

**OVERVIEW OF THE AFCI
REACTOR-ACCELERATOR COUPLING EXPERIMENTS (RACE) PROJECT**

Denis Beller*

Idaho Accelerator Center, Idaho State University

Abstract

The RACE Project, which is being conducted within the U.S. Department of Energy's Advanced Fuel Cycle Initiative (AFCI), is a series of accelerator-driven subcritical systems (ADSS) experiments. These ADSS experiments are being conducted with a compact, transportable subcritical assembly at the Idaho State University's Idaho Accelerator Center (ISU-IAC) in 2004, and with TRIGA reactors at the University of Texas at Austin in 2005 and at the Texas A&M University in 2006. In these experiments, we are generating source neutrons by using electron accelerators to induce bremsstrahlung photon-neutron reactions in heavy-metal targets. These accelerator/target systems produce a source of $\sim 10^{12}$ n/s, which will then initiate fission reactions in the subcritical systems. Unique features of the U.S. RACE Project described herein will contribute to the understanding of coupling between accelerator targets and subcritical systems in addition to European programs.

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* RACE Project Director; Idaho Accelerator Center, Idaho State University, 1500 Alvin Ricken Dr., Pocatello, ID 83209; beller@egr.unlv.edu

INTRODUCTION

The RACE Project is a university-based transmutation research project of the U.S. Advanced Fuel Cycle Initiative (AFCI). It is a series of accelerator-driven subcritical systems (ADSS) experiments that will be conducted at the Idaho State University's Idaho Accelerator Center (ISU-IAC), at the University of Texas (UT) at Austin, and at the Texas A&M University. In these experiments, an electron accelerator will be used to induce bremsstrahlung photoneutron reactions in heavy-metal targets producing a neutron source to initiate fission reactions in the subcritical systems. These systems will include:

- a compact, zero-power transportable subassembly at ISU of modular design with multiple target position capability;
- a 1-MW TRIGA reactor at UT-Austin that allows for thermal feedback measurements with a single source location and benchmark experiments with an fresh core; and
- a 1-MW TRIGA modular core at Texas A&M where both multiple target locations and thermal feedback measurements can be conducted in the ultimate test.

In this paper we discuss international ADSS experiments and describe a growing U.S. program that will complement these international research programs.

International Efforts

The purpose of accelerator coupling studies is to demonstrate ADSS concepts and to develop as complete as possible an understanding of source terms and their coupling to subcritical reactors. Additionally, computer codes must be validated and benchmarked for use in designing safe and reliable ADS systems for transmutation of nuclear waste. To validate these computer codes and demonstrate that they are applicable to a variety of ADSS configurations, a wide array of coupling experiments must be performed. A major contribution to this field was recently completed with the European program MUSE¹ (Multiplication avec Source Externe, CEA, Cadarache, France) in which U.S. AFCI personnel guided the experimental program. The next phase in the European ADSS Program is the new TRADE Project^{2,3} (TRIGA Accelerator Driven Experiment) at the ENEA (Italian Agency for New Technologies, Energy and the Environment) in Cassacia, Italy.

Complete knowledge of the spectral, temporal, directional, and intensity characteristics of the neutron source as well as its coupling to a subcritical system is essential for determining the performance and safety of ADSS. The current lack of reliable nuclear reaction data for many chemical elements with neutron energies greater than 15-20 MeV increases the uncertainty of calculations of this coupling. A variety of point neutron sources were used for the MUSE experiments: Californium-252 ($\sim 10^9$ n/s, near-fission spectrum), DD ($\sim 10^8$ n/s, 2.45-MeV), and DT ($\sim 10^{10}$ n/s, 14.1 MeV). For the DD and DT sources, neutron generators (accelerators) produced a point source of nearly mono-energetic neutrons with very slight anisotropy in energy and direction. These sources are not characteristic of a high-energy spallation source. MUSE will have provided valuable measurements of source importance up to 14 MeV (a range in which data are less questionable), albeit with a point source. The future TRADE experiment will begin with a DT source and will continue with a high-energy proton cyclotron to produce a spallation-neutron continuum that will extend up to 140 MeV and $\sim 10^{15}$ n/s. In addition, the TRADE proton source will have other properties of spallation sources: it will be asymmetric, anisotropic, and distributed over a larger volume.

