**OPEN REPORT**
SCK•CEN-BLG-1051

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Safety calculations of the BR2 reactor

S.Kalcheva, B.Ponsard and E.Koonen

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SCK•CEN
Boeretang 200
BE-2400 Mol
Belgium

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Status: Unclassified
ISSN 1379-2407

SCK•CEN
Boeretang 200
BE-2400 Mol
Belgium

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Studiecentrum voor Kernenergie
Centre d'étude de l'énergie Nucléaire
Boeretang 200
BE-2400 Mol
Belgium

Phone +32 14 33 21 11
Fax +32 14 31 50 21

http://www.sckcen.be

Contact:
Knowledge Centre
library@sckcen.be

# SUMMARY

Aim of this report is to validate the computational modules system SCALE4.4a for evaluation of reactivity changes, evolution of macroscopic absorption cross sections and calculations of the positions of the Control Rods during their motion in Xe – Sm transient after a scram (or other reasons for shutting the reactor) of the BR2 reactor.

The rapid shutting down of the reactor by inserting of negative reactivity by the Control Rods is known as a reactor scram. A brief theoretical description of the changes in reactivity and the macroscopic absorption cross sections, caused by fission products poisoning during Xe – Sm transients, following a reactor scram is presented. The most significant fission products in the reactor are $^{135}$Xe and $^{149}$Sm due to their large absorption cross sections. Following reactor scram, a large xenon and samarium buildup occur in the reactor, which may appreciably affect the multiplication factor of the core due to enormous neutron absorption. The negative reactivity changes induced in the reactor by the accumulation of the fission product poisons $^{135}$Xe and $^{149}$Sm are estimated using the equations of the one – group diffusion theory, which lie in the basis of the procedure for evaluation of Xe – Sm transients.

The routine calculations of Xe – Sm transients are performed by the calculation code XESM, developed at the BR2 reactor and used as a standard procedure during the last 20 years. In this report we reproduce by the SCALE system several Xe – Sm transients, which have been taken place after scrams during different BR2 operation cycles: 01/2007A.6, 05/2006A.4, 04/2005A.4 and 02/2005A.5 and compare with the experimental data and with the results by XESM.

The SCALE4.4a system is composed from many separate programme codes (modules). Different modules can be used for evaluation of the isotopic fuel depletion, macroscopic absorption cross sections and k – infinities during Xe – Sm transients. These modules are: XSDRNPM, NITAWL-II, COUPLE and ORIGEN-S. A fuel assembly with heterogeneous description as it is used in MCNP is introduced as input data for calculations by 1 – D discrete ordinates transport code XSDRNPM. The flux calculations can be performed according to several options, including fixed source calculations and k-calculations. XSDRNPM uses the fluxes determined from its spectral calculation to produce one-group cell-weighted cross sections values for fuel depletion analysis by ORIGEN-S, which is a 1-D burn up code. The advantage of the code ORIGEN-S in comparison with the original versions of ORIGEN is that it can be used in combination with other modules of the SCALE system (COUPLE, NITAWL-II, XSDRNPM). Thus, the SCALE system provides the capability of executing ORIGEN with the data that have been rigorously processed for a particular fuel assembly of a particular reactor type and user-specified irradiation history.

The validation of the calculations of Xe – Sm transients by SCALE4.4a has been performed on the measurements of the positions of the Control Rods during their motion in Xe – Sm transients of the BR2 reactor and on comparison with the calculations by XESM. Four operation BR2 cycles with total 8 transients being occurred, have been considered. All eight Xe – Sm transients have been reproduced by the SCALE4.4a system, following the real power during the transient.

A final conclusion is made that the SCALE4.4a modules system can be used for evaluation of Xe – Sm transients in the BR2 reactor. The utilization of the code is simple and convenient, the computational time might take from few seconds to several minutes depending on which modules of the SCALE system are involved in the calculations.

# ABSTRACT

In this report we discuss the application of the SCALE4.4a modules system for the calculation of Xe – Sm transients after a scram of the Material Testing Reactor BR2 at SCK•CEN in Mol, Belgium. A comparison with the calculations by the routinely used during the last twenty years calculation procedure XESM is presented. Validation of SCALE4.4a for calculation of Xe – Sm transients is performed on the measurements of the positions of the Control Rods during their motion in Xe – Sm transient after a scram of the reactor BR2.

# 1. Introduction

The rapid shutting down of the reactor by inserting of negative reactivity by the Control Rods is known as a reactor scram. The most significant fission products in the reactor are $^{135}$Xe and $^{149}$Sm due to their large absorption cross sections (see Fig. 1). Following reactor scram, a large xenon and samarium buildup occur in the reactor, which may appreciably affect the multiplication factor of the core due to enormous neutron absorption.

In this report we reproduce several Xe – Sm transients, which have been taken place after scrams during different BR2 operation cycles: 01/2007A.6, 05/2006A.4, 04/2005A.4 and 02/2005A.5. Different modules of the SCALE4.4a system [1] are used for the evaluation of the evolution of the isotopic fuel composition, macroscopic actinide and non – actinide absorption cross sections and the infinite multiplication factor $k_\infty$ of the BR2 heterogeneous fuel assembly during a Xe – Sm transient. The calculations of the reactivity changes, the evolution of the absorption cross sections of $^{135}$Xe and $^{149}$Sm and the changes of the position of the Control Rods during Xe – Sm transient after a scram of the BR2 reactor are routinely performed using the calculation procedure XESM [2]. The validation of the calculations of Xe – Sm transients by SCALE4.4a is performed on the measurements of the positions of the Control Rods during their motion in Xe – Sm transient of the BR2 reactor and on comparison with the calculations by XESM.

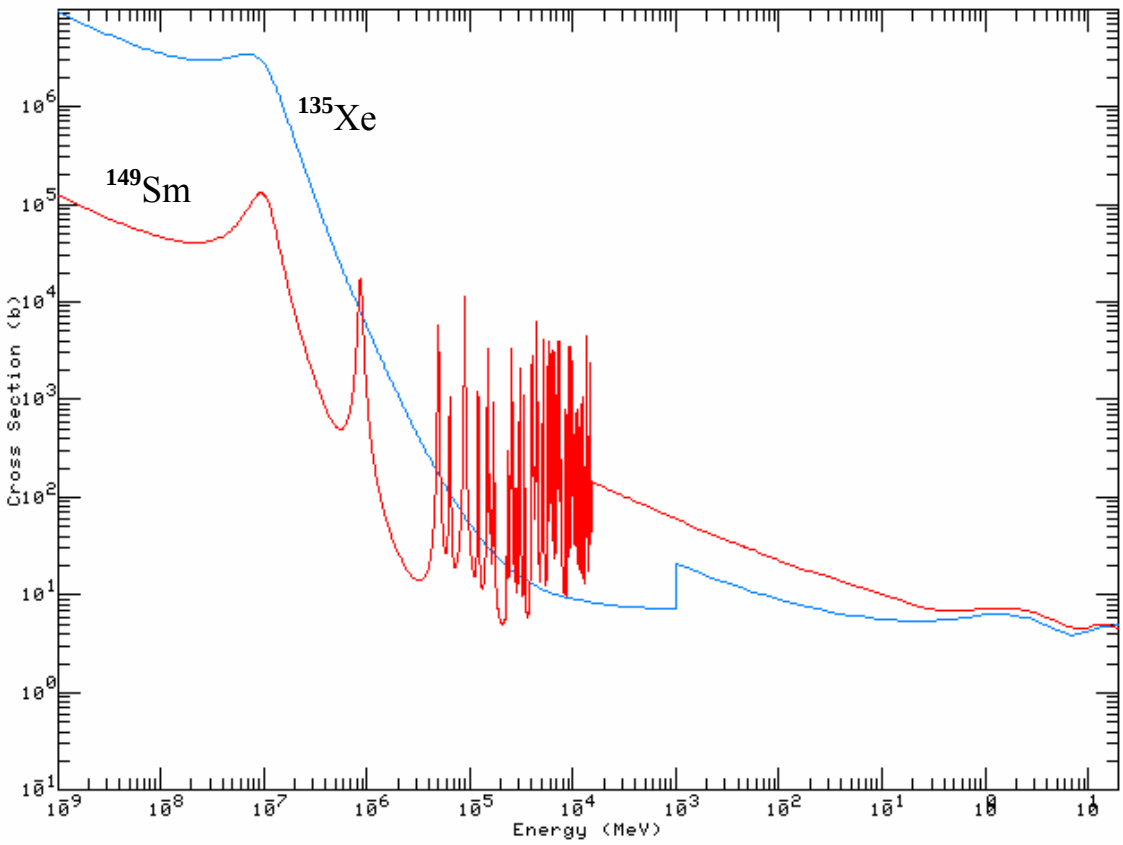


Figure 1. Total microscopic cross section of $^{135}$Xe and $^{149}$Sm (MCNP libraries).

## 2. Reactor scrams and following Xe – Sm transients

In this chapter we give a brief theoretical description [3] of the changes in reactivity and the macroscopic absorption cross sections, caused by fission products poisoning during Xe – Sm transients, following a reactor scram, which lies in the basis of the calculation procedure XESM.

### 2.1. Fission products poisoning after a reactor scram

#### 2.1.1. Negative reactivity introduced by fission products

Let us estimate the negative reactivity change induced in a reactor by the addition of a fission product poison. To a first approximation, the only effect of fission product poisons on the multiplication factor is on the thermal utilization. The reactivity equivalent of the poison having macroscopic absorption cross section $\Sigma_a^P$ in a previously critical reactor will be:

$$\Delta\rho \equiv \rho(\Sigma_a^P) - \rho(\Sigma_a^P = 0) = \rho' - \rho\,; \qquad \rho = \frac{k-1}{k} \tag{1}$$

where the primed values refer to the poisoned reactor and $k$ is given by the six-factor formula:

$$k = \eta f p \varepsilon p_F p_T \tag{2}$$

where:

$p$ – fraction of fission neutrons that manage to slow down from fission to thermal energies without being absorbed;

$p_{TNL}$ - the thermal non-leakage probability that the thermal neutron will not leak the system before absorption, which is given by the following expression:

$$p_{TNL} = \frac{\text{rate of neutron absorption}}{\text{rate of neutron absorption} + \text{leakage}} = \\ = \frac{\int_V d^3 r \Sigma_a(r)\phi(r)}{\int_V d^3 r \Sigma_a(r)\phi(r) - \int_V d^3 r D(r)\nabla^2\phi(r)} = \frac{\Sigma_a \int_V d^3 r \phi(r)}{\Sigma_a \int_V d^3 r \phi(r) + DB_g^2 \int_V d^3 r \phi(r)} = \frac{1}{1 + B_g^2 L^2} \tag{3}$$

where: $L = \sqrt{\frac{D}{\Sigma_a}} = \frac{1}{\sqrt{3\Sigma_{tr}\Sigma_a}}$ is the thermal neutron diffusion length; $B_g^2$ is the geometry buckling of the reactor.

