered by the APOLLO3® code for Fast Reactor are currently under development. A first assembly reference calculation scheme has been elaborated and was used for the ZPPR experimental validation. This calculation scheme for fissile assemblies is validated against Monte-Carlo TRIPOLI4® [15] reference calculations and has proved its accuracy [16].

2.1. Presentation of the APOLLO3-SFR Assembly Scheme Calculation

Figure 2 illustrates how a general calculation scheme is carried out. As usual in deterministic scheme, a first step, called the lattice/assembly calculation, enables to produce self-shielded cross-sections in a reduce energetic mesh structure, eventually homogenized; these cross-sections are stored in a kind of reactor database, with the possibility of tabulation against selected parameters such as burnup, boron concentration, coolant density and so on. This structure is called a Multi-Parametric Output (MPO) in APOLLO3®. Once this database is constituted, the global core calculation can be performed, using, if necessary, interpolation of the database values.
For the APOLLO3-SFR package, two kinds of lattice/assembly calculation schemes have been currently defined, one for fissile assemblies and one for sub-critical regions. More details on this calculation scheme are presented in [17].

The calculation scheme used for fissile assemblies is the following:

- Reading of the Multigroup cross-sections library in a 1968 groups energetic mesh structure with the associated probabilities tables (PT). In the current package, this library is coming from the JEFF-3.1.1 nuclear data evaluation

- Flux calculation using TDT-MOC solver with the Method of Characteristics (1968 groups)
- Self-shielding calculation using the subgroup method within each fine group, particularly suitable for calculations involving complex heterogeneous structures, and with the exact collision probability method of the TDT solver (1968 groups with PT)
- Iterations between the flux and the self-shielding calculation, no leakage model used (B1 homogeneous leakage model available and B1 heterogeneous model under development)
- Homogenization and collapsing in a 33 group structure energetic mesh, then generation of a Multi-Parametric Output library (MPO) for the 3D, or 2D, core calculations.