Contributions and Uniqueness of the RACE Project

The RACE Project is providing an important and unique understanding of source-reactor coupling as well as providing for a U.S. demonstration of ADSS independent of the recent European MUSE and future TRADE projects. To complement MUSE and TRADE and to provide a bridge between them, RACE studies in the range up to 30 or 40 MeV with a source much more representative of high-energy spallation systems (anisotropic, volumetric source) will provide valuable validation and benchmarking information which makes extrapolation in calculations much more reliable. These experiments will provide new data bases in a variety of configurations with greatly reduced uncertainties and a much higher confidence level. To increase the value of these databases, the RACE systems will include at least five different subcritical systems that include a variety of fuel compositions and enrichments and a range of fuel exposure histories, from fresh cores to spent cores.

Although the contribution of RACE from mid-energy neutrons in the range up to 30 or 40 MeV will be small, RACE will provide a more realistic source term than the DT sources of MUSE and TRADE, including a wide energy range, asymmetry, and more volumetric, which will make extrapolation much more reliable with a much higher level of confidence. In addition, the source intensity of the RACE project, $\sim 10^{12}$ n/s, is intermediate between that of MUSE and TRADE, and thermal feedback effects, which were absent in MUSE, can be investigated in RACE in advance of the higher intensity TRADE Project. These RACE measurements will provide valuable data for validation of theoretical work on subcritical system kinetics and dynamics that are not possible within the MUSE and TRADE projects. Figure 1 and Tables 1 and 2 list comparisons of these different concepts for sources for ADSS studies.

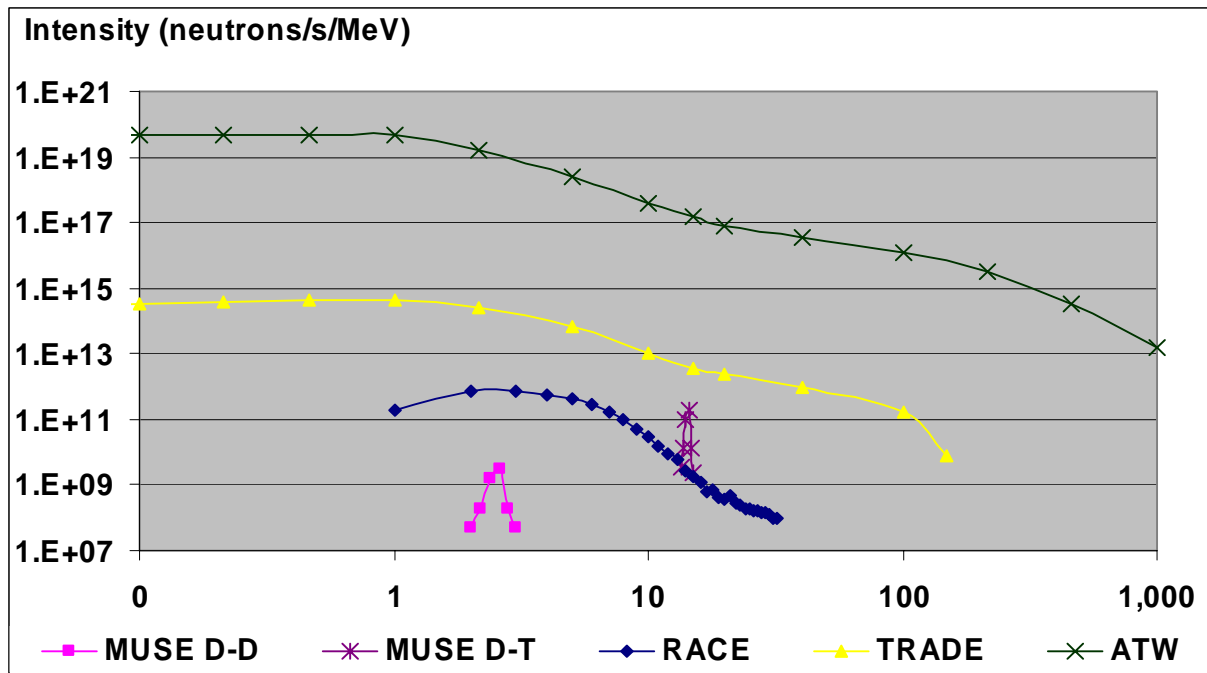


Figure 1. Source Spectra for Several ADSS Concepts. These spectra represent the computed total neutron intensity for several different ADSS concepts; thus they are not normalized. The MUSE DD source was on the order of 10^8 n/s, the MUSE DT source was $\sim 10^{10}$ n/s, the RACE photo-neutron source is 2×10^{12} n/s with a 1 kW beam of 40 MeV electrons, the TRADE proton cyclotron source (140-MeV protons) will be $\sim 10^{15}$ n/s, and an 840 MWth ATW (1000-MeV protons) would require $\sim 10^{19}$ n/s from a lead or lead-bismuth target.

