PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

The TRADE Source Multiplication Experiments

G. Imel[1*], D. Naberejnev[1], G. Palmiotti[1]
H. Philibert[2], G. Granget[2], L. Mandard[2], R. Soule[2], P. Fougeras[2]
J.C. Steckmeyer[3], F. R. Lecolley[3]
M. Carta[4], R. Rosa[4], A. Grossi[4], S.Monti[4], V. Peluso[4], M. Sarotto[4]
[1]*Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Illinois, USA*
[2]*CEA, F-13108, St Paul lez Durance, FRANCE*
[3]*LPC-ENSICAEN-IN2P3-CNRS, F-14050, Caen, FRANCE*
[4]*ENEA, C. R. Casaccia, via Anguillarese, 301, 00060 S. Maria di Galeria, Rome, ITALY*
[*]

This paper presents the results of the first sub-critical measurement campaign performed for the TRADE (TRiga Accelerator Driven Experiment) program in late 2003. The TRIGA reactor at the Casaccia Center of ENEA was studied in a number of configurations ranging from k_{eff} approximately 0.993 to 0.93. Over a two week period, starting from a single reference configuration, fuel elements were removed, control rods were moved outward (required for the eventual TRADE experiments), and fission chambers were inserted. In all configurations, sub-critical counts were taken.

The results of these measurements are given in this paper. First estimates of reactivity in all the states are presented, and our first attempts at correcting the reactivity based on calculations of source importance and detector efficiency---so called MSM factors---are also presented.

KEYWORDS: ADS, TRADE, Source multiplication, MSA, MSM

1. Introduction

The TRADE experiments are scheduled to begin in 2008 at the existing TRIGA facility at the Casaccia Center of ENEA near Rome. The plan is to couple an existing reactor capable of demonstrating features of power operation (notably power coefficients of reactivity) with a neutron spallation source driven by a high energy proton beam. It is felt that TRADE will be able to demonstrate and test many features of operability of an ADS such as relations among reactivity (including feedback), accelerator current, and source importance.

There are a number of relevant measurements that can be made in the reactor before the cyclotron is installed. These include characterization type measurements, such as fission rate traverses or spectral indices, and fundamental reactor physics measurements such as determination of kinetic parameters through noise or other dynamic techniques. In this paper, we present our estimations of sub-critical reactivity levels through source multiplication techniques. This is likely to be an important method of reactivity determination in a future ADS. We will demonstrate that the theory is very simple, but the practical application to determine a reactivity level with acceptable uncertainties is a little more difficult.

[*] Corresponding author: Tel +33 4 25 72 18 imel@anl.gov

2.0 Source Multiplication and MSM

2.1 Simplified Interpretation

To understand the physical meaning of the "modified source multiplication" (MSM) method, we must first recognize that a sub-critical reactor is first and foremost a neutron multiplier of independent source (S) neutrons, assuming they exist in the system. The multiplication of the original S neutrons is described by the series:

$$S(1+k+k^2+k^3+\cdots)$$

where k is the usual multiplication factor. Thus, since k<1, we write the convergent series as:

$$\frac{S}{1-k}$$

It is perhaps obvious, but still important to note, that we as experimentalists are attempting to obtain a single value for k that is representative of the multiplication properties of the entire reactor. When we write the above expression, we are assuming that we can somehow know or infer the total number of neutrons in the system. This of course is experimentally impossible, so we have to introduce quantities such as source importance (effective source) and detector efficiencies to the equation. We will do this in a systematic manner. First, however, we continue the derivation by dealing with total quantities such as S. By this we do mean the total number of source neutrons (per second) in the system---thus k in the above relation also represents the integral behavior of the "multiplier".

First we presume that we have a detector in the system; it will detect C counts/second, with ε being the detector efficiency:

$$C=\frac{\varepsilon S}{1-k}$$

Between two states, k_1 and k_2, we note that the detector efficiency can change (for example because absorbing material between the detector and source was removed). We also note that the source (S) can change (for example when we remove fuel from a Pu containing core, we change the total inherent source). Thus, taking into account the previous statements, we write the ratio of count rates between the two assumed states as:

$$\frac{C_1}{C_2}=\frac{\varepsilon_1 S_1}{\varepsilon_2 S_2}\frac{\rho_2}{\rho_1}$$

