DRAFT Program Plan

AFCI Reactor-Accelerator Coupling Experiments (RACE) Project

Idaho State University
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INTRODUCTION

The RACE Project is a university 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 the ultimate experiment at 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
- 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.

Unique features of the AFCI RACE Project:

- Only U.S. experimental subcritical accelerator-driven assembly research.
- Compact, transportable electron linear accelerator.
- Wide variety of accelerator/reactor configurations:
  - up to five target/core/reflector configurations,
  - four different fuels (20-70% enrichment, rods and plates, U-Al and U-ZrH),
  - a range of fuel exposure histories, from fresh cores to spent cores, and
  - three different accelerator beam targets.
- Ability examine three-dimensional effects of source location, to map source importance, and to study ADS with multiple accelerators and/or targets.
- Four U.S. universities lead this effort for the nation: ISU, Texas A&M, UT-Austin, and UNLV

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 can be validated and benchmarked for use in designing safe and reliable ADS systems for transmutation purposes. To validate these computer codes and demonstrate that they are applicable to a variety of reactor configurations, a wide array of coupling experiments must be performed. A major contribution to this field was recently completed with the European program MUSE (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 (TRIGA Accelerator Driven Experiment) at the ENEA (Italian Agency for New Technologies, Energy and the Environment) in Cassacia, Italy.[i] A variety of point neutron sources were used for the MUSE experiments: Californium-252 (~10^9 n/s, near-fission spectrum), DD (~10^8 n/s, 2.45-MeV), and DT (~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. 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 ~10^{15} n/s.

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. 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, and TRADE will begin with a DT source followed by a proton spallation continuum that will extend to 140 MeV. In addition, the TRADE proton source will have other properties of spallation sources: it will be asymetric, 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 volumetric and anisotropic source that is more representative of high-energy spallation systems will provide valuable validation and benchmarking information.This validation makes extrapolation in calculations much more reliable. Figure 1 illustrates the recent and projected evolution of ADSS experiments including MUSE, RACE, and TRADE. 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.

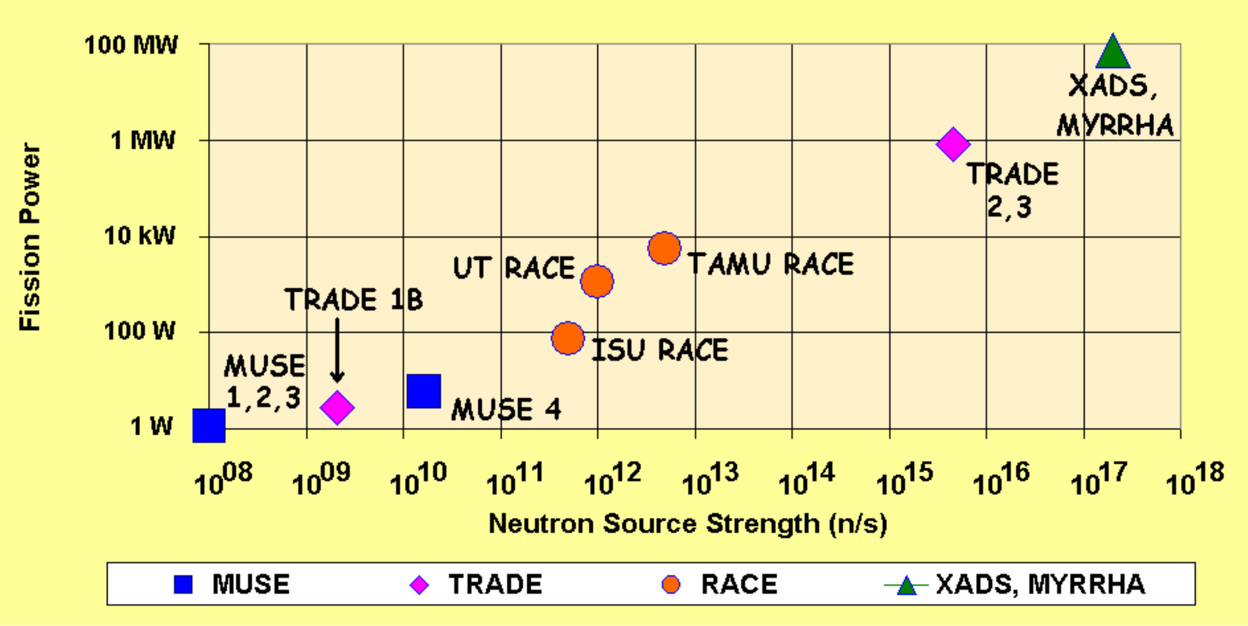

Figure 1. Evolution of ADSS Experiments. MUSE 4 experiments concluded and RACE and TRADE 1 experiments began in 2004. RACE UT will begin in 2005 and RACE Texas A&M will be conducted in 2006. TRADE 2 and 3 will begin in 2007 or later.

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 MUSE and TRADE DT sources. The RACE source will be characterized by a wide range energies, asymetry, and a larger source volume, which will make future extrapolations much more reliable with a much higher level of confidence. In addition, the source intensity of the RACE project, ~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 2 and Tables 1 and 2 list comparisons of these different concepts for sources for ADSS studies.

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.

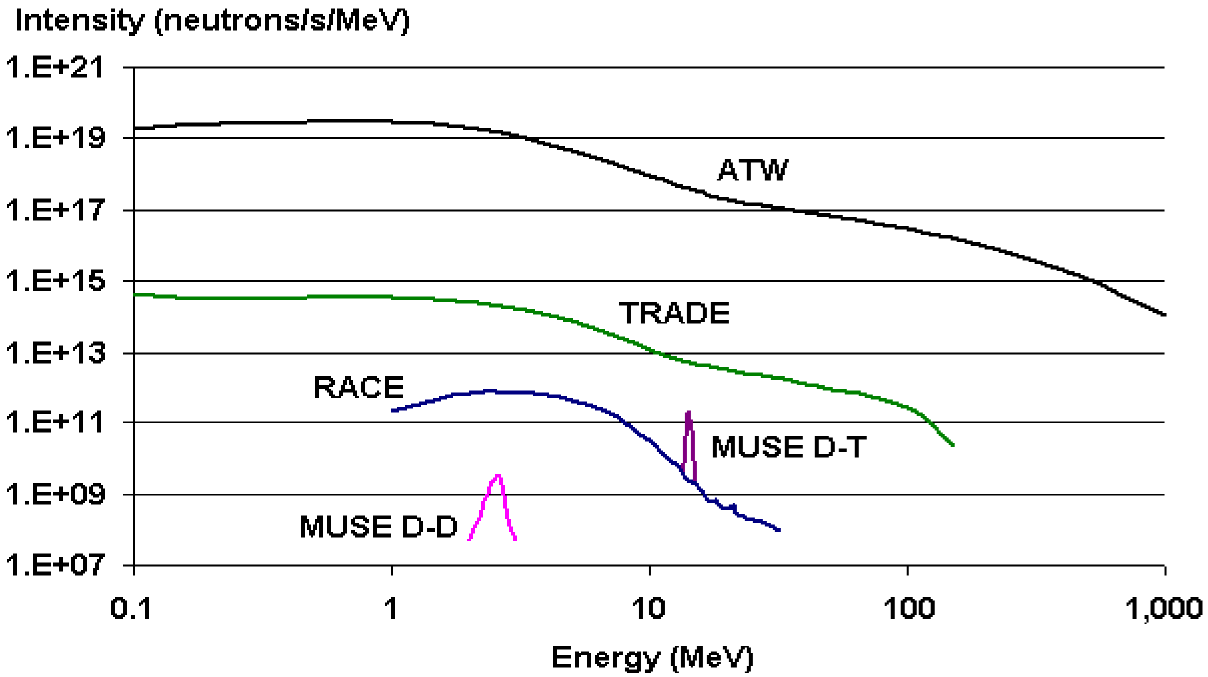

Figure 2. Source Spectra for Several ADSS Concepts. These spectra represent the total neutron intensity for several different ADSS concepts. They were calculated using the MCNPX code and very simple target models, and represent the leakage spectrum from neutron-producing targets. They are not normalized so they represent both energy and intensity characteristics of various sources. The MUSE DD source was on the order of 10^8 n/s, the MUSE DT source was ~10^{10} n/s, the RACE photo-neutron source is 2 x 10^{12} n/s with a 1 kW beam of 40 MeV electrons, the TRADE proton cyclotron source (140-MeV protons) will be ~10^{15} n/s, and an 840 MWth ATW (1000-MeV protons) would require ~10^{19} n/s from a lead or lead-bismuth target.

Table I. Comparison of Neutron 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)	Neutron Source Characteristics	Percent in the range (MeV)				
				0-5	5-10	10-15	15-20	>20
MUSE-DD	10^8	2.45	Mono-energetic, anistotropic, point, pulsed	100	0	0	0	0
MUSE-DT	10^{10}	14.1 (some 2.45)	Mono-energetic, anistotropic, point, pulsed	0	0	99	1	0
TRADE-DD	$<10^8$	2.45	Mono-energetic, anistotropic, point, pulsed	100	0	0		0
TRADE-DT	$<10^{10}$	14.1 (some 2.45)	Mono-energetic, anistotropic, point, pulsed	0	0	99	1	0
RACE	10^{12}	Up to 40	Fission spectrum with small tail, anistotropic, asymetric, volumetric, pulsed	97	2.0	0.23	0.045	0.004
TRADE-proton spallation	10^{15}	Up to 140	Spallation spectrum, anistotropic, asymetric, volumetric, continuous	85.2	6.4	2.4	1.6	4.4
High-energy proton spallation	10^{19}	Up to 1000	Spallation spectrum, anistotropic, asymetric, 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)	Neutron Source Characteristics	Reactor Type	Reactor Power	Cost ($M)
MUSE	DD and DT Accelerator	10^8	2.45 and/or 14.1	Mono-energetic, anistotropic, point, pulsed	Fast	Zero	~15
TRADE	Proton Cyclotron	10^{15}	Up to 140	Mono-energetic, anistotropic, point, pulsed	TRIGA	200 kWth	~35
RACE	Electron Linac (photo-neutron)	10^{12}	Up to 40	Fission spectrum with small tail, anistotropic, asymetric, volumetric, pulsed	ISU ADS & two Texas TRIGAs	1 MWth (pulse to 1 GWth)	2.6

AFCI University Transmutation Studies

In addition to serving as a unique coupling experiment along with the recent MUSE experiments and the future TRADE experiments, in the RACE Project will students and faculty in the U.S. will conduct the research to demonstrate the ability to design, compute, and conduct ADSS experiments, and to predict and measure coupling efficiency, reactivity, and multiplication. Academic researchers will also 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. These faculty and students will also provide data for the development of both steady state and transient benchmarks for accelerator-driven subcritical systems of use by the larger nuclear community and to test new computational codes and methods. These research and education opportunities of the RACE 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.

