OVERVIEW OF THE U.S. REACTOR-ACCELERATOR COUPLING EXPERIMENTS (RACE) PROJECT

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The Reactor Accelerator Coupling Experiments (RACE) Project was developed in 2003 as the only experimental research component within the Advanced Fuel Cycle Initiative (AFCI) of the U.S. Department of Energy for investigation of transmutation using accelerator-driven subcritical systems (ADS). It was a university-based research project lead by the Idaho State University (ISU). RACE Project experiments began at the ISU's Idaho Accelerator Center (IAC) in 2004, and continued there and at the University of Texas at Austin (UT-Austin) in 2005 and 2006.

In these experiments, electron accelerators generated photo-neutrons by inducing bremsstrahlung photon production in heavy-metal targets. These accelerator/ target systems produced a source of ~1x10^{12} n/s at peak power, which then initiated fission reactions in the subcritical systems. Subcritical systems included a compact, transportable assembly at ISU and a TRIGA reactor at UT-Austin. The RACE Project also included collaboration with Domain 2 of EUROTRANS with ECATS (Experimental activities on the Coupling of an Accelerator, a spallation Target and a Sub-critical blanket). The Project concluded with a series of joint experiments with ECATS at ISU in 2006. We present an overview of the Project as well as a discussion of its accomplishments in terms of kinetics and dynamics of ADS.

I. INTRODUCTION

Investigation of transmutation using accelerator-driven subcritical systems (ADS) has been a component of the U.S. Department of Energy's Advanced Fuel Cycle Initiative (AFCI),[1] with the Reactor Accelerator Coupling Experiments (RACE) Project as its only experimental research component. The RACE Project was a university-based research project lead by the Idaho Accelerator Center of Idaho State University (ISU-IAC).[2] The RACE Project was initiated in 2003 at ISU and experiments were conducted from 2004 to 2006 at ISU-IAC and at the University of Texas (UT) at Austin.[3, 4] In these experiments, source neutrons were generated by using electron accelerators to produce high-energy bremsstrahlung photons that then induced photon-neutron reactions in heavy-metal targets. These compact, transportable accelerator/target systems produce a source of ~10^{10}-10^{12} n/s, which then initiate fission reactions in the subcritical systems.

Full-core ADS experiments were conducted at the ISU-IAC in a compact, subcritical assembly that was constructed at the IAC and fueled with a modular core. Accelerator-coupled experiments with the TRIGA reactor at the University of Texas at Austin (UT-Austin) were also conducted beginning summer 2005, and were completed in March 2006. A higher-power phase of the RACE Project was to have been conducted in collaboration with the Integrated Project EUROTRANS (EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an ADS) of the EURATOM 6th Framework Programme (FP6).[5, 6] The high-power phase of ECATS was subsequently cancelled because of unavailability of U.S. or European funding. With increased beam power and uranium-containing targets, Texas RACE could have provided sufficient fission power—up to 50 kW—for examining thermal feedback effects. However, a low-power phase of RACE-ECATS was conducted at ISU-IAC with the participation of a member of the ECATS collaboration and IAC and University of Nevada, Las Vegas.

In the ISU RACE experiments, we have measured k_{eff} in an "approach to critical" experiment, with a value of ~0.88-0.92. ADS experiments were then conducted at a variety of frequencies and intensities (pulse heights and widths), always keeping power in the few to tens of Watts range to reduce activation of the transportable fuel elements. Pulsed Neutron Measurements were done with fission chambers and other detectors, such as BF_3 and ^3He. Photon flash continued to be an issue throughout the RACE Project with these measurements, essentially "blinding" the detectors at the start of each pulse.
At UT-Austin neutron measurements were made with flux wires, fission chambers, and other detectors, and results have been reported.[7] Further experiments at UT and

Texas A&M were cancelled after the RACE Project funding was reduced in 2006.

The RACE Project is reviewed in this paper as an introduction to other papers in these Proceedings as well as overview of the activities and accomplishments of the project. We first discuss the original purpose of the project, which was to provide a bridge between the European MUSE and TRADE projects as well as to maintain U.S. activities in ADS research. We then discuss the ADS experiments that were conducted at ISU and Texas and the computational participation of the University of Michigan and UNLV. In addition, the RACE-ECATS collaboration, which included conceptual high-power target and experiment design studies in the U.S. and Europe as well as a series of experiments conducted at the ISU-IAC, will be described. We conclude with a discussion of the termination of the RACE project.

