FINAL REPORT

Project Title: Innovations and Enhancements for a Consortium of Big-10 University Research and Training Reactors

Covering Period: September 30, 2009 – September 29, 2010

Date of Report: May 16, 2011

Recipient: Pennsylvania State University

Award Number: DE-FG07-02ID14423

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SUMMARY

The Consortium of Big-10 University Research and Training Reactors was by design a strategic partnership of seven leading institutions. We received the support of both our industry and DOE laboratory partners. Investments in reactor, laboratory and program infrastructure, allowed us to lead the national effort to expand and improve the education of engineers in nuclear science and engineering, to provide outreach and education to pre-college educators and students and to become a key resource of ideas and trained personnel for our U.S. industrial and DOE laboratory collaborators.

While all members worked in the four task areas, each concentrated their activities in one or two specific tasks: Ohio State, Penn State and Wisconsin focused on upgrading facilities; Illinois and Purdue developed software and visualization tools; Michigan established a teaching and research laboratory utilizing neutron generators; and the University of Cincinnati focused on sub-critical reactor modification designs and distance learning course support. Our innovative Consortium Mini-Grant Program enabled collaboration among our institutions and provided external researchers and educators access to our facilities.

The Consortium and its members had many notable accomplishments that came about as a direct result of the INIE Program. A summary of Consortium accomplishments and those of the individual members is presented in the report. Additionally, the impact of the INIE funding on each member's institution is summarized in the report.

Consortium members leveraged INIE funding through matches of equipment, renovation, construction and contributed staff and faculty time. The INIE Program was successful in that it had a very positive impact on our nuclear engineering programs, laboratories and reactors. Additionally, the INIE funded infrastructure prepared our institutions for the rapid increase in undergraduate nuclear engineering majors that we have experienced in the past decade.

Project Objectives

Our team goal was to improve our consortium of Big-10 University Research and Training Reactors (URTR) and their nuclear engineering programs by innovations, laboratory and facility upgrades that advanced research and education through focused collaboration and natural synergisms between our departments and institutions. This goal was realized through strategic investments in the infrastructure of this consortium of Big-10 URTR facilities and programs. In so doing, we were better prepared to expand and improve the education of this human resource of engineers in nuclear science and engineering, to provide outreach and education to pre-college educators and students and to become a key resource of ideas and trained personnel for our industrial and national laboratory collaborators.

Our objectives that allowed us to achieve this goal involved:

1. Developing innovative programs in graduate education and research and undergraduate education and training that utilize these URTR facilities both on-site and at-a-distance;

2. Identifying the needed attributes for advanced university research and training reactors by the development and design of a 'Virtual' URTR for use in education and research with the intention to take the next step forward toward constructing a new generation of URTR;
3. Enacting a novel educational outreach and training program for the nuclear industry, the DOE laboratories as well as other regional educational institutions at all levels;
4. Developing a multi-disciplinary, multi-university research grant program to enable collaborative research between the seven consortium university programs, other schools and colleges as well as our industrial and laboratory partners.

Our approach involved improving the current URTR operational and research instrumentation and associated reactor facilities for our team of Big-10 institutions, as well as, a coordinated alignment of our nuclear engineering educational programs to serve our graduate and undergraduate students across the Big-10, the nuclear industry, the DOE laboratory staff, and outreach to teachers/students at colleges, high schools and middle schools.

Background

The Consortium of Big-10 University Research and Training Reactors was a strategic partnership of seven leading institutions. We received the support of both our industry and DOE laboratory partners. Investments in reactor, laboratory and program infrastructure, allowed us to lead the national effort to expand and improve the education of engineers in nuclear science and engineering, to provide outreach and education to pre-college educators and students and to become a key resource of ideas and trained personnel for our U.S. industrial and DOE laboratory collaborators.

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Consortium members leveraged INIE funding through matches of equipment, renovation, construction and contributed staff and faculty time. Thus, the INIE Program was successful in that it had a very positive impact on our nuclear engineering programs, laboratories and reactors.

Projects from 9/30/09 through 9/30/10

The following is a detailed list of projects that were undertaken in the project year September 30, 2009 through September 30, 2010. As we entered the final year of the INIE contract, only a few sub-tasks that had been continuing over a number of contract years remained to be completed.

The program activities are reported in four separate categories: educational enhancements, research innovations, infrastructure improvements and intra-consortium integration.

1. Educational Enhancements

PENN STATE UNIVERSITY

Title: Spacer Grid Test Facility
Objective: To provide undergraduate and graduate students with a laboratory facility that will enable them to visualize reactor spacer grid effects in reactor fuel assembly flow
Status: Completed
Explanation of Activity: We have designed and constructed a transparent flow facility that allows both undergraduate and graduate students to perform two-phase fluid flow experiments to visualize the effects of fuel assembly grid spacers on flow and heat transfer. The design is scaled to provide very realistic data. The larger dimensions permit not only a qualitative understanding of the flow, but instrumentation in the flow channels enable students to calculate pertinent flow data and compare their results to those predicted by the analytical models. The facility is used for both teaching nuclear engineering courses and for undergraduate research projects. A design report (PSU/MNE-AMFL-09-01) entitled "The Air-Water Spacer-Grid Separate-Effects Scaled Test Facility" was completed in July 2009. The fabrication, construction and testing of the facility was completed in September 2010.