PROGRAM OVERVIEW

The overall goal of this three phase RACE project is to demonstrate a U.S. capability to design, construct, and conduct unique ADSS coupling experiments. These transmutation experiments would enable us to predict and measure coupling efficiency, reactivity, and multiplication. Most importantly the project will 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 assembly configurations. The project 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, providing diverse education and training in nuclear science, in the operation and modeling of accelerator-driven systems, as well as diagnostic measurements of subcritical systems.

Phase I: ISU RACE

The RACE tests at ISU require the construction of an accelerator and a subcritical assembly, and the physical movement of fuel elements from the sub-critical assembly in the ISU Nuclear Engineering laboratory to the White Room of 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 will yield about $2\text{x}10^{-3}$ neutrons per electron, or $2\text{x}10^{10}$ 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 sub-critical 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 below). The plates will be arranged in three horizontal trays surrounding the target and beam tube. The core will be reflected with graphite blocks on all sides (possibly except that facing the accelerator). This geometry 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 sub-critical assembly should produce a sub-critical 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_{eff}). We have conducted several far-subcritical developmental experiments with k_{eff} ~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. We are currently completing the design of the full-scale experiment and structures, 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. Ongoing research is described in Appendix A.

Phase II: UT-Austin RACE

Several options exist for conducting RACE at UT-Austin. The least expensive is to ship one of the IAC accelerators to Texas and then assemble it at the floor level of the UT Nuclear Engineering Teaching Laboratory TRIGA (the NRC designation is NETL TRIGA). The target could 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 1,500 MW_{th} (1.5 GW_{th}). The target would be immediately adjacent to one side of the core, centered on that side, which is a high-leakage arrangement. An alternative configuration for this concept 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. A second option would be to purchase a used accelerator for UT-Austin at a cost of the order of $200 k. This could be installed as previously mentioned, or it could be located at the top of the pool as previously discussed.

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).

Phase III: Texas A&M RACE

At Texas A&M, we may conduct any one or a series of three different experiments. One option 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 (the Texas Transmutation System, or TTS). 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.

Milestones and Deliverables

Table III-A. Milestones

ISU RACE	Full Core Experiment	Spring 05
UT-Austin RACE	Coupling Experiments	Summer-fall 05
Texas A&M RACE	Coupling Experiments	Summer-fall 06

Table III-B. Deliverables

ISU RACE	Report on Full Core Experiment	June 05
UT-Austin RACE	Report on Coupling Experiments	June 06
Texas A&M RACE	Report on Coupling Experiments	June 07

RESEARCH AND DEVELOPMENT

Reactor Physics Research

Many conceptual arrangements for the RACE experiments have been examined using the MCNPX[ii] Monte Carlo radiation transport code and data libraries. These studies have been performed to predict the performance of the system and optimum arrangements of materials for both reactivity and source 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

Instrumentation and Monitoring

Two types of measurements/results are needed for comparison of ADSS performance to predictions with reactor kinetics code systems. First, integral measurements of fission rates, source multiplication, power levels, and others must be possible. In addition, the sub-criticality of systems is typically measured by a variety of methods that all rely on response to pulsed sources or criticality withdrawal or injection (control-rod drop or ejection). A variety of instrumentation and monitoring equipment will be used to measure the time-dependent and integral production of neutrons and gamma rays from the target, to measure time-dependent neutron flux in and around the core, and to measure the leakage of neutrons and gamma rays out of the experiment and into the experiment bay. In addition, environmental monitoring equipment will be installed in the experiment bay to monitor for fission product leakage from the fuel plates. Instrumentation will include BF_3 counters, ^{3}He tubes, fission chambers, and alpha and beta monitors. Some of this detection equipment has been well qualified through extensive use in the ISU Health Physics program, the Nuclear Engineering program, and/or at the Idaho Accelerator Center. Other equipment, such as fission chambers for measuring pulsed neutron flux, will be purchased before commencing full-core experiments. At each of the Texas universities instrumentation is available for conducting tests, monitoring performance, and measuring results of coupling experiments.

Fuels and Materials

The RACE Project provides the opportunity to develop and test codes for a wide variety of fuels and other materials. Each of the existing reactors at the three universities contains a different fuel composition. At ISU the fuel is 20%-enriched U-Al alloy clad with aluminum in the form of plates. At UT-Austin the fuel is 20%-enriched U-ZrH alloy clad in steel. The new fuel in the TRIGA reactor at Texas A&M is 70%-enriched "FLIP" fuel, which is also U-ZrH alloy clad in steel. In addition, Texas has a used core of 20%-enriched used fuel stored in the swimming pool adjacent to the TRIGA reactor. This core can be reassembled in any geometry around an accelerator target, which provides for complete flexibility in experiment design.

RACE Computational Support

Several AFCI universities may participate in the RACE Project by providing computational support. Faculty and students at the University of Michigan and the North Carolina State University (NCSU) have conducted various studies in support of international collaborations. Michigan has provided computation support for the MUSE Project at Cadarache and NCSU has supported the MEGAPIE design. A method was developed at Michigan to compute space-time correction factors to reconcile criticality measurements. Before the development and implementation of this methodology, measurements in different parts of the MUSE facility provided widely varying multiplication (k_{eff}) values for the same experiment. NCSU has done extensive studies on the predicted production of displacement and other radiation damage in MEGAPIE designs. 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.

Safety Issues

The RACE Project is designed to address safety issues with larger scale ADSS by providing benchmarking of reactor physics and thermal hydraulics codes for subcritical systems as well as operating experience. In addition, the RACE project will provide information to improve the benefits of international ADSS experiments such as TRADE and SAD. While these issues are not present with the RACE tests because of the design of the subcritical assemblies at ISU and Texas universities, there are safety issues that must be addressed. These issues include radiation safety, accelerator safety, and reactor safety.

The reactor safety issues at ISU have been addressed through a request to the NRC to modify the ISU license for their subcritical facility. Extensive criticality studies have been completed with a wide variety of core geometries using all the ISU fuel plates and optimized reflection and spacing. The studies demonstrate that the assembly cannot have a multiplication greater than $k_{eff} = 0.95$, which means that this facility will be safe against a criticality accident in any configuration. Reactor safety issues at the Texas universities are minor and are addressed in their existing licenses. Because the reactors are designed to be pulsed hard while critical or super critical, and then shut themselves down by thermal feedback without damage to the fuel, they will be safe with a large pulsed neutron source provided by the ISU electron linac.

Accelerator safety issues at ISU have also been addressed in their existing permits and operating procedures and experience, and a radiation safety committee and a reactor safety committee review and approve experiments, operation, etc. However, these accelerator systems are new items at the Texas universities, and they must be approved by Texas licensing authorities.

Finally, radiation safety issues are addressed by existing procedures, health physics staff, and radiation safety offices at each of the universities.

COST AND SCHEDULE

The projected cost and schedule for FY04 includes expenses at ISU, UT-Austin, Texas A&M, U of Michigan, and UNLV. The total budget is estimated to be $820 k for FY04 and $2.6 Million for the project.

Table IV. Schedule

RACE Project Planning	Initiation	Jul. 03
	Workshop	Aug. 03
ISU RACE	Develop concepts	Jul.-Oct 03
	Design	Nov. 03-Mar. 04
	Accelerator/Target testing	Mar.-Apr. 04
	System Fabrication	Dec. 03-Apr. 04
	NRC Application	**Aug. 04**
	System Assembly (10 fuel plates)	Apr.-Jun. 04
	Experiments	May 04+
	Full System Assembly	**Jun. 04**
	Experiments	Sep. 04-Jun. 05
	ADSS Workshops	Annual
UT-Austin RACE	Planning	Jun.-Dec. 04
	Move accelerator to Austin	Spring 05
	Install accelerator & test	Jun. 05
	Coupling Experiments	**Summer 05+**
	Analysis	Fall 05
Texas A&M RACE	Planning	Jan. 06
	Move accelerator to A&M	Summer 06
	Install accelerator	Summer 06
	Experiments	**Fall 06+**
	Analysis	Spring 07

Table V. Budget

Budgets (k$)	FY03	FY04	FY05	FY06	Totals
ISU-IAC (Direction & Administration)	80	150	150	150	530
ISU-IAC (RACE, Test & Analyses)	60	350	250	250	910
UT-Austin (TRIGA RACE, Test & Analyses)	-	90	50	-	140
Texas A&M (TRIGA RACE, Test & Analyses)	44	80	120	120	364
UNLV (Analysis)	-	105	110	115	330
U of Michigan (Space-time sub-criticality corrections)	25	-	80	80	185
LANL (U of Mich Faculty)	30	30	30	30	120
LANL (Tech Adv Group)	2	10	10	10	32
ANL (Tech Adv Group)	5	10	10	10	35
RACE Program total	**246**	**825**	**810**	**765**	**2,646**