II. PURPOSE OF THE RACE PROJECT

The RACE Project was intended to fit an important niche between the European programs MUSE (CEA, Cadarache, France) and the TRADE Project (TRIGA Accelerator Driven Experiment, ENEA, Cassacia, Italy).[8, 9] In the MUSE experiment, DD and DT neutron generators produced nearly mono-energetic neutrons (2.45 and 14.1 MeV) with an intensity up to ~10^{10} n/s, whereas the TRADE experiment was intended to include a high-energy proton cyclotron to produce a spallation source up to ~150-300 MeV and ~10^{15} n/s. Source importance and source strength are among the most important parameters of driven subcritical systems, and the current lack of reliable data for neutron energies greater than 20 MeV make calculations of this parameter questionable. MUSE provided valuable measurements of source importance up to 14 MeV (a range in which data are less questionable), and TRADE began with a spallation continuum that was to be extended to 150-300 MeV following the construction of a new cyclotron. Although the contribution from mid-energy neutrons in the range up to 30 or 40 MeV would be small, RACE can provide a valuable bridge, and one that makes extrapolation much more comfortable. In addition, the source intensity of the RACE project is intermediate between that of MUSE and TRADE, and thermal feedback effects, which are absent in MUSE, could be investigated in RACE in advance of the higher intensity TRADE.

In addition to serving as an intermediate step between the recent MUSE experiments and the future TRADE experiments, the RACE Project was intended to demonstrate in the U.S. the ability to design, compute, and conduct ADS experiments, and to predict and measure coupling efficiency, reactivity, and multiplication. In this project we intended 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. We also provide data for the creation of both steady state and transient benchmarks for accelerator-driven subcritical systems for the nuclear community to develop and test new computational codes and methods. This project helped attract students and post-docs to nuclear science and technology, provided them a diverse nuclear science education, and trained them in operation and modeling of accelerator-driven systems as well as in measuring reactivity of subcritical systems.

III. ISU RACE

The RACE tests at ISU were based on a subcritical assembly of 150 flat plates of 20%-enriched uranium-aluminum fuel alloy clad in aluminum, moderated by light water, and reflected by graphite. The plates were arranged in three horizontal layers (six fuel trays) surrounding the target and beam tube to form the core. The core was reflected with graphite blocks on all sides. This geometry resulted in a maximum estimated multiplication (k_{eff}) of 0.94 and measured k_{eff} of 0.9 to 0.92.

The neutron source for this experiment was created by a ~25-MeV electron Linac that could produce a total beam power of about 1 kW. The accelerator beam structure was a few-microsecond length current pulse repeated with a variable rate. Both of these parameters were continuously variable up to 5 microseconds and 200 Hz respectively. Neutrons were produced in a water-cooled tungsten (75% tungsten and 25% copper alloy) target aligned horizontally in line with the electron beam. The system yielded about $2x10^{-3}$ neutrons per electron, or $1x10^{10}$ n/s per μA of electron current at 20-25 MeV. A neutron output of a few times 10^{12} n/s was possible, but in actual experiments the intensity was reduced to minimize activation of ISU's transportable fuel elements.

Reactivity and multiplication studies with the Monte Carlo radiation transport code MCNPX[10] indicate that the ISU subcritical assembly should produce a subcritical multiplication of about 10 with k_{eff} of 0.93 {coupling, leakage, and absorption losses between the target and fuel reduce the expected multiplication from the theoretical value of $1/(1-k)=14$}. However, gaps in graphite block assembly plus other physical restrictions resulted in a k_{eff} less than 0.92. Several far-subcritical developmental experiments were conducted with 10 of the fuel plates, k_{eff} ~0.20, and multiplication just greater than 1. These tests were conducted to develop operating procedures as well as experience with static and dynamic flux measurements. A major challenge was the development of dynamic instrumentation that could operate in the presence of the accelerator "flash" (electromagnetic and gamma-ray radiation). The experiments at ISU required the physical movement of fuel elements from the ISU subcritical assembly in the Nuclear Engineering Department to the Idaho Accelerator Center. The full 150-plate experiments were begun after the award of a NRC license amendment in 2005.

