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Experimental R&D innovation for Gen-II,III & IV neutronics studies in ZPRs: a path to the future ZEPHYR facility in Cadarache

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Abstract

The experimental programs performed in EOLE and MINERVE ZPRs for the last 40 years have been very fruitful for the understanding of LWR physical phenomena, and have generated a large experimental database of core physics data. Today these facilities are nearly fifty years old and would require an important refurbishment in order to comply with new safety criteria against earthquakes and to meet the post-Fukushima requirements. Therefore, the French Atomic and Alternative Energies Commission (CEA) started the project of building a new facility in Cadarache, called ZEPHYR, designed for offering at least the same level of services as EOLE and MINERVE. ZEPHYR, for Zero power Experimental PHYsics Reactor, an acronym in reference to its mythology family ties with EOLE, is a project led by CEA, in parallel to its numerous international collaborations in experimental reactor physics. ZEPHYR is intended to be a modern R&D tool dedicated to reactor physics research (nuclear data, code validation in fundamental, mock-up and degraded/accidental configurations) open to the international community and Academia, whose functionalities and versatility will make it unique in the world.

1. Introduction

For several decades, the French Atomic and Alternative Energy Commission has been undertaking experimental programs aimed at validating the calculation tools used to design standard and advanced LWRs. Two critical facilities [1] located at Cadarache have been mainly used to mock-up actual situations arising in LWRs in the EOLE facility, and measuring integral absorption cross-section of specific materials in the MINERVE pool reactor.

For example, after having investigated HCLWR concepts through the ERASME experiments in EOLE in the 80's, many programs were launched for mocking-up PWR situations in France, and then in ALWRs - in collaboration with Japanese industrial partners - from 1990 to 2005. The MINERVE facility was used to investigate burn up credit in collaboration with UK or to measure absorption cross-sections of heavy nuclides in collaboration with USA, through the INERI collaboration. More recently, MINERVE was

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used to determine integral capture cross-sections of current GEN-II&III absorbers and nowadays for measuring neutron characteristics of structural materials involved in the EPR™ GEN-III PWR reactor. Today, the EOLE facility is dedicated to investigate neutron vessel fluency ageing depending on both core loading and internal structures of NPP from the French fleet, through the FLUOLE2 program. In the same time, MINERVE should be used to perform the first comparison tests a new in-core instrumentation system.

These two facilities are connected to an experimental room where several γ-spectrometry benches are used to perform axial radial pin-by-pin fission ate measurements. Additionally, the MADERE platform is also used for specific measurements involving foils and dosimeters. Figure 1 and Figure 2 reproduce a bird's eye view of EOLE and MINERVE respectively.

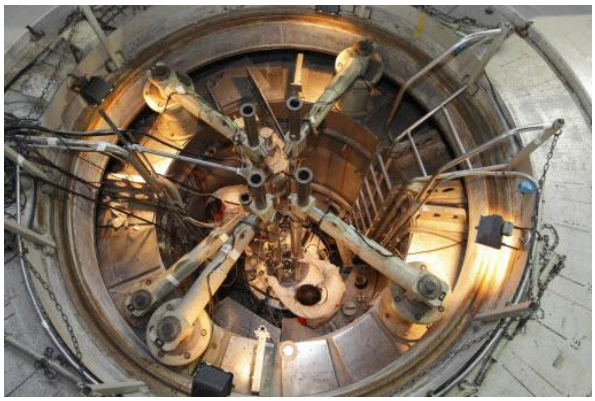


Figure 1 : The EOLE facility



Figure 2 : The MINERVE pool-type reactor

2. The ZEPHYR Facility

The experimental programs performed in EOLE and MINERVE were very fruitful for the LWR physical phenomena understanding, but today these facilities approach fifty years old and should be strongly refurbished in order to satisfy the safety criteria against earthquake and to meet the post-Fukushima requirements. Instead of renewing these facilities, CEA and its partners have begun to design a new facility in Cadarache, called ZEPHYR[2], aimed at offering at least, the same level of services as EOLE and MINERVE for the LWR codes experimental validation.

