CURRENT STATUS OF THE NUCLEAR ENGINEERING TEACHING LABORATORY AT THE UNIVERSITY OF TEXAS AT AUSTIN

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Abstract.

The Nuclear Engineering Teaching Laboratory at The University of Texas at Austin houses a 1.1 MW TRIGA Mark II nuclear reactor. The reactor has multiple in-core irradiation facilities and five beam ports. Currently the reactor is utilized for training, research, and service work. Beam port facilities include neutron radiography, prompt-gamma activation analysis, and neutron depth profiling. Associated facilities include a radiochemistry laboratory, α spectroscopy, three Compton suppression γ-ray spectroscopy systems, two β-γ coincidence systems and a 14 MeV D-T neutron generator.

1. INTRODUCTION

A nuclear technical option at The University of Texas at Austin has been in existence for fifty-seven years. The earliest known course was Nuclear Reactor Operation and Maintenance and was first offered in 1957. Nuclear Engineering became an option in Engineering Science in 1960 and in Mechanical Engineering in 1970, where it is currently administered. In August 1963, the TRIGA nuclear reactor went critical at 10 kW. In 1968, the power was upgraded to 250 kW. In 1992 the reactor facility was moved to the Nuclear Engineering Teaching Laboratory (NETL) and upgraded to a power level of 1,100 kW(th). The reactor bay area of the new facility is shown in Fig. 1. Throughout its long history, The University of Texas at Austin nuclear program has had a commitment to educating the brightest students in the United States and abroad. This dedication which continually grows stronger now as the program has expanded to encompass health physics, radiation engineering, research reactor beam port experiments, radioactive waste management and reactor and computational nuclear engineering, homeland security and nuclear non-proliferation.

FIG. 1. NETL Bay Area.

2. FACILITIES

A cornerstone of research at The University of Texas at Austin is the Nuclear Engineering Teaching Laboratory (NETL). NETL houses a 1.1 MW TRIGA reactor with multiple in-core irradiation facilities and five beam ports. The reactor can operate in manual, automatic, square-wave, and pulse mode. In pulse mode operations can reach power levels up to 1,600 MW.

NETL has both in-core facilities for irradiations and beam port facilities for experiments. Neutron fluxes cover a wide range within the core and beam port facilities are optimized for different experiments. Facilities at NETL include:

- In Core Irradiation Facilities
  - Pneumatic Transfer Facility;
  - 3-Element Irradiator;
  - 7-Element Irradiator;
  - Rotary Specimen Rack;
  - Central Thimble Facility.
- Beam Port Facilities
  - Neutron Radiography;
  - Neutron Depth Profiling;
  - Prompt-Gamma Activation Analysis with Cold Neutron Source.

2.1. In-core irradiation facilities

NETL's in-core irradiation facilities may be utilized for sample activation. The pneumatic transfer facility and the 3-Element Irradiator have options for a lead liner and a cadmium liner. With the cadmium liners utilized for epithermal neutron irradiations, the reactor power is limited to 500 kW due to increased temperatures within the facility. Table 1 shows the in-core facilities along with their associated neutron fluxes.

TABLE 1. NEUTRON FLUXES FOR IN-CORE IRRADIATION FACILITIES

Facility	**Thermal Neutron Flux (at given power)**	**Epithermal Neutron Flux (Cd-lined Facilities)**	**Maximum Sample Size (cm)**
Pneumatic Transfer Facility	2×10^{12} cm^{-2} s^{-1} (950 kW)	5×10^{11} cm^{-2} s^{-1} (500 kW)	1.27 diameter 9.91 height
3-Element Irradiator	4×10^{12} cm^{-2} s^{-1} (950 kW)	1×10^{12} cm^{-2} s^{-1} (500 kW)	3.81 diameter 38.1 height
7-Element Irradiator	4×10^{12} cm^{-2} s^{-1} (950 kW)	1×10^{12} cm^{-2} s^{-1} (500 kW)	5.71 diameter 38.1 height
Rotary Specimen Rack	2×10^{12} cm^{-2} s^{-1} (950 kW)	n/a	2.29 diameter 11.43 height
Central Thimble	1×10^{13} cm^{-2} s^{-1} (950 kW)	n/a	3.17 diameter 38.1 height

2.2. Beam port facilities

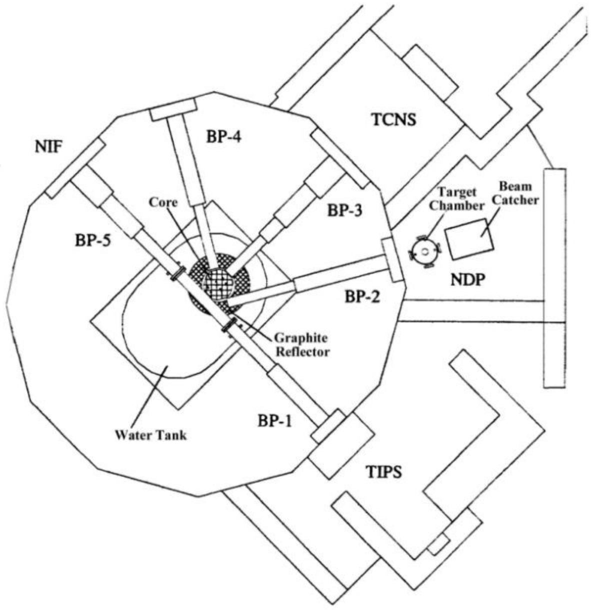

FIG. 2. Layout of beam ports.

Access to horizontal neutron beams is created by five beam tubes penetrating the reactor shield structure. All beam tubes are 6 inch (15.2 cm) diameter tubes originating at or in the reactor reflector. One tangential beam tube is composed of a penetration in the reactor reflector assembly with extensions through both sides of the reactor shield. A second tangential beam tube penetrates and terminates in the reactor reflector. The two remaining tubes are oriented radial to the reactor core.

The beam ports, shown in Fig. 2, provide tubular penetrations through the concrete shield and reactor tank water, making beams of neutrons (or gamma radiation) available for experiments. The beam ports also provide an irradiation facility for large sample specimens in a region close to the core. The five beam ports are divided into two categories: tangential beam ports and radial beam ports. The beam port facility properties are shown in Table 2.

TABLE 2. BEAM PORT FACILITIES

Beam Port	Name	Thermal Neutron Flux at 950 kW (cm^{-2} s^{-1})	Cadmium Ratio	Applications
1	Texas Intense Positron Source (TIPS) [1]	2×10^{12} (near core) 5×10^{6} (exterior)	44 (near core)	Positron imaging.
2	Neutron Depth Profiling (NDP) [2, 3]	1.2×10^{8} (exterior)	293	Depth profiling light elements such as B and Li.
3	Texas Cold Neutron Source (TCNS) [4]	5.3×10^{6} (at beam focus point)	81,000	Prompt gamma activation analysis, active interrogation techniques, and precise neutron shielding characterization.
4	Not currently in use	4.6×10^{11} (inside port)	58	Explored for fast neutron prompt gamma activation analysis. [5]
5	Neutron Imaging Facility (NIF) [6]	1.2×10^{6} (at imaging location outside of beam port)	2.6	Neutron radiography and neutron tomography.

3. CURRENT ACTIVITIES

The NETL remains a cornerstone of the Nuclear and Radiation Engineering program for undergraduate and graduate teaching, research and outreach activities.

3.1. Teaching

At the undergraduate level we incorporate experiments in introductory, senior and graduate classes. Experimental skills are important complimentary attributes to nuclear scientists and engineers. In our introductory overview course entitled Concepts in Nuclear and Radiation Engineering three laboratories in half-life determination, neutron activation analysis of uranium in geological samples and a simple shielding experiment including a tour of the reactor. The course in Nuclear Power Systems has a tour of reactor and a half-life measurement. The undergraduate/graduate course in Nuclear Operations and Reactor Engineering/Nuclear Power Engineering has two on-line reactor experiments in temperature coefficients of reactivity and low power reactor kinetics. The undergraduate/graduate course in Radiation Protection Laboratory/Nuclear Health Physics has a series of eight laboratories including gamma shielding, neutron shielding, radiation contamination verification, counting statistics, personnel monitoring, Geiger- Müller, NaI and germanium counting, and reactor radiation measurements. The graduate course in Nuclear Engineering Laboratory has experiments using the TRIGA reactor for measurement of reactor characteristics and operational parameters. The graduate course in Nuclear and Radiochemistry has laboratories in low-level counting, fission product identification, air sampling of environmental radioactivity and liquid scintillation counting and alpha spectrometry.

In recent years distance learning laboratories have been developed to support education via internet based methods. [7] These distance learning laboratories are designed to target two groups of students. The first group of students are undergraduates at The University of Texas at Austin enrolled in larger on-campus courses. The on-campus classes often have more than

30 students, and it is not practical to have all the students go to Pickle Research Campus for experiments. Distance learning laboratories are utilized in these courses to reinforce course concepts with experiments. The second group of students are off-campus, and often enrolled at other universities. For this group, two nuclear reactor based modules were developed for a collaborative distance laboratory course offered through the University Engineering Alliance. The first laboratory is on neutron radiography. The second laboratory is on the measurement of temperature coefficients of reactivity within the UT TRIGA reactor.

3.2. Research

Research at the graduate level comprises a very important aspect of the Nuclear and Radiation Program. The research is typically split up evenly between experimental and computational work. As can be expected the NETL plays an extremely important role in providing the TRIGA Mark II reactor with its in-core irradiation facilities, beam ports, ancillary laboratories and 14 MeV neutron generator for cutting edge research. As well, the NETL provides the valuable experimental know-how to students who pursue their Ph.D.'s at national laboratories in conjunction with faculty members. Below is a list of the Ph.D. and Masters of Science (M.S.) titles in the past thirteen years. Each year an average of one Ph.D. and two M.S. graduate students who receive their degrees utilizing the NETL facilities. There are also many undergraduate students who perform various experiments in conjunction with graduate students or NETL staff, are trained as reactor operators or perform service work. Often these students receive credit from their respective departments for independent research courses.

3.2.1. Ph.D. Graduates Utilizing NETL Facilities: 2002-2014

1. Characterization of Sources of Radioargon in a Research Reactor.
2. Development of Thermal Hydraulic Correlations for the University of Texas at Austin TRIGA Reactor Using Computational Fluid Dynamics and In-Core Measurements.
3. A Study of the Ferroelectric Properties of Neutron Irradiated Lead Zirconate Titanate.
4. Radioargon Production at The University of Texas at Austin.
5. PYRAMDS (Python for Radioisotope Analysis with Multi-Detector Systems) Code Used in Fission Product Detection Limit Improvements.
6. Design and Characterization of an Irradiation Facility with Real-Time Monitoring.
7. Producing Beta-Gamma Coincidence Spectra of Individual Radioxenon Isotopes for Improved Analysis of Nuclear Explosion Monitoring Data.
8. Operation and Reactivity Measurements of an Accelerator Driven Subcritical TRIGA Reactor.
9. Neutron Depth Profiling Benchmarking and Analysis of Applications to Lithium Ion Cell Electrode and Interfacial Studies Research.
10. A New Semi-Empirical Mesh-Grid Method to Predict Germanium Detector Efficiencies.
11. Hydrogen Determination in Chemically Delithiated Lithium Ion Battery Cathodes by Prompt Gamma Activation Analysis.
12. Characterization of an In-Core Irradiator for Testing of Microelectronics in Mixed Radiation Environment.
13. Development of Neutron Beam Analytical Techniques for Characterization of Carbon Fiber Composite Materials.
14. Characterization of Finnish Arctic Aerosols and Receptor Modeling.

15. Development of Composite Materials for Non-Leaded Gloves for Use in Radiological Hand Protection.

3.2.2. M.S. Graduates Utilizing NETL Facilities 2002-2014

1. Development of Fast Pneumatic System for the Study of 14 MeV Fission Product Yields.
2. 14 MeV Neutron Generator Dose Modeling.
3. Evaluation of Nylon 6,6 in Use in Fire Foe™ Suppression Systems within Plutonium Gloveboxes.
4. Determination of Fission Yields Using Gamma Ray Spectroscopy.
5. Characterization of Volcanic Ash from 2010 Mt Merapi, Indonesia Eruption by Neutron Activation Analysis and Leaching Analysis.
6. Measuring Activity of 235, 238U, 232Th and 40K in Geological Materials Using Neutron Activation Analysis.
7. Gel Electrophoresis of Trivalent Lanthanide and Actinide Cations.
8. Characterization of Neutron Flux Spectra for Radiation Effects Studies.
9. Advances in Gamma-Ray Spectroscopy: Compton Suppression and Gamma-Gamma Coincidence.
10. Mitigation of Radioxenon Memory Effect in Beta-Gamma Detector Systems by Deposition of Thin Film Diffusion Barriers on Plastic Scintillator.
11. Leaching Dynamics of Uranium Ore.
12. Comparison of the Phoswich and ARSA-type Detectors for Radioxenon Detection.
13. Determination of Silver Using Cyclic Neutron Activation Analysis.
14. Measuring Fluid Phase Change in Capillary Tubes Using Neutron Radiography.
15. Identifying Short-Lived Fission Products by Delayed Gamma-Ray Emission.
16. Design of Aerosol Sampler to Remove Radon and Thoron Progeny Interference from Aerosol Samples for Nuclear Explosion Monitoring.
17. Determination of Boron in Fuel Cell Catalysts Using Prompt Gamma Activation Analysis.
18. Compton Suppression and Nuclear Spectroscopy Techniques.
19. Light-Element Neutron Depth Profiling at the University of Texas.
20. Simulation and Measurement of Total Flux and Neutron Energy Spectra During RACE Experiments.
21. Evaluation of Hypalon and Polyurethane For Use in Plutonium Glovebox Environments.
22. Development of a Neutron Radiography and Computed Tomography Systems at a University Research Reactor.
23. Creating a Robust, Reliable, Reproducible, Automated Electrodeposition System for Analyzing Trace Quantities of Actinides.
24. Characterization of the University of Texas Nuclear Engineering Teaching Laboratory Beam Port 3 Texas Cold Neutron Source-Prompt Gamma-Ray Activation Analysis Facility.
25. Monte Carlo Simulations of Germanium Detector Efficiency Curves.
26. Development of a Transport System for the Copper Source of the Texas Intense Positron Source Facility.
27. Minimizing Glovebox Breeches in Plutonium Handling Facilities at Los Alamos National Laboratory.
28. Health Physics in a Neutron Activation Analysis Laboratory.

29. Characterization of the Prompt Gamma Neutron Activation Analysis System at the University of Texas at Austin.

3.3. Training

For many years the NETL has made its facilities open to international, national and governmental organizations for training and lecturing. As part of the Partnership for Nuclear Security (U.S. Department of State) and CRDF Global the NETL has been involved in giving short courses to several educational groups from Morocco, Indonesia, Jordan and South Africa. Presentations of nuclear security culture, non-proliferation implementation of nuclear security lectures within a nuclear engineering curriculum, overview of experimental facilities and a tour of the TRIGA research reactor.

Figure 3 shows a visit for Dr. Lyabo Usman from the University of the Witwatersrand Tebogo and Dr. Tebogo Kupi from the North West University. This visit was part of a Nuclear Security Education program sponsored by the U.S. State Department Partnership for Nuclear Security and CRDF Global.

FIG. 3. NETL Director Dr. Steven Biegalski (left), Dr. Lyabo Usman (middle), and Dr. Tebogo Kupi (right) discuss applications of radiochemistry in education.

Figure 4 shows a group of six Indonesians faculty members who visited November 6-8, 2013 from the Universitas Gadjah Mada, the only university in Indonesia offering a nuclear engineering curriculum.

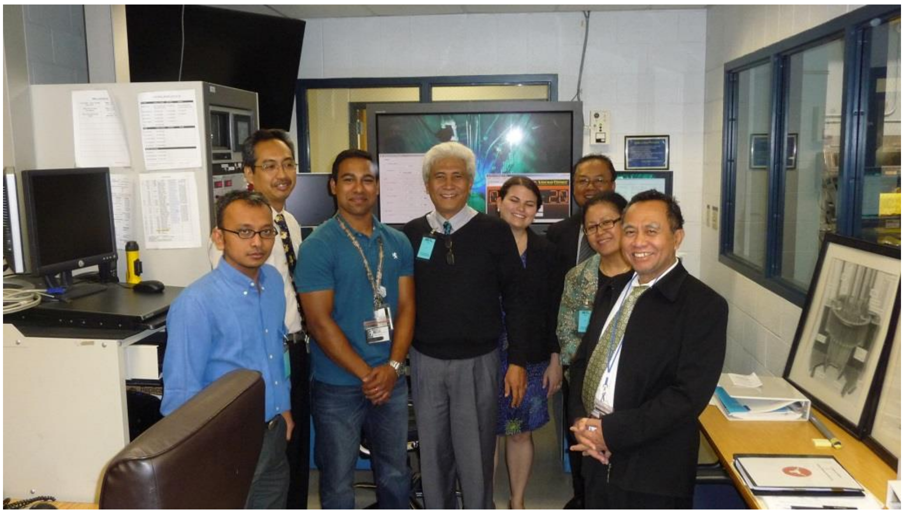

FIG. 4. Visit from Indonesian Faculty Members. From left to right are Ferdiansjah, Susetyo Hario Putero, Udit Chatterjee (reactor operator at NETL), Haryono Budisantosa, Mary Jo Sterne (CRDF), Sunaro, Ester Wijayanti, and Sihana.

In past years, the NETL has established a strong educational collaboration with the Ecole Nationale Superieure d'Ingenieurs de Caen (ENSICAEN), France. Undergraduate students at ENSICAEN are required to have an internship outside of France. While many of the students stay in neighbouring European countries, others have chosen the United States. The students are mainly involved in neutron activation analysis experiments.

The International Atomic Energy Agency (IAEA) in Vienna, Austria, in conjunction with Argonne National Laboratory in Illinois, provides fellowships to persons who are or soon will be entrusted with responsibilities which are important to the nuclear technology development in their countries. The fellowship provides the opportunity to broaden the fellow's professional knowledge and experience, and to learn new skills and up-to-date techniques. The main objective is to help fellows improve their professional competence so that they can solve scientific and technical problems related to their country's development. To accomplish this, the IAEA engages the NETL to provide hands-on training and instruction for extended time frames, typically three to four months. Over the twelve years, the NETL has hosted fellows from a number of countries including Albania, Bangladesh, China, Democratic Republic of Congo, Malaysia, Morocco, Nigeria, Portugal, Russia, Tunisia and Vietnam. Typically fellows are engaged in reactor operations training or experiments in nuclear analytical methods.

Through a three-year grant (2009-2011) from the Nuclear Regulatory Commission the Nuclear and Radiation Engineering Program developed the Summer Nuclear Engineering Institute open to U.S. and international students. The one month course involved two weeks of health physics and radiation protection laboratories and two weeks of introduction to nuclear engineering and reactor experiments. Students from the following US universities attended: Alvin Community College, Texas Southern University, North Carolina A&T State University, University of Nebraska, Kansas State University, Angelo State University, University of Texas at Arlington, Florida Memorial University, Oklahoma Christian University, Oklahoma State University, University of California at Berkeley, Texas Tech University, University of Texas at Austin, Prairie View A&M, Huston-Tillotson University, Georgia Institute of Technology, University of Wisconsin-Madison, South Dakota State University, University of California-Los Angeles and Virginia Polytech Institutes. Eight students from the National Institute of Singapore and one student from Tartu University in Estonia also attended.

