FUTURE EXPERIMENTAL PROGRAMMES IN THE CROCUS REACTOR

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ABSTRACT

CROCUS is a teaching and research zero-power reactor operated by the Laboratory for Reactor Physics and Systems Behaviour (LRS) at the Swiss Federal Institute of Technology (EPFL). Three new experimental programmes are scheduled for the forthcoming years.

The first programme consists in an experimental investigation of mechanical noise induced by fuel rods vibrations. An in-core device has been designed for allowing the displacement of up to 18 uranium metal fuel rods in the core periphery. The vibration amplitude will be 6 mm in the radial direction (±3 mm around the central position), while the frequency can be tuned between 0.1 and 5 Hz. The experiments will be used to validate computational dynamic tools currently under development, which are based on DORT-TD and CASMO/S3K code systems.

The second programme concerns the measurement of in-core neutron noise for axial void profile reconstruction. Simulations performed at Chalmers University have shown how the void fraction and velocity profiles can be reconstructed from noise measurements. The motivation of these experiments is to develop an experimental setup to validate in-core the method in partnership with Chalmers University.

The third experimental programme aims at continuing the validation effort on the nuclear data required in the calculation of GEN-III PWR reactors with heavy steel reflectors. This is a collaboration with CEA Cadarache that extends the results of the PERLE experiments carried out in the EOLE reactor at CEA. Scattering cross sections at around 1 MeV will be studied separately by replacing successively the water reflector by sheets of stainless steel alloy and pure metals – iron, nickel, and chromium. Data will be extracted from the measured flux attenuation using foils in the metal reflector and from the criticality effects of these reflectors.

In parallel to the three reactor experiments, we develop in-core detectors and measurement systems. Following the last development of a neutron noise measurement station in pulse mode, a second neutron noise station in current mode is being designed. In current mode the reactor can be used at higher power without dead time effects. It allows faster measurement time or lower results uncertainties. Finally, a joint development of a full new detection system based on chemical vapour deposited (sCVD) diamond has been started with the CIVIDEC instrumentation start-up company. A first prototype has been tested in November 2015 in CROCUS. One of the main purposes is to work on the discrimination of gammas, thermal and fast neutrons for demonstrating the interest of this detector type in a mixed neutron-gamma field.

1. Introduction

This last decade, the CROCUS reactor operated by the LRS at EPFL was primarily used for teaching purposes. Only a few research collaborations with the Paul Scherrer Institute (PSI) were carried out on safety analysis [1] and neutron noise measurements [2]–[5]. After the closure of the PROTEUS research reactor at PSI in 2011, CROCUS was and remains as of today the only zero-power reactor in Switzerland. As of national interest, PSI and EPFL agreed to develop new research experimental programmes in the CROCUS reactor. An extensive review of possible experiments was carried out in 2015 [6] and resulted in the selection of three new experimental programmes. From their design, the programmes were carried out in the framework of national and international cooperations with renowned research institutes and universities, such as PSI, CEA and Chalmers University, which pledge for their usefulness for the international community. In parallel to these experimental programmes and supporting their needs, the LRS initiated the development of new instrumentations and measurement methods. This article presents in turn CROCUS, the selected experimental programmes and the activities to develop the reactor instrumentation and measurement methods.

2. The CROCUS reactor

CROCUS is an experimental zero-power reactor, uranium-fuelled and water-moderated, mainly dedicated to teaching radiation and reactor physics [7], [8]. It is licensed for operating at 100 W, i.e. ~$2.5 \cdot 10^9$ $cm^{-2}.s^{-1}$ at the core centre. Power is controlled either by water level using a spillway, or two B_4C absorber control rods, with an accuracy of ±0.1 mm (equivalent to approximately ±4 pcm) and ± 1 mm respectively. It operates at room temperature using a controlled water loop with secondary and tertiary circuits, two heat exchangers and an electrical heater.

The core is located in an aluminium vessel of 130 cm diameter and 1.2 cm thickness (see Fig 1). It is filled with demineralised light water used as both moderator and reflector. Its active part has the approximate shape of a cylinder of about 60 cm in diameter and 1 m in height. It consists of two interlocked fuel zones with square lattices of different pitches:

- an inner zone of 336 UO_2 rods with an enrichment of 1.806 wt.% and a pitch of 1.837 cm,
- an outer zone of 172 U_{metal} rods in nominal configuration, 0.947 wt.% and 2.917 cm,
- a water gap between the two zones because of the two different pitches.