2.1 main experimental characteristics

The experimental capabilities expected for ZEPHYR will not only include those of EOLE and MINERVE, but also several ambitious improvements in terms of operation margins, fuel loadings, heterogeneous configurations, as well as innovative experimental techniques and associated instrumentation. One main ZEPHYR challenge is to combine the basic functionalities of EOLE and MINERVE in a single facility, which implies preserving both EOLE's experimental flexibility to validate a wide range of reactor physics methods and calculation procedures, as well as MINERVE's capabilities for oscillation measurements in various spectra for improving nuclear data. Other additional features of ZEPHYR are the following:

- Possibility to perform coupled core configurations:

[2] ZEPHYR for Zero power Experimental PHYsics Reactor.

  - central area under water and self-critical (EOLE-like configurations) or –
  - central area under air (harder spectrum with possibility of MOX fuel rods and/or a smaller moderation ratio for fast spectrum configuration, with a sufficient size and a modular driver core,
- Multiple control rod mechanisms, adding more flexibility in the programmes with regard to the safety constraints,
- Homogeneous sample heating and cooling system to measure high and low temperature Doppler effect under air or water configuration,
- Mobile automatic pilot with controlled feed-back from the oscillation function (oscillator or handling cask) and from the function of sample permutation under air and water configurations,
- Thermal/fast reference flux device for detector inter-calibration (fission chambers).
- Intensive training tool after the ISIS reactor shutdown,
- Qualification of computational tools and experimental devices for Jules Horowitz Reactor (JHR),
- Computation of irradiated fuel sample worth,
  - Reception of GEN-II,III, GEN-IV and MTR irradiated fuel samples for oscillation,
  - prediction of reactivity loss,
- study of power distribution and neutron/gamma fluxes, using PIE on activated fuels under air or water by γ-spectrometry measurements.

Besides the above improvements, other potential ZEPHYR functions could include:

- Possibility to insert experimental loops of JHR type, such as NaK loop, possibly heated,
- Enhanced dosimetry capacities.
- Enhanced operation capabilities, particularly dedicated to education and training,
- Criticality/safety representative configurations,
- …

2.2 Status of engineering design

The main civil engineering work design is under completion. The reference design includes only one concrete structure to duplicate both EOLE and MINERVE specificities, namely the "2 in 1" concept but with a significant limitation regarding the operational point of view. Thus, the initial “2 in 1” concept has been revisited and other designs, among which a “2 in 2” with enhanced capacities. An example of a design very close to the current EOLE/MINERVE is given on figure 3. The decision between the different concepts will be made at the end of the preliminary design phase, foreseen at the end of 2016.

For the EOLE part, the core layout has been enlarged in order to treat coupled cores, as well as larger LWR lattices for the study of eigenvalue separation. The number of possible safety rods has been extended from 4 to 6. The EOLE part will mainly be dedicated to industrial applications (code validation, validation of innovative designs,…).

For the MINERVE part, the pool reactor concept has been maintained. The structures are reproduced as it is, but with the possibility to study coupled fast/thermal lattices.