Neutron activation analysis (NAA) remains an excellent technique to introduce undergraduate students to nuclear science and engineering coming from different academic areas. The NAA methods encompass an appreciation of basic reactor engineering concepts, radiation safety, nuclear instrumentation and data analysis. The NETL has continued to provide opportunities through outreach programs to Historically Black Colleges and Universities including Huston-Tillotson University in Austin, Texas Southern University in Houston and Florida Memorial University in Miami Gardens.

NETL has also hosted students from University of Tartu, Estonia, the Autonomous University of Zacatecas, Mexico, and Jordan University of Science and Technology.

3.4. Outreach

One of the important functions of the NETL is to provide outreach opportunities for the public and student organizations. The student chapter of the American Nuclear Society at the University of Texas participated in the Merit Badge University, an annual gathering of local Boy Scouts troops working with the University of Texas at Austin community to earn merit badges in a variety of topics. Members of the University of Texas at Austin student branch of the American Nuclear society, some of whom are graduate research assistants at the NETL, taught classes that helped approximately three hundred Scouts earn their Nuclear Science Merit Badges through lectures and hands-on activities demonstrating the fundamentals of nuclear radiation, radiation safety, and applications of radiation in nuclear power production, industry, nuclear medicine, and fundamental scientific research. The NETL also hosts Boy Scout troop tours as part of the merit badge process in nuclear energy.

The NETL is happy to host tours of the reactor facility and has hosted many groups over the years. Tours have been given to local high schools (Anderson, Regan, Rouse, Westwood, and Lanier); Welch Scholars and Honours Colloquium for academically talented high school students; Austin Young Chamber of Commerce, Austin Area Home-school Science, Austin Police Department, Sinopec and to several departments and groups at the University of Texas. Other universities including San Angelo State and Southwestern University send classes on a regular basis. NETL staff members have hosted a number of local tour groups like home school organizations on a repeat basis. Having people tour our facility and learn more about nuclear research is an excellent way for us to promote the discipline and foster understanding of nuclear science and its many applications.

3.5. Service work

Service work at NETL mainly falls into three categories: 1) isotope production, 2) nuclear analytical services, and 3) laboratory support. Isotope production largely focuses on tracer and calibration radionuclides. In particular, NETL has developed techniques for the production of Xe isotopes (^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe) and ^{37}Ar to support monitoring of noble gasses in support of the Comprehensive Nuclear-Test-Ban Treaty. The main nuclear analytical service provided at NETL is neutron activation analysis with both delayed instrumentation neutron activation analysis along with prompt gamma activation analysis. Neutron depth profiling, neutron radiography, radiation shielding quantification and gamma-ray spectrometry are also provided. The last category of service work is laboratory support.

This category includes the support of visiting companies and scholars to perform their own experiments at NETL.

4. CONCLUSIONS

The NETL remains an active centre for educating the next generation of leaders in nuclear science and engineering. The 1.1 MW TRIGA reactor provides a foundation for activities involving nuclear reactor operations, isotope production, and nuclear analytical techniques. Community outreach is achieved through tours, community programs, and educational collaborations. The culmination of NETL's activities provides support to the citizens of Texas, the U.S., and the international community.

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KANSAS STATE UNIVERSITY TRIGA MK II REACTOR FACILITY

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Abstract.

The history, status, and capabilities of the Kansas State University (KSU) TRIGA reactor facility are summarized. A discussion of the utilization of the facility and the potential for future upgrades is provided.

1. BRIEF HISTORY

The Kansas State University TRIGA reactor was obtained through a grant from the United States Atomic Energy Commission. Planning began in 1956, and construction of the facility commenced in 1958. Criticality was first achieved on October 16, 1962 at 8:25 pm. At the time the facility first went critical, it was one of two university reactors in the state of Kansas, with a smaller facility in operation at the University of Kansas. Now, the KSU reactor is the only research and training reactor in the state. In 1968 pulsing capability was added and the maximum steady-state operating power was increased from 100 kW to 250 kW. The aluminum-clad fuel elements were replaced with stainless-steel clad elements in 1973. With support from the U.S. Department of Energy, coolant system replacement was completed in 1993, as was replacement of the reactor operating console, and enlargement and modernization of the reactor control room. All neutronic instrumentation was replaced in 1994 [1]. In 2008 the reactor license was renewed and the maximum power level was upgraded to 1250 kW.

Another significant event occurred in 2008 when the facility was struck directly by an EF4 tornado. The roof was severely damaged, but the reactor core, control, and safety systems were unharmed. The reactor resumed operations within a week following the tornado strike.

2. CURRENT TECHNICAL STATUS

The KSU TRIGA reactor is currently licensed to operate at 1250 kW of thermal power. A license amendment request is pending which will allow the reactor to approach closer to this power level by loading 12 weight percent fuel elements in place of four of the 8 weight percent elements currently in use. However, at the present time, due to the lack of sufficient reactivity to overcome the strong negative temperature coefficient of reactivity characteristic of TRIGA reactors, the reactor is limited to approximately 650 kW of thermal power. The reactor is equipped with four beam ports, a thermal column for dry irradiation experiments in a thermal neutron field, a thermalizing column for submerged thermal neutron irradiation experiments, a rotary specimen rack (RSR) well for submerged experiments in the reflector region, and a central thimble for submerged experiments in the center of the core. Of these facilities, all four beam ports are operable and have been used for experiments over the past four years. Two of the beam ports are known as radial beam ports, and terminate at the outer edge of the graphite reflector. A tangential beam port penetrates the reflector but does not point directly at the reactor core. Finally, a piercing beam port penetrates the reflector and terminates at the outside of the core to provide a relatively high-flux, hard source of neutrons. One of the two radial beam ports is equipped with a graphite monochromator, which diffracts neutrons through a collimator set at the Bragg angle for 0.025 eV neutrons, and can provide about 1.2×10^4 $n \cdot cm^{-2} \cdot s^{-1}$ of monoenergetic 0.025 eV neutrons at 100 kW of reactor power [2]. Therefore the reactor has four beam ports, each with a different average neutron energy and flux per unit reactor power.

The central thimble is operable and is frequently used for neutron activation analysis (NAA) and other neutron transmutation experiments. The RSR well is still in use, but the RSR itself was removed from service because it was broken and welded shut, which prevents its repair, as the weld is radioactive. Instead of using the RSR, samples are manually lowered in polymer and lead sample racks. The reactor is also no longer equipped with a helium-driven sample transfer system (rabbit). The terminus of the rabbit was removed to increase the space available for nuclear fuel. However, there is no significant technical obstacle to re-installing the rabbit terminus should the need arise, and all of the equipment necessary to operate the rabbit was in working order when it was removed from service. A student design team is presently engaged in designing a new automatic sample insertion device that will occupy a portion of the RSR well. This new device will provide functionality similar to that of the old RSR, with the capability to independently raise and lower six samples into the reflector region. The device will also include a new terminus for the rabbit, so that the rabbit can be reinstalled without requiring a vacant fuel lattice location. The thermalizing column is out of service due to the apparent flooding of the inside of the thermalizing column with water, which greatly reduces the neutron flux in the bulk shield tank, the intended location for experiments using neutrons transmitted through the column. The repair of the thermalizing column would require the bulk shield tank to be drained so that the thermalizing column could be opened and re-sealed. The thermal column is not operational because the casters and tracks for the thermal column door are rusted. These could be repaired should the need arise. However, the repair is costly and will only be undertaken if needed for a funded research project. (The rusting of the thermal column tracks and casters was caused by the facility sump back-flowing into the thermal column tracks, which are recessed into the floor with a drain to the sump). When operational, the thermalizing column and thermal column provide a means for conducting submerged and dry thermal neutron irradiation experiments (respectively). Figure 1 shows a cross-sectional view of the reactor core and biological shield, with all of the beam ports, thermal column, and thermalizing column. Table 1 lists the neutron flux and gamma dose at 250 kW(th) reactor power for various irradiation locations, and Table 2 provides characteristics for two of the four beam ports.

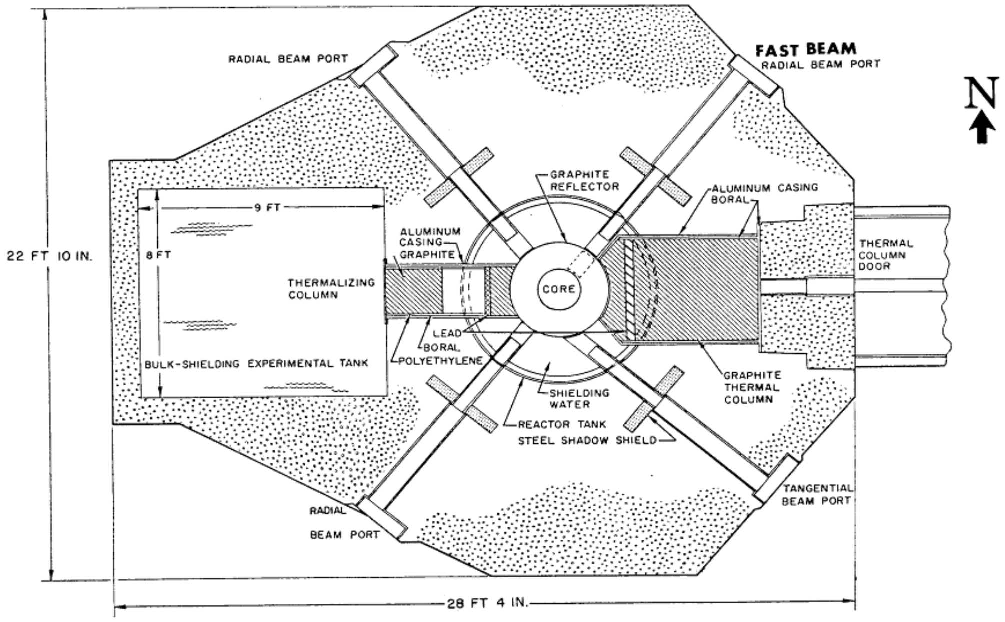

FIG. 1. Cross-sectional view of KSU reactor core, beam ports, and biological shield.

TABLE 1. DOSE RATES AND FLUXES AND EXPERIMENTAL LOCATIONS

	Neutron fluxes and Dose rates at 250 kW		
	Fast, $cm^{-2}\cdot s^{-1}$ (>10 keV)	Thermal, $cm^{-2}\cdot s^{-1}$ (<0.21 eV)	Gamma (Sv/s)
Central Thimble	1.2×10^{13}	1.0×10^{13}	250
"E" Ring	6.4×10^{12}	4.1×10^{12}	150
Pneumatic transfer system (F-ring rabbit terminus)	3.5×10^{12}	4.3×10^{12}	150
Piercing beam port next to core	2.0×10^{12}	2.0×10^{12}	100
Rotary Specimen Rack	1.5×10^{12}	1.8×10^{12}	40
Reactor pool outside reflector	6.8×10^{10}	6.8×10^{11}	4.5
Reactor pool inside reflector	1.1×10^{11}	3.4×10^{11}	---------

TABLE 2. GAMMA EXPOSURE RATES AND NEUTRON FLUXES AT SELECT BEAM PORTS PER WATT OF REACTOR POWER

	Total neutron flux ($cm^{-2}\cdot s^{-1}$)	Flux-avg neutron energy (MeV)	Neutron dose rate (μGy / h)	Gamma exposure rate (X)
Piercing Beam Port	1700	0.5	640	2.3×10^{-5}
Tangential Beam Port	560	0.1	69	4.4×10^{-7}

The reactor is operated primarily by undergraduate students in the Mechanical and Nuclear Engineering department at the university. There are typically two student senior reactor operators, four student reactor operators, and four students in training at any given time. Only the Reactor Manager is a full-time staff member. The extensive use of student operators helps maintain a low cost of operation, but adds challenges related to the constant need to train new operators to replace graduating students. The use of part-time operators also allows significant flexibility in the operation schedule of the reactor.

3. APPLICATIONS AND UTILIZATION EXAMPLES

The reactor facility is heavily utilized by Kansas State University for teaching and outreach activities. The facility receives approximately 2500 visitors per year on tours, with slightly more than half coming from off campus. Two laboratory classes, NE 250: Reactor Operations Lab, and NE 648: Nuclear Reactor Lab, utilize the reactor on a weekly basis, with students operating the reactor under instruction to take laboratory data. Many other classes utilize the reactor for sample irradiation, end-of-semester projects, neutron detector testing, and tours. The reactor also occasionally serves as a customer for senior design (i.e., capstone) projects for nuclear engineering students. Past senior design projects conducted for the benefit of the reactor facility have included a shield and beam port design for a neutron radiography system, a gamma cell facility, and a silicon irradiation facility.

Many off-campus groups visit the reactor, including: elementary school gifted and talented programs; 4-H and Boy Scouts; STEM outreach for under-represented groups; public and private high schools; military groups; engineering summer scholarship programs; and regional colleges and universities.

The primary research applications of the reactor are neutron activation analysis [3], radiation detector testing, and gamma irradiation. The reactor facility has multiple high purity germanium (HPGe) detectors and spectroscopy apparatus for neutron activation analysis. Other neutron transmutation experiments can also be performed using the reactor. Another common research application of the KSU reactor is detector testing. One detector beam port produces monoenergetic 0.025 eV electrons through a diffractometer; this beam is ideal for testing neutron detectors for efficiency and response [2]. The reactor can also be used to test instrumentation in the core. An array of 8 mm holes in the upper grid plate can accommodate flux wires or other small devices, and has been previously used to test micro-pocket fission detectors [4]. Finally, the reactor is used to perform decay gamma irradiation experiments (up to ~20 Sv dose) by lowering samples next to the outer reflector in a rotating drum immediately following reactor shutdown.

4. FUTURE PROSPECTS

The future of the Kansas State University reactor facility is secure, primarily due to the heavy utilization of the facility for University outreach activities and classes, the growth in the number of faculty and students in the KSU nuclear engineering program, and the low cost of operations due to the facility's heavy reliance on student operators. However, prospects could further improve if the facility could secure a broader portfolio of research clients. To this end, the facility should be promoted to research universities and businesses within the state of Kansas and nearby states without research reactors, such as Oklahoma and Nebraska. Ideally, the reactor facility should bring in enough money through consistent research support that the facility could afford to hire an additional professional staff member to assist the reactor manager. So doing would free the reactor manager to focus on further improving the research portfolio of the facility, and would improve the overall level of professionalism at the facility as well.

The prospects of the reactor facility will also be improved by adding or restoring research capabilities. For example, an effort is underway to replace the rotary specimen rack and rabbit system. The facility may also pursue the licensing and installation of a cobalt gamma irradiation cell, which has already been designed and constructed.

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THE UNIVERSITY OF UTAH NUCLEAR ENGINEERING PROGRAM

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Abstract.

As of 2014, the University of Utah Nuclear Engineering Program (UNEP) manages and maintains over 7,000 ft^2 (~650 m^2) nuclear engineering facilities that includes 100 kW TRIGA Mark I and numerous laboratories such as radiochemistry, microscopy, nuclear forensics, nuclear medicine, radiation detection and instrumentation laboratories. The UNEP offers prestigious educational and training programs in the field of faculty reserach: reactor physics, reactor design and operation, advanced numerical modeling and visualizations in radiation transport, radiochemistry, nuclear forensics, radiation detection and detector designs, signal processing, nuclear medicine, nuclear space and nuclear robotic's engineering and radiological sciences. With the state-of-the-art nuclear instrumentation and state-of-the-art numerical modeling tools, reserach reactor and modernized educational and training programs, we positioned ourselves in the last five years as the fastest growing national nuclear engineering program attracting the students from many disciplines such as but not limited to: chemical engineering, civil engineering, environmental engineering, chemistry, physics, astronomy, medical sciences, and others. From 2012, we uniquely developed and implemented the nuclear power plants' safety culture paradigm that we use for day-to-day operatation, management and maintainance of our facilities, as well as train all our students at undergraduate and graduate levels of studies. We developed also a new distance-learning approaches in sharing knowledge about experiential learning based on no-cost internet-tools combined with the use of mobile technologies.

1. UTAH NUCLEAR ENGINEERING PROGRAM BRIEF HISTORY

1.1. UNEP location and brief history

The Utah Nuclear Engineering Program (UNEP) is located on the campus of the University of Utah in Salt Lake City, Utah, U.S.A. The University of Utah TRIGA Reactor (UUTR) is a Mark I TRIGA reactor that reached its first criticality in 1975. The UUTR is licensed to operate at 100 kW(th). The reactor is established as a university-wide facility to promote *research, education and training* in nuclear engineering, radiochemistry, nuclear forensics, radiation science, nuclear medicine and health physics. It is used for training the students to operate the reactor, for various experiments such as but not limited to Neutron Activation Analysis (NAA), materials irradiation studies, nuclear medicine, and on-line analysis of radiation effects on NEMS/MEMS devices, in addition to numerous laboratories for our undergraduate and graduate classes; and many more.

In the late 1980's the University of Utah decommissioned a 5 W(th) AGN 201 reactor that was located close to the UUTR; the empty vessel is used for demonstrations on AGN internals and soon to become a simulator tool. At the same time a Fast Neutron Irradiation Facility (FNIF) was added into the UUTR pool. In the 1990's the UUTR reactor control console was upgraded with digital equipment and a radiochemistry lab and class 100 clean rooms was added to the facility. In May 2007 the pneumatic irradiator (PI) facility was added for irradiation experiments. In December 2011, we installed the grating over the rector pool (the grating is removed for every reactor run, but remains intact during non-operational hours). In April 2012, we established the safety culture practices, and we operate and maintain the whole facility under the DevonWay ("Track & Trace") corrective action program. With this approach, we became the first University research facility that mirrors the rigor of nuclear power plant operation and maintenance, and as well have it became an integral part of training and education of our students. From July 2013, we introduced novel to academia, but known to nuclear industry, approaches and practices in training our students using dynamic learning activity laboratory settings and human performance tests for building novel skills in students as expected in nuclear industry and national labs world-wide. In January 2014, we have expanded our facilities and expertise into radiochemistry, analytical nuclear forensics and detector developments.

UNEP educational and training programs were revitalized starting from the autumn of 2009 to include a Minor in Nuclear Engineering for undergraduate students, a newly structured graduate program developed with the goal to create the degrees in nuclear engineering subfields of immediate and future needs in the U.S.A. (nuclear power engineering, nuclear forensics, nuclear medicine, and nuclear detection, to mention the four most important ones), and new training programs for reactor operation. Our program, as of 2014, is one of the smallest nuclear engineering programs in the U.S.A., but the fastest growing Programs: number of faculty (only three), however in the number of students per undergraduate classes (between 30 to 53), and in the number of graduate students (reaching 35), we are becoming competitive with the historically well-established and nationally high-ranked nuclear engineering programs. Our popularity among the students rose in just the last few years with new administration taking over the development of the Program, and for these reasons: we have modernized our educational programs adding many new innovative approaches never used before in teaching and training, such as for example an integrated use of our facilities (research reactor and associated labs) including the experiments coupled with numerical modelling and simulations of the basic principles covering the operation of our facilities, or novel approaches in training our students for future nuclear jobs, as it is the DevonWay software in promoting and learning the safety culture never before applied to a university learning curriculum [1].

