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ABSTRACT

The Superphénix reactor was a Sodium-cooled Fast Reactor (SFR) developed under a European framework that intended to provide a general design of a commercial power plant. During the start-up of the reactor, six different batches containing dummy assemblies allowed to verify the main safety criteria at zero-power conditions tests at 180°C. The present paper presents a stochastic analysis of two start-up cores by comparing the experimental results with the performed calculations with TRIPOLI-4 and the JEFF 3.1.1 nuclear data evaluations. The main and back-up control rod evaluations, the critical mass, as well as the handling error experiment are examined. In addition, two particular irradiation tests are studied to determine the flux distribution of the core and finally, the assessment of a subcriticality analysis is performed to verify the validity of the former MSM factors. In general, the obtained results show good agreement with the experiment, having a general reactivity bias with the performed calculations, the flux distribution is also in great agreement with the tests with small discrepancies and the MSM evaluation permitted to observe better consistency with experimental data. The obtained results allowed to validate our model and will serve as reference calculation for further research.

KEYWORDS: Superphénix reactor, start-up commissioning tests, TRIPOLI-4.

1. INTRODUCTION

Since past decades, the generated amount of depleted uranium motivated the development of a technology that could maximize uranium utilization and hence, extend the fuel reserves for several centuries. The Sodium-cooled Fast Reactor (SFR) concept was the selected candidate to attend this need because of its neutronic properties and its breeding capabilities.

In France, the construction of an experimental facility called Rapsodie in 1959, followed by the demonstrator reactor Phénix, provided the basis knowledge of this technology. Subsequently, a large-scale reactor intended to consolidate the SFRs as a choice for electricity production by including the gained experience in the past reactors [1]. This commercial size reactor was called Superphénix and it was developed under a European framework between France, Italy and Germany.

The construction of the plant began in 1975 and after ten years of construction, in 1985, the first phase of the commissioning tests was performed, in which sodium flow technical problems were successfully fixed. The second phase was devoted to the core loading and a set of tests to assess the safety criteria of the core. A particular core loading strategy enabled to minimize the time between the defined core patterns, in which a total of six batches accomplished the full loading of the

Superphénix core, reaching the first criticality in a configuration known as *Coeur de Première Divergence* (C1D) on 6 September 1985 [2]. Before the core reached full power, the safety commissioning tests in Superphénix were performed in a core named *Cœur de Montée en Puissance* (CMP). The main objective in the CMP core was to verify the safety criteria related to the control rod systems, as well as to evaluate the available reactivity reserves for the full power cycle.

Early analysis of Superphénix was based in diffusion approach with the former CARNAVAL-IV calculation scheme and implied a large number of corrections due to the existing calculation route, such as mesh, transport and heterogeneity corrections among others. Afterwards, in the 1990 decade, the Superphénix analysis led to the production of the adjusted library ERALIB1 [3]. This adjustment was done from JEF2.2 library with a simplified transport approach, and it consisted in cross-section corrections in nuclear data of a set of isotopes (^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{56}Fe, ^{52}Cr, ^{58}Ni, ^{23}Na, and ^{16}O). Despite the obtained results with this library were close to measurements [4], the ERALIB1 library misses all the nuclear data improvements that are coming from new evaluations since JEF2.2.

At the present day, the evaluation of the Superphénix core can be performed with the late developed neutronic platforms, which will bring a better comprehension of the core physics and the associated bias of the different calculation schemes. The present paper presents a stochastic analysis of the start-up cores by comparing the experimental results with the performed calculations. The TRIPOLI-4 code is used as the stochastic reference with the European nuclear data evaluations JEFF 3.1.1.

Chapter 2 presents the main characteristics of the Superphénix core as well as the general description of the batches under analysis and the performed tests of each of these core patterns. The chapter 3 provides a brief description of the model considerations in this paper. Obtained results are shown in chapter 4 and finally, in chapter 5 the concluding remarks are presented as well as the further research to be done.

2. THE START-UP CORES

2.1. Core Characteristics

The Superphénix core was composed by two concentric fissile regions with axial blankets at the top and the bottom of the fuel zone boundaries. Radially, fertile assemblies were placed surrounding the outer fuel core. Sintered $UPuO_2$ pellets were introduced into the fuel pin elements in the fissile assemblies and depleted uranium pellets were placed in the upper, lower and radial blankets. Figure 1 presents the core map of the Superphénix core in which the distribution of the fuel and blanket zones is shown.

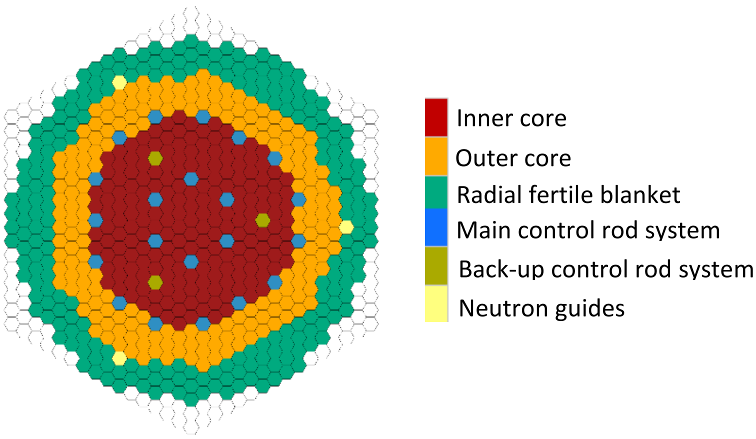

Figure 1. Superphénix core map

The main control rod system SCP (Système de Commande Principal) contained 21 assemblies divided in two curtains, one in the inner core and another in the interface of the inner and outer core. Each of the SCP control assemblies contained 31 absorber pins of B_4C enriched at 90% in ^{10}B. The back-up control rod system SAC (Système d'Arrêt Complémentaire) was placed in the inner core and its objective was to assure the shutdown of the rector. Since this system was only used for shutdown and not for the reactor control, it has only two positions: inserted (core shutdown) and withdrawn position (core operation).

