ADS Reactivity Measurements from MUSE to TRADE (and Where Do We Go From Here?)

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Abstract

This paper provides a link between the MUSE (MUltiplication avec Source Externe) program performed at CEA-Cadarache in France, and the TRADE (TRiga Accelerator Driven Experiment) program performed at ENEA-Casaccia in Italy. In both programs, extensive measurements were made to determine the best methods for sub-criticality measurements in an accelerator-driven system. A very serious attempt was made to quantify the uncertainties associated with such measurements. While both MUSE and TRADE studied the methods of sub-criticality determination, in fact the two systems are very different. MUSE was a fast system with MOX fuel (generation time around 0.5 μs), and TRADE was performed in a TRIGA reactor (generation time around 50 μs). This paper will summarize the important results of these two experiments, with the main purpose being to tie them together to attempt to draw generic conclusions that can be applied in the future to a real ADS.

In addition, this paper will briefly discuss the next series of experiments that will continue this work in the U.S. (RACE, Reactor Accelerator Coupled Experiments), Belarus (YALINA), Belgium (GUINEVERE), and Russia (SAD, Sub-critical Assembly Dubna). MUSE and TRADE have contributed greatly to our understanding of the uncertainties associated with sub-critical measurements, but there are still some gaps that must be covered. This paper will describe the gaps that exist, and demonstrate how the above future programs will fill in the missing information needed for the design of an actual ADS system in the future.

KEYWORDS: ADS, Sub-critical, Reactivity Measurements, MUSE, TRADE

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1. Introduction

This paper provides a link between the MUSE (MUltiplication avec Source Externe) program performed at CEA-Cadarache in France, and the TRADE (TRiga Accelerator Driven Experiment) program performed at ENEA-Casaccia in Italy. In both programs, extensive measurements were made to determine the best methods for sub-criticality measurements in an accelerator-driven system. A serious attempt was made to quantify the uncertainties associated with such measurements. While both MUSE and TRADE studied the methods of sub-criticality determination, in fact the two systems are very different. MUSE was a fast system with MOX fuel (generation time around 0.5 μs), and TRADE was performed in a TRIGA reactor (generation time around 50 μs).

The MUSE experiments terminated in August 2004 and the final results were synthesized in a final report issued in June 2005 [1]. The TRADE reactivity experiments concluded in late 2005[a], and the results are presented in a companion paper in these proceedings [2].

In the following sections we present a brief synopsis of the principal MUSE and TRADE results, with the main objective being to show what has been learned from these two programs, and what remains to be studied in future programs.

2. MUSE Results

A summary of the MUSE reactivity measurements is given in Table 1 taken from [1].

Table 1: MUSE reactivity in dollars and standard error in percent

	MSM	PNS-F			kp	PNS-A	SJ-Cf	MOD	Rossi-α
		1	2	3					
SC0	-1.9	-1.93	-1.92		**-2.01**	-2.0	-1.92	-1.96	**-2.04**
	(4.7)	(1.6)	(0.3)		(15.0)	(1.0)	(5.2)	(0.2)	(6.9)
SC2	**-9.1**			-8.7		**-8.9**			-8.8
A	(5.5)			(8.0)		(3.4)			(2.2)
SC2	-9.7				-9.6			-9.23	
B	(5.2)				(3.1)			(1.3)	
SC3	-14.1		**-15.6**	-11.7	-14.2	-13.7	**-14.6**		-13.4
	(5.7)		(3.8)	(7.7)	(2.1)	(3.6)	(6.2)		(3.7)

In this table, the reactivities are given in dollar units (β_{eff} for MUSE is approximately 335 pcm; 1 pcm is 10^{-5} $\Delta k/k$), while the standard errors are in percent. The MSM column gives the results of source multiplication with a rod-drop conventionally giving the reference reactivity. The columns of PNS-F give the PNS exponential fitting results using 1, 2, or 3 exponentials reflecting the non-point kinetic behavior of the MUSE system. The k_p method makes use of the fact that the time behavior of the pulse decay in the reflected MUSE configuration can be explained by assuming a spread in the effective generation time. SJ-Cf is the standard source jerk using a Cf source, and MOD is a method developed to estimate β based on running the neutron generator at different frequencies. The Rossi-α method uses the correlation of detector events