The state 1 is assumed known (for example, through a rod-drop or through a previous MSM measurement). We also note that the reactivity (ρ) is referenced to the critical state (k=1). The so-called "MSA" reactivity is that obtained by assuming there is no change in the effective source or detector efficiency between the two states:

$$\frac{\rho_{2MSA}}{\rho_{1REF}} = \frac{C_1}{C_2}$$

The MSM factor is the change in εS between the two states. To obtain the physical meaning, we first conventionally define the detector efficiency as the ratio of the count rate seen by a detector to the total fission neutron production rate in the core:

$$\varepsilon = \frac{\langle \sigma_D \phi \rangle}{\langle F\phi \rangle}$$

We also define the source importance as the ratio of the source to the fission neutron production rate, using the adjoint flux as an appropriate weighting function:

$$\frac{\langle \phi^* S \rangle}{\langle \phi^* F\phi \rangle}$$

We multiply by the total fission neutron production rate to obtain the total number of "effective" source neutrons:

$$S_{eff} = \frac{\langle \phi^* S \rangle}{\langle \phi^* F\phi \rangle} \langle F\phi \rangle$$

Note that use of the adjoint as the weighting function is not completely necessary in this physical derivation, but it is certainly well-grounded in the fundamental definition of the adjoint flux as being directly related to source importance. However if the adjoint flux is not easily available, reasonable results may be achieved by simply using the fission rate distribution as the weighting function.

Finally, our MSM factor is defined as the change in the following derived quantity as we go from state 1 to state 2:

$$\varepsilon S = \frac{\langle \phi^* S \rangle}{\langle \phi^* F\phi \rangle} \langle \sigma_D \phi \rangle$$

2.2 Computational Methodology

We could solve the forward and adjoint inhomogeneous equations in the two states, and obtain the MSM factor as given above by direct integration. We can take another approach however, beginning by solving the homogeneous adjoint equation below:

$$A^* \phi_0^* = \frac{1}{k} F^* \phi_0^*$$

Multiplying this by a forward flux obtained through an inhomogeneous equation:

$$(A-F)\phi = S$$

and utilizing the adjoint properties, we can write

$$k = \frac{\left\langle \phi_0^* F \phi \right\rangle}{\left\langle \phi_0^* A \phi \right\rangle}$$

Defining

$$\rho = 1 - \frac{1}{k}$$

we can combine all the above and obtain

$$\rho = \frac{\left\langle \phi_0^* S \right\rangle}{\left\langle \phi_0^* F \phi \right\rangle}$$

Thus, our sub-critical reactivity is directly related to source importance that appears in the MSM relation, and we can write that:

$$\left(\frac{\rho_2}{\rho_1}\right)_{MSM} = \left(\frac{\rho_2}{\rho_1}\right)_{CALC} \left(\frac{T_2}{T_1}\right)_{CALC} \left(\frac{C_1}{C_2}\right)_{EXP}$$

where T is the calculated detector count rate, $<\sigma_D\phi>$ in the previous formulation.

It can be noted that this formulation provides a method to calculate MSM factors with a Monte-Carlo code such as MCNP. A fixed source calculation can be performed to obtain the ratio of detector count rates, followed by a k_{eff} calculation to obtain the ratio of reactivities. This method will be tested in the coming months.

Perhaps more importantly, it demonstrates the relation between the sub-critical reactivity and the source importance. It is not possible to obtain a reasonable value for the source importance if there is not a good calculation of the (sub-critical) reactivity. Thus, when using either deterministic or Monte-Carlo codes to obtain the MSM factors, there must be some adjustment to the models (e.g., through control rod worths) to obtain a reasonable starting reactivity. Our methodology will be demonstrated later in this paper.

3.0 Experimental MSA Results

The starting core for these measurements is shown in Figure 1 (Week 41, State 1) and the ending state (prototypical of TRADE) is shown in Figure 2 (Week 43, State6).