In order to assure the proper control of the reactor, three neutron guides were placed at 120 degrees of the outer core boundary. This neutron guides enabled the flux to be measurable enough in the bottom fission chambers of the core to provide precise reactivity measurements. However, a special assembly for online in-core measurements was used during these tests since the neutron flux in the reactor was very low and the nominal measurement system would not provide accurate measurements. It accounted a telescopic tube in the central channel of the reactor that could be inserted in the central assembly since the central fuel pin elements were not present in this element. It accounted three fission and activation foils to determine neutron flux distribution inside and around the core [2] as it is discussed in next section.

2.2. The Selected Cores in the Checkerboard Loading Pattern

The loading of Superphénix core was performed by applying a strategy called the checkerboard pattern, which consisted in the gradual replacement of previously loaded dummy assemblies by fuel assemblies in predefined batches.

The whole core loading was performed in six different batches and it permitted to predict the first critical core, whose name was "Coeur de Premiere Divergence" (C1D). The last batch was also known as the "Coeur de Montée de Puissance" (CMP), in which an exhaustive experimental program was performed to assess the safety criteria of the core [5]

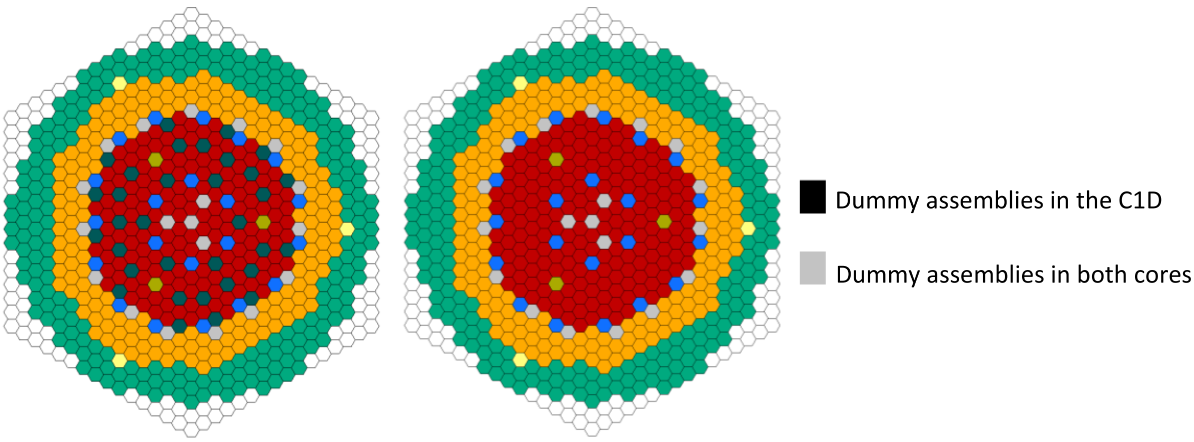

Figure 2. Core layout of the C1D (left) and the CMP (right).

2.2.1. First divergence core

Once a predefined batch was loaded, reactivity measurements were done at zero-power conditions at 180°C. In each batch, the backup and main control rod systems were withdrawn to estimate the first critical core, which was in agreement with previously calculated results [5].

The first divergence core (C1D) was composed of 325 fuel assemblies and 33 dummy assemblies placed in the inner core. Criticality was achieved with the SCP barely inserted and the withdrawn position of the SAC.

2.2.2. The Cœur de Montée en Puissance

The last batch was called *Cœur de Montée en Puissance* (CMP) in which a total of 18 dummy assemblies were placed next to the main control rod systems to limit the reactivity excess at this stage. In particular, the analyzed tests that are presented in this paper are:

Control rod evaluations

An exhaustive SCP analysis program allowed the estimation of reactivity reserve for the first power cycle and determined the main and back-up control rod worth. For the SAC evaluations, two assessments were performed:

- Being the reactor in critical state (SCP in critical position Zc) the SAC was inserted.
- Being the reactor in subcritical state (SCP completely inserted) the SAC was inserted.

Handling error test

Another test to survey local criticality in the core was done. The handling error was performed to verify previous research concerning the amplification of this effect in large size cores. To assess this possibility the following procedure was done:

- The SCP and SAC were inserted except for the control rod 13 (see Figure 3)
- A fuel assembly was loaded instead of the dummy loaded beside control rod 13.

