Neutron commissioning in the new CABRI Water Loop Facility

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***Abstract*— The CABRI experimental reactor is located at the Cadarache nuclear research center, southern France. It is operated by the Atomic Energy Commission (CEA) and devoted to IRSN (Institut de Radioprotection et de Sûreté Nucléaire) safety programmes. It has been successfully operated during the last 30 years, enlightening the knowledge of FBR and LWR fuel behaviour during Reactivity Insertion Accident (RIA) and Loss Of Coolant Accident (LOCA) transients in the frame of IPSN (Institut de Protection et de Sûreté Nucléaire) and now IRSN programmes devoted to reactor safety. This operation was interrupted in 2003 to allow for a whole facility renewal programme. The main goal of this reconstruction project is to meet thermal hydraulics parameters identical to LWR standard and downgraded conditions, in particular for the need of the CABRI International Programme (CIP) carried out by IRSN under the OECD umbrella. For this, the sodium cooled experimental loop is now being replaced by a pressurized water loop.**

The distinctive features of CABRI core allow for a specific neutron commissioning programme. This paper presents the parameters to be measured with associated experimental methods and also briefly introduces the instrumentation set up.

***Index Terms*— Commissioning, Core, Instrumentation, Neutron**

I. Introduction

The experiments to be performed in the CABRI facility will be confined to a pressurized water loop. This device is located at the heart of a pool type reactor. The experimental fuel rod will then stand a powerful neutron flash during the core driven power transient. A vertical channel symmetrical across the core allows the hodoscope, a unique neutron camera, to monitor the course of fissions in the experimental rod along the experiment.

The core is made of 1488 stainless steel clad fuel rods with a 6% ^{235}U enrichment. The reactivity is controlled via 6 bundles of 23 Hf rods. The reactivity worth for these control rods is ~19$.

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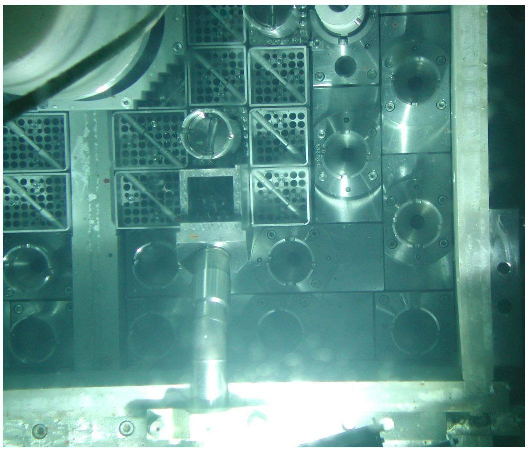

Fig. 1. ¼ CABRI core at unloading.

The key feature of the CABRI core is its reactivity injection system.

This device allows 96 tubes filled with ^3He (major neutron absorber with a capture cross section $\sigma_{He\text{-}3(n,p)T}$ about 500 times larger than Hf) up to a pressure of 15 bars and located among fuel rods to depressurize very fast into a discharge tank. The absorber ejection translates into an equivalent reactivity injection possibly reaching 4$ within a few 10ms. The power consequently bursts from 100 kW up to ~20GW (cf. fig. 2) in a few ms and decreases just as fast due to the Doppler effect and other delayed reactivity feed-backs.

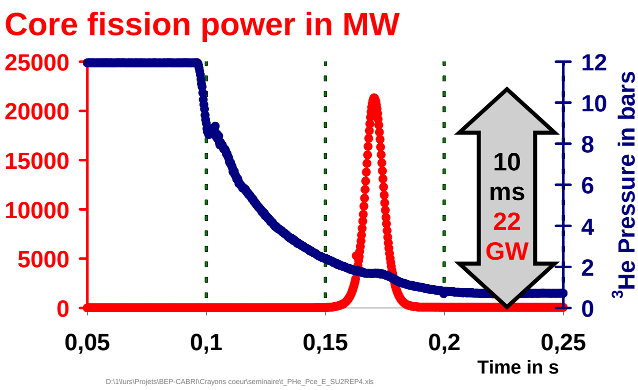

Fig. 2. Typical CABRI ^3He pressure and core power during a transient.

