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ORIGINAL PAPER

Correction methods for pulsed neutron source reactivity measurement in accelerator driven systems

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Abstract. Important issue in the perspective of nuclear energy development in the near future is the partitioning and transmutation (P&T) of spent nuclear fuel. For years the European Commission (EC) has sponsored this scientific activity through the Framework Programmes (FP). One of the milestones for P&T is the development of accelerator driven systems (ADS). Extensive research in this field was carried out within the EUROTRANS project of 6th FP of EURATOM. Part of this research was devoted to testing and development of reactivity monitoring techniques in ADS. This paper concerns the methods of the reactivity measurement using the pulsed neutron source (PNS). Due to the fact that basic methods devoted to determine the core reactivity are derived from point kinetics, while real subcritical core kinetics differs from this model, there is a need to improve these methods in order to deal with the observed spatial effects. There are several ways to make these methods work properly and finally it should be possible to achieve this. However, they still need a validation which is supposed to be done within next FP project FREYA.

Key words: accelerator driven systems (ADS) • EUROTRANS • measurement • reactivity • YALINA

Introduction

The interest in partitioning and transmutation (P&T) of nuclear waste has grown in many countries over last two decades with expectation that P&T technologies will allow to reduce the need of geological disposal of spent fuel and high-level waste. The three main reasons for applying P&T technologies are reduced amount of waste, reduced time of storage (since the plutonium and minor actinides are mainly responsible for the long-term radiotoxicity) and better use of nuclear fuel.

Although, the first stage of transmutation is possible and being done in light water reactors by reusing plutonium from the spent fuel in the MOX (mixed oxides) fuel, a different approach is required for burning also the minor actinides in order to close the fuel cycle. Several reactor technology concepts are, therefore, proposed for the minor actinide burning. First of all, fast reactors are considered as a relevant tool due to the fact that burning-to-production ratio of minor actinides is more advantageous in fast neutron spectra. However, another important issue limiting minor actinides content in the fuel is their smaller delayed neutron fraction than in classic uranium and MOX fuel. The solution is coupling of the subcritical reactor with a proton accelerator and spallation neutron source in the so-called accelerator driven systems (ADS). This additional neutron source allows operating the reactor in subcritical state and makes its distance to super-prompt-criticality

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independent of the fuel isotopic composition. As the result, we are not only making the closed fuel cycle. For ADS, we also reduce to about 10% the needed share of actinide burners from about 35% of installed power in nuclear power plants when using fast reactors for minor actinide burning [5]. It is an important advantage due to the fact that dedicated actinide burners are expected to be more expensive than classic water reactors.

The EUROTRANS project

Different aspects of ADS development were studied within the extensive research called EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System (EUROTRANS). It started in 2005 within the 6th Framework Programme of EURATOM and lasted until 2010. The project consortium was constituted by 28 partners from 14 countries including universities, national research organizations and industrial companies with the Karlsruhe Institute of Technology as the project coordinator. It also included wide cooperation with institutes from non-EU countries [4].

The main long term goal was to carry out a first advanced design of experimental transmutation facility to demonstrate the technical feasibility of transmutation in ADS. In order to do this a wide spectre of topics were analysed. Among the other aspects of the project its domain ECATS (experiments on the coupling of an accelerator, a spallation target and a subcritical blanket) was devoted to examine some unique features of subcritical core kinetics including development and testing of reactivity monitoring techniques. An experimental programme was carried out in the Joint Institute of Power and Nuclear Research (JIPNR) in Minsk using the Yalina subcritical assembly [4].

Various authors took part in the preparation and performing experiments and analysis of the experimental data. That includes neutronic calculations to simulate the experiments, analysis of observed spatial effects and development of methods for correction of the reactivity values from experiment.

Similar research activities are planned within consecutive research in the 7th Framework Programme, i.e. in FREYA project (fast reactors experiments for hybrid applications). These experiments, in which AGH University of Science and Technology (AGH-UST, Kraków) also takes part, include similar reactivity measurements using a GUINEVERE reactor. Design of this reactor was also a part of EUROTRANS project.

