UNIVERSITY OF TEXAS ACCELERATOR DRIVEN SUBCRITICAL EXPERIMENTS

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The Texas phase of the Reactor-Accelerator Coupling Experiment (RACE) was completed in March 2006. The experiment demonstrated the feasibility of operating a TRIGA reactor in a subcritical configuration driven to significant power by an electron LINAC neutron source. The pulsing LINAC and various core configurations provided several opportunities to evaluate the subcritical level of the reactor and compare measurements to calculated values. Valuable benchmarking of the original core models was performed as a result of the RACE project which will be used to perform additional thermal and hydraulic safety analysis of the critical and subcritical TRIGA reactor. The final result of the experiments met the original goals of the DOE supported feasibility project but was unable to reach the temperature feedback regime of the subcritical system due to neutron source location and LINAC power limitations. Performance data was acquired during a limited campaign due to resource limitations but clearly shows that a high power accelerator-driven subcritical transmutation demonstration project is achievable.

I. INTRODUCTION

A series of experiments were performed at The University of Texas at Austin's (UT) Nuclear Engineering Teaching Laboratory (NETL) in 2005 and 2006 to simulate the full-scale operation of an accelerator-driven subcritical system (ADSS) as has been proposed for the potential transmutation of high-level nuclear waste. These experiments were one phase of an overall multi-university program called Reactor-Accelerator Coupling Experiments or RACE. The RACE project supported the coupling of industrial electron linear accelerators (LINACs) configured as neutron generators to subcritical assemblies or research reactors in order to evaluate instrumentation and modeling of systems intended to simulate high power ADSS. An original goal of the RACE-UT portion of the project was to attempt to drive a small, subcritical university research reactor to the point of adding heat with an accelerator-driven neutron source and attempt to measure the change in core reactivity from temperature affects. Modifications to the original project were necessary due to budget limitations and the project changed to a feasibility demonstration of the concept of an electron LINAC neutron source driving a subcritical reactor core to support international ADSS research.

II. EXPERIMENT DESCRIPTION

In July and August of 2005, a modified Varian Clinac 2100 electron linear accelerator was delivered from the Idaho Accelerator Center (IAC) and installed into the neutron beam port #5 radiography cave. The "Clinac" brand is used for radiation therapy applications and will produce an electron beam with maximum electron energy of 20 MeV and a pulse width of 5 μsec. The LINAC was configured to operate between zero and 240 Hz but was unable to sustain frequencies greater than 180 Hz for long periods without overheating the klystron and causing the LINAC to trip off. This was not a flaw in the machine was a result of the limited cooling capacity of the installed chill water system. The high-energy electrons from the LINAC would stop quickly in a tungsten-copper target near the NETL research reactor and produce high energy Bremsstrahlung photons and then neutrons from secondary reactions. Previous calculations showed that the neutron source strength would be approximately 5E11 neutrons/sec at full LINAC power of 1 kW. The NETL beam port #5 radiography cave was completely torn down and enlarged to provide sufficient room for the accelerator to couple to the vacuum pipe and direct the electron beam to the tungsten-copper target but allow temporary disassembly and storage of the LINAC during normal, critical reactor operations and neutron radiography experiments. The NETL is a university research reactor with a relatively active operational schedule and a significant number of facility users. Because of the high facility usage during the academic year, the RACE-UT project could not monopolize the NETL and commit the facility to exclusive subcritical operations for a single six month period. This operational limit required the overall design of the installed LINAC system make it possible for the reactor to be converted from critical to an ADSS configuration in a few days for maximum flexibility.

For maximum coupling of electron or proton produced neutrons, the target in an operational ADSS is generally expected to be placed within the center of the subcritical assembly surrounded by fuel. The Mark II TRIGA grid plate allows the removal of six fuel pins from the core center to produce an area with a cross-section of roughly 100 cm^2 for large sample irradiations so it is feasible to install a linac target in the center. However, the time and expense necessary to convert the NETL facility into a configuration allowing a vertical electron beam was far beyond the research budget and the idea was dismissed. To produce a reactor core that was closer to final ADSS designs, a subcritical configuration was selected that would be slightly subcritical (~0.980-0.999) with all four control rods fully withdrawn. The smaller core had between 77 and 79 fuel elements versus the 104 for a fully operational reactor. The reactor fuel was placed in an offset location within the core grid plate to provide the best available coupling to the neutron source in the beam port (Figure 1). A secondary reason for the particular core design was to maintain all control rods surrounded with fuel for reactivity control and to prevent damage to the rod mechanisms during the frequent core shuffles.