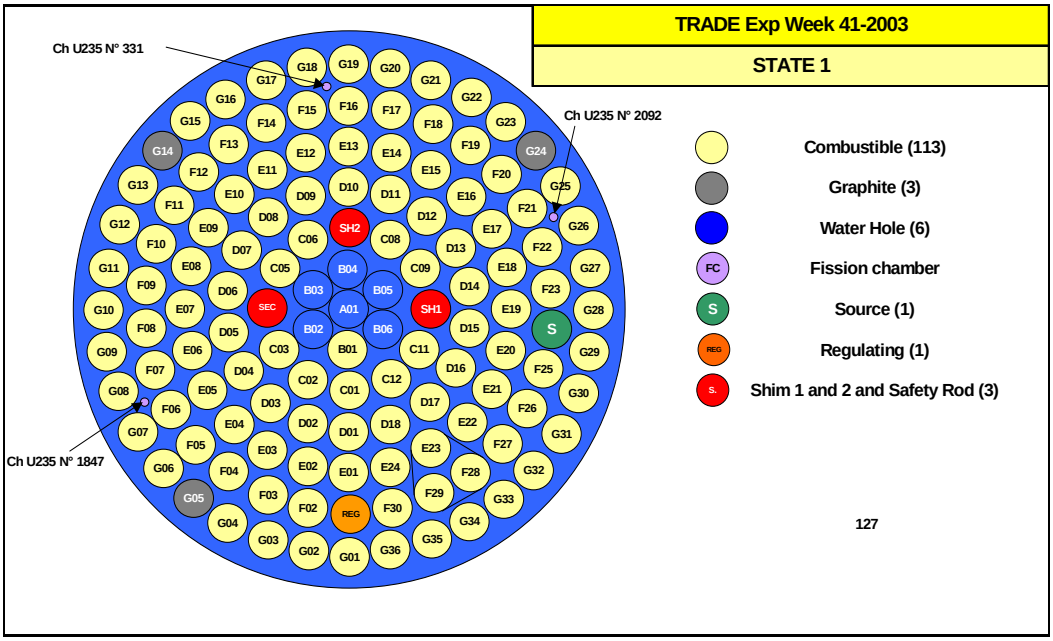

Fig. 1 Starting core for MSA measurements

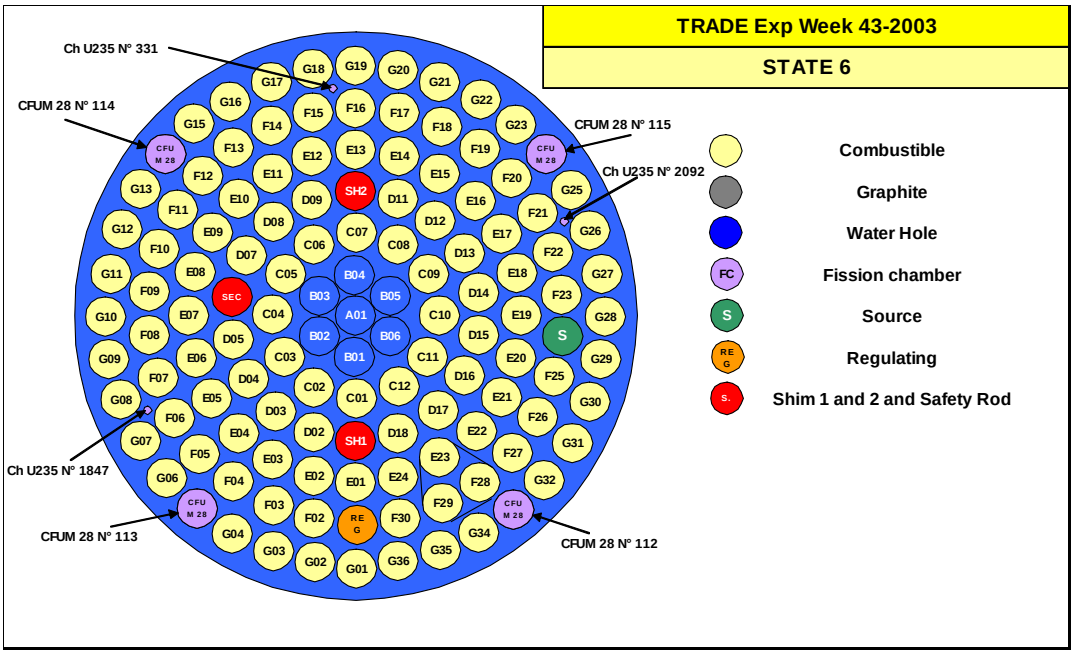

Fig. 2 Final TRADE mock-up core for MSA measurements

The progression in the two weeks was the same:

1. Reference reactivity obtained by withdrawing 3 main control rods, obtaining a critical configuration with the REG rod, then performing a rod drop. The critical

configuration was obtained with the REG rod nearly out (about 6 cents excess). It should be noted that the three main rods are fuel followed, while the REG rod is water followed. We thus start with a reasonably clean core.
2. Withdraw element B1
3. Exchange 3 graphite elements in G ring for sensitive fission chambers.
4. Re-insert element B1
5. Change G33 element for a fourth fission chamber.
6. Withdraw element B1.