Both uranium fuels consists of a 1-m pile of cylindrical pellets cladded in aluminium. The rods are maintained vertically by two octagonal aluminium grid plates spaced 1 m apart. The grids have a 0.5-mm cadmium layer to limit axial neutron leakage, with the active zone of the fuel starting above the lower cadmium layer.

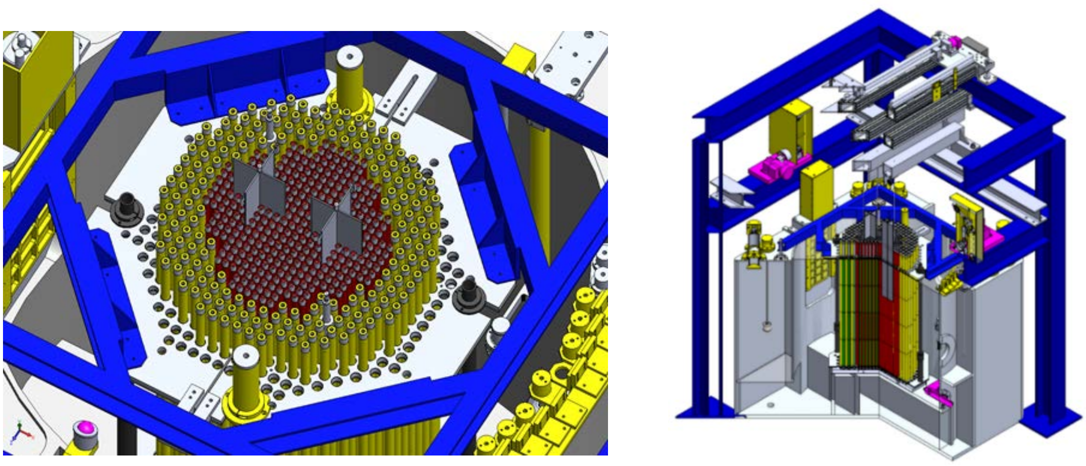

Fig 1: Top view of CROCUS core with fuel rods and systems such as cruciform safety blades and control rods (left); cross-section view of the full reactor with core and structures (right).

The six independent safety systems consist of two cruciform-shaped cadmium blades and four expansion tanks. The safety blades are held by electromagnets for top to bottom gravity insertion. The expansion tanks trap air when valves are closed, allowing a fast drop of the water level when opened. Any of these systems allow shutdown within less than a second.

3. New experimental programmes in CROCUS

3.1. COLIBRI experiments - Investigation of mechanical noise induced by fuel rod vibrations

The motivation for this investigation is the increased amplitudes in the neutron noise distributions recorded in ex/in-core detectors that have, in recent years, been observed during normal operation conditions in Siemens pre-Konvoi type of PWR reactors. Several potential explanations have been put forward, but no definitive conclusions could yet be drawn. Among others, changes in fuel assembly vibrations patterns, due to recent modifications of assembly structural designs, were pointed out as a possible primary cause. Such mechanical noise is suspected to arise from vibration of groups of fuel assemblies.

In this context, the aim of the COLIBRI programme is to carry out rod vibration experiments in CROCUS with different numbers of rods and different displacement amplitudes and frequencies. The vibration amplitude will be 6 mm in the radial direction (±3 mm around the central position), while the frequency can be tuned between 0.1 and 5 Hz, i.e. the frequency range in which the neutron flux fluctuations are most pronounced. A device meeting these requirements has been designed and manufactured (Fig 2). A first test has been carried out of pile in January 2016 with dummy fuel rods. The device allows oscillating single or groups of up to 18 fuel rods simultaneously.