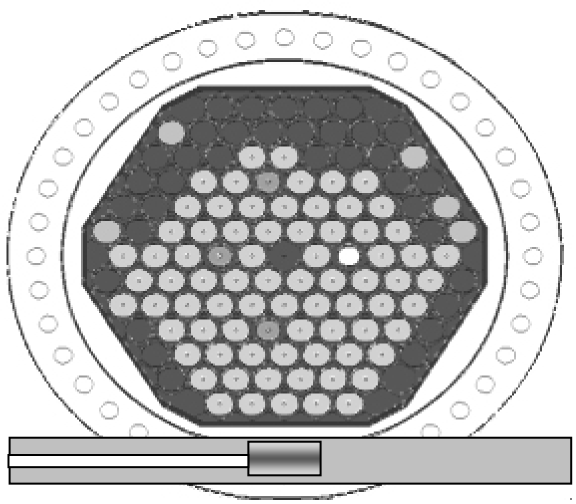

Fig. 1. MCNP Model of NETL TRIGA with Target/Source location shown.

The initial testing phase of the system in the late summer of 2005 successfully produced neutrons adjacent to the reactor and drove the subcritical research reactor to a power of approximately 70 watts equivalent as indicated on the uncalibrated reactor neutron power detectors. However, problems in beam optics and focusing produced very high gamma radiation fields (>100 R/hr) externally to the beam port #5 cave and this resulted in a significant delay during the testing phase to install additional radiation shielding and move the LINAC control panels further from the experiment area. An unexpected cooling water leak into a high voltage power supply prematurely suspended LINAC operations in August and required an early conversion to critical reactor operations for other experiments.

Another short series of subcritical experiments were performed in October 2005. These experiments were performed to evaluate new methods of beam localization and detection as well as performing neutron flux measurements using foil detectors and further verifying the radiation shielding was adequate. During the installation of the LINAC for this second series of experiments, the electron steering magnet on the front of the LINAC was found to be slightly out of alignment. Adjustment of the magnet substantially reduced the gamma ray dose on the exterior of the shielded cave area. From these indications, it seemed clear that more electrons were now passing through the quadrapole and a higher electron current was expected to interact in the tungsten-copper target. A pickup coil was installed around the beam pipe on the target side of the quadrapole magnets in an attempt to measure beam current. This system was relatively effective and indicated the LINAC was producing the designed beam current of 100 mA. Higher target temperatures and higher neutron production rates were expected after aligning the beam optics but these indications were not seen. These anomalous measurements required further analysis and evaluation and it is now suspected the electron beam quality was poor and a significant fraction of the electrons were low-energy and did not reach the target.

One well-known and major difficulty with neutron production utilizing Bremsstrahlung radiation in a high-Z target is the so-called “gamma flash” from the initial electron pulse which is such a high intensity as to produce long detector and pre-amplifier deadtimes. A great deal of effort was spent in evaluating various methods of compensating for the gamma flash during all experiments but the final and most effective method for RACE-UT was to not use traditional pulse counting techniques and operate the fission neutron detectors in current mode. This decision was aided by the fact there were no available pulse-counting systems at the NETL for the experiment. In the overall RACE project, the IAC group was tasked to design and provide an instrumentation system for all the RACE projects. However, due to delays caused by lengthy initial equipment procurement and unsuccessful initial instrumentation tests in Idaho, the IAC was still testing the designed neutron counting systems on a similar electron LINAC in Idaho when the equipment was needed in Texas for the experiments. Very little (<$5K) equipment was budgeted for the project at the NETL because the electronics were to be provided by IAC for contractual reasons. When it became clear that instrumentation would not be provided for the RACE-UT experiments, two fission chambers were borrowed from the Texas A&M University Nuclear Science Center. These chambers had different ^{235}U loadings (12.0 and 75.0 mg) making direct comparisons between core locations and efficiencies difficult. In addition, one detector (12 mg) had previously been used in a high neutron fluence in a research reactor and was electronically noisy. This detector had also become very radioactive from previous use thus making it difficult to use. Ideally, the neutron detectors used would have been a matched set but a second set of matched detectors ordered by the NETL nearly six months in advance did not arrive until the end of the experimental program and it was necessary to use a non-optimal system for data acquisition. In order to acquire data in current mode without a multichannel scaler, a pair of Keithley 6485 Picoammeters (K-6485) were purchased to monitor the current from the detectors. The picoammeters were relatively low cost with a 1 kHz sampling rate and a A/D conversion time of 1.667 msec. The analog outputs of the picoammeters were connected as inputs to an available data acquisition system (16-bit, 200 kHz) used by the NETL for student laboratories. The final acquisition system was a breakthrough for the project and enabled the operators to monitor the detector current signal via inline oscilloscopes and acquire data for later analysis. The data acquired was time-stamped with data time steps of 20 microseconds and stored in list form in binary or text files.