III.A. ISU RACE Core

The core was constructed of 6 flat aluminum trays each containing 25 flat plates of aluminum-clad, 20%-enriched uranium-aluminum alloy; and they were arranged 3 trays high by 2 wide (see Fig. 1). The subcritical assembly was contained in a rectangular tank made of 1/4-inch aluminum that is approximately 0.5 m high x 0.9 m wide by 1.2 m long. The tank was filled with de-ionized water after the fuel trays and graphite reflectors are in place. The active, fueled zone of the plates 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 269 g 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 were 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. The bottom trays were lowered into the tank on each side of the beam tube, then slid together. The middle trays were then stacked on top of the bottom trays and butted up against the beam/target tube. The top trays were stacked on the middle trays, and the graphite reflectors were inserted beside, in front and back, and on top of the fueled core.

III.B. Target and Beam Tube

The target was cut from a solid piece of tungsten-copper alloy (75% W and 25% Cu). It is 7.62 cm long by 7.62 cm in diameter (3 in x 3 in). It is welded to a 2.75 inch "Conflat" flange that is welded to a 2.75 inch diameter Al tube. This tube is mated to the wall of the Al tank with an o-ring flange. With a total beam power of about 1 kW, the face of the target, which is inside the vacuum beam port, would heat up to several hundred C. This heat was conducted throughout the massive target (>6 kg) and was dissipated from its much lower temperature surface by natural circulation of water. This

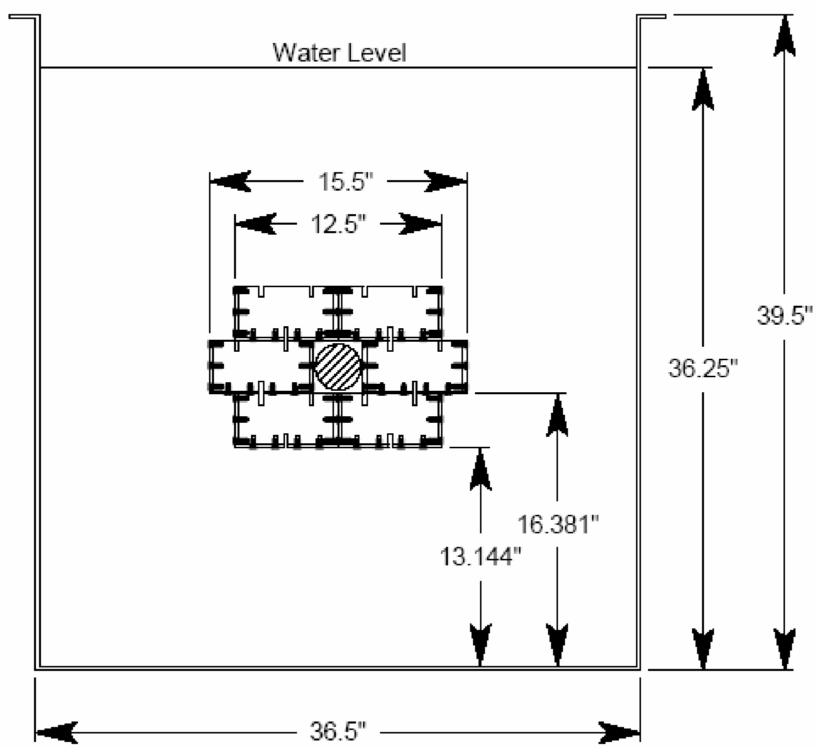

Figure 1. Front view of a cross section of the ISU RACE including the tank, the beam tube/target, and the stacked fuel trays. The cross section is cut to show the ends of the fuel trays. The in-tank graphite reflector and the support stand are not shown.

arrangement was tested 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 would be just 400 W (0.4 kW), or 0.0026 W/cm^2 from the surfaces of the fuel plates, which is easily dissipated by natural circulation. Thus, the maximum power (beam plus fission) of just 3.4 kW that could be deposited in the RACE assembly would be easily dissipated without heating the fuel substantially. The mass of water and graphite in the tank was 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 was more than 3.5 m^2, so that the dissipation was less than 0.1 W/cm^2 (c.f. a 100-Watt light bulb at about 2.5 W/cm^2). The system warmed slightly during experiments, but it did not get hot.

III.C. ISU RACE 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 30 to 40 MeV electron linac. This neutron source has great flexibility; pulse widths are variable from nanoseconds to microseconds with pulse rates up to a hundred hertz. The neutron source is physically small, with volume ~ 300 cm^3, thus usable flux is relatively high. Yields of ~10^{10} n/pulse for microsecond pulses are easily achieved; thus total average rates are ~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 20 to 30 MeV. Thus, only a few percent of the source neutrons are in this high-energy tail. There is little slow neutron contamination.

