Absolute Reactivity Calibration of Accelerator-Driven Systems after RACE-T Experiments

Christian C. Jammes[*1], George R. Imel[2], Benoît Geslot[1], Roberto Rosa[3]
[1]*Commissariat à l'Energie Atomique, Centre de Cadarache, DEN/CAD/DER/SPEx/LPE, 13108 Saint Paul-Lez-Durance, France*
[2]*Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA*
[3]*Ente per le Nuove tecnologie, l'Energia e l'Ambiente,Centro della Casaccia, Via Anguillarese, 301, 00060 Roma I, Italy*

Abstract

The RACE-T experiments that were held in november 2005 in the ENEA-Casaccia research center near Rome allowed us to improve our knowledge of the experimental techniques for absolute reactivity calibration at either startup or shutdown phases of accelerator-driven systems. Various experimental techniques for assessing a subcritical level were inter-compared through three different subcritical configurations SC0, SC2 and SC3, about -0.5, -3 and -6 dollars, respectively. The area-ratio method based of the use of a pulsed neutron source appears as the most performing. When the reactivity estimate is expressed in dollar unit, the uncertainties obtained with the area-ratio method were less than 1% for any subcritical configuration. The sensitivity to measurement location was about slightly more than 1% and always less than 4%. Finally, it is noteworthy that the source jerk technique using a transient caused by the pulsed neutron source shutdown provides results in good agreement with those obtained from the area-ratio technique.

KEYWORDS: Accelerator-driven subcritical systems, reactivity calibration, transient techniques, area-ratio method, measurement method comparison

1. Introduction

As it is well known, the concept of accelerator-driven systems (ADS) can provide a solution for the nuclear waste management issue by burning minor actinides. The subcritical nature of ADS makes them safer regarding prompt criticality accidents. However, the question of the reactivity control of ADS remains a main concern since their power is inversely proportional to their reactivity level.

The objective of the European Integrated Project EUROTRANS [1] of the EURATOM 6th Framework Program is to bring answers to the high level nuclear waste transmutation in ADS. The EUROTRANS experimental activities have been joined into the ECATS domain, namely Experiment on the Coupling of an Accelerator, a spallation Target and a Sub-critical blanket.

The RACE-T experiment, formerly named TRADE [2], is part of ECATS. The experimental campaign presented in this paper were held in november 2005 in the

[*] Corresponding author, Tel. +33 4 4225 3926, Fax. +33 4 4225 7025, E-mail: christian.jammes@cea.fr

ENEA-Casaccia research center near Rome in order to propose experimental techniques for absolute reactivity calibration at either startup or shutdown phases.

We propose to evaluate the applicability of various experimental techniques for assessing a sub-critical level. Those techniques are based on either (a) the response to a pulsed neutron source, (b) the transient due to a source jerk (or extraction), (c) the transient due to a rod drop or (d) the source multiplication formula.

2. Experimental setup

2.1 Reactor configurations

The RACE-T experiments were conducted at zero power in a Mark II TRIGA reactor that is a light-water reactor, with a cylindrical core (with 127 locations that are arranged in seven concentric rings, namely A, B, C, D, E, F and G) and an annular graphite reflector (see Fig. 1 and 2). That reactor was coupled to a pulsed deuterium-tritium neutron generator that produces 14.1 MeV-neutron bursts with a strength of 3.3×107 neutrons/s at maximal frequency. The frequency range spans from 1 to 50 Hz. The neutron generator was placed in the core center. A Cf-252 source with a strength of 0.4 Ci, which also plays the role of a startup source, was used to perform source jerk experiments using a fast rabbit (FR). The Cf source was located quite in the B-ring (Fig. 2).

The four investigated core configurations are as follows: one reference critical configuration and three subcritical configurations (Fig. 2). The fission chambers, the fast rabbit (FR) pipe and the neutron generator were always placed in-core during the experimental campaign. One can note that the REF core configuration was critical with the regulating rod (REG) 51% inserted (see Fig. 1 and 2).

2.2 Instrumentation

The instrumentation consists of fission chambers (labeled from A to D in Fig. 2), current-sensitive amplifiers and the X-MODE data acquisition system [3]. The fission

Figure 1: TRIGA reactor overview. There are four boron-carbide control rods: two fuel-follower shim rods (SH1 and SH2), one fuel-follower safety rod (SEC) and one regulating rod (REG) not fuel followed. The three control rods are in red color while the REG rod is in orange color.