III. RESULTS AND DISCUSSION

A necessary component in the evaluation of the operational RACE system was the determination of various subcriticality levels of the ADSS while operating the system at relatively high powers and frequencies. Ideally, the TRIGA fuel would reach the point of adding heat and some evaluation of the subcritical monitoring methods with temperature reactivity feedback would be possible. This was unlikely to occur given the source location and the strength of the neutron source but the project proceeded as a first-step in the evaluation for a future, higher power accelerator. The system was operated at various LINAC frequencies and currents in order to determine if the prompt neutron decay signal could be reliably separated as the electron pulses became closely spaced in time and the delayed neutrons reached a steady-state value. During the same set of experiments, the target neutron production rate was evaluated and correlated to various LINAC operational parameters. A number of single LINAC pulses were used to evaluate the core subcriticality level without consideration of the delayed neutrons as another method of benchmarking the system and this was used to calibrate other measurements.

Operation of a true ADSS at high powers is expected to require a high frequency, high power electron or proton accelerator to drive the subcritical assembly. To this end, standard pulsed neutron source techniques would not be necessarily effective for monitoring the subcriticality level as these generally require the pulse period (τ) to be significantly greater than the inverse of the prompt neutron decay constant, $1/\alpha$ to separate the delayed neutron background from the prompt neutron decay constant. New or modified methods must be employed if the subcriticality of an ADSS at full power is to be continuously monitored for safety and control.

Several subcritical core configurations were established in the limited time available for RACE-UT. The primary configuration was an offset reactor core of 79 fuel elements and all 4 control rods fully withdrawn, however; additional experimental configurations included operation with various control rod heights, removal of a single fuel element from a central location, rod drops and rod ejections. The LINAC frequency was varied from very low frequency to 200 Hz during these configuration changes to evaluate various methods of subcritical monitoring. The safety analysis for the experiment approval did not allow the LINAC and target to be installed while the reactor was critical so a critical reactivity calibration was performed following the LINAC removal at the end of the experiment campaign. The NETL reactor was made slightly supercritical (with no installed source) by the addition of two graphite reflecting elements to the 79 element core and the resulting change in neutron level versus time (reactor period) was correlated to a positive reactivity. The removal of the two graphite elements was modeled using two MCNP5 calculations for a differential reactivity from critical to arrive at the subcritical level of the actual RACE-UT configuration[1]. The multiplication factor for the 79 element configuration was calculated to have been 0.997118 ±0.00096 or a reactivity of -0.4127$. Following these critical tests, enough fuel (four additional elements) was added to the core to perform critical rod calibrations on two control rods previously used for reactivity changes in the RACE-UT experiments. These calibrations proved valuable in benchmarking the sensitivity of several subcritical evaluation methods.

One method used to evaluate the subcritical level of the reactor core was the pulsed Feynman-alpha method derived by Pázsit and Ceder[2]. The technique is based on the well-know Feynman-α method but was extended to accommodate the periodic nature of a pulsed ADSS. In the following equation for the stochastic pulsed Feynman-α, Y(T), the first term is identical to the Feynman-α for a continuous neutron source while the second term accounts for the time dependence of the LINAC-driven neutron source.

$$Y(T)=\frac{\sigma^2(T)}{\mu(T)}-1=$$

$$(1)\quad \left[\frac{\varepsilon\lambda_f\lambda_d\overline{(\nu(\nu-1)}}{\alpha^2}\left[1-\frac{1-e^{-\alpha T}}{\alpha T}\right]\right]$$

$$+\frac{2\varepsilon S_0 T_0^5\alpha}{T\pi^4}\sum_{n=0}^{\infty}\frac{1}{4n^6\pi^2+n^4\alpha^2T_0^2}\sin^2\left(\frac{\pi nT}{T_0}\right)\sin^2\left(\frac{n\pi W}{T_o}\right)$$

This technique is divided into two performance methods, deterministic or stochastic. In deterministic pulsing, the data acquisition or multichannel -scaler is synchronized to start counting when the LINAC fires but in stochastic Feynman-alpha the counting gate opens at a random time between LINAC pulses. Previous work indicated the stochastic pulsed Feynman-alpha method (SPM) to be more effective than the deterministic method for thermal systems[3].

