RESEARCH, EDUCATION AND SERVICE UTILIZATIONS OF BREAZEALE NUCLEAR REACTOR AT THE RADIATION SCIENCE AND ENGINEERING CENTER AT THE PENNSYLVANIA STATE UNIVERSITY

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ABSTRACT

The Radiation Science and Engineering Center (RSEC) facilities at the Pennsylvania State University include Penn State Breazeale Reactor (PSBR), gamma irradiation facilities, several radiation detection and measurement laboratories and neutron irradiation facilities. The PSBR is a 1 MW, TRIGA with moveable core in a large pool with pulsing capabilities. A variety of dry tubes and fixtures are available for in or near core irradiations. The RSEC facilities are heavily used for nuclear science and engineering research, education and services. Examples of multidisciplinary nuclear science and engineering research, educational as well as industrial service utilizations at the RSEC will be presented.

1. Introduction

1.1 Radiation Science and Engineering Center

The Penn State Breazeale Reactor (PSBR) at the Radiation Science and Engineering Center (RSEC) is a 1 MW TRIGA Mark III reactor with pulsing capabilities. The moveable core at PSBR has no fixed reflector and is located in a 24 ft deep pool with ~71,000 gallons of demineralized water. A variety of dry tubes and fixtures are available in or near the core for irradiations. When the reactor core is placed next to the D_2O tank and graphite reflector assembly at the beam port locations, thermal neutron beams become available. In steady state operation at 1 MW, the thermal neutron flux is $1x10^{13}$ n/cm^{2}sec at the edge of the core and $3x10^{13}$ n/cm^{2}sec at the central thimble. The peak flux during a maximum pulse is ~ $6x10^{16}$ n/cm^{2}sec with a pulse half width of ~10 msec. The PSBR, the centerpiece of the RSEC, first went critical in 1955 and is the longest continuously operating university research reactor in the United States. The Nuclear Regulatory Commission renewed the PSBR's license for an additional 20 years in November 2009. A significant redesign of the core-moderator/beam port is currently underway to make full use of the PSBR's capabilities and to establish state-of-the-art neutron beam facilities.

1.2 Department Mechanical and Nuclear Engineering

The Pennsylvania State University (PSU) Nuclear Engineering Program is a leader in undergraduate and graduate-level nuclear engineering education in the USA. Currently 248 junior and senior undergraduate and 51 graduate students are enrolled in the Nuclear Engineering Program. Additionally, approximately 90 graduate students are taking nuclear engineering courses for the Master of Engineering degree program from the PSU World-Campus. The PSU undergraduate program is one of the largest nuclear engineering programs in the USA. One of our strategic goals is to increase the quality, stature and visibility of the PSU Nuclear Engineering degree programs, especially at the graduate level, by increasing our emphasis of nuclear science research and education. To achieve our strategic goal and support the DOE-NNSA-GTRI Nuclear Security Education Initiative, PSU developed a new graduate degree program in nuclear security in collaboration with the Massachusetts Institute of Technology and Texas A&M University. Our new nuclear security graduate level curriculum will enable the PSU to equip the next generation of nuclear engineers, within the United States as well as worldwide, with a strong background in nuclear security. The nuclear security education program at Penn State will grant a Master of Science or a Master of Engineering degree after completion of the curriculum.

2. Multidisciplinary Research at the Radiation Science and Engineering Center

Some recent research projects that utilize the neutron beam laboratory at the RSEC are listed below. Most of these are multidisciplinary in nature and involve other faculty members and graduate students from within the College of Engineering, other colleges, other universities, national laboratories, 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 Neutron Activation Analysis and Thermal and Fast Neutron Irradiation continue at the RSEC. Brief descriptions of some recent research projects and planned new techniques for neutron beam research at the RSEC are given below:

2.1 Gamma Ray Burnup Analysis of Penn State TRIGA Reactor Used Fuel Rods

Effective material control and accountability of reprocessing facilities requires the verification of operator declared burnup, cooling time, and irradiation history before fuel dissolution for safeguards and process control purposes. To perform this task rapidly, inspectors utilize nondestructive radiometric methods relying on the buildup of fission products during the burning of fuel. Many of these burnup metrics are derived from nuclides that are not direct fission products and arise from fission, capture, and decay pathways. Research reactor fuel poses an even more challenging problem, since their fuel has a more complex and irregular history that complicates the traditional calculation of burnup using the paired isotope analysis method. The PSBR at the RSEC has an inventory of irradiated TRIGA research reactor LEU fuel spanning 48 years of operation. Direct gamma ray measurements of the nuclide composition of irradiated fuel removed from the core were used to calculate the incremental and average burnup of several used fuel elements from the vertical length of the fuel elements using a collimated beam port to determine the segmented burnup across the axial length of the fuel rod as shown in Figure 1. Actual burnup values came from the highly specialized, Monte Carlo-coupled depletion simulation code TRIGSIM developed for the PSBR to provide detailed burnup information. Resulting burnups ranged from 1.56% to 30.45% error relative to the TRIGSIM simulated values [1]. A correction factor for irradiation history data to account for periods of shutdown and variable power was attempted, but the handwritten daily operator logbook requires further investigation, as the approximated value did not reduce the relative errors.