III.D. ISU RACE Reactor Physics

Many conceptual arrangements for the RACE experiments have been examined using the MCNPX 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. Example input and output files are included in the Appendices. Fuel plates may be assembled in the core in single (each plate is separated from each other plate by water), 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, inverse multiplication measurements experiments were conducted to verify the transport predictions. In addition, the accelerator was operated at low energy, low power, and low frequency prior to full-core, high-power testing.

III.E. ISU RACE Instrumentation and Monitoring

A variety of instrumentation and monitoring equipment was used to measure neutron and gamma-ray production from the target, to measure time-dependent neutron flux in and around the core, and to measure neutron and gamma-ray leakage out of the experiment and into the experiment bay. In addition, environmental monitoring equipment was installed in the experiment bay to monitor for fission product leakage from the fuel plates. Instrumentation will include BF_3 counters, ^3He 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, were purchased before commencing full-core experiments.

III.F. ISU RACE Experiments

Early ISU RACE Experiments were conducted to develop instrumentation and techniques for measuring subcriticality of the ISU RACE assembly.[11, 12] These experiments produced delayed neutron signatures and activation foil measurements, and data for examination of criticality estimation techniques at very low levels of subcriticality.

IV. UT-Austin RACE

An IAC accelerator similar to that used in ISU RACE was constructed at ISU, shipped to Texas, and installed in the summer of 2005.[13, 14] It was assembled in a cave at the floor level of the UT Nuclear Engineering Teaching Laboratory (NETL), adjacent to the NETL TRIGA reactor. This reactor can operate at 1 MW_{th}, and can produce pulses up to 1000 MW_{th} (1 GW_{th}) .[15] The accelerator target was placed immediately adjacent to one side of the core, centered on that side.

The first UT experiments were conducted with the reactor completely shut down with a criticality of about 0.92, similar to the ISU RACE criticality. Follow-on experiments were conducted with k_{eff} between 0.92 and 0.95 to possibly 0.97, 0.98, or even critical. In addition, beam diagnostics and monitoring techniques were developed at UT to improve the performance of the linac/target system.[16, 17]

IV.A. Texas A&M University RACE

Another phase of the RACE project that did not materialize due to funding constraints was at Texas A&M, where a series of three different experiments was studied. One option was to use the TAMU Nuclear Science Center (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}). 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). [18]

V. University of Michigan

The University of Michigan supported the AFCI RACE Project with computational reactor physics studies of the kinetics of subcritical systems.[19, 20] They studied dynamic response in ISU RACE tests to aid in the design of instrumentation. They optimized the ERANOS transport theory model for a RACE configuration by using several different energy group structures and orders of polynomial expansion for the neutron flux. With a reasonable agreement obtained between ERANOS and MCNP5 results, they began to perform transient calculations simulating source trips and restarts. A ERANOS simulation of the decay of a neutron pulse in the full-core ISU RACE configuration has yielded, in the point kinetics option, a meaningful estimate of the subcriticality. In addition, they worked to resolve difficulties encountered with the time-dependent VARIANT transport theory solution.

VI. High-power RACE with ECATS Collaboration

The purpose of accelerator coupling studies is to demonstrate ADS concepts and to develop as complete as possible an understanding of source terms and their coupling to subcritical reactors. This understanding is necessary for the construction of prototype and demonstration transmutation facilities, such as the European eXperimental demonstration of the technological feasibility of Transmutation in an ADS (XT-ADS) and the European Facility for Industrial Transmutation (EFIT). Additionally, ADS experiments are used to validate and benchmark computer codes 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. In Europe, Domain 2 of EUROTRANS is their component of ADS experiments: Experimental activities on the Coupling of an Accelerator, a spallation Target and a Sub-critical blanket (ECATS).

In the U.S. RACE Project, we initially planned a limited number of experiments with each configuration, along with limited instrumentation and measurements, at low beam and reactor powers. However, following cancellation of the proton-spallation phase of the TRADE Project,[21] ECATS participants became available to expand the benefits of the RACE Project by participating in design, planning, and execution of higher-power experiments in the U.S. Some of this design and analysis was conducted, but the full high-power race project was not realized because of funding constraints.

RACE collaborations with ECATS engineers would permit a much broader range of experiments including more detailed measurements with a wider range of instruments. ECATS-RACE collaborators contributed expertise in target design and analysis (neutronics, thermalhydraulic performance, and reduction of residual radiation/doses), planning of reactor experiments (both critical and driven subcritical), and analysis (using MCNPX, KTAR, and other codes). In addition, equipment that was previously used for MUSE and TRADE (e.g. fission chambers, EM shielding, Piccolo micromegas, and data acquisition systems) would have been available to enhance RACE instrumentation and data acquisition. Thus, contributions that the ECATS group could make toward the RACE Project would have enhanced our technical success, advanced the significance of our project in the overall advanced nuclear energy arena, and would have promoted academic involvement and education and training, which was one ultimate goal of both the RACE and EUROTRANS Projects.

