# EXPERIMENTAL RESULTS OF THE RACE-ISU INTERNATIONAL COLLABORATION ON ADS

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*A series of experiments dedicated to the monitoring of the reactivity of Accelerator driven subcritical systems were carried out in the thermal subassembly of the Idaho State University. First, it was shown that the pulsed neutron source techniques can be utilized in a thermal subassembly coupled to an electronic linear accelerator in spite of the strong gamma field generated after every accelerator shot. Second, reactivity estimates using the area-ratio method and the beam trip one for a far subcritical level are consistent before applying calculated correction.*

## I. 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 (Ref. 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. In the year 2003, Idaho Accelerator Center (IAC), part of Idaho State University (ISU), proposed to couple a subcritical assembly and a linear accelerator (LINAC) in order to contribute to the international research on ADS: It was the beginning of the RACE (Reactor-Accelerator Coupling Experiments) project (Ref. 2 and 3). Although the original goal, which was to carry out such a coupling with a TRIGA reactor, was abandoned because of a lack of financial support, a series of experiments were successfully performed in the ISU thermal subassembly from May to October 2006 in tight collaboration with Commissariat L'Energie Atomique (CEA).

Two main results were obtained. First, it was shown that the pulsed neutron source techniques can be utilized in a thermal subassembly coupled to an electronic LINAC in spite of the significant gamma field generated right after every accelerator shot. Second, we obtained reactivity estimates using either the area-ratio method or the beam trip one for a far subcritical level using current-sensitive amplifiers and the X-MODE acquisition system developed by CEA (Ref. 4).

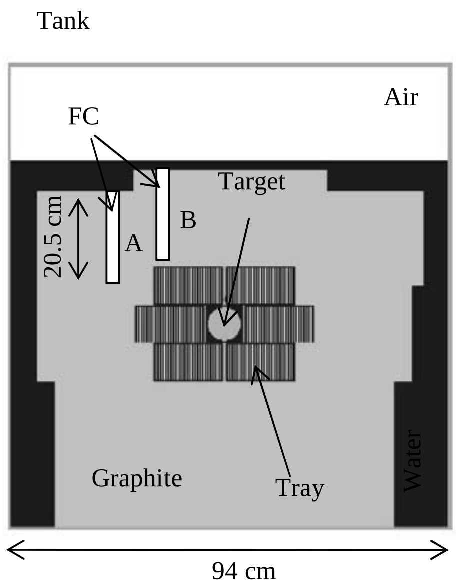
## II. EXPERIMENTAL SETUP

### II.A. IAC Subassembly

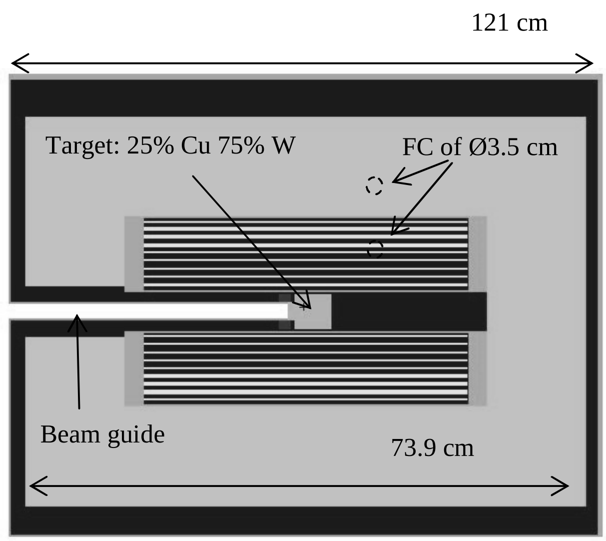
The IAC subcritical assembly (Ref. 3), which surrounded a neutron-generating target, consisted of 150 fuel flat plates of 20%-enriched uranium-aluminum alloy cladded in aluminum inside a water-filled aluminum tank. As shown in Fig. 1, 6 trays, each one containing 25 fuel plates, were arranged in three horizontal rows of two trays, and the target was put at the center of that arrangement. The total mass of uranium was 7.61 kg. The core was reflected with means of graphite blocks placed on every side. A simulation performed using the general-purpose Monte Carlo radiation transport code MCNPX (Ref. 5) gave an estimate of the effective multiplication factor of this subcritical configuration. That estimate is equal to 0.92 (Ref. 6).