$p_{FNL}$ - probability that the fast neutron will not leak the system (fast non-leakage), which is given by the following expression:

$$p_{FNL} = \exp(-B_g^2 \tau_T) \tag{4}$$

$\tau_T$ - the age corresponding to thermal energies (usually taken as ~ 1 eV):

$$\tau_T = \int_{E_0}^{E_{th}} dE \frac{D(E)}{\xi \Sigma_s(E) E} \tag{5}$$

If the reactor is infinite $B_g = 0; p_{FNL} = p_{TNL} = 1$. Then Eq. (2) for an infinite and a finite reactor will take the forms:

$$k_\infty = \eta f p \varepsilon \text{ and } k = k_\infty p_T p_F \tag{6}$$

$\varepsilon$ - fast fission factor, which is defined as the ratio of the total number of fission neutrons (from both fast and thermal fission) to the number of fission neutrons from thermal fissions:

$$\varepsilon = \frac{\int_0^\infty \phi(E) \Sigma_f(E) \nu(E) dE}{\int_0^{E_{th}} \phi(E) \Sigma_f(E) \nu(E) dE} \tag{7}$$

$\eta$ - the average number of fission neutrons emitted when a neutron of energy E is absorbed by the fuel is defined as:

$$\eta = \frac{\sum_j \nu_j \Sigma_f^{(j)}}{\sum_j \Sigma_a^{(j)}} \tag{8}$$

$f$ - thermal utilization, which is given by the following formula:

$$f = \frac{\int d^3 r \Sigma_a^F(r) \phi(r)}{\int d^3 r \Sigma_a^F(r) \phi(r) + \int d^3 r \Sigma_a^M(r) \phi(r)} \tag{9}$$

Since in a heterogeneous reactor the fuel and moderator are separate regions, the quantities $\Sigma_a^F$ and $\Sigma_a^M$ are constants in their respective volumes, $V_F$ of the fuel and $V_M$ of the moderator, and therefore Eq. (9) becomes:

$$f = \frac{\Sigma_a^F \int d^3 r \phi(r)}{\Sigma_a^F \int d^3 r \phi(r) + \Sigma_a^M \int d^3 r \phi(r)} \tag{10}$$

If we include the fission product poisons, which are characterized with macroscopic absorption cross section $\Sigma_a^P$, Eq. (10) becomes:

$$f' = \frac{\Sigma_a^F \int d^3 r \phi(r)}{\Sigma_a^F \int d^3 r \phi(r) + \Sigma_a^M \int d^3 r \phi(r) + \Sigma_a^P \int d^3 r \phi(r)} \tag{11}$$

which is the thermal utilization in the poisoned reactor. For a poison characterized by a macroscopic cross section $\Sigma_a^P$ distributed uniformly throughout a homogeneous reactor core, then Eq. (11) becomes:

$$f' = \frac{\Sigma_a^F}{\Sigma_a^F + \Sigma_a^M + \Sigma_a^P} \tag{12}$$

Now Eq. (1) can be written as:

$$\Delta\rho = \frac{f' - f}{f'} + \frac{p'_{TNL} - p_{TNL}}{p'_{TNL}} \tag{13}$$

where:

$$\frac{f' - f}{f'} = -\frac{\Sigma_a^P}{\Sigma_a^F + \Sigma_a^M} \tag{14}$$

$$\frac{p'_{TNL} - p_{TNL}}{p'_{TNL}} = \frac{L^2 B_g^2}{1 + L^2 B_g^2} \left[ \frac{\Sigma_a^P}{\Sigma_a} + \frac{\Sigma_{tr}^P}{\Sigma_{tr}} \right] \tag{15}$$

Thus:

$$\Delta\rho = -\frac{\Sigma_a^P}{\Sigma_a} \frac{1}{1 + L^2 B_g^2} \left[ 1 - L^2 B_g^2 \frac{\Sigma_{tr}^P / \Sigma_a^P}{\Sigma_{tr} / \Sigma_a} \right] \cong -\frac{\Sigma_a^P / \Sigma_a}{1 + L^2 B_g^2} = -\frac{\Sigma_a^P / \Sigma_a}{\nu p \varepsilon} \tag{16}$$

where we have ignored the second term in the brackets which usually is quite small ($<10^{-3}$). In fact for many reactors leakage is small so that $L^2 B_g^2 << 1$ and the reactivity change due to the poison is just the fraction of the total macroscopic absorption cross section due to the poison.

The macroscopic cross section for the poison is given by $\Sigma_a^P = N_P \sigma_a^P$, where $N_P$ is the number density of the poison, $\sigma_a^P$ is the effective thermal microscopic absorption cross section. Therefore, in order to estimate the reactivity change due to the poison, it is necessary to calculate the change of the number density of the poisoning isotope $N_P$ at any time *t*. In order to determine $N_P$(t) we must solve the rate equations describing the various production and decay processes that can affect the poison concentration, which can be done using the module ORIGEN-S of the SCALE 4.4a system. This module solves the isotopic depletion equations and computes the time-dependent densities of large number of isotopes which are simultaneously generated or depleted through fission process, transmutation and radioactive decay.

### 2.1.2. Xenon poisoning

$^{135}$Xe is a direct product from fission process and also may result from the β - decay of $^{135}$Te, which decays into $^{135}$I (see Fig. 2). Due to the short half-life of $^{135}$Te, it can be neglected, as well as $^{135m}$Xe. The simplified decay scheme of $^{135}$Xe is given in Fig. 3.

Using the one – group values for the macroscopic cross sections and for the neutron flux, we can write the following equations, which describe the simplified decay scheme:

For *Iodine* ($\sigma_a^I \approx 7$barns , can be neglected):

$$\frac{\partial I}{\partial t} = -\lambda_I I(r,t) - \sigma_a^I \phi(r,t) I(r,t) + \gamma_I \Sigma_f \phi(r,t) \qquad (17)$$

where: the first term in Eq. (17) describes the iodine decay; the second term – the iodine absorption of neutrons, which however can be ignored and the third term describes the direct production of iodine from fission, so that we can use the following approximate equation:

$$\frac{\partial I}{\partial t} \approx -\lambda_I I(r,t) + \gamma_I \Sigma_f \phi(r,t) \qquad (18)$$

For *Xenon* (the total effective thermal absorption cross sections, calculated by SCALE is equal to $\sigma_a^X \approx 1.68\text{E}+06$barns ):

$$\frac{\partial X}{\partial t} = \lambda_I I(r,t) + \gamma_X \Sigma_f \phi(r,t) - \lambda_X X(r,t) - \sigma_a^x \phi(r,t) X(r,t) \qquad (19)$$

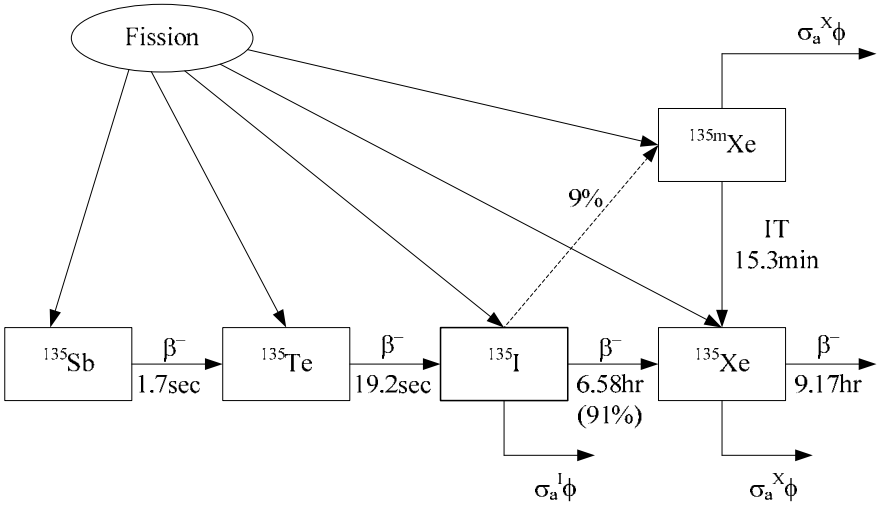


Figure 2. Decay scheme for $^{135}$Xe.

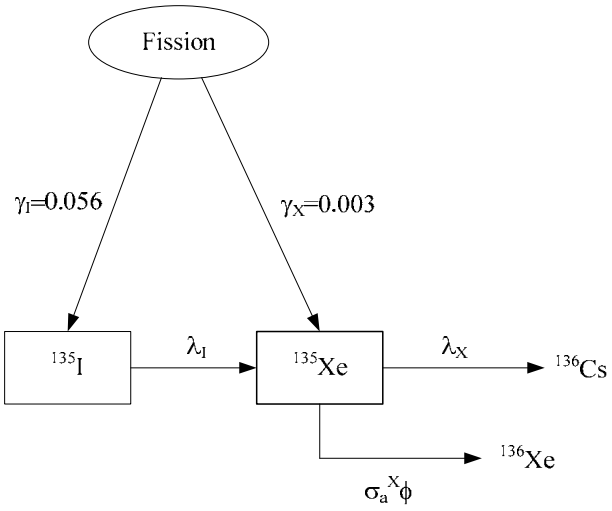


Figure 3. Simplified decay scheme for $^{135}$Xe.

The values of the yields and decay constants as used in the SCALE4.4a system are tabulated in Table I.

Table I. Fission Product Yields and Decay Constants.

| Fission Product Yields | $^{233}$U | $^{235}$U | $^{239}$Pu | $^{241}$Pu | Decay constants |
|---|---|---|---|---|---|
| $\gamma_I$ (%) | 4.884 | 6.386 | 6.100 | 7.694 | $\lambda_1 = 0.1035\text{hr}^{-1}$ |
| $\gamma_X$ (%) | 1.363 | 0.228 | 1.087 | 0.255 | $\lambda_1 = 0.0753\text{hr}^{-1}$ |
| $\gamma_P$ (%) | 0.660 | 1.130 | 1.900 | | $\lambda_1 = 0.0128\text{hr}^{-1}$ |

In order to solve equations (18) and (19) we assume that the flux behavior is a known function of space and time. Than integrating the iodine equation (18) we find that:

$$I(r,t) = \left[ I(r,0) + \gamma_I \int_0^t dt' \Sigma_f(r,t')\phi(r,t') \exp(\lambda_1 t') \right] \exp(-\lambda_1 t) \tag{20}$$

Substituting Eq. (20) into the xenon equation (19) and integrating, we find the concentration of $^{135}$Xe as function of space and time:

$$X(r,t) =$$
$$\left\{ X(r,0) + \int_0^t dt' \left[ \lambda_1 I(r,t') + \gamma_X \Sigma_f(r,t')\phi(r,t') \right] \exp\left[ \int_{\grave{a}}^{t'} dt'' \left[ \lambda_X + \sigma_a^X \phi(r,t'') \right] \right] \exp\left[ -\int_0^t dt'' \left[ \lambda_X + \sigma_a^X \phi(r,t'') \right] \right] \right\} \tag{21}$$

For complicated flux behavior the solutions (20) and (21) require numerical integrations. However the time-behavior of the xenon concentration can be examined for several particularly simple examples of flux behavior, such as startup of a clean core reactor, reactor shutdown and reactor scram. We are interested in the last of these cases.

