Scientific needs for a new generation critical facility at CEA: the ZEPHYR (Zero power Experimental PHYsics Reactor) ZPR

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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 on core physics. These fifty years old facilities could not comply with new post-Fukushima earthquakes safety criteria requirements, and the decision to close them was taken at the end of 2017. Therefore, the French Atomic and Alternative Energies Commission (CEA) started the project of designing a new facility in Cadarache, called ZEPHYR (Zero power Experimental PHYsics Reactor), for offering at least the same level of services as EOLE and MINERVE, and extending their capacities to several fast range applications. 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 should make it unique in the world. The scientific needs of a new critical facility were analyzed considering the foreseen needs of neutron calculation tools within 10-20 years, beside the unique experimental database provided by 50 years of experiments in EOLE and MINERVE to date. The major issues of current R&D needs address both nuclear data improvement for Gen2 to Gen-IV applications and innovative calculation tools (in particular non-equilibrium situations such as transients, 3D kinetics effects, as well as explicit instrumentation, and residual models). Analysis showed that the ZEPHYR project, as currently designed, versatile and flexible, with extended spectral capabilities, could be an essential element of the validation strategy by separate effects of future core physics calculation tools in a large range of spectra and configurations.

1. Context

For several decades, the French Atomic and Alternative Energy Commission – CEA - has been undertaking experimental programs aimed at validating the calculation tools used to design standard and advanced LWRs. Two critical facilities located in Cadarache center have been mainly used to mock-up actual situations arising out of LWRs in the EOLE facility, and measuring integral cross-section of specific materials in the MINERVE pool reactor. The experimental programs performed in EOLE and MINERVE were very fruitful for the LWR physical phenomena understanding, but today these facilities are fifty and almost sixty years old respectively and should be strongly refurbished in order to comply with the safety criteria against earthquake and to meet post-Fukushima requirements. Instead of renewing these facilities, CEA has begun to design a new facility in Cadarache, called ZEPHYR – Zero Experimental PHYsics Reactor - aimed at offering at least the same level of services as EOLE and MINERVE for both LWR core physics experimental validation and, to a certain extent, nuclear data for Gen-IV applications.

EOLE and MINERVE ZPRs were definitively shut down by the end of 2017, MASURCA – the last but one ZPR for fast application in the world - in 2018, and their replacement by a multipurpose ZPR is mandatory. However, before launching such an investment, it is essential to ask the question of the scientific need still lacking that could potentially be covered by such an experimental facility for the next decades.

The two elements needed to calculate a neutron reactor are **computing software** solving the Boltzmann equation (or simulating life of neutrons by the Monte Carlo method) and **nuclear data** which are the coefficients of this equation. The validation of calculations must therefore treat these two elements, in the most comprehensive way possible and by separate effect (as far as possible) to reduce trade-off between uncertainty and bias in models, data, measurement conditions….

However, with the emergence of HPC, Monte Carlo methods are now considered as "reference", or "best estimate" solution for core physics problems. Hence, the use of ZPR evolved in time, from an historical period where - to be a bit caricatural - any core design needed its own ZPR, to a current situation where mock-up is based on representativity approach, to infer the correct feedback on nuclear data and calculation schemes. The latest PERLE and FLUOLE programs made in EOLE for example (respectively for Gen-III+ stainless steel validation and fluence calculation in mixed cores), were fully designed using Monte Carlo and addressed propagation problems.

The last twenty years saw the rise of extensive Monte Carlo capacities: through Monte Carlo models, reference calculations (without methodological bias) are now available, and allow to separately evaluate computational biases due to deterministic schemes and uncertainties propagated from the nuclear data. Therefore, for all situations where Monte Carlo calculations are already validated (ie the programs already performed in EOLE and MINERVE), this need for deterministic validation – with fixed nuclear data evaluations - is almost completed without going through a C/E comparison, as Monte Carlo can serve as "numerical reference". However, the Monte Carlo "residual" models (which sometimes involve nuclear data in a very intricate way) still remain to be fully validated at all scales: they encompass 3D kinetic situations (transients), instrumentation modeling (electromagnetic cascades and others) statistical modeling of "stochastic" fuels or absorbers (« double heterogeneity » linked to the nature of the material). In the first two cases, the need for validation mixes both code models and nuclear data - as time passes by, the border between becomes less and less clear. The mock-up need is still considered, but essentially for safety demonstration. This awaited evolution is reproduced on Figure 1.