PURDUE UNIVERSITY

NONE – Tasks Completed

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

NONE – Tasks Completed

UNIVERSITY OF WISCONSIN-MADISON

NONE – Tasks Completed

OHIO STATE UNIVERSITY

NONE – Tasks Completed

UNIVERSITY OF MICHIGAN:

NONE – Tasks Completed

UNIVERSITY OF CINCINNATI

NONE – Tasks Completed

2. Research Innovations

PENN STATE UNIVERSITY

Title: Neutron Computed Tomography of Freeze/Thaw Phenomena in Polymer Electrolyte Fuel Cells
Objective: To 1) design and construct a sophisticated high-resolution neutron computed tomography (NCT) facility, 2) to develop sophisticated liquid water and ice quantification analysis software for computed tomography and 3) to apply the advanced software and NCT capability to study water distribution in polymer electrolyte fuel cells (PEFCs) under cold-start conditions.
Status: Completed
Explanation of Activity: A DOE NEER grant was awarded in 2005 and completed in 2008 to support this project. The high-resolution neutron computed tomography (NCT) water quantification methodology and software greatly added to the capabilities of the neutron imaging community, and the quantified water distribution provided by its application to PEFCs enhanced our understanding and guided design in the fuel cell community. The methodology for three-dimensional multi-phase flow visualization and quantification is extendable to a myriad of other systems. The project benefits from the neutron beam port and neutron radiography facility improvements made through the Innovations in Nuclear Infrastructure and Education (INIE) program. A low-light cooled CCD camera and the image processing computer was purchased separately as part of the neutron radiography facility upgrades that made through the INIE program. A new camera mounting and shielding were assembled from INIE program equipment upgrade funds. The new system yielded images with a factor of two improvement in resolution and a 65% increase in image size. Improvement and refinement of the system continued through the end of the INIE contract.

PURDUE UNIVERSITY

NONE – Tasks Completed

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

NONE – Tasks Completed

UNIVERSITY OF WISCONSIN-MADISON

Title: Neutron Radiography (NR) Facility
Objective: Improve a current facility that continues to be used for research.
Status: Completed
Explanation of Activity: The UWNR NR facility has had modifications of its engineering design. The changes include new external shielding and imaging system. The imaging system incorporates an integrated scintillator-micro channel plate amplifier design. The goal of the redesign was to provide imaging of diesel fuel injector spray patterns. Oak Ridge National Laboratory has initiated a new contract to provide such radiographic images.

OHIO STATE UNIVERSITY

NONE – Tasks Completed

UNIVERSITY OF MICHIGAN

NONE – Tasks Completed

UNIVERSITY OF CINCINNATI

NONE – Tasks Completed

3. Infrastructure Improvements

PENN STATE UNIVERSITY

Title: Neutron Imaging System Improvements
Objective: Developing a more efficient means of data acquisition and storage, better post processing techniques, and a more accurate quantification of water present in the radioscopic images.
Status: Completed
Explanation of Activity: To meet the requirements for our recent fuel cell research, a "turn-key," completely digital, image acquisition system was added in Year 2 of the INIE program. The system included a CCD camera, a custom computer, and Norpix's Streampix image acquisition software. Image capturing and storage is done in the form of proprietary image stacks called "sequence files." PSUMagic is the latest incarnation of the PSU Frame Grabber software originally designed for use with the older analog imaging system. Several post-process image enhancement techniques were incorporated to increase the overall image quality and accuracy of the water quantification process. Other image enhancement techniques to improve qualitative analysis were also added. The previous year we focused on the development of a neutron computed tomography system to support a new DOE NEER entitled Neutron Computed Tomography of Freeze/Thaw Phenomena in Polymer Electrolyte Fuel Cells. Activity in 2010 focused on beam improvements and CT system refinement.

Title: Computed Radiography Neutron Imaging System Purchase
Objective: Purchase a Computed Radiography system for use in education and research that would provide neutron images at approximately 50 micron spatial resolution without film.
Status: Completed
Explanation of Activity: The GE Inspection Technologies' Computed Radiography (CR) system called the CRxFlex was purchased after evaluation of three systems. This impressive CR scanner replaced the older CR100 and CRxTower scanners. The CRxFlex scanner has (a) excellent imaging quality achieved by using a 30-micron laser spot size, 16-bit electronics (offering 65,536 shades of gray) and high-quality photo-multiplier tubes (PMT's), (b) dual-scan operation capabilities (Daylight hard cassette scanning using Standard-Sized imaging plates as

well as scanning of Custom-Sized imaging plates), (c) advanced imaging plate transport design to minimize scratches/artifacts (IPs remain flat and are transported via their substrates with the sensitive phosphor side facing up), (d) exposure time reduction due to premium light collection optics and user-selectable gain settings, (e) sealed scanner housing to prevent dust and airborne debris from entering the scanner. The system was ordered in May 2010 and received in mid-September 2010. The system meets our criteria and has greatly expanded our neutron imaging suite of instruments.

PURDUE UNIVERSITY

NONE – Tasks Completed

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

NONE – Tasks Completed

UNIVERSITY OF WISCONSIN-MADISON

NONE – Tasks Completed

OHIO STATE UNIVERSITY

NONE – Tasks Completed

UNIVERSITY OF MICHIGAN

NONE – Tasks Completed

UNIVERSITY OF CINCINNATI

NONE – Tasks Completed

4. Intra-Consortium Integration

Title: Infrastructure Enhancements: Building Better Facilities for the Consortium
Objective: Upgrade and build state-of-the art facilities for Nuclear Science and Engineering research and teaching in support of the Big-10 institutions.
Status: Completed
Explanation of Activity: The goal of our the Big-10 Consortium was to establish a leading organization for reactor-based research, outreach and next generation University Research and Training Reactors (URTR) design in the U.S. To that end, we are developed facilities at our institutions that can be shared by researchers from other Big-10 members with common research interests. Members have made major improvements in Nuclear Research and Training Reactor facilities, various teaching and research laboratories and nuclear science and engineering programs. Some infrastructure improvements for Big-10 consortium universities were: Neutron

Beam Hall expansion and new Neutron Beam Port design; purchasing a Compton Suppression Spectroscopy System, a Computed Radiography System and a Fast Neutron Spectrometer; Improvements on Neutron Imaging System; and developing a Slow Neutron Chopper for thermal neutron spectrometry (Penn State University), Building a new nuclear reactor visitor center; improving NAA and Instrumentation Laboratory; Purchasing a Stack Exhaust Air Monitor and Continuous Air Monitor system, (University of Wisconsin), Improvements on the Nuclear Engineering Radiation Laboratory Instrumentation (Purdue University), establishing a Virtual Laboratory for Education (University of Illinois), Control Rod Drive Upgrades, Improvements of safety and security at the reactor and outreach capabilities (Ohio State University), Establishing a new Neutron Science Laboratory (University of Michigan).