After of setting the flux $\phi$ suddenly to zero (after a reactor scram), the terms in Eqs. (18) and (19), which contain $\phi$, will disappear. However the production of $^{135}$Xe via decay of $^{135}$I, which half-life is shorter than that of $^{135}$Xe will continue. Therefore, the concentration of $^{135}$Xe may initially build up before decaying out. Therefore, after the scram we will have the following two equations:

$$\frac{\partial I}{\partial t} = -\lambda_I I(r,t) \tag{22}$$

$$\frac{\partial X}{\partial t} = \lambda_I I(r,t) - \lambda_X X(r,t) \tag{23}$$

At the time of the shut down (t=0) the poison concentrations of $^{135}$I and $^{135}$Xe have attained their equilibrium values, i.e. $I(0)=I_\infty$ and $X(0)=X_\infty$. Then the solutions of the iodine and xenon equations are:

$$I(r,t) = I_\infty(r)\exp(-\lambda_I t) \tag{24}$$

$$X(r,t) = X_\infty(r)\exp(-\lambda_X t) + \frac{\lambda_I I_\infty(r)}{\lambda_I - \lambda_X}\left[\exp(-\lambda_X t) - \exp(-\lambda_I t)\right] \tag{25}$$

Then, the negative reactivity introduced by the $^{135}$Xe build-up is:

$$\Delta\rho(t) = -\frac{1}{vp\varepsilon}\left[\frac{(\gamma_I + \gamma_X)\phi_0}{\lambda_X / \sigma_a^X + \phi_0}\exp(-\lambda_X t) + \frac{\gamma_I \sigma_a^X \phi_0}{\lambda_I - \lambda_X}\left[\exp(-\lambda_X t) - \exp(-\lambda_I t)\right]\right] \tag{26}$$

The maximum value of the negative reactivity depends quite sensitively on the flux level prior to scram. Assuming high flux values before the scram, we can estimate the time at which the negative reactivity reaches maximum as:

$$t_{max} = \frac{1}{\lambda_I - \lambda_X}\ln\left[\frac{\lambda_I / \lambda_X}{1 + \frac{\lambda_X}{\lambda_I}\left(\frac{\lambda_I}{\lambda_X} - 1\right)\frac{X_\infty}{I_\infty}}\right] \xrightarrow{\phi_0 >> \lambda_X / \sigma_a^X} \frac{1}{\lambda_I - \lambda_X}\ln\left(\frac{\lambda_I}{\lambda_X}\right) = 11.6h. \tag{27}$$

The xenon transient during the change in reactor flux level from $\phi_0$ to $\phi_1$ can be obtained from Eqs. (18) and (19) at conditions $I(0)=I_\infty$, $X(0)=X_\infty$. Following the power level change the iodine and xenon concentrations will change as:

$$I(t) = \frac{\gamma_I \Sigma_f \phi_0}{\lambda_I}\left[1 - \left(\frac{\phi_1 - \phi_0}{\phi_1}\right)\exp(-\lambda_I t)\right] \tag{28}$$

$$X(t) = \frac{(\gamma_I + \gamma_X)\Sigma_f \phi_1}{\lambda_X + \sigma_a^X \phi_1}$$
$$\left\{1 - \left(\frac{\phi_1 - \phi_0}{\phi_1}\right)\left[\frac{\lambda_X}{\lambda_X + \sigma_a^X \phi_0}\exp\left[-(\lambda_X + \sigma_a^X \phi_1)t\right] + \left(\frac{\gamma_I}{\gamma_X + \gamma_I}\right)\left(\frac{\lambda_X + \sigma_a^X \phi_1}{\lambda_X + \sigma_a^X \phi_1 - \lambda_I}\right)\left[\exp(-\lambda_I t) - \exp(-(\lambda_X + \sigma_a^X \phi_1)t)\right]\right]\right\} \tag{29}$$

### 2.1.3. Samarium poisoning

The isotope samarium – 149 is stable (unlike $^{135}$Xe) and it is produced by the radioactive decay of promethium – 149 ($T_{1/2} = 47 hrs.$, i.e. it can be neglected); the latter is produced directly from fission and also by the decay of neodymium – 149 ($T_{1/2} = 1.7 hrs.$). Thus, it can be assumed that $^{149}$Pm is a direct F.P. with $\gamma_p \sim 0.014$. The decay scheme of samarium-149 is given in Fig. 4. If neglect the contribution from $^{149}$Nd and assume fission yields $^{149}$Pm directly, then the corresponding equations for the concentrations are:

For *Promethium* (the total absorption cross sections, calculated by SCALE is $\sigma_a^P \approx 885 \text{barns}$ ):

$$\frac{\partial P}{\partial t} = \gamma_P \Sigma_f \phi(\vec{r},t) - \lambda_P P(\vec{r},t) \tag{30}$$

For *Samarium* (the total absorption cross sections, calculated by SCALE is equal to $\sigma_a^P \approx 2.7E+04 \text{barns}$ ):

$$\frac{\partial S}{\partial t} = \lambda_P P(r,t) - \sigma_a^S \phi(r,t) S(r,t) \tag{31}$$

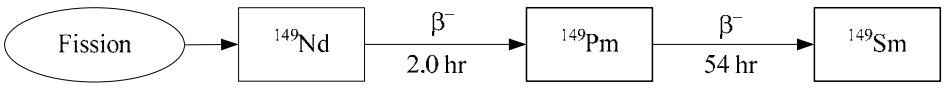


Figure 4. Decay scheme for $^{149}$Sm.

The equilibrium concentrations are obtained at conditions: $\partial P / \partial t = 0 = \partial S / \partial t$ :

$$P_\infty = \frac{\gamma_P \Sigma_f \phi_0(\vec{r})}{\lambda_P} \qquad S_\infty = \frac{\gamma_P \Sigma_f}{\sigma_a^S} \tag{32}$$

The negative reactivity due to saturated samarium poisoning is:

$$\Delta\rho \cong -\frac{\gamma_P}{\nu} \cong 0.00463 \tag{33}$$

Because $^{149}$Sm is stable, it can be removed only by neutron capture. After shutdown samarium-149 builds up to a steady level, which can be described by the following equation:

$$S(t) = S_\infty + P_\infty\left[1 - \exp(-\lambda_P t)\right] \xrightarrow[t\to\infty]{} S_\infty + P_\infty \tag{34}$$

The corresponding reactivity is:

$$\Delta\rho(t) = -\frac{\gamma_P}{\nu}\left[1 + \frac{\phi_0 \sigma_a^S}{\lambda_P}\left(1 - \exp(-\lambda_P t)\right)\right] \tag{35}$$

### 2.2. Evaluation of the evolution of the macroscopic absorption cross sections during Xe – Sm transient by SCALE4.4a

The changes of the macroscopic absorption cross sections after a scram and during Xe – Sm transient can be evaluated using the SCALE4.4a modules system. Typical behavior of Σ [$cm^{-1}$] of $^{135}$Xe and $^{149}$Sm are shown at Fig. 5a and Fig. 5b.

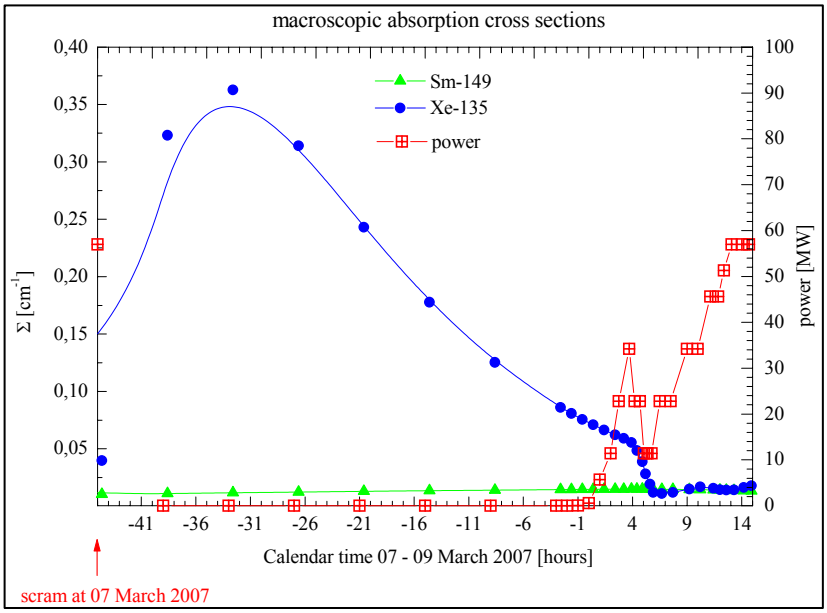


Figure 5a. Evaluation of the macroscopic absorption cross sections during Xe – Sm transient of the BR2 reactor by SCALE4.4a.

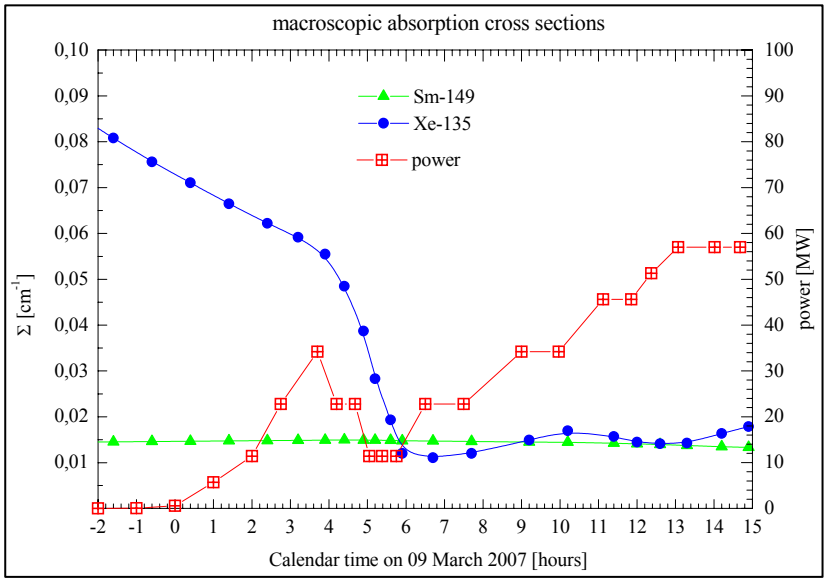


Figure 5b. Evaluation of the macroscopic absorption cross sections during Xe – Sm transient of the BR2 reactor by SCALE4.4a.

### 2.3. Evaluation of the reactivity changes during Xe – Sm transient after a scram by SCALE4.4a

The SCALE4.4a modules system has been used for calculation of the reactivity changes, caused by changes in the power level during Xe-Sm transient. The k-infinities of an infinite lattice heterogeneous BR2 cell are calculated by ORIGEN-S using a cell-weighted cross sections library for all materials of infinite lattice pin geometry and for all requested time steps. Typical behavior of the reactivity during Xe-Sm transient is given in Fig. 6.