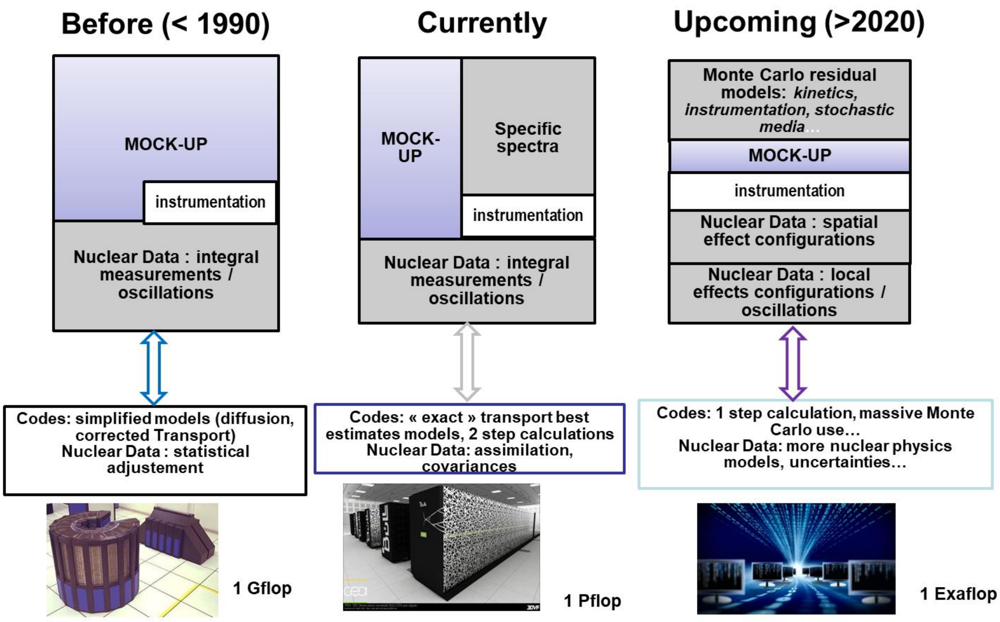

Figure 1. Evolution of ZPR through the « Nuclear age »

Based on this preliminary analysis, the flexibility of the ZEPHYR facility is studied.

2. Main experimental characteristics

The expected experimental capabilities for ZEPHYR not only will 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. We will hereafter mainly focus on work done so far on core versatility for nuclear data applications and "exotic" studies, applied on severe accidents or transient analysis.

2.1 Nuclear Data experimental validation needs

Given the maturity of calculation tools (improvement of numerical methods, increased computer power ...), the need for qualification of nuclear data has become essential, uncertainties on nuclear data being the predominant part of uncertainties in all core calculations.
Current uncertainties given by so-called "differential measurements", limited by the experimental techniques and instrumentation, do not allow reaching target uncertainties on core parameters, such as critical mass, reactivity coefficients, or power distributions. The analysis of representative configuration in ZPR is the only way to assess the integral information required to reduce the posterior uncertainties on nuclear data, using Bayesian-based assimilation techniques. *The analysis of integral measurements is the only way to obtain target uncertainties on safety and performance key-parameters*, unachievable through differential measurements. To this end, integral measurements and oscillation (including in temperature) are essential to reduce margins and uncertainties in the design of future reactors. The objective of the current work on nuclear data integration is increasingly pushing nuclear physics models in assessments, to complement more effectively the available measurements, or even to replace them. A combined analysis of oscillations measurements (giving information on the searched isotope), which can be described as *semi integral*, and critical (ie *integral*) configuration (giving the missing correlations between isotopes) is the tool of excellence to ensure the best validation of these models, as a supplement to differential measurements.