Reactivity monitoring techniques in ADS

Due to the fact that accelerator driven systems will be operated in subcritical mode and for safety reasons the current core reactivity must be known. The development of adequate reactivity monitoring techniques is one of the key points for ADS development. Because they are supposed to never approach criticality any techniques based on control rod are inadequate. The following techniques are, therefore, proposed for that purpose [7]:

1. During power operation:
   - Current-to-power: based on the proportionality between reactivity and the current-to-power (or current-to-flux) ratio;
   - Beam trips technique: based on the dependency of the neutron flux evolution after short interruption of the beam on the reactivity;
   - Noise technique; based on statistical properties of the fission chains.
2. During loading and start-up operation:
   - PNS technique: based on the kinetic response off the neutron flux after a series of periodical neutron pulses;
   - Noise technique.

All of the methods mentioned above were tested during the experiments in the Yalina facility. Some of them (beam trips, current-to-power) for the first time. Apart from the authors involved, the experimental team included also specialists from Helmholtz-Zentrum Dresden-Rossendorf, Karlsruhe Institute of Technology, Joint Institute of Power and Nuclear Research in Minsk, Research Centre for Energy, Environment and Technology (CIEMAT, Madrid) and Royal Institute of Technology (KTH, Stockholm).

Yalina facility

The Yalina-booster subcritical facility is placed in the Joint Institute of Power and Nuclear Research in Minsk, Belarus. It's a subcritical zero-power reactor divided into fast and thermal zone surrounded by a graphite reflector. The fast zone consist of highly enriched metallic uranium fuel pins in a lead matrix, while in the thermal one less enriched fuel in a polyethylene moderating matrix is used (see Table 1). Both zones are separated with B_4F valve zone to prevent thermal neutrons to re-enter the fast zone. The cross-section of Yalina booster showing the positions of the experimental channels for detector placement is shown in Fig. 1.

The core is coupled with an NG-12-1 neutron generator which uses a D-T reaction neutron source. It

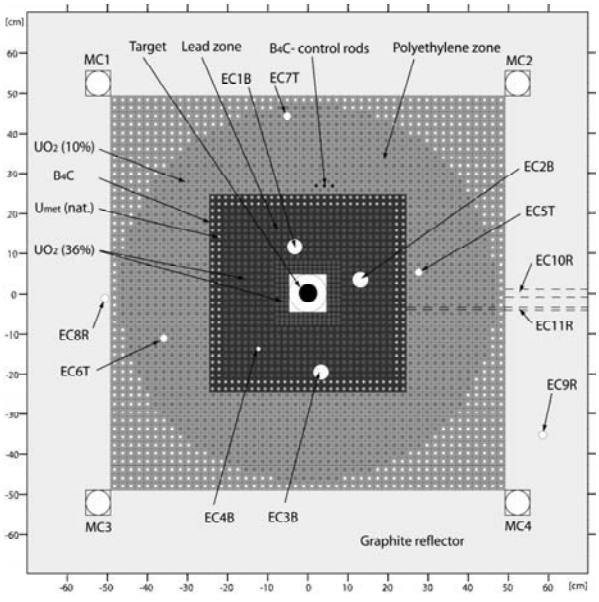

Fig. 1. Yalina-booster core cross-section.

Table 1. Yalina-booster core configurations applied in measurements

Zone	Inner booster		Outer booster	Thermal zone	k_{eff} (MCNP)
Enrichment	90%	36%	36%	10%	
SC0	132	–	563	1141	0.977
SC3a	–	132	563	1077	0.950
SC3b	–	–	563	1090	0.950
SC6	–	132	563	726	0.850

can be operated in both pulsed and continuous mode. When using the continuous mode short interruptions of the beam (beam trips) are also possible.

Different core loading patterns are possible to obtain different core reactivities. Core configurations used in the experiments are shown in Table 1 where the expected reactivity values calculated with MCNPX code are also given. It is worth to notice that SC3a and SC3b have the same reactivity obtained by using different loading patterns. Slight reactivity changes can be also done by moving the control rods placed in a thermal region.

During the pulsed neutron source (PNS) experiments, the neutron generator was operated in the pulsed mode to generate 5 μs long pulses with repetition rate between 50–166 Hz depending on the core configuration (respectively 50 for SC0 and SC3a, 56 for SC3b and 166 for SC6). He-3 detectors and fission chambers (1 mg and 500 mg U-235) were used to measure the time evolution of the neutron flux in the reactor core during the consecutive pulses. A liquid scintillation counter was applied for monitoring of the neutron source intensity. Measurements for all core configurations were done both with control rods inserted and extracted.