[a] There are some reaction rate experiments planned for 2006

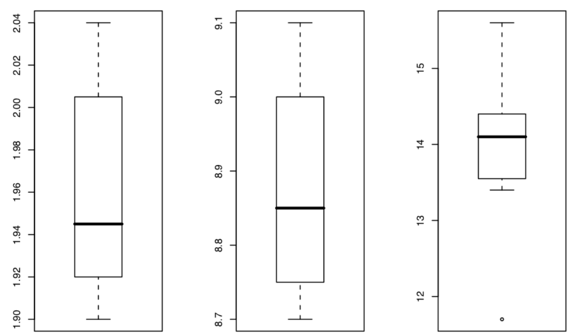

Figure 1: Boxplot of MUSE Results SC0, SC2 A, and SC3

to deduce the fission chain decay curve, which is related to the reactivity, generation time, and β analogous to a PNS decay curve. In these Rossi-α results the areas under the deduced decay curves were analyzed in a manner similar to the PNS area method. These techniques are well documented in References [3], [4], [5], [6], [7], [8], [9], [10], [11] and [12].

We can note from Table 1 first that there is a range of uncertainties quoted and second that there is a dispersion in the results from method to method. Because the goal of each technique is to determine the same integral parameter (reactivity), we can treat this dispersion as a kind of uncertainty (Type B in the NIST nomenclature). The individual uncertainties given in the table are statistically based, and thus would be Type A. We have no *a-priori* means of knowing the ”correct” result, so we need some means of assessing the suitability of these techniques. There have been years of demonstration of the MSM method, which was considered the reference to which all others were to be compared. However in Table 1 we see that the uncertainties associated with the MSM values are larger than those of other techniques. Thus, the MSM does not provide a very good reference for our experiments. In consequence, when we assess these results given no other information, we consider each and all techniques as being viable candidates.

A useful tool for visually examining groups of data is the so-called boxplot. We show the boxplots for the three MUSE configurations in Figure 1.

In these plots, the box represents the first and third quartile, such that 50% of the data falls within the range defined by the box. The horizontal line above and below the box, the ”whiskers”, are the lessor of 1.5 times the box dimension and the actual data points. If there are data outside the whiskers, they are considered outliers and are marked by asterisks (note the outlier in SC3). Finally, the solid horizontal line within the box is the median of the data. We use the boxplots to visually characterize the dispersion of the results. For example, we see that in SC0 that the whiskers are well within the 1.5 times box dimension, meaning there is a relatively tight grouping. This is obvious by directly examing the data in Table 1, but we notice in Figure 1 that the same is true for SC2 which would not be so immediately obvious. Actually, the spread in SC3 is not so bad either, if one removed the very low outlier.

One interesting feature of Figure 1 is that the distribution of values greater (in magnitude) than the median are consistently broader than those lower. That is to say, the data below the median are grouped more tightly than those above. The question then is, do one or two techniques always over-estimate the reactivity, i.e., is there an inherent bias? The two highest values of reactivity for each sub-criticality level are printed in bold in Table 1. We can immediately see that there is absolutely no pattern, as no technique was in the highest two more than once. This appears to confirm that there is no significant bias in any given measurement technique.

Our goal is to judge the suitability of various techniques for sub-critical measurement. One approach is to look for consistency among measurements. Again, without knowing the correct answer lacking a reference, we are going to assess suitability by a sort of ”vote”. Therefore, in Table 2 we list the band defined by the boxes in Figure 1 as being ”good” since 50% of the measures agree within this range. Also in the table we list the standard error in percent and the techniques by name that fall within the 50% band.

We see results for the dispersion ranging from a low of 1.9% (surprisingly not for SC0, but for SC2), and a high of 8.6% for SC3 (not surprising). More interesting though are the results of the ”vote”. We see that the only method that is consistently in the 50% band for all three reactivities is the PNS-A. None of the other methods even shows up twice, let alone for all three. We can thus conclude that the PNS-A results agree with at least half the other results for each level of sub-criticality, but the other results in the band come from different techniques depending on the level of sub-criticality. This result is not really surprising because we expect very little dispersion near critical (SC0), but the differences in the methods start to unveil at lower levels like SC3. At the lower levels, the non-point kinetic behavior starts to come into play, making a technique such as the fitting of the alpha curve in the PNS-F technique difficult, for example. It appears that the PNS-A method, being integral rather than differential, appears to be less sensitive to spatial and temporal effects such as pulse propagation times and non-single exponential decay curves.