Title: Big-10 Mini-Grant Program
Objective: To encourage collaboration with our URTR facilities, to allow researchers and educators from a wide-range of disciplines access to our facilities by providing small grants.
Status: Completed
Explanation of Activity: The Mini-Grant Program was a catalyst for researchers, a resource for high school teachers and students and another tool for industry. The Program provided an opportunity to engage new and cooperative research in diverse fields of study. Participating teachers reported that the Program has helped improve their curriculum, laboratory capabilities, and student interest in nuclear science. It is estimated that over one thousand students have been enriched in the high school grants. During the period 2003-2007, 108 grant proposals were received: 56-universities, 49-high schools, and three-industry. Applications have come from 11 states, the District of Columbia, and the Union of South Africa. A total of $865,537 was allocated and dispersed in amounts from $1,000 to $25,000. The Program was operated through web-based application, review, and reporting system (http://www.mne.psu.edu/minigrant/.) During the INIE grant, 70 grants were awarded. Consortia personnel have increased communication between Big-10 members and reported positive interaction experiences with grantees. New partnerships with other colleges and universities were also realized. The Program functioned at an international level as well as within the United States.

Plans for Next Year

Contract completed.

Milestone Status Table

The table below presents the cumulative status of all INIE activities, including the Mini-Grant contracts.

Task Group	Institution	Task Title	Status
Educational Enhancements	**Penn State**	NucE 001S: Freshman Seminar	Completed
		Improvement of instruction and research areas in reactor building	Completed
		Renovation of RSEC Room 2	Completed

Task Group	Institution	Task Title	Status
		into an instructional technology/outreach facility	
		Upgrading computer capabilities for core/beam port modeling	Completed
		Design and development of student projects related to radiographic and radioscopic techniques for high school students and freshman	Completed
		Spacer Grid Test Facility – Two phase fluid flow experiments in teaching and undergraduate research	Completed
	Purdue	"Virtual Reactor" in Education: To provide students with direct experience in neutronic computational simulations	Completed
	Illinois	Internet-based lab**:** To provide real-time laboratory and reactor experiences at remote locations	Completed
		Outreach Program Upgrades	Completed
		NPRE 100, Orientation to Nuclear Engineering, and NPRE 199, Freshman Seminar	Completed
	Wisconsin-Madison	Distance Learning Courses and Monitor System for UWNR	Completed
		Outreach Program Upgrades	Completed
	Ohio State	Presentation and Outreach Upgrades: Development of Materials	Completed
		Equipment and Procedures for Laboratory Courses	Completed
		Presentation and Outreach Upgrades: Equipment	Completed
	Michigan	Establishment of Neutron Science Laboratory	Completed
	Cincinnati	Development of Three Distance Learning Classes	Completed
Research Innovations	**Penn State**	Studies of Water Distribution and Transport in a Polymer Electrolyte Fuel Cells Using Neutron Imaging	Completed
		Modeling and Design Optimization of the Beam Port	Completed

Task Group	Institution	Task Title	Status
		Facility of Penn State's Breazeale Reactor (PSBR)	
		Neutron Activation Analysis of Absolutely-Dated Tree Rings	Completed
		Testing Neutron-Induced Soft Errors in Semiconductor Memories	Completed
		Neutron Computed Tomography of Freeze/Thaw Phenomena in Polymer Electrolyte Fuel Cells	Continuing
		Distribution Diagnostics and Visualization of Polymer Electrolyte Fuel Cell Performance During Freeze-Thaw Cycling	Completed
	Purdue	"Virtual" Reactor – Neutronic Analysis	Completed
		"Virtual" Reactor – Neutronic – Thermal Hydraulic Coupled Analysis	Completed
		MCNP/AGENT modeling of PUR-1 and OSURR	Completed
		Novel approach in AGENT code acceleration – a generic model with applications to acceleration of other numeric codes	Completed
		Developing higher order of anisotropy in the AGENT methodology	Completed
		Developing a tool for accurate nuclear diagnostics with Hilbert-Huang transform	Completed
		Analyzing new material composites behavior in neutron field and numerical modeling	Completed
		Advanced computational analysis for radiation treatment and imaging	Completed
		Developing a tool for accurate detection of nuclear materials	Completed
		"Virtual" Reactor development, AGENT Code Advancement and Research Reactor Neutronic Analysis	Completed