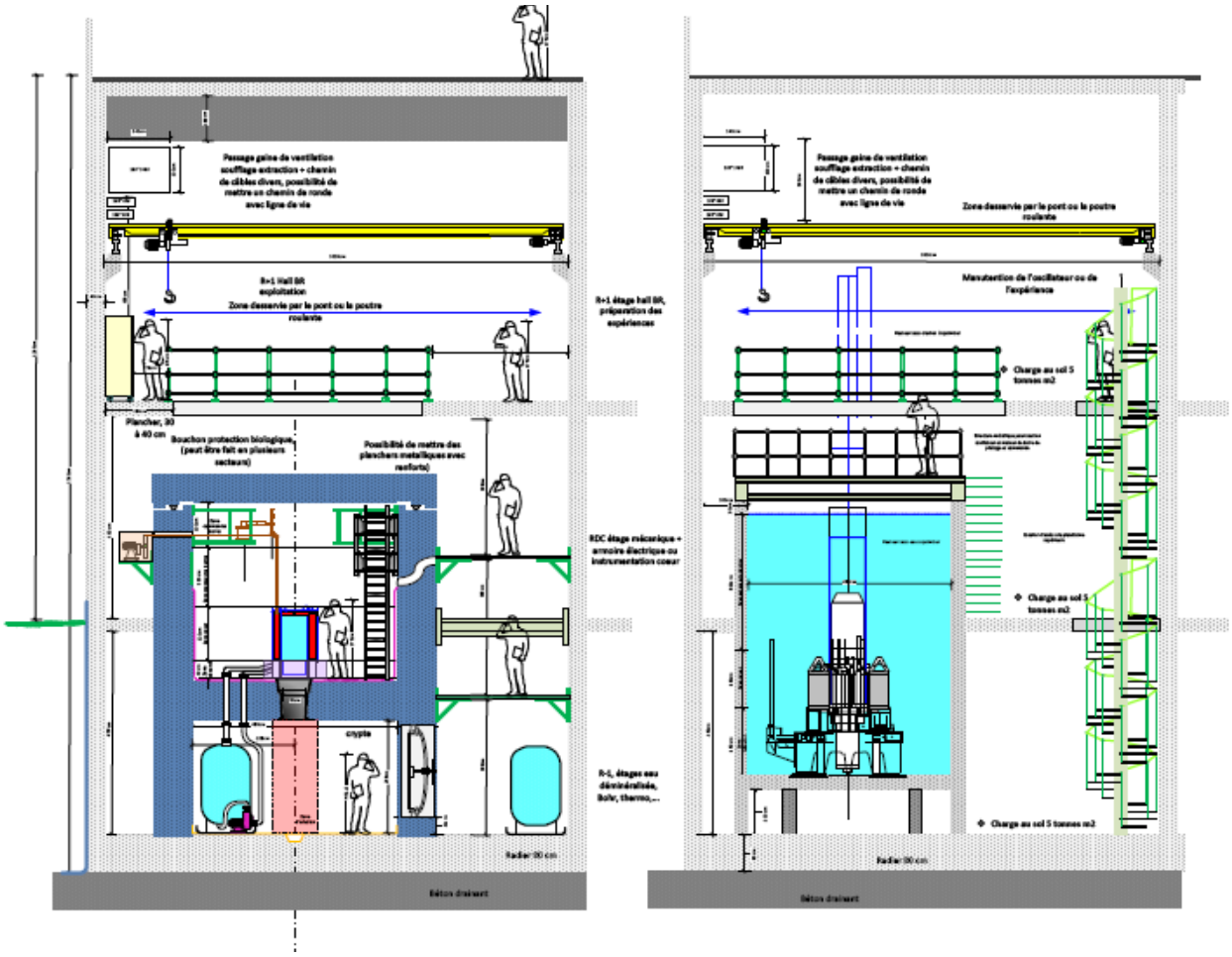


Figure 3. Axial cross-sectional view of the main building

The facility storage has been designed to accept current EOLE and MINERVE fuels, as well as (limited amount of) rods and plates from MASURCA, for fast/thermal coupled core studies.

3. Focus on some on-going R&D work

The two following paragraphs will detail on going R&D studies on awaited experimental improvements. For the sake of synthesis, we will only focus on two main R&D innovations: fast/thermal coupling for spectral emphasis, and core degradation recriticality studies in fast reactors. Those R&D works are lead through 2 PhD theses.

3.1 Nuclear Data improvement through optimized fast/thermal coupled lattices

For the last decades, the MINERVE ZPR located in Cadarache has produced a large range of experimental data, mainly for LWRs but also for the fast spectrum reactors through the PHENIX and SUPERPHENIX projects [2,3]. In parallel with R&D studies about sodium fast reactors, in particular the ASTRID technological demonstrator, a new interest for fast-thermal coupled cores has risen up. Those configurations consist of getting fast-spectrum neutronics characteristics in a reduced central zone, also

called the “measurement zone” or “experimental zone” while criticality is achieved thanks to a thermal driver zone. As this latter gathers the majority of fissions, such configurations allow an important reduction of fissile materials and a higher flexibility due to the thermal-spectrum kinetics parameters. The main issue is then to provide a proper fast spectrum in the center thanks to an adapted spectral conversion zone, surrounded by the thermal spectrum zone.

In order to understand the neutronics specificities of fast/thermal coupled cores, simplified calculations were performed using the fast-lattice deterministic ECCO/ERANOS system of codes. It enables an accurate calculation of the fast zone - the one of interest - whereas the thermal zone is also well computed thanks to a 1968-group cell calculation based on subgroups and probability table methods for self-shielding. Core calculations are performed in (R-Z) geometry using the BISTRO transport code in S_4-*P1* and 33 energy-groups

3.1.1 From Thermal to Fast Spectrum: Conversion and Transition Zones

The challenge to convert a thermal spectrum into a fast one requires the conception of an adaptation zone. The reference fast cell is not efficient enough to lead to the targeted spectrum within an approximate 35 cm radius zone, the current radius of the experimental zone in MINERVE. Many calculations have been performed in order to improve the spectral adaptation. It seems that two successive zones with different and specific compositions is a satisfactory compromise:

- *A conversion zone* has to suppress the main part of thermal and epi-thermal neutron flux coming from the thermal zone so as to get a fast spectrum. Fissile isotopes have been selected, in order to convert efficient slowed-down neutrons into fission neutrons on the other hand, as it appears to be more efficient because neutrons from the thermal zone strongly contribute to the criticality.