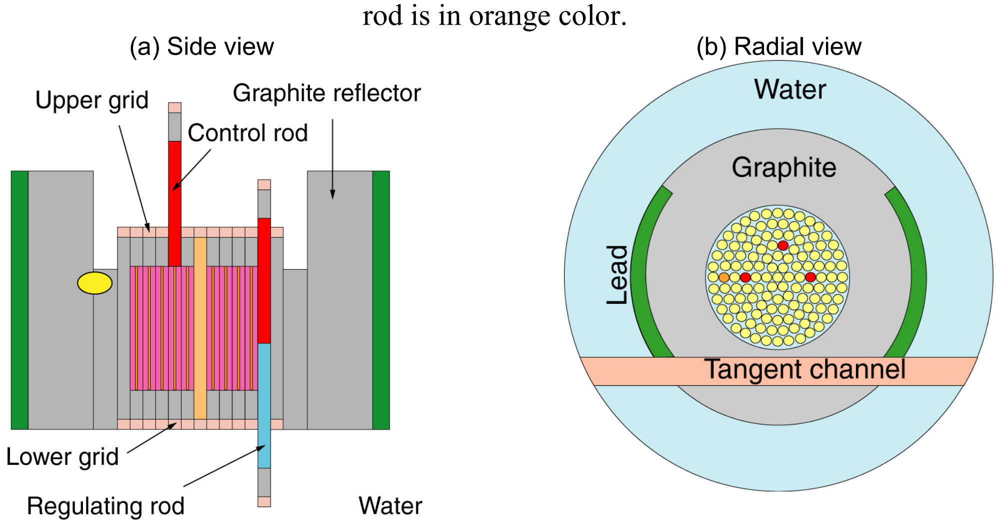
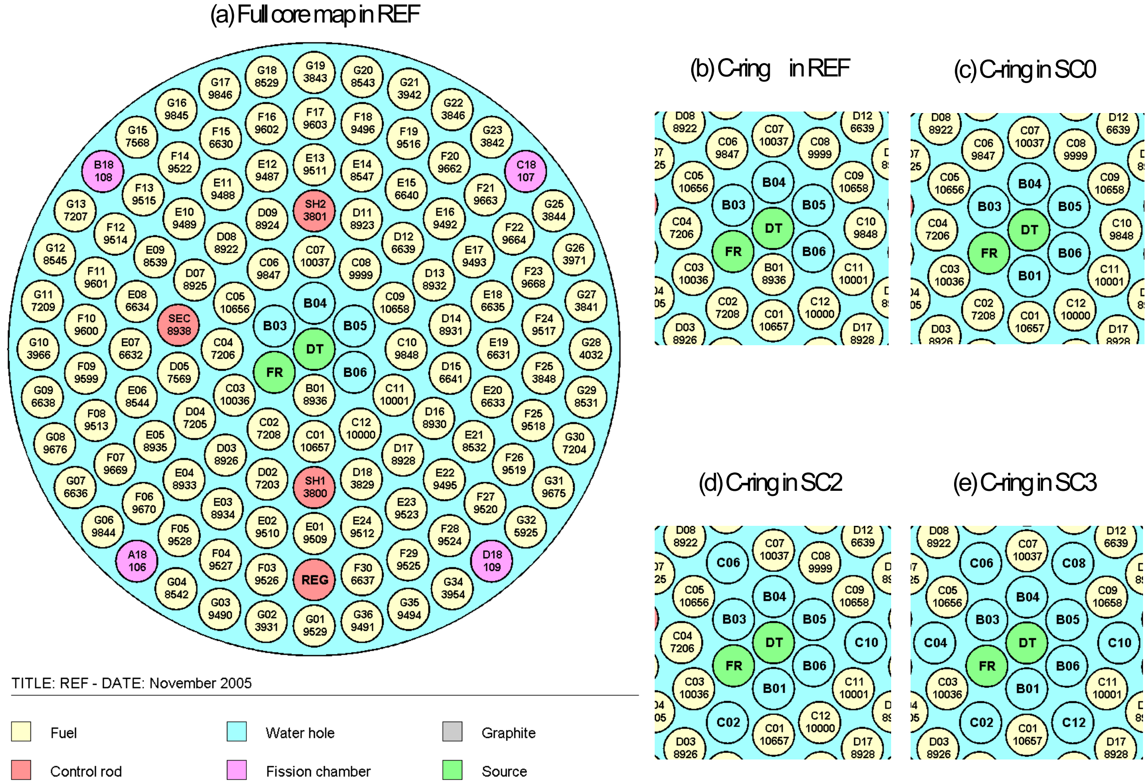