At the end of 2010, when the core reloading process is engaged, the facility will start monitoring count rates. This will be the renaissance of neutron commissioning, more than 45 years after this CABRI core first reached criticality.

II. Upgrading CABRI with a water loop

The CABRI International Programme was decided in order to realize tests representative of PWR accidental conditions. Initially designed for safety studies on fast reactor fuels in a sodium loop, the facility is thus being modified in order to have a water loop able to provide thermohydraulical conditions representative of nominal PWR's.

The CABRI + project is a facility side of the CABRI INTERNATIONAL PROGRAM initiated by IRSN in the late 90's and including about 20 partners.

In that respect, IRSN is the technical support for the french safety authority.

The main goal of the CABRI + project was to replace the experimental sodium cooling loop by a pressurized water loop.

Installing water cooling for the test rod will allow to be more representative of PWR's, essentially during the post rod failure phase when there can be fuel-coolant interactions. It will be used to test future high burn up fuels and to re-assess current safety margins.

Fig. 3. The basket : support structures for the new CABRI water loop.

Figure n° 3 before shows what volume it takes to put a pressurizer, a pump, a few heat exchangers and a couple of valves.

The experiments performed in the past with sodium cooling were mostly Fast Breeder Reactor oriented but some tests were done with Light Water Reactor severe accident features.

The CABRI facility is made of an experimental loop containing the test rod at the core center. A special neutron camera, called a hodoscope, allows to track the power burst in the test rod from outside the core.

The core is made of 1488 UOX fuel rods. These rods are steel clad to allow them to withstand the numerous power bursts performed in the facility. There have been about 700 pulses since the beginning. The active part of the core is the size of a small refrigerator.

Upgrading this facility is a major challenge that has to be carefully accounted for. Six years after the beginning of operations several safety and technical improvements have already been achieved to fulfil the project and only a few still remain to be done.

The technological upgrade issues essentially concerned replacing a major heat exchanger, inspecting and fixing all primary circuits, installing new vessels and capacities where necessary, putting a safety brake on the crane for heavy lifting, designing and realising a handling cask for experimental fuel, controlling the ^{3}He circuit, installing a new water treatment station and developing the current facility liquid waste circuit.

The safety issues were largely dedicated to strengthening the buildings, major mechanical equipments and core structures against seismic assaults, to the overall building fire protection, to the development of a new ventilation (5 times more powerful), to the design and construction of a new storage building and eventually although not the least, to a comprehensive revision of the core safety case. The safety topics were of course conducted in agreement with the prescriptions of the safety authority.

III. Reactivity

The CABRI reactor is a world unique facility for its Reactivity injection system (cf. figure n°5 next page). The main feature of this device is of course to sharply control reactivity injections however, it also could allow antireactivity injections and this might be used in the upcoming neutron commissioning.

During these tests the reactivity will be monitored in a static mode either by control rods level difference or by ^{3}He pressure difference. The integral and differential rods and ^{3}He reactivity worth will be measured.

The rods worth will be measured according to the MSA method [2]. This approach is based on the observation that in a subcritical system $\rho \times N = C^t$.

where ρ is the subcritical reactivity, and

N is the count rate for high sensitivity fission chambers.

Thus knowing ρ_0 for a control rods level and the corresponding count rate allows building the efficiency curve of the absorbers. This initial reactivity standard will be obtained from another type of measurement described hereafter.

Direct measurements essentially provide either a count rate or a control rods level so that only the condition of criticality ($\rho = 0$) is easy to assess. Meanwhile, this condition does obviously not allow to use the $\rho \times N = C^t$ equation.

The standard that will be used to assess the efficiency of absorbers will be given by a small positive reactivity step insertion from criticality. This offset will come from a slight extraction of the control rods, causing a slow and controlled power excursion. The relationship between power doubling time and inserted reactivity is provided by the computed “inhour“ (Nordheim) equation (cf. § VI Computational support). Then the symmetry of absorbers efficiency around the criticality level is used. It allows considering the insertion of control rods identical to their extraction will carry away the same reactivity as that injected previously.