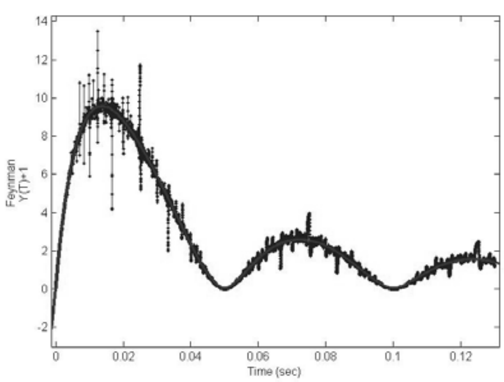

Fig. 2. The variance to mean ratio as a function of gate width and fitted curve utilizing stochastic pulsed Feynman-alpha method (20 Hz, α=205.4 ±1.4).

These methods generally assume a data acquisition system that allows multichannel scaling and variable gate times but the extraction of the current mode data from RACE-UT for the SPM was fairly straightforward using MATLAB by writing several processing routines for the large data files.

Using MATLAB, the starting time in a data file was randomly selected with longer gate widths synthesized by adding consecutive 20 μsec data blocks. This data processing method would often generate matrices with 2E9 or more elements. The mean and the variance of these synthesized data blocks were then calculated as a function of constructed gate length. The ratio of the variance to the mean (V/M) was then plotted ((Figure 2) and a curve fit of Equation 1 was generated using MATLAB. Several unique features of the RACE-UT SPM curves were not seen in previous data found in the literature due to the unique characteristics of the RF electron LINAC and the operation of the fission chambers in current mode. Beyond the expected oscillation at the LINAC period (in this case 0.05 sec or 20Hz) the plot shows several spikes in the variance at the temporal location of the fundamental LINAC period harmonics (e.g. 0.025 sec and 0.075 sec). This may be related to a cyclic, low frequency oscillation in the LINAC source intensity and pulse width previously detected by analyzing the neutron detector data visually and with a MATAB signal analysis package. These SPM curves also show essentially no dependence on the stationary source multiplicity (first term in Eq. 1) and disregarding this term usually gave a better curve fit. This indicates that the subcritical core power level was dominated by the source statistics and strength and not the fuel multiplicity. This may be due to the neutron source strength of this system being much higher than previous experiments simulating an ADSS. A comparison of reactivity measurements using SPM to the rod calibrations of Shim Safety #2 control rod with the additional correction of a known reactivity offset for the subcritical core indicates SPM is more accurate at low subcriticality levels but begins to diverge significantly as the subcritical level approaches one dollar (Figure 3).

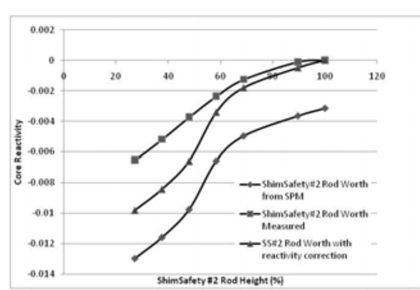

Fig. 3. Comparison of reactivity determined by calibrated control rod and stochastic pulsed Feyman-alpha method (SPM).

IV. SUMMARY AND CONCLUSIONS

The RACE-UT project has been considered a success in that a high-power, electron LINAC configured as a neutron generator was coupled to a subcritical research reactor core and operated safely for a sustained period while acquiring data for the determination of the subcritical levels. The LINAC neutron source induced significant neutron multiplication as a first, low-level step to prove that this configuration can be utilized to demonstrate simple ADSS operations. Although the RACE-UT project was handicapped by inadequate instrumentation resources, sufficient data was acquired to confirm several core models and subcriticality measurement methods. Ideally, a future experiment would operate with a more efficient source location and closer to critical (0.999 < keff < 1.0) but it is recommended that any future project of this scale be performed on a dedicated facility that could be created for educational and research purposes.

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