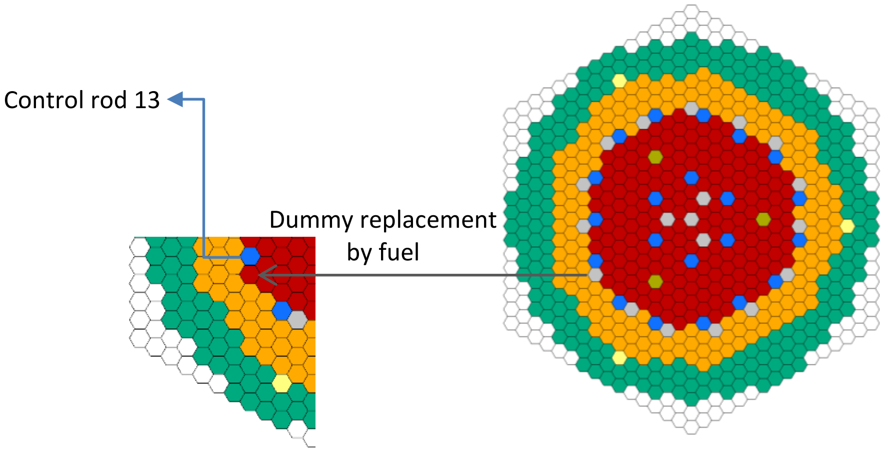

Figure 3. Handling error test in the CMP

Transversal irradiation tests

During the start-up commissioning tests, a particular experiment was performed to determine the radial flux profile of the core. For this test, a series of special subassemblies containing measurement capsules instead of the central pins (replacement of 19 central fuel pins for the fuel assemblies and 7 fertile pins for the blanket assemblies [2]) were radially loaded as shown in Figure 4. Fission and activation foils were installed inside these capsules, after the irradiation tests these detectors were analyzed to determine neutron flux distribution inside and around the core. The core and blanket rate distributions were measured by irradiating these assemblies at 3 MW for two hours [6].

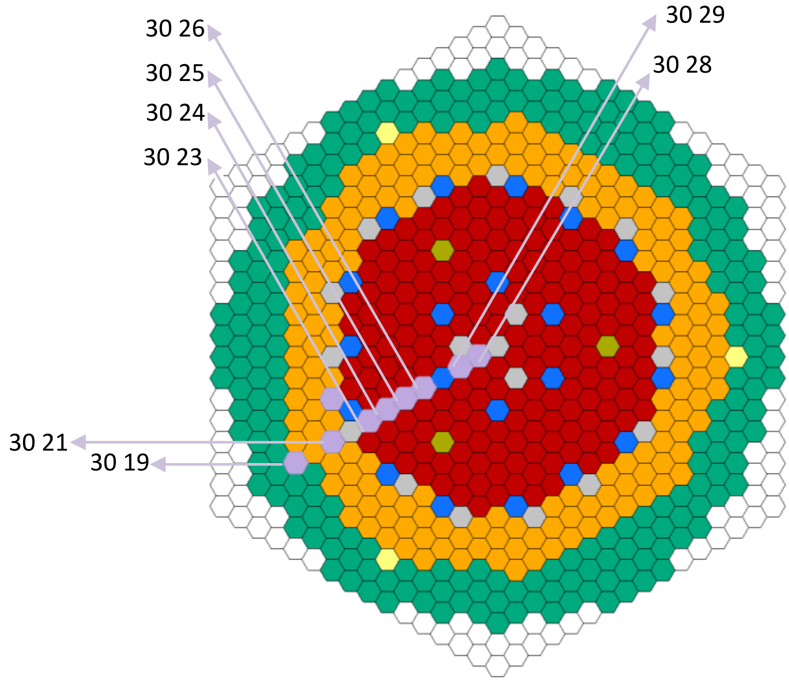

Figure 4. Core layout of the Irradiation tests T1 and T2 and experimental assembly measurement positions

Subcriticality analysis

The experimental reactivity was determined by the Modified Source Multiplication (MSM) method, as stated in reference [7], therefore, the available measurements of Superphénix are spatially corrected with the former CARNAVAL-4, which may be a source of bias. The MSM method was previously validated in the MASURCA facility, from which the experimental reactivity is related to the MSA (méthode de source approchée, approximated source method) and a spatial correction given by the MSM method. The sub criticality test consisted in measuring each of the control rods worth by independently extracting and inserting each of the control rods. As stated in section 2.1, a special assembly for online measurements contained three fission chambers with different axial position (see Figure 5), from which the reactivity was corrected with the MSM method.

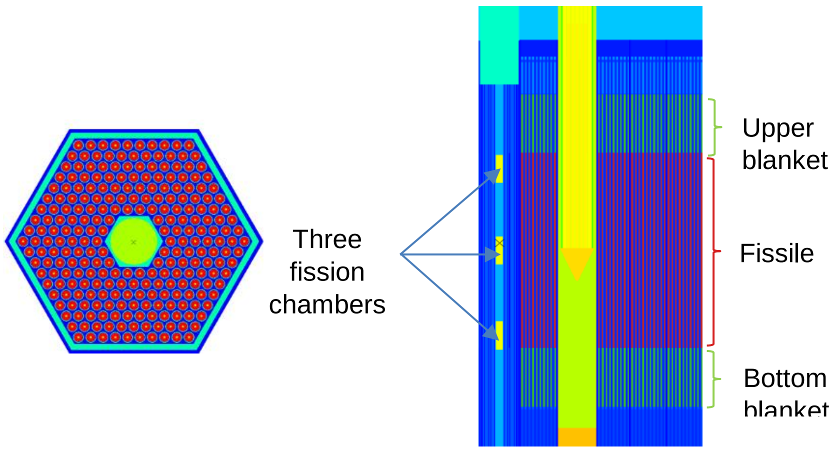

Figure 5. Start-up measurement system in Superphénix

Currently the interest is to determine whether or not the reactivity worth improvement can be done with the TRIPOLI-4 code, based in previous references that show a better agreement with the MSM method when using a Monte Carlo method. Besides, the uncertainty impact by its inclusion in the experimental correction with no use of adjusted libraries (JEFF 3.1.1 in this case, ERALIB1 in former calculations).