- *A transition zone* stands as a first step to the targeted fast spectrum. The conversion zone softens the fission neutrons coming from the conversion zone and cuts off the residual thermalized neutrons. Then, several sizes of materials with scattering properties (stainless steel, graphite, natural UO_2) were tested. Thanks to its “natural” and “specific” slowing-down power, $\xi\Sigma_s$ and $\xi\Sigma_s/\Sigma_a$, natural UO_2 has appeared to be the best candidate..

In ZPR, highly precise measurement techniques such as pile oscillations enable to achieve uncertainties in the range of 0.01 pcm in thermal lattices. Nonetheless, total and integral effects can only be measured. The spectral emphasis technique, relying on the modification of the adjoint-flux energy-dependence [3][4], gives a way to separate reactivity effects in integral experiments.

3.1.2 Principle of the Spectral Emphasis Technique

For a non fissile isotope, the total reactivity variation splits up into two parts: $\Delta\rho_{tot} = \Delta\rho_s + \Delta\rho_a$. The perturbation theory, here developed in a *G* energy groups in the diffusion theory, leads to :

$$\Delta\rho_a = -\sum_{g=1}^{G} \Phi^{\dagger}_{ref,g}\,\Delta\Sigma^{g}_{a}\Phi_{pert,g} \quad \text{and} \quad \Delta\rho_s = \sum_{g=1}^{G}\sum_{g'=1}^{G}\left(\Phi^{\dagger}_{ref,g'} - \Phi^{\dagger}_{ref,g}\right)\Delta\Sigma_{s}^{g\to g'}\Phi_{pert,g}$$

The main difference between those expressions is the adjoint flux contribution to the reactivity effect. Indeed, whereas the $\Delta\Sigma^{g}\Phi_{pert,g}$ term is multiplied by $\Phi^{\dagger}_{ref,g}$ for absorption, it is multiplied by $\left(\Phi^{\dagger}_{ref,g'} -\right.$

$\Phi^{\dagger}_{ref,g}$) for scattering. Consequently, if the adjoint flux is energy-independent, $\Delta\rho_s = 0$ and therefore, $\Delta\rho_{tot} = \Delta\rho_a$. Using another configuration, with a strong energy dependency of the adjoint flux, we would be able to separate the absorption and scattering reactivity effects. Lattice design is slightly different, as the effect to be emphasized is different.

Nevertheless, the main principle of conversion/transition zone remains identical. Figure 4 hereafter reproduces a steep adjoint (left) as well as a flat adjoint (right), obtained in optimized configurations.