UNEP follows the University of Utah's mission to provide excellence and equal opportunity in the areas of education, research, and public service. The mission of the UNEP is to advance education and promote R&D in supporting nuclear science and engineering in line with the nation's nuclear energy challenges.

UNEP is nested within the Department of Civil and Environmental Engineering of the University, but maintains its own administrative office where UNEP admissions, graduate student records, and other program business are processed.

The UNEP is an independent Program that draws students from a wide variety of academic backgrounds, and utilizes the resources and expertise of engineering faculty from all of the following areas to meet the academic and research needs of nuclear engineering graduate students:

- Chemical Engineering (CHE),
- Civil and Environmental Engineering (CVEE),
- Mechanical Engineering (ME),
- Bioengineering (BIO),
- Physics and Astronomy,
- Chemistry,
- Material Science and Engineering,
- Computer Science and Engineering,
- School of Medicine,
- School of Law,
- School of Business,
- Biology,
- Geology,

- Earth Sciences,
- Metallurgy,
- Forensics Sciences.

In summary, UNEP underwent a dramatic transformation in the autumn of 2009 with the goal to expand the Program curriculum and develop new research endeavours attractive to current student generations while addressing the needs and expectations of the today's nuclear industry in the nation and world-wide. The changes in the Program from 2009 are summarized in brief as follows:

Nuclear Engineering Minor was developed in 2009 and approved by the Board of Regents in May of 2010; the Program started in autumn of 2010 with the goal to increase the number of students in UNEP, recruit and retain increased number of graduate students, and provide a unique education for engineers in demand by the State, nation and the world;

Senior Reactor Operator Training Program was established in 2010 with the goal to prepare the students in obtaining their licenses to operate the TRIGA reactor at the University Utah managed and operated by the staff and faculty of the Nuclear Engineering Program (as indicated in Fig. 1).

Graduate Program Curriculum was advanced in spring of 2010 to meet the challenges of the 21st century nuclear industry and national needs including but not limited to: safe, secured and green energy; advancement in medicine; materials science and engineering; space science and engineering; nuclear forensics; radiochemistry; and agriculture. From a handful number of graduate students in autumn 2009, the UNEP graduate student body increased to 35 as of autumn 2013.

Outreach Program was revitalized in reaching students from elementary to high school students, other universities, governmental organizations, industry and first responders in the region and beyond.

1.2. UNEP mission and vision

Vision: The faculty and staff of the Nuclear Engineering Program at the University of Utah (UNEP) are committed to excellence in providing and sustaining high quality education, research and training programs with the forefront achievements in preparing nuclear engineers to provide effective, yet innovative solutions to the national and world's challenges in sustaining safe and reliable energy generation, advancing human health condition, and safeguarding the nation, in care for all segments of contributing to advanced and safe human lives.

Mission: The mission of the UNEP is to provide the highest quality environment in fostering education, research, and training in nuclear engineering by creating opportunities for creative and critical thinking in building technically challenging, innovative, and leadership skills in our students, as well as, in assuring life-long learning skills are supported by experiential training and hands-on schooling for innovation to our profession in benefiting the State of Utah, Nation and the World.

Graduate students together with UNEP staff and faculty, strive collegially to inspire, teach, and train the next generations of nuclear engineers through the exploration of innovative ideas, solutions, and creation of new technologies in support of positive change of improved conditions for sustainable, safe, and healthy human lives.

Organization as of 2014: The Program is financially independent although administratively supported by the Department of Civil and Environmental Engineering. The UNEP Director, Prof Tatjana Jevremovic, has appointments in two Departments, the Department of Civil and Environmental Engineering, and the Department of Chemical Engineering. Other faculty that constitutes the UNEP are housed in the Department of Civil and Environmental Engineering. The UNEP faculty participate in the Program's and the Departments' Committees in the College of Engineering. The Program houses and is solely responsible for over 7,000 ft^2 (650.32 m^2) facility that includes 100 kW TRIGA (research reactor) and numerous state-of-the-art laboratories. The Program Director is at the same time a Director of the overall facility, and the Director of the TRIGA facility with all responsibilities as defined by the U.S. Nuclear Regulatory Commission. As of 2013-2014, there are two Reactor Supervisors, and a few senior reactor operators and reactor operators. Besides the reactor facility supervisors, as of 2012-2014, the laboratories are managed by the Laboratory Planner and Analyst, a position that was established in 2012. All the facility positions, as described, are filled by the UNEP's graduate students, except for one Reactor Supervisor, Ryan Schow, who is employed as a staff. More details on staff can be found in Section 2.

2. UNEP CURRENT TECHNICAL STATUS

2.1. UNEP infrastructure and utilization capabilities

UNEP houses a number of laboratories divided into the blue and the white wing. The white wing includes the microscopy laboratory (Fig. 1), the nuclear instrumentation and measurement laboratory (Fig. 2), the nuclear forensics laboratory (Fig. 3), and the radiochemistry laboratory (Fig. 4) with additions used for nuclear medicine and sensitive biological-related experiments. The microscopy lab is equipped with the high-resolution microscopes and associated electronics. With the grant from DOE, the nuclear forensics laboratory has been equipped with four new radiation counting stations including novel gamma and alpha spectrometry instrumentations. The nuclear instrumentation and measurement laboratory is where the majority of the Neutron Activation Analysis (NAA) counting is taking place. In addition, the lab is also equipped with a liquid scintillator counting station, scintillation detector station, two TLD readers and the workbenches. The radiochemistry laboratory was mostly designated to the lab sessions for one of our most popular, the radiochemistry class; since the class increased to over 60 students on average in the last couple years, we have moved the class labs to another location. At the same time, the number of students at UNEP increased 300% in 2013 when compared to the number of students in 2011; this lab space is therefore now dedicated to the research experiments and benches are divided into sections assigned to undergraduate and graduate students' research projects. Additionally, this lab is also used for the NAA samples preparation, [1]. In the white wing starting from July 2013, we have a dynamic learning activity laboratory used to train the students on human performances error reduction.

The blue wing houses our TRIGA and the facilities related to its operation: reactor control room, the reactor room, fuel inspection room and in addition the nuclear museum area (Figs 5 and 6). The use of both wings, the blue and the white wing, includes on average 50 – 80 students per year in doing their labs or research, and a number of faculty coming from other departments with the requests to use our facilities for advancing their own research ideas.

FIG. 1. Microscopy Laboratory.

FIG. 2. Nuclear Instrumentation and Measurement Laboratory and Exhibition Table.

FIG. 3. Nuclear Forensic Laboratory (one section).

FIG. 4. Radiochemistry Laboratory.

Our TRIGA has a number of vertical irradiation ports that present a great asset for carrying out numerous and diversified types of research related experiments. It is also providing us with the capabilities to offer a service to interested parties in using our facility for their own research such as but not limited to NAA of various types of samples (core samples from various mines, irradiation of metals, ceramics and other materials of interest to nuclear and space engineering), on-line (in-time) monitoring of NEMS/MEMS performances under irradiation at various reactor power levels, and nuclear medicine related investigations (mainly studies including the cell-line experiments). We use TRIGA facility for training the students interested in receiving the operational license. The training consists of two consecutive graduate level classes followed by additional three-months training during the summer session. The operational license's exam is administrated by the U.S. NRC (Nuclear Regulatory Commission) at our site. A number of laboratory practices are developed as a part of our on-going undergraduate and graduate classes; examples are: reactor power change due to control rods movements, criticality, Cherenkov radiation, NAA, effects of radiation on various materials and similar. A number of laboratory practices involving running our reactor is combined with the use of our equipment and instrumentation housed by the white wing, such as for example counting the samples after activation in a reactor using gamma spectroscopy stations, or analysis of samples for alpha emitters, and many more.

FIG. 5. UUTR Reactor Bridge.

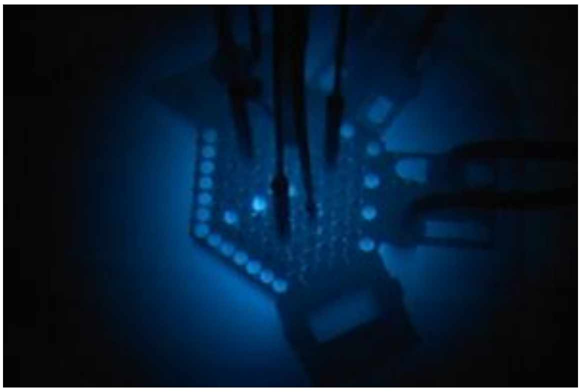

FIG. 6. UUTR Core Operating Showing the Cherenkov Radiation.

2.1.1. Safety Culture: Corrective Action Program and Dynamic Learning Activity Training at UNEP

Corrective Action Program. Regardless of our well-established safety and security practices covering the operation and maintenance of all the facilities housed by both wings, establishing an industry-approved and industry-wisely used corrective action program, we provide a new way in training our students for the future jobs, as well as a novel environment at university settings in teaching all involved (faculty and students) of the importance and values in learning and applying the safety culture principles. This is the first step in demonstrating nation-wide the importance to start operating and maintaining our university nuclear engineering research facilities through certified general action tracking processes [1-5].

A new generation of nuclear engineers and workforce needs to be trained to meet the needs of the nuclear industry. The current nuclear workforce is approaching retirement and as they retire, they will take with them a large amount of experience and knowledge. New methods to meet the needs and styles of learning for the younger generation need to be developed and employed to fill the nuclear workforce void. The new generation of nuclear workers are accustomed to being connected with technology, but have a limited background with lessons learned and what makes nuclear different and special. Establishing a strong nuclear safety culture is a vital part of the process for training the new nuclear workforce. [5]

A corrective action program (CAP) is an integral part of maintaining and establishing a nuclear safety culture. The Nuclear Energy Institute (NEI) released a document titled Fostering a Strong Nuclear Safety Culture, NEI 09-07. In this article, they gave a flow chart for a Site Nuclear Safety Culture Process. We at UNEP, modified and developed a flow process very similar to the one given in NEI 09-07. Figure 7 shows the nuclear safety culture process being implemented at UNEP. It can be seen that the CAP is an integral part of the Safety Culture Process and is well incorporated into UNEP's framework. Specifically we use the "Track and Trace" software component of the DevonWay CAP system.

The "Track & Trace" software program is used to manage our daily activities, such as maintenance, merchandise acquisition and to record corrective actions regarding potential incidents; the following four types are created under the "Track & Trace" software:

- Maintenance for the UNEP Reactor Facility;
- Maintenance for the UNEP Laboratory Facility;
- Purchasing;

- Incidents.

Each of these four types follows its own specific action workflow. All of these workflows are designed by UNEP faculty and students with the help from DevonWay. Our students are trained on regular basis in this new corrective action program since April 2012; all actions are recorded under the DevonWay highly secured cloud [2, 3, 4, 5].

Dynamic Learning Activity Laboratory and Training in Human Performance Error Reduction. A dynamic learning activity (DLA) was developed in 2013 at UNEP and was implemented starting spring session of 2014 in all classes and laboratories to introduce and establish the nuclear safety process to all incoming and new students. Students involved with laboratories and classes in UNEP receive training with the expectation that everyone is responsible for documenting deficiencies or areas for improvement and entering them in the DevonWay software [2, 3, 5].

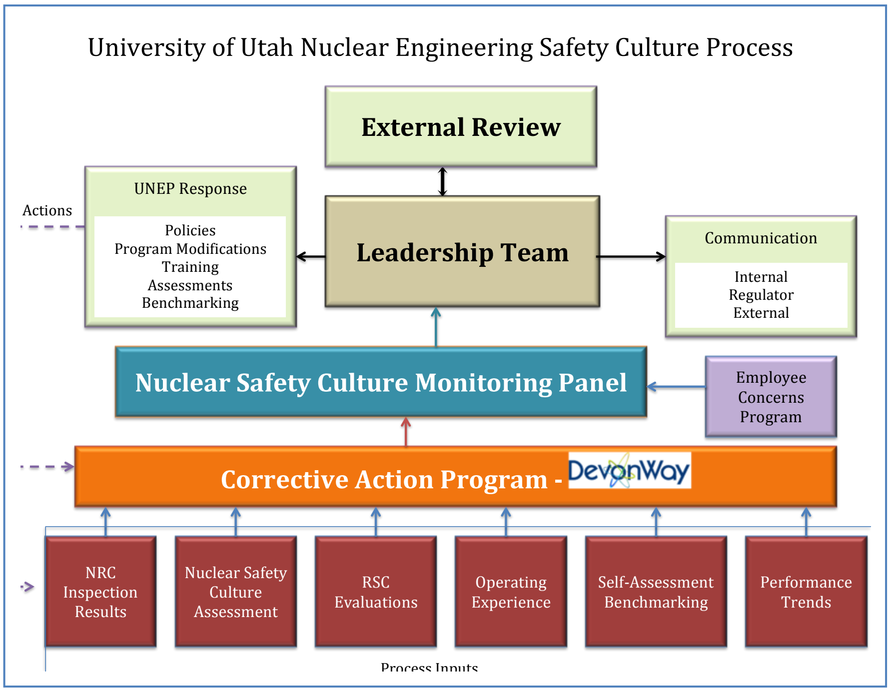

FIG. 7. UNEP Safety Culture Flow Chart [5].

The DLA includes a training on human performance error reduction techniques that are used in the industry such as STAR (Stop, Think, Act, Review), critical steps, verification techniques, procedure use and adherence, and communications. Another important aspect that is presented in the DLA is proper methods of coaching that should be implemented in the nuclear environment. Finally, hazard identification and practical exercises have been developed to test the students comprehension and internalization of concepts presented in the DLA. Mock up work stations are set up in the laboratory environment at our white wing part of the facility. The students must identify hazards and demonstrate proper coaching techniques in order to pass the activity and be permitted to conduct research in the facilities as seen in Fig. 8 [4, 5].

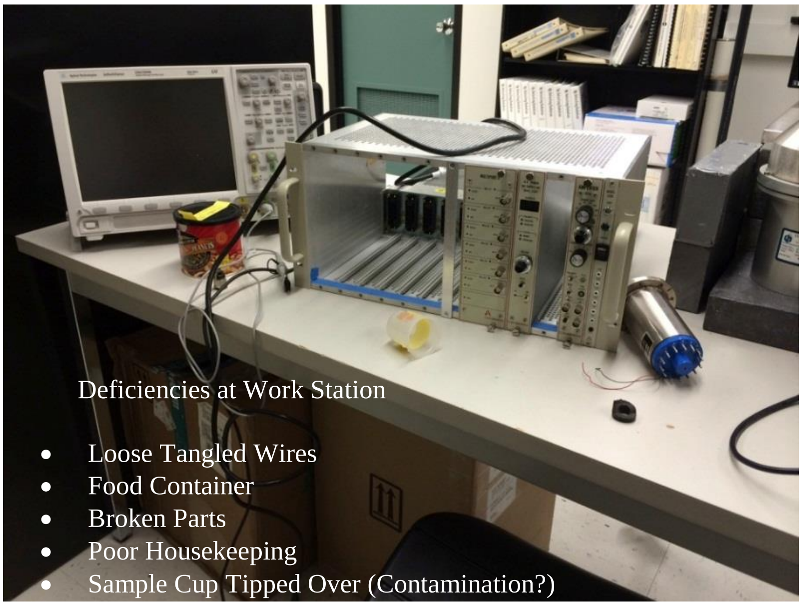

FIG. 8. UNEP DLA Mock-Up Work Station Deficiencies (Beginning of Semester)[5].

2.2. Distance learning classes in sharing THE NAA experiential learning practices

UNEP and the Catedra de Radioquimica from Montevideo in Uruguay, together, have created a real-time practice on neutron activation analysis, more specifically on how gamma spectra systems operate and how we measure the samples after irradiation in a research reactor. We call this a digital NAA class that we developed in 2012, and we offer it since then, every year. Our practical exercise consists of sending unidentified gamma spectra we generate within our NAA experiments in our reactor, to the group of students at the University in Montevideo in Uruguay. After a week from sharing these spectra, we connect again through the Skype-system to discuss the elements as detected and shown in these spectra. Some different specimens used for examples in the NAA shared were various fruit seeds, different kinds of cigars, and different human fingernails. We develop detailed discussions on the meaning of the spectra and provide final analysis on the nature of the samples. The class includes graduate and undergraduate students from both programs in live discussion and exercises on neutron activation analysis, [4, 5, 6]. The digital class on NAA attracts many students from UNEP and in Montevideo, showing that the class is well structured and beneficial to all involved.

2.3. UNEP staff as of 2014

Professor Tatjana Jevremovic, joined UNEP in 2009 as the Energy*Solutions* Presidential Endowed Chair Professor in Nuclear Engineering and Director of UNEP and nuclear engineering facilities. She is also a professor of civil and environmental engineering, and professor of chemical engineering. She received her BS and MS degrees in nuclear engineering from the University of Belgrade, Serbia and the PhD from the University of Tokyo, Japan. Prior to moving to Utah, she worked as a project manager in Energoprojekt Co., in Belgrade (Serbia); after that she has spent 11 years in Japan where she worked as a professor at the University of Tokyo for two years and as a Chief Engineer in Nuclear Fuel Industries, Ltd. for close to six years. In 2001, she relocated to Purdue University, in Indiana in USA where she stayed until 2009. She has published over 200 papers in journals and conferences, and she authored the book, *Nuclear Principles in Engineering*, published by Springer. She serves at many committees nationally and internationally, and she is a consultant to IAEA. She developed the neutron transport codes ANEMONA (while at NFI in Japan), and AGENT code with her students while in USA. In 2014, she advises over 30 students in their individual research projects. Her research interests include: reactor physics, advancements in neutron transport modelling and visualizations, nuclear medicine, nuclear forensics, research reactor experiments, new nuclear materials (specifically new concrete designs), use of neutron activation analysis in many various science and engineering fields, Gen IV designs, and application of various new technologies (such as mobile technologies and FPGAs) in reactor physics and radiation transport. At UNEP, she developed and started the Minor in Nuclear Engineering in 2010 that on average enrols around 30 undergraduate students yearly; she has also revitalized the graduate programs and increased enrolment from handful in 2009 to over 30 students yearly starting from 2011. From 2012, she has established a new operational, educational and training paradigm at UNEP research reactor facility and associated labs, the safety culture in mirroring the rigor of nuclear power plant environment.