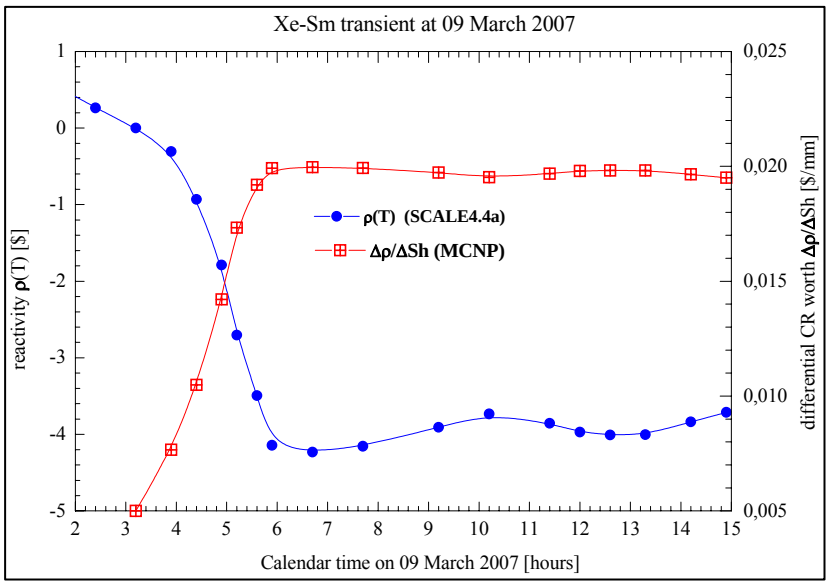


Figure 6. Reactivity changes during Xe – Sm transient after a scram of the BR2 reactor.

## 2.4. Calculation of the differential CR worth by MCNP

In order to evaluate the motion of the CR bank during the Xe-Sm transient, we must preliminary calculate the differential CR worth for the given reactor core load. In this paper, the total and differential CR worth were calculated using MCNPX [4] for the full-scale 3-D heterogeneous geometry model of the reactor BR2. Typical total and differential CR worth are shown at Fig. 7.

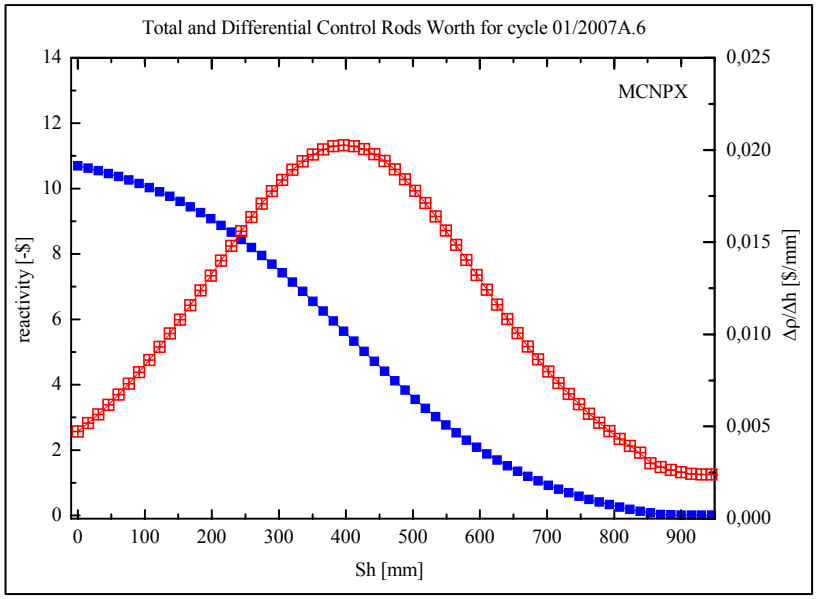


Figure 7. Total and differential CR worth during typical BR2 operation cycle.

## 2.5. Evaluation of the positions of the CR motion in transient after a scram by SCALE4.4a

The final aim is to evaluate the positions of the CR motion during the transient. For this purpose, the reactivity values (Fig. 6) and the values of the differential CR worth (Fig. 7) are used to estimate the positions Sh of the CR during their motion in the transient. A typical CR motion during a transient after a cram, evaluated by SCALE4.4a, is given in Fig. 8.

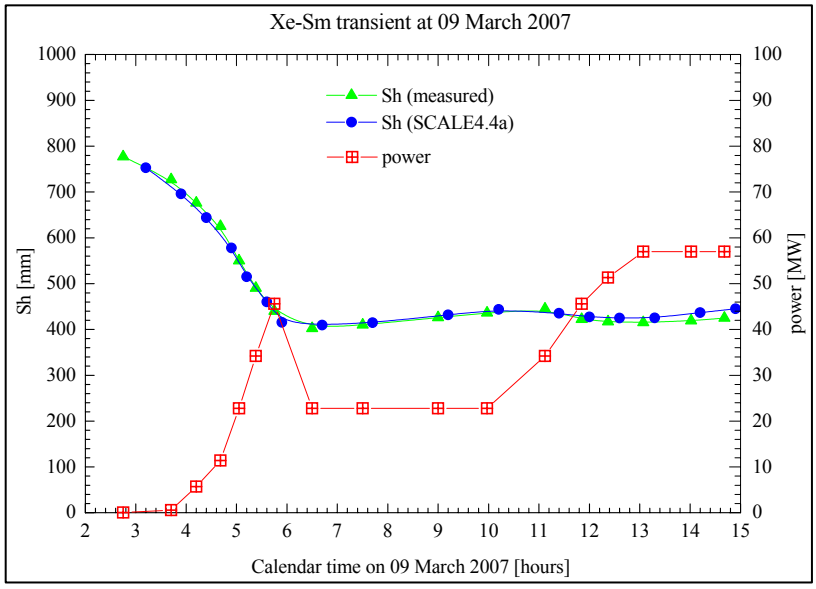


Figure 8. CR motion during Xe – Sm transient after a scram of the BR2 reactor.

## 3. Calculation methodology by SCALE4.4a

The SCALE system is composed from many separate programme codes (modules). Different modules of the SCALE4.4a system can be used for the evaluation of the isotopic fuel depletion, evaluation of the macroscopic absorption cross sections and k – infinities during Xe – Sm transients. These modules are: XSDRNPM [5], NITAWL-II [6], BONAMI [7], COUPLE [8] and ORIGEN-S [9].

Two different approaches can be applied:

- The first approach is to use a combination of the mentioned above modules in order to perform the depletion and criticality analysis;
- Another approach is to use the control module SAS2H [10] (a coupled 1 – D depletion and shielding analysis module), which utilizes all mentioned above five codes (plus some others) into one computation programme.

XSDRNPM [5]:

- The module XSDRNPM is a 1 – D discrete-ordinates transport code that solves the one-dimensional Boltzmann equation, based on various specified geometries: slab, cylindrical, or spherical geometry. The number of the spatial intervals, the number of the energy groups, the number of nuclides, etc. are arbitrary, and practically limited only by computer memory. A fuel assembly with heterogeneous description as it is used in MCNP is introduced as input data for calculations by XSDRNPM.

- The flux calculations can be performed according to several options, including fixed source calculations and k-calculations. The code uses the fluxes determined from its spectral calculation to produce one-group cell-weighted cross sections values for fuel depletion analysis by ORIGEN-S.

NITAWL-II [6]:

- On the basis of a user-specified system description (i.e. geometry of a heterogeneous fuel assembly in the module XSDRNPM) the module NITAWL-II performs problem-dependent resonance shielding analysis by applying the Nordheim Integral Treatment (NIT). NIT involves a solution for the energy dependence of the neutron flux in a material region, containing one or more resonance absorbers and maximum of two mixed moderators.
- Additionally, NITAWL-II is used to read and to convert data from an AMPX master library into the AMPX working library format. An AMPX master library is not suitable for direct use in a multigroup particle transport calculation. The aim of the master AMPX library is to provide a library, which is problem-independent. NITAWL-II combines all data into a form which is ready to be used by particle transport code (like XSDRNPM). The final output is the AMPX working library.

BONAMI [7]:

- Performs resonance self-shielding calculation based on Bondarenko method and produces problem – dependent cross sections (especially suitable for unresolved resonance energy region)
- Solves problems in 1 – D multizone slab, cylindrical or spherical geometry. A variety of Dancoff expressions are provided to account for heterogeneous effects.

COUPLE [8]:

- The function of this module is the production of binary libraries to be input to the ORIGEN-S code and to update the cross-sections constants included in the ORIGEN-S nuclear data library from the cell-weighted cross-sections library produced by XSDRNPM.

ORIGEN-S [9]:

- This module is 1-D depletion code. It can be used in combination with mentioned above modules, utilized by the SAS2H module or used as a stand alone code. The original ORIGEN programme has been developed to perform depletion isotopic analysis and radioactivity analysis from fission products, cladding and fuel materials in LWRs, LMFBRs, MSBRs, and HTGRs reactors.
- The advantage of the code ORIGEN-S in comparison with the original versions of ORIGEN is that it can be used in combination with other modules of the SCALE system (COUPLE, NITAWL-II, BONAMI, XSDRNPM). Thus, the SCALE system provides the capability of executing ORIGEN with the data that have been rigorously processed for a particular fuel assembly of a particular reactor type and user-specified irradiation history.

# 4. Xe – Sm transients at the BR2 Reactor

## 4.1. Cycle 01/2007A.6

### 4.1.1. Irradiation history and standard calculation procedure.

The cycle 01/2007A.6 started at 04 March 2007 after a shutdown of 106.5 days. The reactor core load can be found in the document [11]. The reactivity evolution of the reactor core during the cycle has been evaluated by TRPT3/TRPT4 [12] and MCNP&ORIGEN-S method [13] and reported in [14], [15] and [16], respectively. All three curves have pointed out that after the first several days of the reactor operation the position of the CR bank decreases quickly due to the large poisoning of the beryllium matrix by $^{3}$He (~ 6.5$ ÷7.0 $) and its rapid burning and reaches minimum after about 8 ÷ 10 days of reactor operation. Several scrams have been observed during the cycle 01/2007A.6. The first one happened about 2.5 days after the start, i.e at 07 March, following by stop of the reactor. After a shutdown of about 2 days during the next several days 2 to 3 scrams have taken place, not involving stop of the reactor. However the scram at 13 March due to damage of the mobile mechanism of the CR S2 has caused the second stop of the reactor, followed by ~ 2 days shutdown.

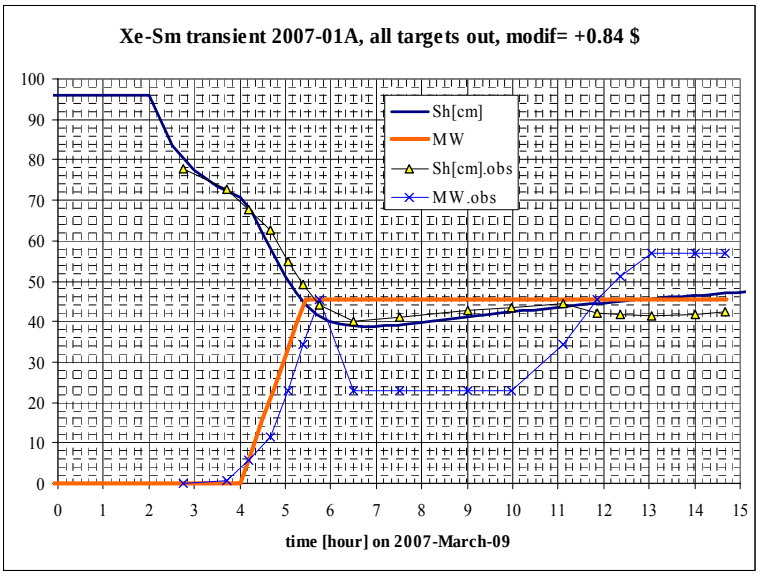


Figure 9a. First Xe – Sm transient during cycle 01/2007A.6 [17].