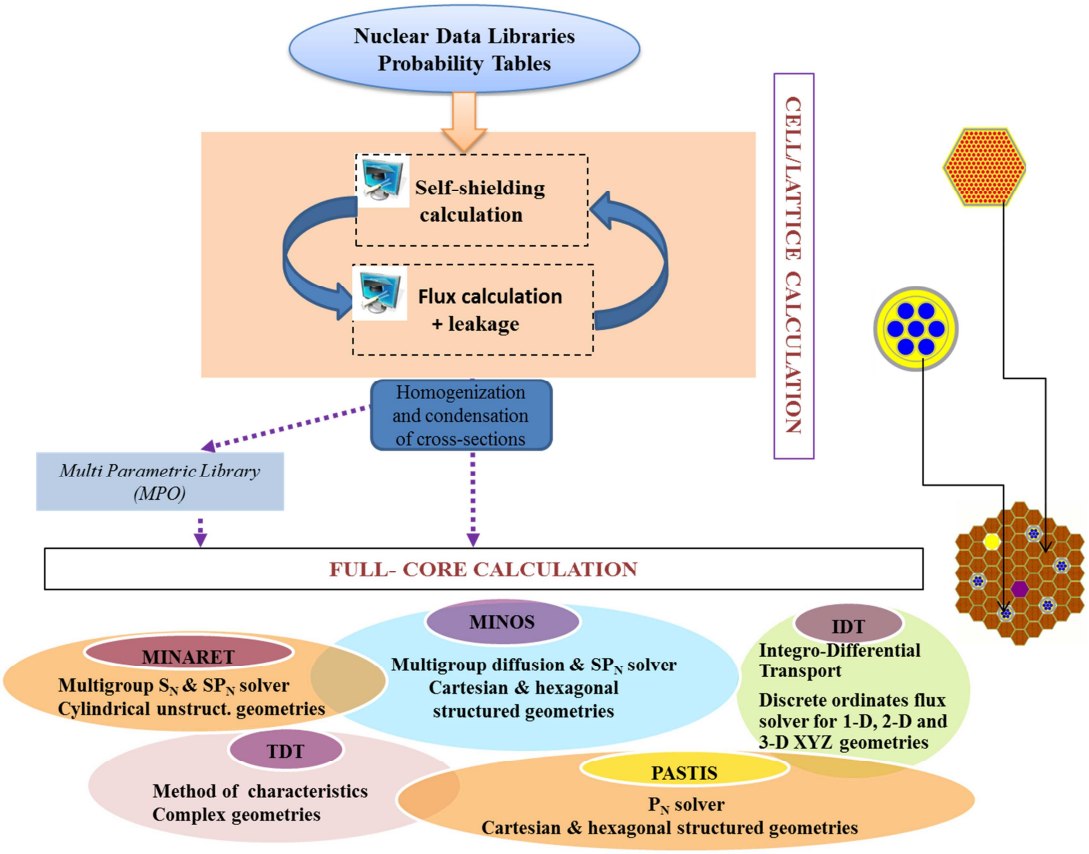

Figure 2. Calculation scheme using APOLLO3® for SFR calculations

Among the numerous developments required to enhance the computational schemes, the ones devoted to sub-critical regions are the most difficult. In ECCO-ERANOS scheme for example, the control rod cross sections can be processed with a reactivity equivalence procedure, while the steel reflector can use a condensation technique using angular fluxes and requiring many groups [18].
At the moment in APOLLO3®, we have adopted a different strategy: it consists of modelling the sub-critical medium surrounded by fissile assemblies previously calculated.
For example, in the ZPPR case, the self-shielded cross-sections for the axial blanket are obtained from geometrical model presented on Figure 3, in which each color represents a medium in the drawer. The surrounding fissile assemblies are chosen in order to represent the in-core environment of the axial blanket drawer.

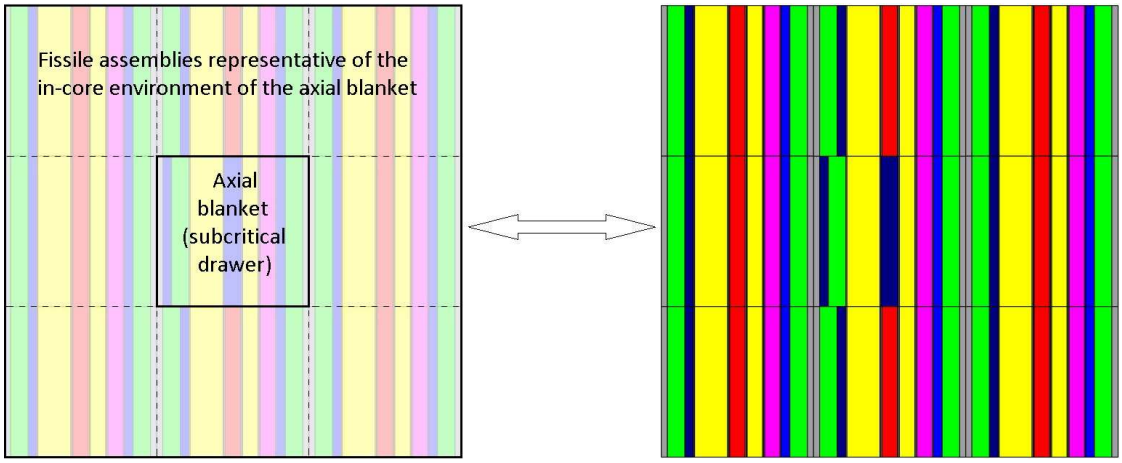

Figure 3. Geometrical model used for the generation of axial blanket self-shielded cross-sections

2.2. The Sn MINARET Flux Solver for Core Calculation

For the 3D core calculation of the ZPPR-10A benchmark, the calculations are performed using the MINARET solver. It solves the time-independent first-order form of the Boltzmann equation using the Galerkin discontinuous finite elements method to treat the space variable. The mesh is triangular and unstructured but conform in 2D and semi-unstructured in 3D (cylindrical). This transport solver is accelerated with a DSA method. The angular integration is based on the standard Sn level-symmetric quadratures.

2.3 The INCA Neutronic Interface

In order to simplify neutronic conception and experimental validation studies workflow, CEA is currently developing a design software, named INCA, by offering user-friendly tools to technical design teams. INCA, as shown on Figure 4, is on top of neutronic numeric codes such as APOLLO3® and TRIPOLI4® and dedicated to neutron fast reactor conception. Uneasy tasks such as geometrical design process, calculation scheme definition or advanced post-processing were rethought using user based data model. Numeric engines are automatically driven by INCA using a service based mechanism. Final user can interact with INCA either by means of a programming user interface based on Python language or by means of a graphical user interface, currently under development.