Professor Luther McDonald joined the faculty in UNEP in January 2014 after serving as a postdoctoral fellow in National Technical Nuclear Forensics at Pacific Northwest National Laboratory (PNNL). Previously, he studied the extraction and identification of inositols and O-methylinositols from plant roots under the supervision of Dr. James Campbell (PNNL). In January 2010, he joined the research group of Professor Sue Clark at Washington State University (WSU) as a Distinguished WSU/PNNL Graduate Fellow of Radiochemistry. There he developed rapid, inexpensive, in-line analytical monitoring tools which could be used to follow the flow of U, Pu, and minor actinides through a reprocessing facility. He then performed research as a visiting scientist at the Commissariat à l'énergie atomique (CEA) in Saclay, France where he developed mass spectrometric methods for the characterization of uranium and plutonium complexed to tributyl phosphate and dibutyl phosphate. Professor McDonald currently serves as the Secretary of the American Chemical Society's Division of Nuclear Science and Technology. He joined the faculty at UNEP to educate students on the fundamental and applied aspects of nuclear forensics including analytical chemistry, environmental radiochemistry, the nuclear fuel cycle, and advanced nuclear instrumentation design. At UNEP, Professor McDonald manages approximately 2,000 sq. ft. of wet chemical laboratories. These laboratories are currently being used in teaching and research of environmental radiochemistry and analytical nuclear forensics. The laboratories are well-equipped with instrumentation including an automatic titrator stocked with a variety of electrodes for determining acid dissociation constants and stability constants, a high resolution quadrupole-time-of-flight mass spectrometer with both electrospray ionization and atmospheric pressure chemical ionization, and a dual beam UV-VIS with a Multicell Peltier controlled autosampler that is temperature regulated from -10 to 100°C.

Ryan Schow is the new Reactor Supervisor and has held this position since June 2013. Ryan graduated in December 2001 from the University of Utah with a Bachelor of Science Degree in Mechanical Engineering. Ryan brings a broad range of nuclear experience from both the Navy and Nuclear Utility Industry to UNEP. He was stationed on the USS OHIO (SSGN 726), home ported in Bangor, WA. While on board the USS OHIO, he served as the Electrical Assistant, Reactor Controls Assistant, Chemistry and Radiological Controls Assistant, Assistant Engineer, as well as taking part in the first OHIO class refueling, over-haul, conversion, and sea trials process. Ryan most recently came from American Electric Power's D.C. Cook, Nuclear Power Plant, in Bridgman, MI. He was licensed with the Nuclear Regulatory Commission (NRC) as a Senior Reactor Operator (SRO) on both D.C. Cook Units 1 and 2 and was working as a Unit Supervisor. Ryan currently holds a SRO

License for operating the UUTR and oversees all day-to-day operations and experiments in the blue and white wings.

From 2012, we developed a new practice in hiring our graduate students on the year-basis rotation, to help with the facility. The Laboratory Planer and Analyst, and Senior Reactor Operator / Reactor Operator are the three positions reserved for graduate students who showed the best skills and the highest interest in working at the facility. These students then train a new group of students interested to have one of these positions for the coming academic year. We find this approach highly beneficial to operation of our facility and to the students in providing them with new set of skills, knowledge and practical experience. From 2009, we try to have on average two Post Doctoral fellows at the time who, besides doing their own research, are occasionally asked to teach or help with the class laboratories; they also work closely with our graduate and undergraduate students in helping their research efforts.

3. APPLICATIONS AND UTILIZATION EXAMPLES

Safety Culture – UNEP is the first university research reactor to implement a safety culture initiative and formal corrective action program (CAP). Regardless of our well-established safety and security practices covering the operation and maintenance of all the facilities, establishing an industry proven CAP, has provided a new way in training our students for the nuclear industry and the importance and values in learning and applying the safety culture principles. This is the first step in demonstrating nation-wide the importance to start operating and maintaining our university nuclear engineering research facilities through certified general action tracking processes. UNEP has selected software developed by DevonWay [2] called “Track & Trace” to implement a corrective action tracking program [1]. DevonWay software is in use by many nuclear power plants in the industry to meet their CAP needs, [3]. The software is web-based and hosted by DevonWay in its certified data center. The software is also being used to track purchasing and maintenance processes as well. Students will be well prepared to enter the workforce and understand the corrective action process and be able to immediately add value to their organization of employment.

Essential parts of establishing an effective nuclear safety culture in a University/Research setting is using modern technology and tools and centering it on a useful CAP. The University of Utah Nuclear Engineering Program is working with industry, social media, and other research facilities to bring about a new and modern training program for the new nuclear workforce. UNEP has also developed an interactive safety culture laboratory and is tracking how students implement human error reduction techniques, [4 - 6].

Amount of students and faculty usage of the reactor facility – During the past five years, our facilities have been utilized by over 130 graduate students and close to 230 undergraduate students. The purpose of our facilities usage is multi-fold: undergraduate students practice basic principles and knowledge pertaining to nuclear energy and associated disciplines; facilities and UUTR are used for research or laboratory training. All UNEP faculties and the associated faculty (over 20) use regularly UUTR and associated labs, either as an integral part of their teaching commitments or their on-going research activities. UNEP graduate students, scientists, visitors and postdocs use the facility for their research.

Variety of research provided by UUTR and UNEP – The UNEP research is extensive and spans between the reactor physics and neutron transport modelling, experimental measurements and benchmarking, to nuclear medicine, nuclear forensics, signal processing, radiochemistry and development of new nuclear engineering materials. A very few examples follow (our research portfolio is very extensive, thus we have selected just a few aspects of our research to describe in this paper):

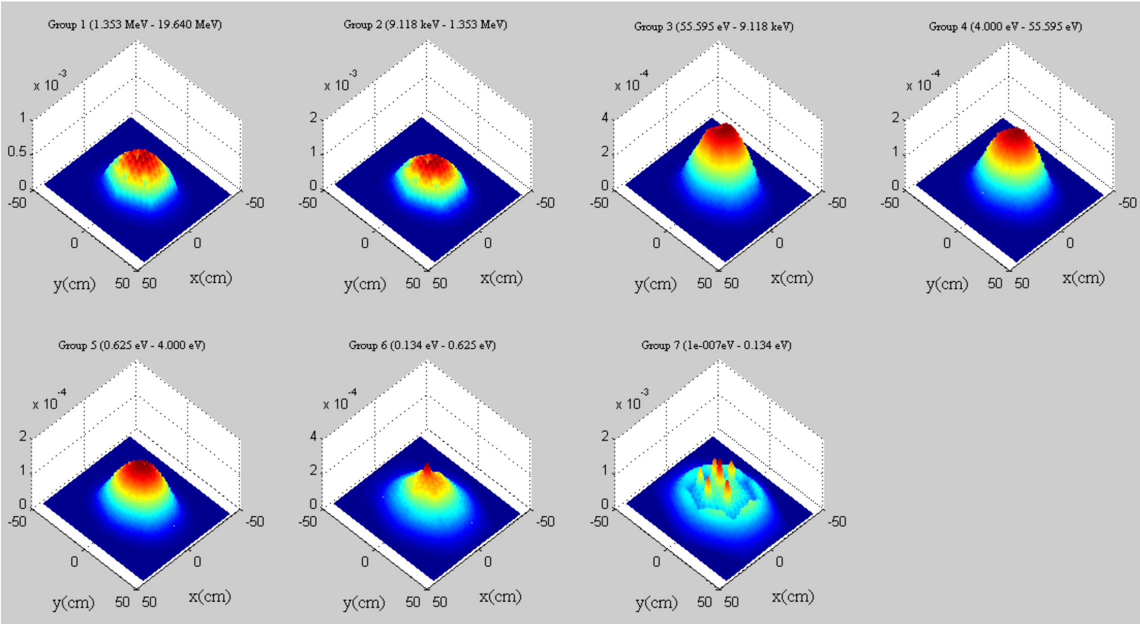

FIG. 9. 3D UUTR Flux Map at the Central Plane, [7].

- Advanced computational modelling and simulations of radiation transport and radiation detection in conjunction with measurements in our advanced labs; using the state-of-the-art numerical codes such as but not limited to AGENT (our home code), MCNP, GEANT4, SCALE, KENO, we developed detailed 3D models of the UUTR, its radiation ports, with point-wise flux distributions maps *vs* core power and control rods positions (Fig. 9). As a part of on-going research but also in contributing to an advanced educational approach, we developed mobile-phone apps in displaying calculated 3D flux and reaction rate maps for the UUTR using AGENT code. An example is shown in Fig. 10.

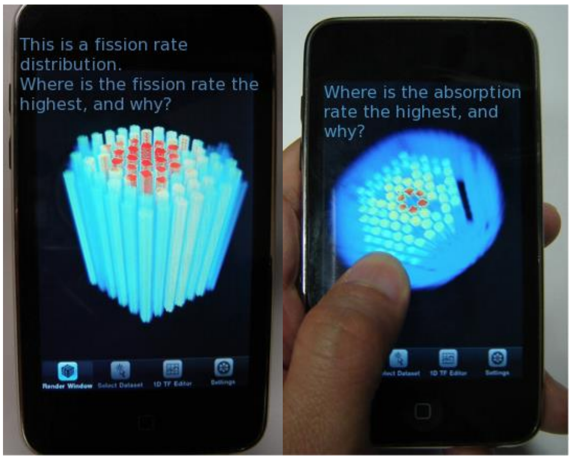

FIG. 10. iPhone-Based Class Practice Session (UUTR 3D Flux and Reaction Rates Images Produced with the AGENT Code) [8].

- Development of special nuclear material detection techniques inclusive of computational simulations using dynamic GEANT4 platforms and development of measurement techniques for accurate signal processing. This research includes the use of our laboratories (spectroscopy, nuclear forensics and radiochemistry labs, as well as our reactor) to benchmark our computational models and suggested new approaches in detecting hidden nuclear materials.

- Nuclear forensics studies are well developed at UNEP started from 2011. The new faculty, Prof. Luther McDonald, contributes to the field of studies in merging radiochemistry and environmental chemistry with computational part of our associated studies (see below for more information on our new graduate program).
- We have a well-characterized irradiator for unbiased and real-time irradiation of electronic components. Neutron fluence delivered is determined using either sulfur pellets (ASTM E265) or nickel foils (ASTM E264). Range of fluences calibrated are from 1E10 to 2.5E14 (15-30,000 W hours). Power level is used to minimize errors due to ramp rate. Neutron Energy Spectrum fluence is reported in terms of 1 MeV equivalent for Si (ASTM E 722). The electrostatic discharge control program follows ANSI/ESD S20.20-1999 and MIL-STD 1686. Isofluence contours are determined yearly and after any core loading changes. The gamma component of the exposure is kept to a minimum by a lead shield located in the stand, and low burn-up fuel [10].
- In the past, a fission track analysis (FTA) at UNEP was refined as a method to quantify the levels of Pu-239 in an individual. Urine samples were collected and chemically processed to reduce the volume and contaminants. The samples were placed on Lexan slides or electrodeposited onto stainless steel planchets prior to irradiation in our reactor facility. Neutrons from our reactor induce fission and the fission fragments then create small tracks in the Lexan detectors that can be optically viewed and quantified. The FTA process has been modified and tested in other sample types and can be used to measure levels of activity for other fissionable isotopes. The current procedure has a Pu detection limit of 2.8 microBq/L (76 aCi/L), much lower than typical alpha spectroscopy equipment [11].
- Neutron activation analysis (NAA) of various samples in supporting novel research in astronomy, agriculture, geological science, materials science, environmental studies; we provide service to local industries and collaborate with the institutes within the university research park. Recently, we have developed precise steps of the NAA to meet the expectations and standards of modern and advanced applications. These steps include:
    - Sample science: sample preparation protocols that are developed per sample type, and sample accountability that includes sample *logs* once samples enter the facility and samples *faith* once samples are complete with analysis which includes storage at the facility, or samples are destroyed or returned;
    - Sample irradiation protocol that requires for every user to start with the NAA pre-calculator: the NAA pre-calculator is developed by our students, especially Greg Moffitt, as a part of is MS thesis with the goal to provide accurate information about the samples' irradiation specifics. The calculator is Python-based interactive tool developed for easy and straightforward use. The calculator requires that user inputs the mass of a sample, irradiation time (and specifies in which of the irradiation ports in the UUTR), duration of irradiation, and based on the calculated dose-rate and activity of that sample provides with the time needed for a sample to stay in the reactor pool before taken out and be moved to one of our radiation counting stations. This calculation requires a guessed/estimated sample isotope composition. If the sample is atypical, user must firstly perform the passive counting that will provide with better-estimated composition needed to use the NAA pre-calculator. All calculations are performed based on the 3D fine group flux spectrum per irradiation port.

- o Post-irradiation protocol requires measurement of the sample dose-rate before taken out from the reactor and comparison to the estimated value. Then, the sample is moved inside the facility and tracked before its faith is decided.

In recent years, we have expanded the application of the NAA activities at our facilities in developing new studies and in developing joint collaborative research, such as for example:

- o Studies of core samples from mining: these analysis provided industrial partner with information on the presence of naturally occurring radioactive materials and their potential impact on the environment, as well as the content profile of the mining in regard to its economical values;
- o Analysis of elemental compositions of various meteorites: in collaboration with the Astronomy department at the university we developed a series of such analysis with the goal to complement other types of analysis (such as for example Raman spectroscopy) in understanding the formation of complex molecules in the universe;
- o Agricultural studies in analysing the "cycles" of rice, cherries and grapes by sampling soil, plant and rice or fruit to follow what minerals move from the soil to the final product and what affects such migrations or lack of. More precisely, we developed detailed studies on white and brown rice in analysing what minerals might be removed from brown to white rice. More information can be found in Ref. [12].
- o Development of new nuclear engineering materials. Our recent success is a concrete that does activate above the low level radioactive waste limit, and thus as such can be reused after exposure at nuclear facilities for 40 or more years.

The use of facilities to support education and training at UNEP – Nuclear engineering course work and laboratory training for graduate and undergraduate students under the guidance of UNEP faculty provides our students at all levels with a unique experiential and hands-on educational opportunity critical for their progress to become qualified researchers and nuclear engineers:

- We are building a modernized curriculum with the goal of strengthening disciplinary depth in students' education. The UNEP education infrastructure has recently been revised to incorporate experiential learning tools (exposure to and training in laboratory practices and nuclear engineering codes) as an integral part of on-going courses. All efforts support the goal that all students build a sufficient level of nuclear engineering literacy in order to be able to contribute productively to the nuclear engineering work force or continue their education toward doctoral degrees, [9]. In moving away from a classical lecture setting, in which the teacher is focused on the most efficient time-constrained delivery of abstract knowledge to the students, we combine methods and techniques to increase students' involvement in lectures and avoid the "rote memory" approach. As a result, the students expected to just 'remember' are guided to 'understand' the key concepts and 'think to higher levels' rather than just restating facts. Therefore, we use advanced technologies coupled with our facilities to provide a new experience and better learning environments for our students (as illustrated with Figure 10 for example and though other examples shown in this paper).
- From 2012, we became the only one graduate program with approved track in nuclear forensics studies. From autumn 2012, we have had over 20 graduate students attending

the core classes at the Masters and PhD levels of their studies. These students perform mainly their graduate research in the applied fields of nuclear forensics.

- From 2010 we have established training for the students wishing to obtain the UUTR operating license certified by the U. S. Nuclear Regulatory Commission. The training consists of two graduate level consecutive classes, with the training continuing over the summer in assuring the best preparation for the final operating exam.

Variety of services provided at UNEP – Our facilities are open to visitors and put in use for a variety of outreach efforts; in brief:

- We provide the tours of our facilities; on average, over 700 individuals annually tour our facilities, including elementary and high-school students from local schools, University of Utah students, students from other universities, visiting researchers, faculty from the University of Utah and from other universities, and others. We consider the time and effort given to these tours part of our commitment to providing knowledge about nuclear science and nuclear engineering to the larger community. This became of special focus and interest with the nuclear renaissance and the awareness of the necessity to observe and work toward the green energy production in our country. In 2010 we have established a museum, The Utah Energy Playground, emphasizing the like for science and engineering disciplines: visitors (especially elementary and high-school students) can play with the glove box to move toys or assemble Legos, and learn about the fission process and the history of nuclear engineering by walking around the old decommissioned reactor offering lights and cartoon-like illustrations. A special session is reserved for them in our nuclear engineering measurement lab where we demonstrate basic principles in radiation transport and radiation detection and the use of radiation detectors.
- Every year, the Nuclear Day which is organized by the Utah American Nuclear Society Student Chapter attracts on average 100 to 150 visitors to our facilities. All these activities require thorough compliance with NRC regulation.
- Every autumn, we open our facilities for scientific and engineering days organized by the College of Engineering; the purpose of these tours is recruitment of prospective outstanding high school students interested to pursue their professions in the field of engineering disciplines.
- Distance learning specifically focused at the "Digital NAA" class in providing Skype-based communication with the students abroad who do not have equipment to experientially learn about neutron activation analysis, gamma spectroscopy and sample preparations.

4. SUCCESS STORIES, MAJOR ACHIEVEMENTS

UNEP underwent major revisions and revitalizations from 2009. Majority of descriptions provied in this paper, in regard to education, training, reserach and operation of our facilities, is therefore preented in light of these new changes. The following is a brief summary of our achievements and major success stories in this period of time:

4.1. Education programs at UNEP

The Nuclear Engineering Minor, at the University of Utah, is the only undergraduate nuclear engineering minor in the State of Utah. The Minor was developed in late 2009 and submitted for approval in early 2010; it was approved by the Board of Regents on May 5, 2010 followed by classes and student admissions beginning autumn 2010. In these three years, we have observed a remarkable interest among our engineering and science students at the University of Utah and in the State of Utah in declaring for a Minor in Nuclear Engineering. We established the Minor with the goal to emerge as a hub for nuclear engineering and science education, and research in the state of Utah and abroad. Our success story is the number of students attending and graduating with the Minor in Nuclear Engineering, their high GPAs, and their impressive success in research. This is illustrated by their research paper awards at the American Nuclear Society Student Conferences in 2011, 2012, 2013; and their contribution to peer-reviewed journal publications. A number of these students have also successfully completed their exams for the reactor operator license, which we offer as a part of the Minor education. In offering the core nuclear engineering undergraduate courses, we have provided training for operating the UUTR within our UNEP facilities (One of only thirteen research reactors in the U.S.). Starting autumn 2013, we had over 30 students in the Minor in Nuclear Engineering. From autumn 2010, until the end of 2013, we graduated 20 students with a Nuclear Engineering Minor. The majority of these students were admitted to our graduate program establishing a pipeline of high quality graduate students. In addition, their interest in our graduate program illustrates that our Program remains exciting and educational as they have the option to choose from many top ranked programs in the country.

Training nuclear engineers and engineers with a minor in nuclear engineering that can adapt to a changing world, is at the core of our long term visions. UNEP is committed to educating engineers on how to “imagine, innovate, design, and build” projects to provide long-term solutions for both the developed and the developing world. The Minor Program mission is one that embraces students from diverse backgrounds to discover the challenges of nuclear engineering and to bring about innovation using their knowledge of science, engineering, ethics and the broader context of society and the environment. Starting 2009, the engineers educated in the Nuclear Engineering Minor Program are technically trained at the highest level, but the UNEP also integrates leadership into the curricula. Thus, the vision and leadership of our students is established with the goal to create the sustainable future for the region, nation, and abroad.