The current and well-identified lacks in the field of Nuclear Data are, briefly:

- Measurements in the 10eV to 100keV energy range, corresponding to the slowing down part in LWR, spectra in moisturized situations fuel fabrication workshops, requiring additional criticality-safety studies, and lower part of the unresolved resonance range for soft fast spectrum applications.
- Measurements at temperature within representative normal and incidental operation ranges[1], in adequate spectrum
- "inelastic" scattering dedicated measurements (typically transmission/ neutron propagation),
- Measurements of isotopes (poisons, minor actinides, fission products) participating to the loss of reactivity during cycle and burn-up credit for high depletion rates[2].

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[1] A heating/cooling device has been integrated to the initial design, in order to measure Doppler or crystalline effects in samples cooled down to -200°C or heated up to 2000°C (for safety margin characterization)

[2] Possibility to oscillate highly Gen-II to Gen-IV irradiated samples up to 150 GWd/T. This functionality is still under investigation, as the associated initial investment (shieldings, glove boxes & alpha boxes) is high.

Nuclear data are expressed in two ways: **locally** for reactivity effects associated with absorption (capture and fission, typically highlighted by oscillation) or **spatially** for scattering effects (typically a reflector effect) or the delayed neutron data. Therefore, providing a mock-up core, offering spectral flexibility, instrumented with an oscillation device could potentially cover all nuclear data issues.

The ZEPHYR project incorporates innovative features that meet the above requirements. In particular, the fast/thermal coupled core approach will permit to cover a wide range of spectra. Connected to the newly validated local/global oscillation technique in MINERVE [9] and associated instrumentation, it will enable to reduce experimental uncertainties by unfolding partial cross sections effects, and improve nuclear data.