3. PERFORMED ANALYSIS

The objective of the present paper is to evaluate the start-up commissioning tests Superphénix in a stochastic perspective. To accomplish this task, a developed model in the stochastic TRIPOLI-4 code [8] is validated to serve as further reference in this research. The TRIPOLI-4 code is a reactor physics probabilistic code based on the Monte Carlo method in which the neutronic behavior is reproduced by following the neutron histories in a defined geometry with assigned material characteristics. In our case, the specified geometry accounts a high heterogeneous description considering the geometrical and material implications due to the dilatation at 180°C.

3.1. Evaluated tests

Control rod evaluations

The first critical core presented a considerable amount of dummy assemblies, from which 18 were strategically placed next to the main control rod system and 33 were located in the inner core. In this core, criticality was obtained with main control rods barely inserted in the fuel core. For the C1D only the evaluation of the main control rod is presented. Secondly, the analysis concerning the CMP includes the evaluation of the main control rods and the back-up control system assessment as well as the handling error test.

For these cores, two fuel approaches are considered: the first considers the average fuel composition of the assemblies per fuel zone. The second assessment, called the per assembly composition approach, accounts each assembly composition by taking into account the heavy isotopes in each of these fuel assemblies. The composition of each assembly was measured in October 1984, and it was adjusted to accord the test's date by considering the ^{241}Pu decay to ^{241}Am. By comparing these approaches, the bias by considering average fuel in the core regions will be known as a modeling bias in fuel composition definition.

Transversal irradiation test

For the CMP, two different tests are presented, the first identified as Transversal Irradiation 1 (T1) accounts all of the control rods at the same axial position at the half height of the active core. The second irradiation test is recognized as Transversal Irradiation 2 (T2), with an axial displacement of the control rods curtains as seen in Figure 6. To analyze the radial flux distribution only five sub assembly positions of the internal core are selected, one for the outer core position and the last one in the fertile position.

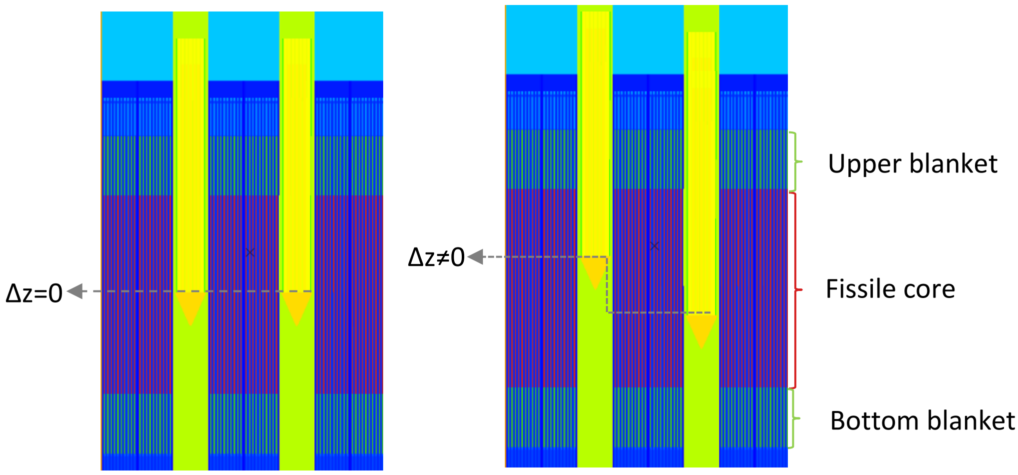

Figure 6. Control rod displacement for Irradiation tests T1 (left) and T2 (right)

Subcriticality analysis

The evaluation of each of the control rod worth in the SCP is done with the TRIPOLI-4 code accounting a new MSM spatial correction. Several references state the methodology of the MSM method [9], [10], [11], [12] and in this paper the objective is to observe the impact in the control rod worth for the subcritical analysis. The generation of MSM factors with a stochastic code requires the reference and the configuration reactivity calculations as well as the corresponding reaction rates.

4. RESULTS

In this section, results of the evaluations are presented in three subdivisions. First the control rod evaluations for SCP are presented for three positions (↑: withdrawn position, Zc: critical position and ↓: inserted position) and for the SAC, two evaluations are presented with the SCP in extracted and inserted position. Control rod worth is also discussed in these sections. Secondly, the flux distribution is given for two different tests, the T1 and T2, as it was described in the previous chapter and finally, the subcriticality analysis is presented with the corresponding evaluations of the MSM method.

Before commenting the results, a couple of remarks are needed in this section. The first concerns to the use of nuclear data evaluations and its impact on calculations. A previous analysis performed with ERANOS and the use of the COMAC V2 covariance matrix provided a nuclear data uncertainty propagation of almost 700 pcm, so even with the use of the Monte Carlo method this uncertainty is present for all the calculations. Therefore, one has not to be surprised for the presence of bias within this range for these evaluations.

The second remark involves the experimental uncertainty determination and its components. The considered sources to its evaluation are the inherent measurement uncertainty (counting rates uncertainty) which are unavoidable in all experimental tests. The reactivity reference uncertainty and the reactivity determination method (MSM method) are also accounted to the final uncertainty estimation, and of course the delayed neutron fraction (β_{eff}) uncertainty, being this very important for the final uncertainty determination. To evaluate the β_{eff}, the IFP method already implemented in TRIPOLI-4 is used, however its uncertainty is not included for the present values, instead the former uncertainty evaluation with ERANOS code is taken. Further analysis includes the β_{eff} uncertainty analysis with IFP method and its inclusion in the experimental uncertainty.