The graduate program (MS and PhD) is revised to meet the challenges of the 21st nuclear and associated industries. The curriculum is revised with the educational objectives to prepare the students to become nuclear engineering professionals trained in-depth in their selected areas of studies, and to provide the students with training in becoming life-long learners, capable of transitioning to new research areas or job assignments associated with challenges in the field of nuclear engineering. Our success is measured in the number of graduate students, their accomplishments (how fast they complete high quality thesis research and how many journal publications they produce during their studies at UNEP). The UNEP revitalized graduate program assures that students are provided with a wide range of opportunities in developing skills as expected by industry, national labs, and the private sector in nuclear engineering and associated disciplines. This is accomplished by exposing the students to challenging projects (as part of regular course work and/or thesis research) with the focus of problem-solving engineering concepts. From a handful number of graduate students in 2009 to over 30 graduate students (with only two full-time UNEP faculties) from 2011, we consider our program to be a success.

One of our great accomplishments is our newly established graduate program in nuclear forensics. Starting autumn 2012, this program offers interdisciplinary approach to nuclear forensics, with the classes being offered by faculty from UNEP, in addition to faculty from

Chemical and Civil Engineering. Our laboratories greatly support the nuclear forensics graduate course work and associated research.

4.2. Training programs and professional development at UNEP

From autumn 2009, the new UNEP Director started establishing training practices integrated into new curricula by emphasizing aspects of interest to professional development and professional ethics and standards. Nuclear engineering profession regardless of the type of the job that can range from nuclear industry, nuclear power plant operator, nuclear medicine, to research in fields pertaining to nuclear forensics, homeland security, space engineering, material science and engineering, reactor design, radiochemistry, agriculture and many more, all require the very same rigor of safety, discipline and organization. Here are some highly successful examples:

- *Tracking activities and preserving information*: UNEP seems to be the only nuclear engineering program with research facilities including research reactor to operate mirroring the rigor of nuclear power plant environment; as described in Section 2, we run our nuclear engineering facilities under the corrective action program (CAP) developed by DevonWay. The DevonWay CAP software system is adopted by more than 70% of nuclear power plant fleet in the U.S.A. We have deployed their "Track & Trace" system and adapted to our facility for tracking every single action at the facility in: purchasing, maintenance, and operation. Additionally, any incident can be recorded easily. Every action is cross-linked and easily tracked in past. On this way students are developing the soft-skills such as but not limited to work tasks planning, personal time-management, team-work, and compliance with the rules, regulations and policies at work-place.
- *Training the safety culture*: An effective safety-culture is essential to nuclear safety and can help prevent errors and misconduct by ensuring expectations and consequences are clearly stated and understood. Academic and research reactors present additional challenges as new students are joining the program and nuclear environment for the first time. Often, the new students lack familiarity with the nuclear safety-culture expectations needed to conduct their research and studies in accordance with regulatory requirements and require extra guidance. For example, they may not understand and recognize the significance of their signatures as they relate to complying with the regulatory requirements. In addition, new students new to nuclear may wrongly believe based on previous experience, that they can interpret certain work procedure steps or have more latitude in deviating from procedural guidance. UNEP is leading the way in establishing and building a strong nuclear safety culture. Social media and practical training is being developed that is intertwined with class and laboratory work along with integrating industry used tools and software to prepare the future nuclear workforce to meet the needs of the nuclear industry. UNEP safety culture principles/training are also found on UNEP Facebook and Twitter. The safety culture-training framework is shown in Figure 7.
- *Developing 'dynamic learning' skills*: UNEP has developed dynamic learning activity (DLA) training labs for all students involved in UNEP classes and research (Described in brief in Section 2). Students involved with laboratories and classes in UNEP receive training with the expectation that everyone is responsible for documenting deficiencies or areas for improvement and entering them in the DevonWay software. The DLA contains training on Human Performance Error Reduction techniques that are used in the industry such as STAR (Stop, Think, Act, Review), critical steps, verification

techniques, procedure use and adherence, and communications. Another important aspect that is presented in the DLA is proper methods of coaching that should be implemented in the nuclear environment. Finally, hazard identification and practical exercises have been developed to test the students comprehension and internalization of concepts presented in the DLA. Example scenarios are set up in the laboratory environment and students must identify hazards and demonstrate proper coaching techniques in order to pass the activity and be permitted to conduct research in the facilities.

4.3. Outreach education provided by UNEP

Outreach program is extremely important to provide good recruitment into theprogram but as well as assure retention of the students. Our success are measured in the number of both through various activities that include and involve our facilities, staff and UNEP students. In summary, from autumn 2009, our accomplishments are based on the following activities that are described very breifly:

- We offer tours of our facilities to elementary, junior-high and high schools, as well as freshman students from various universities. The touring of our facility by the freshman students of the engineering at the University of Utah is established starting autumn of 2010 and is carried out every year. Our efforts extend beyond the schools and universities, in reaching out the general public with the goal of providing facts about the nuclear engineering to the parents who made 75% of our visitors! We also make effort to reach out to the College of Science, School of Law and School of Medicine at the University of Utah in inviting students to visit our Program and our facilities. For example, in last three years we have established tours for the students from the School of Law. Our record high in the number of visitors was in 2012, reaching 780 visitors, of which over 70% were visitors from the schools.
- Revitalized UNEP students' societies, the American Nuclear Society Student Utah Chapter and the Honorary Alpha Nu Sigma Utah Chapter Society, became very active in reaching out the students at the campus with the goal in recruiting them into UNEP minor or UNEP graduate programs. Additional efforts, such as scientific workshops and help-sessions, provided a new UNEP culture that students seem to appreciate and respond in favour. We find such activities to provide the ground for trust in the Program, resulting in students deciding to pursue their degrees at UNEP. The ANS University of Utah Chapter is reactivated in their activities, and especially the outreach branch of the Chapter is making important impact in developing new strategies for informing and recruiting the students into UNEP. The Chapter organizes tours, call-outs, cinema-evenings, *hot-chocolate* nights with topics for discussions, and learning.
- Recently we have started reviewing and advancing our programmatic and strategic initiatives in recruiting students into our nuclear engineering program. Director of the UNEP with the support from the College and the University, is building advanced programs to meet the needs of the 21st century nuclear industry in the country and therefore prepare graduates in the fields of nuclear engineering of interest to nation in benefiting the nuclear sector broadly. The newly established recruiting protocol is designed to attract a large and diverse pool of applicants. Newly established Minor in Nuclear Engineering allows that large pool of students learn about the new minor and join the program.

4.4. Reserach at UNEP benefited from facilities and the reactor

The UNEP tenure-track and research faculty, postdocs and students, are engaged in world-class research in energy, nuclear reactor design, advanced nuclear reactor simulations, modelling and advanced visualizations applicable to all chip-based devices, nuclear medicine, radiation detection, nuclear signal processing, nuclear complex system modelling and analysis, nuclear forensics, nuclear safeguards and nuclear security, radiochemistry, nuclear environmental engineering, the nuclear fuel cycle, and nuclear materials. The unique strengths of UNEP research stem not only from faculty expertise but from the ability to connect this research to experimental analysis using the UNEP facilities: nuclear research reactor and associated laboratories, radiochemistry lab, microscopy lab, nuclear forensics lab, nuclear bio-medical lab, and radiation counting labs. The major objective of UNEP research is the extensive use of the reactor facility and the state-of-the-art laboratories.

A number of successful stories in our research accomplishments rely on our merging the theoretical and computational research with experimental and the use of facilities. For example, our newly established protocol for the NAA as described previously, has helped us develop new concrete that remains activated below the limit for low level radioactive waste and thus after being exposed to radiation for 40 or more years, can be simply reused and recycled. Our development of new modelling tools in respect to reactor physics and neutron transport for example, is easily benchmarked against the real-time operation of our UUTR. At the same time, we use these tools in demonstrating the physics behind operation of a reactor before the students have the opportunity to perform experiments by themselves. In addition, our newly established laboratories for radiochemistry and environmental chemistry, run by Prof Luther McDonald, provides a series of new success stories in research, training and education of our students.

5. FUTURE PROSPECTS

Many of the research reactors in the country are experiencing issues related to aging mechanical and electrical components. While most of these issues do not affect safety, due to the “inherently safe” design of research reactors, their unplanned repairs do create scheduling issues that make conducting student training and research activities challenging. Additionally, the proper maintenance of these systems is a requirement of the facility license and there have been several instances where the U. S. Nuclear Regulatory Commission has fined research reactors for not properly maintaining their systems.

The TRIGA reactor at UNEP, which first came online in 1975, is not immune to these types of concerns. Recently over the summer of 2013 to spring of 2014, several issues directly related to aging of the reactor control systems required emergency repair to continue operations. These unscheduled repair activities created a significant disruption to facility operations, disrupting both student training activities and research schedules. The emergent repair issues were successfully addressed by the UNEP Staff with the help of talented and knowledgeable students. Of additional concern is that the console wiring was conducted by a graduate student in the 1990’s, and while it is functional, many items were not completed with the best quality control and engineering practice. Overtime the lack of correct installation methods has been causing many components to fail pre-maturely. UNEP has written proposals for funding and is currently working on securing funding for a total replacement of the UUTR Control Console with a new design by students and staff at the facility using the most up-to-date technology and equipment. This will require open communications and work with the U. S. Nuclear Regulatory Commission but will also be a great learning opportunity for many of the students to be involved.

All of our irradiation ports are well profiled (experimentally and using computational tools) in assuring our experiments are accurate and well managed. In addition to stationary irradiation ports, our rabbit system installed many decades ago has not been extensively used. After establishing the NAA procedure as described in Section 2, we are now reviewing the rabbit system to re-install its capacities toward automatized NAA related research, education and training.

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CURRENT STATUS AND FUTURE CHALLENGES OF THE TEXAS A&M UNIVERSITY NUCLEAR SCIENCE CENTER RESEARCH REACTOR

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Abstract.

The Texas A&M Nuclear Science Centre Reactor has provided isotope production, research, and training to the scientific community since operation first began in 1961. Located in College Station, TX, the reactor has provided these services to Texas A&M University and surrounding customers. The reactor is an open pool type TRIGA-Mark I conversion reactor, previously converted from MTR fuel. The maximum power of the reactor is 1.0 MW and it uses low enriched uranium fuel designed by General Atomics. Currently, the reactor is used for research and to provide radioisotope production to a wide range of customers and looks to expand these endeavors in the future. Future challenges include the replacement of an original heat exchanger used to cool the pool, expansion of facilities to provide irradiation positions, and a new hot cell. Other challenges include the expansion of irradiation locations for additional capacity.

1. INTRODUCTION

1.1. Brief history

The Nuclear Science Centre Reactor (NSCR) is operated by the Texas Engineering Experiment Station (TEES) as a service to the Texas A&M University (TAMU) System in College Station, Texas, United States of America. The Nuclear Science Centre (NSC) is a multi-disciplinary research and education centre supporting basic and applied research in all nuclear related fields of science and engineering as well as providing educational opportunities for students in those fields. The NSC also provides services to commercial ventures requiring radiation or isotope production services.

The NSCR is an open pool type TRIGA Conversion reactor using light water as a coolant, moderator, reflector, and shield. Initial planning for the NSC began in 1957 [1]. At that time, the university embarked on a program of expanding graduate education and research programs. Administrators recognized that a research reactor capable of serving many departments and supporting a large variety of research activities would significantly contribute to this program of expansion.

In March of 1958, the application for a construction permit and operating license was submitted along with the Hazard Summary Report. The construction permit was issued in August of 1959. After construction was completed, this permit was converted to operating license R-83, which authorized operation of a Materials Test Reactor (MTR) swimming-pool type reactor at 100 kW.

The NSCR first achieved criticality on December 18, 1961. The reactor operated from 1962 until 1967 with MTR-type curved aluminum plate elements. During this time, the reactor functioned extensively at a maximum power level of 100 kW. By January 1965, increased use of the facility necessitated almost continuous operation. Only four years passed from initial reactor operation before the NSC implemented a comprehensive upgrade program. In December 1965, the NSC submitted proposals to support a long-range expansion program. The plan not only changed the initial facility physical plant but also established a new reactor program.

The NSC modified the reactor pool by installing a multipurpose irradiation cell. This facility allows exposure of large objects to the radiation from the reactor core in a dry environment. A permanent stainless steel liner was installed as part of the pool modification to eliminate problems of pool leakage, which was a source of previous significant operation problems. To allow steady state operation at power levels up to 1.0 MW, the NSC provided a cooling system for the reactor. The installed cooling system has a rated capacity of 2.0 MW to facilitate possible future needs.

The NSC converted the reactor core to utilize standard TRIGA fuel elements, and on July 31, 1968, an amended facility license allowed the NSCR to operate at a maximum steady state power level of 1.0 MW and to pulse of up to $3.00 reactivity insertion. The inherent safety of the TRIGA fuel allowed increased flexibility and utilization of the reactor. Pulsing was possible due to the prompt negative temperature coefficient of reactivity and the integrity of TRIGA fuel at pulse peak temperatures. The 1.0 MW reactor power improved a number of existing research programs and encouraged the initiation of new projects.

The initial core loading was quite satisfactory, but fuel burn-up and samarium buildup soon affected experimental capability. To restore excess reactivity, the NSC periodically added additional fuel to the core and graphite reflectors to all core faces. This eventually led to a core with many fuel rods which led to a resultant decrease in the flux of almost 40% and the elimination of most of the irradiation facilities.

Operating experience with standard TRIGA fuel revealed a high fuel burn-up rate resulting in fuel additions to maintain sufficient reactivity. In August 1970, the installation of fuel-followed control rods lead to a gain in excess reactivity helping to solve the problem of maintaining excess reactivity. This installation required modification of the grid plate to allow passage of the fueled portion of the control rod through the grid plate. Modifying the reactor grid plate extended core life by approximately 1.5 years and provided for the installation of fuel-followed control rods. This modification achieved an average $1.10 increase in reactivity per fueled follower. The high fuel burn-up rate of standard TRIGA cores continued to be an operational problem for the NSCR.

It was obvious that a solution was needed that could fit within the constraints of a university budget and limited external support. Replacement of the core with new fuel would have led to considerable expense with a very short effective life of a standard core. Since the average core burn-up was only 10% and a reasonable amount of fuel would only provide small reactivity increases, cycling new fuel into the core was no more attractive. The solution to the problem was in a new fuel developed and marketed by General Atomics, TRIGA Fuel Lifetime Improvement Program (FLIP) fuel. It is almost identical to the standard TRIGA fuel except that the uranium enrichment is HEU rather than LEU [2]. The hydrogen to zirconium ratio decreased from approximately 1.7 to 1.6, and 1.5-weight percent natural erbium was added as a burnable poison. The fuel designated as FLIP has a calculated lifetime of approximately 9 MW-years. This contrasts with experience for a standard core, where it was possible to operate only 6 months (approximately 0.14 MW-years) without a fuel addition.

Inasmuch as funds for a complete FLIP core were not available, it was necessary to considered operation with a core comprised of a mixture of FLIP and standard TRIGA fuel. A precedent for this had been established by General Atomics when they operated a standard core loaded with eighteen centrally located FLIP elements in a fuel test program. Calculations performed by the NSC led to the conclusion that satisfactory core arrangements were possible with a mixed core. As funds became available, the amount of FLIP fuel could increase until the core was completely FLIP fuel. This concept provided the additional satisfaction of producing substantially greater burn up in the standard fuel used in the mixed core. In June 1973, the United States regulating authority, the Nuclear Regulatory Commission (NRC), licensed the NSCR to operate full standard, mixed, or full FLIP TRIGA cores.

The license for the mixed core permitted the NSC to operate at a maximum steady state power of 1.0 MW with maximum pulse reactivity insertions of $2.00. Sufficient funds provided for a partial loading of FLIP fuel in a standard size core with a 35% of the elements containing FLIP fuel and the rest containing standard elements. This configuration achieved criticality in July 1973. The burn-up data indicated that the burn-up rate was initially 0.5 ¢ per MW-day and after samarium buildup, the rate dropped to 0.2 ¢ per MW-day.

Since initial approval in 1973, the NSCR operated with two mixed core loadings. The first core contained 35% FLIP elements and the other core contained 60% FLIP elements. Thus, the incorporation of FLIP fuel increased the lifetime of the core by a factor of three. The reactor was not fully converted to a full FLIP core until 1979. However, in the time between the full core conversion, there were changes made to the allowable maximum pulse rates.

In July 1975, the maximum permissible pulse reactivity insertion increased to $2.70. On September 27, 1976, during a loading operation, four elements failed to pass through a gauge test for transverse bend. Steady state hydrogen migration followed by rapid hydrogen pressurization during reactor pulses caused the damage. The reactor was not pulsed again until a complete analysis was submitted to the NRC in 1981. The maximum pulse allowed by the NSCR was reduced to that amount which would not cause the peak reactor temperature to exceed a temperature limit of 830°C (1525 F).

The FLIP core provided a significant improvement in core lifetime. In 2004, the FLIP core began experiencing xenon-precluded startups due to significant fuel depletion. In 2005, the NSC submitted a Safety and Accident Analysis Report prepared in conjunction with General Atomics for a core conversion to TRIGA LEU fuel.

In 2006, the NRC issued a conversion order to perform the requested conversion. The core conversion occurred in late 2006. The reactor configuration following the conversion was identical to the configuration used for the previous TRIGA FLIP core. The reactor was declared steady state operational in November of 2006 and pulse-operational in December 2006.

While first bringing the LEU core to full power during startup testing, it was noted that indicated fuel temperature was higher than expected, though still within operational safety limits. The NSC and General Atomics conducted an investigation of the anomaly and determined that the instrumented fuel element providing reactor fuel temperature did not exhibit the expected fuel-cladding gap closure. Although the anomaly presented no safety-related concerns, the NSC prudently replaced the instrumented element. The NSC has operated to date with the installed TRIGA LEU fuel without incident.

1.2. Description and site location of the NSCR

The NSCR is located in College Station, Texas, United States and is in close proximity to Texas A&M University on a site about 24,300 m^2. The core of the reactor contains low enriched uranium-erbium-zirconium-hydride (UZrH-Er) fuel. The erbium is added as a burnable poison designed to extend the operating life of the TRIGA fuel. The 304 stainless steel cladding provides adequate protection of the fuel against corrosion and wear.

The Texas A&M University NSC TRIGA LEU is the first conversion core of its kind, and no empirical data for a reactor of this type was available prior to core construction. General Atomics provided safety and accident analysis for the fuel produced using computational methods. The Puerto Rico Nuclear Center (PRNC) TRIGA HEU FLIP core provided an opportunity to benchmark the computational technique to be used for evaluating the TRIGA LEU fuel in the NSC TRIGA core. In addition, empirical data collected during the NSC core conversion was used to further validate the computational methods used.

Fuel elements of the NSCR are designed to fit into a core configuration previously occupied by MTR fuel. This differs from the traditional TRIGA hexagonal configuration because the fuel elements are arranged in a square array instead [3]. A total of six control rods provide reactivity manipulation of the core through four shim rods, a regulating rod, and a transient rod. The regulating rod can operate in manual or automatic mode to provide a constant power level for the reactor.