Figure 2: RACE-T core configurations. One removes three fuel elements in C-ring to shift from one subcritical configuration to another. The Fast Rabbit (FR) pipe is in B02 and the neutron generator (DT) in A0.



chambers with nominal sensitivities 10−1cps/nv were operated in pulse mode. They were placed within the core region close to the reflector (See Fig. 2). The main purpose of X-MODE is to integrate in a single system all the features needed for reactor measurements. The main asset of X-MODE is an accurate time stamping capability that offers many methods of investigating acquired data.

3. Improvement of measurement techniques and data analysis methodology

We consider three types of measurement techniques for assessing a subcritical level. The first type of techniques is based on the impulse response of a subcritical system to a Dirac pulse. They will be referred as the pulsed neutron source techniques. The second type of techniques is based on the flux transient resulting from a source or reactivity step. They will be referred as the transient techniques. The third type is the well-known source multiplication method. The two former types are detailed in this section.

3.1 Pulsed neutron source techniques

The response of a subcritical neutronic system to neutron pulses is an exponential-shaped decay function. The experimental histogram is obtained by means of the periodic pulse signal trigger. We applied one pulsed neutron source (PNS) technique only, namely the area-ratio technique. This is more accurate and robust than prompt neutron decay fitting technique. It is shown in Ref. [4] that the area-ratio estimator is superior to the prompt decay fitting one in the case of a reflected system. The area-ratio method is based on the ratio of the area under the response peak, that is the decaying part of the PNS response, and the area under the background level due to the delayed neutron decay [4]. The negative value of that ratio provides an estimation of the reactivity in dollar units, which is the reactivity normalized to the effective total delayed neutron fraction.

In Ref. [5], we proposed an area-ratio estimator well-adapted to the use of a time stamping acquisition system since one takes into account the PNS period T and its uncertainty:

$$\rho(\$) = 1 - \frac{I - B_0 T}{(B - B_0)T}$$

with the total area I of the PNS histogram, the background level B of that histogram and the residual background B_0 due to another optional continuous neutron source. We derived the estimator uncertainty formula including the covariance terms. Various biases were identified and corrections were proposed. The most important corrections are: the pulse width correction [4,5], the delayed-area correction [5] and the effectiveness correction [4,5,6]. The delayed-area correction comes from the fact the delayed area cannot be exactly obtained from the histogram background. The closer to critical, the more significant the correction is. The effectiveness correction can only be obtained from simulation given that it accounts for the bias between the effective multiplication factor and the reactivity based on the area-ratio rationale and the point kinetics assumption.

When assessing a reactivity value using the area-ratio technique, we paid attention to three crucial points. First, we verified that the PNS period was consistent with the prompt decay constant estimated by fitting the PNS histogram. The product of those two parameters has to be greater than 10 in order to be able to assess the PNS background level without bias [4]. Second, we checked that the acquisition time was long enough so that the area-ratio reactivity estimate reached its convergence value [4], which is explained mainly by the delayed neutron buildup. Third, we carefully chose the lower boundary of the PNS background in order to have reactivity estimates statistically equivalent beyond that boundary [5].

3.2 Transient techniques

Using the point kinetics equation, one can assess a subcritical level from a flux transient induced by a perturbation and driven by the delayed neutrons. Two transient techniques are thought of great interest: the well-known inverse kinetics method (IK) and the non linear fit method (NF) [7]. Those two techniques have complementary pros and cons. The IK method does not provide an easy way to calculate uncertainties since it requires the use of a re-sampling approach [8]. While it also fails in case of low count rate, it is not sensitive to the initial flux conditions [5]. In other words, the flux variations prior to a transient do not impede the applicability of the IK method. That makes successful the application of the IK method to the transient caused by the instantaneous shutdown of a non-steady neutron source. Conversely, the NF method fails in case flux variations prior to a transient [5]. However, that second method allows us to easily calculate uncertainties and is advantageously applied in case of low count rates [7].