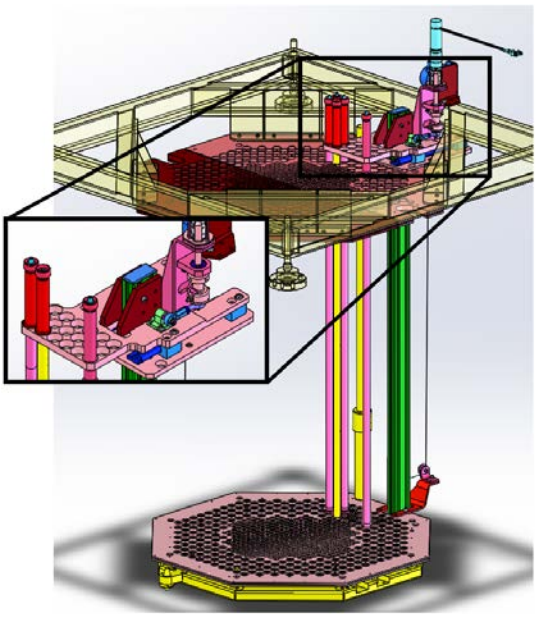

Fig 2: CROCUS Oscillator for Lateral Increase Between u_m Rods and Inner zone (COLIBRI).

Preliminary CASMO and MCNP calculations were performed to dimension the system. Moving 18 U_{metal} rods in CROCUS in the radial direction by ± 3 mm resulted in a reactivity change of ± 8 pcm with a 3 pcm uncertainty. Such a perturbation translates into a neutron flux variation that is large enough to be measured and interpreted with standard noise post-processing techniques. Considering for instance cross-power spectral density technique (CPSD), such a perturbation will generate a Dirac peak at the frequency of oscillation whose amplitude is about three times larger than that due to neutron noise – as measured in previous experiments [2].

The programme is planned to start in summer 2016. The safety assessment was performed and the licensing process will be started after the test phase with dummy fuel rods. In parallel to this experiment, computational dynamic tools – based on DORT-TD and CASMO/S3K – are currently developed at LRS to help understand the source of the additional amplitude of the noise. The experiments planned at CROCUS will be used for the first validation of the code.

3.2. VOID - Void fraction determination using neutron noise measurements

The measurement of in-core neutron noise for axial void and velocity profiles reconstruction has been demonstrated theoretically at Chalmers University assuming an idealised 1D bubble distributions measurements [9], [10]. The motivation of these experiments is to develop a setup to validate experimentally the method in-core in collaboration with Chalmers University.

The method will be tested in clean conditions in CROCUS. A square Plexiglas tube of 5x5 cm^2 located at the periphery of the core will be filled with a known void density. The axial void profile is controlled thanks to nozzle injecting air bubbles at several different elevations (see Fig 3). The airflow rate at the different elevations will be adjustable to reproduce several axial void profiles of interest – such as that of a BWR with 80 % void at the top of the channel. We will measure the void distribution at five axial elevations using the neutron noise measurement station developed at LRS [2]. The results will be compared with the same void profiles measured in a copycat channel outside of the core using standard techniques for two-phase flow visualization, like X-ray imaging.

After designing the experiments and purchasing the required hardware components last year, the safety case for this experiment will be submitted to the authorities this year. Preliminary calculations with MCNPX showed that the increase of reactivity due to an inadvertent filling of the tube (worst case scenario considering it fully voided at first) is lower than the +20 pcm excess reactivity operation limit, which should be no problem from a safety point of view.