Measurement methods

Two basic methods applied to obtain the value of core reactivity were: the Sjöstrand method (also called "area" method) and the prompt decay constant fitting method. Theoretical core response to the neutron pulse injection is shown in Fig. 2. Its shape depends on several core parameters, among them on the reactivity. At the beginning, we can observe the rise of the neutron flux after the pulse, then the exponential decay and at the end the background in which core is being fed by delayed neutrons.

The prompt decay constant method relies on fitting the decay constant of prompt neutron population (α) to the part of the core response where exponential decay is observed. Reactivity (ρ) is then given by [3]

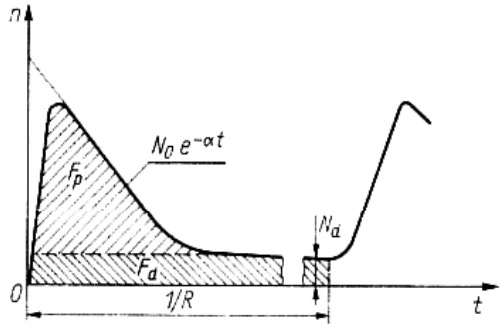

Fig. 2. Neutron flux after pulse [3].

$$-\frac{\rho}{\beta}=\frac{\alpha\times\Lambda}{\beta}+1 \tag{1}$$

The values of delayed neutron fraction (β) and neutron generation time (Λ) must be known values and for experiments they can be calculated using MCNP code for each core configuration.

The Sjöstrand method is an old method proposed by N. G. Sjöstrand in 1956 to measure negative reactivities. It is based on the fact that the ratio of prompt (F_p)-to-delayed neutron area (F_d) is dependent on the reactivity and the delayed neutron fraction. The value of the reactivity normalized to β is, therefore, given by the simple relation [6]

$$\frac{\rho}{\beta}=-\frac{F_p}{F_d} \tag{2}$$

This method does not require any additional data to obtain such value from the experiment.

Preliminary results

Example of kinetic response measured in the core after the neutron pulse injection is shown in Fig. 3. It is showing a signal from detectors placed in different core regions (fast zone – EC1B, thermal zone – EC6T and reflector – MC2). We can observe some differences in the neutron flux behaviour depending on the part of the core where the detector was placed. Significant differences occur in the very beginning of the pulse. Afterwards, prompt decay slopes can be observed and then the delayed neutron background. As expected, a slow decay of the delayed neutron level was observed but its influence on the results was negligible thus it

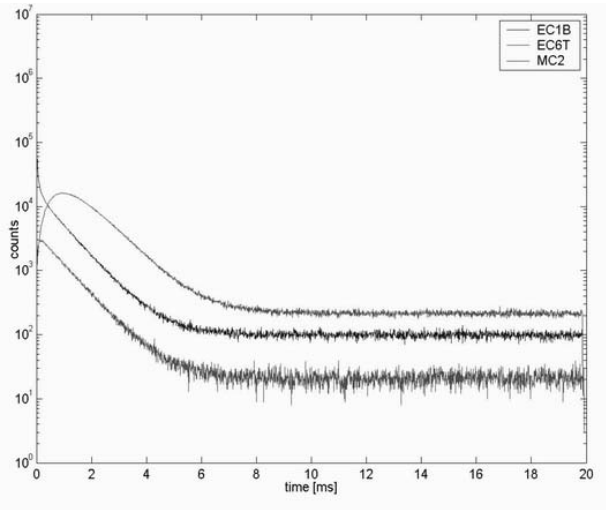

Fig. 3. Example results plot – SC3a, control rods inserted (CRI).

Table 2. Results for prompt decay constant method – SC3a

		CRE[a]		CRI[b]	
		α (s^{-1})	ρ ($)	α (s^{-1})	ρ ($)
Booster zone	EC1B	–1014 ± 19	–7.89 ± 0.23	–1113 ± 13	–8.76 ± 0.29
	EC2B	–	–	–1108 ± 16	–8.72 ± 0.33
	EC3B	–	–	–1091 ± 9	–8.57 ± 0.23
Thermal zone	EC5T	–1029 ± 36	–8.02 ± 0.65	–1104 ± 24	–8.68 ± 0.46
	EC6T	–	–	–1060 ± 8	–8.30 ± 0.21
Reflector	MC2	–985 ± 15	–7.64 ± 0.20	–1017 ± 12	–7.92 ± 0.26
	MC3	–901 ± 49	–6.91 ± 0.45	–1006 ± 19	–7.83 ± 0.37

[a]CRE – control rods extracted.
[b]CRI – control rods inserted.