### II.B. LINAC and Neutron Source Target

The neutron source was created by electrons produced by a LINAC and impinging on a water-cooled




(a) Vertical view




(b) Horizontal view

Fig. 1. The IAC subassembly, the target and fission chambers (FC) emplacements

target made of 25% copper and 75% tungsten. That copper-tungsten alloy target is supposed to yield 1 neutron per 1000 incident electrons (Ref. 3). The LINAC was run with a beam power (*W*) as low as few Watts at the incident electron energy (*E*) of 20 MeV:

$$W = I \times f \times \Delta t \times E$$

where the peak current *I* was of few 10 mA, the repetition rate *f* could be selected between 10 Hz and 100 Hz, and the pulse width $\Delta$t was set between 1 μs and 3 μs. The source strength thus spanned from $10^9$ to $10^{12}$ neutrons per second.

### II.C. Instrumentation

The employed neutron detectors were two LND 30763 fission chambers (FC) with 16 mg mass of uranium 235. As shown in Fig. 1, they were placed within the reflector region: one of them was as close to the core as possible (FC labeled B). Those fission chambers were operated only in current-sensitive pulse mode using the analog electronic CANBERRA ADS7820 modules that feed the X-MODE data acquisition system with a TTL signal of 5 V amplitude and 100 ns width.

The X-MODE data acquisition system was designed to operate on experimental nuclear reactors (Ref. 4 and 6). It can process both digital and analog signals and can be utilized to perform state of the art neutronic experiments (Ref. 6). The great asset of X-MODE is a precise relative time-stamping capability (25ns), which is a powerful way to investigate acquired data.

## III. ELECTRON BEAM SIDE EFFECTS

The neutron production using a LINAC may cause two issues that might hinder the neutron detection: the detector saturation and the parasitic dark current.

### III.A. Detector saturation

A significant gamma field generated right after every accelerator shot causes to saturate the signal delivered through the fission chamber and the associated amplifier. As displayed in Fig. 2 and 3, such saturation was observed during the ISU-RACE experimental campaigns. In order to get around that issue, fast amplifiers that are current-sensitive were successfully employed. One sees in Fig. 2 and 3 that the perturbation time scale is less than the neutron generation time that is greater than 100 ms in a thermal neutronic system.

### III.B. Dark current reduction

One recalls that a LINAC is composed of a microwave source (klystron), a waveguide and an accelerator structure (series of cavities). The electrons are accelerated by the electric field of microwaves traveling in cavities. The so-generated microwave are likely to cause a parasitic signal, also called dark current, to appear on the signal coming out of detectors and transported by cables. As shown in Fig. 2, such a dark current was observed during an ISU-RACE experiment. As shown in

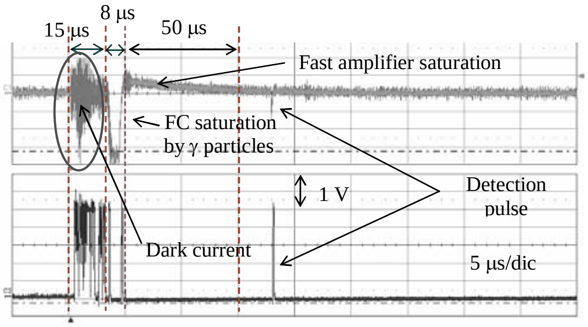



Fig. 2. Dark current and gamma flash

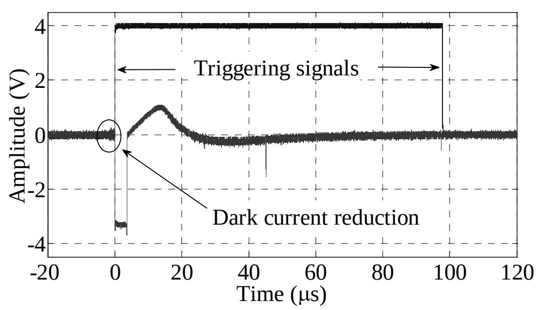



Fig. 3. Dark current reduction

Fig. 3, we successfully managed to significantly reduce that dark current by using better shielded cables, FILECA "Etudes" cables provided by CEA.