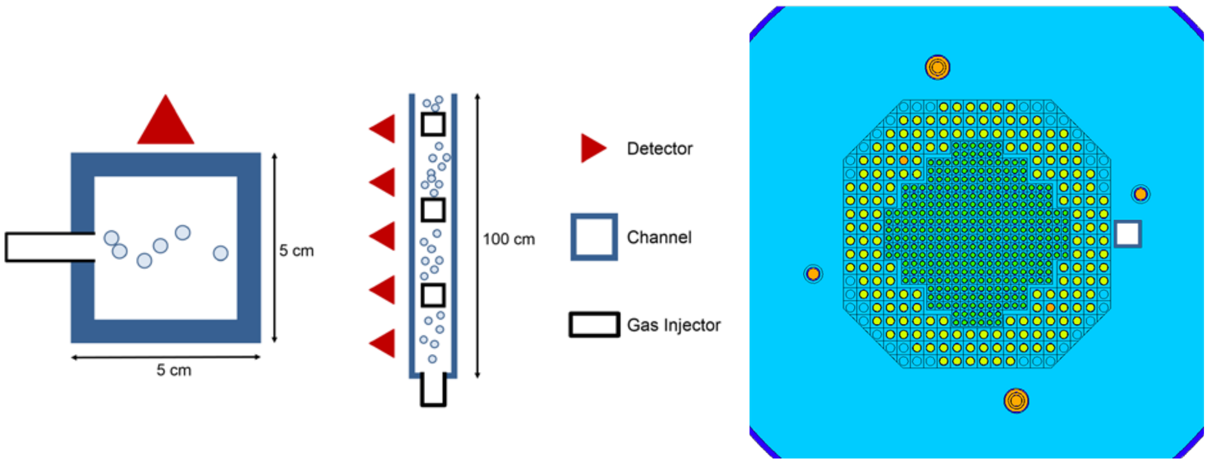

Fig 3: Top and side view of the bubbling channel (left) and location in the reflector of the CROCUS reactor (right).

3.3. PETALE experimental programme - Qualification of reflector materials for GEN-III reactors

CEA Cadarache performed an experimental programme in the EOLE reactor – PERLE – whose main purpose was to validate the nuclear data required in the calculation of GEN-III PWR reactors with heavy steel reflectors and to characterise reactor parameters such as reflector savings [11]. The PERLE experiments featured a large stainless steel buffer around a UO_2 core. Reactivity effects, reaction rates in the pin at the interface of the core and the reflector, and attenuation in the stainless steel block were measured. The latter measurements were carried out with different foils and fission chambers to assess the attenuation of the flux over different energy domains, which is sensitive to the elastic and inelastic cross-section of ^{56}Fe. These experiments showed that the ^{56}Fe nuclear data were rather well predicted in JEFF-3.1.1 and that optimized variance-covariance files could be issued.

In collaboration with CEA, the PETALE experiment in the CROCUS reactor aims to continue the validation effort on the ^{56}Fe cross-sections and its resonant behaviour and to extend the validation to the Ni and Cr isotopes by studying separately their scattering cross-sections around 1 MeV. To this end, the neutron attenuation in sheets of various thicknesses located close to the CROCUS fuel will be measured using dosimeters (foils) and possibly fission chambers. In addition, reactivity worth will be measured by the change of water level necessary to reach criticality.

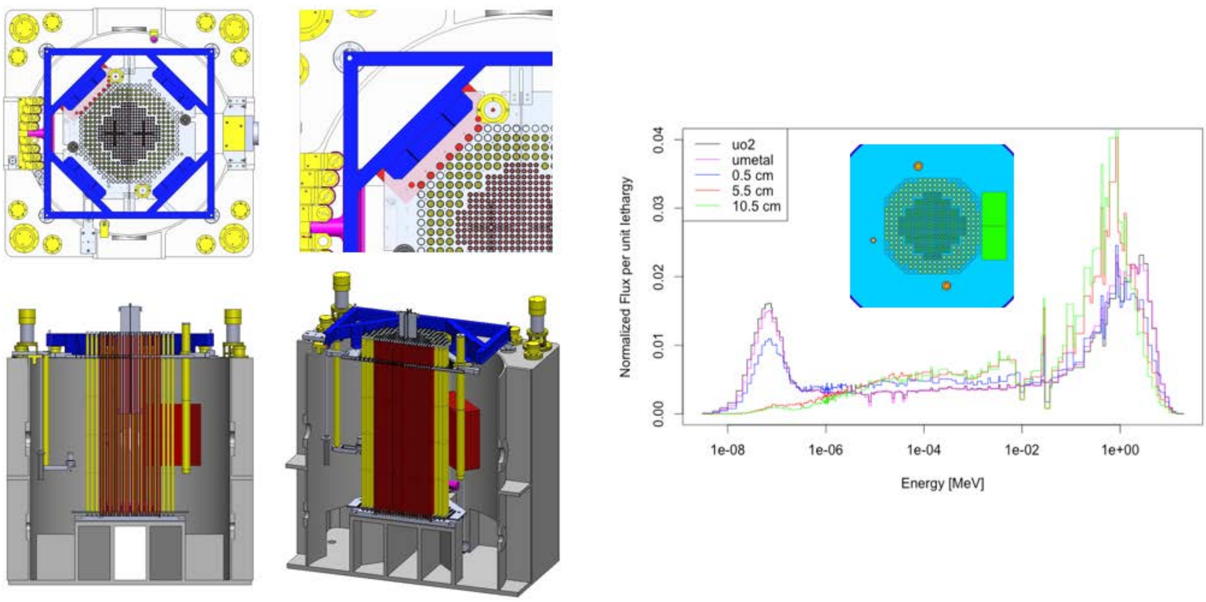

Fig 4: Top and side view of the CROCUS reactor with the positioning of the reflector sheets in red (left) and flux per unit lethargy at different location in the reflector sheets and in the UO_2 and U_{metal} pins (right).