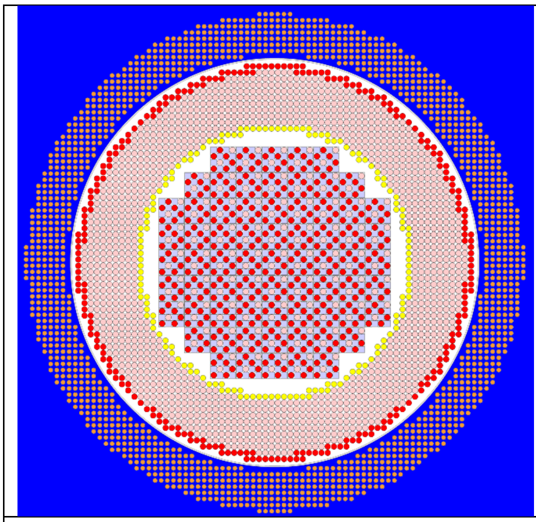


Figure 2. Fast-thermal configuration - TRIPOLI-4® model in X-Y plane

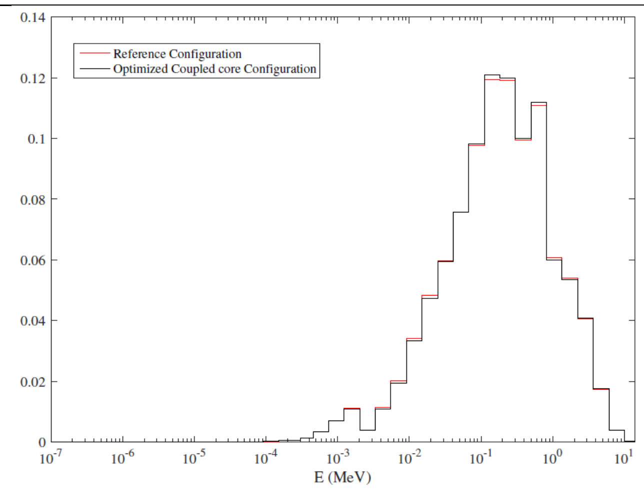


Figure 3. Fast-thermal configuration - Neutron spectrum in the central channel

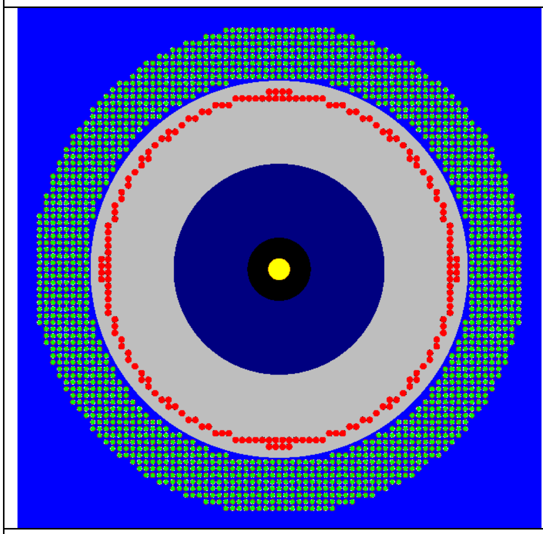


Figure 4. Epi-thermal configuration - TRIPOLI-4® model in X-Y plane

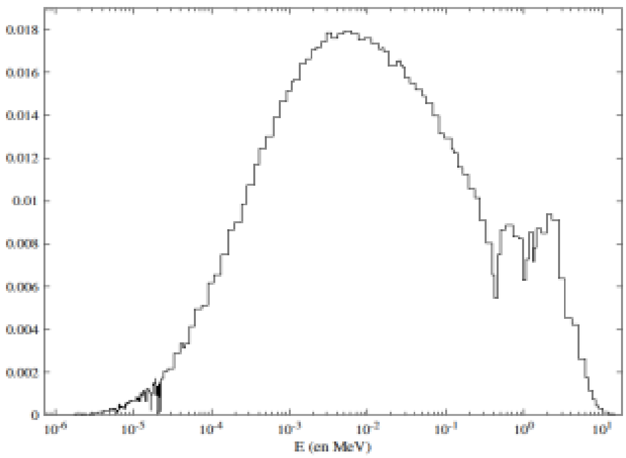


Figure 5. Epithermal configuration - Neutron spectrum in the central channel

Legend: Light blue: light water – Dark blue: heavy water - Orange: UO2 e=3.7% – Red (ring): metallic U e=30.2% – Black: Boron Nitrate - Salmon: natural UO2 – Yellow: B4C – Red (pin): MOX f=27% – Light purple: sodium – White: air

A new collaborative project is currently being started with the University of Cambridge, to address ND targeted experiments dedicated to advanced molten salt AGR designs.

2.2 Neutron codes experimental validation needs

The needs for new SCO (Scientific Computing Tools) was also investigated, as part of next functionalities. Within this analysis, uncommon use of ZPR was proposed. The ability to perform reference (ie full 3D) transient calculations in Monte Carlo (coupled *a minima* with thermal hydraulics) would be a significant improvement for the understanding and analysis of these situations: The aim is to provide designers and operators with calculation models offering a comparable degree of confidence (margins and uncertainties) than the current static calculations. Innovative hybrid MC-based approaches (transient fission matrices and multipoint kinetics) are currently studied, using challenging dominant ratio / flux harmonics approaches, to design dedicated weakly to strongly coupled configurations in ZEPHYR, and conduct first-of-a-kind dynamics measurements.

Some examples of new core physics problems and their investigation in the ZEPHYR facility are given below.

2.2.1 Severe accident reactivity modelling

Genetic algorithms have been used to design representative configurations of severe core degradation sequences, from local fuel melting, to larger melted zones. The challenge was to take into account temperature effect arising n the actual core (> 3000°) and translate it into a mock-up condition (20°C°. This was done using a two-step sensitivity based algorithms: assembly level using particle swarm approach as a first picture of the target, followed by a steepest descent algorithm to converge to the highest core representativity. This first-of-a-kind design methodology [5] was tested on the ASTRID heterogeneous core (Figure 6), and extended to the ELSY lead cooled fast reactor [6], as a demonstration of ZEPHYR versatility.