This whole approach is summarized in figure 4 hereafter.

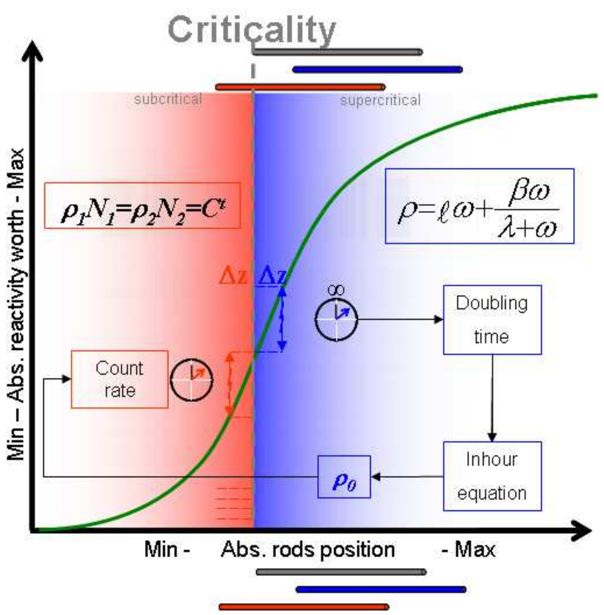

Fig. 4. Reactivity standard measurement process.

An attempt to monitor slow dynamic reactivity feedback mechanisms like moderator and coolant effect will be initiated. But also during the power bursts effort will be dedicated to make an assessment of the Doppler effect.

Eventually, the main parameters to be measured in CABRI are of course the weight of delayed neutrons and the neutron lifetime β and l. Both parameters will be acquired with a neutron noise measurement approach [1].

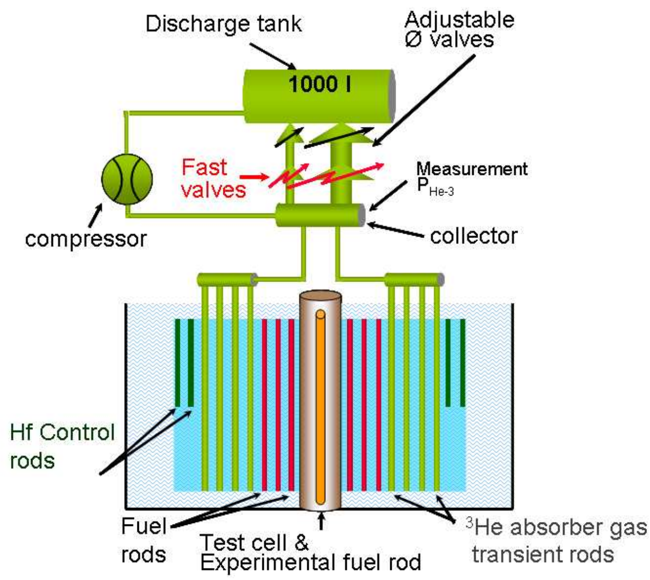

Fig. 5. Principle of operation of the CABRI facility.

IV. Power and Energy

The absolute power module will be measured at medium power by a heat balance. This will allow the calibration for experimentalists and facility operators ion chambers. During the power burst and as there can be no heat balance in such conditions, it will be necessary to rely also on an integration methodology corresponding to a dosimetry experiment. This power integration will be compared to the energy integrated by ion chambers during the peak of power as well as during a heat balance at a steady power level.

The coupling between core and experimental rod will be validated through a set of dosimetry measurements. The nature and location of dosimeters has been optimized in order to assure the best measurement.

The test device holding the dosimeters is currently being fabricated. It consists of an aluminum foil in which gold and cobalt disc dosimeters will be set. The choice for these elements will allow a comparison with the computed core neutron energy spectrum as gold is more efficient in the thermal range whilst cobalt is rather dedicated to the epithermal range.