Control rod evaluations

The calculated reactivity for different SCP positions of the C1D core is presented in TABLE I. For the average composition approach a reactivity difference of about 560 pcm is registered for the extracted and the critical position of the SCP, while for the inserted position this difference is reduced about 140 pcm. When using the per assembly approach the difference between measurements and calculations are reduced about 100 pcm for the withdrawn and critical positions and for the inserted position this difference is reduced to 50 pcm. In consequence the control rod worth evaluation is different depending on the composition approach. However, one has to be aware that the inserted position of the SCP registers a large subcriticality state and hence a large uncertainty is related to this measurement.

Table I. Reactivity results in pcm (C-E) of the C1D core for average and exact approaches. Measurement in pcm with 1$ = 365 pcm and uncertainty at 1σ.

Measurement	321 ± 22 pcm	0 pcm	-8221 ± 231 pcm
Composition approach	SCP ↑	SCP Zc	SCP ↓
	C-E	C-E	C-E
Average	562	566	424
Per assembly	461	471	413

Control rod worth of the SCP in the C1D is shown in Table II. All the results are in good agreement with the measurements, remaining within the experimental uncertainty range. The fuel composition approaches have an impact in this evaluation, for instance, when using the average approach the total control rod worth has an error of about 1.6% however, when the per assembly composition approach is used, this error is reduced down to 0.5%, this means that a slight improvement of the control worth is observed with the per assembly approach. An overestimation of the control rods is seen for the Δρ (Zc to ↓) and Δρ (↑ to ↓) positions with TRIPOLI-4.

Table II. Control rod worth results (C-E and C/E) by position of the C1D core for average and exact approaches. Measurement in pcm with 1$ = 365 pcm and uncertainty at 1σ.

Measurement	321 ± 22 pcm		8221 ± 231pcm		8542 ± 231pcm	
Composition approach	Δρ (↑ to Zc)		Δρ (Zc to ↓)		Δρ (↑ to ↓)	
	C-E	C/E	C-E	C/E	C-E	C/E
Average	-4	0.98	141	1.017	138	1.016
Per assembly	-10	0.96	58	1.007	48	1.005

Results for the SCP evaluation in the CMP are seen in Table III for three different positions, still one has to recall that the reactivity reserves of the CMP were not directly measured and they are related to the S curve of the main control rod system. When observing these evaluations a reactivity bias is also present, as in the C1D. Nevertheless, this bias seems to be reduced to about 100 pcm in general. For directly measured positions (Zc and ↓) a bias of 370 pcm is identified while for the reactivity reserves an increase of about 90 pcm is seen independently from the composition approach. The influence of the per assembly composition approach is not identical to the observed in the C1D, now only about 50 pcm reactivity decrease is seen compared to nearly 100 pcm in some positions of the C1D.

Table III. Main control rod reactivity difference (C-E) in pcm in the CMP. Measurement in pcm with 1$ = 370pcm and uncertainty at 1σ.

Measurement	3774 ± 264	0	-4414 ± 151
Composition approach	SCP ↑	SCP Zc	SCP ↓
	C-E	C-E	C-E
Average	468	374	369
Per assembly	412	321	306

Control rod worth of the SCP for the CMP is shown in Table IV. The evaluations are in good agreement with measurements within the experimental uncertainty range. For the evaluation involving the critical and the inserted position of the SCP a remarkable agreement is seen with diminutive discrepancy face to the measurements. The per assembly composition approach is very similar to the average approach evaluation with minimal differences, and contrariwise to the C1D evaluations, the analyzed composition approaches have no major influence on control rod worth for the CMP. An overestimation of the control worth is seen in all positions with TRIPOLI-4 with a maximum value of 106 pcm.

Table IV. Control rod worth results (C-E and C/E) by position of the CMP core for average and exact approaches. Measurement in pcm with 1$ = 370 pcm and uncertainty at 1σ.

Measurement	3774 ± 264		4414 ± 151		8188 ± 294	
Composition approach	Δρ (↑ to Zc)		Δρ (Zc to ↓)		Δρ (↑ to ↓)	
	C-E	C/E	C-E	C/E	C-E	C/E
Average	94	1.025	5	1.00	100	1.012
Per assembly	90	1.025	15	1.00	106	1.013

The reactivity change from the C1D core to the CMP core can be evaluated at this point since the only modification is the loading of 33 fuel assemblies in the CMP core. In Table V two different conditions are evaluated for the reactivity reserves change from C1D to CMP, the extracted control rod position (SCP ↑) and the inserted control rod position (SCP ↓). Results remain within the experimental uncertainties, however one has to perceive the wide uncertainty experimental range. For the extracted SCP position of the CMP presents a large experimental uncertainty due to the critical mass determination method, which contributes to the large uncertainty at this position. In the other hand, for the inserted position, the C1D has a large subcriticality state, which provides a large uncertainty range in this evaluation. However, the presented evaluations are within the experimental uncertainty range, with a major discrepancy of 107 pcm. For the withdrawn position of the SCP a better agreement is found with the per assembly approach with only 50 pcm difference while the average approach presents almost double reactivity difference with measurements. In the other hand, for the inserted SCP evaluation the average approach has a better agreement with 56 pcm difference, and this time the per assembly composition approach doubles the difference with measurements.

Table V. Reactivity reserves difference between C1D and CMP cores in pcm. Measurement in pcm with 1$ = 370pcm and uncertainty at 1σ.

