DETECTOR POSITIONING
FOR THE INITIAL SUBCRITICALITY LEVEL DETERMINATION
IN ACCELERATOR-DRIVEN SYSTEMS

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ABSTRACT

Within the GUINEVERE project (Generation of Uninterrupted Intense NEutrons at the lead VEnus REactor) carried out at SCK•CEN in Mol, the continuous deuteron accelerator GENEPI-3C was coupled to the VENUS-F fast simulated lead-cooled reactor. Today the FREYA project (Fast Reactor Experiments for hYbrid Applications) is ongoing to study the neutronic behavior of this Accelerator Driven System (ADS) during different phases of operation. In particular the set-up of a monitoring system for the subcriticality of an ADS is envisaged to guarantee safe operation of the installation.
The methodology for subcriticality monitoring in ADS takes into account the determination of the initial subcriticality level, the monitoring of reactivity variations, and interim cross-checking. At start-up, the Pulsed Neutron Source (PNS) technique is envisaged to determine the initial subcriticality level. Thanks to its reference critical state, the PNS technique can be validated on the VENUS-F core.

A detector positioning methodology for the PNS technique is set up in this paper for the subcritical VENUS-F core, based on the reduction of higher harmonics in a static evaluation of the Sjöstrand area method. A first case study is provided on the VENUS-F core. This method can be generalised in order to create general rules for detector positions and types for full-scale ADS.

**Key Words:** Accelerator-Driven Systems, subcriticality, reactivity, Pulsed Neutron Source (PNS)

## 1. INTRODUCTION

### 1.1. The GUINEVERE and FREYA Project

Accelerator Driven Systems (ADS) [1] are advanced nuclear systems in which a subcritical core is coupled to a particle accelerator. Thanks to the subcriticality of the core, fuels with small delayed neutron fractions can be operated in a safe way. On the long term, the transmutation of long-lived fission products could be envisaged in ADS. With the MYRRHA project [2], SCK•CEN plays a key role in the ADS research.

The GUINEVERE (Generation of Uninterrupted Intense Neutrons at the lead Venus Reactor) project [3], [4] was launched in 2006 within the FP6 IP-EUROTRANS programme [5]. During the project the existing zero-power VENUS reactor at the SCK•CEN site in Mol (Belgium) was modified towards VENUS-F, a fast spectrum lead reflected system that can be operated in both critical and subcritical mode. In the latter mode, the reactor is coupled to the GENEPI-3C accelerator [6], an updated version of the GENEPI-1 machine previously used for the MUSE experiments [7]. Deuterons accelerated to an energy of 220 keV hit a Ti-T target in the middle of the core, producing 14 MeV fusion neutrons. The unique GENEPI-3C accelerator is able to work in both pulsed and continuous mode coupled to a subcritical core. A schematic overview of the updated VENUS facility (with additional accelerator room) is shown in Fig. 1.

Criticality of the VENUS-F core was obtained in February 2011. A reference critical state was characterised [8], allowing to obtain well-defined subcritical cores [9]. Recently the FREYA (Fast Reactor Experiments for hYbrid Applications) [10] was launched, in order to validate a methodology for on-line subcriticality monitoring. Future experiments will be made to investigate the extrapolation of this methodology on full-scale ADS like MYRRHA.

### 1.2. Subcriticality Measurements

The MUSE project showed that the current-to-flux technique is a suitable candidate for robust on-line subcriticality monitoring [7]. This technique can detect changes in reactivity. However at a regular base during operation of ADS, cross-checking techniques are required to have absolute reactivity measurements. The investigation of different methods, such as the Pulsed Neutron Source (PNS) and source jerk method, is foreseen within the FREYA project [10].
Several methods for the evaluation of subcriticality (e.g. for the PNS technique) rely on the point-kinetic reactor theory. In (deep) subcritical states driven by a source, the flux is composed not only by its fundamental mode, but also by higher harmonic modes. In order to take into account this effect, correction factors are proposed for the methods evaluating the subcriticality level. Also intelligent detector positioning can help reducing the influence of higher harmonics. When performing a static analysis of the experimental PNS technique via $\lambda$-modes, the use of kinetic parameters can be avoided. Time-dependent evaluation techniques are also envisaged, based on the evaluation of the so-called $\alpha$-modes, however this study falls outside the scope of this paper. Both techniques were successfully applied in the past on the Uranium fueled cores of the VENUS reactor, based on intelligent source and detector positioning [11].

In this paper the design of the VENUS-F core will be presented, which can motivate the choice of the calculational model. Then the modal expansion technique will be presented to study the difference between the fundamental mode and the total flux. By an evaluation of the correction term for the PNS method, we can deduce detector positions for this technique. A case study is performed on a simplified model of the VENUS-F core, in order to show the capabilities of the technique. Finally some recommendations for a generalised detector positioning methodology for the PNS technique on different subcritical VENUS-F cores are made.