Week 43 was the same, but the three main control rods were shifted to the D ring, and SH1 was rotated 90 degrees (necessary to accommodate the beam tube of the accelerator for TRADE).

Note that through all the measurements, there are 3 miniature fission chambers (1.5mm) inserted between the F and G rings. We thus progressed from 3 chambers in steps 1 and 2 to 6 chambers in steps 3 and 4 to 7 total chambers in steps 5 and 6. In all the steps above, measurements were taken with all control rods inserted, only the REG rod inserted, and with all rods withdrawn (except of course in State 1, which would be super-critical). It is also important to note that with the fuel followed control rods, there is no practical difference between measures in Week 41 versus Week 43 except in the case when all rods are inserted.

Our reference sub-critical level, obtained in State 1 with the REG rod inserted, is –718 pcm (1 pcm = 10^{-5} $\Delta k/k$). In a TRIGA, this is about 1 dollar. We show the MSA reactivities obtained from this reference in Figure 3 for all the states, separated by detector. Note that all reactivities are given in units of pcm.

We can see a fairly good agreement among all the chambers' predicted MSA reactivities for the case when all rods are withdrawn. This is actually typical of the previewed operation of TRADE, so that is good news. For the case with the REG rod withdrawn (middle plot), there is more dispersion, and it is clear that MSM factors will be needed to correct the MSA reactivities. In the case where all control rods are inserted, the dispersion is enormous, and must be corrected (one could live with the dispersions in the first two cases, but the MSA prediction in the case with all rods inserted ranges from –3000 to –10000 pcm, clearly unacceptable).

We can also estimate the control rod worth from the above measures. We show the values obtained for the total rod worth in Figure 4.