Task Group	Institution	Task Title	Status
		Advanced Code Development	Completed
		Developing higher order of heterogeneity in the AGENT neutron transport methodology	Completed
	Illinois	Virtual Reactor Models	Completed
		Research Reactor Design and Analyses	Completed
		Advanced Hybrid Method Code Development	Completed
		Advanced Fuel Development	Completed
		Virtual NPP Models using Gaming Technology	Completed
		Code and Tools Development	Completed
		Compact High Energy Neutron Detector Development	Completed
		Hydrogen Incorporation into Ni-Ti Neutron Supermirrors	Completed
	Wisconsin-Madison	Supercritical Water Loop	Completed
		Computer Modeling of the UWNR	Completed
		Neutron Radiography (NR) Facility	Completed
	Ohio State	Upgrade of Co-60 Gamma Irradiator	Completed
		Expansion of Reactor Irradiation Capabilities	Completed
	Michigan	Establishment of Neutron Science Laboratory	Completed
	Cincinnati	Sub-critical Reactor Modifications & Analysis	Completed
Infrastructure Improvements	**Penn State**	Neutron Beam Laboratory Expansion and New Beam Port Design	Completed
		Infrastructure Improvements on Neutron Activation Analysis and Student Spectroscopy and Outreach Activities Laboratories	Completed
		Cold Neutron Source Cooling System Design	Completed
		Compton Suppression System	Completed
		Neutron Imaging System Improvements	Continuing
		Slow Neutron Chopper for	Completed

Task Group	Institution	Task Title	Status
		Characterization of Beams from the Breazeale Nuclear Reactor	
		Fast Neutron Spectrometer Purchase and Testing	Completed
		Purchase new ^{60}Co irradiator	Completed
	Purdue	Nuclear Engineering Radiation Laboratory (NERL)	Completed
	Illinois	Virtual Laboratory for Education	Completed
	Wisconsin-Madison	New UW Nuclear Reactor Visitor Center	Completed
		Stack Exhaust Air Monitor and Continuous Air Monitor	Completed
		Nuclear Instrumentation Laboratory	Completed
		Neutron Activation Analysis (NAA) Laboratory	Completed
		Reactor Research Manager	Completed
		Nuclear Reactor Technician	Completed
		Cooling System Replacement and Upgrade	Completed
		Perimeter Intrusion Detection System Replacement	Completed
		Fuel Temperature Safety Monitor	Completed
		Independent Plant Air System	Completed
		Demineralizer Upgrade	Completed
	Ohio State	Laboratory Data Acquisition and Sharing Infrastructure	Completed
		General Infrastructure Upgrades	Completed
		Upgrades to Reactor-Related Systems	Completed
	Michigan	Establishment of Neutron Science Laboratory	Completed
	Cincinnati	None	
Intra-consortium Integration	**Consortium Wide**	Mini-Grant Awards totaling 70 individual awards	Completed
		Building Better Facilities for the Consortium **Objective:** Upgrade and build state-of-the art facilities for Nuclear Science and Engineering research and teaching in support of the Big-10 institutions.	Completed
		Virtual Reactor and Next Generation University Reactor	Completed

Task Group	Institution	Task Title	Status
		Design Environment	

Patents

None

Budget Data

The Big-10 Consortium used its DOE INIE funds wisely and worked aggressively to find supplemental funding to maximize the impact of INIE funds by internal and external leveraging. We took advantage of the ability to carry over funds to gain the best equipment and infrastructure improvements. The delay in spending was most evident in the delayed purchases and fabrication of equipment and infrastructure improvements that will utilize new structures being built with non-INIE funds. Each year (with new funding) there were delays with Penn State's Office of Sponsored Programs getting the funds out to the subcontracts. Penn State continued to work on this issue throughout the contract period. Additionally, there was often a delay in invoicing from the subcontracts. In some cases the funds were committed but Penn State's system could not encumber the funds, e.g. when the Mini-Grant monies were awarded, the funds were committed but not encumbered. Finally, there were significant delays in expenditures as we wait for the completion of construction at the University of Wisconsin and while waiting for Penn State University's planned beam hall expansion and beam port redesign project to be scheduled.

The Penn State expansion delays have prevented the completion of the beam hall renovations. We had delayed ordering equipment because we do not want 1) to purchase equipment that may be out of date when the construction is finished, 2) to purchase equipment until the facilities are completed in case the final design and construction changes the facility and 3) to spend INIE funds on the project if alternate funding is being considered. In 2010 the decisions on which equipment should be purchased were made and the equipment acquired.

The members recognize that these delays have resulted in carry over funds, but majority of the funds were expended in the final year (2010). The table below presents a financial summary:

Year (Sept. 30 – Sept. 29)	DOE Award ($)	Actual Amount Spent ($)	Balance ($)
2002 - 2003	1,971,663	939,989.62	1,031.676.38
2003 - 2004	1,971,663	1,430,812.02	1,572,527.36
2004 – 2005	2,171,663	1,873,807.87	1,870,382.49
2005 - 2006	1,915,500	1,517,335.26	2,268,547.23
2006 - 2007	2,125,000	2,062,192.90	2,331,354.33
2007-2008	No-cost extension	1,132,340.78	1,199,013.55
2008-2009	No-cost extension	577,589.67	621,423.88
2009-2010	No-cost extension	597,965.35	23,458.53
Totals	**10,155,489**	**10,132,033**	23,458.53

Spending Plan for the Next Year

None; the INIE contract was completed in September 2010. The remaining unspent funding at the end of the contract (September 30, 2010) was $23,458.53.

Notable Accomplishments of Big-10 INIE Consortium

BIG 10 CONSORTIUM

- Established a Mini-Grant Program that lead to an increased awareness of research reactors in the Big-10, but also seeded new collaborative programs within and among institutions.
- Engaged high-school students in nuclear science and engineering through grants to established educational units such as the Central Virginia Governor's School (CVGS) in Lynchburg, Virginia and Westinghouse High School Honors Institute (WSHI).
- Developed and held a The Summer Institute in July 2006 at Argonne National Laboratory 21 students that addressed the issues associated with advanced fuels, including fabrication, operation, reprocessing, disposal, cost, and associated non-proliferation issues.
- Created and expanded the Big-10 Consortium that included seven major institutions including all Big-10 institutions with Nuclear Engineering Programs and the University of Cincinnati, who worked in close collaboration on a variety of educational and research projects.