VII. High-power studies and target design.

In addition to the above, ECATS participants investigated the potential to increase neutron generation by one to two orders of magnitude, which would allow us to drive high-average-power experiments with significant, and easily measured, thermal feedback.[22] In a separate effort the IAC investigated connecting a high-power modulator and klystrons to existing 20 and 25-MeV linacs. This new configuration would provide 20 to 30 kW of electron current, compared to 1 to 2 kW with the existing ISU RACE and Texas RACE accelerators. Although the high-power linac was not assembled for the RACE Project, another unit is now in operation at ISU. In addition, we investigated incorporating depleted or natural uranium into existing heavy metal targets to increase the photon-neutron yield. A high-power RACE Target was designed and constructed at UNLV[23] and tested for thermal and neutron generation performance at the IAC.[24, 25] Simultaneously, an ECATS Target Working Group examined several alternate high-power target designs.[26] The combination of these two enhancements, if successful, would generate 5 x 10^{13} to 10^{14} n/s in the center of one of the Texas reactors. With this new source strength, we would be able to perform studies in the range of 50-150 MW_{th}, which could provide very reliable thermal feedback information as well as start-up and shut-down experience.

Thus, the RACE-ECATS collaboration was expected to yield a much broader set of data for code verification, which would greatly benefit both the U.S. and European transmutation research programs. This project would also help attract students to nuclear science and technology, provide them a diverse nuclear science education, including experience in international collaborations, and train them in operation and modeling of accelerator-driven systems as well as in measuring reactivity of subcritical systems. However, this phase of the RACE-ECATS collaboration was terminated due to lack of funding from the U.S. DOE and the European community. The collaboration concluded with an extensive series of experiments at the IAC.

VIII. ISU RACE-ECATS EXPERIMENTS

During 2006 Jammes of ECATS participated in a series of RACE-ECATS experiments at the IAC. We first measured keff in an "approach to critical" experiment, with a value of ~0.88-0.92. A wide variety of ADS experiments were then conducted at a variety of frequencies and intensities (pulse heights and widths), always keeping power in the tens of Watts range. Pulsed Neutron Measurements were done with fission chambers and other detectors, such as BF_3 and ^3He. Photon flash continued to be an issue with these measurements, essentially "blinding" the detectors at the start of each pulse. Instrumentation modifications were made to attempt to overcome this problem. Results are reported in several papers in this Proceedings. [27, 28, 29] Comparisons of experimental results to modeling are ongoing, and techniques are being refined. In addition, several other projects are ongoing at ISU, including beam characterization, measurements of target yields, and others.

IX. SUMMARY

The Reactor Accelerator Coupling Experiments (RACE) Project, which began in 2003 at the Idaho State University (ISU), was the only experimental research component within the Advanced Fuel Cycle Initiative (AFCI) of the U.S. Department of Energy for investigation of transmutation using accelerator-driven subcritical systems (ADS). It was a university-based research project lead by ISU's Idaho Accelerator Center (IAC). RACE Project experiments began at the IAC in 2004, and continued there and at the University of Texas at Austin (UT-Austin) in 2005 and 2006.

In these experiments, electron accelerators generated photo-neutrons by inducing bremsstrahlung photon production in heavy-metal targets. These accelerator/target systems produced a source of ~1x10^{12} n/s at peak power, which then initiated fission reactions in the subcritical systems. Subcritical systems included a compact, transportable assembly at ISU and a TRIGA reactor at UT-Austin. The RACE Project also included collaboration with Domain 2 of EUROTRANS with ECATS (Experimental activities on the Coupling of an Accelerator, a spallation Target and a Sub-critical blanket) in a series of design studies that were intended to lead to high-power experiments with thermal feedback effects. The Project concluded with a series of joint experiments with ECATS at ISU in 2006. The RACE Project accomplished it's original goals: to demonstrate in the U.S. the ability to design, compute; to conduct ADS experiments to predict and measure coupling efficiency, subcriticality, and subcritical multiplication.In addition, we demostrated that accelerator-driven transmutation of waste is an attract topic for students and can attract them to study 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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