Final Technical Report

Innovations in Nuclear Infrastructure and Education

DG-FG07-02ID14420

By

MIT Nuclear Reactor Laboratory
Cambridge, MA 02139

September 30, 2002 – September 30, 2010

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Final Technical Report – MIT Nuclear Reactor Laboratory
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Funding provided to U.S. research reactors through DOE's Innovation in Nuclear Infrastructure and Engineering (INIE) Program successfully revitalized interest in maintaining the United State's leading edge in nuclear education and research by providing funding that supported improvements to its nuclear educational infrastructure. This funding opportunity was especially beneficial to members of the collaboration formed by Massachusetts Institute of Technology, Rhode Island Nuclear Science Center, and University of Massachusetts – Lowell (MIT/RINSC/UMass-Lowell) because it gave each of their organizations the opportunity and means to upgrade and improve upon existing instrumentation and equipment necessary to support their research reactor's operations as well as their research initiatives. In addition, INIE funding had a direct result in the increasing usage by faculty and researchers at each organization thereby strengthening their respective educational and research goals.

The decision to implement the Innovation in Nuclear Infrastructure and Engineering Program (INIE) was an important first step towards ensuring that the United States preserves its worldwide leadership role in the field of nuclear science and engineering. Prior to INIE, university nuclear science and engineering programs were waning, undergraduate student enrollment was down, university research reactors were being shut down, while others faced the real possibility of closure. For too long, cutting edge research in the areas of nuclear medicine, neutron scattering, radiochemistry, and advanced materials was undervalued and therefore underfunded. The INIE program corrected this lapse in focus and direction and started the process of drawing a new blueprint with positive goals and objectives that supports existing as well the next generation of educators, students and researchers.

This funding opportunity was especially beneficial to members of the consortia formed by Massachusetts Institute of Technology Nuclear Reactor Laboratory (MIT), Rhode Island Nuclear Science Center (RINSC), and University of Massachusetts – Lowell Radiation Center (UML), because it gave each of these organizations the opportunity and means to upgrade and improve upon existing instrumentation and equipment necessary to support their research reactor's operations as well as research activities. In addition, although the MIT/RINSC/UMass-Lowell Program had no formal educational components, INIE had a substantial indirect effect by providing opportunities for increased student usage. Further, INIE funding was successful in increasing reactor usage by faculty and researchers at each organization thereby strengthening their respective educational and research goals.

Details regarding research projects and infrastructure improvements can be found in the Annual Reports submitted to DOE from 2003 to 2010 (See Appendix A-G). On November 18, 2010, MIT submitted a Final Report Expenditures, Federal Financial Report and MIT's Final Contract Document. (See Appendix H). All funds received under this grant have been expended and reported upon.

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Annual Progress Report on MIT-RINSC INIE Program

DE-FC07-021D14420

1 October 2002 – 30 September 2003

by

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Annual Progress Report on MIT-RINSC INIE Program

Introduction

The MIT-RINSC proposal for the DOE-INIE program represents a collaboration between the reactor laboratories at the Massachusetts Institute of Technology and the Rhode Island Nuclear Science Center (RINSC).

The primary uses for the proposed INIE funds at MIT were:

- to create a new state-of-the-art in-core materials test facility at the MITR focused on advanced nuclear power reactors, including both new materials and fuel testing capabilities;
- to transform the existing BNCT facilities at the MITR into a very much needed national user facility;
- to initiate two new projects involving beamports; and
- to greatly enhance both the hands-on educational training of the next generation of nuclear managers as well as the research training of future nuclear engineers through a multitude of thesis research projects.

The primary use for the proposed INIE funds at RINSC was to relieve senior staff from day-to-day operation of the facility and thereby allow them to focus on research, particularly in the area of Gd-NCT.

The budget request for the first year was $1.3M of which about $1.15M was received. This forced certain cuts in the original proposal. Nevertheless, the program remained successful. Progress on the major tasks is described here.

MIT Research Reactor

Efforts for the first year were focused on the BNCT user facility; the startup of a new research endeavor in neutron interferometry; the startup of a new research activity in phase contrast imaging; and the design of an advanced in-core loop.

- **<u>BNCT User Facility</u>**

  This portion of the MITR INIE Program is under the leadership of Professor Otto K. Harling. He is assisted by Dr. Kent Riley and Dr. Peter Binns. The MITR staff person who interfaces with the

BNCT group is Mr. Thomas Newton. Appendix A to this report describes the activities that have been undertaken.

- **<u>Neutron Interferometry</u>:** This portion of the MITR INIE Program is under the direction of Professor David Cory. He is assisted by a graduate student, Dmitry Pouchine. The MITR staff person who interfaces with this project is Mr. Thomas Newton. The INIE funds for the project were used to support Mr. Pouchine. Significant leveraging of these funds has been obtained through informal cooperation with NIST. Appendix B to this report describes the activities that have been undertaken.

- **<u>Phase Contrast Imaging</u>**: This portion of the MITR INIE program is under the direction of Professor Richard Lanza. He is assisted by a graduate student, Vivian Leung. The MITR staff person who interfaces with this project is Mr. Edward Lau. Appendix C to this report summarizes the progress made on this project.

- **<u>In-Core Loops</u>**: This portion of the MITR Program involves the design and construction of a post-irradiation examination facility (PIE) for in-core irradiations of both advanced fuels and materials. The advanced fuels work is under the direction of Professor Mujid Kazimi. The materials studies are coordinated by Professor Ronald Ballinger. Both are assisted by Dr. Gordon Kohse and Mr. Yakov Ostrovsky. The MITR staff person who interfaces with these projects is Dr. Lin-Wen Hu. The emphasis during the first year was on the design of a very high temperature loop that will allow studies related to GEN-IV fuel and materials design. INIE funds, which were fairly small for this project for the first year and which increase significantly in year two, were used to partially support Dr. Il Soon Huang, an MIT Ph.D. with considerable industrial experience, to assist with loop design.

Rhode Island Nuclear Science Center

Efforts for the first year focused on Gd-NCT and related studies. The person in charge is Mr. Terry Tehan. Each project is summarized below.

- **<u>*In Vitro* F98 Rat Brain Tumor Cell Survival after exposure to Gadolinium-Porphyrin or to Boronophenylalanine-Fructose</u>**

  The *in vitro* survival of exponentially growing F98 rat brain tumor cells was measured after irradiation with thermal neutrons alone or thermal neutrons plus either 200 μg/ml of gadolinium-porphyrin (Gd-P, 15.65%

^{157}Gd) or 6.8, 25.0 or 42.2 µg/ml of enriched boronophenylalanine-fructose (BPA-F, $^{10}B \geq 97\%$). Gd-P or BPA-F was added to the medium at 37 ºC one hour before irradiation. Cells were irradiated 1.7 feet from the cooling grid in the thermal column where the ratio of thermal to epithermal neutrons was the greatest. After neutron irradiation cells were trypsinized and seeded into flasks for survival by assessment of colony forming efficiency (CFE). All thermal neutron cell survival curves were exponential in shape. Therefore, the dose modifying factors (DMFs) for Gd-P or BPA-F were determined by comparing the slopes of the survival curves to the survival curve obtained from irradiation with thermal neutrons alone. The DMF of the Gd-P was 1.99 at 100 µg/ml while the DMFs for the BPA-F were 1.47, 2.26, and 2.59 at 6.8, 25.0 and 42.2 µg/ml. A plot of the DMFs of the various BPA-F concentrations indicated that 200 µg/ml of Gd-P is equivalent to 17.8 µg/ml of BPA-F, i.e., the BPA-F was more effective than Gd-P by a ratio of 11.2 (200 µg/ml Gd-P/17.8 µg/ml BPA-F). However, correcting for the numbers of ^{157}Gd (15.65%) and ^{10}B (>97%) atoms in these samples that can be activated by thermal neutrons indicates that atom for atom, ^{10}B is approximately 1.8 times more effective in killing cells than is ^{157}Gd. This difference in biological effectiveness is most likely related to the differences in linear energy transfer of the byproducts of nuclear decay of ^{10}B and ^{157}Gd.

Publications

Leith, J. T., et al., "In Vitro Comparison of Nontoxic Concentrations of Gadolinium-Porphyrin and Boronophenylalanine-Fructose on Survival of Exponentially Growing F98 Rat Brain Tumor Cells After Thermal Neutron Irradiation, to be submitted to Radiotherapy and Oncology, Fall, 2003.

- **MCNP Calculations on Rhode Island Nuclear Science Center Thermal Neutron Beam**

Work began with the Monte Carlo experts at Brookhaven National Laboratory, Brookhaven, NY to determine the theoretical flux at the position of cell iradiations for the thermal neutron beam at RINSC. Drs. Eugene Hu, Norman Holden, and Richard Ricinello were in contact with RINSC during the past year and visited the reactor in September 3, 2003 to discuss preliminary MCNP modeling studies. In this regard, a detailed discussion of the thermal column at RINSC ensued with modifications taken to the first set of models. Dr. Holden will perform thermoluminescent dosimeter studies before the end of the year to determine the thermal, epithermal, and photon doses throughout the thermal column.

- **Rat Brain Endothelial Cell Studies**

  Rat brain endothelial cells were received from Dr. J. Pachter of the University of Connecticut Medical Center, Farmington, CT. These rat brain endothelial cells will be used in comparison with the F98 rat brain tumor cells to compare survival and gadolinium-porphyrin and boronophenylalanine-fructose uptakes using ICP-MS (see below). We feel that this is a relevant comparison (i.e., rat brain tumor cells vs. rat brain endothelial cells).

  These studies will be used to determine the following: 1) what are the differences in survival and repair in the two cell lines after thermal neutron irradiaton alone; 2) what are the differences in cell size in the two cell lines; 3) how do differences in cell size relate to any potential differences in the intracellular uptake of Gd or B using ICP-MS; and 4) can any differences in intracellular levels of Gd or B be related to any differences in survival after thermal neutron irradiation.

- **Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Studies on Tumor and Endothelial Cells**

  We have begun studies with Dr. Richard Kingsly to determine intracellular levels of gadolinium-porphyrin and boronophenylalanine-Fructose using ICP-MS. Dr. Kingsly operates an ICP-MS resource at the Bay Campus of the University of Rhode Island. A comparison will be made of the time dependent levels of Gd (or B) inside the F98 cells and the rat brain endothelial studies as a function of time. The results from these studies will be used to help us understand any differences seen in cell survival.

Other Developments

MIT and RINSC are both proud to report that the University of Massachusetts at Lowell has joined our consortium effective 1 October 2003. The person in charge of the UMass-Lowell activities will be Professor Mark Tries of the Department of Physics.

Appendix A

MIT BNCT Activities Related to MIT-RINSC INIE Award

By

Otto K. Harling
Kent Riley
Peter Binns

REPORT: BNCT ACTIVITIES RELATED TO INIE AWARD: 2002/3

Improvements to the Thermal Neutron Beam Irradiation Facility

A significant fraction of this work was supported by the INIE award, the remainder was from another DOE grant.

1) The old wiring and manual control system were replaced with a new digital dose monitoring system and automated beam control. This required the purchased of electronic equipment that included a set of programmable logic controllers (PLCs) for beam control and nuclear instrumentation modules (NIM) for signal processing of beam monitors. The industrial grade PLCs ensure that certain safety conditions are satisfied prior to commencing an irradiation and issue a series of commands to turn the beam on that entails opening a series of three shutters in the beam line. Two redundant sets of PLCs operate in series for the beam to be turned on and in parallel to be turned off. Should either fail during an experimental irradiation all shutters will close. The irradiation can however continue in manual mode with just one PLC to allow completion of the experiment. Neutron fluence is measured continuously with four fission counters housed in the beam delimiter and the signals processed with four separate trains of NIM electronics. These signals are monitored by the PLCs and determine the end of an irradiation
.
2) Radiation exposure levels with the reactor operating at full power (5 MW) were too high close to the beam aperture to permit unrestricted access for outside experimenters into the treatment/radiation room. The levels also posed a serious possible risk to staff. This problem was remedied with the addition of a new beam shutter that was designed, manufactured and installed during 2003. The shutter is essentially a 1.8 m long slab of boron loaded polyethylene, 7 cm thick that travels beneath the existing lead and boral shutters. Measurements confirmed the reduction by an order of magnitude of radiation (neutron) levels in the vicinity of the beam line that does away with the need to reduce reactor power before entering the room. This avoids interruptions to other beam port users of the reactor and minimizes the time delay (approximately 30 minutes) between changing irradiation samples in the beam which will reduce the time to complete a series of irradiations and thus eventual costs of the experiment. The design of the shutter formed a student project in the Undergraduate Research Opportunities Program (UROP)

3) The new shutter was designed to accommodate the future irradiation needs of both experimental and clinical users of the facility. Experimental users typically require more intense beams than is necessary for human therapy and this can be achieved by placing samples or small animals inside the shutter itself so as to be closer to the radiation exiting the beam line. This was achieved by designing a

series of interchangeable plugs for different uses that fit into the shutter. Initially a plug has been built that accommodates the special shielding box in which small rodents (mice or juvenile rats) are placed for irradiation. The box is made of Li6 loaded polyethylene that effectively absorbs all thermal neutrons from the beam. The shield box spares the animals from receiving a whole body dose that would otherwise be fatal and end the experiment. A custom aperture is made in the box lid for each experiment depending upon the chosen irradiation site and the animals are restrained inside the box with the radiation site directly beneath the aperture. The box locates precisely inside the shutter and the animals are positioned in the beam when the shutter is opened. The same box and plug combination also accommodates detectors used for dosimetry of the beam.

4) Trouble shooting with the new control system was performed and extensive testing has proven its satisfactory performance in both manual and automatic modes. An absorbed dose (neutron fluence) can be delivered using the system with a precision of 1%. The accuracy of positioning samples and small animals in the 15 cm diameter beam was examined and was reproducible within 5 mm. The small positioning error was identified as due to travel of the mechanical shutters themselves and while not an immediate problem will be investigated further.

5) The influence the new shutter and shield box design have on the radiation environment at the position of the sample/animals was investigated experimentally by a series of dosimetry characterizations of the beam. This entailed mapping cross field profiles of the thermal neutron flux and photon absorbed dose rates. Further dedicated dosimetry studies were performed as necessary prior to performing an experiment to investigate an advanced boron delivery agent on tumor bearing mice. A new multi energy gamma ray reference source from NIST was purchased to calibrate the HPGe detector used to count activity of the Au foils used for thermal flux measurements.

6) The thermal neutron beam used in animal experiments was computationally modeled in three dimensions using MCNP, a continuous-energy code capable of simulating neutron, photon and electron transport. The model has been updated to reflect recent modifications in the beam line. This basic MCNP model can be augmented to accurately reflect the conditions of a particular experiment and the ensuing calculations are normalized to corresponding reference measurements of the absorbed dose rate from photons and neutrons. Calculations can then determine detailed information for the experimenter about the dose distributions inside the animal, which is not conveniently obtained from measurement. This approach has been applied for irradiations to study the radiation sensitivity of rat lung. Calculations are also in progress for upcoming irradiations to test the efficacy of different infusion schemes on tumors implanted in the brains of bred rats.

User Support

1) Irradiation facilities and in-house services such as dosimetry expertise and assistance with the design and manufacture of experimental jigs for holding samples and animals were advertised for use to the greater BNCT scientific community. Beam time applications were requested at 6 month intervals. In response to the requests received it became apparent that as well as the services offered some prospective outside experimenters required radiobiological facilities as well as expertise. This is particularly true of chemists who are developing the next generation of capture agents for NCT. To screen these compounds requires skills that these developers do not possess and accordingly a radiobiology initiative has commenced.

2) In vitro cell survival curves have been a standard tool for the evaluation of the effectiveness of anti-cancer therapies for many years: BNCT is no exception. The ability to pre-incubate cells in culture with medium containing a new neutron capture agent followed by neutron irradiation, allows a quantitative assessment of the cell-killing effectiveness of the test compound. A major part of the INIE/BNCT program is to offer this capability to outside chemists who have developed new boron or gadolinium compounds and are now ready to submit these compounds to a screening procedure to find the ones that are most effective. During the first year of INIE funding the capabilities for in vitro compound screening have been established. An MIT graduate student (Yoonsun Chung) has been assigned to this project. Prof. Coderre already has a cell culture laboratory that has most of the equipment for basic cell culture: laminar flow hood, incubators, microscopes, centrifuges. This laboratory is available for users of the BNCT irradiation facilities at the MITR-II. Two pieces of equipment were purchased with INIE funds to enable more accurate use of cell survival as an endpoint in new boron compound evaluation: 1) Beckman Coulter Model Z2 Coulter Particle Counter; 2) BioTek Instruments EL800 Universal Plate Reader. Progress with this task to date includes the design of a holder for cell culture flasks or 96-well tissue culture plates, the design of dosimetry phantoms for the measurement of the doses received by cells in the irradiation positions.

3) Establishment of a murine squamous cell carcinoma cell line in the laboratory. This is an animal model for head and neck carcinoma, a likely future clinical target for BNCT applications. Establishment of the colorimetric assay used in the 96-well plates and the plate reader for quantification of cell growth. The ability to work in the 96-well plate format is a major advantage to the MIT compound screening capability. The small volumes per well (0.2 ml) greatly reduce the amount of test compound required for the cell survival screening assay. Boron chemists will thus be able to get detailed radiobiological evaluations with just milligram amounts of compound.

Experiments Performed During the Year with Reactor Beams and Staff Assistance

1) Evaluation of Novel Boronated Amino Acids (Dr. George Kabalka, Dept. of Chemistry, University of Tennessee)

   Several new boronated compounds have been prepared that are based on amino acid structures and show selective uptake in tumor tissue. The biological properties of these new compounds must be characterized in cells and in animals. An initial experiment was undertaken to establish a crude biodistribution of the compound WU-3 in 14 nude mice. 12 of which had previously been implanted with FaDu cells (human head and neck tumors). Retro orbital sinus injection of 0.2 ml of WU-3 (calculated to be approximately 472 ppm of ^{10}B) was administered to each animal and these were subsequently sacrificed after 1, 3 and 5 hours. Samples of liver, skin, muscle, brain, blood and tumor were taken and analysed for ^{10}B, using the PGNAA facility of the reactor.