PENN STATE UNIVERSITY

- Designed an RSEC expansion for a new Neutron Beam Hall and Neutron Beam Ports. Worked with a professional architectural firm, a contractor, research colleagues, and graduate researchers to develop the design.

- Made numerous improvements and enhancements to the existing Radiation Science and Engineering Center Facility including 1) immediate upgrades to improve existing analysis tools and reactor research facilities, 2) adding analysis tools and research facilities that are well suited to a specific URTR that expands its research user base, 3) designing, building and testing new techniques and facilities that would eventually add new capabilities to all URTRs. Examples include:
    - replacement of the GammaCell Co-60 irradiator
    - renovation of the outreach and teaching space in Room 2
    - renovation of RSEC Room 121 used for giving lectures to tour groups
    - renovation of the neutron activation analysis laboratory
    - upgrades associated with neutron imaging.
- Increased capabilities and infrastructure to support graduate research by obtaining and developing tools such as the Slow Neutron Chopper, the Fast Neutron Spectrometer, the development of models of beam ports using Monte Carlo N-Particle Transport Code, MCNP5, and deterministic codes, and adding neutron imaging equipment.
- Utilized INIE sponsored development and infrastructure improvements were utilized to generate a number of externally sponsored research projects that have resulted in innovative research. All are tied to graduate student projects that were used for thesis work.
- Penn State in its role as lead institution provided the coordination and over-all management of the INIE grant. The success of the consortium lead to the Big-10 nuclear engineering programs working in a collaborative manner, on both INIE and non-INIE initiatives.

PURDUE UNIVERSITY

- Advanced the neutron transport computational methodology based on the synergism between the method of characteristics, diffusion theory and mathematical formalism of R function theory (resulted in journal publication).
- Modernized undergraduate and graduate courses by introducing the virtual reactor simulation tool **as** a part of a curriculum (resulted in growing interest of domestic students to continue to graduate school).
- Established interdisciplinary research related to the application of nuclear principles in medicine (resulted in new project with the local hospital).
- Developed the public domain virtual reactor web site with the interface links to the neutronic modeling of the PUR-1 and other reactor examples (resulted in the undergraduate curriculum modernization and advancement).

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

- Virtual Reality in Nuclear Engineering. Among others, models of nuclear reactors, fuel assemblies, control rooms, reactor sites, and a GA Tokomak were developed.
- A virtual model of the fission chain reaction for teaching and outreach was developed.
- A high fidelity reactor simulator using RELAP5 as its engine has been developed using LabVIEW as the user interface.
- The RELAP/LabVIEW package was used to include a "live" simulator in the 3D, immersive, virtual model of a reactor control room.
- Internet based virtual laboratory was extended to webcast and receive reactor laboratories. Collaborations with UW-M and University of Massachusetts at Lowell have resulted in webcasting of reactor labs and two presentations at ANS annual/winter meetings.
- New neutronics and thermal hydraulics methods and analyses tools were developed to better analyze future nuclear energy systems.
- Design analysis of a high flux, innovative research reactor (using low enriched uranium) was extended to include thermal hydraulics analysis.
- Specific fuel analysis capabilities were developed to permit design of advanced fuel compositions and forms. In addition, the effects of actinide management and thermal-hydraulic feedback in fuel performance were incorporated into this effort.
- Significant outreach activity involving the virtual reality tools and models was conducted. Target audience was high school students and general public. A major event was the display of the virtual reality models at the Chicago Museum of Science and Industry during the Chicago Public School's Annual Science Fair.

UNIVERSITY OF WISCONSIN-MADISON

- Upgraded UWNR Infrastructure - INIE has contributed to the UWNR reactor systems and operational infrastructure including the following:
  - A new three loop cooling system utilizing two plate and frame heat exchanger and variable frequency drives has restored the reactor's capability to operate indefinitely at steady state license power, thereby increasing the reactor's availability to users.
  - A long term effort to replace nuclear instrumentation was a priority. Funds have been expended to purchase two Sorrento NLI-1000 logarithmic wide range monitors to replace the existing Logarithm Power and Period Amplifier. Furthermore, digital counter scalers have been purchased to integrate into the new Source Range Monitors. The new nuclear instrumentation will increase reactor availability by reducing inadvertent shutdowns due to equipment failure.
  - A new Perimeter Intrusion Detection System was installed to fully integrate into the UW Police Department 911 computerized dispatch center and increased the number of redundant reporting paths to reduce common mode failures and tempering. This modification has brought the reactor in line with NRC strategic

thinking in the area of security. This in turn enhances the public perception of the reactor facility and improves community commitment to the reactor.

- The new Fuel Temperature Safety Monitor was installed that provides additional features above those of the old system, including, scalable analog outputs and mathematical functions including maximum, minimum, average values, and rates of change. The new monitor increases the availability of the reactor by reducing inadvertent shutdowns due to equipment failure and provides enhanced features to integrate into our Distance Learning System.
- A new air compressor and pressure monitor was purchased and installed to provide emergency air to the reactor during a loss of building air event. This enhancement increases the availability of the reactor and increases the availability of the Neutron Activation Analysis lab which is dependent upon the pneumatic sample transfer irradiation and counting systems to provide research support.
- A new Demineralizer system was installed to eliminate operational issues and to increase the availability of the reactor, by reducing the frequency of shutdowns to regenerate and the duration of the shutdown to repair leaking valves.
- The existing Stack Exhaust Air Monitor (SAM) and Continuous Air Monitor (CAM) were replaced by two Thermo Eberline Particulate Iodine Nobel Gas (PING) carts utilizing the AMS-4 beta monitor for each channel. The new PING carts have greater sensitivity, modular design and enhanced communications capabilities. The modular design allows any one of the AMS-4 beta monitors to be replaced by another. This enhancement increases the availability of the reactor, by reducing the duration of a shutdown for repairs to the exhaust stack monitor.