Table I. Comparison of source characteristics. Based on computational results with the MCNPX code, the RACE spectrum appears to better approximate that of a large ATW target than does TRADE DT.

Project	Flux	Energy (MeV)	Characteristics	Percent in the range (MeV)				
				0-5	5-10	10-15	15-20	>20
MUSE-DD	10^8	2.45	Mono-energetic, anisotropic, point, pulsed	100	0	0	0	0
MUSE-DT	10^{10}	14.1 (some 2.45)	Mono-energetic, anisotropic, point, pulsed	0	0	99	1	0
TRADE-DD	$<10^8$	2.45	Mono-energetic, anisotropic, point, pulsed	100	0	0		0
TRADE-DT	$<10^{10}$	14.1 (some 2.45)	Mono-energetic, anisotropic, point, pulsed	0	0	99	1	0
RACE	10^{12}	Up to 40	Fission spectrum with small tail, anisotropic, asymmetric, volumetric, pulsed	97	2.0	0.23	0.045	0.004
TRADE-proton spallation	10^{15}	Up to 140	Spallation spectrum, anisotropic, asymmetric, volumetric, continuous	85.2	6.4	2.4	1.6	4.4
High-energy proton spallation	10^{19}	Up to 1000	Spallation spectrum, anisotropic, asymmetric, volumetric, continuous	83.4	6.3	2.3	1.3	6.5

Table II. Comparison of ADSS Experiments.

Project	Source	Source Strength (n/s)	Energy (MeV)	Source Characteristics	Reactor Type	Reactor Power	Cost (\$M)
MUSE	DD and DT Accelerator	10^8	2.45 and/or 14.1	Mono-energetic, anisotropic, point, pulsed	Fast	Zero	~60
TRADE	DT Accelerator and Proton Cyclotron	10^{15}	Up to 140	Mono-energetic, anisotropic, point, pulsed	TRIGA	200 kWth	~90
RACE	Electron Linac (photo-neutron)	10^{12}	Up to 40	Fission spectrum with small tail, anisotropic, asymmetric, volumetric, pulsed	ISU ADS & two Texas TRIGAs	1 MWth (pulse to 1 GWth)	2.6

Most importantly, RACE will uniquely provide the ability to examine three-dimensional effects of source location. Because of the linear, modular nature and compact size and design of the electron-linac-driven neutron source, we can place the neutron-generating target in the center of a subcritical

assembly, or at any available position on the inside or outside of the core. This repositioning of the target in and around the subcritical assembly will allow for measurement of the spatial variation of source importance (neutron multiplication as a function of source characteristics) and adjoint flux. In contrast, the TRADE design will restrict the target location to the center of the TRADE TRIGA. By doing this, we can measure the spatial dependence of the neutron multiplication on target location. This will allow us to “map” source importance and adjoint flux, which has been determined to be a critical element in correcting space-time kinetics for ADSS. These measurements will provide valuable data for validation of theoretical work on subcritical system kinetics and dynamics, and will subsequently provide for the development of codes used in the design and operation of future full-scale ADSS.

AFCI University Transmutation Studies

In addition to serving as a unique coupling experiment along with the recent MUSE experiments and the future TRADE experiments, the RACE Project will demonstrate in the U.S. the ability to design, compute, and conduct ADSS experiments, and to predict and measure coupling efficiency, reactivity, and multiplication. The project will also be able to demonstrate the ability to predict and analyze subcritical source-driven transients while also mapping the importance of a driving neutron source in various regions of a variety of subcritical assemblies. The project will also provide data for the development of both steady state and transient benchmarks for accelerator-driven subcritical systems of use by the nuclear community and to test new computational codes and methods. Educationally the project will help attract students to nuclear science and technology, provide them a diverse nuclear science education, and train them in operation and modeling of accelerator-driven systems as well as in measuring reactivity of subcritical systems.