The reactor is cooled by the pool water through natural convection. This water is circulated through a heat exchanger to a secondary cooling system which is then cooled by a cooling tower fan. Originally designed for 2.0 MW of thermal capacity, corrosion of the heat exchanger has reduced the thermal conductivity of the heat exchanger and has reduced overall cooling capability for the reactor [3]. Pool water is drawn from the bottom of the pool and passed through the heat exchanger before being returned to the bottom of the pool.

Experimental facilities of the NSCR include 5 beam ports with 2 tangential beam ports to reduce gamma radiation streaming. A thermal column provides irradiation to samples up to 80 cm in length. Larger samples up to a few meters may be irradiated in the dry cell with capability for both neutron and gamma irradiation. A pneumatic transfer system is used to irradiate small samples up to a few centimetres in length. Most irradiations occur using internal and external core positions for maximum reactor flux. These experimental positions provide radioisotope production, neutron activation analysis, and digital neutron radiography.

2. CURRENT TECHNICAL STATUS

2.1. Reactor core

The NSC conversion reactor is a light water moderated and cooled, pool-type reactor with a full core of TRIGA LEU fuel in a four-rod cluster configuration. A 13 cm thick aluminum grid plate supports the fuel clusters. A typical NSC core configuration contains fuel elements, 4 fuel-followed control rods, a water-followed regulating rod, and an air-followed transient rod. Graphite reflector blocks are used in-core for reflection in addition to the graphite in the coupler box and thermal column.

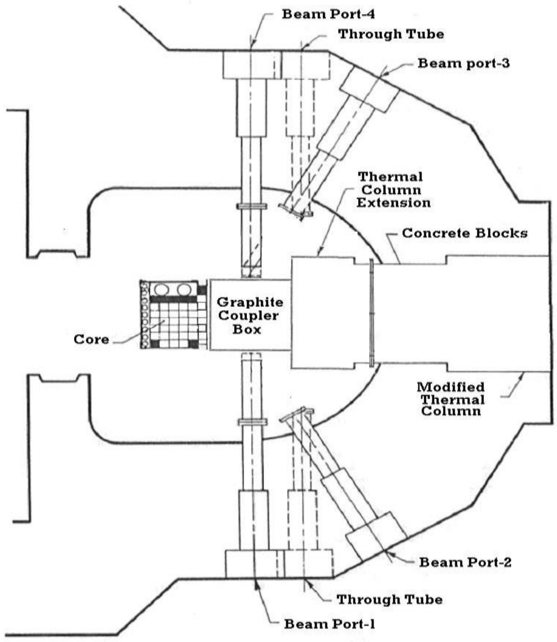

FIG. 1. Stall Beam Port installation with Graphite Coupler Box and Thermal Column Extension.

The reactor is supported by a moveable bridge with rails on top of the pool wall and allows the core to be moved along the central axis of the reactor pool. The reactor is controlled by four fuel-followed control rods plus one water-followed regulating rod and one air-followed transient rod. All six control rods are supported from the bridge structure.

2.2. Fuel elements

The fuel is arranged in three or four-element bundles that allowed conversion to TRIGA fuel with the existing grid. The four-element fuel assemblies of the TRIGA core provide easy passage of cooling water between the elements. Water flows by natural convection through the 5 cm diameter hole in the grid plate adapter, passes through the large cruciform opening and then over the entire element until it leaves the core through the numerous openings in the aluminum handle at the top of the bundle. In addition to the coolant passages through the grid plate adapters, the NSCR grid plate has additional coolant holes 1.25 cmin diameter located at the corner of each four-rod bundle.

The four-element assembly consists of an aluminum bottom adapter, also called a grid plug, a total of four stainless steel clad elements (either fueled or non-fueled elements) and an aluminum top handle. The four elements screw into four tapped holes on the top of the grid plug which fits into the NSC reactor grid. A TRIGA element threads into the grid plug until a flange on the element sits firmly on the adapter providing a cantilever support.

A three-element fuel assembly holds three fuel elements and a control rod, an instrumented fuel element, or an experiment. The NSCR utilizes two separate types of three-element fuel assemblies for housing control rods with or without guide tubes.

The three-element assembly substitutes one fuel element with a fuel-followed shim safety control rod. In this instance, control rods do not have a guide tube because the fueled follower portion of the rod remains in contact with the assembly. Since the fueled follower must pass through the fuel assembly base, it was necessary to design a base that serves as a guide for the fueled follower portion that extends through the bottom of the grid plate. The top handle of the bundle serves as the upper guide for the fuel-followed control rod. In the event the transient rod has a follower, it uses a specially designed control-rod guide-tube and must have a base assembly.

The NSCR utilizes TRIGA LEU type self-moderated elements. Zirconium hydride, homogeneously combined with partially enriched uranium fuel, provides moderation. A 4.6 mm hole in the center of the active section of the fuel elements facilitates hydriding during fabrication. A zirconium rod, inserted after hydriding, fills the hole. Graphite slugs, 89 mm in length, act as top and bottom reflectors. Serial numbers identify individual fuel rods.

Three thermocouples embedded in the fuel of specially fabricated instrumented elements measure fuel temperature during reactor operation. The sensing tips of the fuel rod

thermocouples are located halfway from the vertical centerline at the center of the fuel section and 2.5 cm above and below the center. The thermocouple lead wires pass through a seal contained in a stainless steel tube welded to the upper end fixture. This tube projects about three inches above the upper end of the element and connects to extend tubing by Swagelok® unions to provide a watertight conduit protecting the lead wires up to the pool surface.

2.3. Control rods

Six motor-driven control rods (four shim safety rods, a regulating rod, and a transient rod) control the reactor and provide scram and shutdown capability. The shim safety and transient control rods provide scram capability. They fall into the core whenever power is lost to a valve solenoid or electromagnets. The regulating rod regulates reactor power during steady state operations and does not have scram capabilities.

The four shim safety control rods are fuel followed. Each consists of a fueled region and a poison region. The poison region is borated graphite with the same cladding as the fuel elements. The fueled region of the control rod is active fuel-moderator compositionally identical to the other fuel elements. When fully inserted, the fueled portion of the control rod extends through the grid plate, below the reactor core with the poison section in the core. The fuel-followed control rods do not have guide tubes, as a guide tube would limit cooling to the fueled section.

In the absence of a guide tube, a hold-down foot fits over the top handle cross bar. This foot prevents the bundle from moving with the control rod should it bind. The blade attaches to the side of the tube that houses the control rod extension. When the rod drive unit is secured to the reactor support structure, there is a 3.175 mm clearance between the foot and fuel element top handle cross bar. This clearance permits small thermal expansion of the fuel without vertical restriction.

The transient control rod is void followed. It consists of a poison section and an evacuated section. The poison section is borated graphite with aluminum cladding. The follower portion is also aluminum clad. The guide tube surrounds the rod and has holes for proper cooling. The regulating rod is water followed (no physical follower section). The poison section of the regulating rod is a B_4C powder. The regulating rod uses a guide tube similar to the transient rod.

2.4. Staff

For each shift, a minimum of one senior reactor operator and one console operator are assigned on duty. The senior reactor operator is responsible for the safe operation of the reactor during the shift. In practice, multiple senior reactor operators and multiple console operators are assigned to each shift. The reactor supervisor, manager, and directors all oversee operation of the reactor and address any issues that may arise.

The Radiation Safety Officer is responsible for radiological safety throughout the facility. Their primary duties include preparing radiation safety plans to enter and to work in areas that may involve radiation or contamination. The Radiation Safety Officer works in conjunction with the senior reactor operator on shift to ensure radiation safety compliance.

3. APPLICATION AND UTILIZATION EXAMPLES AND COLLABORATIONS

The NSCR is extensively applied in the fields of industrial isotope production, neutron radiography and training. The core provides a flexible plethora of irradiation configurations, the primary of which are bulk irradiation facilities, The western core face has an average thermal neutron flux (<625 meV) of $\sim 8 \times 10^{12}$ $n \cdot cm^{-2} \cdot s^{-1}$, as well as within the core with an average thermal neutron flux of $\sim 1.2 \times 10^{13}$ $n \cdot cm^{-2} \cdot s^{-1}$. Higher flux in-core configurations can be assembled (albeit smaller in volume) to provide $>2 \times 10^{13}$ $n \cdot cm^{-2} \cdot s^{-1}$ irradiation capacity. Multiple pneumatic transfer facilities with average thermal neutron fluxes of $\sim 6 \times 10^{12}$ $n \cdot cm^{-2} \cdot s^{-1}$, are available for smaller irradiations. The core is nominally positioned with its east face against a graphite coupler box which allows for a high thermal-to-fast ratio neutron current to the beam ports as well as to a large 0.325 m^2 thermal column (Fig.2).

The reactor's irradiation capacity is mainly focused on isotopes for use as radioactive tracers in the petroleum industry and includes the bulk irradiation of scandium, antimony and iridium. The facility is also equipped to produce ^{41}Ar-gas. Other utilization activities include research in support of neutron transport studies, multi-physics simulations and power reactor technology. Finally, the reactor is very effectively applied towards training.

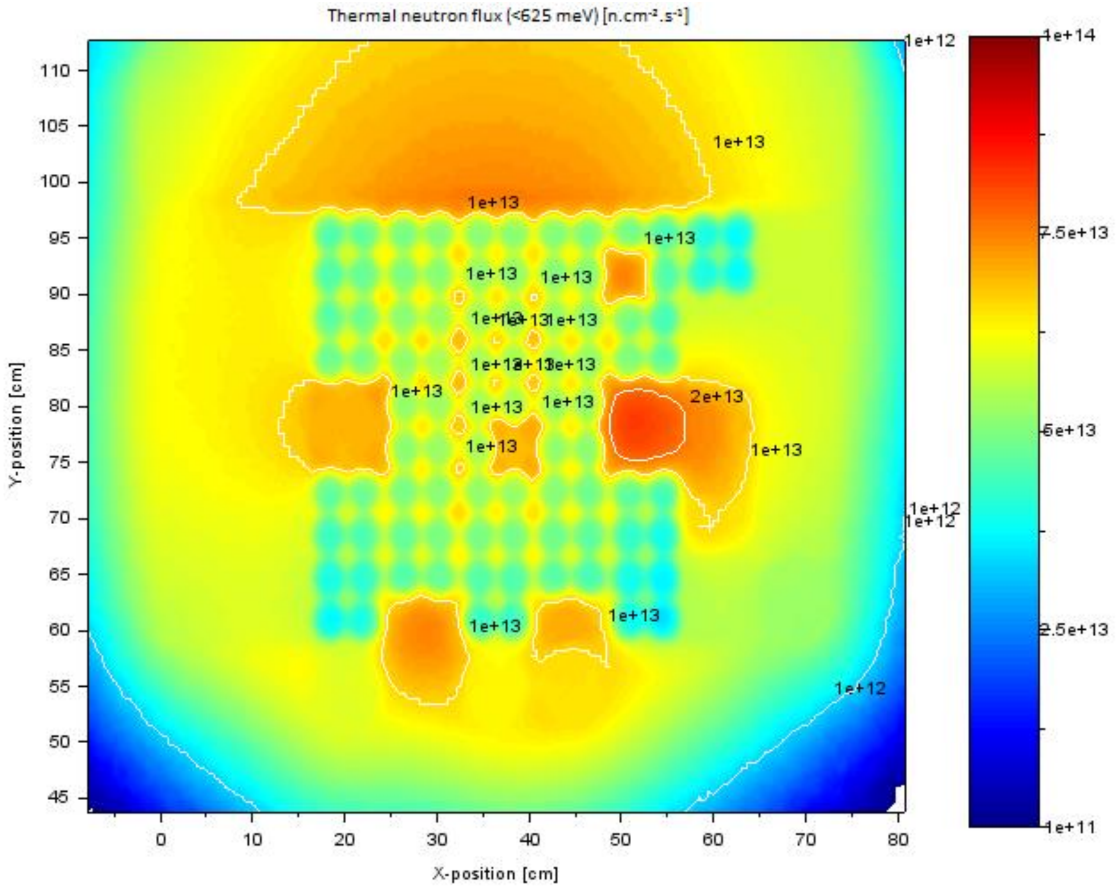

FIG. 2. Thermal neutron (<625 meV) [cm^{-2}·s^{-1}] flux-map of the core centerline while positioned against the graphite coupler box.

4. SUCCESS STORIES AND MAJOR ACHIEVEMENTS

4.1. Refueling

In 2006, the NSC underwent refueling to replace all HEU fuel with LEU fuel to meet the requirements of the Global Threat Reduction Initiative. Through this process, the NSC quickly converted the reactor to use LEU fuel and shipped all HEU fuel offsite. The LEU fuel performance is comparable to the HEU fuel and operation of the facility was able to quickly resume without incident.

4.2. Education and outreach

The NSC is involved in many educational and outreach activities. Through collaboration with the Texas A&M Nuclear Engineering Department, the NSC has trained and educated the largest nuclear engineering program in the United States. Each undergraduate is afforded the opportunity to interact with the reactor through laboratory classes and student employment.

4.3. Commercial training

Many commercial power reactors utilize a short course offered at the NSC that trains reactor operators for careers in the nuclear commercial power industry. In the early stages of training, the students are brought to the NSC where they are exposed to theories of reactor operation and kinetics and are given the chance to operate the reactor and apply the concepts that they have learned in the classroom. This training better prepares the students to obtain commercial nuclear power plant reactor operator certifications.

5. FUTURE PROSPECTS

Despite a stable customer base over the last few years the commercial utilization of the reactor remains focused on a relatively small portion of the industry. This poses an inherent risk to the financial stability of the facility and in this light initiatives are brought forward to diversify the reactor’s utilization to many other fields, whether it will be industrial or for research only. In this fashion, major movement in certain industries can be avoided.

To this effect the NSC is looking towards a few short term prospects: 1) A new hot-cell. The current operational setup limits the capacity of the facility to handle and move around radioactive materials and thus a higher capacity materials handling operation is needed. 2) Projects in support of medical isotope supply in the United States. The reactor is situated directly adjacent to an airport which could make the shipping of irradiated targets very efficient. This however, has not been capitalized on and can be used to support medical isotope suppliers. 3) Reactor systems upgrade. In order to ensure stable operations and availability, significant United States Department Of Energy (USDOE) funding has been received to ensure to operation for many years to come. 4) Radiography research. Some first-of-a-kind technology is developed and applied at the NSC.

6. CONCLUSION

The NSCR is a robust reactor with many capabilities and has demonstrated flexibility throughout the lifetime of the reactor. The two most pressing challenges currently facing the reactor is a need to expand current irradiation facilities to handle future experimental needs and procuring a replacement of the current heat exchanger. As more experiments are added to the reactor, a greater number of irradiation positions are desired to decrease the needed reactor runtime to accommodate all requests. This increased demand for reactor irradiation services has also led to an increased demand in the pool cooling system, preventing adequate cooling from taking place with the reactor operating almost continuously.

One of the solutions to mitigate these two challenges is to replace the original heat exchanger which has been in service for almost 50 years with a smaller, more efficient heat exchanger that greatly reduces the space needed overall for cooling equipment. The other solution is to redesign the core loading configuration to ascertain any possible configurations that could produce more irradiation locations while still maintaining adequate neutron fluence in all of the core positions.

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THE PENN STATE BREAZEALE REACTOR

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Abstract.

The Penn State Breazeale Reactor (PSBR), which first went critical in 1955, is the nation's longest continuously operating university research reactor. The PSBR is a 1 MW, TRIGA Mark III reactor with pulsing capabilities. The moveable core has no fixed reflector and is located in a large size pool. A variety of dry tubes and fixtures are available in or near the core for irradiations. A pneumatic transfer system is also available for irradiation of samples. When the reactor core is placed next to a D_2O tank and graphite reflector assembly near the beam port locations, thermal neutron beams become available for neutron beam experiments. In steady state operation at 1 MW, the thermal neutron flux is 3×10^{13} $n{\cdot}cm^{-2}{\cdot}s^{-1}$ at the central thimble. The peak flux during a maximum pulse is ~ 6×10^{16} $n{\cdot}cm^{-2}{\cdot}s^{-1}$ with the pulse half width of ~10 msec.

Several research projects that utilize the Radiation Science and Engineering Center (RSEC) facilities yearly. Most of the research projects are interdisciplinary in nature and involve other faculty members and graduate students from within the College of Engineering, other colleges at Penn State, universities, national laboratories, and industry. Currently, about 250 undergraduate nuclear engineering students and 55 graduate students utilize the RSEC facilities for laboratory classes and several special topics classes. The RSEC is also the home of the Nuclear Security Master's Degree Program. Additionally, the RSEC is strongly engaged in outreach activities with the public. The PSBR is a primary neutron source for industrial research and service for many companies and government institutions, focusing on in-core irradiations (NAA and isotope production and radiation aging), fast-neutron irradiations (radiation hardness testing, radiation effects testing, and semiconductor irradiations), thermal neutron irradiations (neutron radiography and neutron gauging), and a variety of gamma irradiations.

The RSEC is continually seeking to improve its capabilities for cutting-edge research. Due to inherent design issues with the current arrangement of beam ports and the reactor core-moderator assembly, utilization of neutron beams has been limited. Therefore, a new core-moderator assembly in the PSBR pool and new beam port geometry are needed in order to achieve the full potential of the RSEC's neutron beam capabilities. A major funding was received from US Department of Energy (DOE) to build and install a new core moderator assembly and new beam ports at RSEC. The new core-moderator and beam port arrangement requires expansion of the existing beam laboratory in order to place instrumentation, neutron guides, etc. We are currently seeking funds to build a new neutron beam hall building to house the new neutron beam experiments and neutron guides.

1. INTRODUCTION

The PSBR was built in 1954 as a result of the *Atoms for Peace* initiative of US president Dwight Eisenhower, which he launched at the United Nations meeting in December 1953. In this speech, he called for the formation of an international atomic energy agency (IAEA). He envisioned that the new agency would devise ways to use atomic energy "to serve the peaceful pursuits of mankind". It is in this spirit that the PSBR has operated these past nearly 60 years.

The PSBR, housed in the RSEC, is the longest operating licensed reactor in the US and received a license extension until 2029 by the US Nuclear Regulatory Commission (NRC). The license number R-2 was the first Atomic Energy Commission license awarded on July 8, 1955 and the reactor went critical for the first time on August 15, 1955. The American Nuclear Society recognized the facility as a Nuclear Historic Landmark in 1991. There have been many upgrades and changes over the years, but the dedication to safe, efficient, and secure operation of a nuclear facility continues.

Penn State was one of the first universities to take advantage of the *Atoms for Peace* program. In early 1953, the Board of Trustees authorized to start the project. Construction of the reactor began in 1954 and was completed in time for the dedicated by US President Dwight D. Eisenhower on February 22, 1955 (Fig. 1).

FIG. 1. US President Dwight D. Eisenhower at the dedication ceremony for Penn State's Nuclear Reactor on February 22, 1955. Shown here with President Eisenhower from left to right are Dr. William Breazeale, Penn State President Milton Eisenhower, and dean of Engineering Dr. Eric Walker. (Courtesy of The Pennsylvania State University Archives.).