V. Instrumentation

There will be 2 dosimetry sheets located along the hodoscope channels on either sides of the core (cf. fig. 6 hereafter). Another dosimetry device will house gold and cobalt wires, encapsulated into a tube of glass. It will be located outside the core case for an improved ease of use. It will be used to check the accuracy of high power ion chambers during pulses. An additional dosimetry experiment should be conducted within the experimental loop in order to monitor the neutron coupling factor with the core region.

All fission power related phenomena will be tracked with ion chambers: Fission chambers for absolute power levels during stable and peak conditions, compensated and uncompensated boron chambers (^{10}B enriched) for steady state power. The calibration of these chambers will be made against the heat balance described previously. Their location will be optimized within a computational approach (Méthode de la Source Modifiée –MSM– or Méthode de la Source Approchée –MSA–type [2]) in order to minimize any sensitivity to external perturbations (like flux tilting due to the ^{3}He escape) during pulse conditions.

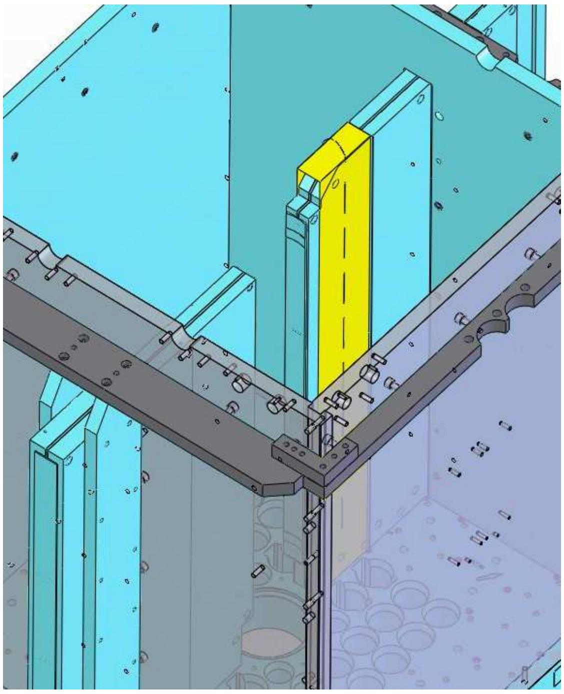

Fig. 6. Dosimetric sheet (yellow) on the irradiation channel at core center.

Temperatures and flowrates will be classically monitored in the core cooling circuit as well as in the experimental loop chiefly in order to control the heat deposited into the experimental rod. The experimental channel benefits an up-to-date specific instrumentation system with miniature and radiation proof flowmeters, pressure transducers, thermocouples and microphones but these features will not be used for neutron commissioning.

A cluster of mobile thermocouples has been added to keep away from any unexpected core heating during the first divergence. Each control rod has been equipped with a rheostatic ribbon to provide a record of the rod location including during scram. This will help evaluating the share of each individual positive and negative reactivity component like ^{3}He ejection, solid absorbers insertion and all neutron feedbacks.

Possibly, additional instruments like an ordinary fast digital camera might be used to better analyze the off core Cerenkov radiation distribution.

VI. Computational Support

None of the measurements considered in this innovative core starting programme would be possible without a massive computational support. This support will essentially be based on reactor physics characterizations of the reactor but the analysis will also benefit from the expertise of core thermal hydraulics, gas mechanics and as much as possible all coupled phenomena. The stationary neutronics are fully computed with TRIPOLI 4, the main CEA 3D Monte-Carlo neutron and γ transport code [3]. There is no need for depletion calculations as the core has a burn up lower than 3 equivalent full power days. A quarter core rodwise power distribution is given in figure 7 hereafter. It shows in particular how the fission rate is depleted in the ^{3}He rods region on the right of the figure. This corresponds to the situation before the power burst when the gas absorber pressure is high in the tubes. This power distribution has a so strong dependence on ^{3}He pressure that we have to account for the time evolution of individual peaking factors during the ^{3}He depressurization for the accuracy of thermal and mechanical performance predictions in the hot rod and adjacent pins.