EXPERIMENTS PROGRAM OVERVIEW

The RACE Project is being conducted in three phases. The first phase began at ISU, UT, and Texas A&M with conceptual studies and initiation of subcritical experiments at the ISU-IAC. Phase II will involve moving the IAC electron-linac to UT-Austin, coupling it to a TRIGA reactor, and conducting ADSS experiments. In Phase III, the linac will be moved to Texas A&M and coupled to one or more TRIGA cores there. Experiments in Phase III will build on experience and capabilities developed during Phases I and II.

Phase I: ISU RACE

The RACE tests at ISU require the physical movement of fuel elements in the ISU subcritical assembly from the Nuclear Engineering Department to the Idaho Accelerator Center. The neutron source for the first experiments was created by coupling two ~20-MeV electron Linacs to produce a total electron energy of more than 30 MeV and a total beam power of less than 1 kW. Neutrons are produced in a water-cooled tungsten (75% tungsten and 25% copper alloy, W-Cu) target aligned horizontally in line with the electron beam. The system produces about 2×10^{-3} neutrons per electron, or 2×10^{10} n/s per μA of electron current at 30 MeV. With a projected time-averaged beam current of 100 μA and electron energy of 30 MeV, we expect to produce a driving source in excess of 10^{12} n/s. The subcritical assembly that will surround this neutron-generating target will consist of 150 flat plates of 20%-enriched uranium-aluminum fuel alloy clad in aluminum inside a water tank (a detailed description is in an accompanying paper⁴). The plates will be arranged in three horizontal rows of two trays with the target in the center. The core is reflected with graphite blocks on all sides. This configuration will result in a maximum estimated multiplication (k_{eff}) of 0.94. Reactivity and multiplication studies with the Monte Carlo radiation transport code MCNPX indicate that the ISU

subcritical assembly should produce a subcritical multiplication of about 10 with k_{eff} of 0.94. Coupling, leakage, and absorption losses between the target and fuel will reduce the expected multiplication from the theoretical value of 14 ($1/(1-k_{\text{eff}})$). We have conducted several far-subcritical developmental experiments with $k_{\text{eff}} \sim 0.20$ and multiplication just greater than 1. These tests have been conducted to develop operating procedures as well as experience with static and dynamic flux measurements (preliminary results are described in ref. 4). We are currently completing the design of the full-scale experiment, modeling the coupled system to predict its performance (fission rates, radiation fields, detector responses, fission-product production, activation of the target and other materials, etc.), and developing dynamic instrumentation, including fission chambers and self-powered neutron detectors.

Phase II: UT-Austin RACE

Several options exist for conducting RACE at UT-Austin. ISU will first ship one of the IAC accelerators to Texas in winter 2004. The IAC accelerator may be assembled at the floor level of the UT Nuclear Engineering Teaching Laboratory TRIGA (the NRC designation is NETL TRIGA), and the target may be located in a neutron beam port that passes completely through the pool of the reactor. The NETL TRIGA operates at 1 MW_{th}, with a capability to produce pulses up to 1,000 MW_{th} (1.0 GW_{th}). The target would be immediately adjacent to one side of the core, which is a high-leakage arrangement. An alternative configuration for UT RACE would be to place the accelerator on the platform at the top of the reactor pool and provide a long vertical vacuum tube with the neutron-generating target placed in the center of the core. This would likely necessitate the addition of a focusing magnet below the surface of the water.

The first UT experiments would be conducted with the reactor completely shut down, which will have a criticality of about 0.92. Follow-on experiments will be conducted with k_{eff} between 0.92 and 0.95 to possibly 0.97, 0.98, or even 1.0 (critical). Faculty have determined after consulting with NRC contacts that a modification of their NRC license is not required for conducting these experiments. This is simply a permitted external neutron source and a re-arrangement of existing fuel elements. However, the ISU accelerator will need to be licensed as a new source of ionizing radiation in Texas (accelerators are licensed by states whereas reactors are licensed by the Federal government). The UT RACE experiments should be completed by the summer of 2005. Evaluation of results will continue through 2006.