2. THE VENUS-F CORE

As the zero power VENUS-F core should be representative for a full scale ADS like MYRRHA, solid lead blocks have been chosen as reflector material. The fuel assemblies are designed based on the experience from the MUSE project [7]. The fuel rodlets are made of metallic Uranium 30 w% enriched in U-235, with a diameter of 1.27 cm and a height of 20.32 cm. In a fuel assembly, three of them are piled up in a 5x5 lattice filled with lead blocks and fuel rodlets, as shown in Fig. 2, in order to obtain assemblies with a width of 8 cm and an active fuel height of 60.96 cm. The top reflector lead block is included in the fuel assembly in order to obtain a modular core. The fuel is arranged in a symmetrical way in the 5x5 grid, so possible types of fuel assemblies can comprise 4, 9, 13 or 25 positions in the 5x5 grid. In the actual core 9 positions are filled with fuel rodlets, as shown in Fig. 2.
A symmetrical core design as shown in Fig. 3 was chosen for reasons of simplicity. A detailed design is given in [12]. In the center of the core a 12x12 grid has been introduced, in which square assemblies (with width 8 cm) fit. This grid will be filled with lead and fuel assemblies, as well as with safety and control rods. Around the fuel, 40 cm lead top and bottom reflector is foreseen, as well as a radial reflector around the grid that fills the existing VENUS vessel with radius 80 cm. The vertical beam line can be inserted in the core by removing the 4 central assemblies. By this set-up a symmetrical and so-called "clean" core has been obtained, which is representative for a lead cooled ADS.
3. DETECTOR POSITIONING METHODOLOGY FOR THE SJÖSTRAND AREA METHOD

3.1. Pulsed Neutron Source Technique

The Sjöstrand method (also called area method) [13] is an experimental technique for static subcriticality measurements by means of a Pulsed Neutron Source (PNS). It states that the reactivity of a subcritical system can be determined by the ratio of two areas in the decay of the neutron density after a pulse.

\[
\frac{\rho}{\beta} = \frac{A_1}{A_2}
\]  

with

- \(\rho\) the reactivity (in pcm)
- \(\beta\) the delayed neutron fraction (in pcm)
- \(A_1\) the area related to the prompt neutrons
- \(A_2\) the area related to the delayed neutrons

3.2. Correction for Higher Harmonics via Modal Analysis

Corrections on (1) should be applied to take into account the presence of higher harmonic modes in the spatial neutron distribution. As explained in Appendix III of [13], the corrective factor can be obtained by performing modal analysis. For a pulse train with period \(T\), the area ratio can be written as

\[
\frac{A_p}{A_d} = \frac{\rho}{\beta} \frac{1 + \sum_{n=2}^{\infty} k_n 1 - k_1 (1 - \beta) R_n(r) \int_0^T S_n dt}{1 + \sum_{n=2}^{\infty} 1 - k_1 (1 - \beta) R_1(r) \int_0^T S_1 dt}
\]  

with

- \(k_i\) the i-th order eigenvalue of the system (so called \(\lambda\)-modes)
- \(R_i(\vec{r})\) the i-th order eigenfunction of the system
- \(S_i\) the i-th order amplitude coefficient for the source

It is clear that the behaviour of 3D eigenfunctions should be studied, as well as the source multiplication coefficients, in order to reduce as much as possible the correction factor by intelligent detector positioning.
3.3. Eigenfunction Multiplication Coefficients

The deduction of equation (1) relies on the point kinetic model of the reactor, which is not valid for subcritical states. A first step to evaluate the correction factor in (2) is to calculate the contribution of the first eigenfunction to the total solution. In order to determine the eigenfunction multiplication coefficients (see [14]) for the equivalent transport theory, we write the neutron flux as a sum of $\lambda$-modes

$$\psi(\vec{r}, E, \hat{\Omega}) = \sum_{l=1}^{M} B_l \psi_l(\vec{r}, E, \hat{\Omega})$$  \hspace{1cm} (3)

By introducing equation (3) in the diffusion equation, one gets by using the biorthogonality criterion ([14] and [15])

$$\left( \frac{1}{\lambda} - \frac{1}{\lambda^2} \right) \langle \psi_m^+, F \psi_l \rangle$$ \hspace{1cm} (4)

the expression for the multiplication coefficients. For a steady state neutron source the equation for the multiplicative coefficient simplifies towards

$$B_m = - \frac{\langle \psi_m^+, Q_0 \rangle}{(1 - \frac{1}{\lambda_m}) \langle \psi_m^+, F \psi_m \rangle}$$ \hspace{1cm} (5)

3.4. Calculation of the Eigenfunctions Shape

The behaviour of 3D subcritical $\lambda$-modes can be analysed in depth by means of the neutron diffusion theory. Verdu [16] identified different types of 3D harmonic modes for a critical BWR reactor in unstable conditions in order to study out-of-phase oscillations. The two first subcritical harmonic modes are azimuthal folowed by an axial mode and two close azimuthal nodes (rotating modes), as shown in Fig. 4.