2) The Combination of Radiation Therapy (BNCT) and Gene-Mediated Immunoprophylaxis for Glioblastoma Multiforme (Prof. Henry Smilowitz, Dept. of Pharmacology, University of Connecticut Health Center)

   This experiment is to evaluate the effectiveness of combining BNCT with stimulating the immune system to recognize and attack tumor. Preliminary studies at the BMRR indicated that this combined therapy was considerably more effective than either therapy alone. It was necessary to perform a pilot experiment to establish the surgical approach and pharmacological parameters to use in the study proper. The eventual aim is to administer animals (rats) with a drug (Cereport) to induce blood brain barrier opening that will allow a greater amount of blood borne compounds access to the tumor. The animals would then be irradiated using the neutron beam facility and the survival with BNCT alone, immunoprophylaxis alone and combined will be evaluated. Initially the surgical techniques, infusion schedules and concentrations of administration must be established. A number of normal rats were anaesthetised and infusion canulae placed in either the carotid artery, femoral artery or jugular vein. Through these cannulae, the animals were infused with the drug Cereport, known to disrupt the blood-brain barrier. At appropriate time points a marker of blood brain barrier was administered. Animals were sacrificed and the level of opening determined. Data on concentration, speed and route were collected.

3) Boron Distribution in Each Structure of Normal Rat Brain after Intravenous Injection of Boronophenylalanine-Fructose (Dr. Yasushi Shibata MD, Dept. of Radiology, Beth Israel Deaconess Medical Center, Boston)

Boron neutron capture therapy (BNCT) is an experimental form of radiation therapy for malignant brain tumors. The micro-distribution of the boron compound is critical to determining the radiation effect in both tumor and normal tissue. This study examined structure-specific boron concentration in normal rat neural tissue. At 10, 30 and 60 minutes after intravenous injection of 300 mg/kg boronophenylalanine-fructose (BPA-F) to 10 week-old CD Fisher rats, neural tissues and blood were collected. Various neural structures were anatomically and histologically identified and specific boron concentrations were analyzed using high-resolution quantitative neutron autoradiography. At 60 minutes after the injection, only pituitary gland showed 3 times higher boron concentration than that in blood. All other neural structures showed lower boron concentrations than that in blood. The present study demonstrated high boron concentrations in the pituitary gland. In clinical trials of BNCT using epithermal neutron beams in combination with BPA-F, the radiation dose to the pituitary gland should be carefully evaluated. Publication in preparation for submission to the journal *Radiation Research*.

4) Therapy Irradiations with Boronated Porphyrins (Dr Michi Miura, Medical Department, Brookhaven National Laboratory)

To test a new boron delivery agent called PP200 EMT-6 mammary carcinoma were grown in the legs of mice. These mice were administered BNCT using this drug assuming a boron concentration of 130 ppm in the thermal beam. This is an extension of earlier work and a further four dose points (70, 95,105 and 115 Gy) were studied this time with 12 mice per cohort. The survival of the animals post irradiation is followed as a function of time for 200 days and compared with animals that received no irradiation. In connection with the develop of these porphyrin compounds numerous samples were sent to MIT throughout the year for the evaluation of boron concentrations using prompt gamma neutron activation analysis.

Further Experiments Scheduled for This Calendar Year

1) In vivo study of the combination of BNCT and x-ray irradiation for the treatment of gliomas (Prof. Rolf Barth MD, Ohio State University).

2) In vivo investigations of BNCT combined with immunotherapy for advanced malignant gliomas Prof Henry Smilowitz, University of Connecticut).

3) In vitro assessment of compounds containing boron enriched folic acid conjugates (Prof. Werner Tjarks, Ohio State University).

4) In vitro testing of porphyrin based delivery compounds (Prof. Steve Kahl, UCSF).

5) In vitro testing of Gd based compound (Dr. Brian Ross, University of Michigan).

6) Therapy irradiations with a newly formulated porphyrin PP2200 (Dr. Michi Miura, Brookhaven National Laboratory).

Appendix B

MIT Interferometer Activities Related to MIT-RINSC

By

David J. Cory
Dimitry Pouchin

APPENDIX C

MIT Phase Contrast Imaging Activation Related to MIT-RINSC

By

Richard C. Lanza
Vivian Lenny

REPORT: PHASE CONTRAST NEUTRON RADIOGRAPHY

TO INIE AWARD: 2002/3

Introduction:

During this initial period we have concentrated on the development of the beam and detector system for producing phase contrast images.

Experimental Results:

Our initial experiments have been performed using a cooled CCD imager combined with a neutron scintillator. The system components are shown in Figure 1. The basic method has been described in the literature and consists of a neutron scintillator screen, a turning mirror to keep the neutrons from direct interaction in the CCD, a wide aperture lens and a cooled CCD camera. The optics of the system images the 180 mm x 180 mm scintillator onto the 1024 x 1024 pixel CCD. These components are visible in the pictures below.

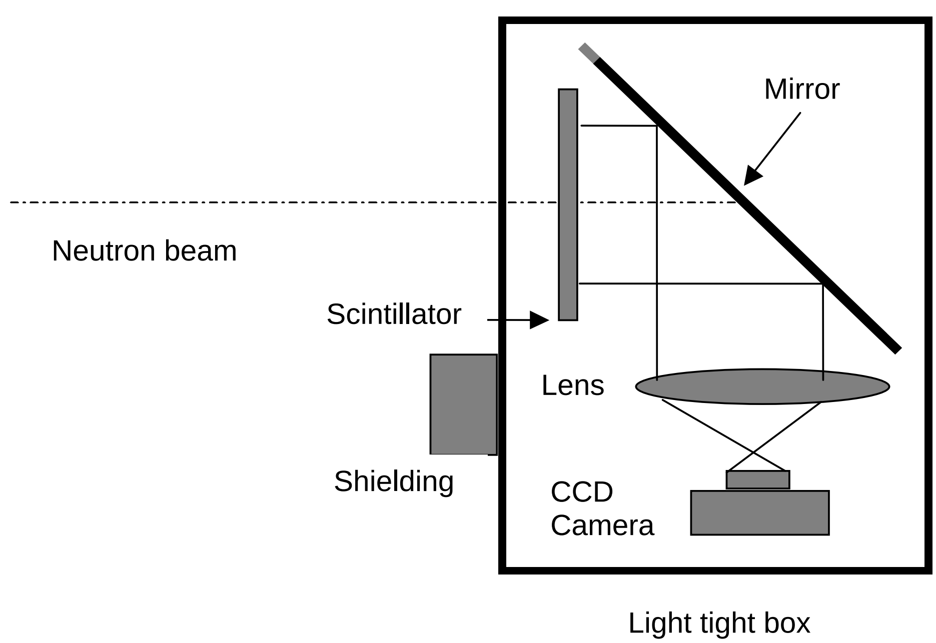


Figure 1: Diagram of System Components.

Figure 2: Photos of System Components

The noise performance of the camera was evaluated using the variance in the signal. The measured variance is the sum of the statistical noise plus the read noise. Thus, a plot of measured variance versus signal yields a straight line whose slope is proportional to the gain and whose intercept is the read noise. This is shown below where the mean ADC count is plotted versus the mean ADC count. The resulting slope is proportional to the gain and the intercept is the equivalent read noise.

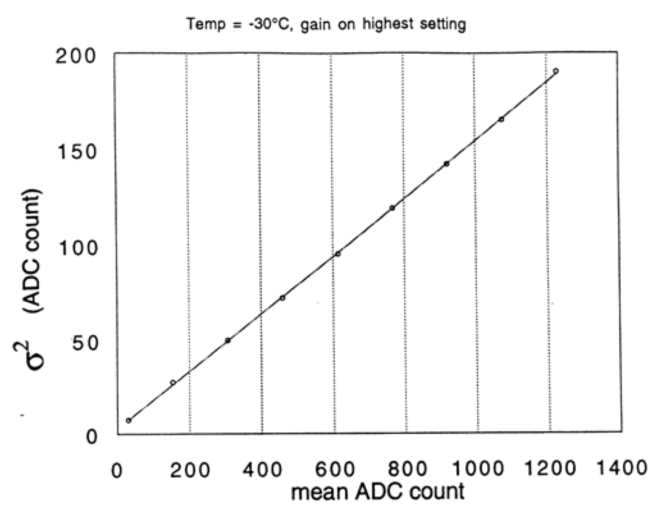
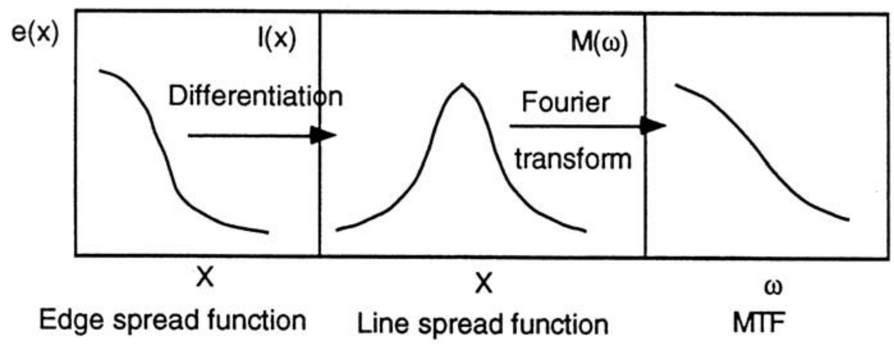


Figure 3: Noise performance of camera using variance in signal.

The spatial resolution of the system was determined by measuring the edge response of the system and converting it into a modulation transfer function.



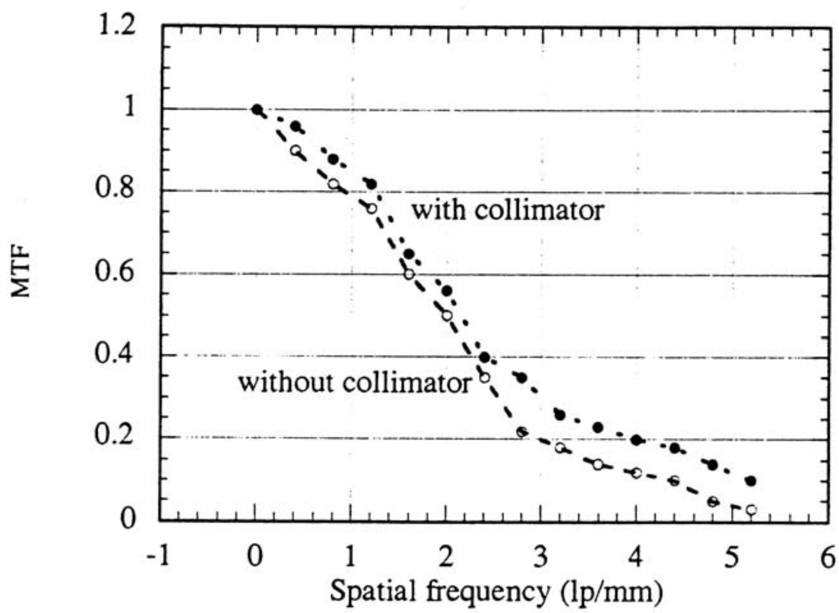


Figure 4: Spacial Resolution of System.

The magnification of the camera system is 7, which results in a pixel size of 150 µm in the plane of the scintillator. The actual resolution is the convolution of the camera resolute ion and the scintillator resolution. The performance of the system can be expressed by the modulation transfer function (MTF). The MTF was measured both with and without an anti-scatter collimator. The collimator reduced the scatter and improved the high frequency response. At the 50% point, the MTF is 2 lp/mm, corresponding to a spatial resolution of 250 µm. This is the convolution of the camera with the intrinsic resolution of the screen 200 µm. From these measurements, it was concluded that

improvements in CCD resolution would not result in improved spatial resolution. In order to improve resolution, alternative imagers will be necessary.
At this time, neutrons have not been available at the MIT reactor since 29 July and we are using the down time to evaluate two different technologies to replace the CCD system we originally proposed.

The first is the imaging plate technology developed by Fuji. In this technique, the neutron detector is a phosphor which "stores" the image in color centers in the phosphor which are then read out using a laser. Typical readout times are 1 to 4 min. We plan to use a Fuji BAS2500 scanner with Fuji ND plates which have a 50μm resolution over an area of 40 x 25 cm.

The second is a combination of a scintillator with an amorphous Si imager. We plan to evaluate systems from Varian and from Thales. Using this technology, images are acquired with frame rates of 1 to 7.5 frames/s depending on the detector. Resolutions are typically 128 μm with active areas of up to 40 x 30 cm.

Beam Design:

During this period, the existing 4H1 beam line was used for testing. This beam is internally collimated and has a relatively small (1 cm x 1 cm) aperture. As a result of these tests, a new beam line is being designed using the 6H1 beam port. In order to have maximum flexibility, the port collimator will be made of a series of removable stainless steel inserts. A similar design has been developed at NIST and we plan to base our design on the NIST port plug.

Student Participation:

Students who worked on the project this year were Vivian Leung, a PhD candidate in the Nuclear Engineering Department and David Jeria and John Cassady, undergraduates who are participating in the UROP program.

Appendix B

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Annual Progress Report on MIT/RINSC/UMass-Lowell INIE Program

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Annual Progress Report on MIT/RINSC/UMass-Lowell INIE Program

I. Introduction

The MIT/RINSC/UMass-Lowell DOE-INIE program represents a collaboration between the reactor laboratories at the Massachusetts Institute of Technology, the Rhode Island Nuclear Science Center (RINSC), and the University of Massachusetts at Lowell

The primary uses for the second year INIE funds at MIT were:

- to create a new state-of-the-art in-core materials test facility at the MITR focused on advanced nuclear power reactors, including both new materials and fuel testing capabilities;
- to transform the existing BNCT facilities at the MITR into a very much needed national user facility;
- to initiate two new projects involving beamports.

The primary use for the second year INIE funds at RINSC was to relieve senior staff from day-to-day operation of the facility and thereby allow them to focus on research, particularly in the area of Gd-NCT.

The University of Massachusetts at Lowell joined the program during its second year. Program funds were used primarily to upgrade neutron radiography.

II. Overview

MIT Research Reactor

Efforts for the second year were focused on the BNCT user facility; a research endeavor in neutron interferometry; a new research activity in phase contrast imaging; and the design of an advanced in-core loop.

- **BNCT User Facility**

  This portion of the MITR INIE Program is under the leadership of Professor Otto K. Harling. He is assisted by Dr. Kent Riley and Dr. Peter Binns. The MITR staff person who interfaces with the BNCT group is Mr. Thomas Newton. Appendix A to this report describes the activities that have been undertaken.

- **Neutron Interferometry:** This portion of the MITR INIE Program is under the direction of Professor David Cory. He is assisted by a graduate student, Dmitry Pushin. The MITR staff person who interfaces with this project is Mr. Thomas Newton. The INIE funds for the project were used to support Mr. Pushin. Significant leveraging of these funds has been obtained through informal cooperation with NIST. Appendix B to this report describes the activities that have been undertaken.

- **Phase Contrast Imaging**: This portion of the MITR INIE program is under the direction of Professor Richard Lanza. He is assisted by a graduate student. The MITR staff person who interfaces with this project is Mr. Edward Lau. Appendix C to this report summarizes the progress made on this project.

- **In-Core Loops**: This portion of the MITR Program involves the design and construction of a post-irradiation examination facility (PIE) for in-core irradiations of both advanced fuels and materials. The advanced fuels work is under the direction of Professor Mujid Kazimi. The materials studies are coordinated by Professor Ronald Ballinger. Both are assisted by Dr. Gordon Kohse, Mr. Yakov Ostrovsky, and Mr. Peter Stahle. The MITR staff person who interfaces with these projects is Dr. Lin-Wen Hu. The emphasis during the second year continued to be on the design of a very high temperature loop that will allow studies related to GEN-IV fuel and materials design. Appendix D to this report summarizes the progress made on these tasks.

- **Nanofluids**: A new project has been initiated at the MITR to evaluate the heat transfer properties of nanofluids while in the presence of radiation fields. An in-core loop is being designed for this purpose.

Rhode Island Nuclear Science Center

The RINSC activity is focused on Gd-NCT. The person in charge is John T. Leith who reports to the facility Director, Dr. Terry Tehan. Appendix E to this report summarizes the advances made by the RINSC program.

University of Massachusetts-Lowell

The UMass-Lowell program is under the direction of Professor Mark Tries. Appendix F to this report covers the accomplishments.

III. Educational Impact

The MIT/RINSC/UMass-Lowell program has no formal educational component because of funding limitations. Nevertheless, the program is having a very substantial indirect effect by promoting usage of the MITR and soon the UMass-Lowell reactor and thereby increasing the need for both student reactor operator and students, both undergraduate and graduate. The following table shows the student usage that is the result of INIE at MIT. The total is 42 students. To put this figure in perspective, MIT's graduate and undergraduate enrollment in nuclear engineering is 48/102 respectively. INIE is clearly having a huge impact.

	MIT		**Other**		**Total**
Program	Undergrad/Grad		Undergrad/Grad		
Reactor Operators	10	-	1	-	11
BNCT	2	4	7	13	26
Interferometer	-	1	-	-	1
Phase Contrast	-	1	-	-	1
Materials/Fuels	-	3	-	-	3
Total	12	9	8	13	42

Appendix A

MIT BNCT Activities Related to MIT-RINSC INIE Award

By

Otto K. Harling
Kent Riley
Peter Binns

REPORT: BNCT ACTIVITIES RELATED TO INIE AWARD: 2003/4

Introduction

The INIE grant was used to fund a number of capital improvements at the MITR. Support under the grant was also provided for the MIT User Center for Neutron Capture Therapy. A number of experimental users were accommodated during the last year. The NCT User Center is the only such facility in the USA and is essential for a viable research and clinical program in neutron capture therapy.