The system to position the sheets is currently being designed. The system will allow positioning with high precision up to eight 30×30×2 cm^3 sheets next to the reactor core to maximise the flux (Fig 4 - left). The total thickness is up to 16 cm, which is representative of the optimal 20−cm reflector thickness in nuclear power plants. The system is located in CROCUS water reflector but is filled with air for the flux attenuation in the sheets to remain unperturbed. The sheets are manufactured from stainless steel, pure Fe (99.85%), Ni (99.7 %), and Cr (99.95 %) and were purchased in 2015. Activation foils will be located between the sheets. Their positions need to be well known because of the strong flux gradient.

In addition, several aspects of the PETALE experiments were investigated with MCNP in 2015. The reactivity effects resulting from the insertion of the sheets were shown to be well below the operating limit of 200 pcm: the larger reactivity worth (iron sheets) is +45 pcm. The flux level and spectra and the activity of foils of interest have been assessed (Fig 4 - right). Results showed that despite the low power of CROCUS, the activity in most foils sensitive to the thermal energy range is high enough to be measured with the LRS-EPFL HPGe stations. Regarding dosimeters with very low activity, due to the limited fast flux component in CROCUS, other possibilities were prospected, e.g. counting in CEA remote low-activity laboratories.

4. Development of measurement methods and new instrumentation

4.1. Neutron noise measurement in current mode

Neutron noise measurement techniques were developed in collaboration with swiss*nuclear* and PSI and applied in CROCUS. The acquisition was performed in pulse mode with BF_3 detectors and the data stored in multichannel scalers and post-processed to yield the Feynman-α and Power Spectral Density curves [2]–[5]. An inherent limitation of the pulse mode acquisition is the dead time of the detector at high count-rate, which set a lower limit on the measurement time. Acquisitions in current mode bypass this limitation by observing the current oscillations around a mean value without isolating each single detection event. The mean current and its variations need to be read with high precisions – typically in the range of 1 nA to 1 µA. Generally the continuous and fluctuating parts of the current are amplified and converted into voltage signals before being analysed, similar to what is performed for the pulse mode acquisitions.

The project aims at building the measurement station in current mode, testing it in the CROCUS reactor and comparing its results with the previous measurements performed in pulse mode. The first stage is concerned with the definition of the specifications of the amplifier (gain, bandwidth, range of input and output signals, etc.), and the definition of the measurement set-up (detector types, location of detectors, power of the reactor, etc.) [12].

MCNP simulations were performed for 1 g ^{235}U fission chambers (Photonis CFUL01) and ^3He detectors located in periphery of the CROCUS core and for four BF_3 detectors located in the periphery and control rod positions that were used during the pulse mode measurements (see Fig 5). Based on the thermal efficiency of the detectors and the impinging flux determined in the MCNP simulation the power needed to have a measurable current and Power Spectral Density curve were estimated. As an example, to achieve a current in the detector of 100 nA – typical value obtained in previous experiments – a power level of 0.3 W was sufficient for the CFUL01 detector, whereas a power of 15 W and 30 W were required for the ^3He and BF_3 detectors. The corresponding PSD levels were $2.1.10^{-20}$, $2.8.10^{-22}$ and $1.2.10^{-20}$ A^2/Hz for the CFUL01, ^3He and BF_3 detectors, respectively. These levels need to be higher than the level coming from the background noise to have a sufficient signal-to-noise ratio. Values for the required power to yield sufficiently high currents and PSD levels will be used to dimension the amplifier and select the measurement set-up.