The routine calculations of the transients during 07÷ 09 March and 13÷15 March 2007 have been performed using a standard calculation procedure by XESM and reported in [17], [18]. The calculation previsions for changing of the positions of the CR during the Xe – Sm transient were in a good agreement with the measured data (see Fig. 9a and Fig. 9b). Some shift of about ~ 4 hrs. between the calculation and experimental curves of the CR motion have been observed during the second transient. Because of the very low position Sh of the CR in each of the scrams, which happened at the minimum of the curves of the CR motion, special power level profiles have been maintained during the both transients as it is shown at Fig. 9a and Fig. 9b.

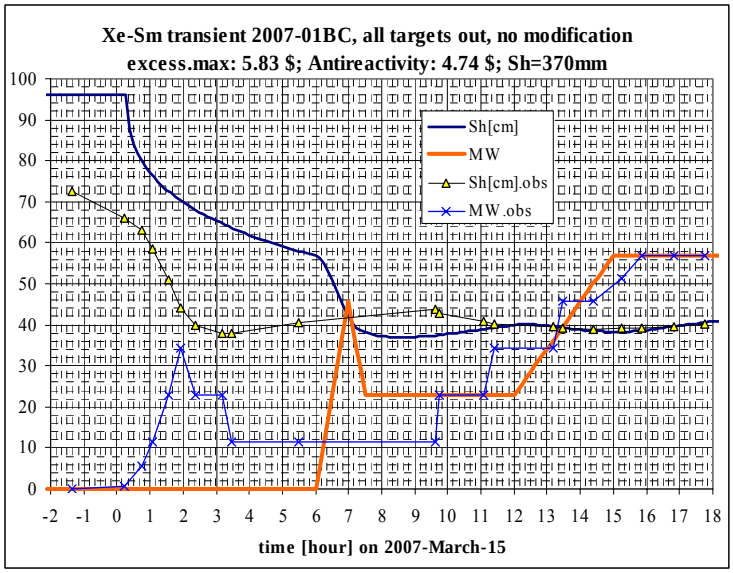


Figure 9b. Second Xe – Sm transient during cycle 01/2007A.6 [18].

### 4.1.2. Evaluation of the reactivity changes during the transients by SCALE4.4a

The reactivity changes, the evolutions of the macroscopic cross sections after the scram and during the both transients of the cycle 01/2007A.6B1C1 have been evaluated with the SCALE4.4a system as described in §2.3 and these are given in Fig. 10a and 10b.

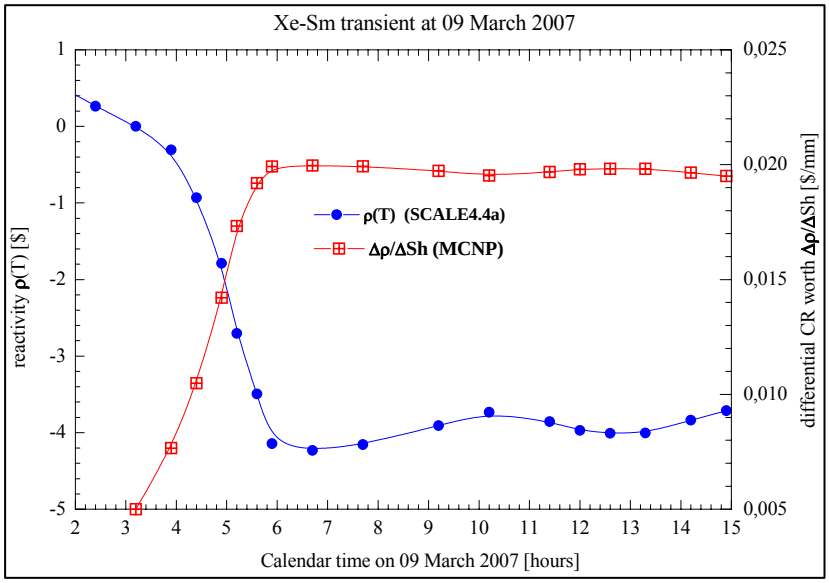


Figure 10a. Reactivity changes during the first Xe – Sm transient of cycle 01/2007A.6 evaluated with SCALE4.4a.

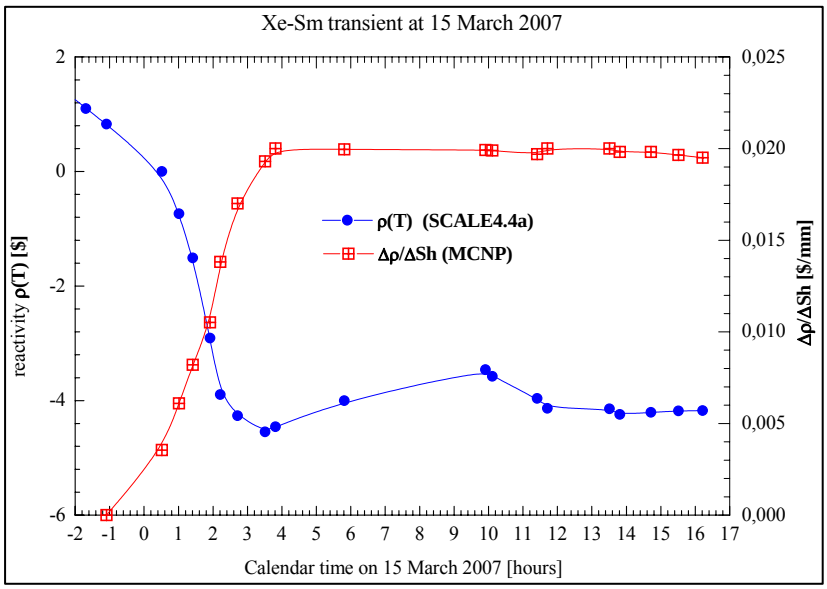


Figure 10b. Reactivity changes during the second Xe – Sm transient of cycle 01/2007A.6 evaluated with SCALE4.4a.

### 4.1.3. Evaluation of the positions of the CR motion during the transient by SCALE4.4a.

The two transients during the cycle 01/2007A.6 have been reproduced using the SCALE4.4a calculation methodology (§3) following the calculation procedure, as described in § 2.2 to § 2.5. The reproduced positions of the motion of the CR bank during the two Xe-Sm transients, which have taken place in cycle 01/2007A.6, are shown at Fig. 11a and 11b. The calculations were performed following the real power level changes during the Xe-Sm transients, which was used as input for the calculations by SCALE4.4a.

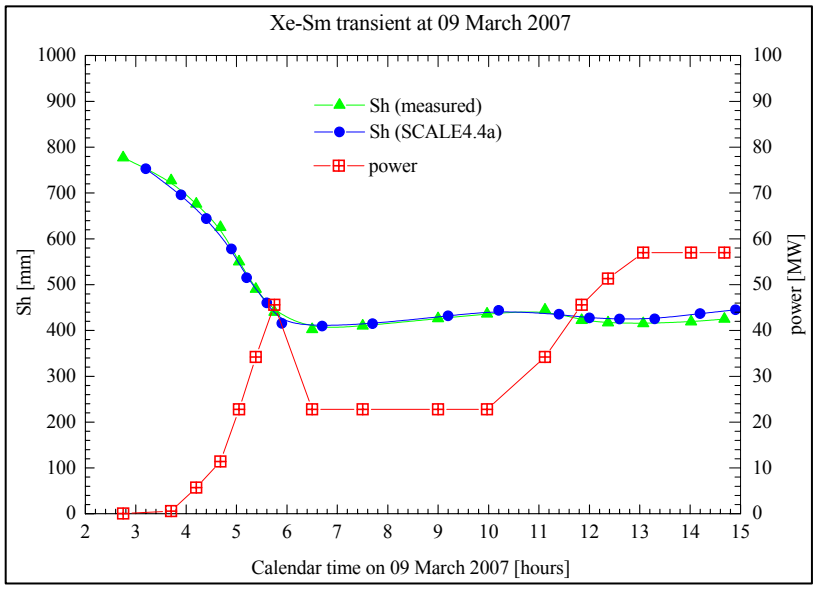


Figure 11a. Positions of the Control Rods motion during the first Xe – Sm transient of cycle 01/2007A.6 calculated by SCALE4.4a.

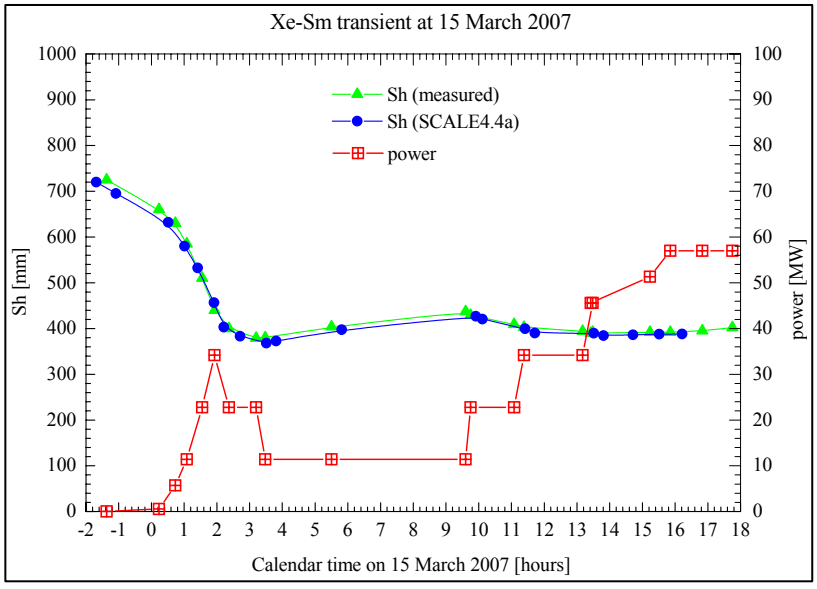


Figure 11b. Positions of the Control Rods motion during the second Xe – Sm transient of cycle 01/2007A.6 calculated by SCALE4.4a.

## 4.2. Cycle 05/2006A.4

### 4.2.1. Irradiation history and standard calculation procedure.

The cycle 05/2006A.4 started at 25 October 2006. The reactor core load can be found in the document [19]. The reactivity evolution of the reactor core during the cycle has been evaluated by TRPT3/TRPT4 [20], [21] and MCNP&ORIGEN-S method [22]. Two scrams of the reactor have occurred during this cycle. The first scram happened about 10.3 days after the start, i.e at 04 November 2006, following by stop of the reactor of about 2 days. The second stop of the reactor was at 10 November 2006 ("STRIKE"), following by shutdown of about 2 days. The routine calculations of the transients during 04÷07 November and 10÷12 November 2006 have been performed using a standard calculation procedure by XESM and reported in [23], [24]. The calculation previsions of the changing of the position of the CR during the Xe – Sm transient were in a good agreement with measured data. The power during the both transients has been gradually increased as it is shown at Fig. 12a and Fig. 12b.