## IV. MEASUREMENT TECHNIQUES AND METHODOLOGY

We employed two types of measurement techniques for assessing subcriticality level. The first type of those techniques is based on the impulse response of a subcritical system to a Dirac pulse. They will be referred as to the pulsed neutron source techniques. The second type is based on the flux transient resulting from the change of source strength, like the shutdown of a neutron source generated by means of an accelerator. They will be referred as to the transient techniques.

### IV.A. 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 method is more accurate and robust than prompt neutron decay fitting technique. It is shown in Ref. 8 that the area-ratio estimator is superior to the prompt decay fitting estimator 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 (Ref. 7). 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. 7, 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, for instance, an additional continuous neutron source. In Ref. 7, we derived the estimator uncertainty formula including the covariance terms. In addition, various biases were identified and corrections were proposed. There are three potential different biases: pulse width correction, the delayed area correction and the effectiveness correction (Ref. 6). The pulse width correction is not needed for a thermal system with generator pulse width of few microseconds. The delayed area correction is irrelevant in the case of a far subcritical system. Only the effectiveness correction is required here. That correction can only be obtained from simulation (Ref. 6 and 9) 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. Such correction factors are proposed in Ref. 6 for the experimental area-ratio reactivity estimates reported in this paper.

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 (Ref. 8). Second, we checked that the acquisition time was so long that the area-ratio reactivity estimate reached its convergence value (Ref. 8), which is explained mainly by the delayed neutron buildup. Third, the lower boundary of the PNS background is chosen so that the reactivity estimates statistically are equivalent beyond that boundary (Ref. 7).

### IV.B. Beam trip technique

Using the point kinetics equation, one can assess a subcriticality level from a flux transient induced by a perturbation and driven by the delayed neutrons. In Ref. 7, it is shown that the well-known inverse kinetics (IK) method is the most appropriate and robust reactivity estimator in the case of a transient, also called beam trip, caused by the instantaneous shutdown of a non-steady neutron source.

## V. EXPERIMENTAL RESULTS AND DATA ANALYSIS

In this section, we present results concerning the application of the area-ratio and beam trip techniques. All reactivity estimates were not corrected for spatial effects.

### V.A. Application of the area-ratio technique

Table I displays the reactivity estimates obtained using the area-ratio technique. The two estimates obtained from the two FC are very consistent. They differ by about one standard uncertainty and a discrepancy of 0.31%. One also notes that the standard uncertainties are about 0.20%. Such small uncertainties are accounted for by only statistical effects. Since the reactivity uncertainty depends on the number of accumulated counts per bin, it is a decreasing function of the acquisition time and can be thus rendered as small as possible.

As shown in Fig. 4, the reactivity estimates differ from their asymptotic value by 2% after 12 minutes. In other words, the maximum bias due the estimator convergence is not greater than 2% after 12 minutes of acquisition time.

TABLE I. Reactivity estimates using the area-ratio technique

| FC location[a] | A | B |
|---|---|---|
| Reactivity ($) | -15.793±0.034[a] | 15.744±0.029 |
| Relative uncertainty | 0.22% | 0.18% |
| Lower boundary[c] (s) | 0.03135 | |
| Upper boundary[c] (s) | 0.03331 | |

a. See Fig. 1.a
b. Standard deviation
c. PNS background boundary (see Sect. III.A)