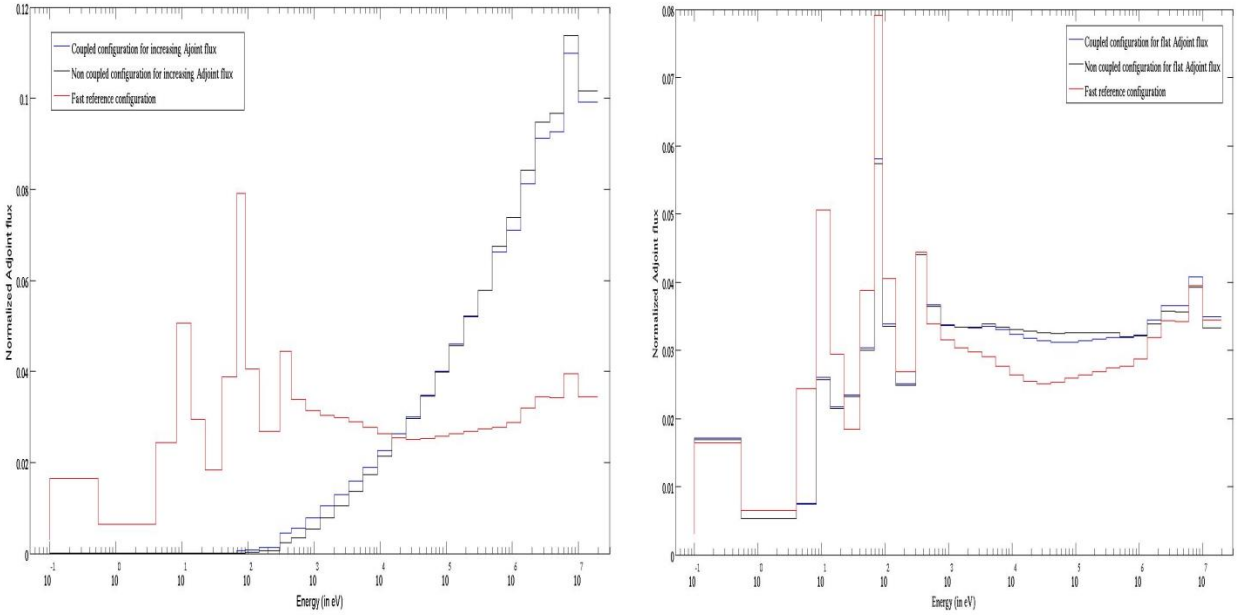


Figure 4. Strongly energy-dependent adjoint flux in the center of fast-thermal coupled or fast configurations (left) and Energy-independent adjoint flux (right)

A complete description of the preliminary design calculation for both optimized transition zones and spectral emphasis unit cells can be found in [5].

3.2. Severe accident modeling

3.2.1 Philosophy

The objective of the current study is to develop a new approach for experiments design in the frame of severe accidents studies in LWRs and FRs, due to the unique capabilities of the ZEPHYR. The underlying idea is to build a full program of tests in the future ZEPHYR facility and to develop innovative approaches to manage the measurement of reactivity effects. In order to address the objective of this work, several studies must be performed in order to provide the best design of the test lattices dealing with the following items:

- Departure from nucleate boiling and local void increase without fuel degradation
- A possibility to use MASURCA (MSK) fuel plate to locally model a fuel bundle degradation, in both LWR and FR situations. This is in order to simulate a small portion of molten fuel, which leads to a bundle blockage and vapor expansion.

Under those constrains the effect of a local reflooding will be studied and characterized. This would allow developing a methodology for slow and precise reflooding, with implementation to actual LWRs and FRs. A suggested model of the fuel lattice is presented in Figure 5. Furthermore, several feasibility studies will be performed relative to several situations:

- Problem of debris stratification – this situation represents a very interesting problem of double heterogeneity for deterministic codes, as a function of debris size.
- Problem of cladding oxidation, and in particular the ZrO_2 oxide layer and its impact on the reactivity.
- Problem of boron presence in water and its a-posteriori deposition above the debris bed.

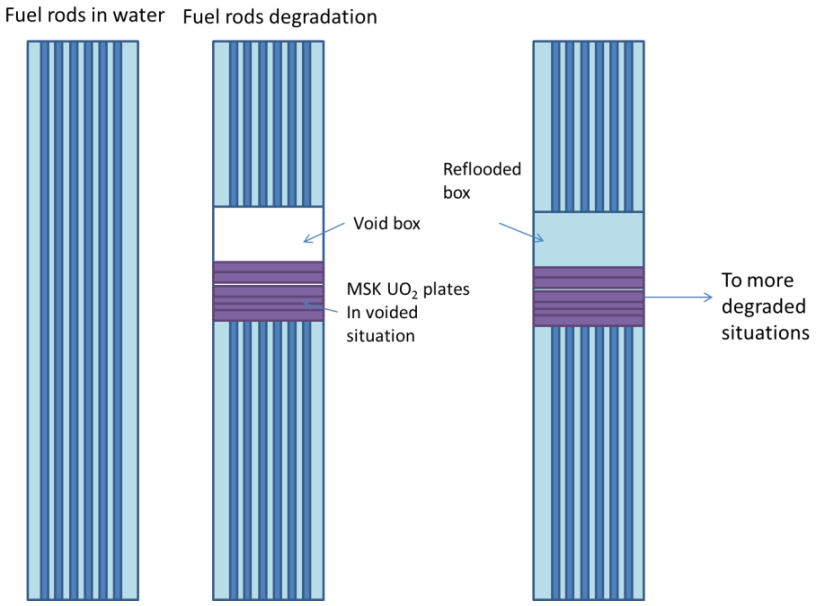


Figure 5 Suggested model for re-criticality studies for LWRs in ZEPHYR

3.2.2 On-going studies for SFRs

The main objective of this work is to evaluate two scenarios of SFR core degradation sequences, small and large core distortions. The sequence leading to core damage is initiated by total sodium dry out of several channels, which is then followed with small and large fuel compactions around the core mid plane. At the final stage the compacted fuel is relocated to the bottom part of the core, where it forms a molten pool representative configuration. The objective of the work is included in a more general framework of developing a new approach for experiments design in the frame of severe accidents studies in LWRs and FRs. The underlying idea is to build a full program of tests in a dedicated facility and to develop innovative approaches to manage the measurement of reactivity effects and local power distributions.