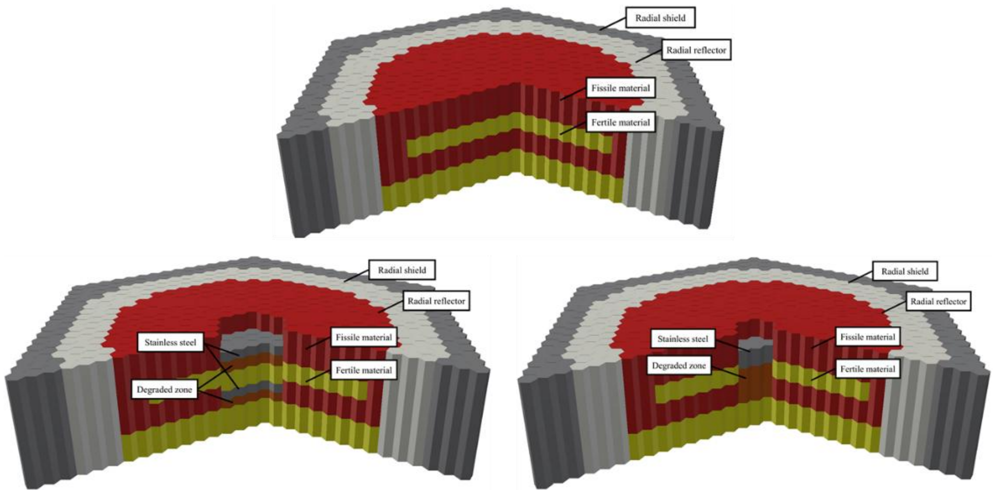
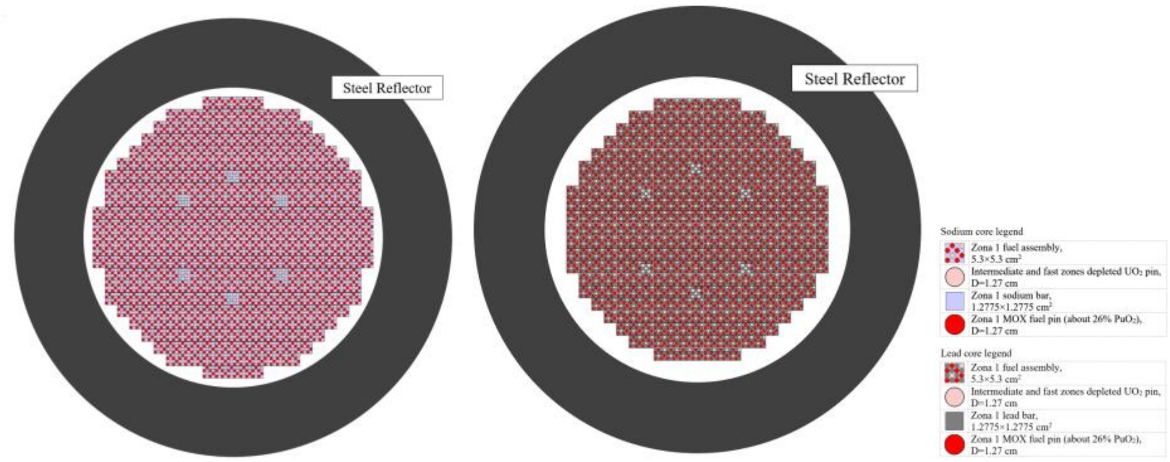


Figure 6 Astrid degradation sequence

This sensitivity approach on reactivity effect also demonstrated that the initial fast/thermal coupled core design was inappropriate for large reactivity effects, since the sensitivity from the indirect part of the perturbation becomes dominant in the perturbation analysis. The best representativity reached is around 0.6 for the coupled core, as the target value is expected to be around 0.85-0.9. So, first images of full fast cores were proposed for that purpose. Their viability (fuel stockpile, associated ventilating system) is under investigation. They are reproduced on Figure 7. The final representative for the full fast SFR configurator is 0.96 (0.86 for the representativity effect of fuel melting). The representativity for the lead cooled ELSY configuration is 0.95.