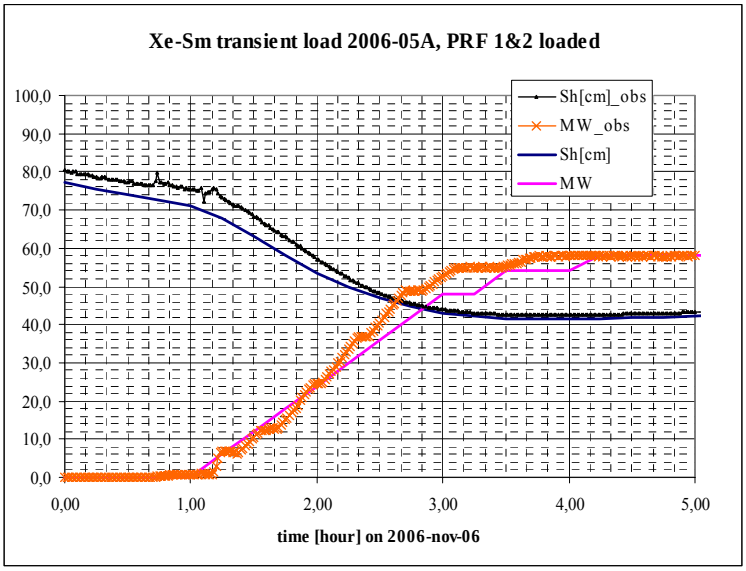


Figure 12a. First Xe – Sm transient during cycle 05/2006A.4, evaluated by standard procedure XESM.

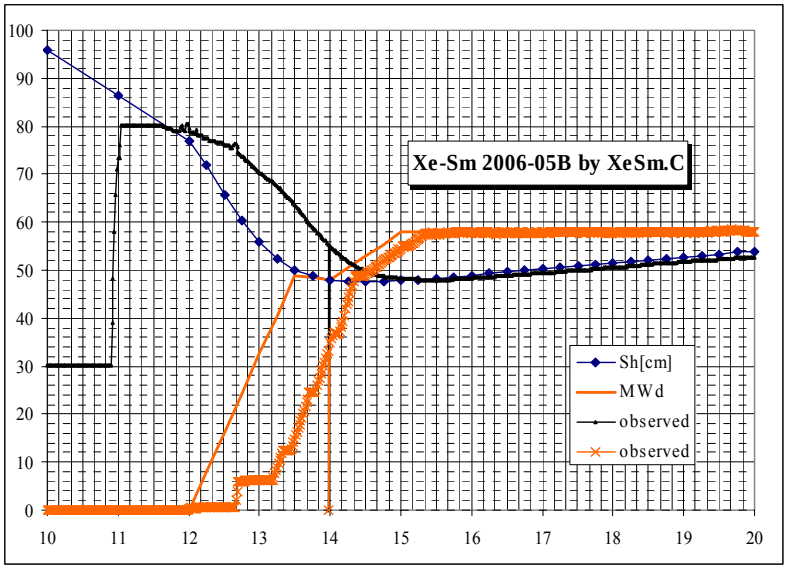


Figure 12b. Second Xe – Sm transient during cycle 05/2006A.4, evaluated by standard procedure XESM.

### 4.2.2. Evaluation of the reactivity changes during the transients by SCALE4.4a.

The SCALE4.4a modules system has been used for calculation of the reactivity changes, caused by changes in the power level during Xe-Sm transients, being occurred in the cycle 05/2006A.4. The k-infinities of an infinite lattice heterogeneous BR2 cell were calculated by ORIGEN-S using a cell-weighted cross sections library for all materials of infinite lattice pin geometry (module XSDRNPM) and for all requested time steps. The calculated reactivity changes during the transients of the cycle 05/2006A.4B1C1 are given in Fig. 13a and 13b.

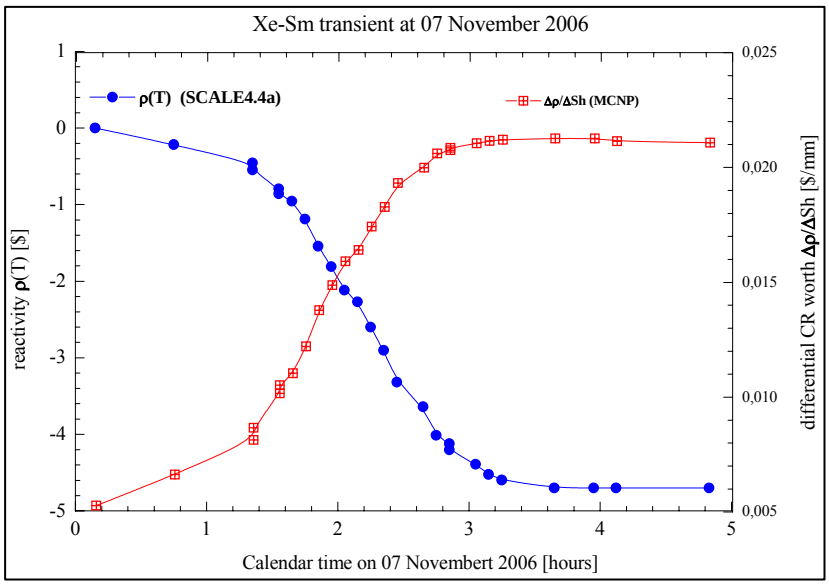


Figure 13a. Reactivity changes during the first Xe – Sm transient in cycle 05/2006A.4 evaluated by SCALE4.4a.

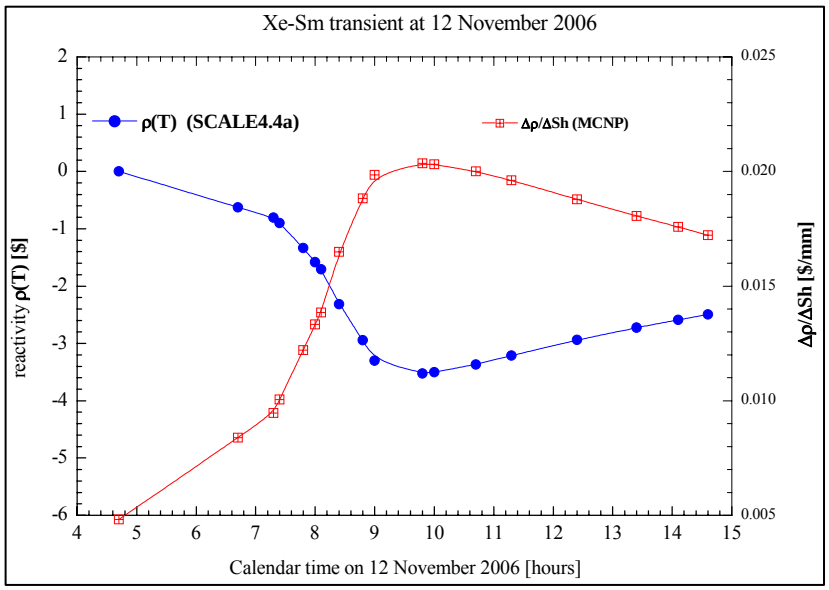


Figure 13b. Reactivity changes during the second Xe – Sm transient in cycle 05/2006A.4 evaluated by SCALE4.4a.

### 4.2.3. Evaluation of the CR motion during the transients by SCALE4.4a.

The two transients during the cycle 05/2006A.4 have been reproduced using the SCALE4.4a calculation methodology (§3) following the calculation procedure, described in § 2.2 to § 2.5. The reproduced positions of the motion of the CR bank following the real power during the Xe – Sm transients in cycle 05/2006A.4, are given at Fig. 14a and 14b.

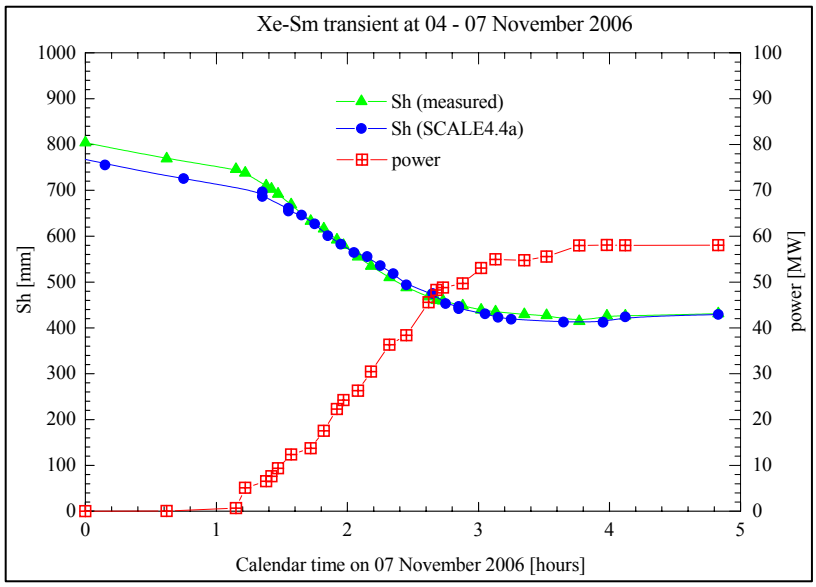


Figure 14a. Positions of the Control Rods motion during the first Xe – Sm transient of cycle 05/2006A.4 calculated by SCALE4.4a.

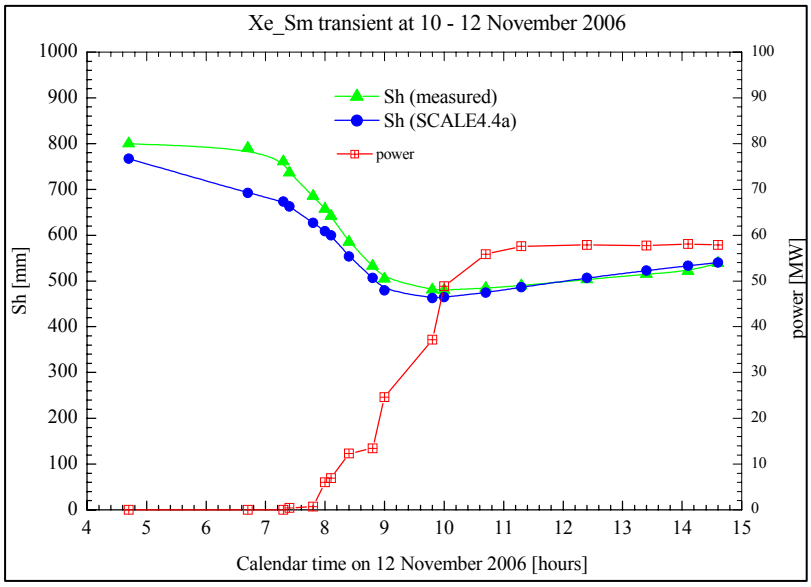


Figure 14b. Positions of the Control Rods motion during the second Xe – Sm transient of cycle 05/2006A.4 calculated by SCALE4.4a.

## 4.3. Cycle 04/2005A.4

### 4.3.1. Irradiation history and standard calculation procedure.

The cycle 04/2005A.4 started at 30 September 2005. During the first ten days of the cycle the reactor has been operated at low power (P ~ 6.5 MW) to satisfy the irradiation conditions for the experiment RIED [25]. The reactor core load can be found in the Technical Note [26]. The reactivity evolution of the reactor core during the cycle has been evaluated by TRPT3/TRPT4 [27], [28] and MCNP&ORIGEN-S method [29].