Measurement	3453 ± 268 pcm		3807 ± 275 pcm	
Composition approach	SCP ↑		SCP ↓	
	C-E	C/E	C-E	C/E
Average	-94	0.97	-56	0.98
Per assembly	-50	0.98	-107	0.97

Evaluation of SAC is presented in Table VI and Table VII for the SCP in critical and inserted position respectively. A consistent reactivity bias is seen with the critical position of the SCP in Table III, and the per assembly composition approach has the same tendency and is translated as a reactivity decrease of about 50 pcm. Despite the control rod worth is overestimated in both cases for almost 50 pcm this evaluation is within the experimental uncertainty range.

Table VI. Back-up control rod system (with SCP at critical position) reactivity difference and control rod worth. Measurement in pcm with 1$ = 370pcm and uncertainty at 1σ.

Measurement			**1048 ± 58 pcm**	
Composition approach	**SAC ↑**	**SAC ↓**	**Control rod worth**	
	C-E	C-E	C-E	C/E
Average	374	325	49	1.038
Per assembly	321	275	46	1.044

In Table VII, as in the past evaluation, the reactivity bias is again present in a consistent manner. The per assembly composition approach shows the same trend that was pointed out before, a reactivity decrease is seen when compared to average approach. The control worth evaluation is in good agreement with the experimental data, remaining within the uncertainty range.

Table VII. Back-up control rod system (with SCP at inserted position) reactivity difference and control rod worth. Measurement in pcm with 1$ = 370pcm and uncertainty at 1σ.

Measurement			**1210 ± 52 pcm**	
Composition approach	**SAC ↑**	**SAC ↓**	**Control rod worth**	
	C-E	C-E	C-E	C/E
Average	369	371	-2	0.998
Per assembly	306	291	15	1.01

Results concerning the handling error test are shown in Table VIII for both composition approaches. This evaluation consists in calculating the reactivity difference between the withdrawn position of the all the control rods and the inserted position of all control subassemblies except for the 30 22 position, as described in Section 2.2.2. The evaluations are consistent and in good agreement with measurements, remaining within the experimental uncertainty range. A deviation of almost 100 pcm is seen between calculations and measurements. However, this difference is related to the withdrawn position of the SCP, as it was discussed in Table V. Finally, the composition approaches are consistent between them with practically no reactivity difference.

Table VIII. Handling error test in the CMP. Measurement in pcm with 1$ = 370 pcm and uncertainty at 1σ.

Measurement	**6621 ± 279 pcm**	
Composition approach	**Δρ (SCP ↑ , SAC ↑) –(SCP ↓ except 30/22, SAC ↓)**	
	C-E	C/E
Average	-91	0.98
Per assembly	-90	0.98

As a final remark of the control rod evaluation, the CMP criticality reserves has to be revisited to check consistency of this evaluation given the discrepancy between measurements and calculations. It is likely to correct this measurement since the S curve evaluation does not accounts spatial corrections, whose importance may be conducted in further research.

Transversal irradiation tests

Results for the Transversal irradiation 1 are shown in Figure 7 with the TRIPOLI-4 code. As stated before, in this test the control rods position was identical for all control rods and flux is normalized to the recorded flux in 30 29. The results presented in this section correspond to the flux at the mid-height of the active core. The measurement uncertainties are also provided at each assembly position, however it does not includes another uncertainty sources such as the control rod axial position.

The TRIPOLI-4 evaluation presents very good agreement with the experimental data with less than 1% error, besides, the results are less dispersed than those compared to the former evaluation. The largest discrepancy is seen at the position 30 25, which is in the internal core at the half distance between the central assembly and the periphery of the internal core. The outer core position assembly (30 21) and the fertile position assembly (30 19) are well described with minimal error.

The contiguous assemblies to the control rods, 30 28 in the inner core and 30 21 in the outer core, permit to observe its flux distribution impact at the mid-height of the active core. The developed model in TRIPOLI-4 can describe with remarkable agreement the flux at this state, with less than 0.50%.

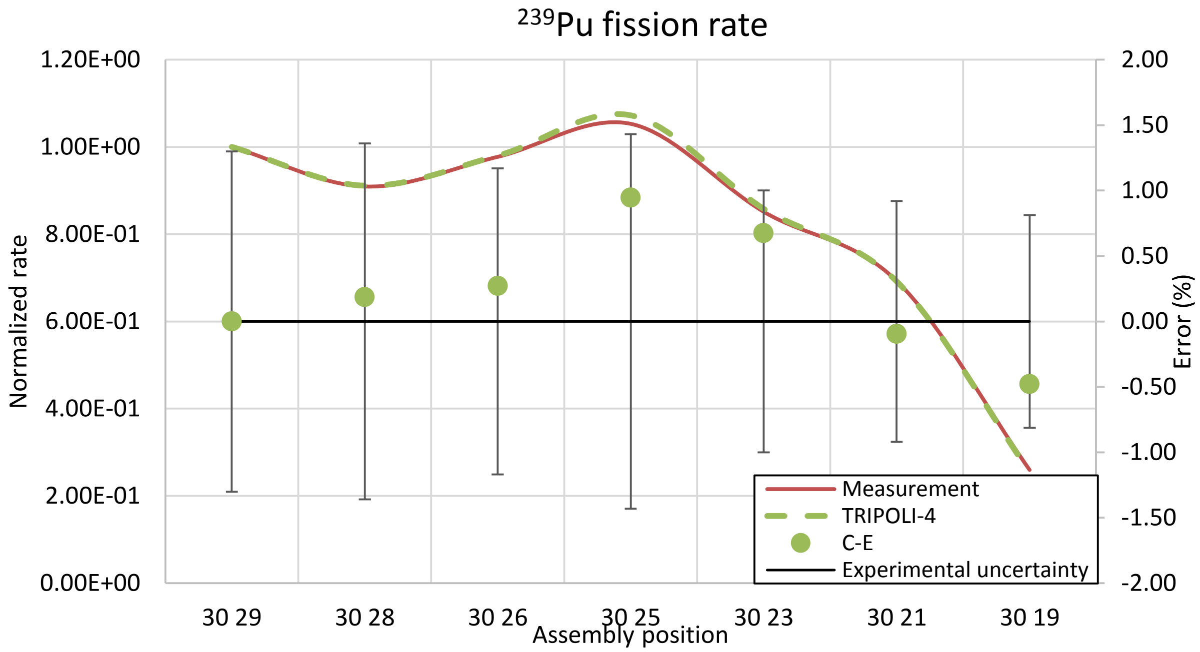

Figure 7. Fission rate of ^{239}Pu at mid-height of the active core for the irradiation test T1.