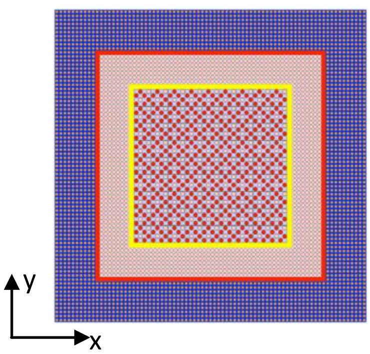


(a) ZEPHYR-S(odium). (b) ZEPHYR-L(ead). (c) Legend.

Figure 7. ZEPHYR full fast lattices. Left: SFR-like, Right: LFR-like

2.2.2 Complex 3D kinetics capabilities

Two methods are currently being used to analyze ZEPHYR's neutron kinetics behavior. The first method is a variation of the well-known point kinetics model called multipoint kinetics. The second method is called the Transient Fission Matrix method [8] or TFM. Fission matrices are used to describe the spatial probability distribution of fission events in a region-discretized geometry (assuming said geometry contains fissile elements), occurring from neutrons coming from other regions. The TFM approach is a time-dependent version of the standard fission matrix method. The method pre-calculates the time-dependent transport characteristics and enables less resource-demanding transient calculations. A few examples of the TFM method at work are given below. The geometry in question is a square 2D representation of ZEPHYR, shown in Figure 8. Figure 9 shows the part of the geometry where the 1D TFM analysis was performed.



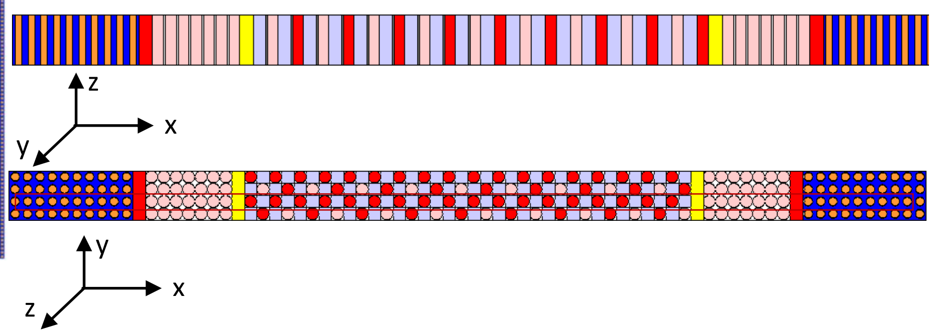


Figure 8: squared 2D representation of the ZEPHYR optimized fast/thermal coupled configuration

Figure 9: 1D Traverse of the optimized fast/thermal coupled configuration

Figure 10 and Figure 11 show the contribution of prompt neutrons. The diagonal terms represent the probability that a neutron born in a given node will produce another neutron in the same node. In the thermal part of the geometry (nodes 1-10 and 64-74), this is even more pronounced, a result of the lower neutron mean free path. All figures also show that the metallic uranium placed in node 11 produces most fissions occurring in the system, as expected.

It can also be seen that the two parts of the core – fast and thermal – are quite decoupled. Neutrons produced in the thermal zones do not reach the fast zone, due to the fact that most of them are quickly thermalized in water and the rest are either being utilized by the metallic or natural uranium between the zones or ultimately thermalized and absorbed in the B_4C ring. As for the adaptation zone, any fissions there are the result of fast neutrons mostly coming from either the metallic U or the central fast zone.