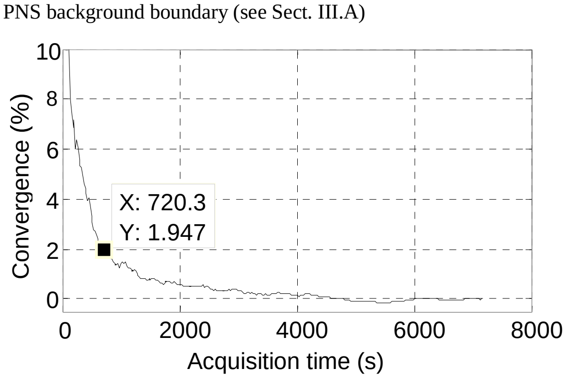


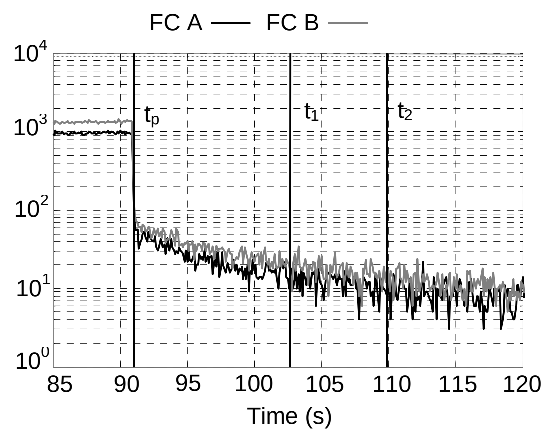

Fig. 4. Area-ratio estimator convergence

### V.B. Application of the beam-trip technique

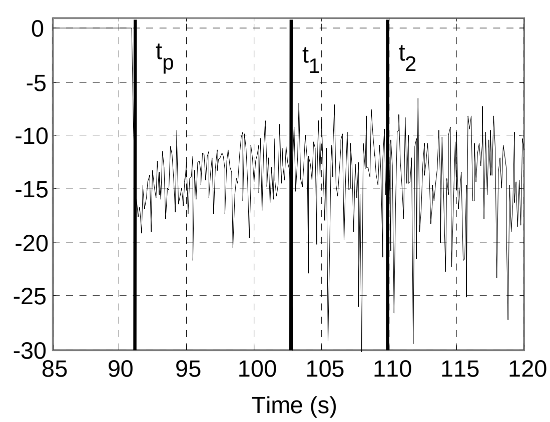
Unlike the area-ratio technique, the beam-trip technique requires the knowledge of the delayed neutron data, namely the delayed neutron fraction $\beta_i$ and decay constants $\lambda_i$ (Sect. III.B). Table II gives those nuclear

TABLE II. Delayed neutron data. The delayed neutron fractions were computed with a modified version of MCNP4C (Ref. 10).

| Group | Fraction (pcm) | Decay constant ($s^{-1}$) |
|---|---|---|
| 1 | 26.6 | 0.0136 |
| 2 | 141.3 | 0.0316 |
| 3 | 131.1 | 0.1228 |
| 4 | 297.4 | 0.3195 |
| 5 | 121.1 | 0.8947 |
| 6 | 50.9 | 3.0095 |
| Total | 768.4 | |




(a) Transient and analysis ranges




(b) IK Reactivity vector for FC A

Fig. 5. Transient analysis with the IK mehod. The transients corresponding to the experimental data acquired with the fission chambers A et B are shown in (a).

data. The delayed neutron fractions were computed with a modified version of MCNP4C (Ref. 6 and 10). The decay constants are derived from those of the fissile isotopes weighted by their atomic densities. The standard uncertainty due to the delayed neutron data were estimated (Ref. 11 and Ref. 12) using the covariance matrix given in Ref. 13.

The reactivity estimates using the beam-trip technique are shown in Table III. Those estimates are clearly more spread than those obtained with the use of the area-ratio technique. They differ from the area-ratio estimates by between -7.6% and 3.8%. That fairly satisfactory result comes from the known bad performance of the inverse kinetics method (Ref. 11) in the case when the final counting is low (Fig. 5). The time time discretization is also another important matter to consider. Given that the counting range, after the perturbation, greater than 10 counts per bin was as short as about 30 s (Fig. 5), was much better to have a time binning of 100 ns in order to better take into account the derivative component of the inverse kinetics reactivity estimator (Ref. 11). Improving the time discretization allows us to retrieve the maximum information that lies in the first second after the perturbation (Ref. 11).