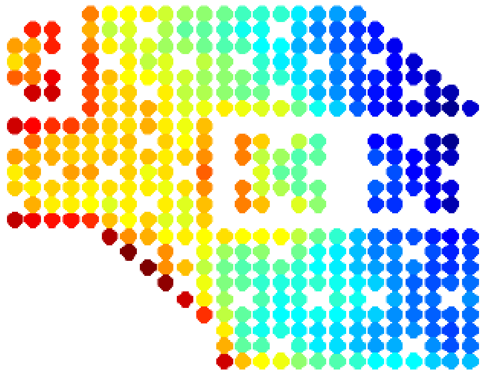

Fig. 7. CABRI Quarter core rodwise power distribution thermogram

The core behaviour during power transients is predicted and analysed with a CEA dedicated neutron kinetics tool called DULCINEE [7] and providing a time function of power to SCANAIR [4], a code from IRSN dedicated to RIA heat transfer and mechanics. DULCINEE was developed at the beginning of CABRI. It was initially dedicated to fuel plate geometries and then was adapted to rod bundle cooling configurations. The geometric model is 1 D ½, corresponding to a full radial heat transfer from the fuel center to the coolant and an axial heat flux profile without transfer. It has been especially validated against low pressure coolants like sodium and LP water. In the late 80's, a fractured fuel model was inserted allowing a better validation against experimental temperatures. It was successfully validated against the CAPRI experimental Thermal-Hydraulics programme realized at CEA-Grenoble in the late 70's. A systematic reproduction of key experiments has been recently modeled in DULCINEE. It has been compared with profit (cf. figure 8) to the comprehensive experimental data background gathered in the CABRI facility (several hundred power bursts) in the past 40 years.

The use of DULCINEE also has been improved. It now complies with better quality and ergonomics standards in the perspective of neutron commissioning. Raw experimental data now can be directly inserted into the computation. A set of simple filters selects the most pertinent channels and secures the quality of results. Users do not need open the box to choose which option corresponds to their request but just have to reply to the interface for 3 types of most standard computations. These 3 configurations are *a)*user generated reactivity or *b)*power plot or *c)*experimental power input.

The DULCINEE – SCANAIR computation scheme is the backbone of all safety studies to be done prior to commissioning. The feedback parameters were computed with TRIPOLI 4. It includes the instant Doppler effect and all delayed phenomena like clad expansion or coolant density. The delayed neutron fraction β and generation lifetime ℓ were computed with MCNP [5] according to the method proposed by Meulekamp et al. [6]. The resulting values are now completely consistent and have been successfully tested with DULCINEE against experimental data acquired during the sodium loop past programmes.

The reactivity feedbacks will be deconvoluted using inverse kinetics. As a consequence, the computational support brought to the making of this test programme will be used as much during the preparation phase as after the tests in order to improve the predictivity of computation tools.

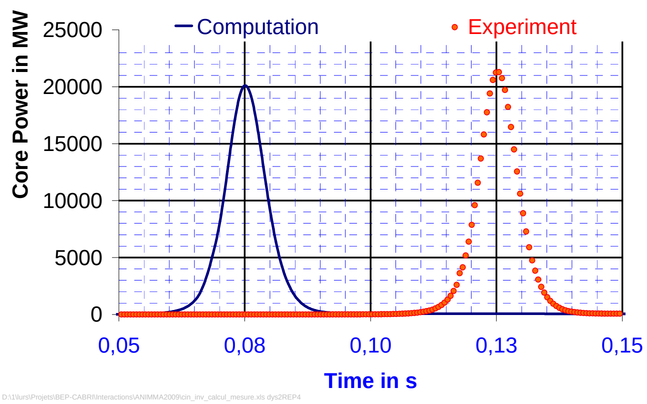

Fig. 8. Agreement between computation and experiment for DULCINEE

Figure 8 just above shows the very good agreement between computation and experiment for the DULCINEE kinetics tool during a past 10 ms duration typical pulse. The "experiment" plot corresponds to the measurement of an ion chamber whereas the "computation" plot corresponds to a reactivity driven DULCINEE computation. In this latter case, the reactivity comes from the product of 2 functions : ^{3}He pressure measurement as a function of time during the depressurization $[P_{He-3}(t)]_{meas.}$ and reactivity as a function of pressure as computed with TRIPOLI 4 $[\rho(P_{He-3})]_{calc.}$.