Table 3. Results for prompt decay constant method – SC3b

		CRE[a]		CRI[b]	
		α (s^{-1})	ρ ($)	α (s^{-1})	ρ ($)
Booster zone	EC1B	–1036 ± 11	–8.25 ± 0.13	–	–
	EC2B	–1029 ± 12	–8.18 ± 0.14	–1086 ± 13	–8.70 ± 0.15
	EC3B	–1039 ± 14	–8.28 ± 0.15	–	–
Thermal zone	EC5T	–1032 ± 11	–8.22 ± 0.13	–	–
	EC6T	–1030 ± 13	–8.20 ± 0.14	–1083 ± 16	–8.67 ± 0.17
Reflector	MC2	–983 ± 16	–7.78 ± 0.16	–1078 ± 12	–8.63 ± 0.14

[a]CRE – control rods extracted.
[b]CRI – control rods inserted.

Table 4. Results for Sjöstrand (area) method

		SC3a		SC3b	
		CRI[a] ρ ($)	CRE[b] ρ ($)	CRI ρ ($)	CRE ρ ($)
Booster zone	EC1B	–16.93 ± 0.21	–14.78 ± 0.23	–	–14.87 ± 0.31
	EC2B	–15.04 ± 0.33	–	–15.04 ± 0.31	–13.73 ± 0.43
	EC3B	–10.17 ± 0.13	–	–	–9.61 ± 0.18
Thermal zone	EC5T	–12.25 ± 0.88	–11.54 ± 0.98	–	–8.71 ± 0.93
	EC6T	–7.63 ± 0.25	–	–8.65 ± 1.71	–7.27 ± 1.21
Reflector	MC2	–8.05 ± 0.16	–7.29 ± 0.17	–8.68 ± 0.22	–7.25 ± 0.16
	MC3	–9.68 ± 1.70	–8.93 ± 1.79	–	–

[a]CRI – control rods inserted.
[b]CRE – control rods extracted.

can be considered constant in any further calculations. It should be noticed that despite being fast-thermal coupled assembly, the core kinetics is clearly dominated by the thermal part. For example, such parameter like neutron generation lifetime (~60 μs) [1] resembles rather thermal reactors.

The results for core configurations SC3a and SC3b are shown in Tables 2–4. In those preliminary calculations only the detector dead time correction was applied. The values of the neutron lifetime and delayed neutron fractions for different core configurations necessary to obtain reactivity values from prompt decay constant were calculated using MCNPX 2.7 code and JENDL 2.2 nuclear data libraries. The reactivity values used for comparison with experimental results were calculated in the same way.

It is clearly visible from the results in Table 4 that the measured value of reactivity strongly depends on the respective detector position. This spatial distribution of measured values with comparison to MCNPX simulated reactivity value is shown in Fig. 4. It is caused by the fact that all methods of calculating the reactivity are derived from the point kinetic equations while behaviour of the

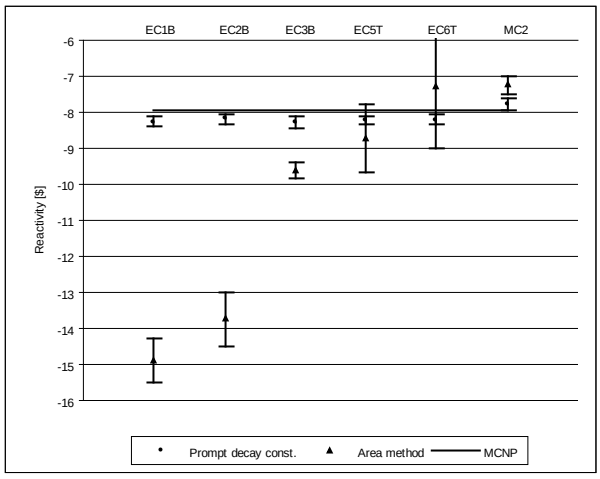

Fig. 4. Spatial distribution of measured reactivity values – SC3b, control rods extracted (CRE).