RACE Project Participants

Name	*representing*	*role*
Prof. Denis Beller	ISU/UNLV	RACE National Project Director
Prof. John Bennion	ISU Nuclear Engineering	ISU experiments, licensing
Prof. William Charlton	UT-Austin and TxA&M	Texas experiments, licensing
Prof. Frank Harmon	ISU-IAC	IAC Director and AFCI Project Director
Prof. Alan Hunt	ISU-IAC	Accelerators and experiments
Dr. Konstantin Sabourov	ISU-IAC	Instrumentation and experiments
Dr. Jianwei Chen	ISU-IAC	Reactor physics and experiments
Prof. Sean O'Kelly	UT-Austin	Reactor supervisor
Prof. Dan Reece	Texas A&M	Reactor supervisor
6 to 10 Students	ISU, UNLV, UT-Austin, Texas A&M, and Michigan	

RACE Project Technical Advisory Group

Name	*representing*
Dr. Frank Goldner	U.S. DOE Office of Nuclear Energy, Science & Technology
Dr. Tom Ward	TechSource, Inc. (DOE-NE AFCI Consultant)
Dr. George Imel	ANL, AFCI & Director of Experiments for MUSE and TRADE
Dr. Michael Cappiello	LANL, AFCI NTD for Transmutation
Dr. Steven Clement	LANL, critical experiments
Dr. Waclaw Gudowski	Royal Institute of Technology, Sweden
Dr. John Lee	U of Michigan, core physics
Dr. Giuseppi Palmiotti	ANL, reactor analysis
Dr. Massimo Salvatores	FZK and ANL

APPENDIX A: PHASE I--ISU RACE

RACE Core

The core will be constructed of 6 flat aluminum trays each containing 20 to 30 flat plates of aluminum-clad, 20%-enriched uranium-aluminum alloy. The trays will be arranged 3 high by 2 wide (see Figure A-1). The active, fueled zone of each plate is 0.10 cm thick, 7.0 cm wide, and 61 cm long (0.04 in x 2.75 in x 24 in). The plates are clad in Al, giving them overall dimensions of 0.20 cm x 7.6 cm x 66 cm (0.08" x 3.0 in x 26 in). Each plate weighs approximately 330.1 ± 4.1 g (based on actual measurements of 8 randomly selected fuel plates) and includes 50.8 g of U (the plates have not been individually characterized, but the total mass of U and ^{235}U is known to be 7.61 kg and 1.51 kg respectively). The plates will be placed in the trays, separated by aluminum shims (nominally 4 mm thick) and clamped with a long bolt and nut at each end before the tray is inserted into the tank (see Figure A-2). The bottom trays will be lowered into the tank on each side of the beam tube, and then slid together. The middle trays will then be

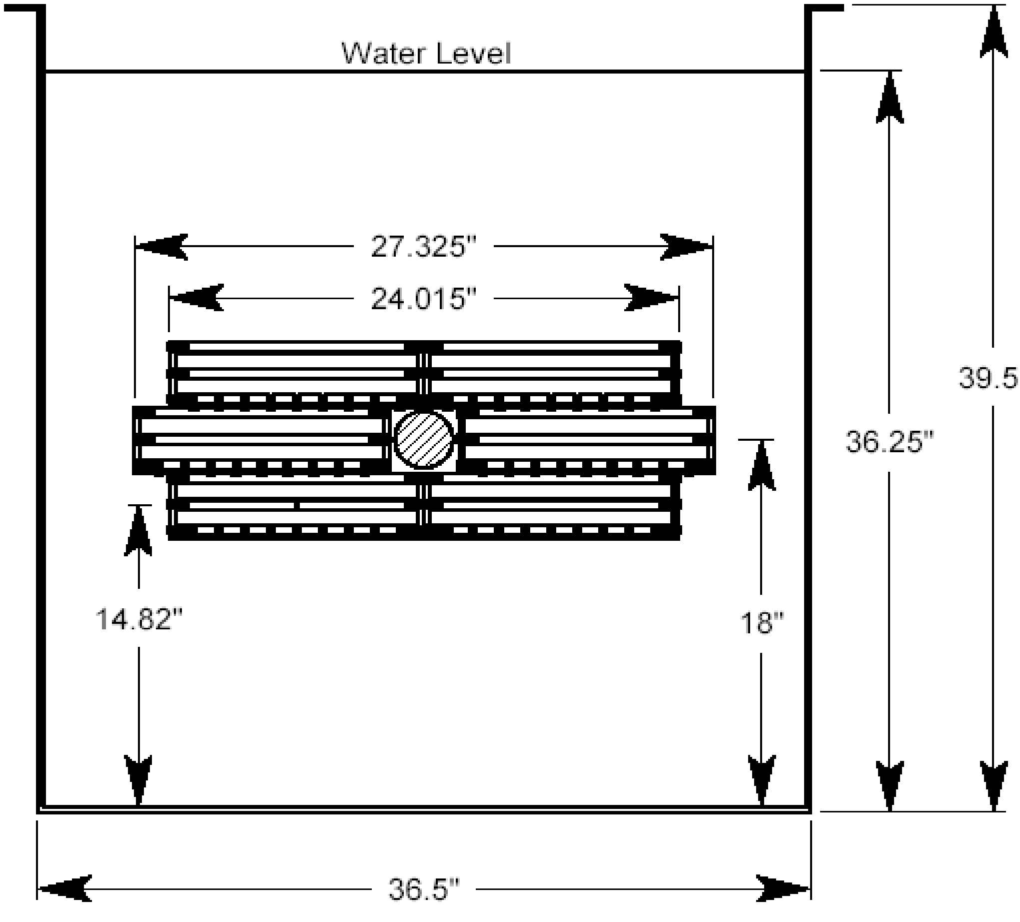

Figure A-1. Front view of a cross section of the ISU RACE including the tank, the beam tube/target, and the stacked fuel trays. The cross section is cut to show the ends of the fuel trays. The graphite reflectors and in-tank support stand are not shown. The dimensions in this drawing will not be the final dimension of the RACE structure.

stacked on top of the bottom trays and butted up against the beam/target tube. The top trays will then be stacked on the middle trays, and the graphite reflectors will be inserted beside, in front and back, and on top of the fueled core. The remaining space inside the tank, between the fuel plates, around the target, etc. will be filled with de-ionized water.

Figure A-2. Top view of an aluminum fuel tray. The dimensions in this drawing are 30.7 cm x 73.9 x 8.1 cm high (12 in x 29.1 in x 3.2 in high). While the length and height of the final trays will remain, the width will depend on the final configuration of the core and optimum placement and spacing for the fuel plates. Widths for the six trays may vary between 10 and 20 cm (4 and 8 inches). A single fuel plate is also illustrated.

Target and Beam Tube

The target was cut from a solid piece of tungsten-copper alloy (75% W and 25% Cu). It is 8.89 cm long by 6.99 cm in diameter (3 ½” x 2 ¾”). It is welded to a 2 ¾ inch “Conflat” flange that is welded to a 2.75-inch diameter steel tube. This tube is mated to the wall of the Al tank with an O-ring flange (see Figure A-3). With a total beam power of about 3 kW, the face of the target, which is inside the vacuum beam port, will heat up to several hundred C. This heat will be conducted throughout the massive target (> 6 kg) and will be dissipated from its much lower temperature surface by natural circulation of water. This arrangement has been tested in air and in water for convective and conductive heat transfer to ensure safe operation in the vicinity of the inner fuel plates. With a core neutron multiplication of 10, fission energy will be just 400 W (0.4 kW), or 0.0026 W/cm^2 from the surfaces of the fuel plates, which will be dissipated easily by natural circulation. Thus, the total power (beam plus fission) of just 3.4 kW that will be deposited in the RACE will be easily dissipated without heating the fuel substantially. The mass of water and graphite in the tank will be about 1.1 tonnes (1100 kg), and the surface area of the tank exposed to ambient air conditions and structure to dissipate beam and fission power will be more than 3.5 m^2, so that the dissipation will be less than 0.1 W/cm^2 (c.f. a 100-Watt light bulb at about 2.5 W/cm^2). The system may warm slightly during experiments, but it will not get hot.

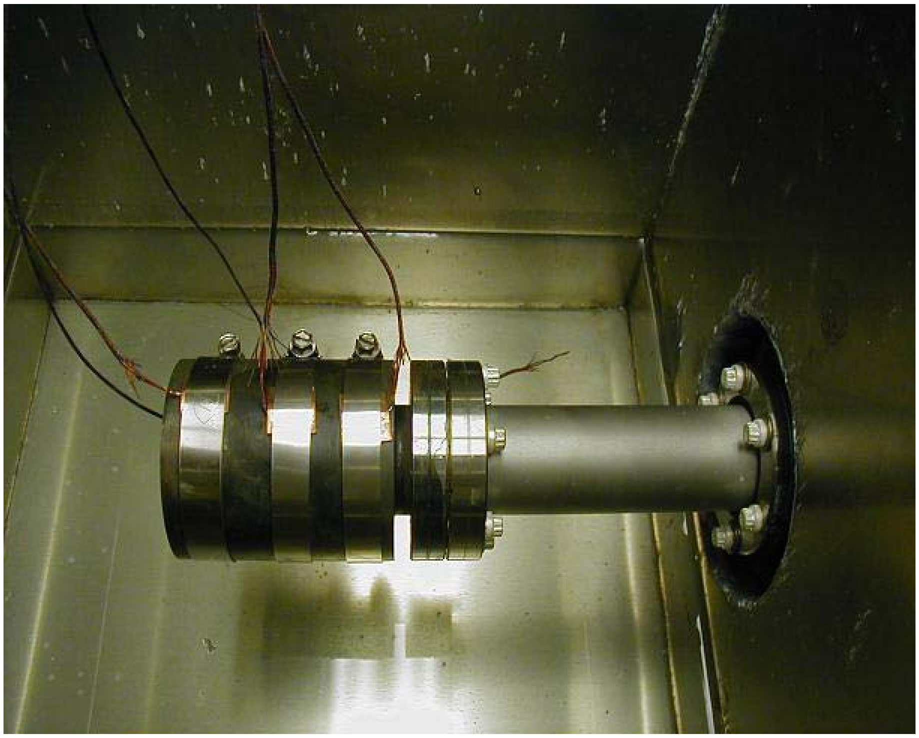

Figure A-3. RACE Target Assembly. The tungsten-copper target, flanges, and beam tube inside a small water-filled test tank. The target in this photograph is fitted with thermocouples. The dimensions of the tank are 12” x 12” x 13” long.