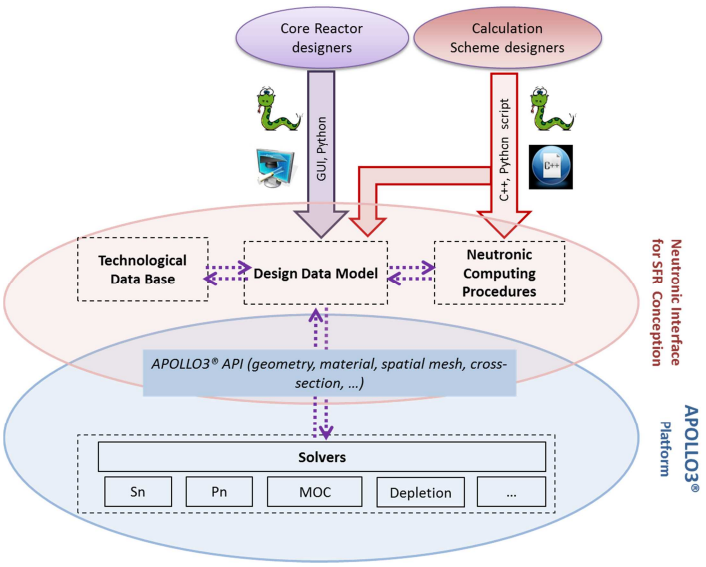

Figure 4. The INCA Neutronic Interface

3. DESCRIPTION OF THE ZPPR-10A EXPERIMENT

ZPPR-10A is an experiment of the JUPITER program, which was performed in ANL-Idaho between 1978 and 1988 to study Large Fast Breeder Reactor Cores. This experiment described in the IRPhE handbook of the NEA Data Bank, uses a conventional homogeneous core of 600–800 MWe with two zones of different enrichments. It is of particular interest because sodium void effects have been measured and are available ; its spectrum is interesting for ASTRID and, more generally, is in an energy range representative of GEN-IV large SFRs.

The core was assembled from small plates of depleted uranium, sodium, sodium carbonate, iron oxide (Fe_2O_3), depleted U_3O_8, stainless steel and Pu-U-Mo alloy loaded into stainless steel drawers. The drawers were loaded into square stainless steel tubes of matrices on the stationary and movable halves of a split-table machine. Due to the nature or the positioning of the plates and the positioning of each assembly in the core, the ZPPR-10A experiment is very heterogeneous. An example of a typical fuel unit cell is presented below on Figure 5.

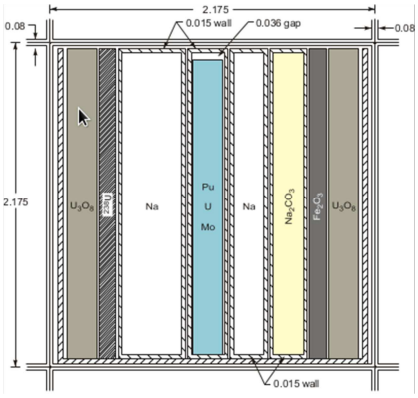

Figure 5. Typical ZPPR-10A Single Column Fuel Unit Cell

In our study, we have used the benchmark specifications proposed in the IRPhE database. These specifications proposed by JAEA, consists in two steps. The first step is the evaluation of homogeneous effective cross-sections in a one-dimensional plate heterogeneity structure for important drawer types in order to use these sections in the succeeding whole-core analysis. The second step is the core calculation in a three-dimensional XYZ model where compositions are homogenized in each typical drawer type, as defined in the benchmark specification.
The first step is done using the calculation schemes as described in 2.1 and the second step by using the MINARET solver. All calculations are performed through the INCA interface.

4. CALCULATION RESULTS

We have modeled ¼ of the ZPPR core. The corresponding geometry given by INCA and the one generated in APOLLO3® format, used by MINARET, are presented below. This enables us to verify the good transmission between the new neutronic interface and the MINARET solver.

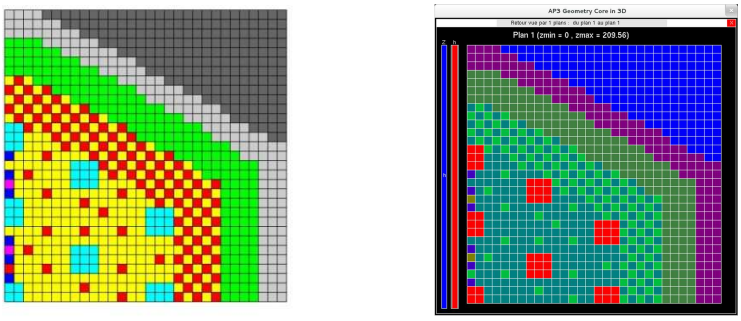

Figure 6. ZPPR-10A core geometry XY mid-plane

A lot of measurements are available in the benchmark; however, we have focused our work on model for critical calculation and on four Sodium Void Reactivity configurations. These four cases differ with the number of voided drawers and the depth of voided zones.
The obtained results are presented below. The self-shielded cross-sections are in a first step generated with the previous ECCO-ERANOS package. This enable us to validate the ZPPR core modelling with MINARET, which is a bit complicated, and also all the Python procedures of the INCA platform. Then, in a second step, we have used the APOLLO3® code with the calculation schemes described in 2.1 for the generation of self-shielded cross-sections. The XYZ calculations are also obtained with MINARET.