- Improvement in UWNR Nuclear Instrumentation Labs via new equipment
  - Several expenditures were made to improve the existing Nuclear Instrumentation Laboratory. Each laboratory station was equipped with DELL XPS workstations and Princeton Gamma-Tech MCA 8000 multi channel analyzers with Quantum Gold software. Additionally, several new detectors were purchased including a hand held NaI, a water proof probe and teleprobe. These expenditures enhance the quality of the students' education by exposing them to modern equipment and instruments that are used in industry.
  - Expenditures to enhance the Neutron Activation Analysis (NAA) Laboratory included a new pneumatic sample transfer irradiation and counting system. These new systems provide totally automatic sample handling to increase the volume of samples and reduce the exposure to personnel handling the samples. New DELL XPS workstations and Princeton Gamma-Tech System 8000 multi channel analyzers with Quantum Gold software were integrated into the new pneumatic sample transfer irradiation and counting systems and existing HPGe detectors. Shielded radioisotope storage cabinets were purchased to handle increase usage of the NAA lab. These enhancements increase the volume of samples handled and therefore the number of research programs supported and increase the availability of the NAA lab by reducing down time due to equipment malfunction.
  - The Neutron Radiography (NR) Facility has undergone an engineering design to modify the existing facility. The changes included new external shielding and

imaging system. The imaging system incorporated a new scintillator. The redesign enhanced imaging of diesel fuel injector spray patterns.
    - The outreach program was enhanced with the purchase of a laptop PC and table top projector. The outreach program can now bring a virtual reactor tour to the class room of local schools.
- Enhanced Competencies into New Areas of Research and Education; i.e., Supercritical-water chemistry/corrosion loop and neutron radiography beamline.
    - The reactor laboratory conducted the study of neutron radiolysis in water at supercritical pressures and temperatures. In order to investigate this radiolysis, a water loop was designed, assembled and inserted into beam port 2. This loop was designed to pressurize water to 25 MPa (3600 psi) and heat it to 500 C (932 F). The water was then transported near the core of the reactor and returned to be analyzed. Expenditures for student support to operate the experiment provide valuable data as well as providing students with valuable experience.
    - Several student projects have led to the development of a MCNP model of the reactor core and experimental facilities. The purpose of the modeling was to provide accurate estimates of radiation dose for engineering design of new experiment and research projects. Gamma dose and neutron flux mapping was conducted in the reactor beam ports. Expenditures for student support for design has provided valuable results and benchmarking of the code as well as provides the students with valuable experience.
    - Personnel expenditures were being used for designing and implementation of a web base system that monitors temperature and control panel data from the reactor. This data is incorporated into a web based video course to teach reactor based course at a distance; thereby, reaching a larger audience and enhancing non-reactor owning school curriculums.
    - New personnel were hired at the reactor lab including the Reactor Research Manager. The role of the manager is to provide expert advice and works closely with faculty and students in the development and implementation of research and instructional programs and activities using the lab's equipment and facilities. Specific duties include designing radiation shielding, calculating induced radioactivity, measuring and calculating core reactivity effects, performing thermo-hydraulic analysis, updating CADD prints, and developing computer codes to calculate: radiation dose, effluent releases to the environment, and probabilistic risk assessments. The manager is then responsible for administration of these research activities including the Neutron Activation Analysis Lab.
    - New personnel were hired at the reactor lab including the Nuclear Reactor Instrumentation Technician. The role of the technician is to maintain operable all nuclear instrumentation, radiation monitoring instrumentation, and reactor plant process indicators. Performance of these activities by a qualified technician improves the quality of the research programs at the UWNR as well as increases reactor availability by reducing the duration to effect repairs on equipment failure.

- Physical improvements to the rector facility were made. Over the years, OSU has not had difficulty in finding the funding for the continued operation of the facility but has had major difficulty in finding funding to maintain and modernize the facility. INIE funding was essential in upgrading the operability (e.g. replacement of coolant pumps and a number of upgrades that are in the planning stages, such as upgrades to the reactor protection system) of the reactor as well as bringing the security of the facility to modern requirements. Examples of improvements include:
  - New lighting in the reactor bay that both improves appearance and usability and enhances safety in the reactor building.
  - New, more substantial front door installed, improving security and appearance
  - Steel grates over gamma-irradiator pool retrofitted to create a safer and more secure work environment.
  - Improved elevator assembly for in-pool gamma irradiator designed and built
  - Replacement hoist for shielding cave purchased and installed.
  - Improved shielding cask lifting mechanism designed and assembled.
  - Replacement neutron-sensitive tube for hand-held neutron meter purchased.
  - Replacement single-board computer card purchased and installed for the gamma-ray spectroscopy system.
  - Components for robust shielding plugs for the beam ports with cable-ways and means to attach experimental assemblies purchased.
- INIE enabled the purchase of modern teaching aids as well as detectors, multi-channel analyzers and radioactive sources. This equipment greatly improved the content of the courses taught at the reactor laboratory and the ability of the laboratory to support an active community outreach program. INIE funding was used for the following:
  - Presentation system: laptop computer, software, and LCD projector purchased and set up for presentations and lab and tour introductions.
  - Equipment for two concurrent student laboratory groups for lab sessions in "Radiations and their Measurement" and "Nuclear Engineering Reactor Laboratory" classes, as well as other classes. This equipment included portable NIM bins, NIM-based counting equipment, digital oscilloscopes, NaI detectors, Canberra DSA-2000 multi-channel analyzers and accompanying laptops, purchase and assembly of components for vacuum systems for alpha spectroscopy measurements labs, gamma radiation button sources and stackable chairs.
- INIE funded purchases substantially enhanced the research capabilities of the reactor. INIE funding was used for the following to both enhance capabilities and improve reactor availability:
  - Replacement of control-rod drive indications.
  - Replacement of drive system for reactor startup source.
  - Replacement of in-pool neutron-sensitive detectors (2 UIC, 2 CIC).
  - Digital strip-chart recorders (2).
  - Replacement high-voltage supplies for use with detectors (3).
  - Design and installation of replacement pump system for secondary cooling loop