Phase III: Texas A&M RACE

At Texas A&M, we may use any one or a series of several different experimental configurations. One concept being studied is to use the TAMU Nuclear Science Center TRIGA (the NRC designation is NSC TRIGA). The NSC TRIGA is fueled with 70%-enriched "FLIP" fuel, and has a capability to be pulsed to 1000 MW_{th} (1 GW_{th}). Options for acquiring an accelerator and locating it and the target will be determined in future studies. One option would be to again place the target in a neutron beam port that passes completely through the pool of the reactor, centered in a graphite column adjacent to one face of the core. Experiments will be conducted with k_{eff} between 0.95 and 0.99, with the possibility even of driving near-critical, high-power transients. Another series of experiments would include the assembly of an existing used-fuel, 20%-enriched core around the accelerator target in a different part of the NSC pool. We will then conduct experiments with k_{eff} between 0.95 and 0.99. A third series of experiments may be conducted by assembling this used-fuel core in an adjacent facility with several tons of liquid lead-bismuth eutectic instead of water as the reflector, thus producing an epithermal spectrum.

ISU RACE Accomplishments to Date

The RACE Project was initiated in July of 2003, a kick-off workshop was held in August of 2003, and planning for conducting experiments at ISU began that fall. Another smaller workshop was held at ISU in January 2004, and a project-wide workshop was held in August 2004. The following has been done to date:

- The accelerator has been assembled and tested.
- A W-Cu target was purchased and machined, braised to a Conflat® flange, and connected to the accelerator via a vacuum beam port.
- Thermocouples were connected to the target so that we could monitor its temperature during operation to insure safety. Thermal testing was completed; the maximum temperature of the outer surface of the target in water was 52 C with 810 W of beam power at 25 MeV.
- Two aluminum tanks were fabricated: a small tank for target thermal testing and a large tank to hold the target, fuel, moderator, and reflector.
- Six modular aluminum fuel trays were fabricated.
- The full-scale RACE tank assembly has been constructed with the accelerator, target, tank, graphite moderator, and fuel trays. 10-plate experiments have been conducted in this configuration.
- A gun safe was purchased to store the 150 enriched-U fuel elements in the accelerator bay of the IAC.
- Reactor physics studies have been completed at ISU, U of Michigan, and Texas A&M.
- The ISU Reactor Safety Committee reviewed and approved an application to modify the ISU NRC license. The application was submitted to the NRC on Feb. 23, 2004. The application was docketed in August and NRC issues have been addressed.
- Nuclear instrumentation is being purchased and assembled.

This completed work is included in the previous schedule.

Work has also been ongoing at U of Michigan and Texas A&M. Michigan has begun using the same codes that are used for MUSE and TRADE to evaluate the design of the experiments at ISU. Texas has begun modeling their TRIGA reactors using MCNP.

SUMMARY

The RACE Project, which is a university-based transmutation research project of the U.S. Advanced Fuel Cycle Initiative (AFCI), is a sequence of increasingly complex accelerator-driven subcritical systems (ADSS) experiments. These experiments will couple a linear electron accelerator (linac) to a subcritical assembly at the Idaho State University's Idaho Accelerator Center (ISU-IAC) and to TRIGA reactors at the University of Texas (UT) at Austin and at the Texas A&M University. In these experiments, the electron linac will be used to induce bremsstrahlung photoneutron reactions in heavy-metal targets producing a neutron source to initiate fission reactions in the subcritical systems. These systems will include a compact, zero-power transportable subassembly at ISU, a 1-MW TRIGA reactor at UT-Austin, and one or more 1-MW TRIGA cores at Texas A&M. At the ISU-IAC, the modular assembly allows for modifications of core configuration as well as target location. At UT-Austin, thermal feedback effects will be added because of fission heating effects close to the target. Finally, at Texas A&M experiments will include core configuration modifications, multiple target locations, and thermal feedback for the ultimate test.

In addition to serving as a series of unique coupling experiments, along with the recent MUSE experiments and the future TRADE experiments, the RACE Project will demonstrate in the U.S. the

ability to design, compute, and conduct ADSS experiments, and to predict and measure coupling efficiency, reactivity, and multiplication. The project will also be able to demonstrate the ability to predict and analyze subcritical source-driven transients while also mapping the importance of a driving neutron source in various regions of a variety of subcritical assemblies. In addition, it will provide data for the development of both steady state and transient benchmarks for accelerator-driven subcritical systems of use by the nuclear community and to test new computational codes and methods. Educationally the project will help attract students to nuclear science and technology, provide them a diverse nuclear science education, and train them in operation and modeling of accelerator-driven systems as well as in measuring reactivity of subcritical systems.

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