4. Experimental results and data analysis

In this section, we present three different series of experiments dedicated to (a) the MSA technique application, (b) the rod-drop technique application and (c) the application of the area-ratio technique at different reactor locations. The objective was to experimentally study the performance of the area-ratio reactivity estimator. One recalls that all reactivity estimates were not corrected for spatial effects as aforementioned.

4.1 MSA-dedicated experiments

The first series of experiments allowed us to compare the area-ratio technique (PNS-Area) to the approximate source multiplication technique (MSA), the source jerk technique based on the transient caused by the neutron generator shutdown (SJ-Gen) and the standard source jerk technique (SJ-Cf) using the Cf-252 source. The SJ-Cf technique was used for SC0 only. In order to successfully apply the MSA method, two points were done. First, the count rate of each detector was monitored during this experiment series: The variation of those count rates was less than 1.2%. Second, the subcritical level of the REF configuration (see Fig. 2) with the REG rod down was estimated at the four detector locations by analyzing the transient caused by the REG rod drop using the NF method (see Sect. 3.2). All the four estimates with an uncertainty of about 3% are equal with a confidence level of 95%.

All the reactivity estimates for the three subcritical configurations are displayed in Fig. 3. For SC0, the uncertainties are about 1% for the PNS-Area technique, 3.1% for the MSA technique, 4.0% to 4.4% for the SJ-Gen technique. For SC2, the uncertainties are about 0.4% for the PNS-Area technique, 3.1% for the MSA technique, 6% to 7% for the SJ-Gen technique. For SC3, the uncertainties are about 0.5% for the PNS-Area technique, 3.1% for the MSA technique, 5% to 6.5% for the SJ-Gen technique.

First, it appears that the PNS-Area and SJ-Gen reactivity estimates are always equal with a confidence level of 95%. Second, the MSA technique is clearly the most detector location dependent. The discrepancies from the PNS-area estimates are about 1%-5% for SC0, 5%-19% for SC2 and 16%-40% for SC3. Conversely, the PNS-Area technique is the least detector location dependent with a spread of 1.22% at most for SC3.

4.2 Rod-drop-dedicated experiments

The second series of experiments allowed us to compare the area-ratio technique to the rod-drop technique (with the REG rod), the source jerk technique based on the transient caused by the neutron generator shutdown and the standard source jerk technique (SJ-Cf) using the Cf-252 source. It is important to note the detector C was placed in the axial reflector, that is, 230 mm above the core mid-plane. In order to get satisfactory uncertainties with the SJ-Cf and rod-drop methods, it was necessary to perform many runs (3, 7 and 10 for SC0, SC2 and SC3, respectively).

All the reactivity estimates are displayed in Fig. 4. For SC0, the uncertainties are about 0.15% to 0.3% for the PNS-Area technique, 3% to 3.4% for the SJ-Cf technique, 3.7% for the SJ-Gen technique and 3% to 3.5% for the rod-drop technique. For SC2, the uncertainties are about 0.3% to 0.4% for the PNS-Area technique, 3.1% to 3.4for the SJ-Cf technique, 3.2% to 3.7% for the SJ-Gen technique and 16% to 27% for the rod-drop technique. For SC3, the uncertainties are about 0.3% to 0.5% for the PNS-Area technique, 2.8% to 3.4% for the SJ-Cf technique, 3.8% to 4.5% for the SJ-Gen technique.

Comments are fourfold. First, the rod-Drop method is the most sensitive to the REG drop since the reactivity estimates for detectors A and D are the most negative. The Rod-Drop uncertainties are also the worst. The Rod-Drop data for SC3 could not be even analyzed with satisfactory results. Second, the PNS-Area and SJ-Gen estimates are always equal with a confidence level of 95%. The SJ-Cf reactivity estimates are less comparable to those of the PNS-Area method except in the SC0 configuration. The worst case is SC3 in which

Figure 3: Reactivity estimates in subcritical configurations with pilot rod up. The error bars corresponds to a confidence level of 95%.