Improvements to the thermal and epithermal neutron beam irradiation facilities

A significant fraction of this work was supported by the INIE award, the remainder was from another DOE grant

1) The medical room was cosmetically refurbished after 40 years. A new dropped ceiling was installed and a false wall added to hide the additional shielding installed in previous years. An epoxy based terrazzo floor was also laid in which boron was incorporated as shielding material to reduce activation of the inner room surfaces.
2) A Li-6 filter was built, installed and tested in the fission converter beam. The 0.8 cm filter is easily removable depending upon clinical needs and provides enhanced penetration of the thermal neutron flux in the beam by approximately 1.0 cm. Beam characterization measurements were performed to assess the performance of the filter and the results match those predicted by our design calculations. This work formed the basis of an MS degree.
3) Two patient collimators were constructed for the thermal neutron beam. These are detachable devices that affix externally to the ceiling below the lowest shutter. Circular fields of 12 and 8 cm are provided using a combination of sandwiched annuli constructed of lithiated polyeythlene and bismuth. Precollimation is provided by a bismuth and borated polyethylene collimator that locates inside the new neutron shielding shutter installed last year. This precollimation is interchangeable with the animal shielding box described last year. Dosimetric measurements were performed in an ellipsoidal water phantom to confirm the performance of the collimators and showed a thermal flux of $2\text{x}10^9$ n $cm^{-2}s^{-1}$ is realizable for patient irradiations with the reactor operating at 5 MW.

4) High resolution quantitative autoradiography is being established in the laboratory to image the uptake of boron at the cellular level in tissue samples and the ensuing radiation tracks that result from thermal neutron irradiations. This is a unique analytical tool that will be essential for the interpretation of future experimental results with prospective capture compounds. To this end a microtome for tissue slicing, freezer and digital microscopy camera and image frame grabber software were purchased. The system is being commissioned as part of a graduate students Ph.D research thesis.

User support through the MIT NCT User Center

1) Irradiation facilities and in-house services such as dosimetry expertise and assistance with the design and manufacture of experimental jigs for holding samples and animals were made available for use to the greater BNCT scientific community. Radiobiology expertise was also provided to assist with surgical procedures related to animal experiments as were facilities for housing animals on campus. Beam time applications were requested at 6 month intervals. In response to the requests received it became apparent that as well as the services offered some prospective outside experimenters required radiobiological facilities as well as expertise. This is particularly true of chemists who are developing the next generation of capture agents for NCT. To screen these compounds requires skills that these developers do not possess and accordingly the radiobiology initiative that was commenced last year has continued.

2) In vitro cell survival curves are a standard tool for the evaluation of the effectiveness of anti-cancer therapies. The ability to pre-incubate cells in culture with medium containing a new neutron capture agent followed by neutron irradiation, allows a quantitative assessment of the cell-killing effectiveness of the test compound. A major part of the INIE/BNCT program is to offer this capability to outside chemists who have developed new boron or gadolinium compounds and are now ready to submit these compounds to a screening procedure to find the ones that are most effective. During the report period a traditional colony forming assay was performed with a murine squamous cell carcinoma and compared with those obtained using a colorimetric assay in a 96-well plate. The comparison enabled the experimental conditions to be optimized for the well plate system for this particular cell line. The ability to work in the 96-well plate format, is a major advantage to the MIT compound screening capability. The small volumes per well (0.2 ml) greatly reduce the amount of test compound required for the cell survival screening assay. Boron chemists will thus be able to obtain detailed radiobiological evaluations with just milligram amounts of compound. The INIE grant has provided support for one Ph.D thesis student who is developing capture compound screening techniques.

Experiments performed by the MIT NCT User Center during the year with reactor beams and staff assistance:

1) Combination therapy using BPA+BSH for treatment of F98 glioma bearing rats (repeat of earlier study performed in the beam at BNL) and the evaluation of convection enhanced delivery (CED) of BD-EGF either alone or in combination with BPA for BNCT of $F98_{EGFR}$ glioma bearing rats (Prof. Rolf Barth et al., Dept. of Pathology, Ohio State University)

2) To evaluate the efficacy of BNCT following intratumoral (i.t) injection or convection enhanced delivery (CED) of boronated (BD) EGF in rats bearing EGFR positive F98 gliomas (Prof. Rolf Barth et al., Dept. of Pathology, Ohio State University)

3) Evauation of the efficacy of BNCT following convection enhanced delivery (CED) of BD-MoAb (C225 and L8A4) either alone or in combination with BPA in rats bearing EGFR positive F98 gliomas (Prof. Rolf Barth et al., Dept. of Pathology, Ohio State University)

4) In vivo investigations of BNCT combined with immunotherapy for advanced malignant gliomas (Prof. Henry Smilowitz, Dept. of Pharmacology, University of Connecticut Health Center)

5) A series of three pilot study to investigate the mechanism of radiation effects on mouse intestinal crypt cells using the short range of the secondaries produced by the boron neutron capture reaction as a tool for the selective irradiation of the vascular endothelium (Prof. Jeff Coderre, Dept Nuclear Engineering, MIT)

6) In vitro assessment of compounds containing boron enriched folic acid conjugates (Prof. Werner Tjarks, Ohio State University)

7) Several irradiations of prepared tissue samples for developing HRQAR in the laboratory (Mr. Tom Harris Ph. D candidate, Dept Nuclear Engineering, MIT)

8) Development of an immunologic research tool based on the boron neutron capture reaction to study tissue rejection after a heart transplant (Dr. E. Binello, Harvard Medical School)

9) Boron assays of both biological specimens and compound formulations using the prompt gamma neutron activation analysis beam line for numerous users.

Publications (related to this grant):

- Binello, E., et al, "T cell uptake for the use of boron neutron capture as an immunologic research tool," *Applied Radiation and Isotopes* 61, 959-962, (2004).
- Barth, R., et al, "Molecular targeting of epidermal growth factor receptor (EGFR) positive gliomas for neutron capture therapy using boronated bioconjugates," *Applied Radiation and Isotopes*.

- Barth R., et al, “Boronated epidermal growth factor as a delivery agent for neutron capture therapy of EGFR positive gliomas,” *Applied Radiation and Isotopes*
- Harling, O. K., et al., “The MIT User Center for Neutron Capture Therapy Research,” *Radiation Research* (submitted 2004)
- Riley, K. J., et al., “An INIE User Facility for BNCT Research at the MIT Nuclear Reactor Laboratory,” presented at the 2003 ANS/ENS International Winter Meeting, Nov 16-20th, 2003.
- Harling, O. K., et al., “User Center for Neutron Capture Therapy Research at the Nuclear Reactor Laboratory,” presented as a plenary paper at the 11th International Society for Neutron Capture Therapy Congress, Waltham, MA, Oct 14th, 2004.
- Barth, R. F., et al, “Neutron therapy of epidermal growth factor (+) gliomas using boronated cetuximab (IMC-C225) as a delivery agent,” *Applied Radiation and Isotopes* 61, 899-903 (2004).
- Kiger, J. L., “Effects of boron neutron capture irradiation on the normal lung of rats,” *Applied Radiation and Isotopes* 61, 969-973 (2004).
- Yang, W, et al., “Boronated epidermal growth factor as a delivery agent for neutron capture therapy of EGF receptor positive gliomas,” *Applied Radiation and Isotopes*, 61, 981-985, (2004).

Summary

The INIE funds were used for much needed refurbishment and upgrading of the thermal neutron irradiation facility. An important enhancement to the epithermal neutron beam was also made possible by these funds. Increasing numbers of users were served by the MIT NCT User Center which receives significant support from the INIE grant.

Appendix B

MIT Interferometer Activities Related to MIT-RINSC

By

David J. Cory
Dmitry Pushin

Imaging Setup

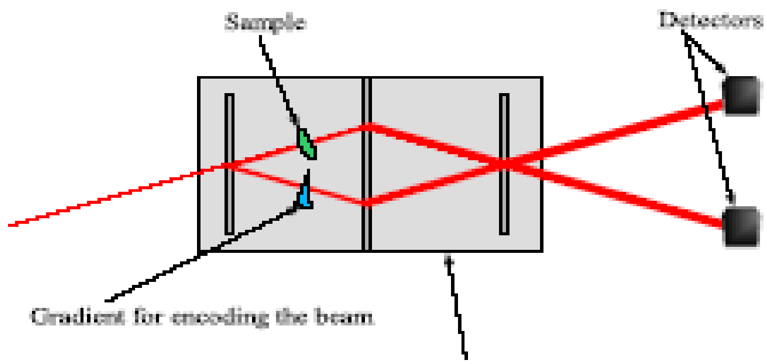

FIG. 1: Schematic diagram of imaging experiment at NIST.

The goal of the proposed work is to develop the theory, experimental apparatus and methods of reciprocal encoding of spatial information for neutron imaging and incoherent scattering. The experimental setup will be based on a Single Crystal Neutron Interferometer where one of the interfering paths includes the sample and the other is spatially encoded with a gradient in neutrons phase (see Fig. 1). This experiment implements a spatial encoding similar to that used in Nuclear Magnetic Resonance (NMR) imaging [1]. Spatial information is encoded in the phase of neutrons. Fourier components are directly measured:

$$I(\mathbf{k}) = \int P(x, y) e^{i\mathbf{k}\mathbf{r}} d^2\mathbf{r}. \qquad (1)$$

Where $P(x, y)$ in Eq. (1) is the scattering function of the sample. The real space image can be reconstructed via Fourier transform:

$$P(x, y) = \int I(\mathbf{k}) e^{-i\mathbf{k}\mathbf{r}} d^2\mathbf{k}. \qquad (2)$$

The idea of this experiment is to overcome the limitation of resolution of present neutron detectors. There have been other experimental setups for neutron imaging [2–4]. In the

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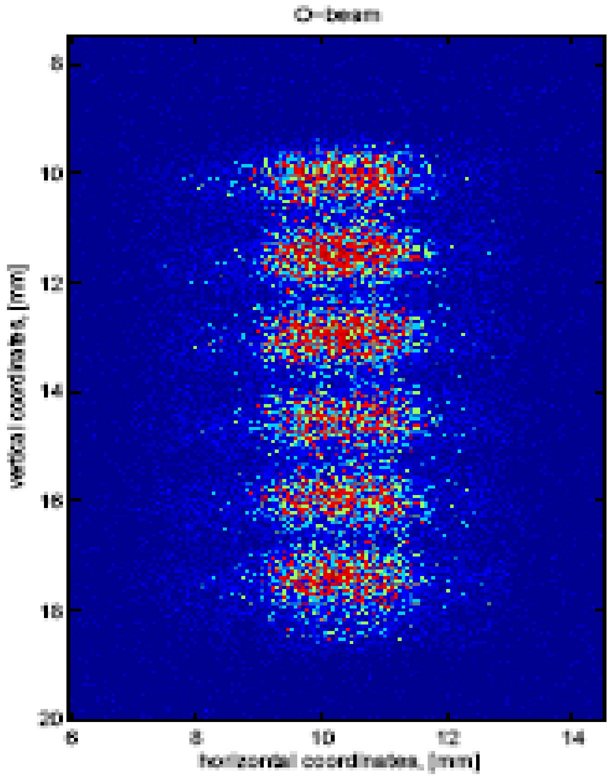

FIG. 2: Interference pattern on the position sensitive detector in the O-beam of the neutron interferometer.

majority of these, the image resolution depends on the spatial resolution of the neutron detectors. In modern days such detectors have demonstrated a resolution of $25\mu m$ [5]. The proposed method allows one to improve spatial resolution in principle up to the Rayleigh limit which in our case may be of the order of several Ångstroms. In practice the resolution will be limited by signal to noise constraint.

From the previous result [6] we know that indeed we can produce a spatially encoded neutron beam and see its interference with a reference beam. Figure 2 shows the interference pattern on the position sensitive detector, which has been set up in the forward beam (O-beam) behind the neutron interferometer.

We also realized that we need a better method for spatially encoding the neutron beam. This time we have developed and realized a (see Fig. 3) double wedge setup. This setup has

FIG. 3: Picture of the "Double wedge setup" for spatially encoding of the neutron beam.

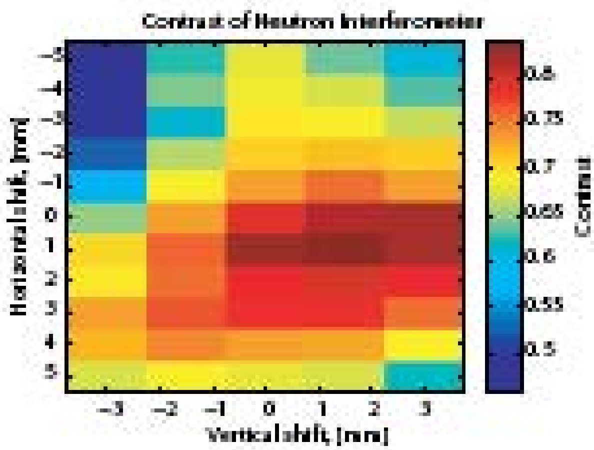

FIG. 4: Position dependable contrast of NIST interferometer.

better control of the spatial encoding of the neutron beam. In figure 3 you can see that we have independent control of rotation of each wedge. By counter rotating the wedges we can keep the neutron beam coding vertically aligned.

Before testing the setup we have performed careful and thorough alignment of the neutron beam (monochromators and slits) and interferometer with respect to the neutron beam. Figure 4 shows the contrast of the neutron interferometer as a function of its spatial position. We select the position of the neutron interferometer to be where it has the highest contrast (84%).

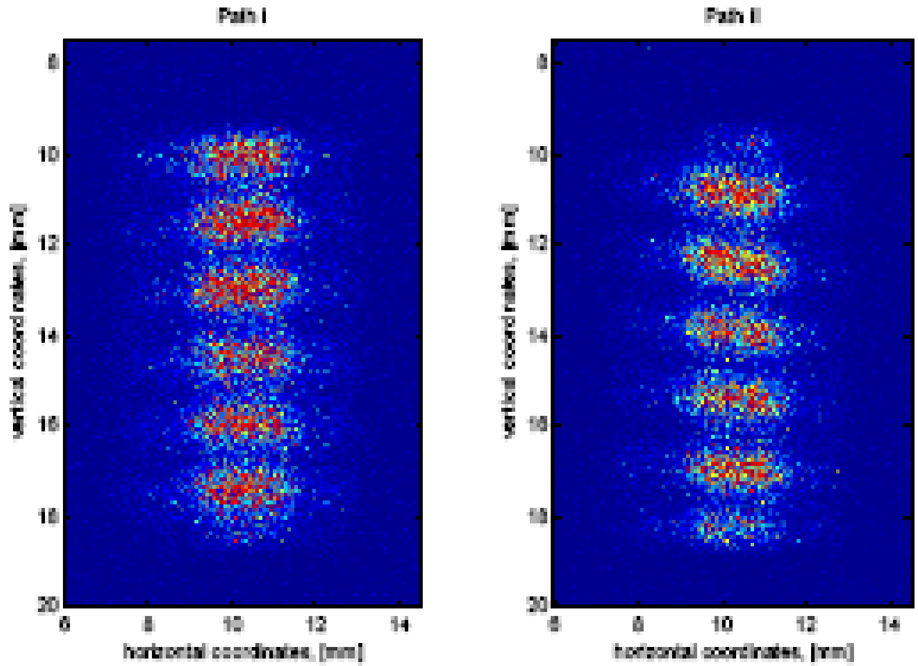

FIG. 5: Interference pictures on the O-beam position sensitive detector when wedge is placed in path I or path II.

Aligning the double wedge setup took also enormous work. In order to fight with phase drifts we installed a temperature control system, which consists of several heaters and two independent PID temperature controllers. We reached stability in temperature of $\pm 5mK$ and $\pm 2^{\circ}$ in phase.

For characterizing spatial encoding we have tried to use the Rad-Eye 1 detector. Unfortunately this detector, after exposure to the neutron beam, shows ghost images, which we could not remove by annealing. That is why we have to use a hand monitor detector with CCD camera, which has worse spatial resolution.

We were able to controllably apply a gradients in phase of the neutron beam and monitor proper phase changes when moving the wedges from one path inside the interferometer to another (see Fig. 5) or introducing phase difference between paths (see Fig. 6) inside the neutron interferometer.

We have also checked that we could change the interference (or phase gradient) by changing the wedge angle. In figure 7 you can see three different measurements of the interference produced by wedges with different wedge angles.

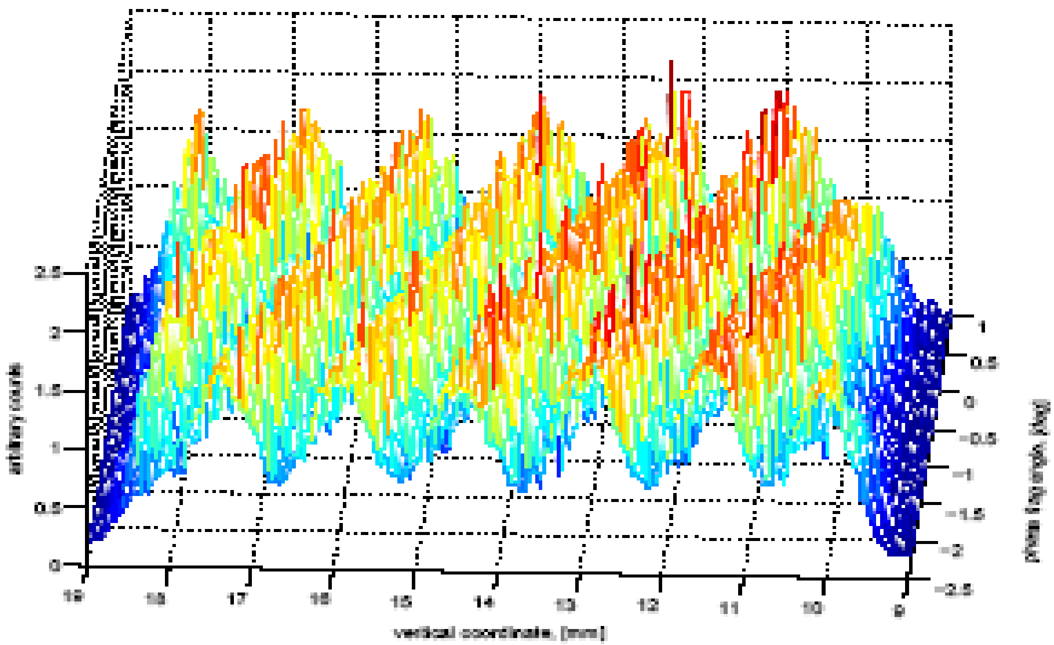

FIG. 6: Phase difference dependence of interference pattern.

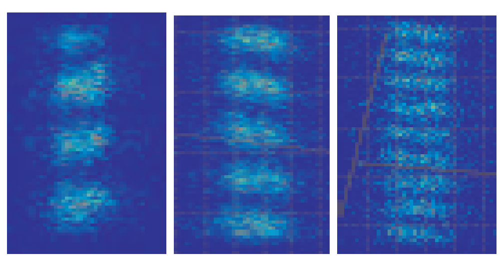

FIG. 7: Phase difference dependence of interference pattern.