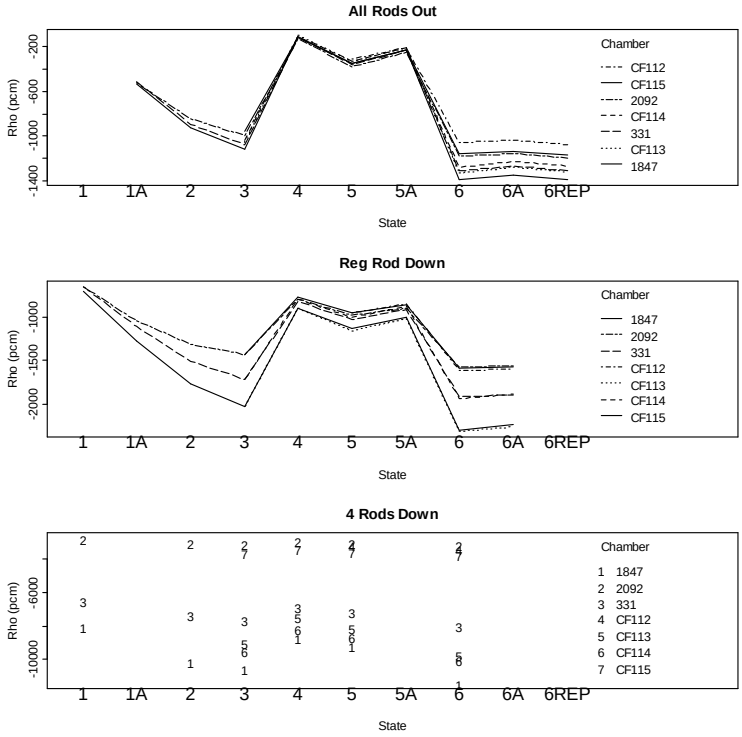

Fig. 3 MSA Reactivities by State

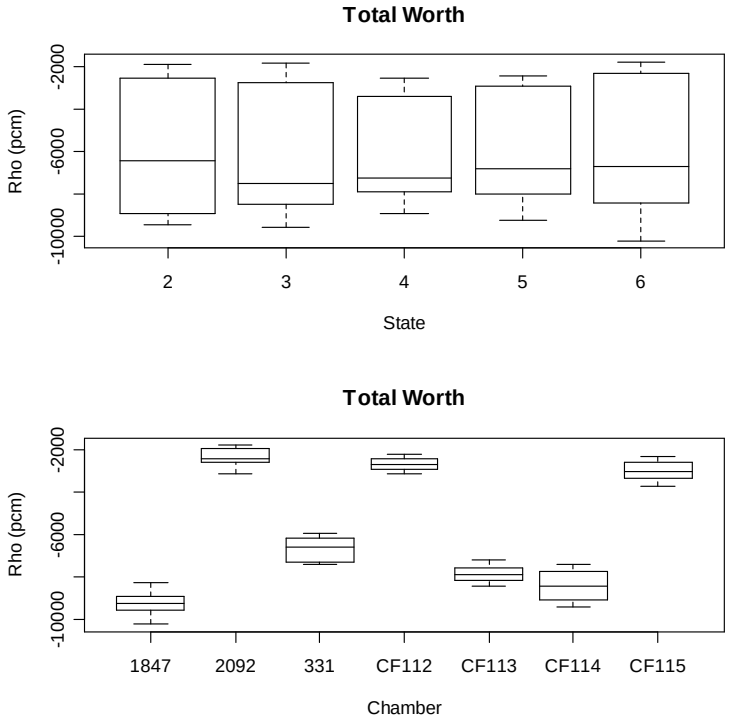

Fig 4 Total rod worth by State and by Chamber

The plots in Figures 4 are “box and whisker” and graphically show the dispersion among

measurements. The median line is in the box, and the box dimension is determined by doubling the quartiles. The whiskers are the outer limit of the data, or 1.5 quartiles if there are outliers.

We show the plots of Figure 4 for one main reason---there is a clear problem with 3 of the chambers regarding MSA reactivity. Chambers 2092, CF112, and CF115 are clearly underestimating the total rod worth. The box and whisker plot shows this quite dramatically. The physical reason can be quickly determined by examining Figure 2. These three chambers are closest to the source, and are thus seeing source neutrons directly and are not representative of the multiplication process.

4.0 MSM Corrections

The reference core was modeled in XY geometry using the ERANOS code [1]. As the first step, the buckling was adjusted such that the calculation predicted the measured reactivity (just above critical) with all control rods withdrawn. Next, the material composition of the REG rod was adjusted such that the calculation yielded the measured value when this rod was inserted (-718 pcm). Finally, the material compositions of the remaining three control rods were adjusted such that the calculation yielded the measured MSA reactivities from the 3 detectors. These compositions thus become the reference model, and they and the buckling are preserved throughout following states.

We show the results of the correction on the MSA sub-critical levels from State 1 to State 2 (removal of element B1) in Figure 5 and 6. In these figures we show the case with the REG rod inserted and the case with all control rods inserted (recall the enormous MSA dispersion in this case).