In SFR, Current investigations show that, under typical accident conditions, a sufficient amount of core material can be removed from the core region within the right time slot, and a neutronically active fuel pool comprising the entire core, with all its potential for recriticality energy, can be prevented. In this way, an additional middle line of defense could be introduced into the safety strategy against recriticality.

Both models show a potential of reducing the probability for recriticality events in FRs. However, they are still under ongoing investigation, both experimental and theoretical studies [6][7][8]. Therefore, there is a possibility to utilize the ZEPHYR unique capacities to investigate those models as part of the experimental program. Current R&D studies are focused on fast/thermal characteristics to reproduced in an condensed zone, severe situation that were modeled in the SNEAK facility [9][10]. The experiments in the SNEAK-12A were focused on reactivity differences between an undistorted core and a series of disturbed configurations that simulated the mentioned earlier disruptions.. The scenario consists of 4 stages:

1. Normal core operation.
2. Small fuel slump in.
3. Large fuel slump in.
4. Molten pool formation.

The next Figure 6 and Figure 7 reproduce the philosophy of SCA in ZEPHYR using its fast/thermal capacities, as well as the results obtained in SNEAK-like configuration using TRIPOLI-4 [11] and Serpent-2 [12] Monte Carlo codes, together with the JEFF3.1.1 nuclear data library .