We have finished the alignment and are now ready to collect the first data. The first sample will be a step-like sample made of $25\mu m$ fused silica.

For measuring the autocorrelation function we are developing two new experimental setups, one based on the Stern-Gerlach Interferometer and another on a Multilayered Magnetic Mirror Interferometer (See Fig. 8 and Fig. 9).

The idea of the experiment we are setting up in the MIT Reactor is to spatially separate

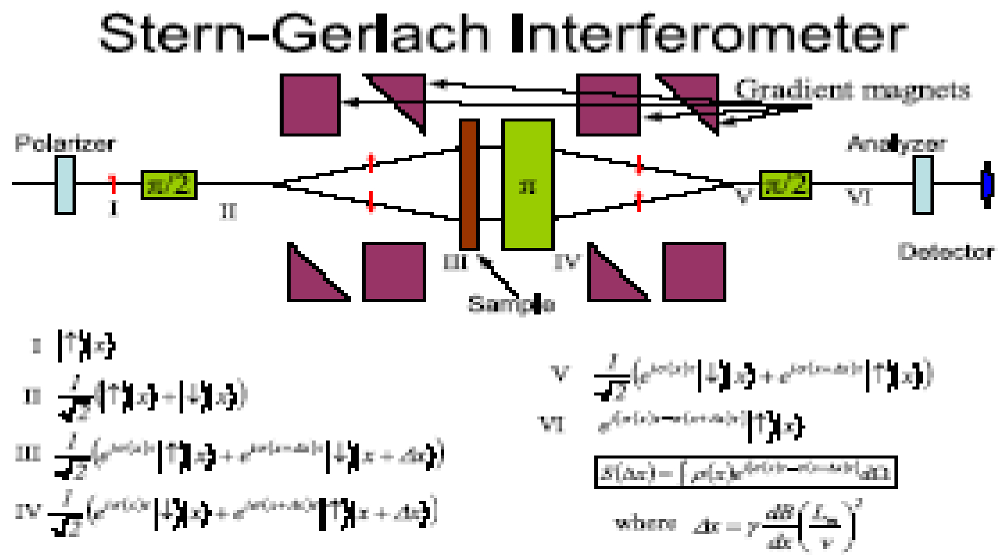

FIG. 8: Schematic diagram of Stern-Gerlach Interferometer setup.

the spin state paths of moving neutrons inside the sample and interfere them in front of the detector in order to measure the autocorrelation function of the sample. Fig. 8 provide an explanation of how the experiment works. Both approaches (Stern-Gerlach and Multilayered Mirror) work similarly and implement a Spin Interferometer setup. The only difference is how the spin state paths are spatially separated.

For the experimental setup at MIT we have tested and calibrated a monochromator and detector in the NIST facilities. In order to make the magnetic multilayered mirror we contacted Prof. Yuji Kawabata from the Research Reactor Institute, Kyoto University and are setting up a collaboration.

We have also spent time on setting up an Interferometric Fourier Spectroscopy experiment at NIST. This experiment will allow us to study Spatial and Temporal Fourier Spectroscopy. We have been testing parts for vertical beam shifters and designing and testing the limiting switch. The idea of the experiment is to separate the two neutron beam paths in the Single Crystal Interferometer vertically (Fig. 10) and measure the contrast vs separation distance.

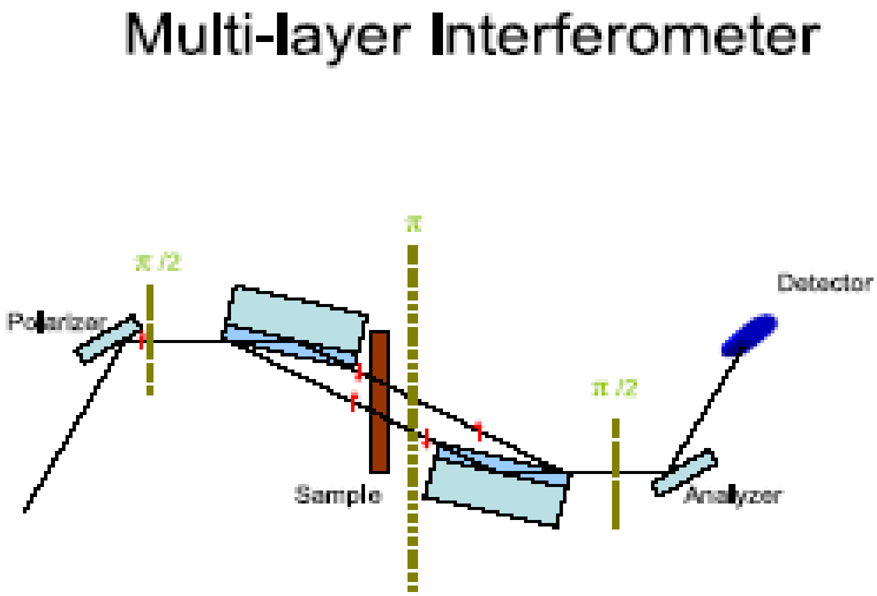

FIG. 9: Schematic diagram of a Multilayered Magnetic Mirror Interferometer setup.

This contrast dependence is directly proportional to the Fourier transform of the momentum distribution of the neutron beam. We have made preliminary measurements which showed that the contrast changed when we varied the vertical separation between the neutron beam paths. Unfortunately, the separation was not big enough to see oscillation in the contrast. We are considering using heavy water for introducing bigger separation between the beams. In this setup we will have a syringe-like system where the ends are placed under angle with respect to vertical. Externally (using motors) we can change the size of this system and excess/deficiency of the heavy water will move to/from connected reservoir. By changing the size of this reservoir we are changing the separation between the neutron beam path.

Thermal and cold neutron imaging has a variety of applications. Unlike other radiographic sources (i.e. X-ray), neutrons can penetrate deep through metal, which allows one to study bulk properties of a large variety of samples, nondestructive imaging of the interior of engines, hydrogen fuel cells, etc. Neutrons also are attenuated mostly by light materials like hydrogen atoms or some selected isotopes. Therefore one can study density fluctuation

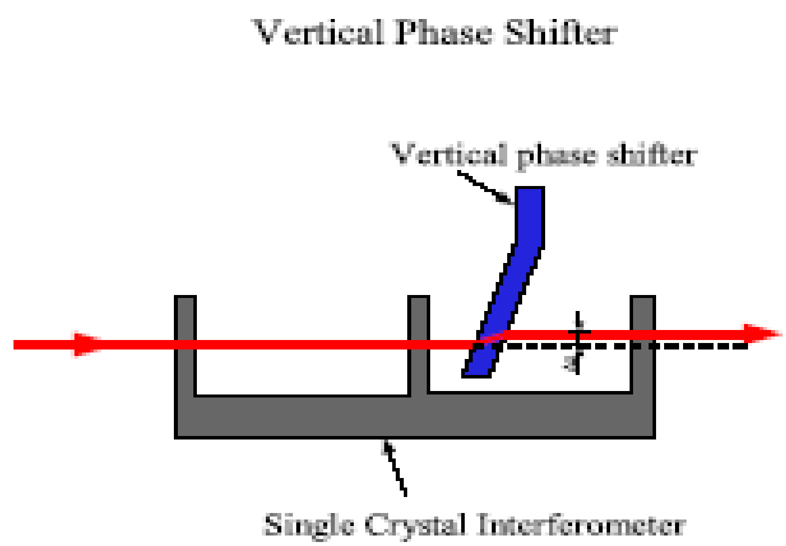

FIG. 10: Schematic diagram of a vertical phase shifter setup.

due to inhomogeneities caused by hydrogen in metals, density of polymeric overlayers, formation of water in hydrogen fuel cells and crystallography for structural biology. Since the neutron experiences all four fundamental forces of nature (electromagnetic, gravitational, weak, and strong interactions) it opens possibility of using neutron interferometry in solid state physics and material science (as example neutron phase tomography of magnetic domains [7]).

For all these applications, spatial resolution is very important. In case of reciprocal space imaging we can avoid limitations of position sensitive detectors and increase the resolution, which, in our case, will be limited by signal to noise constraint.

Measurement of the autocorrelation function of the samples is very important but in general experimentally difficult. The experiments we have proposed for measurement of autocorrelation function are simpler and more direct than currently available methods.

We believe that the proposed experiment will be an important development in the field of neutron scattering.

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[2] G. Badurek, R. J. Buchelt, and H. Leeb, Physica B 276-278, 588 (2000).

[3] P. Lukas, B. Alefeld, A. Ioffe, P. Mikula, and M. Vrana, J. Phys. D: Appl. Phys. 28, A88 (1995).

[4] H. Pleinert, E. Lehmann, and S. Körner, Nucl. Instr. and Meth. A 399, 382 (1997).

[5] Del Mar Ventures, San Diego, CA 92130.

[6] C. Do, Master's thesis, Massachusetts Institute of Technology (2003).

[7] M. Schlenker, W. Bauspiess, W. Graeff, U. Bonse, and H. Rauch, J. Magn. Magn. Materials 15-18, 1507 (1980).

APPENDIX C

MIT Phase Contrast Imaging Activation Related to MIT-RINSC

By

Richard C. Lanza

Report of Activities
Phase Contrast Neutron Radiography
1 October 2003 - 30 September 2004
Massachusetts Institute of Technology
Cambridge, MA 02139

Richard C. Lanza
Principal Investigator

Report of Activities

Phase Contrast Neutron Radiography

1 October 2003 – 30 September 2004

Massachusetts Institute of Technology

Cambridge, MA 02139

Richard C. Lanza
Principal Investigator

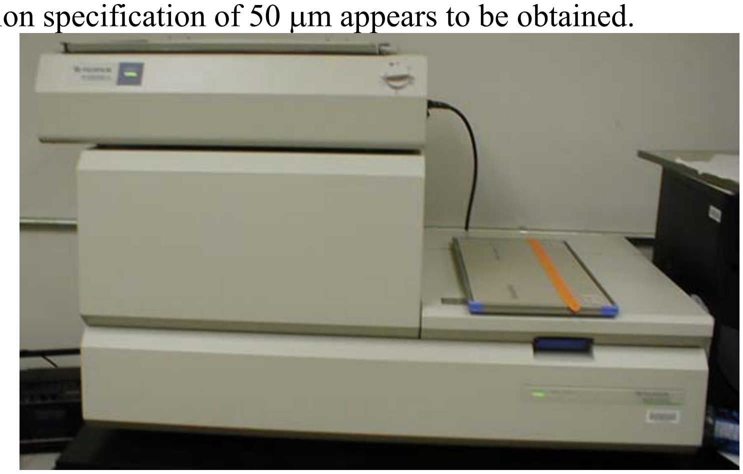
Introduction:

During this period we have continued the development of the beam and detector system for producing phase contrast images.

Experimental Results:

Detectors:

We have received two new detection systems and have started evaluation. The first is a Fuji BAS2500 imaging plate system. Initial measurements were made using an existing beam line. Although we have not completely characterized the performance, it appears that the resolution specification of 50 μm appears to be obtained.

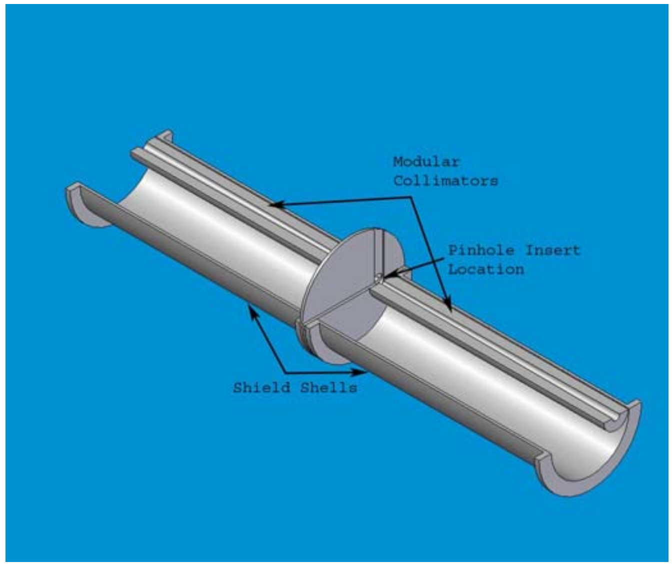


The major limit to this system lies in the large data files (60 Mb) and the relatively slow readout times, ~5 min for images taken at full resolution (50 μm pixels, 16 bit). A neutron imaging plate is shown below.

The second detector, a Thales FlashScan33 is still being evaluated. This detector is 30 x 50 cm with 127 μm pixels. The system uses a Gadox screen as a neutron detector. Its primary advantage in our application is the faster readout, approximately 1.5 s for a full screen image. Our initial measurements have shown that performance appears to be within specification. We have not yet characterized completely either detector with respect to MTF and noise characteristics.

Beam Design:

The beam pot design is shown below in a cutaway view. In the view shown below, the "modular collimator" is a stepped tube for the insertion of one or more of several filter materials that we have made. One is a 15 cm long monocrystalline Bismuth filter and two others are available, both 10 cm of optical sapphire. The Bi filter will remove both gammas and fast neutrons, while the sapphire filters are primarily for fast neutrons. We may use various combinations, depending on the final beam quality. The pinhole insertion point will take several sizes of pinhole. Currently we have both 200 μm and 400 μm pinholes in Cd, which have been fabricated for us by NIST.


Modular
Collimators
Pinhole Insert
Location
Shield Shells

APPENDIX D

In-Core Loops for Advanced Fuels and Materials

By

Mujid Kazimi
Ronald Ballinger

Summary of Fueled Loop and Materials Experimental Activities October 2003 to September 2004

Two Activities were undertaken with support from this INIE section:

1) Design, calibration and irradiation of high performance annular fuel segments in support of the NERI program High Performance Fuel Design for Next Generation PWRs

2) The design and validation of a high temperature facility for advanced fuels and materials testing.

A brief description of the INIE related activities for both projects is given here.

A. High Performance Fuel Design for Next Generation PWRs

PI: Professor Mujid Kazimi; Co-PIs: Pavel Hejzlar, Gordon Kohse

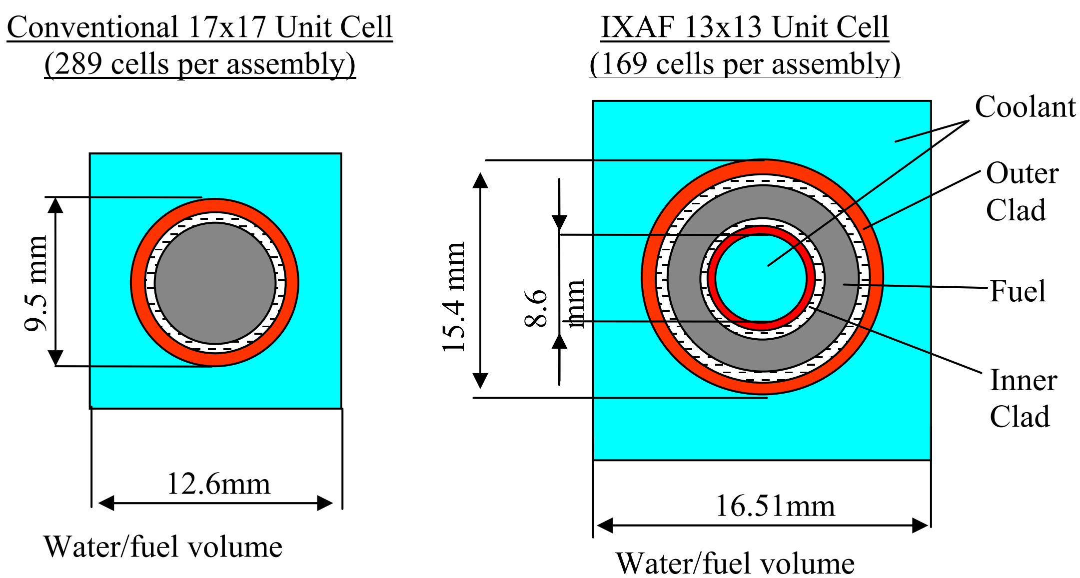
Research Objectives

This is a NERI project (#01-005). Portions of the research are being facilitated by the upgrade of the MITR post-irradiation examination facilities that is being supported through INIE. The overall objective of this NERI project is to examine the potential for a high performance advanced fuel for Pressurized Water Reactors (PWRs), which would accommodate a substantial increase of core power density while simultaneously providing comparable or larger thermal margins than current PWRs. This advanced fuel will have annular geometry that allows internal and external coolant flow and heat removal. The fuel temperature in the new fuel would be much lower than the solid fuel.

One of the tasks is to evaluate the performance of UO_2 fuel forms obtained by production technologies different from current US practices (e.g., vibropacked or VIPAC fuel), and operating under new conditions (especially low fuel temperature and low temperature gradients) with regards to fission gas release, and fuel dimensional properties during burnup. For this purpose special test segments irradiations have been planned in the MITR-II research reactor.

Research Progress

The work on this project in the previous years has identified the most promising fuel assembly arrangement of the internally and externally cooled annular fuel for PWRs to achieve a significant increase of power density (currently estimated to be 150%). That design is a 13x13 square fuel assembly with the same dimensions as the typical Westinghouse 17x17 PWR assembly using solid cylinder fuel pins (see Fig1). This is a significant power uprate, raising the extracted power and increasing the plant output from the current 1150MWe to 1750MWe. At this high power, the peak fuel temperature is still about 1300°C lower than the solid fuel in today's PWRs.