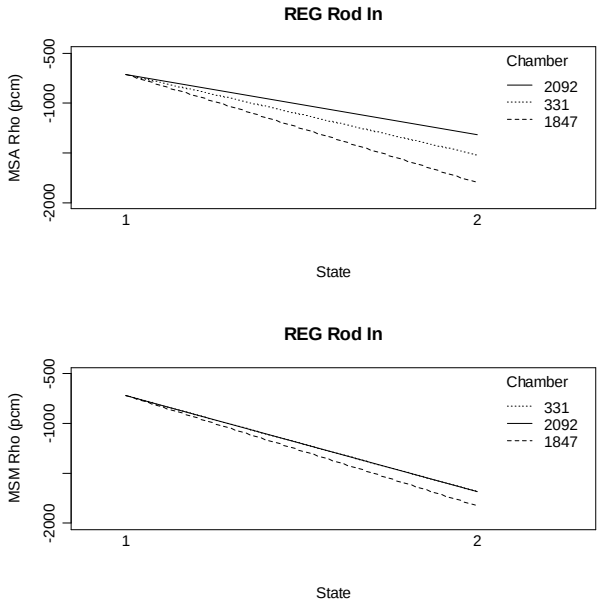

Fig. 5 MSM correction, REG rod inserted

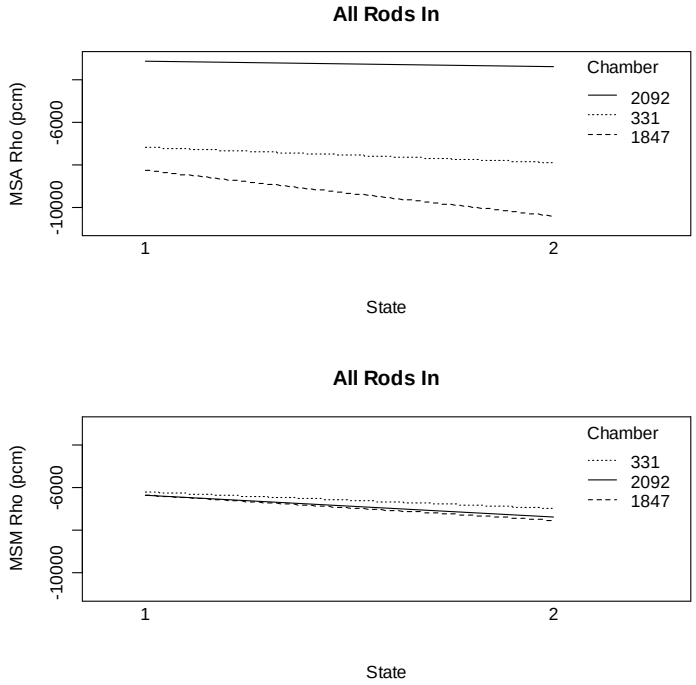

Fig. 6 MSM correction, all rods inserted

These two figures dramatically show how the MSM factors can correct MSA values, even in extremely perturbing cases such as when all control rods are inserted in a small core such as a TRIGA.

In Table I we present the comparison between experimentally obtained sub-critical reactivities (corrected for MSM) and those directly calculated, for several cases. We see excellent agreement. From the measures, we can also estimate control rod worths. These are presented in Table II. Again we are quite happy with the agreement between experiment and calculation.

At the time of this writing, we have not been able to finish the calculation of the MSM factors for the remaining conditions (states 3 to 6), but we have no reason to believe that the MSM methodology we are using will not continue to give us good results.

Configuration	**ρ_{exp} (pcm)**	**ρ_{calc} (pcm)**	**$\Delta\rho$ (E-C) (pcm)**
STATE 1 – REG ↓ Reference	-718	-720	2
STATE 1 – all CR's ↓	-6634	-6740	106
STATE 2 - all-CR's ↑	-1032	-984	-47
STATE 2 – REG ↓	-1813	-1729	-84
STATE 2 - all CR's ↓	-7688	-7613	-75

Table I: Sub-critical reactivities

Rod	**$\Delta\rho_{exp}$ (pcm)**	**$\Delta\rho_{calc}$ (pcm)**
B1 fuel rod Transition STATE 1 → STATE 2 (REG ↓)	-1095	-1009
REG rod STATE 2	781	745
3 CR's STATE 1 - (REG ↓)	5916	6020
3 CR's STATE 2 - (REG ↓)	5875	5884
3 CR's + REG STATE 2	6656	6629

Table II: Control rod worths

5.0 Conclusions

We began this set of experiments not really knowing how sensitive the TRIGA reactor would be to core geometry changes, control rod perturbations, etc. As we collected our data and performed preliminary MSA analysis, it became quickly clear that the TRIGA reactor is very sensitive to perturbations. We initially thought that all of our detectors were far enough away from the source so they would not see source neutrons directly. A glance at Figure 4 dispels that notion immediately. Likewise, we thought that the REG rod would be a minor perturbation. That this is not the case can be seen by looking at the middle plot of Figure 3. On the other hand, we have demonstrated that we can use the MSM factors and correct for the sensitivity of the TRIGA core. This methodology will be very important as we progress through the TRADE experiments, but it is just as important to remember that these techniques will also be required for understanding the sub-critical behavior of a future ADS.

6.0 Acknowledgements

The authors greatly appreciate the support of the TRIGA staff at the Casaccia Center. They made it possible to perform a great number of valuable measurements.

This work has been performed in the frame of an International Working Group on the TRADE experiment. The original membership – ENEA (Italy), CEA (France), CERN (Switzerland), and ANSALDO (Italy) – is extended to FZK (Germany), DOE (USA), CIEMAT (Spain), CNRS (France), JRC-ITU (EU), PSI (Switzerland), SCK-CEN (Belgium), AAA (France), AIMA (France), and IBA (Belgium).

7.0 References

1. G. Rimpault, et al., "The ERANOS code and data system for fast reactor neutronic analyses", Proc. PHYSOR 2002, Seoul, Korea, October 7-10, 2002.