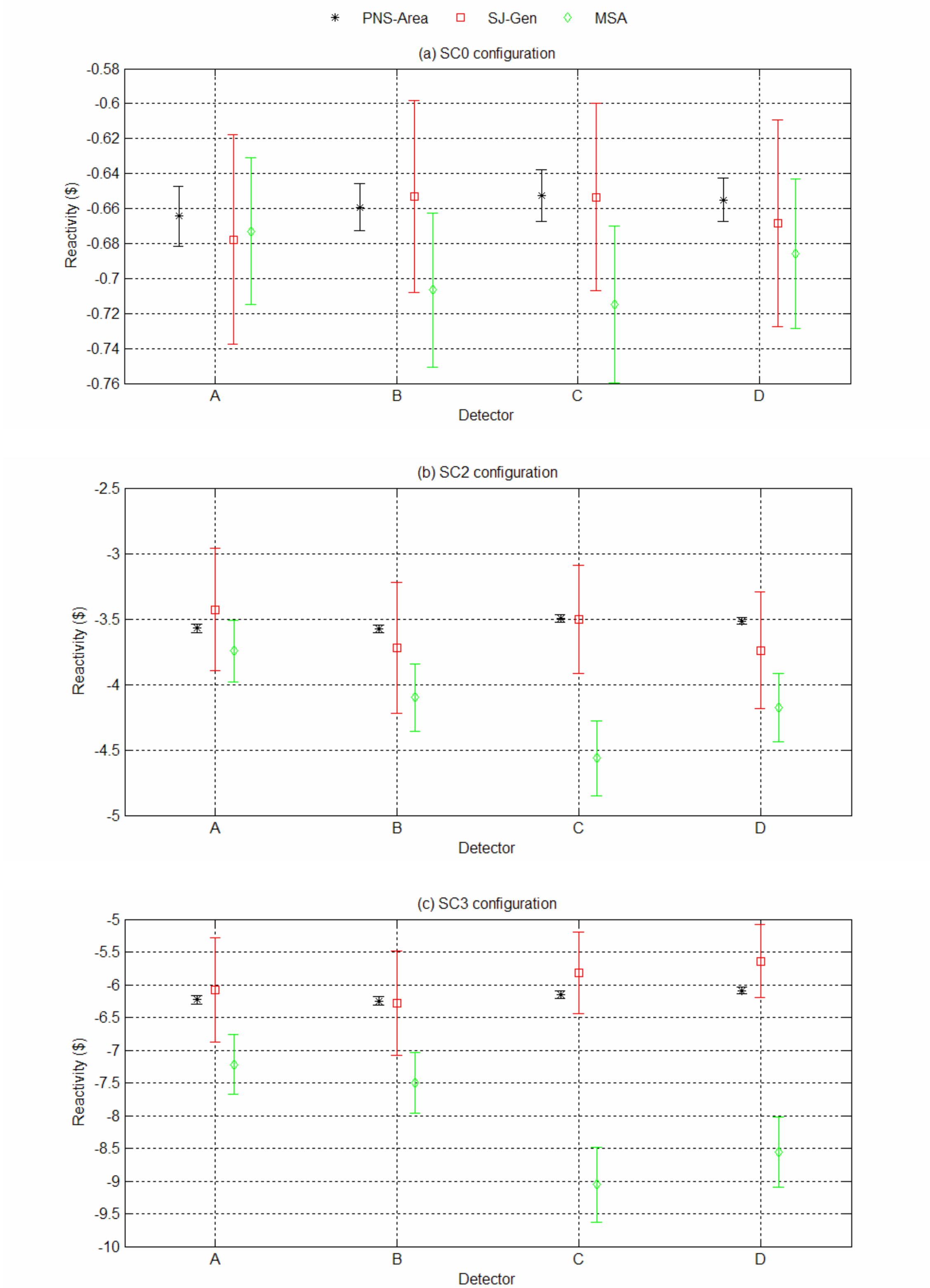