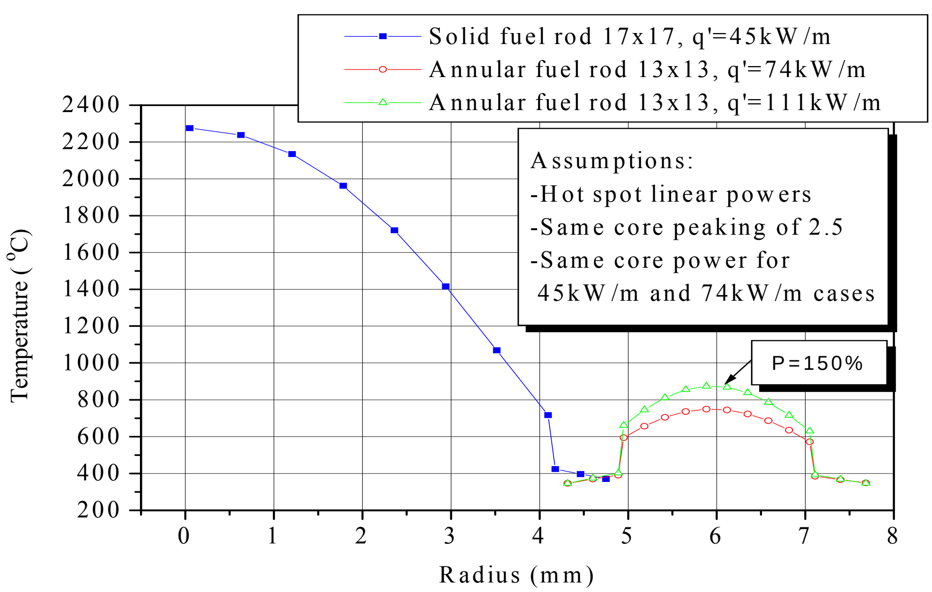


Figure 1 The graphic compares performance of solid and annular fuel

Based on the reference annular fuel design, preliminary specifications of key components were developed. An evaluation showed that existing commercial nuclear fuel cladding manufacturing technology could produce the cladding tubes required by the annular fuel without prohibitively higher costs. It was also assumed that Vibrational Packing (VIPAC) of fuel powder could reduce the fuel cost. Using VIPAC fuel fabrication technology, AECL produced six annular fuel test specimens for irradiation testing at MIT. The AECL work provided valuable insight into Vipac fabrication techniques and product characteristics.

The design of the fuel irradiation experiment was completed. To raise the fuel temperature to prototypic conditions, a thermal bath of liquid lead bismuth eutectic alloy separates the cladding from an outer aluminum jacket that is cooled by the reactor coolant. Thermal testing of the liquid metal heat transfer medium for the in-core sample capsules was completed and final dimensions for the capsules were calculated based on this test data and the as-received parameters for the fuel samples. A Safety Evaluation Report was presented to the MITR-II Reactor Safeguards Committee and a revised version has been accepted by the designated subcommittee after resolving of the issue of ultimate disposal of the irradiated fuel elements by acceptance at DOE and INEEL to take back the irradiated fuel. The license amendment required to permit irradiation of sample fuel in the MITR-II was approved and received from the US Nuclear Regulatory Commission. Initial core flow experiments were completed and leak testing of four manufactured capsules allowed the introduction of two segments in the core for irradiation in March of 2004. Irradiation of the two VIPAC fuel specimens continued until the beginning of September 2004, at which point they were extracted and stored for cooling until post-irradiation examination becomes possible.

Planned Activities

Post irradiation examination of the two segments (fission gas release, burnup confirmation, gamma scan) will be done within the next year. Irradiation of the four fuel samples for 4-6 months and analysis of results are proposed through a new U- NERI program, as well as further development of the FRAPCON-ANNULAR code for modeling of VIPAC fuel and evaluation of VIPAC annular fuel performance.

B. In-Pile High Temperature Irradiation Facility.

(PIs: Professors Ronald Ballinger and Mujid Kazimi/Co-PIs: Peter Stahle, Gordon Kohse, Yakov Ostrovsky, Lin-Wen Hu, Thomas Newton, Zhinwen Xu, Peter Titus)

This project is entirely supported by INIE. There is considerable interest within the GEN-IV program in a very high temperature reactor to improve the efficiency of electricity production and to facilitate hydrogen production using thermochemical splitting of water. To examine the performance of fuel and structural materials at very high temperatures (from 1000 to 1400 C), a new facility has been designed. It will consist of in-core tungsten crucibles with graphite-lined sample positions. The high density tungsten provides a large mass to increase nuclear heating and allow the desired high temperatures to be achieved. Cooling will be provided from outside the crucible, with a gaseous gap that will be composed of a mixture of helium and neon. The composition will be adjusted to achieve the temperature desired for the experiment.

An out of pile simulation test has been conducted using an electric heater, and the results show that the predicted temperature in the crucible matches the expected temperature. The design of the in-pile facility has been completed. A safety evaluation report has been submitted to the MIT Committee on Reactor Safeguards. Copies of the design report are available upon request.

Figure 2 is an in-core section of the HTIF.

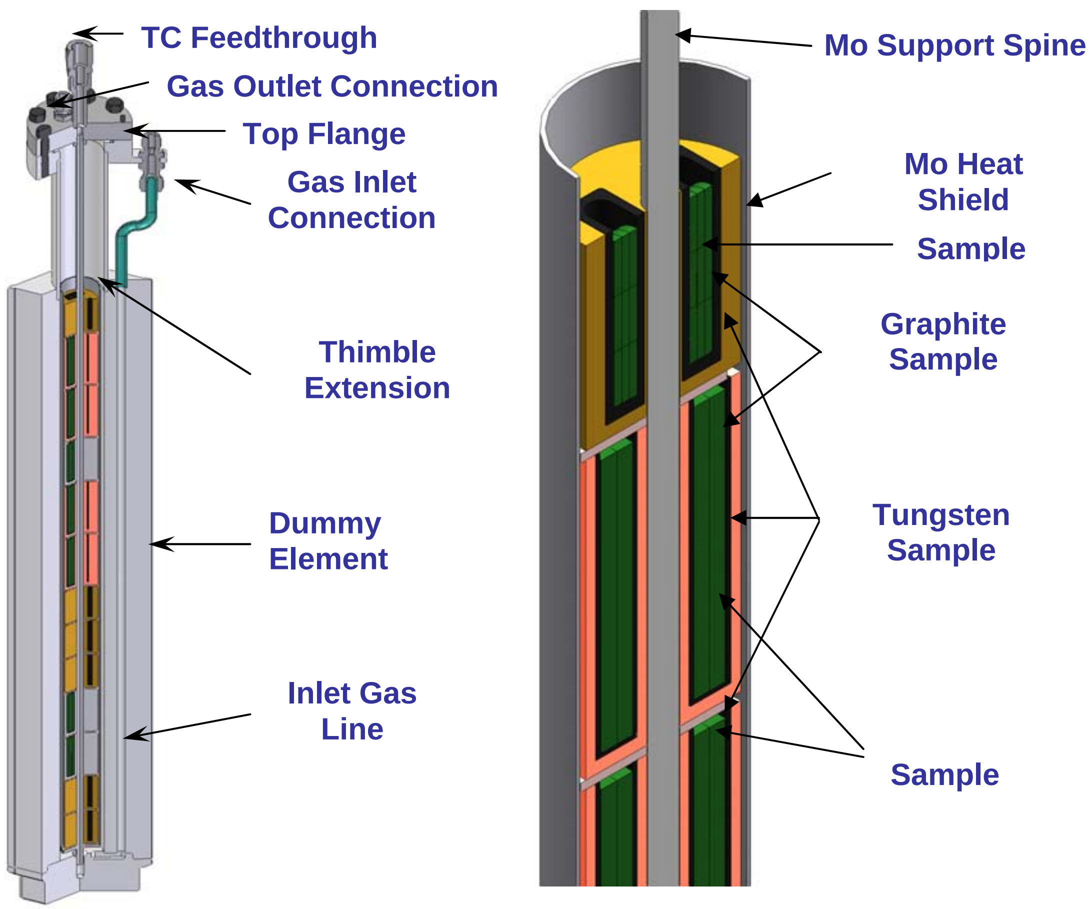


Figure 2. Cutaway views of the HTIF in-core section.

C. Shadow Corrosion Irradiation Studies

PIs: Professor Ronald Ballinger, Peter Stahle, Gordon Kohse, Lin-Wen Hu

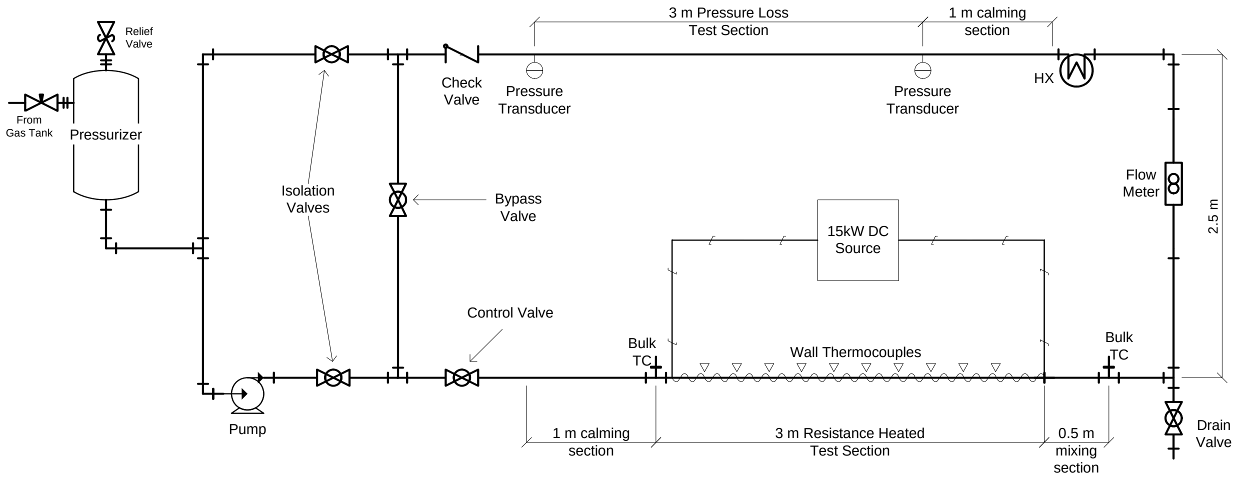
This project is supported by private funding. The objective is to identify the course of "shadow" corrosion which is a newly observed phenomenon in reactors. The word "shadow" is used to describe it because the image of one core component is visible on another. Hence, the corrosion is being mediated by the radiation fields and/or the coolant. Two irradiations were performed during 2003-2004. Both were supported by equipment obtained through INIE.

D. Experimental Study of Water-Based Nanofluid Heat Transfer Enhancement

PIs: Lin-Wen Hu, Professor Jacopo Buongiorno

The goal of this project is to investigate the heat transfer enhancement of water-based nanofluids. Nanofluids are nanometer-sized particles (~10 nm) dispersion in conventional heat transfer fluids, such as water, oil, and ethylene glycol. Various types of nano-particles were investigated, including Cu, CuO2, alumina, gold. Recent studies reported up to a two-fold increase in heat transfer coefficient with a small amount (<2 vol%) of nanoparticles suspension. There is a potential for development of advanced heat transfer fluids that can benefit the nuclear industry. For example, existing LWRs could be retrofitted with a water-based nanofluid coolant, to increase safety margins, or allow for power uprates.

The INIE funding for this project will be primarily used to purchase parts and equipment for the construction of a loop dedicated for the nanofluid heat transfer experiment. . Figure 3 is a schematic of the loop. This facility is designed to operate at 1 MPa. The effect of nanoparticle sedimentation (if any) will be evaluated by observing the change in the heat transfer coefficient with time, and periodically analyzing the test-section surface at the microscope.



Reynolds Number	Grashof Number	Velocity (m/s)	Bulk Temp. (C)	Pressure (bars)	Heat Input (kW)	Heat Flux (kW/m2K)	Mass Flow Rate (kg/s)
<400000	<1800000	<8	30 to 180	1 to 10	<15	<160	<0.63

**Operating parameter calculated w/ water properties, actual nanofluid performance may vary*

Figure 3. Schematic and operating parameters of the MIT experimental test loop.

Appendix E

Rhode Island Nuclear Science Center INIE Activities

By

Terry Tehan
John T. Leith

Rhode Island Nuclear Science Center INIE Activities

The accomplishments for the DOE-INIE grant from MIT are as follows:

1. We have completed survival studies on F98 rat brain tumor cells using graded single exposure to thermal neutrons alone versus F98 cells exposed for 1 hour prior to irradiation to a media concentration of 200 ug/ml of gadolinium-porphyrin. Our thermal neutron survival curves for the thermal neutrons alone and the thermal neutrons plus Gd-P are linear and <u>differ in their slopes by a factor of 2.00</u> (summarized in Table 1).

TABLE 1

Survival curve parameters (from fits to the linear-quadratic equation) and dose-modifying factors for F98 cells exposed to various concentrations of gadolinium-porphyrin

	Log Percent Survival at 0 Flux	**Percent Survival at 0 Flux**	**Slope ($n/cm^2 \times 10^{12}$)**	**Dose Modifying Factor (DMF) (Gd-P/Controls)**
Treatment Groups				
F98 cells (controls)	1.985 (±0.033)	96.6 (89.5-104.2)	0.280 (±0.042)	1.00 ------
F98 cells + 200.0 ug/ml Gd-P	2.022 (±0.170)	105.2 (71.1-155.6)	-0.560 (±0.067)	2.00 (±0.38)

Values in parentheses indicate the 95% confidence limits. The value for the calculation of the DMF is the propagated 95% confidence limit.

2. In regard to these survival data, we have also completed initial inductively coupled pulse mass spectrometry (ICP-MS) studies on these F98 cells exposed to 200 ug/ml of Gd-P in the medium. Measurements were made after the same exposure time as was done for the thermal neutron irradiations. Our results are as follows:

TABLE 2

- There was 85.89% of the original Gd in the medium remaining in the supernatant.
- The first wash with phosphate buffered saline (PBS) reduced the Gd-P to 8.62 % of the original Gd.
- The 2nd wash with PBS reduced Gd-P to 2.44% of the original Gd.
- Cells were then removed from flasks using trypsin, and the supernatant of the centrifuged cells contained 1.00 % of original Gd.
- The cells themselves contained 2.05% of original Gd as determined by ICP-MS.
- This 2.05% corresponds to 24.6 ug in the cell pellet.
- As there were 1.70 x 10^6 cells in the samples, there was 0.145 x 10^{-5} ug of total Gd-P per cell, and, since ^{157}Gd is only 25.67% of the total Gd measured by the ICP-MS, this indicates that there was 3.77 x 10^{-7} ug/cell of ^{157}Gd. Using the formula weight of ^{157}Gd, we then calculate that, on average, 1.42 x 10^9 ^{157}Gd atoms per cell. These experiments have been done twice to date.

3. Our calculation that a change in slope by a factor of 2.0 with addition of Gd-P corresponding to an average value of 1.42 ^{157}Gd atoms per cell as compared to thermal neutrons alone indicates that Gd-P has a significant radiosensitizing effect when F98 tumor cells are exposed to thermal neutrons.

4. We have recently obtained endothelial cells from rat brain (from Dr. J. Pachter, Chairman, Dept. of Neurobiology, University of Connecticut Health Sciences Center, Farmington, CT). These endothelial cells will allow us to directly compare F98 rat brain tumor cells versus normal rat brain endothelial cells. This is a syngeneic comparison. We will compare survival responses of both types of cell lines to thermal neutrons (± Gd-

P) to see if they are similar or different. We will then compare the uptake of Gd-P using ICP-MS to see if the uptake per cells is similar or different. We will then compare the survival versus the Gd-P uptake per cell detemine if the results are the same or if there are differences between normal and tumor cells.

5. We already have initial data on the cross-sectional areas of both endothelial and F98 cell nuclear and whole cell areas. The endothelial cells are smaller than the F98 tumor cells. To our knowledge, the sizes of rat brain endothelial cells have not been previously determined. We will use these cross-sectional areas to determine whether the responses of normal endothelial cells versus F98 tumor cells are similar or different when expressed as percent survival per Gd-P atom/cell per μM^2 of area.

Appendix F

University of Massachusetts at Lowell INIE Initiatives

By

Professor Mark Tries

To the Nuclear Reactor Laboratory at the Massachusetts Institute of Technology,

A Summary Report From the

University of Massachusetts Lowell Radiation Laboratory

For the First Year of a Four-Year Research Program to Develop and Implement

Digital Neutron Radiography With Remote Object Examination Capability

Prior to this program, thermal neutron radiography at the UMASS Lowell Research Reactor (UMLRR) was conducted using film in accordance with applicable ASTM standards. The beam used for neutron radiography was extracted from the thermal column facility on the first floor of the UMLRR, and film preparation and development were performed in a nearby laboratory. The digital neutron radiography facility makes use of the same beam, and digital image acquisition and analysis currently is performed in proximity to the thermal column. It is noteworthy that essentially all of the components that comprise the digital neutron radiography facility, exclusive of the thermal column, were fabricated or acquired in the past year.

This report provides an illustrative summary of the new digital neutron radiography facility. Fig. 1 contains an overview of the facility. Image acquisition and analysis is performed in the partitioned area; the camera box and sample positioning system are placed on a rail cart just to the left of the partitioned area; and the beam stop (comprised of concrete blocks) is located near the top left corner of the partitioned area between the rails in the floor. Fig. 2 contains a view of the rail cart assembly and the beam stop at floor level, and Fig. 3 contains a view of the rail cart assembly and the thermal column door.

Fig. 4 contains a view of the beam shutter mounted on the thermal column door. The beam shutter consists of two-inch thick lead bricks encased in a layer of [boron carbide]-aluminum metal matrix composite, and is located approximately midway between the *General Electric* logo and the floor. The shutter slides horizontally using pneumatic control which will be interfaced with the computer in the near future. In the closed position, the boron content of the shutter is sufficient to stop the thermal neutron beam emitted from a hole in the thermal column door, and the lead content of the shutter reduces the gamma ray intensity. The blue light above the shutter will illuminate during reactor operations when the shutter is open.

Fig. 5 contains a view of the rail cart assembly. The rail cart is an aluminum platform on which the camera box and sample positioning device are located. The rail cart can move along the rails in the floor to optimize the distance between the camera box and thermal column door. The black object in the foreground of Fig. 5 is the sample positioning device which is capable of translating objects across the image-area on the camera box (both vertically and horizontally), and rotating objects 360 degrees as well.

The sample positioning device therefore allows large samples to be examined completely during a single exposure. The camera box is the aluminum[1] enclosure located just behind and above the sample positioning device. Fig. 6 contains a side view of the rail cart assembly, and Fig. 7 contains a view of the control box for the sample positioning device, which contains its motor control units and computer interface. This control box also will contain the control unit and computer interface for the beam shutter.