The Xe-Sm transient during the first part of the cycle (experiment RIED) has been evaluated using the standard procedure by XESM [2] and reported in [30], [31]. The CR motion during the first ten days of the cycle is given at Fig. 15a. A scram at 20 October 2005 has occurred, following by reactor stop of ~ 2 days. The Xe-Sm transient has been evaluated in accordance with the standard procedure XESM and the CR motion is shown at Fig. 15b. The power during the second transient (at restart of the reactor 48 hours after the scram) has been gradually increased as it is shown at Fig. 15b.

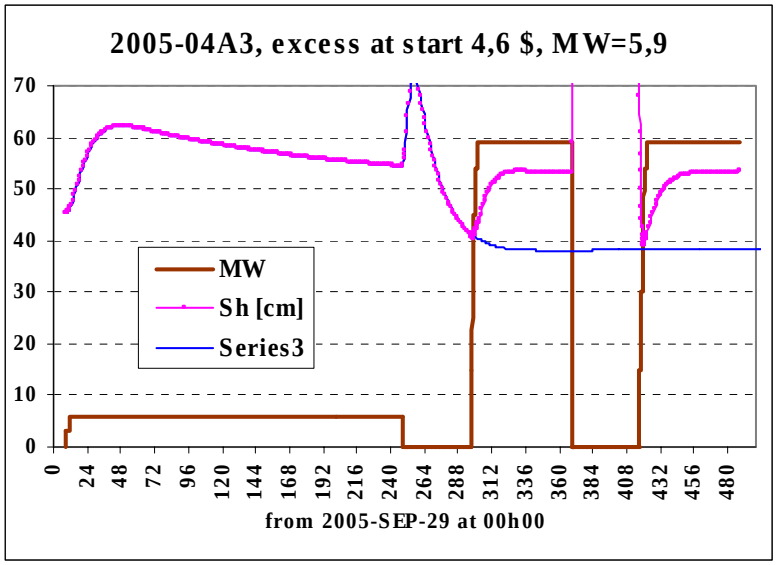


Figure 15a. Xe – Sm transient during the experiment RIED in cycle 04/2005A.4 evaluated by standard procedure XESM.

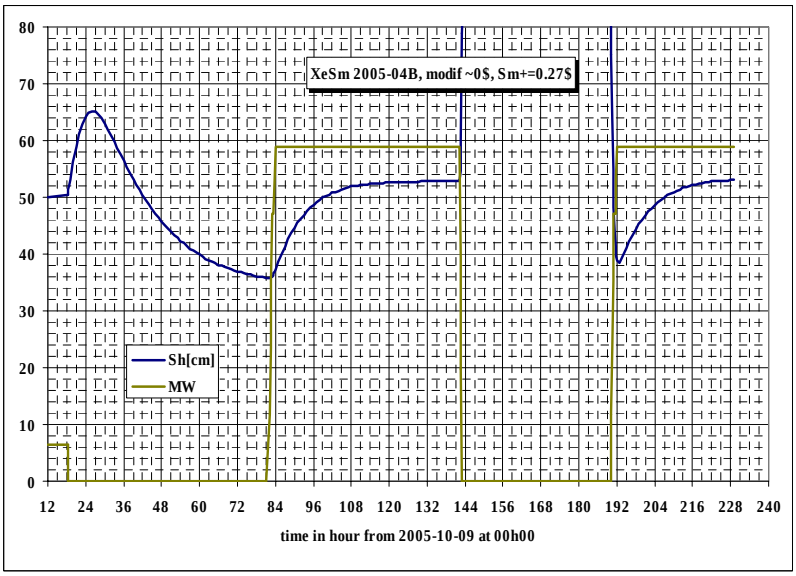


Figure 15b. Second Xe – Sm transient after a scram in cycle 04/2005A.4 evaluated by standard procedure XESM.

### 4.3.2. Evaluation of the reactivity changes during the transients by SCALE4.4a

The SCALE4.4a modules system has been used for calculation of the reactivity changes, caused by changes in the power level during Xe-Sm transients, being occurred in the cycle 04/2005A.4. The calculation results are given in Fig. 16.

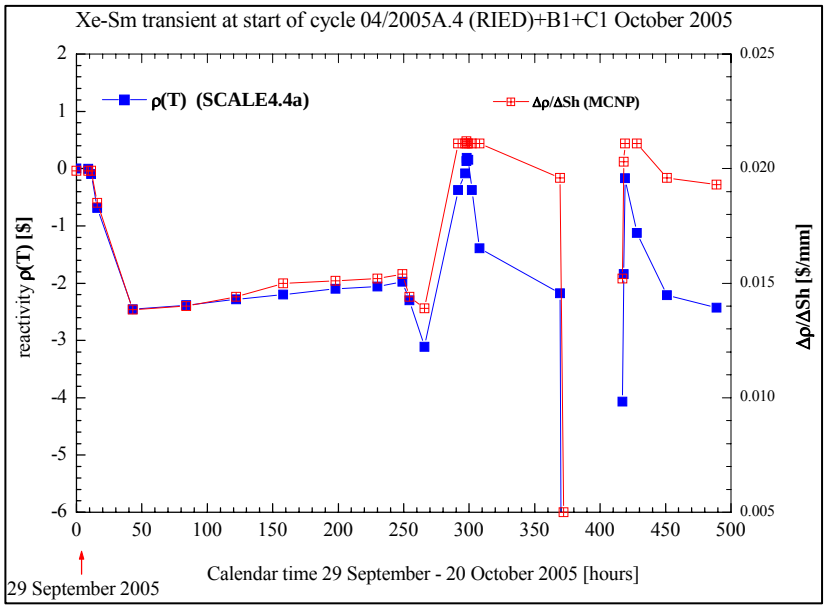


Figure 16. Reactivity changes in Xe – Sm transients (first during the experiment RIED and second - after a scram) in cycle 04/2005A.4 calculated by SCALE4.4a.

### 4.3.3. Evaluation of the CR motion during the transients by SCALE4.4a

The two transients during the cycle 04/2005A.4 have been reproduced using the SCALE4.4a calculation methodology (§3) following the calculation procedure, as described in § 2.2 to § 2.5. The reproduced positions of the motion of the CR bank following the real power during the two Xe-Sm transients in cycle 04/2005A.4, are shown at Fig. 17.

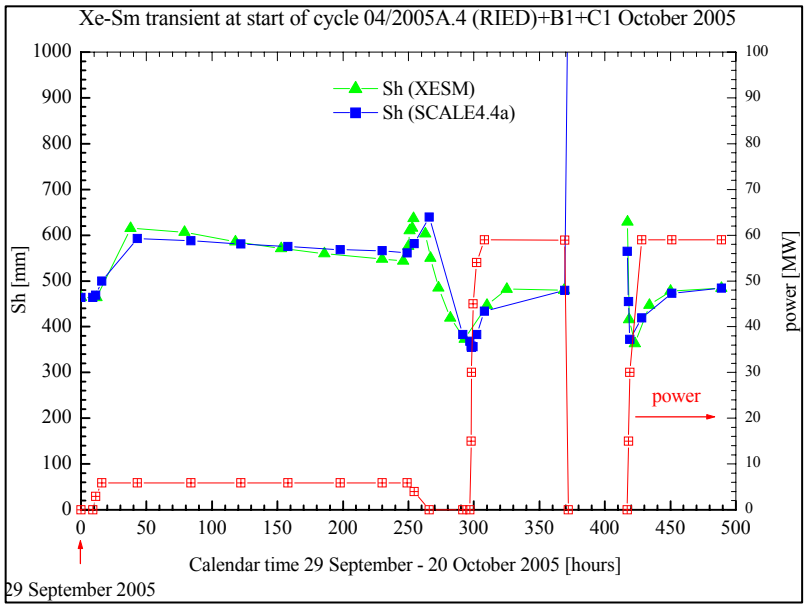


Figure 17. Positions of the Control Rods motion in Xe – Sm transients (first during the experiment RIED and second - after a scram) in cycle 04/2005A.4 calculated by SCALE4.4a and compared with the calculations by the standard procedure XESM [2].

## 4.4. Cycle 02/2005A.5

### 4.4.1. Irradiation history and standard calculation procedure.

The cycle 02/2005A.5 started at 10 April 2005. During the first six days of the cycle the reactor has been operated at low power (P ~ 2.8 MW) to satisfy the irradiation conditions for the experiment RIED. The reactor core load can be found in the document [32]. The reactivity evolution of the reactor core during the cycle has been evaluated by TRPT3/TRPT4 [33], [34] and MCNP&ORIGEN-S method [35].

The Xe-Sm transient during the first part of the cycle (experiment RIED) has been evaluated using the standard procedure by XESM [2] and reported in [36]. The CR motion during the first five days of the cycle is given at Fig. 18a. A scram at 08 May 2005 has occurred. The Xe-Sm transient after the scram has been evaluated in accordance with the standard procedure XESM [37] and the CR motion is shown at Fig. 18b. The power during the second transient (at restart of the reactor 48 hours after the scram) has been gradually increased as it is shown at Fig. 18b.

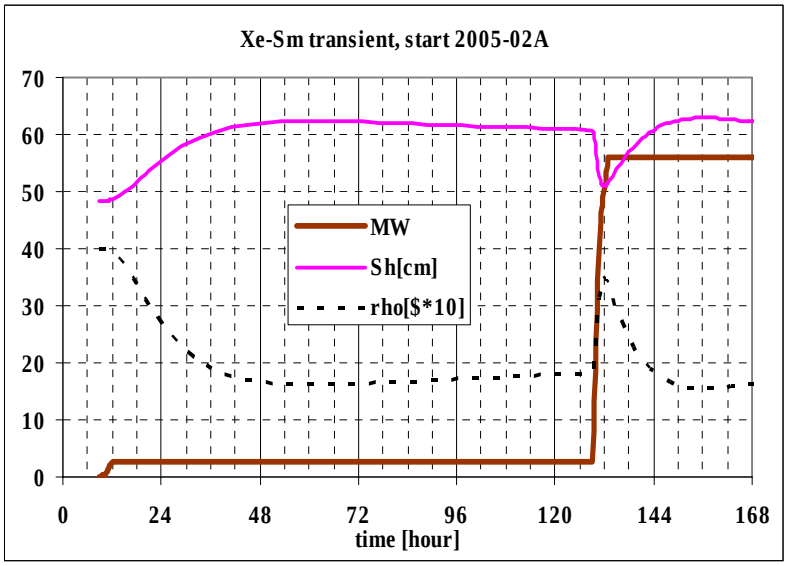


Figure 18a. Xe – Sm transient during the experiment RIED in cycle 02/2005A.5, evaluated by standard procedure XESM.