4.1 ECCO-MINARET Results

The results for the ECCO-MINARET calculations are presented in Tables 1 and 2. The benchmark model uncertainties are also given in the tables (1σ); these uncertainties combine the experimental uncertainty and the corrections due to the benchmark model.

Table 1. Results for ZPPR criticality calculation using ECCO-MINARET

S_N order	S4		S8		S16	
Radial Mesh Size (in cm)	2	5	2	5	2	5
Benchmark k_{eff}	1.00110 ± 150 pcm					
Calculated k_{eff}	1.00143	1.00141	1.00146	1.00144	1.00146	1.00144
C-E (in pcm)	33	31	36	34	36	34

For the critical calculations, we can see a very good agreement between these calculations and the benchmark Keff value since the C-E values are below 40 pcm. Probably due to the use of homogenized assemblies, neither the order of the Sn quadrature nor the radial mesh size have a large effect on the results.

Table 2. Results for ZPPR Sodium Void Reactivity using ECCO-MINARET

Experiment number	Benchmark Void Reactivity Effect (in pcm)	Computed Void Reactivity (in pcm)	C-E (in pcm)	C-E/E (in %)
1	77.3 ± 0.9	90.7	13.4	17.3
2	149.1 ± 1.6	161.4	12.3	8.3
3	193.7 ± 2.1	199.7	5.9	3.1
4	165.4 ± 1.8	165.2	-0.2	-0.12

Calculated sodium void reactivity of four voiding zones is summarized and compared with the benchmark values in Table 2. Although the discrepancies are lower than 15 pcm for all cases which is satisfactory, the fact that the target values for cases 1 and 2 are weak induces non-negligible C/E results. These results demonstrate the validity of the ZPPR core modelling with MINARET. Furthermore the INCA platform has proved its capability to simplify the modelling work and its reliability.

4.2 APOLLO3-SFR Results

The results using the entire APOLLO3-SFR package are presented in Tables 3 and 4 for respectively the criticality calculation and the Sodium Void Reactivity.

Table 3. Results for ZPPR criticality calculation using APOLLO3-SFR

S_N order	S4		S8		S16	
Radial Mesh Size (in cm)	2	5	2	5	2	5
Benchmark k_{eff}	1.00110 ± 150 pcm					
Calculated k_{eff}	1.00433	1.00431	1.00437	1.00435	1.00437	1.00435
C-E (in pcm)	323	321	327	325	327	325

For these critical calculations, results show good agreement between the computed and the experimental values, included in the 95% (2σ) confidence interval.
One can observe a difference, of about 300 pcm, compared to the results obtained with the ECCO-generated library. This difference might be explained by the fact that the two libraries were

not generated with the same drawers' boundary conditions, translation for ECCO and reflection for TDT, and further investigation are needed.

Table 4. Results for ZPPR Sodium Void Reactivity using APOLLO3-SFR

Experiment number	Reference Void Reactivity Effect (in pcm)	Computed Void Reactivity (in pcm)	C-E (in pcm)	C-E/E (in %)
1	77.3 ± 0.9	In Progress	In Progress	In Progress
2	149.1 ± 1.6	157.5	8.4	5.7
3	193.7 ± 2.1	202.9	9.1	4.7
4	165.4 ± 1.8	172.7	7.3	4.4

For the void reactivity effect, the computed values are satisfactory, with discrepancies lower than 10 pcm. These first results demonstrate the validity of the whole simulation process of APOLLO3-SFR package.
However a lot of complementary studies are necessary to assess the target uncertainties associated to the calculation of sodium void effect such as the interpretation of more dedicated integral experiments. In this objective and due to the specificities of the ASTRID core, an important experimental program is planned in the BFS reactor and in the MASURCA facility.

5. CONCLUSIONS

In this paper we have presented an experimental validation of the new APOLLO3-SFR package. The results obtained for the core calculations carried out with the ECCO-generated cross-section library and the TDT one, associated to the MINARET solver, are satisfactory for critical configuration and sodium void reactivity effect as well. Moreover, the INCA interface used for this investigation showed easy handling and reliability to set the whole calculation process up. In addition to this first work, the V&V process must be extended and other experimental validations should be performed to confirm the good trends obtained here.

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