We conclude by noting that PNS-A shows a level of consistency desirable in a measurement technique, but we cannot say that is is giving the most correct answer without some additional information (e.g., improvement of MSM, calculations)

Table 2: Techniques in a 50% band and dispersion in percent for MUSE

	$-\rho_{band}$ ($)	σ (%)	Techniques in 50% band
SC0	1.92-2.0	2.6	PNS-F, PNS-A, SJ-Cf, MOD
SC2 A	8.78-8.95	1.9	PNS-A, Rossi-α
SC3	13.55-14.4	8.6	PNS-A, k_p, MSN

3. TRADE Results

Similar results from TRADE are presented in Table 3. The methodology and explanation of the derivation of the uncertainties is presented in the companion paper in these proceedings [2]. In this paper we just present the principal results.

It is immediately obvious that there are fewer results given in Table 3 than in Table 1. This is because the TRADE program benefited from what was learned earlier in MUSE regarding the most promising techniques for reactivity measurements, thus the concentration on the PNS-A method. Also, the fact is that some methods tested in MUSE are not applicable in a thermal system like TRADE. For example, the k_p method is applicable to a fast reflected system in which

Table 3: TRADE reactivity in dollars and and standard error in percent

	PNS-A	SJ-Cf	SJ-GEN	MSA
SC0	-0.66	-0.67	-0.66	**-0.69**
	(0.78)	(1.47)	(1.81)	(2.75)
SC2	-3.54	-	-3.60	**-4.15**
	(1.11)	-	(4.33)	(8.09)
SC3	-6.18	-	-5.96	**8.08**
	(1.22)	-	(4.74)	(10.7)

returning neutrons have been moderated relative to core neutrons (which effectively spreads the generation time distribution). This effect could be further studied during the YALINA program in Belarus [13] which is foreseen with a fast central area in a thermal driver zone, and in the GUINEVERE program (Belgium) which is aimed at coupling an improved neutron generator of the type used in MUSE in both pulsed and continuous modes to a fast lead reactor (VENUS).

Besides the PNS-A we performed MSA measurements, but these have not been corrected for the MSM factor. Thus, there is a large uncertainty and large dispersion associated with these measures. The Cf source jerk was included to see if we could improve the results compared to the MUSE series, but in fact meaningful measurements were only possible in the SC0 configuration. The SJ-GEN method[b] was included because it is presently seen as a method of checking the reactivity in an ADS during either scheduled or un-scheduled beam trips.

Even with so few results, we show the boxplot for TRADE in Figure 2. For this case, we see the same behavior in MUSE, i.e., a broader distribution towards the higher reactivities (more negative). The difference is that the datum that is pulling the distribution up is the MSA method for all three levels of sub-criticality. With so few results as in Table 3 this is immediately obvious, so the boxplot is not necessary. However, part of the purpose of this paper is to demonstrate a different way of interpreting a group of measurements, and the boxplot is an important tool. We now construct a table for the TRADE data equivalent to Table 2, and this is done in Table 4.

Table 4: Techniques in a 50% band and dispersion in percent for TRADE

	-ρ_{band} ($)	σ (%)	Techniques in 50% band
SC0	0.66-0.675	2.1	PNS-A, SJ-Cf, SJ-GEN
SC2	3.57-3.88	8.9	SJ-GEN
SC3	6.07-7.13	17	PNS-A

Our dispersions in this table are much higher than in the MUSE case except for SC0; this is primarily because the MSA results are heavily skewing the dispersion. This very well shows

[b] SJ-GEN refers to ”source jerk with the generator” which makes use of the fact that an abrupt decrease in the generator intensity is essentially the same thing as the classic source jerk in which a source is physically moved out of the core.