Table 5. Deep-subcritical configuration SC6 results (with control rods extracted)

	Prompt decay constant method		Area method	MCNP
	α (s^{-1})	ρ (\$)	ρ (\$)	ρ (\$)
EC2B	–2598 ± 11	–22.41 ± 0.43	–42.11 ± 2.67	
EC5T	–2603 ± 15	–24.45 ± 0.44	–24.00 ± 2.18	–23.31 ± 0.37
MC2	–1613 ± 38	–13.53 ± 0.43	–17.18 ± 0.78	

reactor core coupled with neutron source placed in its centre is spatially dependent. When the prompt decay constant method is used, the values from detectors placed in the core are differing just subtly. They also fit the simulation value within the range of uncertainties. Both these facts suggest that they can be considered correct. However, the values obtained from detectors placed in the reflector are noticeably lower. It is apparent especially in the results from deep-subcritical core configuration SC6 shown in Table 5. One of the reasons can be the longer neutron lifetime expected in the reflector which causes that the observed decay is slower. However, it affects strongly only the detectors in the reflector thus measurements made in the core can be recognized as reliable.

The results obtained by the Sjöstrand method are strongly affected by spatial effects and none of the single detector values should be considered reliable. The reactivity values obtained from detectors placed in different core regions for the same core configurations differ more than by a factor of two. Application of this method requires, therefore, correcting of the errors introduced by spatial effects.

Spatial effects correction

Development of possible corrections or alternative ways of the core reactivity calculation became the next goal of the research. The first attempt was made by calculating the correction factors for each detector position using MCNPX code to simulate entire PNS experiment. Such factor is assumed as the relation between the expected value of measured reactivity in the position where the detector is placed (respective to the kinetic response of the core in that region) and the simulated global reactivity of the core

$$\text{c.f.} = \frac{\rho_{\text{local, MCNP}}}{\rho_{\text{global, MCNP}}} = \frac{\dfrac{A_{p,\text{ MCNP}}}{A_{d,\text{ MCNP}}}}{\rho_{\text{global, MCNP}}} \tag{3}$$

It was expected that the same relation should occur between experimental values thus the corrected value of reactivity is given by

$$\rho = \frac{\rho_{\text{measured}}}{\text{c.f.}} \tag{4}$$

Correction factors were calculated using MCNPX 2.7 code and JENDL 2.2 nuclear data libraries. What is important, the use of different data libraries (such as JENDL 3.1, JEFF 3.1 and ENDFB/VIII.0) did not have significant influence on the correction factors value [7]. However, important disadvantage of this method lays in the need of making computer simulations for the support of measurement. Correction factors depend not only on the detector position but also on core configuration and possibly on other core parameters (i.e. temperature). The use of this method for real-time reactivity monitoring is, therefore, limited.

Another approach to correct the results was based only on experimental data and moreover did not require any additional simulations. In Fig. 5 the neutron source pulse and the response of the detectors placed in booster zone at the very beginning of the pulse is shown. One can observe there a huge peak of the signal, so-called prompt harmonic effect. For these detectors, even half of the detected neutrons are located in this early part of the pulse and it strongly affects the final results. The shapes of the very beginning of the detector response and the signal from the source neutrons monitor look very similar. It indicates that the source neutrons affect results in the booster area.

The proposed method of the correction relies on subtracting the source signal from the detector signal after normalization. This normalization can be done by comparing the source monitor and the detector signal at the same time point where source signal reaches its maximum or at both signals maxima. Simplified method assumes skipping the detector data from the beginning up to the point where the source influence is considered significant. However, for all methods used the results after correction were similar for all detectors positions (see Table 6).

The last method used for evaluation of the experimental results was using the Gozani method instead of the Sjöstrand one. It is also based on comparison of prompt and delayed neutron fields but it uses extrapolation based on the prompt decay constant to determine the prompt neutron area and is not affected by the prompt harmonic effect. Reactivity is there given by (Fig. 2) [4]

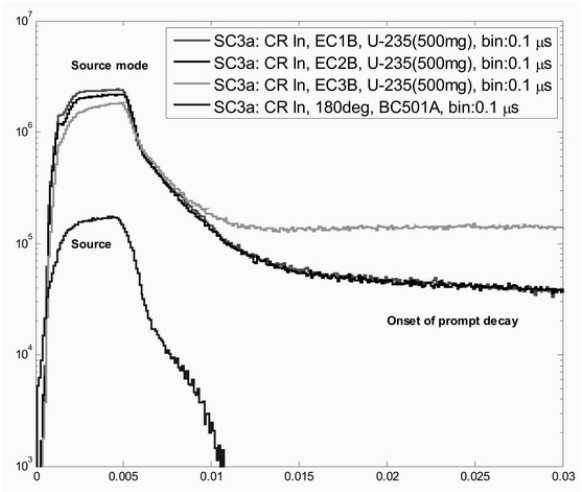

Fig. 5. Source monitor and booster zone detectors signals.