4. CASE STUDY: VENUS-F SUBCRITICAL CORE

4.1. Model Definition

For the calculations presented in this case study, we will use a simplified 2-zone 3D VENUS-F model, consisting of a 27.5x27.5x27.5 cm$^3$ cube with the fuel inside, surrounded by a 80x80x70 cm$^3$ cube with lead reflector. The source is positioned in the center of the core. 1 Group cross sections are calculated for both fuel (which is defined as the homogeneous mixture of fuel and lead as in the 5x5 lattice of the fuel assembly) and lead, by means of the ECCO module of ERANOS [17]. The calculation methodology for the cross sections was motivated in the framework of the licensing process [18]. With this model one obtains a value of 0.94426 for $k_{eff}$.
4.2. DALTON Code

The DALTON code, developed by TUDelft, can solve the 3D multigroup diffusion equations on structured grids. Fundamental and higher lambda and adjoint modes as well as time eigenvalues can be calculated through the Arnoldi method by linking with the ARPACK package. Spatial discretisation is performed using a second order accurate finite volume method.

4.3. Results

4.3.1. Eigenmodes, Eigenfunctions and Multiplicative Coefficients

The 8 first eigenmode values are shown in Table I. As for a 1 group calculation, forward and adjoint modes are equal. The related eigenfunctions are shown in Fig. 5 and Fig. 6. The multiplicative coefficients, calculated according to (5) are shown in Table I for a unit source located in the center of the model.

4.3.2. Contribution of the Fundamental Mode

The difference between full solution and fundamental mode for the 1G 3D VENUS-F model is shown in Fig. 7. Local differences higher than 20 % are obtained very close to the center of the core (source position).
Table I. Eigenmodes and Multiplicative coefficients

<table>
<thead>
<tr>
<th>Mode No</th>
<th>Forward Value</th>
<th>Multiplicative Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.944426</td>
<td>20.518</td>
</tr>
<tr>
<td>2</td>
<td>0.530496 + 7.12778.10^{-11}I</td>
<td>1.134.10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>0.530496 - 7.12778.10^{-11}I</td>
<td>-1.232.10^{-5}</td>
</tr>
<tr>
<td>4</td>
<td>0.527205</td>
<td>3.546.10^{-5}</td>
</tr>
<tr>
<td>5</td>
<td>0.342917</td>
<td>-1.281.10^{-8}</td>
</tr>
<tr>
<td>6</td>
<td>0.342536</td>
<td>-2.173.10^{-8}</td>
</tr>
<tr>
<td>7</td>
<td>0.342536</td>
<td>1.450.10^{-9}</td>
</tr>
<tr>
<td>8</td>
<td>0.299448</td>
<td>1.305</td>
</tr>
</tbody>
</table>

4.3.3. Discussion

The sequence of the eigenfunctions for the VENUS-F core model (see Fig. 5 and Fig. 6) is similar to the one obtained by Verdu (see Fig. 4) for the critical BWR reactor. The positive and negative zones in the 2th and 3rd eigenfunction are however slightly rotated. The higher modes have more asymmetrical z-components than in the Verdu case study. Mode 8 is again an explicit positive eigenfunction. The amplitude of the asymmetrical eigenfunctions is smaller than the one of the symmetrical functions, seen the symmetry of the problem. A case study with more groups will confirm this tendency for the VENUS-F core.

Comprehensive results are shown for the multiplicative coefficients in Table I. As the source is positioned in the center of the model, the 1st and the 8th mode have a significant multiplicative coefficient and contribute to the total solution. Therefore the difference between the fundamental mode and the full solution is small, except in the center of the core. For this case study one can conclude that the correction factor for the area method is small, except in the center of the core.

5. CONCLUSION

Different techniques are needed in order to set-up a methodology for on-line subcriticality monitoring in ADS. For the initial subcriticality level determination, the PNS technique is envisaged. Correction factors need to be calculated for the evaluation of the subcriticality level via the Sjöstrand (area) method, as the point kinetic approach is not valid for subcritical states. The eigenfunctions and their multiplicative coefficients are studied for a basic VENUS-F subcritical core model with centered source, by means of the DALTON 3D diffusion code. For this case study the correction factor is small, except close to the center of the core where the source is located.
In the future this method will be extended by means of a more detailed model of the VENUS-F core with a suitable number of energy groups. The model will be validated by experimental results. Especially for deeper and varying subcriticality levels, and for asymmetric source positions, general detector position rules will be deduced to reduce the correction factor for the area method.

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References


Figure 5. Eigenfunctions 1-4 for the 1G 3D VENUS-F model
Figure 6. Eigenfunctions 5-8 for the 1G 3D VENUS-F model
Figure 7. Difference between full and fundamental flux in the 1G 3D VENUS-F model