In 1960, the Materials Testing Reactor (MTR) core was upgraded in power from 100 kW_{th} to 200 kW_{th}. Another license amendment was made in 1965 with the conversion to the TRIGA reactor design. Penn State was not the first university to install a TRIGA, but was first to convert from the high-enriched MTR to a low-enriched different reactor. The TRIGA design provided a higher steady-state power of 1MW_{th} and the capability to pulse the reactor up to 2,000 MW_{th}. The TRIGA license was first renewed in 1986 for a 20-year period.

Another license renewal application was submitted to the US NRC in December 2005. After the NRC's initial review of the license application, there were several requests for additional information. Once the NRC was satisfied with the responses to the questions and additional information supplied, the NRC granted the renewal of the PSBR license on November 20, 2009.

According to the NRC's report on the reactor, the facility poses "no significant radiological risk to the health and safety of the public, facility personnel, or the environment." The report also concluded the reactor has adequate funding and qualified personnel to continue operation for the next 20 years.

The PSBR research in the early days targeted nuclear theory applications. Other research areas included materials testing and production of radioactive isotopes for tracers. Neutron activation analysis was heavily utilized as a trace element analysis technique. Penn State faculty pioneered the utilization of activatable tracers for environmental investigation and biological systems research. The development of the neutron beam for non-destructive imaging began in the early 1980s with facility upgrades and continues today with plans for expansion.

Penn State was one of only two universities established as an International School of Nuclear Science and Engineering in 1956 to educate scientists and engineers from foreign countries in nuclear science and engineering. A total of 175 scientists and engineers from 39 different countries participated in one of the six programs that were conducted at Penn State from April 1956 to January 1959. The facility also conducted training programs for reactor operators in the US until the early 1980s and developed special training and experiments for operators who would be conducting the de-fueling procedure at the Three-Mile Island Unit-2 reactor vessel. The Penn State reactor continues to support education and outreach for people of all ages. The Penn State reactor was the first university research reactor to use the 12 wt% TRIGA fuel elements, proposed at Penn State in 1968, to improve core life and reduce costs associated with reactor operation. The PSBR was one of the first to install a digital control and monitoring system in the early 1990s.

The RSEC was established in 1990 as a response to the increased use of nuclear techniques in multidisciplinary research. The centre is a university-wide facility, promoting research, education, and various applications of radiation science and nuclear engineering.

2. CURRENT TECHNICAL STATUS

The RSEC facilities include the PSBR, gamma irradiation facilities (In-pool Irradiator and Dry Irradiator), Neutron Beam Laboratory and Hot Cells, Neutron Activation Analysis laboratory with Compton suppression system, Radiochemistry Teaching Laboratory, Nuclear Security Education Laboratory, Graphite Subcritical Assembly, and various Radiation Detection and Measurement Laboratories.

The PSBR is housed in a 270,000 l pool of purified water. The pool can be divided roughly in half with a movable gate for maintenance or installation of new experiments. Figure 2 shows the core picture of the PSBR operating at full power and Fig. 3 shows the front entry of the RSEC. When the pool is divided, part of the pool can be drained to a large onsite tank, so that the purified water is not wasted. The reactor core can be moved in any direction on sets of rails or rotated through 270 degrees. Using these capabilities, the reactor core can be positioned in almost any location in the pool for experiments or maintenance.

The PSBR is a primary neutron source for research and an important educational tool in demonstrating nuclear principles and reactor dynamics. It can operate at a maximum of 1 MW in steady-state mode (flux = 3×10^{13} $n \cdot cm^{-2} \cdot s^{-1}$) and can be pulsed up to 2,000 MW (flux = 6×10^{16} $n \cdot cm^{-2} \cdot s^{-1}$).

The current (2014) Neutron Beam Laboratory (NBL) uses a tangential D_2O thermal column to produce radiographic images and perform neutron science. Well-collimated beams of neutrons are passed into the NBL for use in nondestructive testing and evaluation. State-of-the-art neutron imaging equipment is available to digitize real-time radiography images for processing. A photographic laboratory is available for static neutron radiographs. The neutron

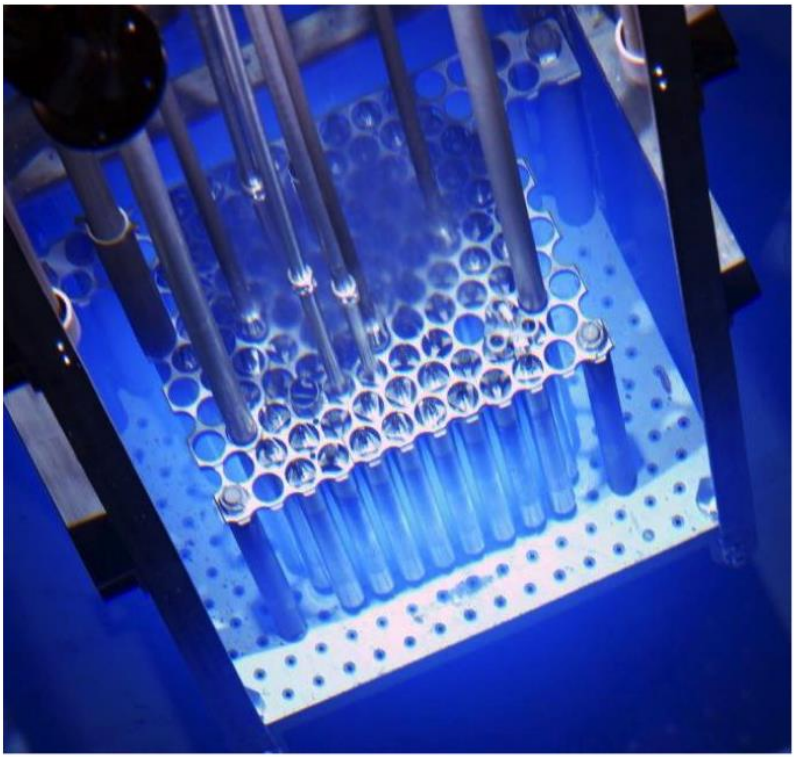

FIG. 2. The Penn State TRIGA reactor core operating at full power (1 MW).

FIG. 3. The front entry of the RSEC.

imaging capabilities have recently been upgraded with a state-of-the-art digital radiography system that supplies fully DICOM/DICONDE compliant digital images. Flash radiography is also available by pulsing the reactor. The NBL includes a Neutron Depth Profiling facility, slow chopper for neutron beam characterization and various fixtures for irradiation testing with neutron beams. Additional systems for prompt gamma neutron activation analysis, a cold neutron source, and a powder diffractometer are planned for the near future.

The Radionuclear Applications Laboratory provides technical assistance to research personnel and industrial users who need to utilize radionuclear techniques in their research. The laboratory houses four complete High-Purity Germanium detector systems with state of the art computers and two automated sample changers (Fig. 4). A Compton suppression system was added to enhance the sensitivity of measurements made in laboratory. Pneumatic Tube Transport Systems allow samples to be transported safely and quickly between the reactor core and the workstation.

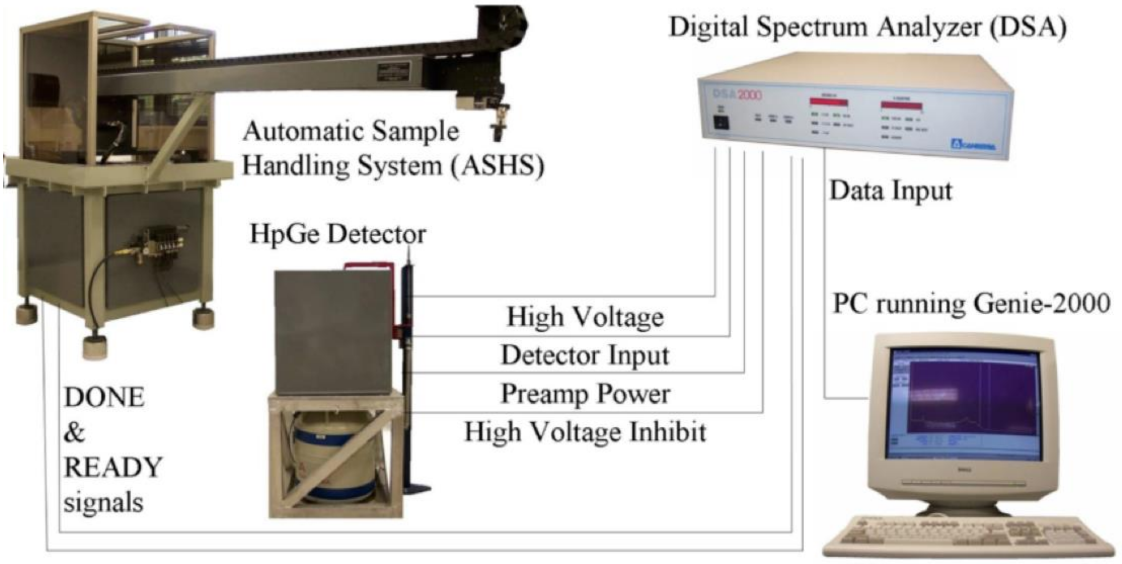

FIG. 4. Automated sample handling system and the High-Purity Germanium detector with shielding and data acquisition system at RSEC-Neutron Activation Analysis facility.

The two fast-neutron irradiation facilities are permanently mounted in the reactor pool. Their mission includes testing for the effects of radiation hardening, enhanced performance of electronic components, and testing of materials in a radiation environment. The current interest in space-based technologies is driving much of their utilization.

Gamma irradiation of materials can be performed in one of two facilities at the RSEC. High doses can be achieved in the Gammacell 220 dry irradiator. Samples can also be cooled by air or liquid nitrogen depending on the application. Lower dose rates are achievable in the pool irradiator (Fig. 5). Movable ^{60}Co sources can be configured for the individual needs of each researcher. There are several premade fixtures ready for use and others that can be installed as needed. Discrete neutron sources can also be used to provide a mixed radiation field as needed. There are two hot cell facilities at RSEC for handling of radioactive materials (Fig. 6). Researchers' samples can be electronically monitoring during irradiation in any of the facilities described.

The RSEC has 13 full-time and 11 part-time employees. The RSEC staff includes a director, an associate director of operations, an assistant director of irradiation services and operations, two research associates, three nuclear applications engineers, three instrumentation engineers, and a master machinist. Most part-time employees are undergraduate interns. Among the staff members and interns, the RSEC currently has 11 senior reactor operators and eight reactor operators.

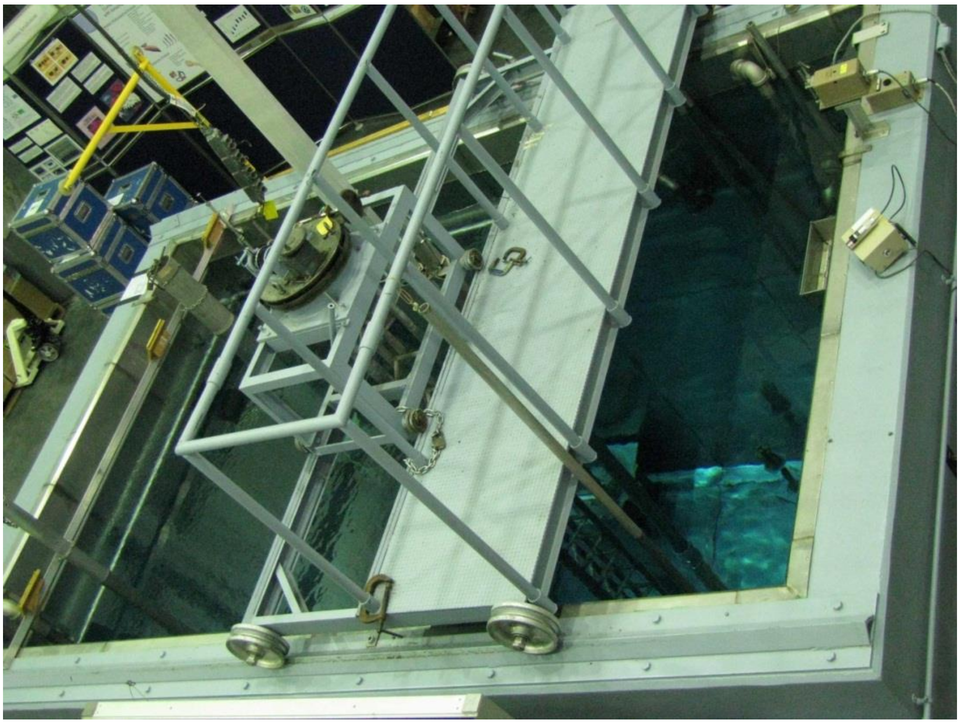

FIG. 5. In-pool gamma irradiation facility at the RSEC located in a separate building adjacent to the PSBR building.

FIG. 6. Picture of one of the two hot cell facilities at the RSEC.

3. APPLICATIONS, UTILIZATIONS AND ACHIEVEMENTS

The RSEC facilities are very actively utilized for teaching, service, and research activities. A brief summary of these activities and recent achievements are discussed below.

3.1. Teaching activities at the radiation science and engineering centre

The RSEC serves as the cornerstone of the nuclear engineering community at Penn State. Years ago, when the student body was smaller, many classes were taught at the RSEC. Currently, with about 250 undergraduate students, the lecture classes have moved into larger classrooms, but all of the laboratory classes and several special topics classes are still taught at the RSEC. The laboratory courses at the RSEC include: Radiation Detection and Measurement, Experiments in Reactor Physics, Reactor Operation and Testing and Nuclear and Radiochemistry. The RSEC is also the home of the Nuclear Security Master's Degree Program. This program was developed as part of the Department of Energy (DOE)-NNSA-GTRI Nuclear Security Education Initiative. There are five core courses at the heart of the program: Global Nuclear Security Policies, Threat Analysis and Assessment, Detector and Source Technologies, Applications of Detectors/Sensors/Sources for Radiation Detection and Measurements (Fig. 6), and Design and Analysis of Security Systems for Nuclear and Radiological Facilities. These courses support the education of hundreds of undergraduate and graduate students each year. Additionally, the RSEC is strongly engaged in outreach activities with the public. Over 3,000 people visit the facility each year. Tour groups range in size from a single family to over a 100 people. Tours are carefully matched to the audience, which range from primary school students to visiting faculty and government officials.

FIG. 6. Nuclear security graduate education laboratory at the RSEC.

3.2. Industrial research and service activities at the RSEC

The PSBR is a primary neutron source for research and an important educational tool in demonstrating nuclear principles and reactor dynamics. The large open pool design and movable core provide maximum flexibility for experimental apparatus. There are four main focuses of service work at the RSEC: in-core irradiations (NAA and isotope production and radiation aging), fast-neutron irradiations (radiation hardness testing, radiation effects testing and semiconductor irradiations), thermal neutron irradiations (neutron radiography and neutron gauging), and a variety of gamma irradiations.

3.2.1. In-Core Irradiations

The PSBR reactor core is very configurable with many options for in-core and near-core irradiations. The current core design has a dedicated location for the pneumatic transfer system. There are also two air-filled dry tubes that are primarily used for NAA, but have been used for isotope production research. The core also has a water-filled central thimble location that has a very high thermal neutron flux. This location has been used for radiation damage testing and isotope production. Currently, the RSEC regularly produces four isotopes (^{41}Ar, ^{56}Mn, ^{82}Br and ^{24}Na) for industrial uses multiple times each year. The RSEC serves the northeastern quarter of the US for these. Additional in-core irradiations have been performed to certify materials and devices for service in nuclear power plant systems. The high neutron and gamma fluences available in the core region make this a highly desirable test bed. The RSEC has partnered with an external testing laboratory to provide mechanical testing of irradiated materials.

3.2.2. Fast-Neutron Irradiations

The fast-neutron work is performed in two air-filled fixtures that are shielded from the core gammas and most thermal neutrons. Radiation effects testing of electronics began in the aerospace and defense industries. These tubes were shielded with 10 cm of lead as well as boron, so the gamma dose to test devices was greatly reduced. The fast-neutron flux was also increased slightly through better coupling with the reactor core. Starting in the early 1990s, a large amount of semiconductor irradiations were conducted to boost the switching speed of transistors on irradiated wafers. Currently, both of these fields are commonly in use at the RSEC. The techniques have been extended to academic and industrial research projects for commercial and aerospace applications. The development of infrastructure at the RSEC has been a great benefit to many.

3.2.3. Neutron Beam Laboratory: Transmission and Radiography

The RSEC has a facility specifically designed to measure the ^{10}B concentration in neutron-absorbing materials and has been working in this field since 1998. The facility and the measurement method are used to characterize the effectiveness of most boron-based aluminum neutron-absorbing materials utilized by the nuclear industry. The neutron beam laboratory also houses a neutron imaging facility for the inspection of materials. The facility has the capability to take film and digital still images with a variety of cameras as well as a new GE Imaging Computed Radiography system that is fully DICONDE compliant. The RSEC also houses an X ray radiography facility that uses the same imaging technology as the neutron beam facility.

3.2.4. Gamma Irradiation Work

The RSEC also has four gamma irradiation facilities. There is a dry cell Nordion Gammacell 220 irradiator, a large pool irradiator, a hot cell facility, and a JL Shepard calibrator source. The Gammacell is used primarily for sterilizations, materials testing, and polymer crosslinking. The pool irradiator is used for biological irradiations and ELDR testing of electronics. The hot cells are flexible, low dose facilities for a variety of custom work. The calibration source is used for health physics work as well as certification of electronics for nuclear applications.

3.3. Multidisciplinary research at the RSEC

Recent research projects that utilize the neutron beam laboratory at the RSEC are listed below. Most of these are interdisciplinary in nature and involve other faculty members and graduate students from within the College of Engineering, other colleges at Penn State, universities, national laboratories (including NIST), and industry. The projects include: Neutron-Induced Soft Error Rate Measurements of Semiconductor Memories; Soft Error

Analysis Toolset Development; Time-of-Flight Neutron Depth Profiling; Study of Water Distribution and Transport in a Polymer Electrolyte Fuel Cell Using Neutron Imaging; Neutron Imaging System Improvements; Neutron Transmission Measurements and Neutron Radioscopy for Borated Metals and Other Borated Materials; Neutron Intercepting Semiconductor Chip Development; Neutron Beam Characterization with Neutron Chopper; Neutron Beam Modeling; Cold Neutron Source Design; and Fission Track Analysis. In addition to neutron beam laboratory activities, several projects related to NAA and Thermal and Fast-Neutron Irradiation continue at the RSEC. Brief descriptions of some research projects, funding sources, and key publication lists are given below.

3.3.1. Neutron-Induced Soft Error Rate (SER) Measurements of Semiconductor Memories

Soft errors are transient circuit errors caused due to excess charge carriers induced primarily by external radiation. Radiation directly or indirectly induces localized ionization that can flip the internal values of the memory cells. Our current study tries to characterize the soft error susceptibility for different memory chips working at different technology nodes and operating voltage. This study intends to observe the effect of ^{10}B and high-energy neutrons on soft error rate. The PSBR is used as the neutron source in experiments in order to investigate the effect of ^{10}B on SER. The experimental setup consists of a custom board interfaced with a computer through a GPIB card (Fig. 7). The circuit board is secured in the beam cave and connected to a PC outside using a 25-ft (7.62 m) cable. This configuration allows for continuous read-write and for changing the operating conditions without interrupting the experiment.