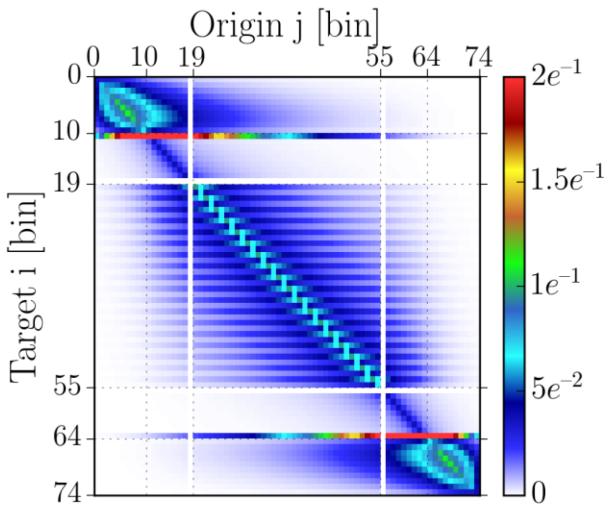


Figure 10: $\underline{G}_{\chi_p\nu_p}$ "prompt-to-prompt" fission matrix

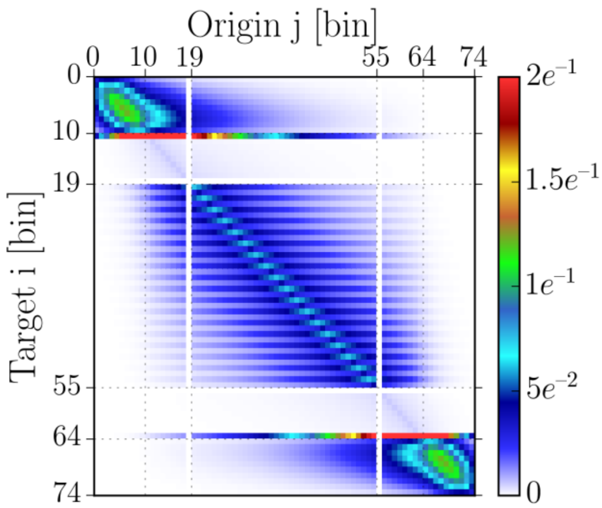


Figure 11: $\underline{G}_{\chi_p\nu_d}$ "prompt-to-delayed" fission matrix

The complete analysis can be found in [7].

2.3 Innovation in Experimental techniques and Instrumentation

A key-issue for improving both models and nuclear data is in the reduction of experimental uncertainties. It currently represents to limitation in the process of ND reassimilation. Hence, an important step ahead is the development of more precise and less intrusive techniques and associated instrumentation is considered. Several improvements have been done the past 5 years in both domain, through techniques (so-called local/global oscillations[9], noise measurements leading to delayed neutron families[10], improved dosimetry, etc…) and associated instrumentation (grated optical fibers for on-line neutron & gamma monitoring[11][12], micromegas development, subminiature and optical fission chambers,…).

Regarding the explicit modeling of nuclear instrumentation, reference spectrum locations for testing and calibration will be provided, both in-core and ex-core (reflector).

3. Project design and schedule

The preliminary design is now being consolidated, with a target budget of about 80M€ (extra-cost margins included). The reactor building includes a single core facility, merging EOLE and MINERVE functionalities. The optimization process included the unique oscillation capacities from MINERVE in the more versatile EOLE ZPR. The core structure, historically made of concrete, is now composed of a stainless steel structure able to sustain various configuration structures, from compact water tank to voided – heavier - fast configurations. The Instrumentation and Control is now composed of 6 control rods and one pilot rod. If the use of 4 control banks remains the reference situation for LWR configurations, its extension to 6 control rods enables larger or less reactive cores (as expected for fast/thermal systems, or full fast systems).

Once the green light provided by the Ministries, the project could enter its detailed design process with an expected review one year later, leading to both call for tender and safety clearance process. The building work itself is foreseen 3 years after the review. The building work, including initial tests should take 4 years, followed by a 1-year inactive tests. The active phase, leading to operational use, is expected to start 10 years after the green light.