Tank and Stand

The subcritical assembly is contained in a rectangular tank made of ¼-inch aluminum that is approximately 1.0 m long x 0.93 m wide x 1.0 m high (water depth will be 0.93 m). The tank is placed on a sturdy stand to provide structural support as well as a work platform for preparing experiments. The tank will be filled with de-ionized water after the fuel trays, graphite reflectors, and neutron and other detectors are in place.

Accelerator

The principle of the accelerator-driven neutron source is the production of neutrons by photon-neutron reactions in a heavy metal target. The photonuclear reactions are induced by high-energy bremsstrahlung photons produced in the target by a 20 to 40 MeV electron linac (see Figure A-4). This neutron source has great flexibility; pulse widths are variable from nanoseconds to microseconds with pulse rates up to several hundred hertz. The neutron source is physically small, with volume ~ 300 cm^3, thus usable flux is relatively high. Yields of $\sim10^{10}$ n/pulse for microsecond pulses are easily achieved; thus total average rates are up to $\sim10^{11}$-10^{12} n/sec. The neutron spectrum is similar to a fission spectrum with a high-energy tail similar to a proton spallation spectrum adjusting for the neutron energy end point at ~ 30 MeV. Thus, only a few percent of the source neutrons will be in this high-energy tail. There is little slow neutron contamination.

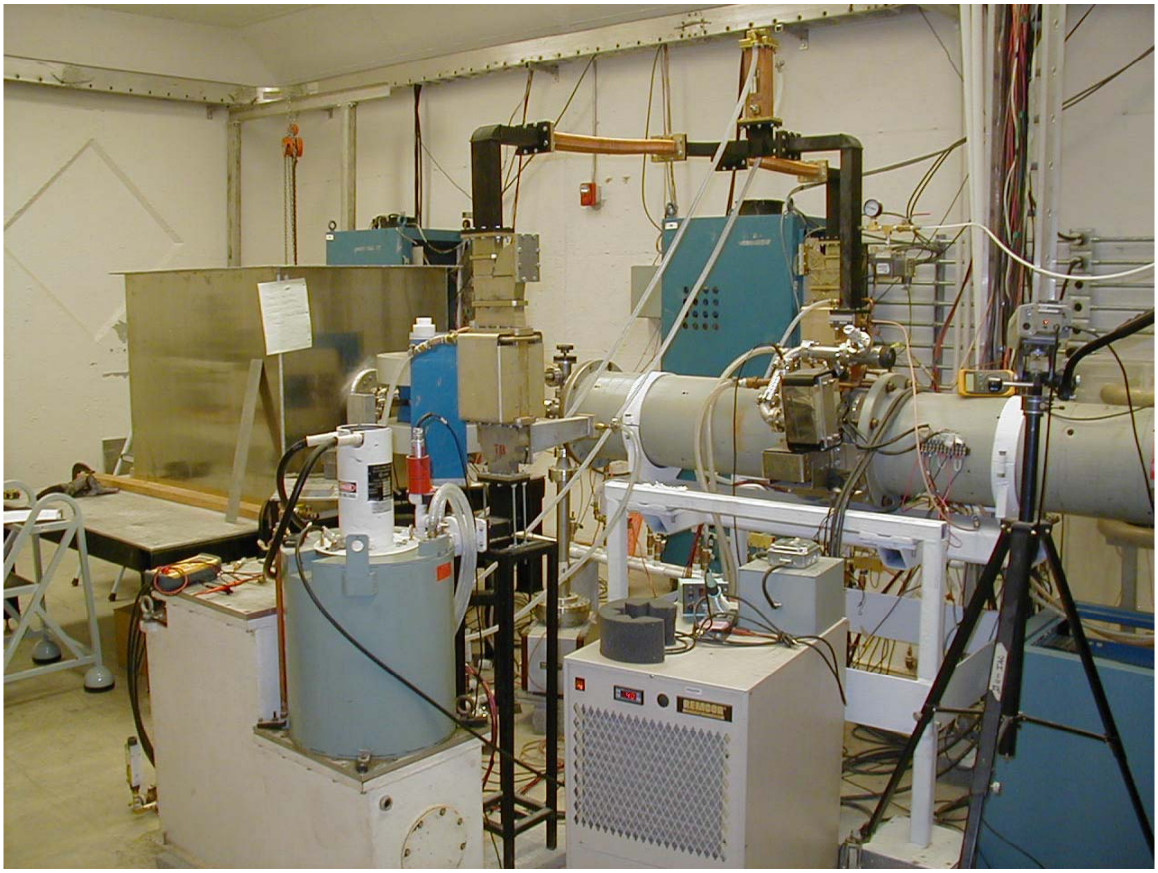

Figure A-4. The 30-MeV Electron Linac and Subcritical Assembly Vessel. This is a 30-MeV Linac connected to an aluminum vessel for containing the ISU RACE subcritical assembly (target, fuel, reflector, and moderator).

Reactor Physics

Many conceptual arrangements for the RACE experiments have been examined using the MCNPX Monte Carlo radiation transport code and data libraries. These studies have been performed to predict the performance of the system and optimum arrangements of materials for both reactivity and source multiplication. Because of the large target and beam tube in the center of the assembly, we have found it difficult to produce an arrangement with a multiplication value, k-effective (k_{eff}), much greater than 0.94 or 0.95. With a fuel-water core surrounded by a thick graphite reflector, k_{eff} of about 0.94 may be achieved. Reducing the thickness of the reflector to practical values, on the order of 20 to 30 cm (8 to 12 in), will produce k_{eff} of 0.93 ± 0.003. Fuel plates may be assembled in the core in single (each plate is separated from each other plate by water, see Figure A-5), double (plates are in pairs), and triple (three plates in contact separated from three more plates by water) arrangements. Parametric studies indicate that the optimum center-to-center spacing for these arrangements is 0.6 cm for single plates and 1.0 cm for double plates. Prior to conducting the full-core, full-power RACE experiments, we will conduct an experiment with just ten fuel plates (k_{eff} of less than 0.30) at low power. This experiment will have a source multiplication just greater than 1, possibly 1.4, and more water in the vicinity of the target. After this experiment has confirmed our ability to conduct the experiments, verified our computations, and demonstrated the performance of measurement, survey, and data acquisition system, we will begin preparing for the full-core RACE. During the loading of the fuel, inverse multiplication measurements experiments will be conducted to verify the transport predictions. In addition, the accelerator will be operated at low energy, low power, and low frequency prior to full-core, high-power testing.

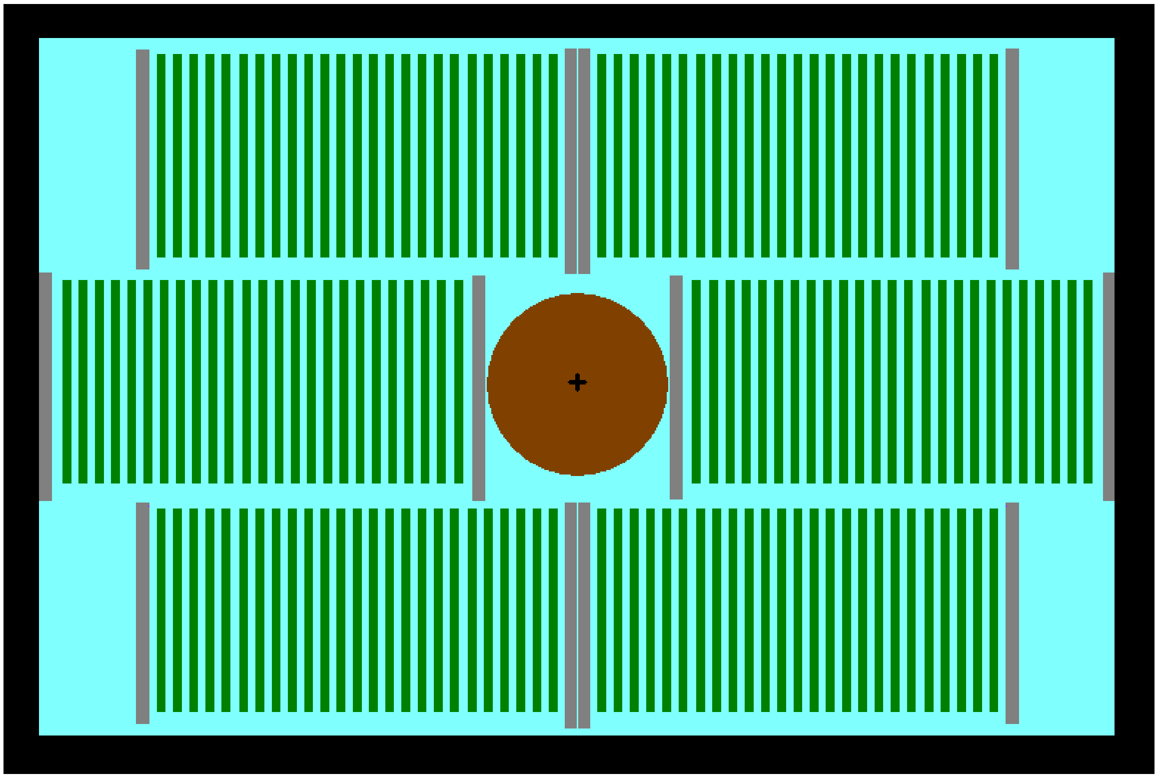

Figure A-5. Cross section of an MCNPX model of ISU RACE fuel trays. This is a drawing generated by MCPLOT, it is a horizontal cross section centered on the axis of the beam tube in the XZ plane at Z=0. Color code: water is blue, target is brown, aluminum is gray, graphite is black, and fuel plates are green. Each tray carries 25 fuel plates.