Results concerning the Transversal Irradiation T2 are shown in Figure 8. The difference with the T1 irradiation test is the displacement of the control rods between them, as previously depicted in section 2.2.2. Results presented correspond to the recorded fission rate at the mid-height of the active core and as in the previous evaluation the presented values are normalized to the 30 29 flux position. Evaluations with TRIPOLI-4 are in great agreement with measurements with less than 1% error, however, C-E differences are more dispersed than in the previous evaluation.

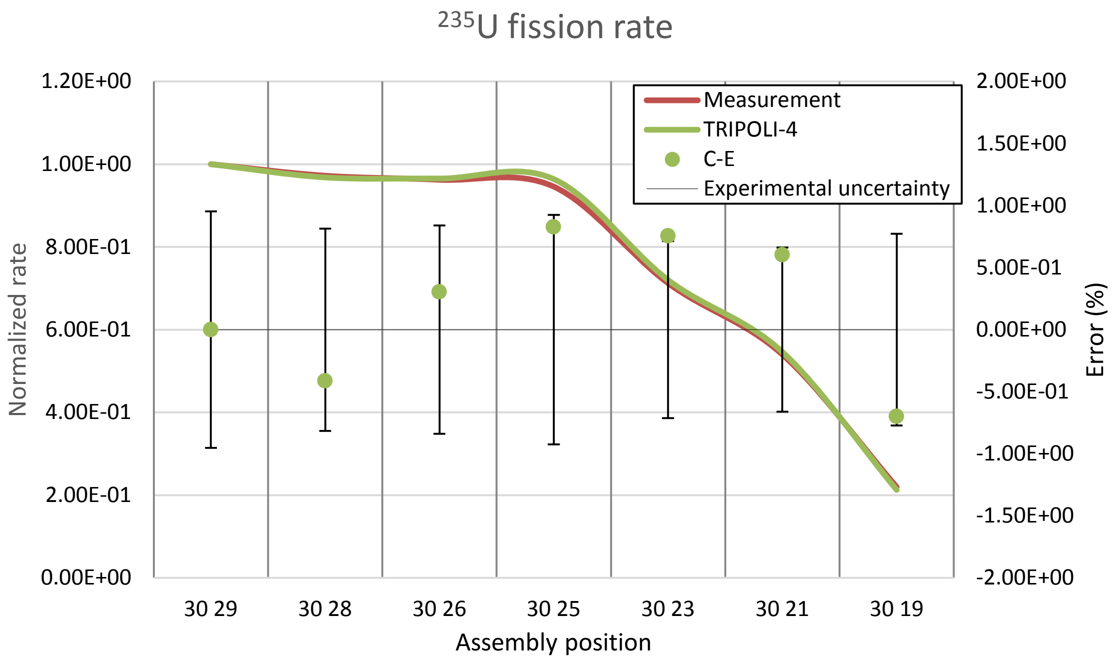

Figure 8. Fission rate of ^{239}Pu at mid-height of the active core for the irradiation test T2.

When comparing the T1 and T2 irradiation tests the flux distribution is clearly different, for instance, the flux in the position 30 28, which is next to the inner control rod curtain, is flatter in the T2 than in the T1 because this curtain is axially higher in the T2. In compensation, since the outer control curtain has a lower position in the T2 than in the T1 the flux in the positions 30 23 and 30 21 is clearly smaller for the T2. In both cases the TRIPOLI-4 model is capable of describe the flux with small difference when compared to the measurements. Finally, for all subassemblies positions the fission rate values remain within the experimental uncertainty range being this valid for both evaluations T1 and T2.

Subcriticality analysis

Results concerning the subcriticality test are compared to the developed model with TRIPOLI-4, and the results are compared with the former correction with CARNAVAL-IV and the present correction with TRIPOLI-4. Figure 9 presents the control rod worth difference from critical to inserted position for each of the 21 control subassemblies in the main control rod system. The inner curtain of the SCP is composed by six control rods (B1 to B6) from which an average bias of 40 pcm is observed with the CARNAVAL-IV corrections, however the values present important dispersion of about 25 pcm. For the outer curtain of the SCP, composed by 15 control subassemblies (B7 to B21) an average bias of about 42 pcm is observed, but a larger deviation of 58 pcm is seen.

Present evaluations show better agreement with minimal dispersions than the former evaluations. For the inner curtain a dispersion of only 3 pcm is seen, compared to the 25 pcm with former evaluations and an average of 41 pcm is seen for these rods, being consistent with past assessments. The outer control rod curtain presents larger dispersed values with a maximal 10 pcm value, however is well reduced compared to the former evaluations. For both evaluations, in general an average bias is identified of about 40 pcm, having good consistency with both evaluations.