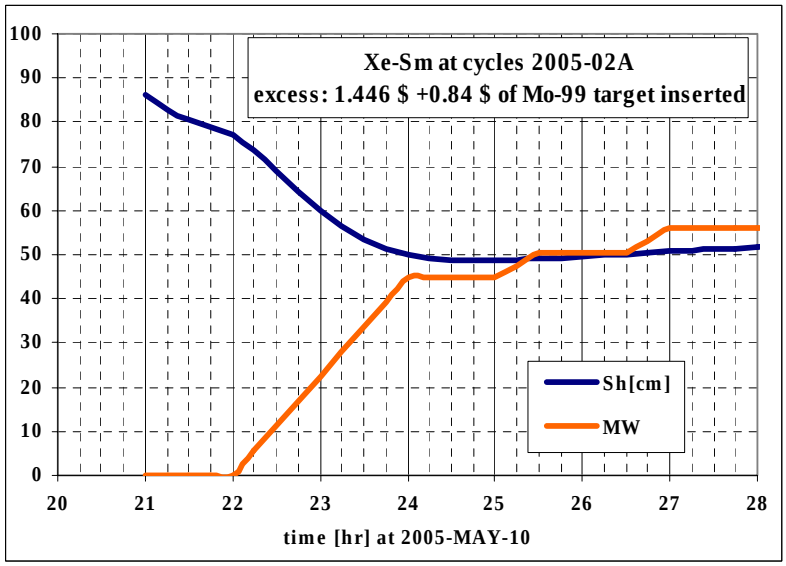


Figure 18b. Second Xe – Sm transient after a scram in cycle 02/2005A.5, evaluated by standard procedure XESM.

### 4.4.2. Evaluation of the reactivity evolution during the transient by SCALE4.4a

The SCALE4.4a modules system has been used for calculation of the reactivity changes, caused by changes in the power level during Xe-Sm transients in the cycle 02/2005A.5. The first transient started with the start up of the operation cycle (see Fig. 19a), the second one occurred after a scram (see Fig. 19b).

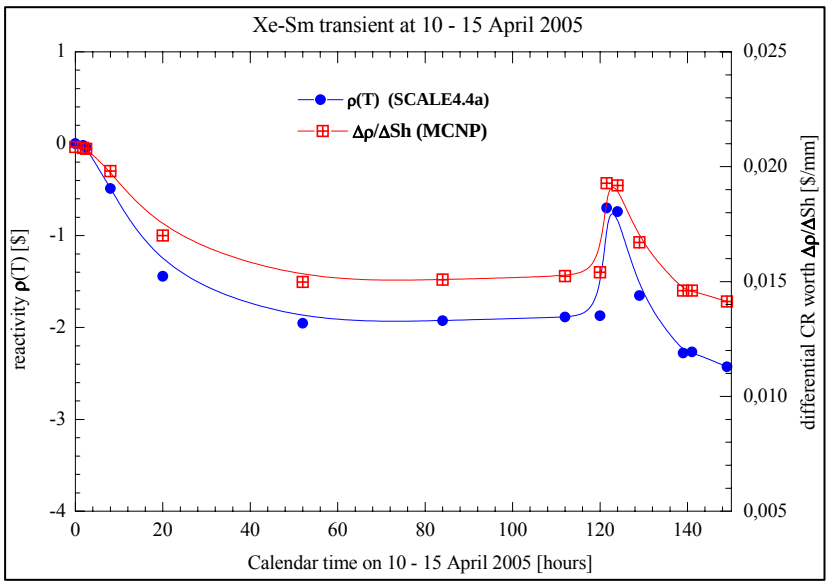


Figure 19a. Reactivity changes in Xe – Sm transient during the experiment RIED at start of cycle 02/2005A.5 evaluated by SCALE4.4a.

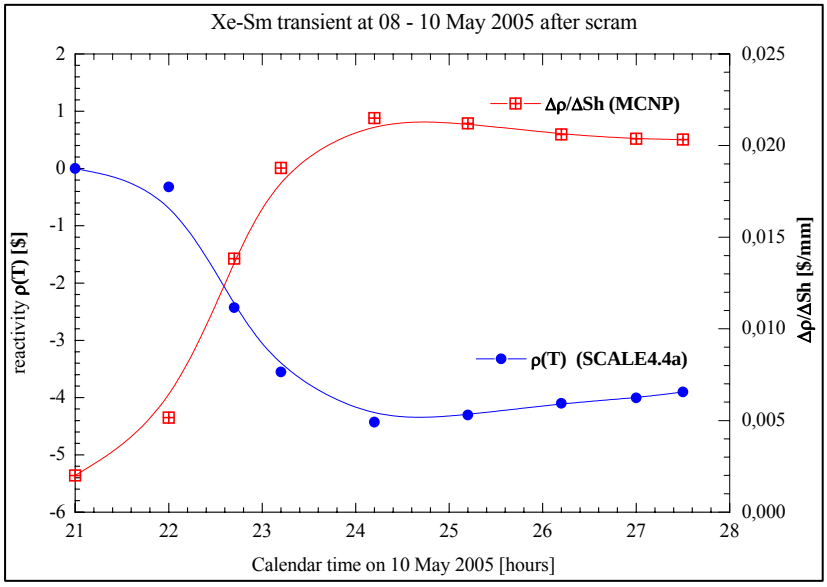


Figure 19b. Reactivity evolution during the second Xe – Sm transient (after the scram at 08 May 2005) of cycle 02/2005A.5 evaluated by SCALE4.4a.

### 4.4.3. Evaluation of the CR motion during the transient by SCALE4.4a

The two transients during the cycle 02/2005A.5 have been reproduced using the SCALE4.4a calculation methodology (§3) following the calculation procedure, described in § 2.2 to §2.5. The reproduced positions of the motion of the CR bank during the two Xe-Sm transients, which have taken place during cycle 02/2005A.5, are given in Fig. 20a and Fig. 20b. The calculations were performed reproducing the real power during the Xe-Sm transients, which was used as input for the calculations by SCALE4.4a.

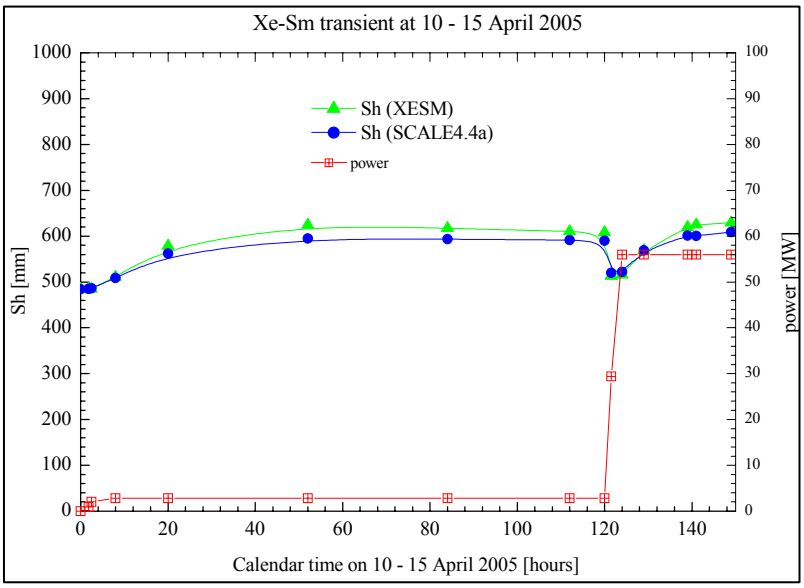


Figure 20a. Positions of the Control Rods motion during the first Xe – Sm transient (experiment RIED) of cycle 02/2005A.5 calculated by SCALE4.4a and compared with the calculations by the standard procedure XESM.

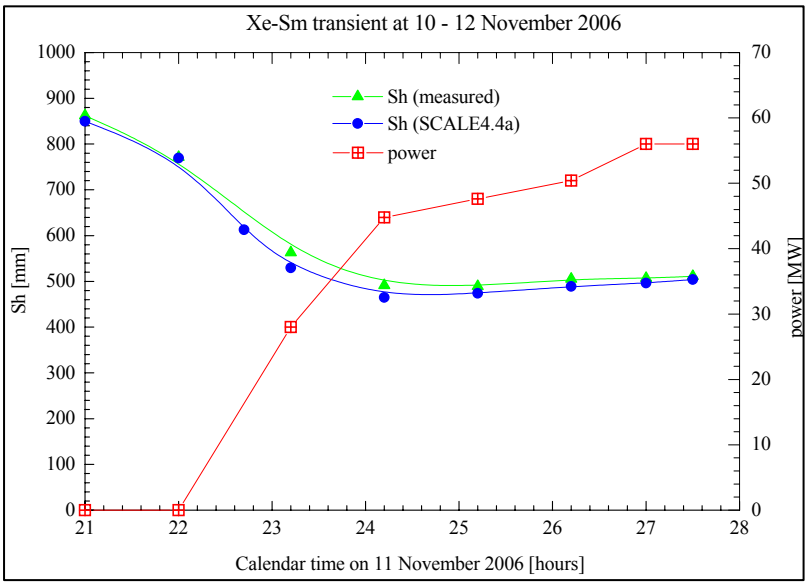


Figure 20b. Positions of the Control Rods motion during the second Xe – Sm transient (after a scram) of cycle 02/2005A.5 calculated by SCALE4.4a.

## 5. Conclusions

Aim of this report is to validate the computational modules system SCALE4.4a for evaluation of reactivity changes, evolution of macroscopic absorption cross sections and calculations of the positions of the Control Rods during their motion in Xe – Sm transient after a scram (or other reasons) of the BR2 reactor. Four operation BR2 cycles with total 8 transients being occurred, have been considered. All eight Xe – Sm transients have been reproduced by the SCALE4.4A system, following the real power during the transient.

The evaluated positions of the Control Rods motion as function of time (in hours) in the transients have been compared with the measured positions Sh. The following conclusions can be made:

- Cycle 01/2007A.6: The agreement between the measured and the reproduced later by SCALE4.4a positions of the CR in the both transients was very good. However, a shift of about 3 to 4 hours has been observed between the measured and the calculated curves.
- Cycle 05/2006A.4: The agreement between the measured and the reproduced by SCALE4.4a positions of the CR for the first transient was good. A deviation of about 30 mm between the measured and the calculated curve in the first hours of the transient operated at low power (P ~ 0 MW) was observed. The same, but larger deviation of about 100 mm, was observed also in the first few hours at low power level (P ~ 0 to 10 MW) of the second transient.
- Cycle 04/2005A.4: The agreement between the calculations performed by the standard procedure XESM and the reproduced by SCALE4.4a positions of the CR for the first transient during the experiment RIED and for the second transient after a scram was very good.
- Cycle 02/2005A.5: The agreement between the calculated with the standard procedure XESM and the reproduced by SCALE4.4a positions of the CR for the first transient in the experiment RIED during the first 6 days after the start of the operating cycle was good. The calculated positions of the CR during the transient in RIED were about 20 to 30 mm lower than the estimated by the standard procedure XESM. A good agreement between the calculations performed with the standard procedure XESM and reproduced positions of the CR afterwards with SCALE4.4a was observed for the second Xe – Sm transient after a scram in the cycle (~ deviation 20 to 30 mm).

The final conclusion is: SCALE4.4a modules system can be used for evaluation of Xe – Sm transients in the BR2 reactor. The utilization of the code is simple and convenient, the computational time might take from few seconds to several minutes depending on which modules of the SCALE system are involved in the calculations.
Future work might be validation of the SCALE5.1/ORIGEN.ARP modules system, which contains a series of updated cross sections data and improvements in comparison with the previous versions of the SCALE system.

## 6. References


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