Instrumentation And Monitoring

A variety of instrumentation and monitoring equipment will be used to measure the production of neutrons and gamma rays from the target, to measure time-dependent neutron flux in and around the core, and to measure the leakage of neutrons and gamma rays out of the experiment and into the experiment bay. In addition, environmental monitoring equipment will be installed in the experiment bay to monitor for fission product leakage from the fuel plates. Instrumentation will include BF_3 counters, ^{3}He tubes, fission chambers, and alpha and beta monitors. Some of this detection equipment has been well qualified through extensive use in the ISU Health Physics program, the Nuclear Engineering program, and/or at the Idaho Accelerator Center. Other equipment, such as fission chambers for measuring pulsed neutron flux, will be purchased before commencing full-core experiments.

Experiment Plan

The tank has been constructed, the trays have been fabricated, and the graphite reflector “building blocks” have been collected. In addition, and accelerator and target were assembled and tests were conducted to confirm passive cooling of the target in the vicinity of the fuel plates. When we have received an NRC license, we will assemble the full-core RACE ADSS and begin static and dynamic experiments. In preparation for this testing, we have begun a series of far-subcritical experiments using just 10 of the 150 fuel plates.

First, the system was assembled without fuel plates and beam/target performance was examined in a water-filled tank: neutron production was measured and target cooling was confirmed. Then, ten fuel plates were moved from the basement of the Engineering building to the IAC and installed in two of the top fuel trays. Reactivity and multiplication were measured using accelerator-produced neutrons, and performance was compared to predictions. The results of these experiments were reported to the ISU Reactor and Radiation Safety Committees and have been reported at an AFCI Semiannual Technical Review Meeting. After discrepancies have been resolved, and after the NRC has granted a license modification to conduct the full-scale tests, the full 150 fuel plates will be moved to the storage location at the IAC.

The final experiments will include an inverse multiplication measurement experiment using first 10 fuel plates followed by the addition of fuel plates as multiplication increases such that we are confident we will not exceed k_{eff} of 0.95 with any addition of fuel. Each of these steps will require removing and replacing at least the top two or three layers of the graphite reflector. After the full core has been assembled and reactivity has been verified, initial accelerator-driven experiments will begin. Because the accelerator can be operated at much less than 30 MeV accelerating potential, much less than the nominal 10 mA peak power, narrower pulse width, and as low as 1 Hz frequency, we can conduct initial experiments with essentially a zero-power beam. We will then gradually increase these parameters to verify the performance of the coupled system in terms of target and fuel cooling, radiation fields, neutron production, and activation. Once we have established complete operating parameters and verified that we can predict safe performance at full power, we will be prepared to begin conducting the full-power experiments. Follow-on experiments may include moving fuel trays away from the optimum positions, moving the target away from the center of the core, reducing fuel below 150 plates, moving detectors, and removing or adding reflector elements.

ISU RACE Accomplishments To Date (as of fall 2004):

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.

APPENDIX B. PHASE II: UT-AUSTIN RACE

Feasibility studies using coupled electron-photon-neutron Monte Carlo transport calculations have been conducted at Texas A&M University to assess the planned RACE experiments at the University of Texas. These studies have been ongoing since January 2004. The principal aim of these studies has been to assess the heat production in the core (for temperature feedback determination) due to the electron-driven neutron source, instrumentation estimations to establish needed neutron measurement instruments, and dose calculations to assess any needed shielding. The heat production calculations for the UT NETL reactor have been completed and the instrumentation and dose calculations are in the process of completion.

A model for the tungsten-copper target in use at ISU was constructed and used to assess the optimal target dimensions for neutron production from the target. This model consisted of the target only surrounded on all sides by a vacuum. Figures B-1 and B-2 show the exiting neutron current from the target as a function of target length and radius. As can be seen, neutron target lengths above 7 cm do not appreciably change the exiting neutron current from the target. The peak neutron current appears to be produced at a target radius of 3.20 cm. It was discovered in the source of these investigations that this optimal target radius however does not produce the optimal heat production in the reactor configuration. A slightly larger target radius is in fact optimal.

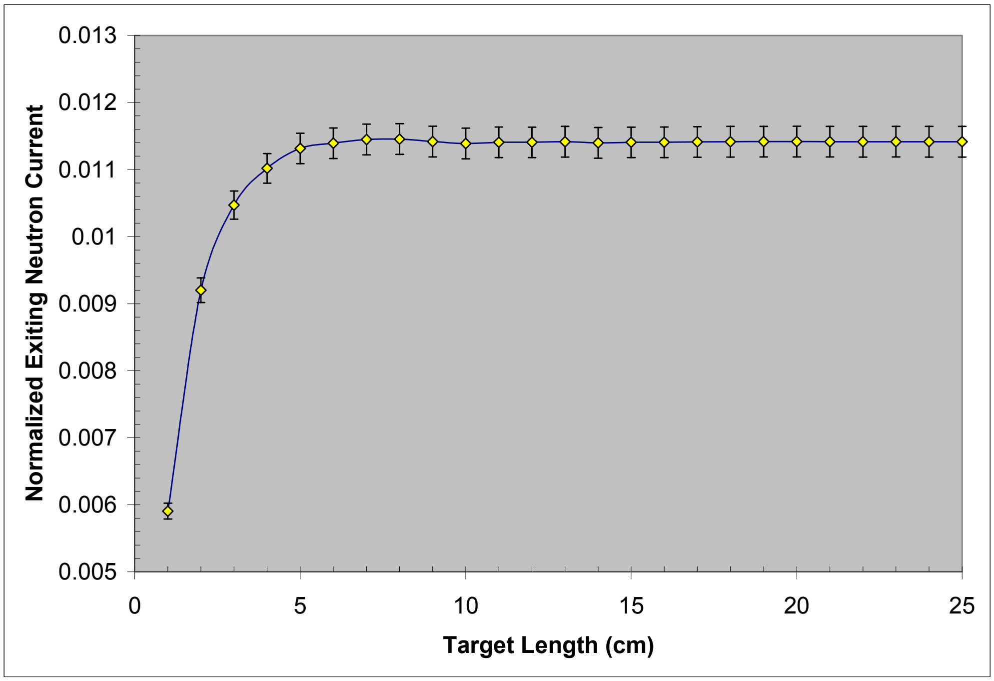

Figure B-1. Normalized Neutron Generation versus Target Length. Neutron current exiting from a W-Cu target with a 40-MeV incident electron beam (error bars are 1σ uncertainties).

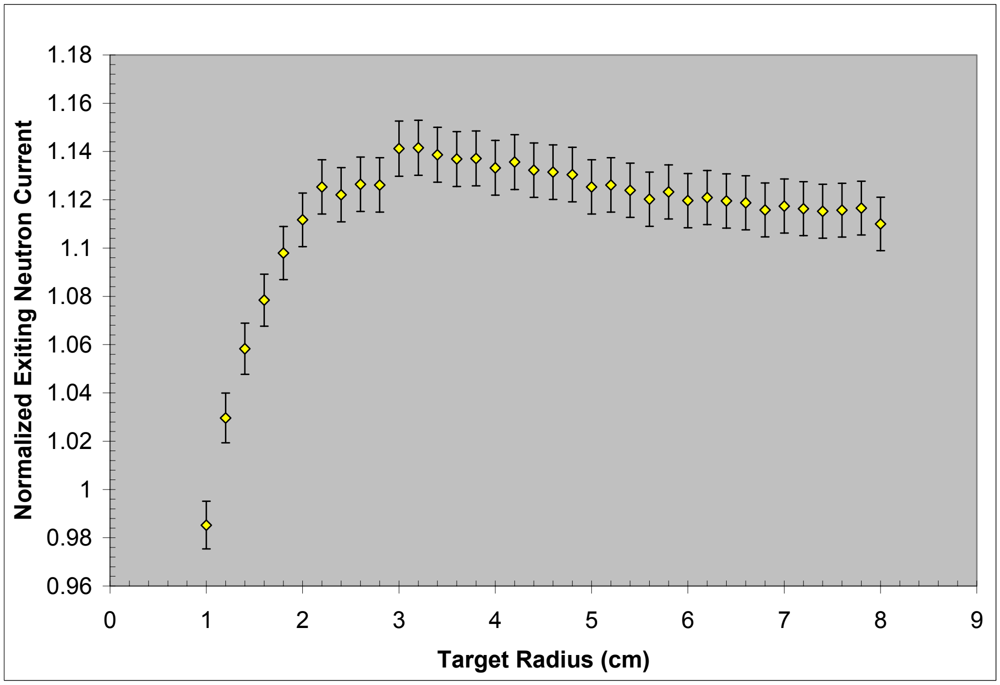

Figure B-2. Normalized Neutron Generation versus Target Radius. Neutron current exiting from a W-Cu target with a 40-MeV incident electron beam versus target radius (error bars are 1σ uncertainties).