    - Minor control-room improvements (improved cable routing, replacement rack panels, LED indicators, etc.).
- A flexible and expandable DAQ system was purchased and installed to acquire and share appropriate data from the control room and experimental facilities, and a networking backbone for the lab was designed and installed to facilitate this sharing. This backbone also supports an IP-based camera system and IP-based intercom system, both purchased with INIE funding. Items purchased with INIE funding to support these upgrades were:
    - Cabling and networking equipment (switches, etc.) for data backbone.
    - Yokogawa chassis and modules for control-room DAQ, Yokogawa chassis and modules in portable rack for DAQ at experimental facilities, Yokogawa software to collect and synchronize data from multiple DAQ chasses onto a computer.
    - Four IP-based cameras as well as screens and hardware upgrades for PCs to support lab monitoring from PCs within the lab.
    - Five IP-based phones for digital intercom system.
    - Equipment rack with rack-mounted computers to support network-based systems.
    - Secure wireless access points to provide wireless capabilities for researchers.
    - VPN box to be used for secure remote data sharing.
    - Upgrade to existing stand-alone National Instruments (NI) DAQ system, including USB module for existing NI DAQ chassis, updated NI software, and laptop.
    - Data-display to show acquired data to researchers in reactor bay.

UNIVERSITY OF CINCINNATI

- Developed of three distance learning classes that can be delivered 24/7 while students are either off-campus or on-campus but unconstrained by traditional class scheduling conflicts for ME-NE dual degree students majoring in mechanical engineering so students could progress with their undergraduate program while on professional practice assignments.
- UC capital funding did not become available as originally anticipated for the modifications in the sub-critical reactor. Therefore, sub-critical reactor modifications & analysis activities were limited to the validation of MCNP simulations with measurements and the study of five system improvement alternatives using MCNP models.

UNIVERSITY OF MICHIGAN

- Created a Neutron Science Laboratory using in-house designed shielding and purchasing an MP320 and a D711 neutron generator to provide a versatile capability to generate neutrons for teaching and research purposes.

INIE's Impact

BIG-10 CONSORTIUM

The INIE Program had a large impact on the Big-10 intuitions with nuclear engineering programs. Collaborations have been established between intuitions, and collectively we embarked on several joint research projects, educational and organizational efforts that probably would never have taken place without INIE. Specific examples include the Purdue/Illinois virtual reactor work, the successful Nuclear Summer Institute Short Course in advanced fuels with instructors from most institutions and a Big-10 member meeting at Argonne National Laboratory on nuclear modeling methods. Undergraduate enrollments at all consortium intuitions have grown dramatically, and this growth was enabled by INIE supported infrastructure. Additionally, university administrators have responded positively on matching or supplementing INIE supported infrastructure enhancement projects, for example, the Beam Hall expansion at Penn State (submitted infrastructure proposals but not selected for funding), the reactor upgrades at Wisconsin and Ohio State, the virtual reality equipment at Illinois, the neutron generator installation at Michigan, and the expansion of the computing capabilities at Purdue. Thus, the Big-10 Consortium achieved the programmatic goals of INIE, namely strengthening the Big-10 nuclear science and engineering programs and increasing the nation's undergraduate nuclear engineering enrollments.

PENN STATE UNIVERSITY

The INIE support had a very positive impact on the Penn State Nuclear Engineering Program and the Radiation Science and Engineering Center. All of the key innovations and enhancements would not have been possible without the INIE program. Our goal was to leverage INIE support with non-INIE funds to place Penn State in a position to further our research and nuclear engineering educational programs. Our major infrastructure improvement is the planed 6000 square foot expansion of the Radiation Science and Engineering Center. Without INIE funding in place this addition would not have been considered by the University which committed over $2 million to the project. While still an ongoing effort, this project lost momentum when DOE funding for infrastructure was eliminated. If completed, we will be able to conduct cutting-edge research in materials, biology and chemistry, making the RSEC a national center for neutron science research. INIE funds committed for the acquisition of the neutron instrumentation needed for this research were expended for instrumentation that can be utilized even if the expansion is delayed. Additional upgrades, improvements, new facilities and equipment were acquired with INIE funding, both by purchase and in-house design and fabrication, resulting in new industry and government research awards. We attribute much of the strong growth in both nuclear engineering undergraduate and graduate enrollments to the improvements in our teaching and research facilities, made by cost-sharing INIE and Penn State funds.

PURDUE UNIVERSITY

INIE support and leadership had a significant impact on Purdue's ability to consolidate and grow nuclear engineering education and research. Purdue research *forte* has been nuclear power engineering and particularly reactor safety and thermal hydraulics. In the 90's, however, the School of Nuclear Engineering experienced significant enrollment declines which raised questions within the University Administration about the viability of the program. The School indeed came under a serious threat of extinction. INIE had a huge catalytic impact in bringing about not only a sea change in enrollments and student interest in reactors and nuclear

engineering but also, and very importantly, in convincing the University Administration that Nuclear Engineering is not an "orphan discipline" in terms of federal support, but it has the backing of the Department of Energy and hence long-term prospects for support and growth. Signs of an impeding global energy crisis and the INIE stamp of federal support for reactor programs have without doubt led Purdue through a 300% growth in student enrollments and convinced the University administration to invest several new faculty positions in Nuclear Engineering. The School is also well known world-wide and we experience a growing interest of international students to join our program. We also observed an increase in female students from undergraduate to graduate level.