Table 6. Corrected results of measured reactivity (in $) – SC3a CRI[a]

Correction method	EC1B	EC2B	EC3B	EC5T	EC6T	MC2	MC3
MCNP c.f.	–9.35 ± 0.33	–9.22 ± 0.28	–9.25 ± 0.12	–12.50 ± 1.11	–8.97 ± 0.19	–9.47 ± 0.17	–11.67 ± 1.73
Source	–8.48 ± 0.26	–8.61 ± 0.25	–9.11 ± 0.11	–12.10 ± 1.09	–7.62 ± 0.17	–8.05 ± 0.16	–9.66 ± 1.64
Source (norm. max. to max.)	–8.40 ± 0.26	–8.50 ± 0.25	–9.06 ± 0.11	–12.06 ± 1.04	–7.58 ± 0.17	–8.02 ± 0.16	–9.63 ± 1.58
Source (skipping data from beginning)	–8.45 ± 0.26	–8.44 ± 0.25	–8.99 ± 0.10	–11.99 ± 1.05	–7.61 ± 0.16	–8.04 ± 0.16	–9.66 ± 1.66
Gozani	–8.26 ± 0.24	–8.31 ± 0.27	–8.48 ± 0.16	–6.91 ± 1.03	–9.82 ± 0.37	–20.20 ± 0.99	–15.57 ± 2.71

[a]CRI – control rods inserted.

Table 7. Corrected results summary

Method		SC3a		SC3b	
		CRI[a]	CRE[b]	CRI	CRE
Prompt decay constant		–8.51 ± 0.27	–7.73 ± 0.21	–8.65 ± 0.14	–8.13 ± 0.15
Sjöstrand	Uncorrected	–11.77 ± 0.31	–10.15 ± 0.23	–10.97 ± 0.44	–9.76 ± 0.34
	MCNP c.f.	–9.30 ± 0.40	–8.46 ± 0.25	–9.17 ± 0.49	–8.37 ± 0.36
	Source	–8.71 ± 0.34	–7.54 ± 0.26	–8.70 ± 0.46	–8.01 ± 0.27
	Source (max. to max.)	–8.65 ± 0.34	–7.50 ± 0.25	–8.69 ± 0.46	–7.97 ± 0.27
	Source (simpl.)	–8.62 ± 0.34	–7.52 ± 0.25	–8.69 ± 0.46	–8.19 ± 0.27
	Gozani	–10.47 ± 0.57	–14.40 ± 0.68	–15.44 ± 0.67	–11.28 ± 0.41
	Gozani/Sjöstrand	–8.33 ± 0.43	–7.46 ± 0.18	–8.63 ± 0.41	–8.00 ± 0.33
Simulation value		–	–7.86 ± 0.10	–	–7.93 ± 0.11

[a]CRI – control rods inserted.
[b]CRE – control rods extracted.

$$-\frac{\rho}{\beta} = \frac{N_0 \cdot R}{\alpha \cdot N_d} \tag{5}$$

where R is the frequency of neutron pulses.

However, the value of the extrapolated starting point (N_0) is strongly dependent on the delay of the core response in the position of the detector comparing to the neutron pulse. This effect becomes the stronger the farther detector is placed and is limiting the use of this method to detectors placed in booster area. The delay is there relatively small and the data from those detectors need this correction most.

Results after correction

The results of the measurement after applying different methods of corrections are listed in Table 6 (for core configuration SC3a with control rods inserted). It is clearly visible that comparing to the preliminary results (Table 2) values are not affected by spatial effects anymore. Slight differences between detectors are still observed, however they are caused rather by statistical dispersion than by any systematic effect. Only exception is the Gozani method when applied to the thermal zone and reflector detectors due to core response delay. The differences between methods of subtracting the source monitor signal are negligible. However, detectors with a small overall number of counts and therefore poor statistics, as for this core configuration EC5T and MC3, are still giving doubtful results, significantly different from the others. In this case the difference can be considered not as the effect of wrong method used, especially if other detectors in this region are giving results similar to the average value. It should be also noted that the correction method based on MCNP calculated correction factors gives us systematically higher values than other methods.