2.2 Characterization of Italian Tile Samples Using Comparative Neutron Activation Analysis

Historically, archaeologists used shape, size, and decorative additions to determine the provenance of ancient pottery. Since the middle of the twentieth century, however, the identification and quantification of minerals and trace elements in archaeological finds has been an instrumental aid in identifying artifact origins [2]. Neutron activation analysis (NAA) is an ideal method to analyze such archaeological samples, as it provides ppm to ppb level elemental quantification without the need for extensive and destructive sample preparation. To expand the NAA capabilities at the RSEC, we developed the necessary sample irradiation fixtures and

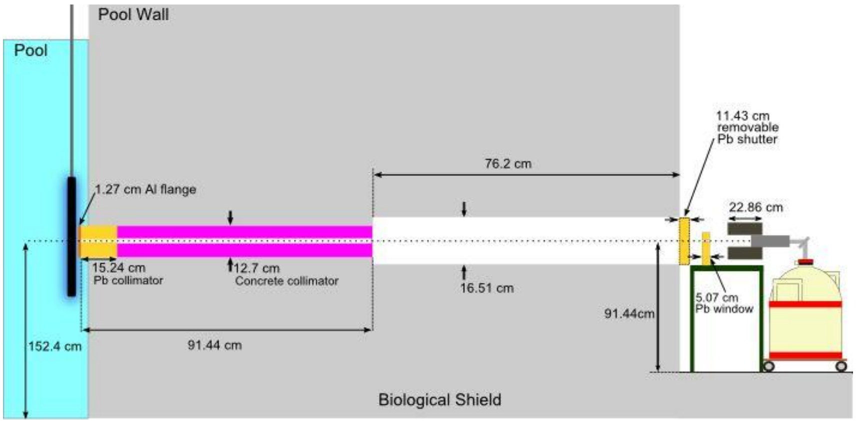

Fig. 1: Schematic diagram of the used fuel measurement system.

expertise to conduct comparative NAA on large numbers of solid samples. Using material provided by our archaeological collaborators, we performed comparative NAA on Italian tile samples with the goal of identifying their elemental composition, especially noting the concentrations of seven target trace elements identified by our collaborators as useful for sample evaluation: europium, thorium, chromium, hafnium, cesium, scandium, and rubidium. A set of 15 tile samples from two archeological sites, Tarquinia and Veii, Italy, were obtained from Colgate University. Sample masses varied from 30 mg to a little over 100 mg. Some of the samples were in powder form, while others were hard, brittle, and rock-like. The samples ranged in color from gray and black to clay-like and brick red. Previous studies [2] determined that for typical archaeological pottery samples of ~100 mg, total neutron fluences of ~$6x10^{14}$ neutrons/cm^2 and ~$6x10^{17}$ neutrons/cm^2 provide sufficient activation and counting statistics for short-lived ($t½$ < 15 h) and long-lived ($t½$ > 15 h) activation products, respectively. Given that the maximum thermal neutron flux available at the PSBR is between $1x10^{13}$ and $3x10^{13}$ n/cm^2/s, short-lived isotopes only require several minutes of irradiation, while longer-lived isotopes would require up to 40 hours of neutron exposure. However, using the PSBR Activity Predictor Tool [3], estimates of the activities expected from the activated elements indicated that an eight-hour irradiation at full reactor power would produce sufficient induced activity for statistically sufficient counting rates. The irradiation of the 15 Italian tile samples demonstrated our ability to identify and quantify 15 elements, including five of the seven elements desired by our archaeological collaborators: europium, thorium, chromium, hafnium, cesium, scandium, and rubidium [4]. Thorium and cesium were not found in any of the samples. As a representative sample, the calculated concentrations from sample 150B are shown in Table I. The majority of the elemental concentrations can be determined with error values of less than 15%. Strontium and zirconium concentrations calculations suffer from large counting errors and would benefit from a longer irradiation time.

Table I. Elements Identified in Pottery Sample 150B

Element	**Concentration (wt %)**	**Standard Uncertainty (%)**
Antimony	3.27E-06	12.6
Barium	9.99E-04	13.0
Calcium	3.03E-03	14.3
Chromium	7.79E-05	15.8
Europium	3.82E-06	11.9
Hafnium	9.64E-06	12.8
Iron	5.40E-02	11.8
Manganese	1.54E-03	11.8
Potassium	2.30E-02	13.3
Rubidium	5.86E-04	13.0
Scandium	1.60E-05	11.8
Sodium	4.54E-03	12.4

2.3 Planned new techniques for neutron beam research at the RSEC:

Cold Neutron Source: 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. A mesitylene-moderated cold neutron source facility improved version of the Nuclear Engineering Teaching Laboratory facility at the University of Texas at Austin [5,6] will be developed at PSBR (Fig. 2).