Figure B-3 shows a photograph of the UT NETL core as well as a cross sectional schematic of the core layout. This facility consists of a 1-MW TRIGA Mark 2 reactor with five external beam ports. RACE experiments are being planned which would consist of the accelerator-driven neutron source in either one of the neutron beam ports or in a central region of the core. Feasibility studies have been conducted to simulate the experiments in both the Beam Port #5 (BP#5) position and in the central region of the core. The UT NETL core consists of low-enriched uranium (LEU) fuel (19.9 w/o ^{235}U).

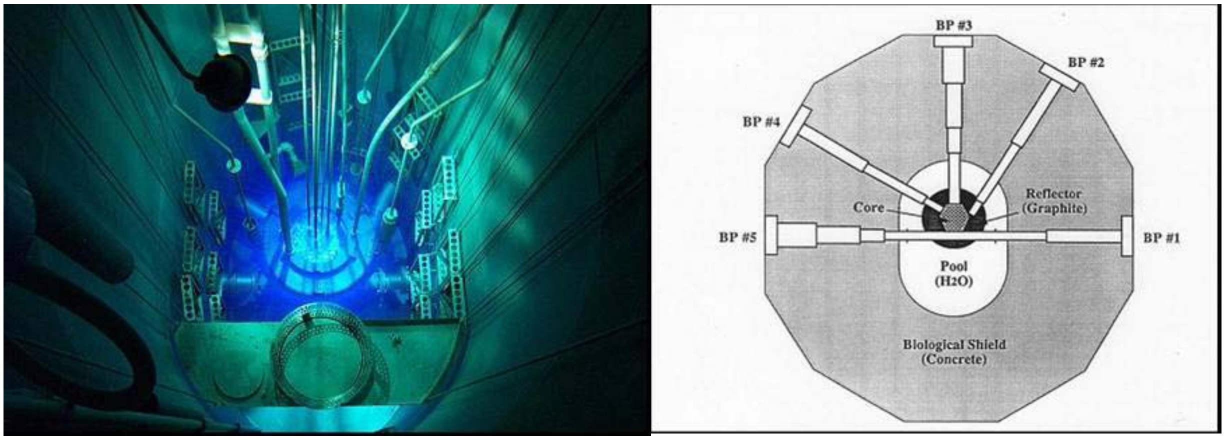

Figure B-3. UT NETL TRIGA Under Power with Schematic. This picture shows the UT NETL TRIGA reactor under power at 1-MW. The reactor fuel, which is surrounded by an aluminum-clad graphite reflector, is visible in the photograph. Also, the five beam ports protruding from the reflector are visible.

MCNP models were created for the UT NETL core and included an accelerator-driven source in the BP#5 position and in the center of the reactor core. Figure B-4 shows a plot of the MCNP geometry for the UT NETL core with the accelerator-driven target in the BP#5 position. This position places the neutron source as close to the reactor system as possible yet maintains the original core configuration and requires no movement of fuel or adjusting of control rod positions. The BP#5 position is expected to have lower heat generation rates than a centralized core position and it has the added complication of target cooling (which would need to be performed using cooling water from either BP#5 or BP#1).

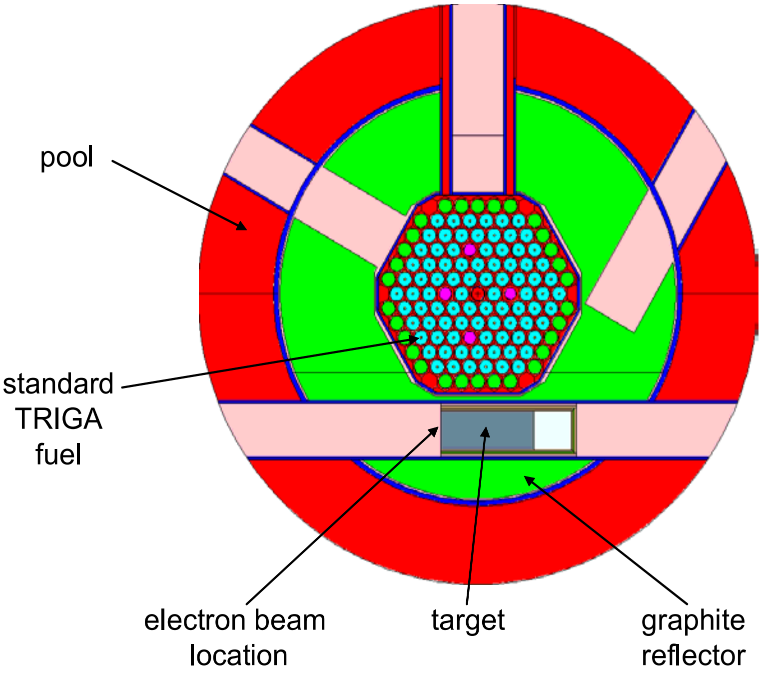

Figure B-4. UT NETL with Accelerator Target in Beam Port #5. The experiment geometry is from a MCNP screen display using MCPLOT.

Figure B-5 shows the top grid plate of the UT NETL core. The large cutouts in the grid plate are locations where the neutron source could be positioned. MCNP simulations were performed for this core with the target in the central location. This position should result in the largest possible heat generation in the core. Also the target will be cooled by the reactor pool water. This water provides sufficient cooling to remove over 10 kW of power from individual fuel elements under normal operation and should be more than sufficient to cool the accelerator-driven target.

Figure B-5. UT NETL TRIGA Top Grid Plate. This picture shows the UT NETL TRIGA top grid plate including the central source region as well as two other possible internal core positions for the accelerator-driven source. This grid plate was recently constructed and installed in Summer 2004.

Table B-I. Heat Generation Rates in the UT NETL TRIGA. Rates are given for three values of k_{eff} with the accelerator-driven neutron source in the BP#5 position and in the central core position. Also shown are heat generation rates using the central core position with three different target radii.

k_{eff}	Heat Generation Rate (kW)			
	Source in BP#5	Source in Reactor Center		
		radius=3.51 cm	radius=4.21 cm	radius=4.78 cm
0.9900±0.0003	2.44±0.29	4.30±0.24	10.12±0.51	8.90±0.49
0.9800±0.0003	1.47±0.15	2.42±0.13	7.05±0.39	6.31±0.35
0.9500±0.0004	1.16±0.11	1.12±0.06	6.11±0.31	4.92±0.27

Results for the calculated heat generation rates for the UT NETL core are shown in Table I. The simulations were performed with varying control rod heights to set the criticality condition of the core at three possible values: 0.99, 0.98, and 0.95. The heat generation rates for the source in the BP#5 position have the control rods located at their current radial position. The heat generation rates for the centralized source have the control rods located one ring further from the center source. Moving the control rods away from the center source provides a significant increase in heat production in the core. In all cases the accelerator source consisted of a 40-MeV, electron LINAC with a beam power of 3 kW. As can be seen heat rates ranging from just above 1 kW to over 10 kW is possible in this core. These heat rates will be sufficient for producing measurable temperature feedback effects in the core.

Outline for Phase II of the RACE Project:

1. Calculations for instrumentation responses and dose estimates are continuing at both TAMU and UT for the UT NETL experiments.
2. Additional TRIGA fuel was acquired by UT in FY04 to compensate for loss of reactivity due to target insertion in the central core region.
3. Discussions with the Nuclear Regulatory Commission (NRC) concerning these experiments at UT have resulted in a plan for approval by the regulatory authority(ies). The proposed experiment will be authorized by the UT Reactor Safety Committee in the next fiscal year. Also, a 50.59 letter will be submitted for approval of the experiments by the NRC. No changes to the UT NETL license or technical specifications (outlined in the facility Safety Analysis Report) will be necessary to conduct the experiments.
4. The accelerator from ISU will be moved to UT in FY05 and the accelerator will be licensed with the Texas Bureau of Radiation Control. The process for licensing this device has already been started by UT.
5. Support structure for the LINAC as well as related electronics and electrical supply needs will be constructed at UT in FY05 (likely after the accelerator has been delivered to UT).
6. Experiments are planned to commence in FY05. The data for these experiments will be analyzed in late FY05 and early FY06.

UT RACE Experiments Plan

Experiments at the UT NETL TRIGA will be focused on development of fundamental dynamic measurement techniques, measurement of basic reactor and source parameters, and initial estimates of source importance. The experiments for the UT NETL RACE Phase are planned to consist of the following (preferably in this order):

UT RACE Preparation (Spring 2005)

1. Preliminary measurements will be performed for the existing reactor configuration including rod worths, power calibrations, etc. This will be necessary for baseline data.
2. ISU-IAC will construct and test the accelerator system and will purchase a data acquisition system for use at UT and TAMU.
3. A new uranium target will be designed and fabricated at TAMU for the UT and TAMU phases of the RACE Project.
4. Measurements of the level of subcriticality will be performed via the source jerk method, the modulated source method, and the pulsed neutron source method. Does UT have another pulsed source?
5. Source importance measurements will be performed using static sources.

UT RACE in Beam Port 5 (BP#5, Summer 2005)

1. An accelerator from ISU-IAC will be delivered to UT-Austin and set up on the floor of the reactor building in a shielded "tomb" adjacent to BP#5. The vacuum tube will be placed in BP#5, with the target adjacent to the reactor core. The use of neutron reflectors to improve target-core coupling is being evaluated.
2. Measurements will be performed to analyze accelerator current, reactor power, and reactivity relations. Simulations of some of these relations have been performed to investigate thermal feedback, as shown in Figure B-6. Thermal feedback is expected to be absent below a reactor power of about 10 kW. Should this be moved to the next section?
3. Measurements will be performed to study ADS dynamics in the transition from the reactivity dominated mode to the source dominated mode.
4. Experiments will be performed to study transients induced by beam interruptions.