Fig. 8 contains a view of the image-area on the side of the camera box. The image-area contains the scintillator sheet that converts the Q-value of thermal neutron capture reactions into scintillation photon energy. Fig. 9 contains a view of the interior of the camera box. The lens and camera assembly are located on the left, and the diagonal reflecting mirror is on the right, just below the exposed square of scintillator sheet (yellow) that constitutes the image-area. Fig. 10 contains a view of the camera box showing the thermo-electric cooling system for the camera. Fig. 11 contains a view of the end of the camera box, showing the four heat-exhaust fans for the camera cooling system. Also visible are two hose barbs (top left and bottom right) that enable a dry nitrogen gas purge to maintain a controlled environment within the camera box.

The remainder of the new items are contained within the partitioned area (partitions donated by UMASS Lowell). Fig. 12 contains a view of the large format printer and a file cabinet for image storage. Figs. 13 and 14 contain views of the computer and monitors. The computer currently controls all the mechanical systems as well as image acquisition and processing. One computer monitor is used for systems control, and the other for image processing.

In conclusion, the capability to perform digital neutron radiography has been achieved at the UMLRR at the end of the first year of this four-year research program. Many additional refinements still must be made to produce a system that is capable of meeting our eventual objective of providing seamless object examination at a remote location. Students have not been involved the first year of this research program due to equipment costs, but we hope to support student research in the second year.

[1] Similarly, all structural components in the thermal neutron field are constructed of aluminum to eliminate long-term neutron activation problems.

Figure 1. Overview of the digital neutron radiography facility.

Figure 2. Rail cart assembly and beam stop (northwest view).

Figure 3. Rail cart assembly and thermal column door (southeast view).

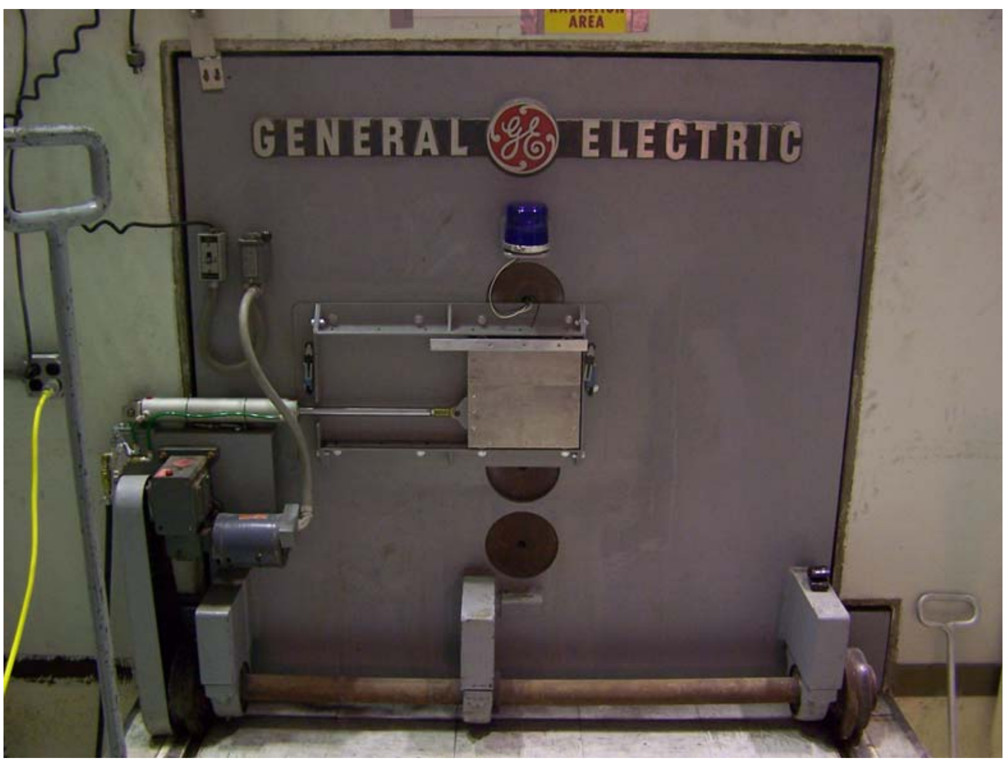


Figure 4. Beam shutter on the thermal column door (east view).

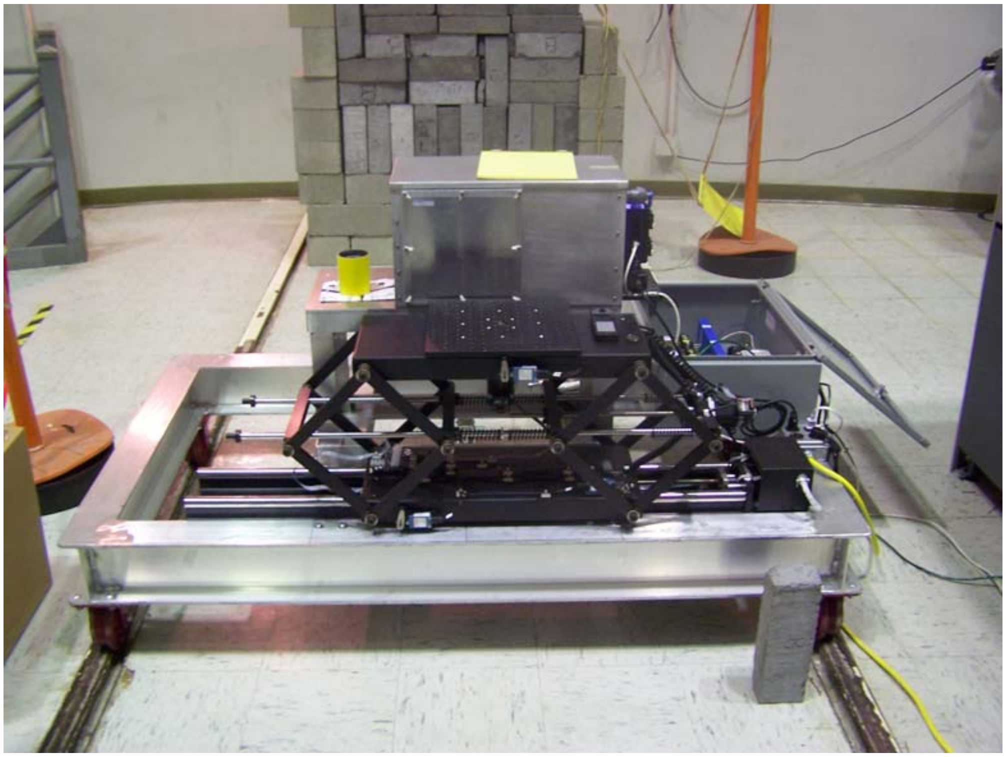


Figure 5. Rail cart assembly (west view).

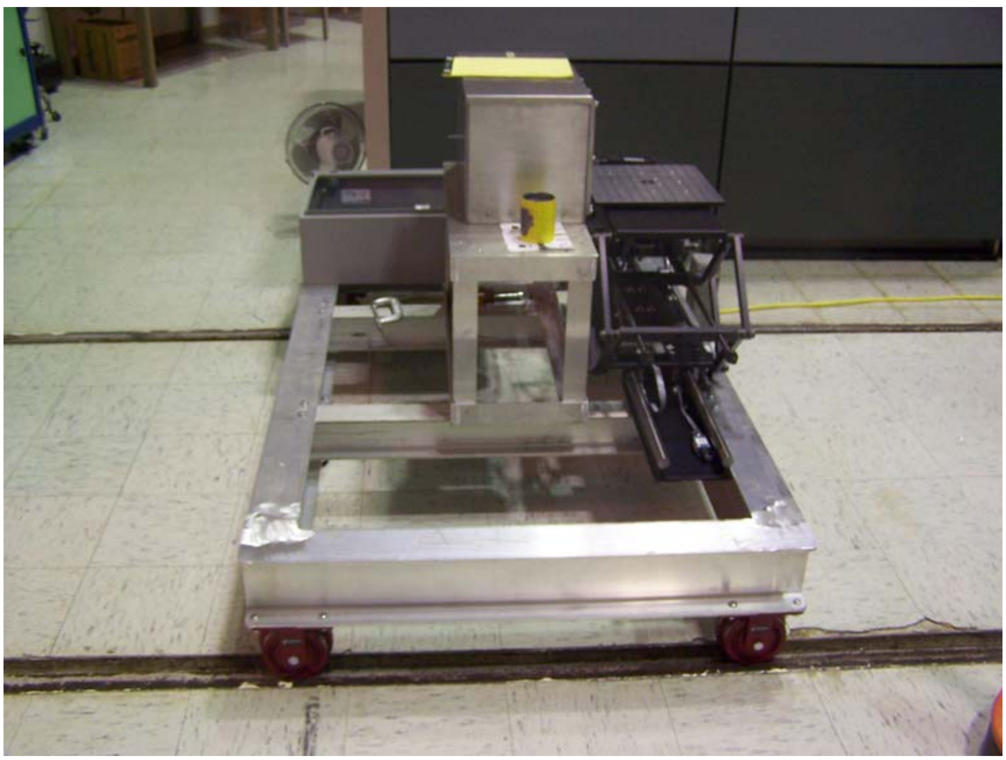


Figure 6. Rail cart assembly (north view).

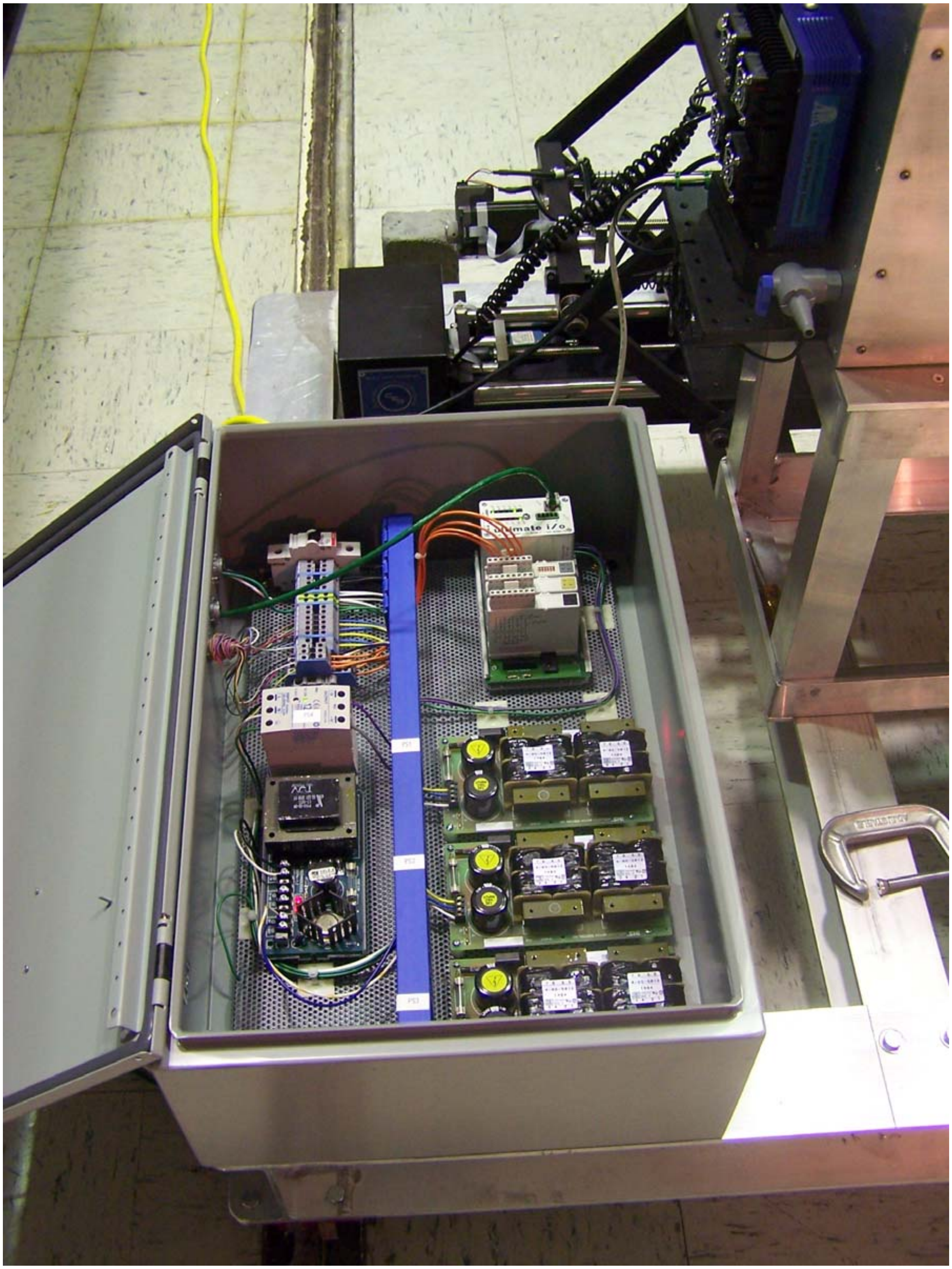


Figure 7. Control box for the sample positioning device.

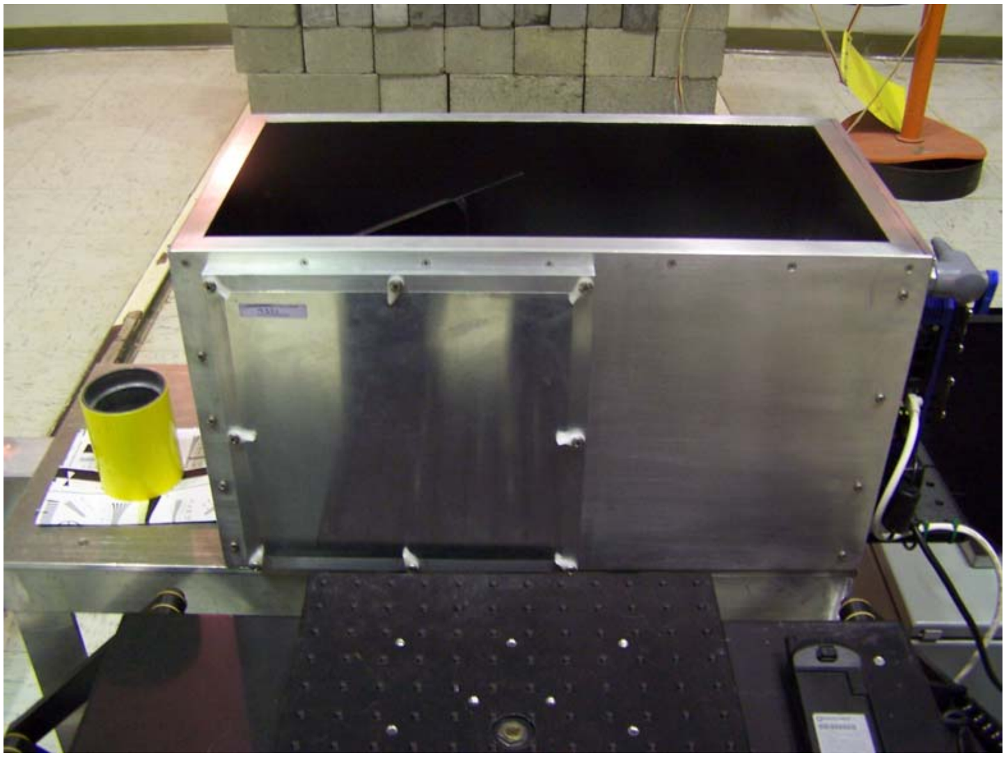


Figure 8. Image area on the side of the camera box.

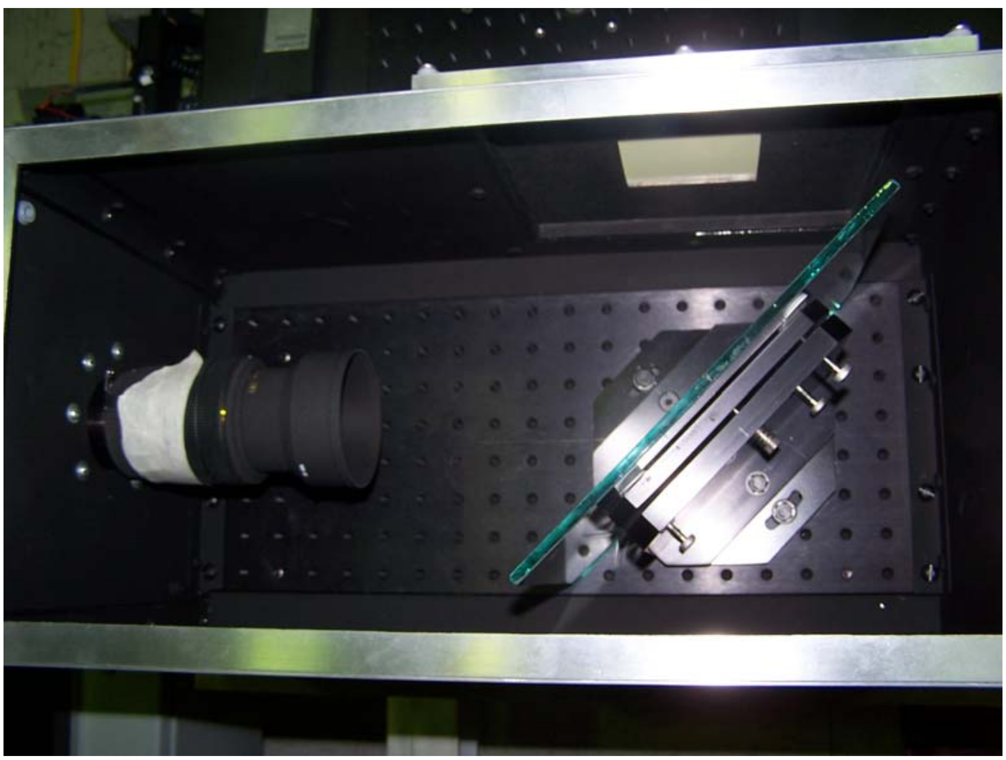


Figure 9. Interior of the camera box (top view).