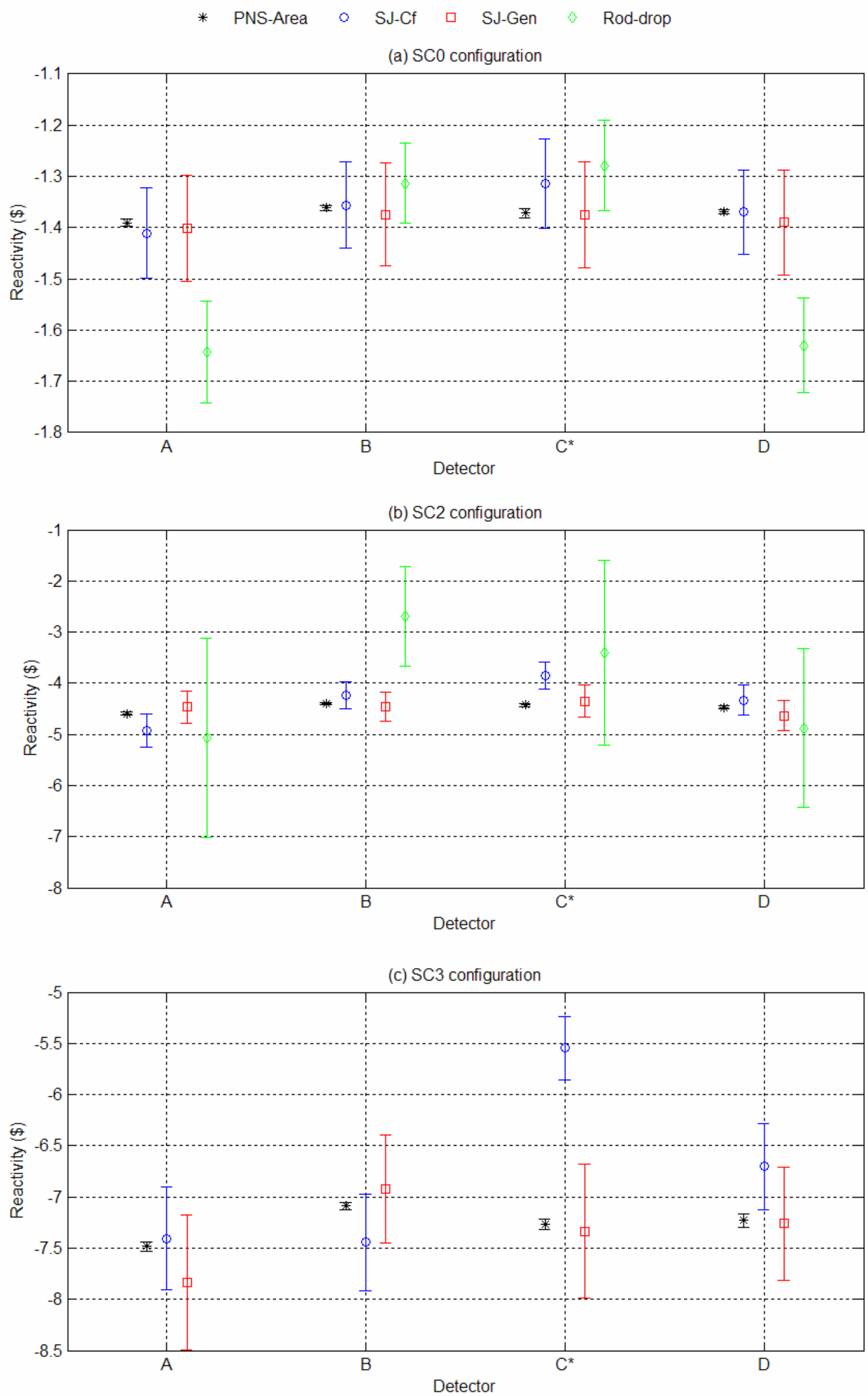