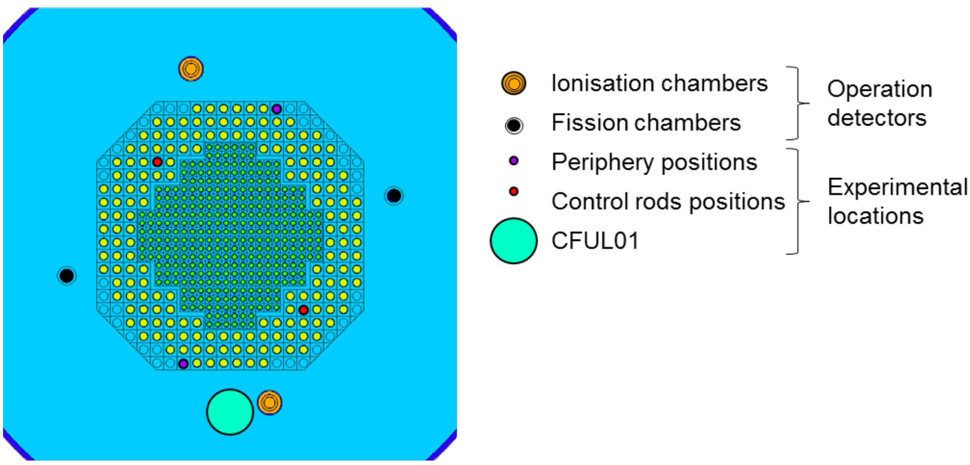

Fig 5: CROCUS model with considered detector locations for neutron noise measurement in current mode.

4.2. sCVD diamond detector and acquisition system

Chemical vapour deposited (sCVD) diamond detectors are currently under study in the nuclear community (e.g. [13]). Their fast response, their ability to withstand high irradiation fluxes and additionally the envisaged possibility to perform simple neutron spectrometry, make them good candidates for in-core measurement. [14]–[16] The LRS started the joint development of a full new detection system based on this material with the CIVIDEC start-up. A first prototype was tested in November 2015 in CROCUS (see Fig 6). The campaign results will be published early 2016. One of the main purposes of the future experiments is to work on the discrimination of gammas, thermal and fast neutrons for demonstrating its possible use in a mixed radiation field like that of CROCUS.

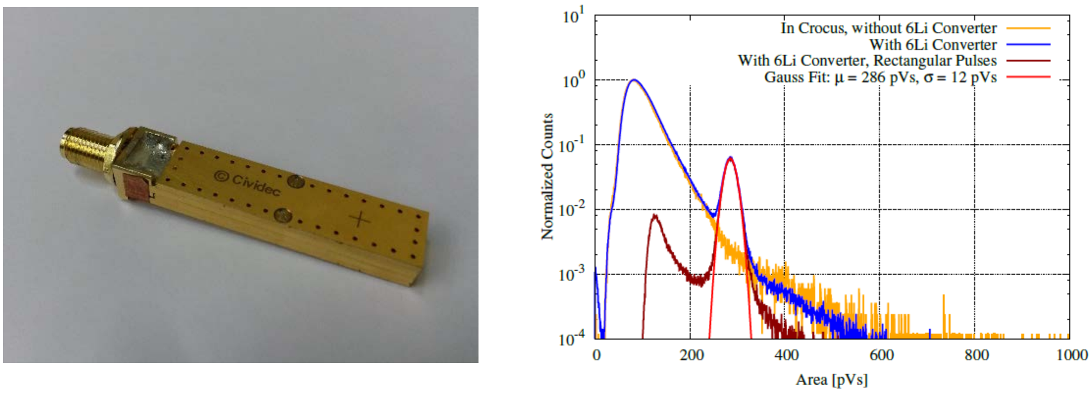

Fig 6: Diamond detector manufactured by CIVIDEC (left) and example of pulse shape discrimination based on measurements in CROCUS (right).

5. Conclusion

In the last decade, the CROCUS reactor was primarily used for teaching purposes. After the closure of the PROTEUS research reactor, it became the only remaining research reactor in Switzerland. As a result, and to keep experimental reactor physics competence in Switzerland, the Laboratory for Reactor Physics and Systems Behaviour at PSI and EPFL decided to increase research activities in CROCUS. In parallel to the existing research experiments for safety analysis and neutron noise measurement, the LRS selected three new experimental programmes. The programmes are related to neutron noise theory, measurements and applications, and to nuclear data for reactor technology. These programmes benefit from strong interactions with national and international research institutes and universities. The first programme will start by the end of 2016, alongside the development of new instrumentation. This effort supports the nuclear competence sustainability in Switzerland and provides a rare place for experiments in zero-power reactors in Europe.

6. References

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