Comparison of the results from core configurations SC3a and SC3b obtained by different methods after calculating weighted average over the detectors is shown in Table 7 and Figs. 6 and 7. The MCNP simulation values are also shown for comparison, but they should not be taken as the reference values, due to the possible small differences between core specifications used for MCNP input file and the real core parameters. For example, even small difference in polyethylene density used as a matrix for thermal zone can have slight, but not negligible, influence on the simulation result. It would affect not only the reactivity value but also the correction factors calculated by MCNP and it can explain why the results obtained using the correction factors

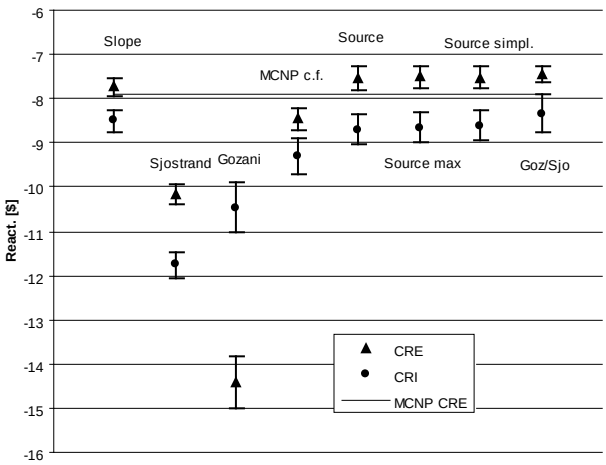

Fig. 6. Methods comparison – SC3a.

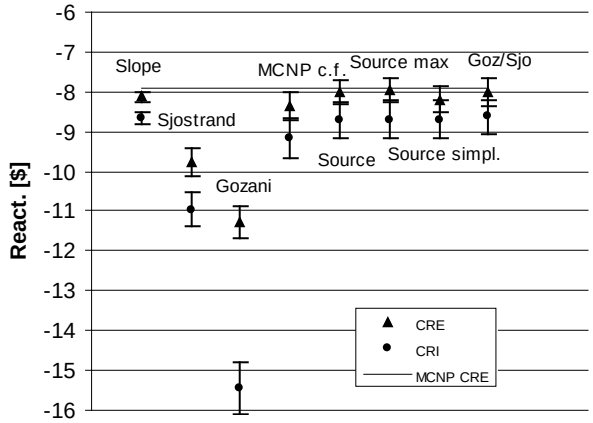

Fig. 7. Methods comparison – SC3b.

are slightly, but systematically, different from the other correction methods. Additionally to Gozani method, the mixed Sjöstrand/Gozani was used to calculate the average using Gozani method results from booster zone detectors and uncorrected Sjöstrand method results from the others.

After applying the corrections, the values of reactivity obtained using different methods fit each other and the simulation value within the range of uncertainties. However, a slight difference between the results, depending on the method used, is still present.

Conclusions

Despite the fact that the subcritical core kinetics differ from the point kinetic equation which was used to derive basic measurement methods their usage is still possible. However, their reliability for reactivity monitoring depends on the possibility of applying proper modifications or corrections to these methods. The experimental results have shown that we are able to get rid of spatial effects and get values that are consistent independently of the detector position or the calculation method. Eventually it was possible to obtain the actual core reactivity from the measurement so the main goal of the research was achieved.

However, we have to keep in mind that the Yalina core behaviour is dominated by thermal neutrons what differs it from the future accelerator driven systems which are designed to work in fast neutron spectrum. Basing on the results of the earlier MUSE project, it is expected that this fact will have a vital influence on reactivity monitoring methods [2] and this has to be put in research as one of the the main goals. Other aspects that are to be studied are the influence of neutron source position and reflector position and material composition on neutron spectrum time evolution and spatial distribution and, therefore, on the reactivity measurement.

Such work is foreseen to be a part of FREYA project along with development of other aspects of reactivity measurement in ADS. It is supposed to create a complex reactivity monitoring system for further application.

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