Figure 4: Reactivity estimates in subcritical configurations with pilot rod down. The error bars corresponds to a confidence level of 95%. The detector C located in the upper water reflector is labeled C*.



the discrepancy between the SJ-Cf and PNS-Area reactivity estimates for detector C is -23.67%. Third, for all the methods, the reactivity estimates for detector C* are not clearly affected by the location of that detector in the upper water reflector region. Fourth, the PNS-Area technique is still the least detector location dependent with a spread of 2.23% at most for SC3.

4.3 PNS-traverse-dedicated experiments

The third series of experiments allowed us to better appraise spatial effects that are likely to affect the reactivity assessment using the PNS-area technique. For each subcritical configuration with the REG rod up, the detector C only was placed at different axial positions from the core region to the upper water reflector.

Fig. 5 shows that the reactivity estimates for detector C start being sensitive to the measurement location in SC2 and they are so, undoubtedly, in SC3 since these estimates are not equal any longer with a confidence level of 95% for the three investigated locations. For detector C in SC3, the discrepancy between the two reactivity estimates at the mid-plane and upper water locations is 3.62%.

4. Conclusion

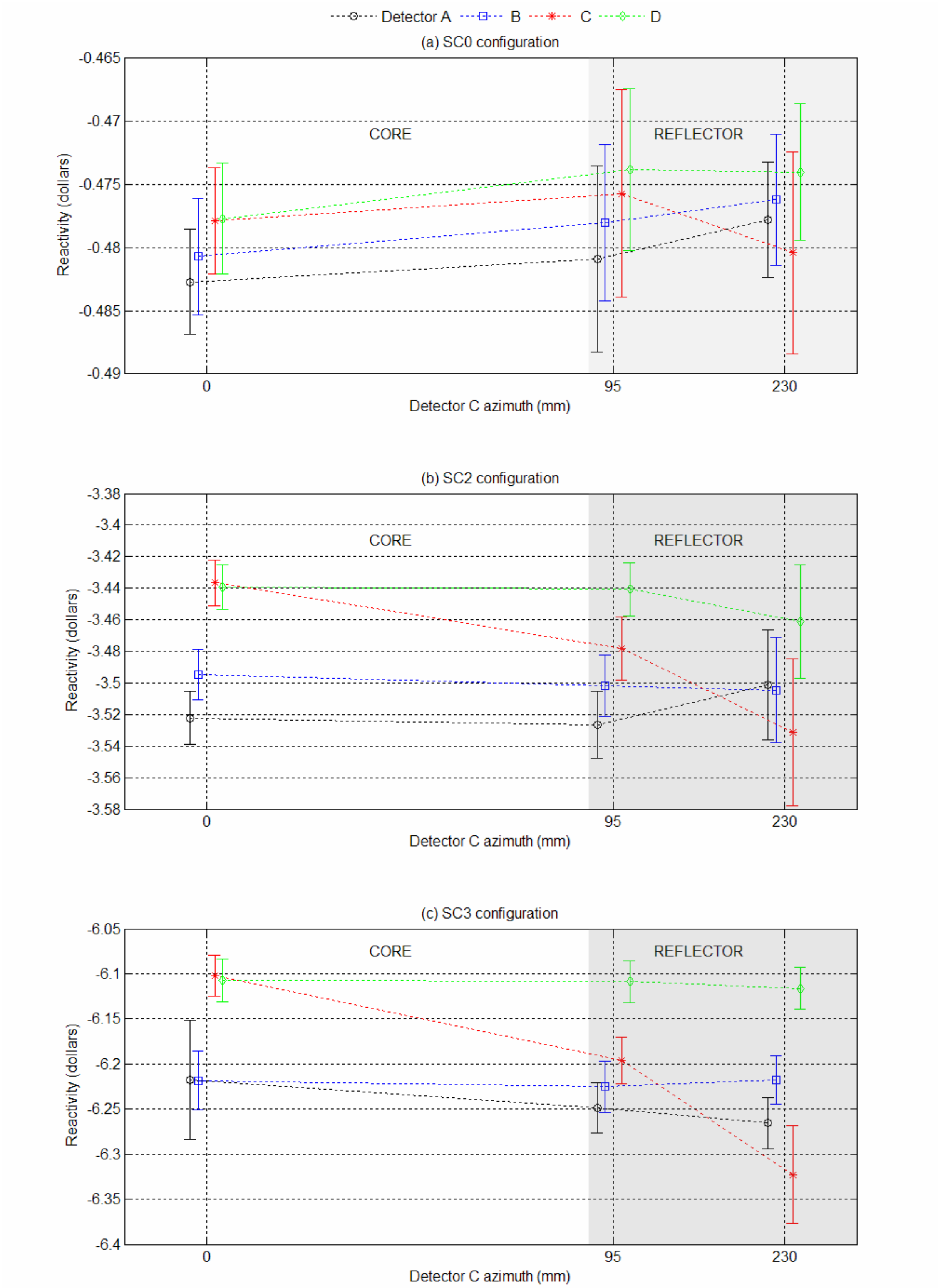
The RACE-T experiments allowed us to successfully validate the PNS area-ratio technique by means of an inter-comparison with the reference techniques, namely, the source jerk, rod-drop and source multiplication techniques. The uncertainties of the area-ratio reactivity estimates expressed in dollar unit were less than 1% for any subcritical configuration given that the method is independent of the delayed neutron nuclear data. Although it was shown using a two-region model that the area-ratio method is much less sensitive to spatial effects than the prompt decay fitting method, one can however note a slight reactivity estimate discrepancy in the core and reflector regions.