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

The INIE program made a major impact in the vitality of our nuclear engineering program. The most important contributions are described here. The first major impact was the credence that it brought to the nuclear engineering program at Illinois. While this is a non-technical impact, the INIE award has garnered the attention of the Dean of the College of Engineering and other university administrators. This elevated their estimation of the value of the nuclear engineering program at Illinois and led to a major new commitment to faculty positions and other resources to support the Department. The second significant impact was the development of a virtual reactor design and analysis system using virtual reality computational techniques and CAVE/CUBE and similar systems. The INIE program allowed us to purchase and use a Vis-Box system, which is a one wall virtual environment. This system has several advantages since it is much brighter than other systems, so visualization is easier, and the single wall provides a better working environment for actual design and analysis work. The advantages of this approach have led to a number of collaborations with national labs and with the nuclear industry. The third major impact was the progress toward the development of a new university research reactor design which would compete with the best newly-developed research reactor designs, particularly the new Australian reactor and the reactor in Munich. This part of the program has been collaborative in nature, across the consortium partners, and has the secondary, but vitally important, impact of supporting intra-Consortium collaborations. Significant efforts under this effort included major new work on reactor analysis, fuel design, neutron detector development and advanced beamline design, all of which support a variety of other DOE-based programs.

UNIVERSITY OF WISCONSIN-MADISON

The University of Wisconsin Nuclear Reactor Laboratory has been in existence since 1960. In 2000, with the strong support of the UW-Madison Chancellor and his administration, we submitted a renewal of our operating license until 2020. In addition, the College of Engineering completed a major renovation of the Mechanical Engineering Building (2004 -2007) and this directly affected the UWNR, since it is housed in the ME building. The major impact of the INIE grand was to provide the funds for infrastructure improvements that were required for our continued operation as well as improved educational opportunities for our students (both undergraduate teaching and graduate research and training). This was a partnership between the DOE and the UW-Madison to maintain and enhance the quality of education in nuclear engineering; i.e., this major investment by the Department of Energy was matched and exceeded by the State of Wisconsin in its renovation of the UW nuclear reactor laboratories within the

overall Mechanical Engineering building renovation. The INIE funds provided the margin of excellence we needed (and the Big-10 generally) to maintain our preeminence in nuclear engineering education.

OHIO STATE UNIVERSITY

Ohio State was not an initial member of the Big 10 Consortium, but the impact of the INIE program was significant. For the first time in over a decade, we added and now have dedicated equipment for the laboratory portions of our courses. That allowed us to improve the students' laboratory experience. Reactor facility security, safety, and appearance were upgraded. Plans, designs and analysis were made to upgrade equipment, such as the Co-60 irradiator and the reactor control rod drive system that will have significant impact on the long-term research capabilities of the reactor. In addition, equipment and materials used for outreach activities were upgraded, giving visiting students and teachers a more positive impression of nuclear engineering as a field of study.

UNIVERSITY OF MICHIGAN

During Michigan's participation in the consortium, the primary impact of INIE grant was to purchase two neutron generators and to set up a new teaching laboratory. The first compact generator was effectively used in a senior laboratory course. This provided a hands-on opportunity for our undergraduate students to perform neutron activation analysis and gamma spectroscopy to verify the importance and efficacy of these techniques for various neutron science applications. Experiments that utilize the D711 generator, purchased in our third year in the consortium, were added to demonstrate key concepts such as the production, slowing down, thermalization, and interaction of neutrons with matter.

UNIVERSITY OF CINCINNATI

The major impact of the INIE Program has been the enhancement of three Distance Learning classes which were initially offered to the students in the ME-NE dual degree program. The development of the capability to deliver the three classes routinely on a 24/7 basis has also increased the marketability of the NE-minor program which was approved by the College in 2007.

Conclusions

The DOE INIE Program provided the initiative and the funding to bring together institutions to improve their facility and educational infrastructure, and created collaborations in research and teaching that would otherwise not occurred. The Consortium of Big-10 University Research and Training Reactors was by design a strategic partnership of seven leading institutions. We believe that we achieved our goal establishing a leading organization for reactor-based research, outreach. We accomplished this over through the period of the INIE by innovative programs and initiatives that advanced research and education through focused collaboration and natural synergisms between our reactors, our departments and our institutions.

All of our team member nuclear engineering programs were strengthened through strategic investments in the consortium infrastructure. The objectives of our INIE sponsored program were met in that we:

1. Developed innovative programs in graduate research and undergraduate education and training that utilize these experimental URTR facilities both on-site and at-a-distance;
2. Identified the key attributes for advanced university research and training reactors by the development and design of a 'Virtual' URTR for use in education and research;
3. Created a novel educational outreach and education programs;
4. Developed a multi-disciplinary, multi-university research grant program, the Mini Grant Program that enabled collaborative research between the Consortium university programs, other schools and colleges as well as our industrial and laboratory partners.

Along the way to satisfying these objectives, we made significant improvements in our current URTR's, teaching laboratories and in our research infrastructure. Additionally, we achieved a coordinated alignment of our nuclear engineering educational programs to better serve our graduate and undergraduate students across the team's institutions, the nuclear industry, the DOE laboratory staff, and reached out to teachers and students at colleges, high schools and middle schools.

Thus, the INIE Program was successful in that it had a very positive impact on our nuclear engineering programs, laboratories and reactors. Additionally, the INIE funded infrastructure prepared our institutions for the rapid increase in undergraduate nuclear engineering majors that we have experienced in the past decade.