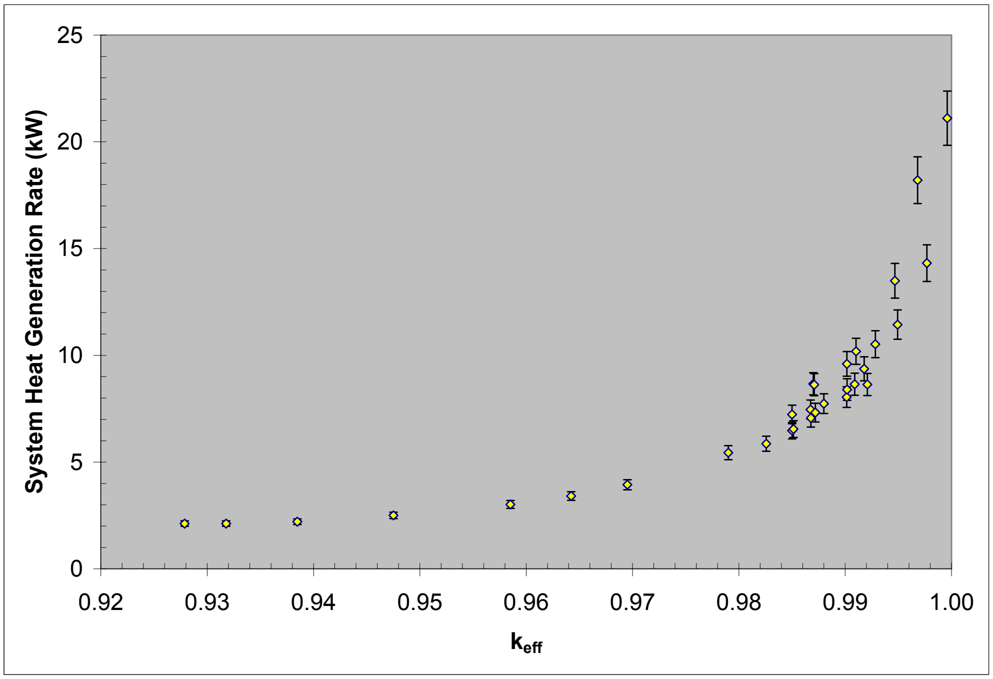

Figure B-6. UT NETL Heat Generation Rates versus k_{eff}. Rates of heat generation were calculated for the UT NETL reactor core with the accelerator target in the central core position.

UT RACE with the target in the core center (Fall 2005)

1. The accelerator will be moved from the floor/core level to the upper level platform above the top of the pool. A beam transport system will be constructed that includes vacuum tubes, 45-deg bending magnets, quadrupole magnets to re-focus the beam, and the target placed in the center of the core. The accelerator/target system will be movable to permit measurement of the coupling effectiveness in a few radial locations.
2. Measurements will be performed to analyze accelerator current, reactor power, and reactivity relations.
3. Measurements will be performed to study ADS dynamics in the transition from the reactivity dominated mode to the source dominated mode.
4. Experiments will be performed to study transients induced by beam interruptions.

Other UT RACE (Fall 2005-Spring 2006)

As a result of lessons learned, other experiments may be planned at UT before moving the accelerator to TAMU.

APPENDIX C. PHASE III: TEXAS A&M RACE

The final phase of RACE will consist of experiments at the Texas A&M University (TAMU) Nuclear Science Center (NSC) 1-MW TRIGA reactor. These experiments will make use of the existing reactor configuration as well as a subcritical lattice configuration using spent fuel from the original core of the NSC TRIGA. Figure C-1 shows a picture of the reactor core under operation as well as a cross section layout of the core. Figure C-2 shows the reactor pool and the beam port configurations. This core has a very flexible grid plate design allowing for target locations essentially anywhere within the core structure and on the core periphery. Also, the fuel in the NSC core consists of highly-enriched uranium (70 w/o ^{235}U). An MCNP model for this core has been created and preliminary calculations have suggested that heat production rates ranging from 7 kW to 15 kW is possible with k_{eff} values of 0.95, 0.98, and 0.99. These values are qualitatively similar to those for the UT NETL experiments.

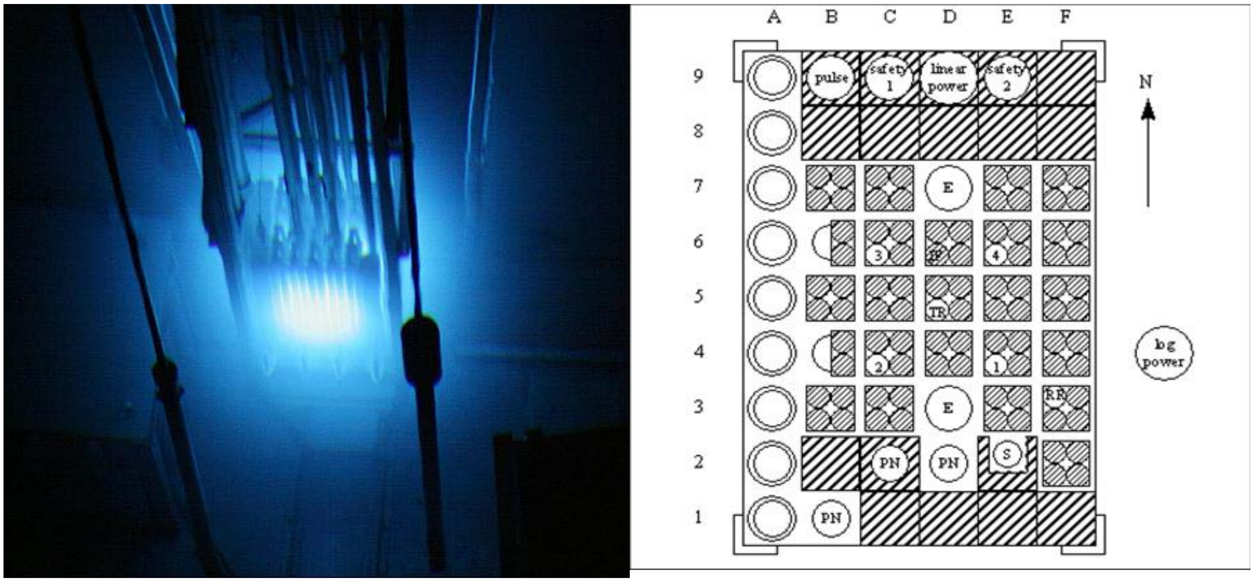

Figure C-1. TAMU NSC TRIGA Under Power with Schematic. This picture shows the TAMU NSC TRIGA reactor at 1-MW. The cross sectional schematic shows the fuel rod positions and available experimental positions.

In addition to experiments with the existing NSC TRIGA reactor, experiments are being planned using the spent fuel available at TAMU. The TAMU NSC has on site a complete core of spent fuel (approximately 105 rods) from the original core loading for the NSC TRIGA. This spent fuel will be assembled into a grid plate structure with multiple accelerator targets in place as well as safety rods for shutdown purposes. The grid plate structure will be designed to ensure subcritical operation even with the safety rods fully withdrawn. This system would then be available as a dedicated ADS training system which can be used for data gathering, method development, and operational training.

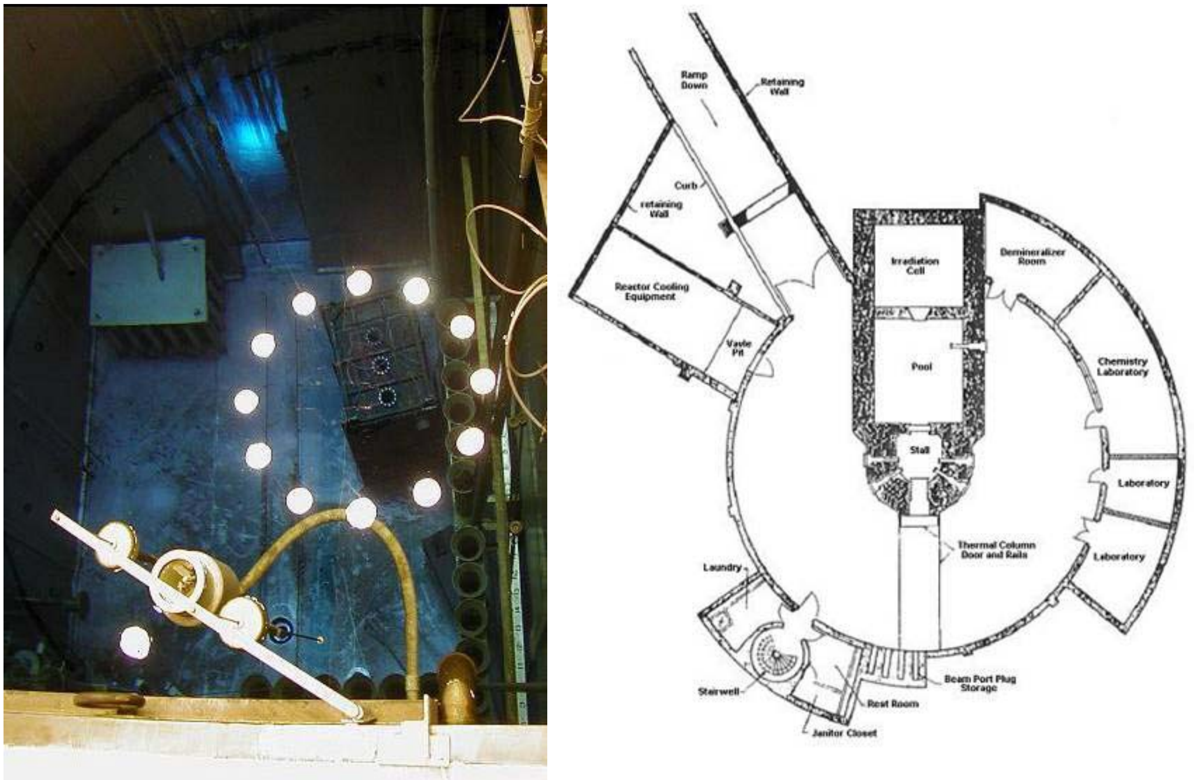

Figure C-2. TAMU NSC Reactor Pool with Reactor Under Power. This picture shows the large TAMU NSC reactor pool with the reactor located in the "stall" position at the top of the photo. The cross sectional schematic shows the pool, stall, dry irradiation cell, and 5 beam port locations. Also pictured in the upper left of the photograph is the spent fuel from the original NSC core (in the large "box-shaped" object to the lower left of the reactor).