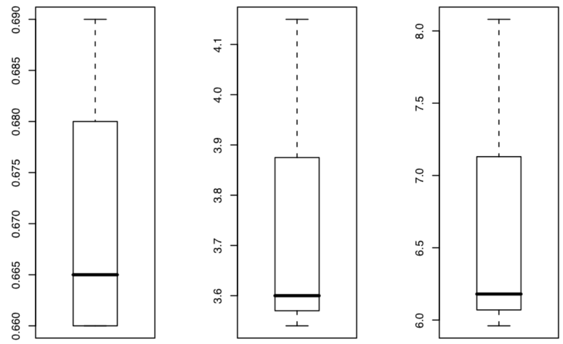

Figure 2: Boxplot of TRADE Results SC0, SC2, and SC3

the need for MSM correction factors. Other than that, we see that there is no method that is in the 50% band for all three levels of sub-criticality, but both the PNS-A and SJ-GEN fall in two out of three[c]. While this hardly constitutes full validation, it does appear that the SJ-GEN method can serve as a check of reactivity at least at zero power. We do not have any data for a source jerk at powers sufficient to have thermal feedback effects, which would have been one of the objectives of a continuation of the TRADE program.

Our results for the SJ-Cf are similar to those obtained in the MUSE program: it is difficult to apply it at lower levels of sub-criticality because of the difficulty of obtaining adequate statistics.

4. Discussion

From the MUSE program, we learned a great deal about the applicable methods of sub-critical reactivity measurements, particularly which of the many possibilities have the most promise for use in an ADS of the future. The preliminary conclusions drawn in MUSE were then verified and refined in TRADE. At this stage, we are now confident that accurate measurements of ”cold” start-up reactivity can be made with some combination of PNS and/or SJ (with a beam trip). However, there are a couple of crucial measurement techniques that have not been qualified in these programs, leading to the need of future experiments.

First, the techniques above are applicable to cold situations (more specifically, low power operation), assuming a small pulsed source can be installed in the system, or a series of beam trips can be requested[d] . However, they are not applicable to an ADS operating at power in CW. What is missing in MUSE and TRADE is the demonstration of a method of continu-

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[c] Actually, the PNS-A results in SC2 and the SJ-GEN in SC3 are only a few cents outside the band.

[d] Actually beam trips during operation at power will produce some reactivity information albeit complicated by thermal feedback effects, but this cannot be used as a continuous monitoring system. However, it could be used as a periodic check method.

ously monitoring the reactivity. We are assuming that this would be done using a form of a current/power/reactivity relationship, such as:

$$\rho = -c\frac{I}{\phi} \tag{1}$$

That is, the reactivity can be monitored by measuring the ratio of the accelerator current and reactor flux (power). The proportionality constant (c) is not crucial if this is to be just a relative measurement to track changes in time in this steady state system[e]. This technique could not be tested in neither MUSE nor TRADE because the frequencies of the generators were not sufficiently above the reactor break frequency to simulate a true steady state[f] Therefore, it is planned to conduct experiments in the YALINA facility in Belarus where a generator is available that can pulse well above the reactor break frequency. In this facility it is hoped to verify the use of the above relation as a ”steady state” reactivity monitoring system. Additionally investigations of the source/flux/reactivity relationship are planned for RACE [14], although the accelerators available are not capable of achieving a quasi-steady state.

A full investigation of the different reactivity monitoring techniques, including the on-line monitoring and the checking techniques at beam trips will be carried out in representative ADS conditions in the GUINEVERVE project where the coupling of a lead core to an enhanced neutron generator will be realized.

A second aspect of a real ADS that must be studied is its operation in the presence of temperature reactivity feedbacks. This cannot be studied in zero power systems such as MUSE, TRADE or YALINA. It was hoped to use TRIGA reactors in Texas during the RACE project to fill in this part of the matrix. In those experiments it was envisioned to obtain sufficient reactor power (above at least 30 kW) from electron accelerators to demonstrate operation which includes the effects of reactor feedbacks. Unfortunately, at the present time there is no funding for this.

Finally, none of the above mentioned experiments directly yield information of the coupling of a very high energy accelerator (in excess of 500 MeV) which can produce true spallation neutrons with a sub-critical system. This is planned in the SAD program in the Dubna facility in Russia [15].

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[e] Perhaps some information on c can be obtained at low powers using SJ or PNS

[f] It should be noted that the proportionality of the source to flux was demonstrated in the MUSE modulation measurements ([11], [12]). As the frequency was changed, the effective source changes, and the flux was indeed proportional. However, it is still desired to approach steady state for this test which requires a frequency well above the reactor break frequency.

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