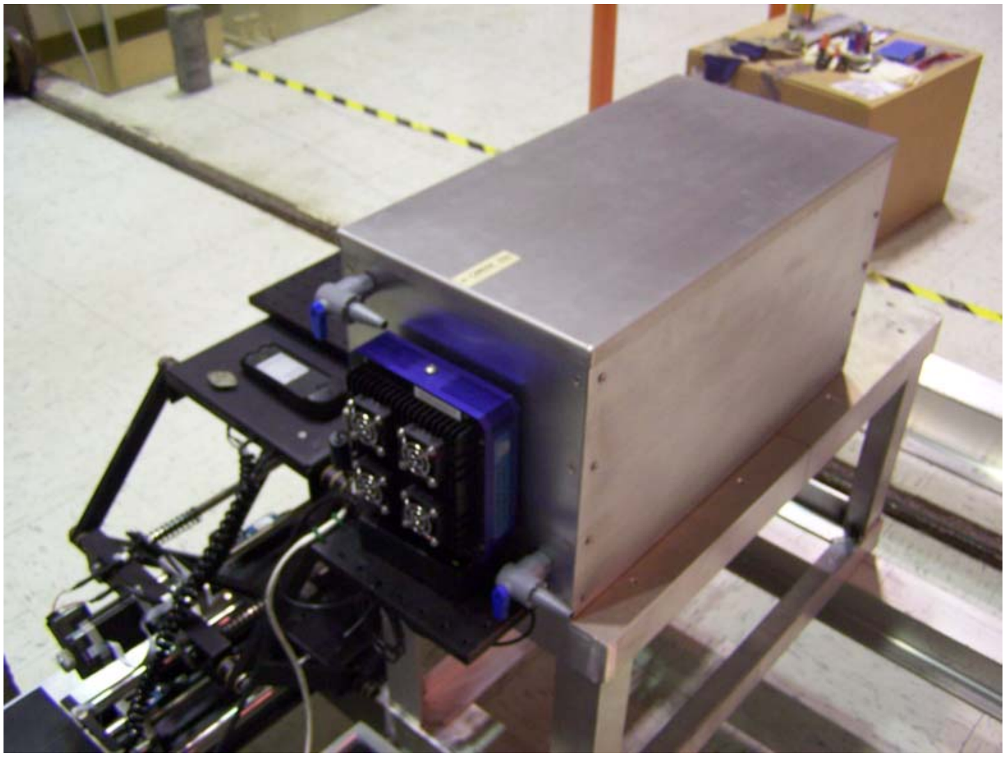


Figure 10. Camera box (southeast view).

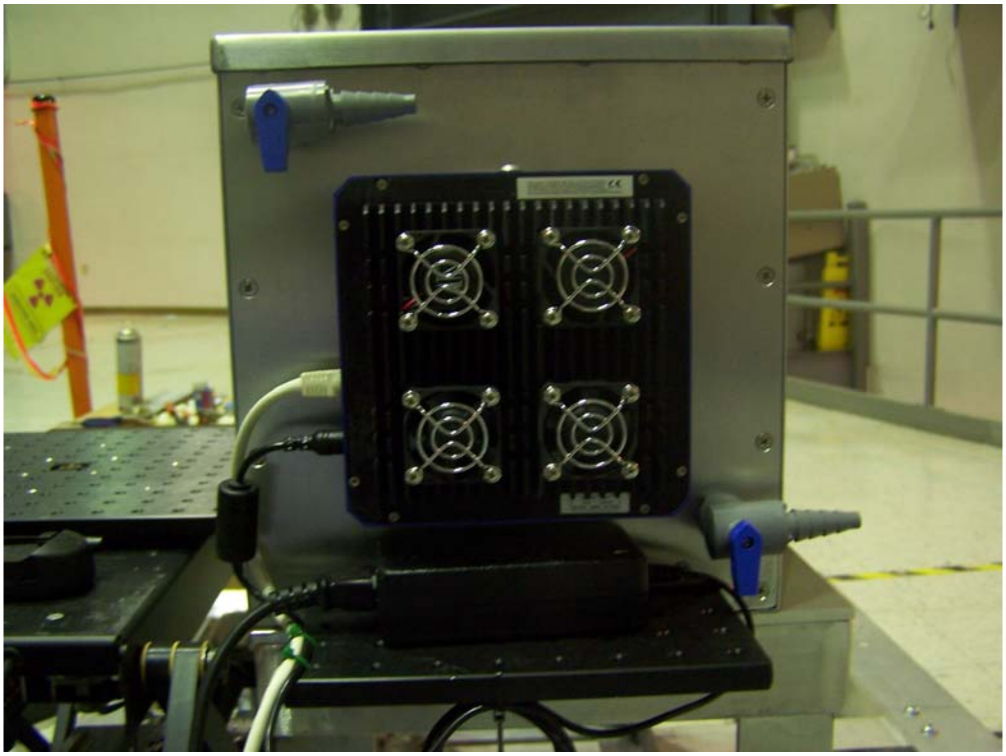


Figure 11. Camera box close-up (south view).

Figure 12. Printer and file cabinet.

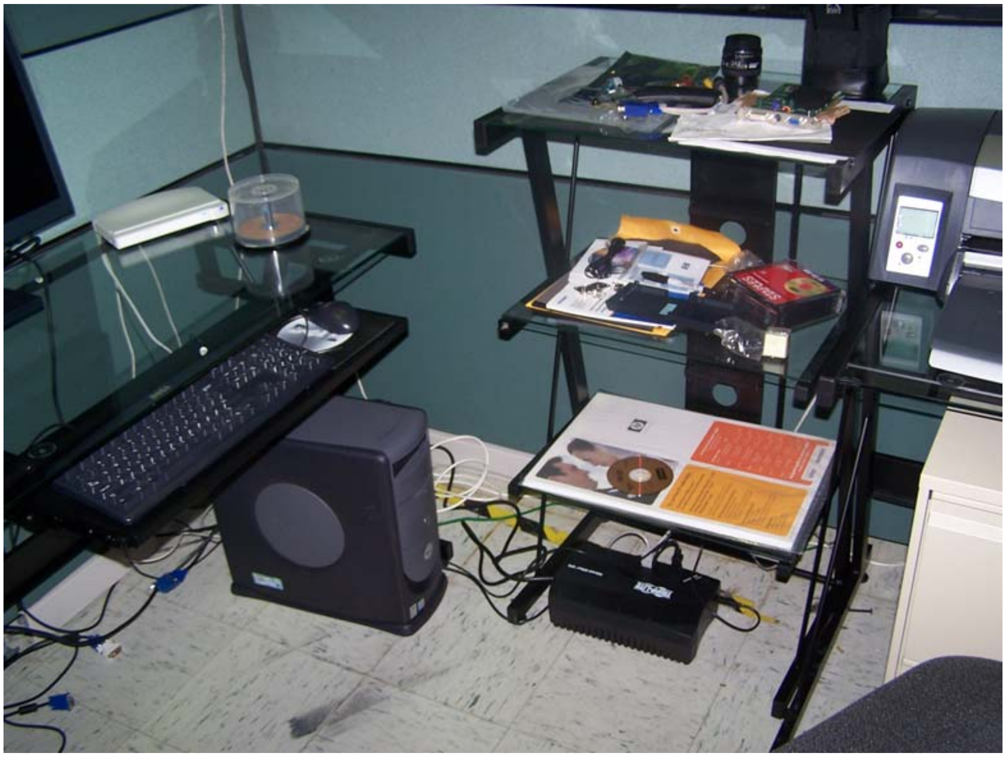


Figure 13. Computer and shelving.

Figure 14. Computer monitors.

Appendix C

MIT NRL INIE Annual Report 2004-2005

INIE ANNUAL REPORT

Period of Performance: 1 September 2004-1 September 2005

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SUMMARY

The decision to implement the Innovation in Nuclear Infrastructure and Engineering Program (INIE) is proving to be a good first step towards ensuring that the United States preserves its worldwide leadership role in the field of nuclear science and engineering. Prior to INIE, university nuclear science and engineering programs were waning, undergraduate student enrollment was down, university research reactors were being shut down, while others faced the real possibility of closure. For too long, cutting edge research in the areas of nuclear medicine, neutron scattering, radiochemistry, and advanced materials was undervalued and therefore underfunded. The INIE program is correcting this lapse in focus and direction and has started the process of drawing a new blueprint with positive goals and objectives that supports existing as well the next generation of educators, students and researchers.

This funding opportunity has been especially beneficial to members of the consortia formed by Massachusetts Institute of Technology Nuclear Reactor Laboratory (MIT), Rhode Island Nuclear Science Center (RINSC), and University of Massachusetts – Lowell Radiation Center (UML), because it has given each of these organizations the opportunity and means to upgrade and improve upon existing instrumentation and equipment necessary to support their research reactor's operations as well as research activities. In addition, although the MIT/RINSC/UMass-Lowell Program has no formal educational components, INIE is having a substantial indirect effect by providing opportunities for increased student usage. Further, INIE funding has had a direct result in increasing by faculty and researchers at each organization thereby strengthening their respective educational and research goals.

A positive impact resulting from the INIE program is the renewed interest in utilization of MIT's 5 MW nuclear research reactor. INIE has supported numerous research initiatives conducted by MIT's Department of Nuclear Science and Engineering (NSE) faculty members and researchers. Funds received during the third year of INIE provided upgrades to the MIT NCT User Facility; design and construction of the MIT post-irradiation examination facility (PIE) for in-core irradiations of both advanced fuels and materials which will ultimately support research for the next generation of power plant initiative; funding for equipment in support of phase contrast imaging research; funding for two MIT graduate students conducting research in the areas of neutron interferometry and neutron capture therapy. In addition INIE funds have supported RINSC research in the area of Gd-NCT and upgrades to University of Massachusetts – Lowell neutron radiography program and the development a distance learning program.

As the only state operated research reactor, RINSC has utilized support from the INIE Program to conduct cutting edge nuclear science based research in the areas of environmental monitoring, cancer research, underwater sensor and biomedical research. Dr. Pszenny of UNH is utilizing RINSC for an extensive NAA study of halogen based environmental transport models. This study is part of the CHAIOS Project that includes a number of universities and government agencies. Dr. John Leith and Dr. Paul Willard of Brown University have been working on developing a gadolinium based compound for

use in neutron capture therapy treatment of brain cancers. They have teamed up with Dr. Practer of the University of Connecticut, Dr. Holden of Brookhaven National Laboratory and the researcher at MIT in these efforts. Dr. Alfred Hanson of the University of Rhode Island has constructed a facility at RINSC for the purpose of developing new methods of underwater detection of weapons of mass destruction and environmental pollution. He has several graduate students involved in these research efforts. BIOPAL, Microinorganics, and RI Consultants utilize the facilities at the center to provide sophisticate nuclear based products. RINSC's mission is to serve the educational, research and commercial needs of the state and the Northeast region. To this end, INIE funds have been of great value in supporting new research, educational and commercial projects.

The UMass Lowell consortium has established digital neutron radiography capability at its research reactor. Digital neutron radiography can provide real-time acquisition of digital images for use in research, commercial activities, and education. Over the past year, UMass Lowell has investigated the efficacy of different imaging systems, and has plans to investigate combined x-ray and neutron imaging techniques. It is noted that neutron radiography effectively requires a neutron radiation field generated by research reactors, and therefore is unique to these facilities. Neutron radiography therefore is an example of the synergy between research reactors and the exploration and application of nuclear science

I. Yearly Report

A. Program Activities

For the purpose of clarity as well as uniformity, program activities are categorized by research activity conducted by the MIT/RINSC/UML consortia members.

A.1 Neutron Capture Therapy

Neutron capture therapy (NCT) for cancer research, directed by Professor Otto K. Harling, is the leading NCT research program in the U.S., and is considered to be among the top in this field worldwide. The neutron facilities at the MITR have been extensively utilized under the DOE (INIE) supported user facility that opens these unique facilities and specialized expertise to researchers both within and outside of MIT. Research groups based at universities and national laboratories from around the country have extensively used the NCT facilities for *in-vitro* and *in-vivo* experiments that are designed to investigate the efficacy of new, tumor-seeking capture compounds and to study the radiobiology of neutron capture therapy.

A.1.1. Educational Enhancements

(a) Title: Design of a Lithium-6 Filter for the Fission Converter Based Epithermal Neutron Beam at MITR-II

Objective: To enhance useful therapeutic penetration of the Fission Converter Beam (FCB) at the MITR for cancer treatments.

Status: Completed. The design of this ^{6}Li filter was completed by an MIT Nuclear Science and Engineering (NS&E) graduate student, Wei Gao, for the thesis component of his M.S Degree. The filter has also been constructed and successfully operated in a routine mode.

Explanation: The FCB epithermal neutron beam was designed and constructed for use in neutron capture therapy treatments of deep-seated cancer. The addition of a 0.8 cm thick ^{6}Li filter was calculated to increase the average energy of neutrons emitted from the FCB without significantly degrading beam quality. This filter was constructed based on the design developed in an M.S. thesis and was then put into operation. Measurements of the beam performance with the ^{6}Li filter have verified the expected dosimetric performance. This filter further enhances the performance of the FCB, which is the highest intensity beam of this type in the world. Substantial collaboration with the Oak Ridge National Laboratories (Y-12) was important to the successful completion of this project.

Note: The graduate student who worked on the project used this research for an M.S. thesis in Nuclear Science and Engineering (completed 2005) and is currently pursuing a Ph.D. in Nuclear Engineering at MIT. Funding for the construction, installation and characterization of the ^{6}Li filter was largely provided by the INIE grant.

(b) Title: High Resolution Quantitative Autioradiography for Boron Neutron Capture Therapy

Objective: To develop a method to image boron in cancerous and normal cells at concentrations relevant to boron neutron capture therapy (BNCT) for cancer and at spatial resolutions, which allow the determination of concentrations at the sub-cellular level.

Status: Continuing. An MIT NS&E graduate student, Thomas Harris, is working on this research project for his Ph.D. thesis and is supported by DOE OBER. The INIE program provides support for all equipment, supplies and services required for this project. He has completed the acquisition of major capital equipment needed for this research using INIE funds. He has made progress in the experimental aspects of his research to produce track etch images from thin tissue sections and in the analytical aspects of his thesis dealing with microdosimetric analysis of the high resolution track etch images of boron in tissue.

Explanation: Of critical importance to the development of improved delivery agents for BNCT is a detailed knowledge of the microscopic distribution of B-10 in the tumor and normal cells. High Resolution Quantitative Autoradiography (HRQAR) is one of only a very few analytical techniques, which has the quantitative resolution combined with adequate spatial resolution to allow estimation of the effectiveness of a boron delivery agent in BNCT. It is for these reasons that we are placing a strong emphasis on developing HRQAR so that it can be used routinely for evaluating the expected effectiveness of boron delivery agents for BNCT. It is planned to add this capability to those currently available to users of the INIE supported "Neutron Capture Therapy User Center."

(c) Title: Development of a Screening Method for the Evaluation of the Effects of New Boron Compounds in Boron Neutron Capture Therapy

Objective: To develop a colorimetric technique for the screening of new compounds for neutron capture therapy.

Status: Continuing**.** An MIT NS&E graduate student Yonsun Chung, who is supported fully by INIE, has developed a 96 well plate colorimetric technique to determine cell survival versus radiation dose with very small amounts of required compound. This is the first phase of this student's Ph.D. thesis research.

Explanation: Chemists are developing new compounds for use in NCT. These compounds are available only in small or limited quantities. A rapid screening technique is needed to test new NCT capture compounds, which are available only in milligram amounts. This research project was undertaken to develop this capability for NCT researchers at the INIE funded MIT NCT User Center.

(d) Title: Selective Irradiation of Vascular Endothelium as a Tool for Elucidating the Mechanism of Radiation Induced Side Effects in Normal Tissues

Objective: To determine if irradiation damage to normal tissue is caused by damage to the microvasculature or by direct damage to the clonogenic cells.

Status: Continuing. This Ph.D. thesis research is in progress. The student, Bradley Schuller, is using this work as part of his requirements for his Ph.D. thesis in the MIT NS&E Department. The INIE program provides essential irradiation and technical support for this work. The remaining financial support for this research is from the Westaway Family Memorial Fund at MIT and a subcontract of an NIH grant to the University of California at San Diego.

Explanation: One of the major unresolved issues in radiation is whether normal tissue damage is caused by damage to the microvasculature or by direct damage to clonogenic cells. This important question is being investigated at MIT by a novel technique to selectively irradiate the microvasculature using the boron neutron capture reaction. The HRQAR technique being developed under INIE support is expected to play an important role in this fundamental study of radiation effects in normal tissues.

(e) Title: Sensitivity of the Normal Rat lung to High LET Radiation

Objective: To determine the sensitivity of normal lung to the high linear energy transfer radiations produced in BNCT.

Status: Continuing. An MIT NS&E student, Jingli Liu Kiger, is completing her Ph.D. thesis research on this research project. Ms. Kiger's research has been primarily supported by the U.S. DOE's office of Biological and Environmental Research. However, important support in mixed field dosimetry and BNCT irradiations was provided through the

INIE project. This research indicates that the fatal lung complications observed in two patients treated in BNCT trials for brain tumors at MIT were not due to BNCT-related scattered radiation dose to the lung.

Explanation: A few years ago two patients, in a DOE-sponsored BNCT trial for brain cancer, experienced fatal lung complications, adult respiratory distress syndrome, (ARDS), after BNCT irradiations. Although the dosimetry used to support these irradiations showed that the expected dose to lung was too low for ARDS a research project using a rat animal model was sponsored by DOE OBER to investigate these two adverse events. This research has recently been completed as described above.

(f) ***Title: Dosimetric Characterization of the M-010 Neutron Beam at the MITR***

Objective: To determine if the M-010 beam would be a useful adjunct to the epithermal beam (FCB) and the M-011 thermal beam at MITR for BNCT studies.

Status: Completed. The dosimetric characterization of the M-010 was completed by Sheel Dandekar, an MIT Physics undergraduate student. This research was carried out as part of MIT's undergraduate research opportunity project (UROP). A complete depth/dose distribution was determined for all the M-10 beam components. The results showed that there was excessive fast neutron contamination, which precludes the M-10 beam from useful application in BNCT irradiations. Substantial support was provided by INIE for this work.

Explanation: The epithermal neutron beam (FCB) has a useful therapeutic depth of approximately 10 cm while the thermal neutron beam (M-011) can reach tumors approximately 4 cm deep and is necessary for some small animal irradiations. However, the maximum absorbed dose for the M-011 beam occurs in skin that is usually radiosensitive and attenuates rapidly with increasing depth. The M-010 beam is less fully thermalized than the M-011 beam and contains some epithermal neutrons, although relatively fewer than the FCB. This type of beam might be useful for irradiations with targets at an intermediate depth and could achieve better skin sparing than the M-011 beam. To investigate this possibility a full dosimetric characterization of the M-010 beam was carried out in a standard phantom for this undergraduate research project.