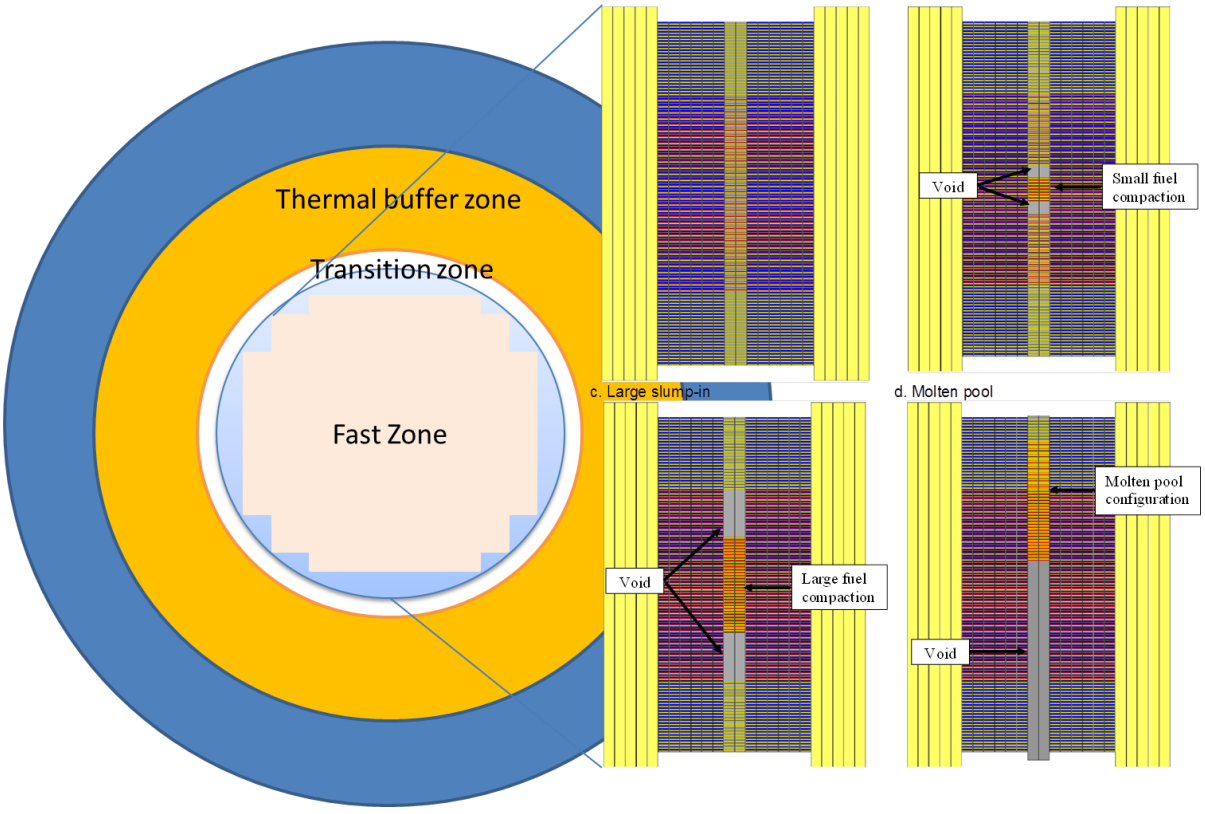
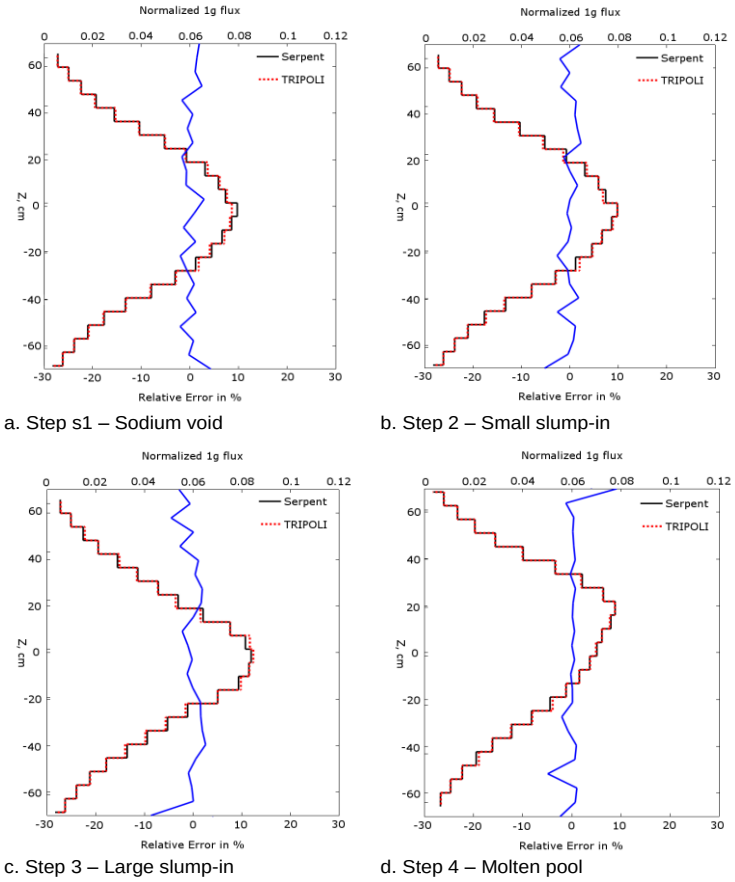


Figure 6 Suggested model for re-criticality studies for SFRs in ZEPHYR



a. Step s1 – Sodium void

b. Step 2 – Small slump-in

c. Step 3 – Large slump-in

d. Step 4 – Molten pool

Figure 7. Preliminary Axial flux shape results in the 4 SCA phase, using MC codes

Several challenges remain, as the way to take into account temperature effects in severe accident sequences. This particular item is under analysis using representativity and transposition studies, are will be treated with the ECCO/ERANOS sensitivity capacities. The complete study on SCA is reproduced in [13] and extended in [14].

4. Conclusions

ZEPHYR, the new facility to be built by CEA in Cadarache by 2025 includes innovative design features to answer key-problems in core physics and neutronics in the next decades. It reproduces, in an enhanced way, both EOLE and MINERVE characteristics, and extends their flexibilities to new features, such as nuclear data for Gen-IV reactors, coupled neutronics/thermalhydraulics capacities, criticality programs , and severe accident modeling for LWR and SFR recriticality problems. In parallel, the facility will be equipped with new capacities for instrumentation R&D, and its calibration in adapted neutron spectra, from thermal to fast.

ZEPHYR is open for international collaboration, within the frame of specific agreements for accessing the facility, and will also propose to the national and international community dedicated operation timeframe for “education and training” of young scientists, as well as operation teams for partners.

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