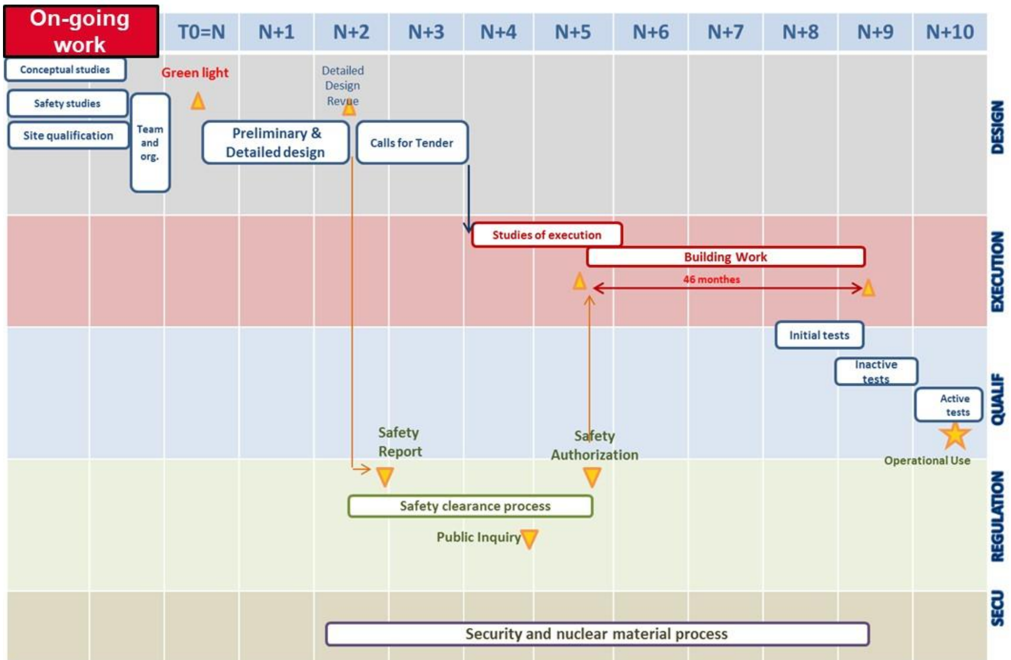


Figure 12. Foreseen ZEPHYR design and building schedule

4. Conclusions

For some time now, the French Alternative Energies and Atomic Energy Commission (CEA), has been working on the design of a new ZPR called ZEPHYR (Zero power Experimental PHYsics Reactor). The ZEPHYR project sets high expectations for the new facility. It is fully replacing the EOLE and MINERVE ZPRs, and partially being a substitute for the MASURCA fast ZPR, now also shut down. As such, it must be able to match and exceed the capabilities of both reactors, while being versatile enough to meet experimental challenges that might arise in the future, in particular innovative Gen-III and fast reactor applications.

The ZEPHYR project, as currently designed, thereby should enable a complete coverage of validation needs for the next generation of calculation tools and nuclear data libraries, encompassing Gen2&3 core physics, as well as Gen-IV for inferring nuclear data improvements through integral measurements.

Its current investigated capacities include:

- Thermal (water cooled) UO_2 and MOX configurations (homogeneous or mock-up),
- Fast (sodium/lead) uranium lattices,
- Fast (uranium and MOX)/thermal (whatever) capacities.

Moreover, due to some design characteristics, some kinetic aspects of Monte Carlo, as well as the residual models will also be studied. Recent work on fast-thermal coupled cores has demonstrated their relevance and performances in terms of spectral conversion. Optimization based on available fissile and structural materials, coming from both EOLE/MINERVE and MASURCA facilities, have led to excellent neutronics characteristics. Besides, spectral emphasis capacities should be used as a powerful technique to separate reactivity contributions in integral measurements and improve the posterior knowledge of important isotopes.

The extension of ZEPHYR functionalities to partial Thorium (fast/thermal, using available MASURCA rodlets), or MSR design capacities is currently being investigated.

Those results will be useful to design new experimental programs for the GEN-IV-reactor generation in the future ZEPHYR ZPR facility in Cadarache, once built. Those unique features will make of ZEPHYR an attractive facility open to the international academic and industrial community.

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