After verifying the excellent agreement between measurements and TRIPOLI 4 computations for criticality levels of the hafnium control rods at several ^{3}He pressures, the $\rho(P_{He-3})$ function has been confirmed. The $P_{He-3}(t)$ function is currently measured or very conservatively extrapolated from initial conditions (^{3}He pressure and valve aperture) but in the coming years, there might be a possibility to predict this function more accurately with a CFD tool. In that perspective, the assessment of local effects in ^{3}He gas absorber tubes will be necessary to help predict the reactivity injection process and in particular a phenomenon –called the TOP effect– that causes a delayed reactivity burst. This effect comes from the flash heating due to internal *n(^{3}He,T)p* reactions and generating a slight but measurable deferred repressurisation of ^{3}He during the power burst.

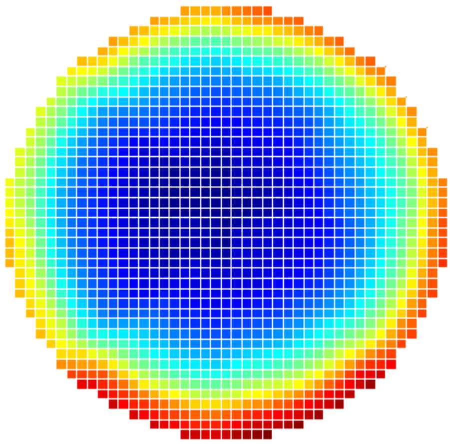

Fig. 9. ^{3}He tube internal *n,p* reaction thermogram

Figure 9 above presents the *n,p* computed reaction rate local distribution into one of 96 ^{3}He tube at a pressure of 15 bar. It shows a steep capture profile at the periphery, due to a strong spatial self-shielding effect. This computed result would justify to check the profile against a dosimetry experiment in a constant pressure mode and during power bursts, when the ^{3}He pressures decreases from ~15 bar to ~0,5 bar.

This perspective has not been considered in the range of the initial neutron commissioning process but should definitely be envisaged in a longer term perspective.

VII. COMMISSIONING PROCESSUS

The neutron commissioning will proceed stepwise from the first criticality up to the maximum allowable core configuration during start up pulses.

The main objectives for commissioning are safety and quality of experimentation.

The safety level of this experimental programme relies on a qualified team with high standard instruments and methods. A new "core start up" training programme has been proposed to the facility and it will be repeated prior to divergence to make sure all aspects are properly shared among operators.

All high sensitivity fission chambers have been checked against a calibrated source and the good behavior of all power -boron lined- chambers has been checked for real in the MINERVE facility. The linearity between low and high power dedicated chambers will be verified during the divergence process. The relation between chambers measurement (either *counts per second* or an *electrical current*) and power has been adjusted to the new computed Pressurized Water Loop configuration. However this is identical to the Sodium Loop situation, all thresholds have been decreased by 50% as if it were to reach terra incognita.

On top of this very conservative approach, the online power measurements rely not only on the chambers but also on a cluster of thermocouples to detect any unexpected heating and thus stop the divergence process.

Eventually, the core power measurement will be brought by nuclear chambers experimental and computed calibration, by heat balance and by dosimetry. Three independent and different methods should bring enough redundancy to focus on the right figure with the highest level of safety.

A nuclear commissioning cluster was initiated in the Nuclear Energy Directorate of CEA in 2008. At the facility level, operators and experimentalists gather to define their needs, then all concerned departments provide their expertise to improve the efficiency of the reactor start up. The first facility this cluster is involved with is CABRI. It has already provided a fair share of the effort devoted to this neutron commissioning and will continue to do so until the tests are completed. Afterwards, other reactors like the RES naval propulsion cores testing facility and the Jules Horowitz Reactor, both in Cadarache, will benefit the outcomes of this endeavor.