TABLE III. Reactivity estimates using the beam-trip technique

(a) The analysis range[b] is $[t_p\ t_1]$=[91.1 s 102.7 s]

| FC location[a] | A | B |
|---|---|---|
| Reactivity ($) | -16.360±0.208[a] | -15.291±0.196 |
| Total uncertainty | 1.27% | 1.28% |
| Statistical uncertainty | 0.03% | 0.03% |
| Nuclear data uncertainty | 1.27% | 1.28% |

a. Standard deviation

b. $t_p$ is the time at which the perturbation occurred.

(b) The analysis range is $[t_p\ t_1]$=[91.1 s 109.9 s]

| FC location[a] | A | B |
|---|---|---|
| Reactivity ($) | -14.679±0.244 | -14.565±0.247 |
| Total uncertainty | 1.66% | 1.69% |
| Statistical uncertainty | 0.02% | 0.02% |
| Nuclear data uncertainty | 1.66% | 1.69% |

## VI. CONCLUSION

The outcome of the ISU-RACE experiment was twofold. First, we showed that the PNS techniques were applicable when using an electronic LINAC. Neither the detector saturation, which was caused by the strong gamma field generated after every LINAC shot, nor the parasitic dark current impeded the experiment conducted in a thermal neutronic system.

Second, the area-ratio technique appeared to be superior to the beam-trip technique. The reactivity estimates obtained with the former technique were by the far less spread for different detector emplacements. That technique does not depend on the uncertainty of the delayed neutron data as well. And, it was few sensitive to the analysis domain.

As a consequence, this very subcritical experiment confirmed the area-ratio technique appears to be the best candidate for reactivity calibration (Ref. 7)

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## 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,” *8th Information Exchange Meeting on Actinide and Fission Product Partioning &Transmutation*, Las Vegas, Nevada, USA (2004)
2. D. BELLER, “Overview of the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project,” *Int. Conf 8th Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation*, Paris, France (2005)
3. D. BELLER et al., “Initial Results from the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project,” *Int. Conf 8th Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation*, Paris, France (2005)
4. B. GESLOT et al., “Multimode Acquisition System Dedicated to Experimental Neutronic Physics,” *Int. Cnf. IMTC 2005*, May 17-19, Ottawa, Canada (2005).
5. J. S. HENDRICKS et al., “New MCNPX Developments,” *12th Biennial Radiation Protection and Shielding Division Topical Meeting*, April 14–18, Santa Fe, NM, USA (2002)
6. C. JAMMES et al., “Modeling of the RACE-ISU Subassembly to Analyze Neutronics Experimental Data,” *submitted to Int. Conf. AccApp’07*, Pocatello, ID, USA, Jul. 30 – Aug. 2 (2007)
7. C. JAMMES et al., “Absolute Reactivity Calibration of Accelerator-Driven Systems after RACE-T Experiments,” *Int. Conf. PHYSOR 2006*, September 10-14, Vancouver, BC, Canada (2006)

8. C. JAMMES et al., “Advantage of the Area-Ratio Pulsed Neutron Source Technique for ADS reactivity calibration,” *Int. Conf. AccApp 2005*, Aug. 29 – Sept. 1, Venice, Italy (2005)
9. M. CARTA et al, “Reactivity Assessment and Spatial Time-Effects from the MUSE Kinetics Experiments,” *Int. Conf. PHYSOR-2004*, April 25-29, 2004, Chicago, IL, USA (2004)
10. R. K. MEULEKAMP and S.C. VAN DER MARCK, *Nucl. Sci. Eng.*, **152,** 142 (2006)
11. B. GESLOT, *PhD Thesis*, Université Louis Pasteur, Strasbourg, France (2006)
12. B. GESLOT and C. JAMMES, “Influence of the delayed neutron group parameters on reactivity estimation by rod drop analysis,” submitted to *Ann. Nucl. Eng.* (2007)
13. D. J. LOAIZA, *Nucl. Sci. Eng.*, **134**, 22 (2000)