The setup described above allows for accelerated testing of semiconductor memory devices with thermal neutrons. Different memories (16 kbit and 4 Mbit) from several vendors were evaluated at various supply voltages and reactor power levels. Linear increases in the SER were observed for corresponding decreases in voltage. For examining the statistical accuracy of the accelerated tests, they were performed at various reactor power levels. Since reactor power and flux at the exit of the beam port are directly correlated, changing the reactor power effectively changes the neutron flux impinging on the test sample; hence the SER is expected to increase. It has been verified that the SER increases as the reactor power increases. This interdisciplinary research involves faculty members and graduate students from nuclear engineering, computer science and engineering, and scientists from AMD/Cerium laboratories. The project is funded by the NSF, DOE, AMD, and Penn State. Further measurements and analysis results were published, and key publications are given in References [1–2].

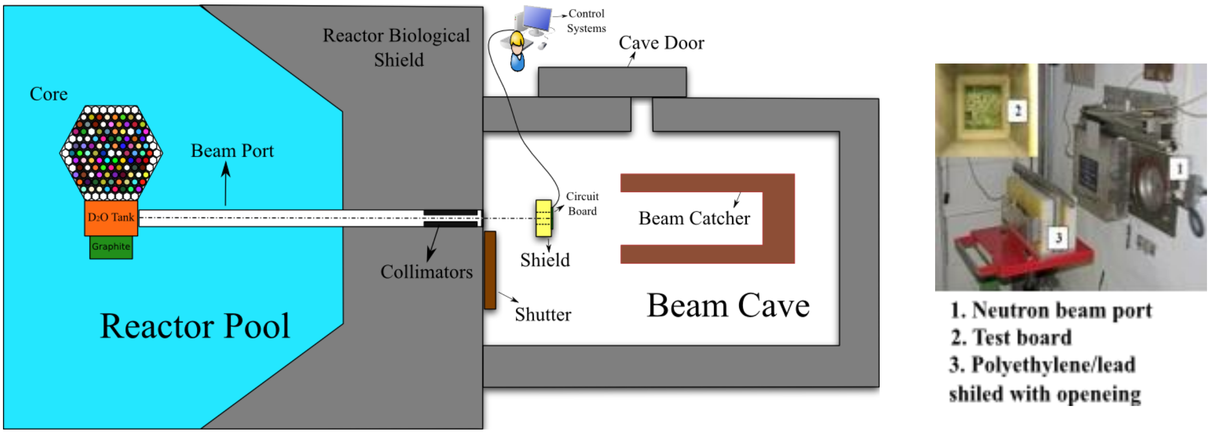

FIG. 7. On the left, a simplified layout of the test board. On the right, a test chip placed in front of the beam tube with the polyethylene/lead shield for thermal neutron testing.

3.3.2. Time-of-Flight (TOF) Neutron Depth Profiling (NDP)

NDP is a near-surface analysis technique to measure the spatial distribution of certain light isotopes of technological importance in substrates with low neutron affinity. Upon neutron absorption, certain light isotopes emit a charged particle, either a proton or alpha depending on the isotope, and a recoil nucleus. The particle emission is monoenergetic and isotropic. As the charged particle and the recoil move in the substrate, they lose kinetic energy through nuclear and coulombic interactions with host atoms. The amount of energy lost can then be correlated to the distance traveled by the particles, which is an indication of the depth at which the particles are created. Conventional NDP is based on the direct measurement of particle energies by charged particle detectors, mostly by silicon semiconductor detectors, passivated implanted planar silicon (PIPS) detectors or PIN photodiodes. A picture of the RSEC conventional NDP setup is shown in Fig. 8. Conventional NDP has been used extensively for obtaining the depth profile of light elements in various fields. However, in tandem with the advances in scientific and technological applications, depth profiling with higher resolutions has become a necessity.

Neutron depth profiling has reached the limits of resolution that can be attained by conventional techniques, limited by the use of charged particle semiconductor detectors. This limitation can be overcome, however, through a technique called time-of-flight neutron depth profiling. TOF-NDP eliminates the semiconductor detector and employs microchannel plates for particle detection in TOF configuration.

FIG. 8. Conventional NDP setup at the RSEC neutron beam laboratory.

Our preliminary measurements with TOF-NDP indicate that it will provide up to a five times better resolution than the conventional NDP, which will make the depth-vs.-concentration measurements of ultra-shallow junction devices possible. This improvement will have a significant impact on the silicon industry as the dimensions of microdevices decreases. There are alternatives to NDP at the nano-scale (e.g., Secondary Ion Mass Spectroscopy); yet, they need to be calibrated against the results of a technique such as NDP. This interdisciplinary research involves faculty members and graduate students from nuclear engineering, as well as scientists from the Advanced Micro Devices/Cerium Laboratory and NIST. The project is funded by DOE and the RSEC. Further measurements and analysis results were published, and key publications are given in References [3–4].

3.3.3. Study of Water Distribution and Transport in a Polymer Electrolyte Fuel Cell Using Neutron Imaging

Since 2002, the Penn State Fuel Cell and Neutron Imaging teams have worked in collaboration to develop tools for analysis of water management and flooding in polymer electrolyte fuel cells (PEFCs). Although PEFCs show much promise to deliver a future generation with environmentally benign, high-efficiency power, technical challenges still exist. In particular, the maldistribution of liquid water has been shown to be responsible for a majority of instability and degradation issues, which limit the performance and lifetime of these systems. Neutron imaging is an ideal non-intrusive tool to observe the liquid water in PEFCs, and the imaging tools and technology for this have been continually advanced by our team at Penn State. Penn State researchers have studied nearly all aspects of material selection, design, and computational model validation in PEFCs. Projects with aspects or focus on neutron imaging in fuel cells have been funded by Toyota, General Motors, Hyundai, Nuvera, NSF, and DOE. Total support to Penn State for these completed projects was over $ 4.7 million.

The Penn State Fuel Cell Imaging Team has also worked directly with the NIST neutron imaging facility researchers. Since the Penn State reactor capabilities are optimized for a larger scale imaging of the entire fuel cell, while NIST has special higher resolution but small image area facilities, there is an excellent coupling of capabilities between the two facilities. Some key relevant publications are given in References [5–6].

3.3.4. Neutron Activation Analysis—Dating Volcanic Eruptions with Tree-Ring Chemistry

Dendrochemical analyses of absolutely dated, overlapping sequences of tree rings allow for the identification of temporally-conscribed, volcanically-influenced periods of environmental change. Dendrochemistry, or the study of tree-ring elemental composition, is a promising new technique for reconstructing climate/environmental history at annual resolution. In particular, dendrochemistry may be useful for identifying periods of climatically and/or environmentally effective volcanic activity. Exciting new dendrochemical applications have been made by a team of researchers at the RSEC and the Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University over the last few years. NAA, Solution or Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS/ICP-MS), and Synchrotron Scanning X ray Fluorescence Microscopy (SXFM) have all been utilized to determine volcanic signatures in tree rings. NAA and Solution ICP-MS are two analytical techniques that have been used with varying degrees of success in attempts to trace volcanic eruptions at annual resolution in tree-ring sequences. NAA measurements are performed at the RSEC and Cornell University facilities are used for SXFM and ICP-MS measurements.

Using dendrochemical analysis via NAA, SXFM, and ICP-MS/AES of samples already collected and dated, and some selected new samples we initially concentrated on defining periods of global environmental stress during the past 500 years. In the next phase of research, we employed data sets from four loci from three distinct regions of the Northern Hemisphere in order to test and identify hemispheric versus regional signals. After we gain confidence in our methodology, we will aim to extend the time line backwards for several thousand years. A sample spectrum from RSEC-NAA for a tree ring sample is shown in Fig. 9.

For future work attempting to trace volcanic events in tree rings, we foresee a combined approach using NAA to create long annual resolution sequences of elemental change, solution ICP-MS analysis of selected events to broaden the range of elements detectable, and SXFM to understand the physiological context of those associations. It is through such a combined approach along with further in-depth research into tree ring physiology that we hope complex hypotheses can be developed to explain the elemental record so that tree-ring chemistry may one day be used as a Holocene-long archive of absolutely dated volcanism. This project is an interdisciplinary research involves faculty members and graduate students from the Penn State's nuclear engineering program and the Dendrochronology Laboratory at Cornell University. The project is funded by the NSF, DOE, Cornell University, and the RSEC. Further measurements and analysis results were published, and key publications are given in References [7–8].

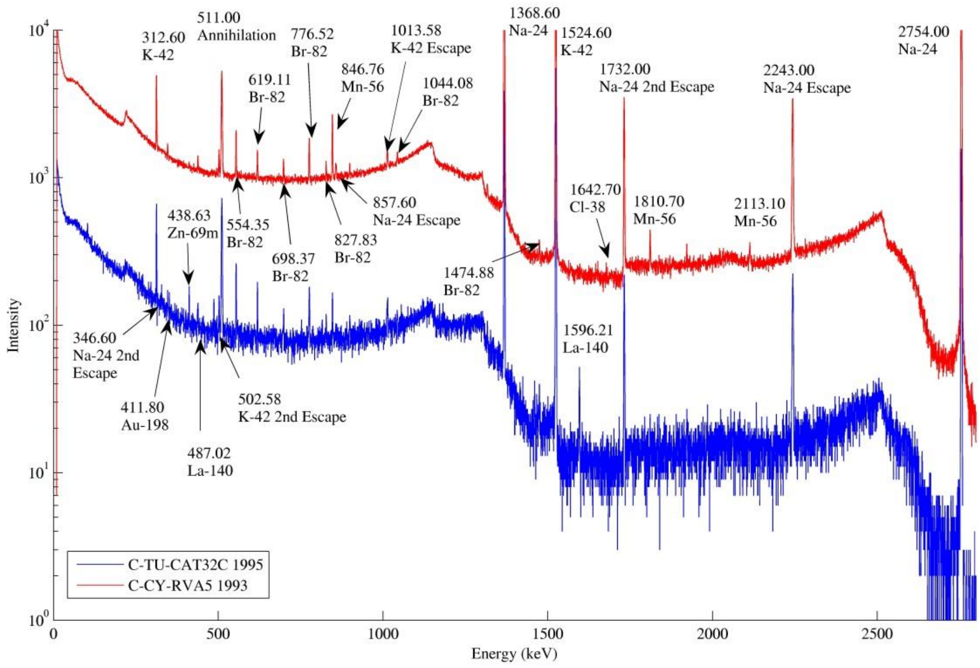

FIG. 9. Typical gamma spectrum from C-TU-CAT32C (1995) and C-CY-RVA5 (1993) tree-ring samples for long irradiation and 1 h count after 24 hours of decay.

4. FUTURE PROSPECTS

Due to inherent design issues with the current arrangement of beam ports and reactor core-moderator assembly, the potential for the development of innovative experimental facilities utilizing neutron beams has been extremely limited. Therefore, a new core-moderator assembly in the PSBR pool and new beam port geometry are needed in order to achieve the full potential of the RSEC's neutron beam capabilities. Several studies (3 PhD dissertations and 2 MSc theses) were completed with the support of DOE and RSEC funds to characterize the existing beam ports for neutron output and to investigate new core- and moderator designs that would make additional beam ports accessible. A major funding was received from DOE to build and install a new core moderator assembly and new beam ports at RSEC. The new core-moderator and beam port arrangement requires expansion of the existing beam laboratory in order to place instrumentation, neutron guides, and beam catcher, etc. Both the new design of core-moderator/beam port arrangement and the expansion of the current beam laboratory to form a beam hall are strongly related. We are currently seeking funds to build a new neutron beam hall building to house the new neutron beam experiments and neutron guides.

The new and expanded laboratory will add new beam ports that are geometrically aligned with the core-moderator assembly for optimum neutron output at experimental positions, a new core-moderator assembly located in the PSBR pool and 715 m^2 of new and ~1,200 m^2 of expanded experimental areas and laboratories for graduate research and graduate student/faculty office areas. The state-of-the-art neutron beam facilities, coupled with the existing PSBR and RSEC capabilities, will position Penn State to take a lead role among the universities in the revitalization of nuclear science and engineering research in the US. The new facility will offer unparalleled research opportunities for Penn State faculty and graduate students in many disciplines and will provide an excellent test-bed for development of instruments and experiments for researchers at Penn State, as well as other regional and national university researchers, industry, and national laboratories.

Five new neutron beam ports were designed for the PSBR facility. This new arrangement would require cutting and removing a section of the existing biological shield and placing five new beam ports with various diameters depending on the intended neutron beam technique to be applied. A mesitylene-based cold neutron source and three neutron guides will be installed in one of the beam port. Four new experimental techniques (triple-axis spectrometer, conventional and TOF-NDP, neutron powder diffraction, and prompt gamma activation analysis) will be added to the existing neutron imaging and neutron transmission facilities. The geometrical configurations along with the filter and collimator system designs of each neutron beam port were selected based on the requirements of the experimental facilities. MCNP5 simulation results predicted that thermal neutron flux will be increased by a factor of between 1.23 and 2.68 in the new beam ports compared to the existing design. In addition the total gamma dose will be decreased by a factor of 100 in the new PSBR facilities.

The areas envisioned for the RSEC's new neutron beam port/beam laboratory are for mostly cutting-edge nuclear and materials science research. Some examples include: a NDP facility for depth vs. concentration measurements, impurity determination of He-3 and B-10 in semiconductors, metals, and alloys; a mesitylene-based Cold Neutron Source and Cold Neutron Prompt Gamma Activation Analysis for neutron focusing research, materials characterization, and determination of impurities in historically or technologically important materials; a Neutron Powder Diffractometer for structural determination of materials; and a Triple Axis Diffractometer to train students on neutron diffraction and perform preliminary structural determinations of materials. Brief descriptions of some these techniques are given below. The majority of funds to develop and implement these techniques are already available at the RSEC. Most of the required equipment (e.g., neutron imaging systems, neutron activation analysis systems, NDP chamber and the related data acquisition and processing equipment, and the prompt gamma activation analysis system) has already been purchased, and some of these techniques are already available at the RSEC with limited capacity. With the new and expanded laboratory, the techniques and associated research projects will be improved and new research projects will be available for the development of cold neutron beam and neutron guides. Some of the new techniques that will be installed for research at the RSEC are described briefly below.

Cold Neutron Source (CNS): Most of the neutron beam applications can be enhanced by using subthermal, "cold," neutrons. The "temperature" of a neutron beam can be lowered by passing it through a moderator that is cooled to well below liquid nitrogen temperature. Cold neutrons have longer wavelengths and lower kinetic energies than thermal neutrons, allowing an increased size scale for structure research and better energy resolution in the study of molecular motion. Also, cold neutrons can be "guided" down cylinders, called neutron guides, without significant loss and can be bent out of line-of-sight paths followed by fast neutrons and gamma rays. Cold neutron beams from neutron guides have low gamma and fast-neutron backgrounds, increasing sensitivity in scattering experiments. In addition, detectors for neutron-capture experiments can be placed closer to the sample, increasing sensitivity and making coincidence techniques feasible in many situations.

Cold neutron beams are used for experiments that require low background and are enhanced by using cold neutrons (e.g., neutron-capture gamma ray analysis and various condensed matter research projects utilizing neutron diffraction or scattering experiments). A mesitylene-moderated cold neutron source facility [9–10] was designed with DOE funds and will be developed at Penn State after the proposed renovation (Fig. 10).

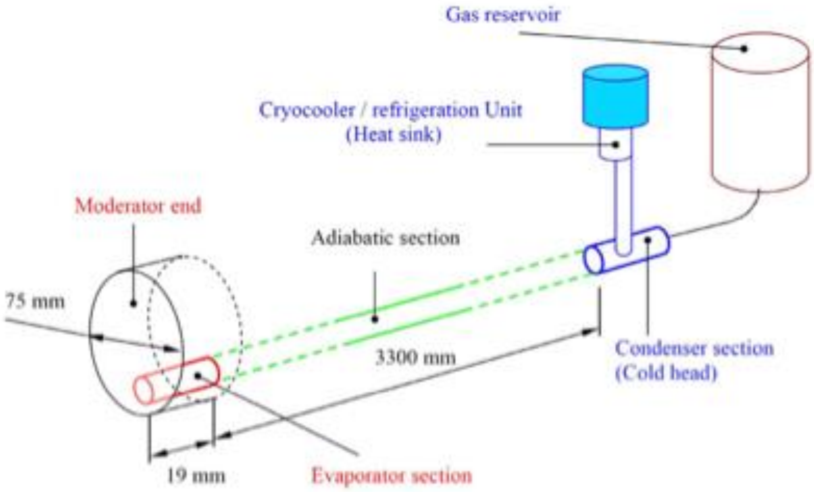

FIG. 10. Schematic diagram of the two-phase closed thermosyphon cooling system for the RSEC.

Prompt Gamma Activation Analysis (PGAA): PGAA is a rapid, nondestructive nuclear technique used for trace and major component analysis of various elements. It is based on the detection of gamma rays emitted by a target material while it is being irradiated with neutrons. PGAA is most applicable in the determination of nonmetals, which are usually found in the common matrices as an impurity or major element (H, C, N, Si, P, S), or trace elements with high thermal capture cross sections (B, Cd, Gd). The analysis of these elements is usually marginal when other techniques are used.

Elemental analysis using PGAA has been confined to only a few laboratories to date [11–12]. The reason for this is mostly the need for continuous access to a reactor neutron beam. Also, the applications of PGAA are limited to the determination of the elements mentioned above. Cold neutron beams are usually used for PGAA in low and medium power nuclear research reactors. An important application of PGAA is to measure bulk hydrogen content in semiconductors since hydrogen in semiconductors is bound to an extensive array of defects and dopants, modifying and often neutralizing the associated electrical and chemical activity and substantially affecting defect evolution. These effects are critical in device technology, due to both the unavoidable presence of hydrogen in processing and to the possibility of controllably passivating unwanted defect centers. We plan to develop PGAA using the cold neutrons that will become available after the proposed renovation.

Neutron Powder Diffraction (NPD): Neutron diffraction is one of the best ways to obtained detailed atomic-level structural information for many different materials. Diffraction experiments on single crystals provide precise data for small samples (<0.1–0.5 mm^3). The recent development of instrumentation and data analysis techniques have made it possible to obtained precise structural information (as in single crystals) from neutron diffraction experiments on powder samples. The ongoing progress in NPD, specifically advances in data analysis methods for crystalline, as well as quasi-crystalline, and amorphous materials have attracted a broad spectrum of scientists in this field. NPD can be ranked as one of the most useful tools for studying condensed matter. NPD is now feasible for low and medium power research reactors due to recent developments of position-sensitive detector systems and focusing monochromators [13]. We plan to develop a NPD at the RSEC after the expansion of the neutron beam laboratory for mainly material science research and training graduate students for materials characterization.

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