A conceptual design for the ADSS with used fuel is shown in Figure C-3. This system [named the Texas Transmutation System (TTS)] has four available target locations and three safety control rods (providing over $6 of shutdown reactivity). An MCNP model for this system was generated, and simulations have estimated a heat generation rate of 7.42±0.55 kW at a k_{eff} of 0.942 and 19.2±0.87 kW at a k_{eff} of 0.980. Much higher heat rates would be possible if multiple accelerator-driven neutron sources were operated simultaneously. Higher k_{eff} values were not explored due to the interest of maintaining the facility highly subcritical for increased safety during training operations.

Outline for Phase III of the RACE Project:

1. Additional heat production calculations will be performed for the TAMU NSC experiments as well as instrumentation and dose calculations.
2. The regulatory approval procedure for these experiments will be similar to that used for the UT NETL experiments and should proceed smoothly once the UT NETL experiments have been approved and conducted.
3. The accelerator from UT will be moved to TAMU in FY06 and the accelerator will be licensed with the Texas Bureau of Radiation Control. The process for licensing this device will be greatly simplified since it will have already been completed at UT.
4. Support structure for LINAC as well as related electronics and electrical supply needs will be constructed at TAMU in FY06.

5. Experiments are planned to commence in late FY06 and early FY07. The data for these experiments will be analyzed in FY07.
6. Significant effort is still needed for designing the TTS and a grid plate may need to be constructed for this system (TAMU actually has an unused TRIGA Mark I grid plate which could be used if funding is not available for a customized grid plate).

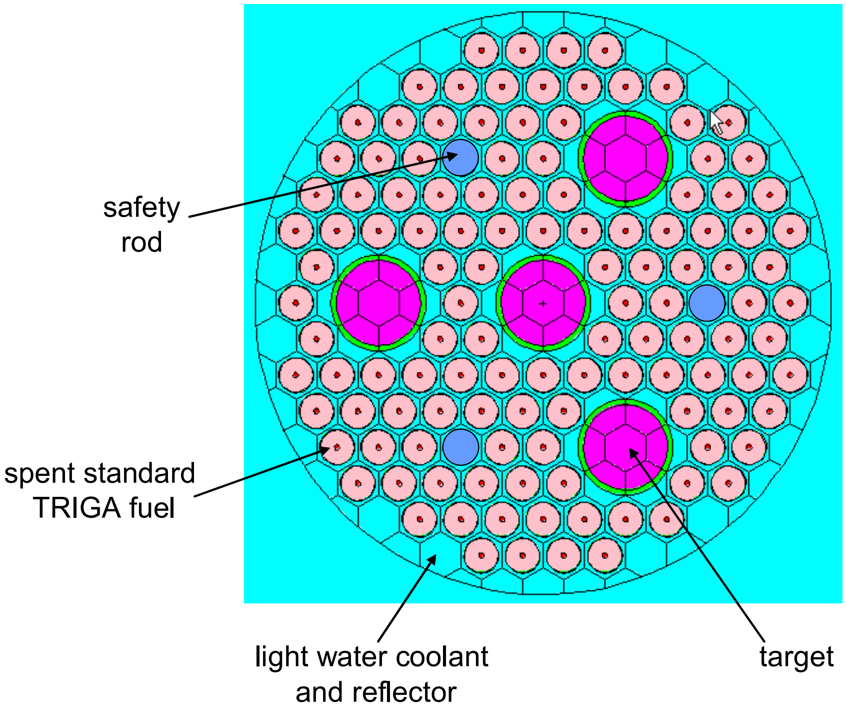

Figure C-3. MCNP model for the Texas Transmutation System (TTS). This subcritical system will be dedicated to data measurement, method development, and training of operators and students on accelerator driven systems. It will make use of existing well-characterized used fuel from the TAMU NSC TRIGA and parts already procured for the other RACE phases.

TAMU RACE Experiments to be Planned

Because of the long lead time and the knowledge that lessons learned in the ISU and UT phases could have a large impact on future directions of the RACE Project, this section is not developed in detail. Initial planning for TAMU experiments includes examining several configurations mentioned previously, including the use of the FLIP-fueled core, assembly of a semi-permanent ADSS using the TAMU used fuel to create a Texas Transmutation System, or others.

TAMU RACE with NSC TRIGA (Spring-summer 2006)

Experiments for the TAMU NSC TRIGA will make use of the unique capabilities of this non-standard TRIGA core. These experiments will also focus more on operation characteristics and on more detailed mapping of source importance. Research will include:

1. Preliminary measurements will be performed for the existing reactor configuration including rod worths, power calibrations, etc. This will be necessary for baseline data.
2. Source importance measurements will be performed. The UT TRIGA is well suited for these measurements because the accelerator source can be placed at almost any position within or around the core whereas in most reactors it can only be located in the center.

3. Measurements of the level of subcriticality will be performed via the source jerk method, the modulated source method, and the pulsed neutron source method. These experiments are similar to those performed for the UT NETL TRIGA, but will make use of the knowledge gained there and may be enhanced by the increased flexibility of the core and reflector layout.
4. Various on-line monitoring techniques will be studied including source monitoring, power monitoring, and reactivity monitoring.
5. Experiments will be performed to analyze methods for power increase/decrease. These methods will include variation of the accelerator current, variation of reactivity in the reactor, and combinations of the two.
6. Experiments will be performed to study transients induced by beam interruptions. Again these will be studied with the source in multiple core locations.

TAMU RACE with TTS (Fall 2006-Spring 2007)

Experiments for the TAMU TTS system will focus on the operation and training experiences to be gained from a dedicated accelerator driven system. These will include:

1. The development of startup and shutdown procedures.
2. Demonstration of the operation and monitoring of a steady-state system.
3. Monitoring of the time evolution of reactivity.
4. If possible measurements of the effect of beam interruptions on a system with multiple operating targets will be performed.

APPENDIX D. PUBLICATIONS AND PRESENTATIONS

D. Beller, “Overview of the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project,” summary, *Transactions of American Nuclear Society, 90*, Pittsburgh, PA, June 14-17, 2004.

D. Beller, “Overview of the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project,” full paper accepted for publication in the *Proceedings of the Eighth Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation*, 11 November 2004, Las Vegas, Nevada.

D. Beller, A. Hunt, M. Reda, and J. Bennion, “Initial Results from the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project,” full paper accepted for publication in the *Proceedings of the Eighth Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation*, 11 November 2004, Las Vegas, Nevada.

D. Beller, A. Hunt, J. Bennion, M. Garfield, K. Folkman, and M. Reda, “Initial Results from the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project,” summary, *Transactions of American Nuclear Society, 91*, Washington, DC, Nov. 14-18, 2004.

S. O’Kelly, T. Green, and W. Charlton, “Reactor-Accelerator Coupled Experiment (RACE) at the University of Texas at Austin,” summary, *Transactions of American Nuclear Society, 91*, Washington, DC, Nov. 14-18, 2004.

S. O’Kelly, W. Charlton, and D. Beller, “Accelerator Driven Nuclear Reactors in Texas,” abstract accepted for poster presentation at CAARI (Conference on Applications of Accelerators in Research and Industry) 2004.

M. A. Reda, J. F. Harmon, et al., “Properties of Photoneutron Sources for Accelerator Driven Sub-Critical Systems,” *Proc. of the Sixth International Meeting on Nuclear Applications of Accelerator Technology (AccApp 03)*, American Nuclear Society, pp.86-90, 2004.

M. A. Reda and J. F. Harmon, “Calculations of the Neutrons Generation during Patient Irradiation with Photons or Electrons Beam,” submitted to the 46th Annual Meeting of the American Association of Physicists in Medicine (AAPM), Pittsburgh, Penn., July 25-29, 2004.

M. A. Reda and J. F. Harmon, “Nondestructive Testing of Moisture Distribution in Wood Using Pulsed Neutron Source,” submitted to 53rd Annual Denver X-ray Conference, Steamboat, Colorado August 2-6, 2004.

M. A. Reda, D. E. Beller, and J. F. Harmon, “Criticality Calculations in Reactor Accelerator Coupling Experiment (RACE),” submitted to Eighth Information Exchange Meeting, Las Vegas, Nevada, November 9-11, 2004.

M. A. Reda, D. E. Beller and J. F. Harmon, “Dose Calculations in Reactor Accelerator Coupling Experiment (RACE),” submitted to the 49th Annual Meeting of the Health Physics Society, Washington, DC, July 11-15, 2004.

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i. M. SALVATORES, et al., “TRADE (TRIGA Accelerator Driven Experiment): A Full Experimental Validation of the ADS Concept in a European Perspective,” *Proc. of the Sixth International Meeting on Nucl. Appl. of Accelerator Tech., AccApp’03*, American Nuclear Society, 2004, p. 8-16.

ii. MCNPX is a trademark of the Regents of the University of California, Los Alamos National Laboratory. MCNPX User’s Manual, Version 2.4.0, September 2002, Report LA-CP-02-408, Los Alamos National Laboratory.