The first operations are essentially dedicated to reactivity monitoring. After core reloading and reaching the first criticality, there will be several reactivity weighting operations where the control rod worths will be measured. It will include integral rods worth as well as differential efficiency around the criticality height.

There should also be an attempt to determine the reactivity worth of a key fuel element. The core has a 4th order symmetry which obviously permits to differentiate fewer sub-assembly families than if it were to identify each of 40 elements.

The filling or voiding of specific core regions, essentially located in or around the experimental test device, should provide interesting data concerning their respective reactivity weight. The distinctive features of the reactivity injection system will be utilized as reference parameters to improve the knowledge of the control rods reactivity worth. Eventually, a set of neutron noise measurement operations will provide data pertaining to the core kinetics parameters [1].

The above mentioned reactivity oriented measurements will be performed at a core power lower than a few kW. A fair share of it might just as well be done while the core is subcritical. The source nature and location should thus be optimized in that respect.

Whilst most of the reactivity experiments should be done at low temperature and in natural convection mode, some of them are dedicated to assess feedback reactions due to forced convection and to different temperature conditions. It will thus appear later in the commissioning agenda.

Some of the power experimentation will take place during reactivity measurements issues. It concerns absolute and relative dosimetry measurements. It also corresponds to absolute power measurements with a new dedicated fission chamber.

The ^{3}He rods reactivity worth will afterwards be measured under conditions representative of actual experimental pulses, i.e. with a power ~100 kW. The usual core operations duration is of the order of a half day so that it is most probable that fission products poisoning need not be taken into account and even less measured during this commissioning campaign.

The core power will later be increased progressively until it reaches a sufficient level for High Level Power chamber calibration. These conditions range from a few MW up to the maximum allowable stationary power i.e. 25 MW. The calibration does not just involve fitting the chamber measurement to the core heat balance. It includes refined corrections due to all positive and negative terms influencing the heat balance e.g. losses to the pool or fission products delayed contribution to the overall power production.

Some regulatory radiation protection measurements will be performed when the core is at high stationary power level. It will produce a dose rate mapping of the reactor hall although the facility is remotely controlled in a building located ~200 m away.

Eventually, the last steps of this commissioning process correspond to the start up phase. This period will allow realizing RIA pulses with increasingly demanding conditions for the core. The key parameters experimentalists use to adjust a pulse to their experimental goal are relying onto the reactivity injection system (described above). It basically concerns the initial ^{3}He pressure and the ^{3}He circuit valves aperture as this latter parameter determines the reactivity injection rate.

As a consequence, it is foreseen that neutron commissioning during the RIA pulses will follow the pattern schematized in figure 9 below. The first test will be made at low ^{3}He pressure and low valve aperture and each parameter will be stepwise increased until no doubt remains on the conditions of power and energy achieved for the last test of a series (nine of them are illustrated in figure 10 below but actual tests might be different).

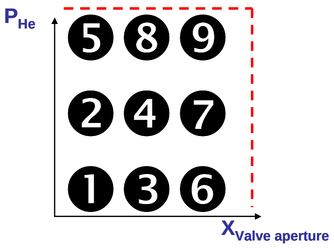

Fig. 10. Neutron commissioning path to maximum core conditions

VIII. Planning

The planning for this commissioning program considers the following four milestones :

- Core reloading : Late **2010**
- 1st criticality : Early **2011**
- 1st Power pulse : Early **2011**
- CIP-Q test : Mid **2011**

IX. Conclusion

This paper presents the neutron testing campaign of the CABRI facility. This programme will monitor Power, Energy and Reactivity. It will rely on mostly traditional instruments like ion chambers or dosimeters. However, the measurements will investigate the key physics parameters of the reactor through a new and innovative methodology. A fair part of the measurements will benefit the support of numerical characterizations either for preparation or for interpretation.

Most tests are of course necessary to assure a safe restart of the facility but some of them will also bring a better knowledge of the unique CABRI core physics.

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