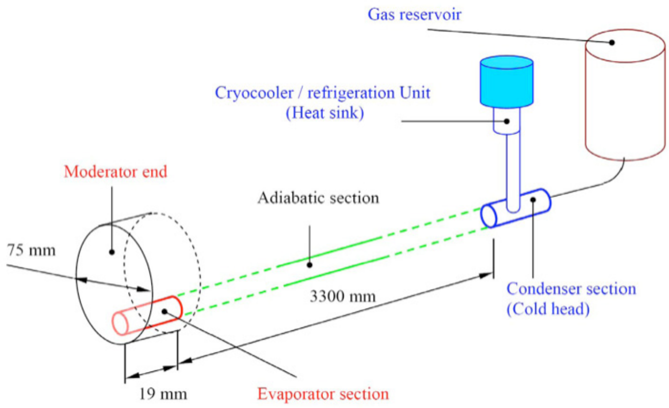

Fig. 2: Schematic diagram of the two-phase thermosyphon cooling system for cold source

Prompt Gamma Activation Analysis (PGAA): PGAA is a rapid, nondestructive 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 [7,8].

Neutron Powder Diffraction (NPD): Neutron diffraction is one of the best ways to obtain detailed atomic-level structural information for many different materials. The recent development of instrumentation and data analysis techniques have made it possible to obtain precise structural information (as in single crystals) from neutron diffraction experiments on powder samples. NPD is now feasible for low- and medium-power research reactors due to developments of position-sensitive detector systems and focusing monochromators [9].

3. Teaching Activities at the Radiation Science and Engineering Center

The RSEC serves as the cornerstone of the nuclear engineering community at PSU. Years ago, when the student body was smaller, many classes were taught at the RSEC. Currently, with about 250 undergraduate junior and senior 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 RSEC is also the home of the Nuclear Security Master's Degree Program. This program was developed as part of the DOE-NNSA-GTRI Nuclear Security Education Initiative. There are five core courses that are 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 and Design and Analysis of Security Systems for Nuclear and Radiological Facilities. The laboratory courses at the RSEC include: Radiation Detection and Measurement, Experiments in Reactor Physics, Reactor Operation and Testing and Nuclear and Radiochemistry. 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 3000 people visit the facility each year. Tour groups range in size from a single family to over a hundred persons. Tours are carefully matched to the audience, which ranges from primary school students to visiting faculty and government officials.

4. 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 foci 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 gaging) and a variety of gamma irradiations.

4.1 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 for industrial uses. ^{41}Ar, ^{56}Mn, ^{82}Br and ^{24}Na are produced in curie quantities multiple times each year. The RSEC serves the northern quarter of the United States for these radioisotopes. 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.

4.2 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 10cm of lead as well as the boron, so the gamma dose to the test devices was greatly reduced. The fast neutron flux was also increased slightly through better coupling with the reactor core. Also starting in the early 1990s was a large amount of semiconductor irradiations to boost the switching speed of the transistors on the 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 the infrastructure at the RSEC has been a great benefit.

4.3 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.

4.4 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.

5. Conclusions

The Radiation Science and Engineering Center is nearing its sixtieth year of operation. During this time, thousands of students have been educated and hundreds of academic and industrial research projects have been explored. The faculty and staff of the RSEC remain committed to the mission of providing an invaluable resource for research, education and service work to the community.

6. References

[1] S. Bender, C. Durrant, B. Heidrich, K. Ünlü, (2013) “Experimental gamma ray burnup analysis of Penn State TRIGA reactor spent fuel rods”. Presented at the 54th Annual Institute of Nuclear Materials Management Conference, Palm Desert, CA, July 2013.

[2] I. Perlman, F. Asaro, “Pottery Analysis By Neutron Activation,” Archaeometry, 11, 21-52 (1969).

[3] D. Sahin, K. Ünlü, “Activity, exposure rate, and spectrum prediction with Java programming,” J. Radioanal. Nucl. Ch., 282, 161-165 (2009).

[4] A. M. Johnsen, C. B. Durrant, and K. Ünlü, “Characterization of Italian Tile Samples Using Comparative Neutron Activation Analysis”, accepted for publication in Transactions in American Nuclear Society Winter meeting November 2013.

[5] K. Ünlü, C. Rios-Martinez, and B. W. Wehring, "The University of Texas Cold Neutron Source," Nucl. Instr. and Meth. in Phys. Res. A 353, 397-401, (1994).

[6] M. Habte, “Thermal Hydraulic Analysis of Two-Phase Closed Thermosyphon Cooling System for New Cold Neutron Source Moderator of Breazeale Research Reactor at Penn State,” PhD Dissertation, The Pennsylvania State University, Department of Mechanical and Nuclear Engineering, (2008).

[7] B. W. Wehring, and K. Ünlü, “Applications of Cold-Neutron Prompt Gamma Activation Analysis at the University of Texas Reactor,” Applied Radiation and Isotopes. Vol. 48, No.10-12, 1343 (1997).

[8] K. Ünlü, C. Rios-Martinez, “Cold Neutron PGAA Developments at University Research Reactors in the USA,” Journal of Radioanalytical and Nuclear Chemistry, Vol. 265, No. 2, 329-338, (2005).

[9] R. Berliner, M. Popovici, W.B. Yelon, “Neutron Powder Diffraction at Low and Medium Flux Sources,” Trans. Am. Nucl. Soc., **82**, 87 (2000).