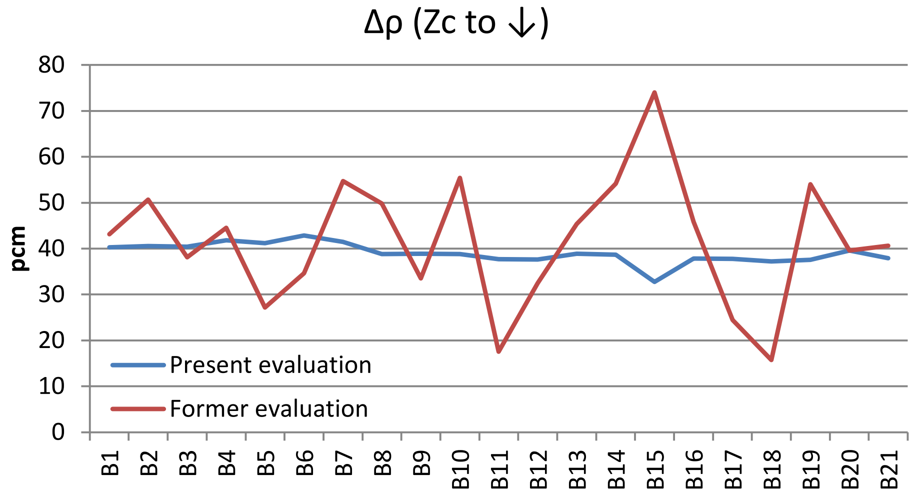

Figure 9. Control rod worth C-E difference between critical to inserted positions. In red the measurements corrected with former CARNAVAL-IV and in blue measurements corrected with TRIPOLI-4.

Figure 10 presents the control rod worth difference between measurements and calculation for the critical to extracted positions of the SCP. The former measurements corrected with CARNAVAL-IV present a considerable dispersion of about 71 pcm, being this 20 pcm larger than the seen in the previous evaluation. Conversely, to the previous evaluation the reactivity values are dispersed with the same behavior in the internal and external curtain. After applying the MSM correction with TRIPOLI-4 for these evaluations the reactivity dispersion is largely reduced to only 5 pcm difference, besides the C-E difference is also considerably reduced.

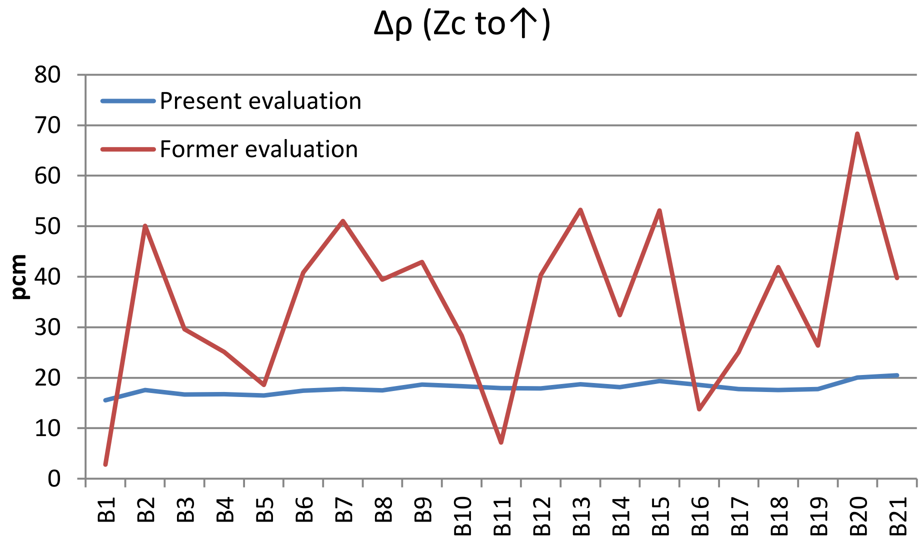

Figure 10. Control rod worth C-E difference from critical to extracted positions. In red the measurements corrected with former CARNAVAL-IV and in blue measurements corrected with TRIPOLI-4.

5. CONCLUSIONS

The evaluation of a selected list of the Superphénix start-up has been done with the Monte Carlo code TRIPOLI-4. Results provide a remarkable good agreement with the experimental data: control rod worth is well described for the main and back-up control rod systems (SCP and SAC) as well as the handling error, which is accurately reproduced. The radial flux profile was also analyzed for two different tests with good agreement against the experimental measurements and finally the evaluation of the MSM factors led to a better agreement and interpretation of the control rod worth in a subcriticality test.

The developed model with TRIPOLI-4 has now been validated against experimental data and its corresponding uncertainty, thus, it serves as calculation reference for future research concerning the Start-up of Superphénix. Moreover, further analysis has to be done to assess the impact of these evaluations when the use of another more recent nuclear data evaluation (JEFF 3.2 for instance). Besides the nuclear data uncertainty propagation assessment is required to determine its impact on current evaluations, nevertheless the use of Monte Carlo codes to perform this task is often complex.

As with all Monte Carlo codes, the calculation time and the memory demands with TRIPOLI-4 is an important drawback, particularly when studying reaction rates. For this reason, the use of a deterministic code, such as ERANOS or the novel APOLLO3, is suggested to avoid these difficulties, besides, the use of its perturbation modules would enable performing detailed reactor physics analyses. A particular interest to perform such assessment with APOLLO3 appears for its considerable improvements for neutronic calculation and its novel treatment at different levels of the core [13].

In the other hand, the experimental uncertainty of these tests has to be revisited, to attribute a possible reduction of each of its sources and to determine whether or not a considerable uncertainty reduction is possible with the later neutronic tools.

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