Two techniques can be rejected for assessing deep subcritical levels. The first one is the source multiplication method without applying spatial correction. That so-called MSA technique fails for deeply negative reactivity values since one observed, for the most subcritical configuration SC3, a significant discrepancy (up to 47%) from the area-ratio reactivity estimates. The second technique is the rod drop one that was clearly sensitive to the perturbation caused by the drop of the regulation rod. In addition, the low count rates did not allow us to use that technique beyond the SC2 configuration although many experiment runs were performed.

Conversely, the results concerning the source jerk technique, which consists in estimating reactivity from the transient caused by a step variation of a neutron source, are pretty much satisfactory. First, the source jerk technique using a Cf-252 source required too many runs for configurations too far from critical even using the non linear fit method for analyzing experimental data (which improves the reactivity estimation). Second, the source jerk technique using the transient caused by the shutdown of the pulsed neutron source could be valuable given that only one run is sufficient for obtaining good statistics. The analysis of these transients provided reactivity estimates always in excellent agreement with those obtained with the area-ratio technique. However, the discrepancy between them clearly increases with the subcriticality level.

As a consequence, if the area-ratio technique appears the best candidate for reactivity calibration, the source jerk technique could also play that role if the source strength is high enough. However, that conclusion will have to be confirmed given that most of the

Figure 5: Area-ratio reactivity estimates at three vertical locations from the mid-core plane to the upper water reflector. The error bars corresponds to a confidence level of 95%.



reactivity estimates presented in this paper have to be corrected by computed factors accounting for spatial effects.

Acknowledgements

This work has been performed in the framework of the European Integrated Project EUROTRANS. The authors also address special thanks to all the ENEA TRIGA RC-1 reactor staff members.

References

1) J. U. Knoebel et al., "IP EUROTRANS: a European research programme for the transmuation of high-level nuclear waste in an accelerator-driven system", in: 8th Information Exchange Meeting on Actinide and Fission Product Partioning &Transmutation, Las Vegas, Nevada, USA (2004).
2) G. Imel et al., G. Imel, et al., "The TRADE experiment and progress", Int. Conf. GLOBAL 2003, Nov. 16-20, New Orleans, Louisiana, USA (2003).
3) B. Geslot et al., "Multimode Acquisition System Dedicated to Experimental Neutronic Physics", Int. Cnf. IMTC 2005, May 17-19, Ottawa, Canada (2005).
4) C. Jammes et al., " Advantage of the Area-Ratio Pulsed Neutron Source Technique for ADS reactivity calibration", AccApp 2005 – Int. Conf. AccApp 2005, Aug. 29 – Sept. 1, Venice, Italy (2005).
5) C. Jammes et B. Geslot, "Experimental reactivity estimates of the three subcritical configurations of the zero-power RACE-T program", CEA Technical Note, DER/SPEX/LDCI/06/014 (2006).
6) M. Carta et al, "Reactivity Assessment and Spatial Time-Effects from the MUSE Kinetics Experiments", In Int. Conf. PHYSOR-2004, April 25-29, 2004, Chicago, IL USA
7) B. Geslot and C. Jammes, "Interest of the non linear fitting method for reactivity assessment using flux transient experiments",submitted to Int. Conf. PHYSOR 2006, September 10-14, Vancouver, BC, Canada (2006).
8) G. Perret and C. Jammes, "Determination of reactivity by a revised rod-drop technique ine the MUSE-4 programme – Comparison with dynamic measurements", Seventh Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, 14-16 October 2002, Jeju, Republic of Korea (2002).
9) C. Jammes et al., "Comparison of reactivity estimations obtained from rod-drop and pulsed neutron source experiments", Ann. Nucl. Energy, **32**, 1131–1145 (2005).