(g) Title: Measurement of Microdose Spectra at the Fission Converter Beam

Objective: To establish a spectrometry system to measure single event spectra in an epithermal neutron beam and enable physical characterization of a mixed beam as a function of event size. This technique could be developed for intercomparing the quality of different beams as well as providing an independent check on the mixed field dosimetry practices employed in clinical protocols.

Status: Completed. This work was carried out as a UROP project by a graduating senior student, Meir Hershcovitch, in Nuclear Science and Engineering. Capital equipment funds from INIE were essential in enabling this project and were used to purchase the detector, gas filling system and electronics necessary for the system. The student successfully assembled the various components needed for the system including offline data analysis, performed commissioning studies that included measuring known test spectra and culminated with successfully measuring a spectrum in the fission converter beam. This system is now fully established and ready for future use.

Explanation: Dosimetry and treatment planning for BNCT with epithermal neutron beams present unique difficulties to the radiation physicist. Neutrons interact with atoms in a medium to set in motion a spectrum of secondary charged particles that deposit energy through coulomb interactions. The nature of this secondary charged particle spectrum describes not only the resultant absorbed dose but relates to the radiobiological effectiveness of the radiation source. This can be studied experimentally using low pressure proportional counters with a special plastic wall that has the same elemental composition as tissue. The measured absorbed dose may be partitioned into electron recoils (photon interactions), protons (fast and slow), alpha and heavy ion recoil events that are associated with neutron interactions in tissue or biological material. This so-called single event spectrum can be convolved with a radiobiological effectiveness (RBE) versus LET functions to obtain a single parameter of radiation quality as well as simply partitioning the absorbed dose between high and low LET components.

(h) Title: Experiments performed at the MIT NCT User Center during the report year 2004/2005 with reactor beams and staff assistance

1) Evaluation of efficacy of BNCT following convection enhanced delivery (CED) of a boronated monoclonal antibody (C225) plus either i.v. or i.c. administration of BPA+BSH in rats bearing

intracerebral $F98_{EGFR}$ (EGFR positive) gliomas (Professor Rolf Barth et al., Dept. of Pathology, Ohio State University)

2) Study the efficacy of BNCT following i.v injection of VEGF-BSD in rats bearing intracerebral $F98_{EGFR}$ gliomas (Professor Rolf Barth et al., Dept. of Pathology, Ohio State University and Dr J Backer, SIBTEK)

3) To evaluate the efficacy of BNCT following convection enhanced delivery (CED) of boronated nucleoside (N5-2OH) and carboranyl porphyrin H_2TCP in rats bearing intracerebral implants of the F98 glioma (Professor Rolf Barth et al., Dept. of Pathology, Professor Werner Tjarks et al., College of Pharmacy, Ohio State University and Professor Maria da Graca Vicente Dept. of Chemistry, Louisiana State University)

4) Evaluation of carboranyl nucleoside (N5-2OH) as a boron delivery agent following intratumoral injection in nude mice bearing subcutaneous (s.c.) L929 TK1(+) and TK1(-) tumor (Professor Rolf Barth et al., Dept. of Pathology and Professor Werner Tjarks et al., College of Pharmacy, Ohio State University)

5) Uptake and biodistribution studies with two different formulations of boron containing liposomes (Professor Fred Hawthorne et al., UCLA)

6) A study of the feasibility of using liposome-mediated BNCT for the treatment of head and neck carcinoma or metastatic brain tumors by irradiating mice bearing either EMT-6 or SSCVII tumors (Professor Fred Hawthorne et al., UCLA)

7) Effectiveness of boron delivery agents targeted by vascular endothelial growth factor in mice bearing subcutaneous mammary carcinoma (Dr. Joseph Backer, SIBTECH)

8) A series of 5 experiments to assess the mechanism of radiation effects on mouse intestinal crypt cells using the short ranged secondaries produced by the boron neutron capture reaction as a tool for the selective irradiation of the vascular endothelium (Professor Jeff Coderre, NS&E, MIT)

9) Assessment of a boronated porphyrin (BOPP) in combination with BPA in the irradiation of undifferentiated thyroid carcinoma (UTC) in vitro. A study to determine the relative biological effectiveness. (Dr. M.A. Dagrosa National Atomic Energy Commission, Argentina, Professor Stephen Kahl UCSF)

10) Quantitative evaluation of a colorimetric assay to test efficacy of different boron containing compounds (Ms. Yoonsun Chung Ph.D. candidate, NS&E)

11) Seven irradiations of prepared tissue samples for developing HRQAR in the laboratory (Mr. Tom Harris Ph.D. candidate, NS&E)

12) Boron assays of both biological specimens and compound formulations using the prompt gamma neutron activation analysis beam line for numerous users.

13) Comparative measurements of thermal neutron flux in a high intensity epithermal neutron beam using an active scintillator with an optical fiber (SOF) detector and activation foils. (Dr. Masayori Ishikawa Research Center for Nuclear Science and Technology, University of Tokyo, Japan).

A.1.2 Research Innovations

(a) ***Title: International Dosimetry Exchange for Neutron Capture Therapy***

Objective: To compare and summarize the results of clinical BNCT from all worldwide clinical centers.

Status: Continuing. MIT has organized an international dosimetry change for the intercomparison of physical dose measurements at all NCT clinical centers, worldwide. Measurements have been completed at the two centers in the US, MIT and BNL, and at four clinical centers in Europe; Petten, Netherlands; Studsvik, Sweden; Espoo, Finland and Rez, Czech Republic. Measurements are planned for the South American clinical center in Argentina and discussions are in progress to eventually include the two Japanese clinical centers and two new centers in Europe.

Explanation: BNCT clinical trials are expensive and a pooling of worldwide clinical results would greatly accelerate the development of this new treatment modality. In order to utilize the clinical results and experience of all clinical centers, and, thereby, to obtain the largest possible date base for evaluation of BNCT clinical results it is necessary to develop a sound basis for inter-comparison of irradiation doses. Dosimetry in BNCT is complicated compared to photon therapy and there is no international standard for dosimetry practice. To help overcome these difficulties and allow a comparison of all clinical results, MIT has begun an international effort to compare dosimetric measurements made by the staff of the various clinical centers and to obtain complete dosimetric characterization of the epithermal neutron beams at all clinical centers. Most of the support for this research has come from the DOE OBER but INIE support was also needed to carry on this work.

(b) Title: Measuring sensitivity of the normal lung to the high linear energy transfer radiations produced during BNCT

Objective: The BNCT project focuses on measuring the sensitivity of the normal lung to the high linear energy transfer radiations produced during BNCT.

Status: Continuing. New methodology was developed for analysis of the effects of radiation on the lung using a Fourier Transform analysis of the breathing rate pressure change signal. This approach has detected fine structure in the breathing rate data that is missed by the conventional peak-counting approach.

Explanation: The lung is not as sensitive to the radiations produced during BNCT as previously assumed. The data indicate that the fatal lung complications observed in two patients treated with BNCT for brain tumors in the MIT reactor were not due to the BNCT-related scattered radiation dose to the lung. The lung radiobiology data indicate that it is feasible to treat lung tumors with BNCT and provide a basis for the treatment planning needed for such a trial.

(c) Title: Basic Radiation Biology

Objective: One of the major unresolved issues in radiation biology is whether normal tissue damage is caused by damage to the micro-vasculature or direct damage to the clonogenic cells. It has long been assumed that early effects are due to damage to the rapidly dividing stem cell populations and that late effects are due to damage to the more slowly growing blood vessels. However, several recent, and controversial, reports have suggested that microvascular damage is causative in an acute effect: the loss of intestinal crypt stem cells and the subsequent development of the gastrointestinal syndrome.

Status: Continuing. A novel method has been developed for selective irradiation of the microvasculature that allows direct experimental testing of the role of the vasculature in normal tissue radiation response. A boron compound has been prepared that will remain inside the blood vessels. The short path length of the radiations from the boron neutron capture reaction allows irradiation of the blood vessel walls but not the surrounding functional cells.

Explanation: Initial data indicate that damage to the blood vessels are not the cause of the gastrointestinal syndrome. These studies could have significant implications for the development of agents to protect normal tissues during radiation therapy or to treat normal tissues after accidental radiation exposure.

(d) ***Title: Lithium-6 Filtration of the MIT Epithermal Neutron Beam***
Objective: To increase the useful therapeutic penetration of the FCB epithermal neutron beam at MIT.

Status: Completed. A Li-6 filter system has been designed, constructed and fully characterized. The filter improves the penetration of the FCB epithermal medical beam at the MIT Research Reactor. The therapeutic ratio (dose to tumor/dose to normal tissue) using the filter has been increased substantially for deep-seated tumor irradiations e.g. for tumors on the midline of the brain.

Explanation: The epithermal neutron medical irradiation beam at the MIT Research Reactor, the FCB, is able to irradiate deep-seated tumors, e.g., at the midline of the brain, approximately 8 cm deep, with a therapeutic ratio greater than one. However, at these depths the therapeutic ratio is not much greater than one. By increasing the average energy of the beam with a Li-6 filter, it has been possible to increase the therapeutic ratio by 20% at depths of approximately 8 cm. This is an important increase especially for brain irradiations where it is necessary to irradiate to the brain midline. The INIE project support was essential for the completion of this innovation.

(d) ***Title: Development of a Screening Method for the Evaluation of New Boron Compounds in Boron Neutron Capture Therapy***

Objective: To develop a rapid screening method for new boron delivery compounds in BNCT where only milligram amounts of compounds are available for testing.

Status: Please see I.A.1.1(c)

Explanation: Please see I.A.1.1(c)

(f) Title: Selective Irradiation of Vascular Endothelium as a tool for illucidation the Mechanism of Radiation Induced Side Effects in Normal Tissues

Object: Please see I.A.1.1(d)

Status: Please see I.A.1.1(d)

Explanation**:** Please see I.A.1.1(d)

(g) Title: High Resolution Quantitative Autoradiography for Boron Neutron Capture Therapy

Objective: Please see I.A.1.1(b)

Status: Please see I.A.1.1(b)

Explanation: Please see I.A.1.1(b)

A.1.3 Infrastructure Improvements

(a) Title: Lithium-6 Filtration of the MIT Epithermal Neutron Beam

Objective: To improve the useful penetration of the MIT epithermal neutron medical irradiation beam facility (FCB).

Status: Completed: This infrastructure improvement has been completed with INIE funding.

Explanation: Please see I.A.1.1 and I.A.2.2.

(b) Title: Reconstruction of the Thermal Neutron Beam for BNCT Irradiations

Objective: To reconstruct a high quality thermal neutron beam in the basement medical irradiation room of the MIT Research Reactor and to update and modernize the beam control system and irradiation room.

Status: Completed: Using INIE funds the upgrade of the MITR based thermal neutron beam irradiation facility was completed.

Explanation: The MITR has a vertical beam port below the core which projects a neutron beam into a shielded medical room. Ten years ago this beam had been converted to an epithermal beam for use in the original epithermal neutron based clinical trials at MIT. With the completion of the high intensity and high quality fission converter based epithermal beam, on the main beam tube floor of the MITR, this vertical beam was reconstituted as a high intensity and high quality thermal neutron beam. Support for this reconversion was provided by US DOE OBER. However, the costs associated with updating and modernizing the reconstructed thermal beam control system and the refurbishing of the medical irradiation room were not completely covered by the OBER funding. INIE funds were needed to fully modernize the automated beam shutter control system and to improve shielding and the appearance of the shielded medical irradiation room.

(c) Title: High Resolution Quantitative Autoradiography

Objective: Please see I.A.1.2

Status: Completed**.** Several major pieces of capital equipment were purchased with INIE funds. These included optical microscopy equipment with a high resolution computer controlled stage, a freezer for tissue

samples, a cryogenic microtome and a computer and image analysis software needed for analysis of tracks in the autoradiography image.

Explanation: Please see I.A.1.2

(e) Title: The MIT NCT User Center

Objective: To develop and operate a user center, at the MIT Research Reactor, which provides BNCT type neutron irradiations and technical support to MIT as well as non-MIT researchers who do not have access to neutron beams.

Status - Continuing: This center has continued successful operation in this last project year. Small animal and cell culture irradiations were performed in 13 different experiments that usually involve multiple runs. Mixed field dosimetry measurements and computations as well as assistance with experiment design and execution was also provided to the users of the NCT User Center.

Explanation: Specialized neutron facilities for neutron capture therapy irradiations are generally only available in a few locations. With the closure of the Brookhaven Medical Research Reactor a number of BNCT researchers were left without neutron irradiation facilities required for their research in radiobiology and capture compound development. To meet this need, the MIT BNCT research group has established an NCT

User Center to assist MIT as well as non-MIT researchers who require specialized neutron irradiations, mixed field dosimetry and experimental design support. The INIE project has provided support needed to operate this center.

A.1.4 Intra-consortium Integration

(a) Title: Rhode Island Nuclear Science Center (RINSC)

Objective: To assist RINSC in the development of a research program in neutron capture therapy.

Status - Continuing: The MIT neutron capture therapy research group has hosted research staff from RINSC and their collaborators on three separate occasions at the MIT Nuclear Reactor Laboratory. Technical assistance needed for the start-up of the RINSC program in BNCT was provided on each occasion by MIT. The RINSC group was also made fully aware of all capabilities and support that is available through the MIT NCT User Center. MIT has also helped RINSC staff to implement mixed field dosimetry for BNCT by detailing the necessary equipment and outlining procedures for acquiring and analyzing data.

Explanation: RINSC operates a 2MW research reactor for various research activities. RINSC has developed an interest in neutron capture therapy research involving a synthetic chemist from Brown University and staff at The University of Rhode Island. The BNCT research program at MIT is currently the leading US group in this field and with INIE support is in a position to assist RINSC with their efforts to develop a BNCT research program.

A.2. Neutron Interferometry

This portion of the MIT INIE Program is under the direction of Professor David Cory. He is assisted by a graduate student, Dmitry Pushin who is supported by INIE funds. The MITR staff person who interfaces with this project is Mr. Thomas Newton. Significant leveraging of funds received through INIE in support of this project has been obtained through informal cooperation with NIST.

A.2.1 Research Innovations

The objective of this research is to develop the theory, experimental apparatus, and methods of reciprocal encoding of spatial information for neutron imaging and incoherent scattering.

(a) ***Title: Reciprocal Space Neutron Imaging***

Objective: Develop and realize phase contrast imaging with neutron interferometer.

Status: Continuing

Explanation: Neutron interferometer can be used as a reciprocal space, spatially coherent imaging device to improve image resolution while maintaining high contrast. In these studies the detector integrates over the entire beam and the spatial distribution of the neutron scattering function for a sample placed in one path of the interferometer is created internally in the interferometer via comparison to a phase grating placed in the other leg of the coherently split neutron beam. This method does not require a 2-D detector and thus has the potential to improve the spatial resolution significantly compared to the current limit of tens of micrometers.

In the previous year the theory was developed and simulations performed of the proposed experiment for one-dimensional imaging, performed test experiment to show that we can code the beam by using fussed silica wedge, and for the first time, a reciprocal space image of the test sample was made. In the upcoming year there are plans to perform a 2-dimensional reciprocal space image of the test sample.

(b) ***Title:*** ***Neutron beam coherence and application for small angle scattering***

Objective: Study of vertical coherence of the neutron beam. Developing of the Neutron Fourier Spectroscopy with neutron interferometer.

Status: New

Explanation: By vertically shifting the beam in one arm of the interferometer with respect to the other we probe the spectra of momenta of neutrons in the incoming beam. If the entrance beam scattered off of a sample prior to entering the interferometer we can measure the scattered momentum distribution of neutrons. The difficult part of this experiment is to shift the beam from its initial path. We have developed a novel approach using two matched wedges. By separating the wedges we can shift the beam in-situ without losing the contrast. Study of the vertical coherence of the neutron beam using interferometer and to map the momentum distribution of the neutron beam by Neutron Fourier Spectroscopy are planned for upcoming year.

A.3 Phase Contrast Imaging

The purpose of this research is to demonstrate the practicality of phase contrast thermal neutron imaging using new neutron imaging detectors. This project is under the direction of Dr. Richard Lanza. The MIT NRL staff person who interfaces with this project is Mr. Edward Lau. INIE funds have supported two graduate students (Vivien Leung and Antonio Damato) as well as one undergrad, David Jeria.

A.3.1 Research Innovations

- ***Title: Development of the beam and detector system for producing phase contrast images***

  Objective: Utilization of the MITR to demonstrate phase contrast radiography in order to detect very small (~10 micron) internal cracks in metals and also to directly measure the internal stress of fabricated materials. This technique has the potential to detect much smaller changes in materials from phase shifts than is practical with transmission methods, which detect only absorption. In principle, for a given neutron flux, the sensitivity of phase contrast may be hundreds to thousands of times more sensitive than conventional radiography for the detection of small cracks and thus it will greatly enhance the usefulness of small reactors for non-destructive testing of components.

  Status: Continuing

  Explanation: Traditional neutron radiography relies on the absorption of neutrons to create images. Phase contrast imaging is fundamentally different in that it uses the wave nature of neutrons to produce images, which are the result of changes in the phase of neutrons when passing through materials. We have acquired two new, all electronic detection systems: a Fuji BAS2500 imaging plate system and a Thales FlashScan33. Initial measurements were made using an existing beam line and although performance has not been completely characterized, it appears that the resolution specification of 50 microns appears to be obtained. The major limit to this system lies in the large data files (60 Mb) and the relatively slow readout times, ~5 min for images taken at full resolution (50 micron pixels, 16 bit). The Thales FlashScan33 detector is still being evaluated but appears to also meet specifications for resolution. This detector is 30 x 50 cm with 127 micron pixels. The system uses a Gadox (gadolinium oxysulfide) screen as a neutron detector. Its primary advantage in our application is the faster readout, approximately 1.5 s for a full screen image. Characterization of either detector is not complete with respect to MTF and noise characteristics. We have fabricated and installed a new beam line on MITR which can be used for both phase contrast imaging and also for three dimensional imaging using tomography. As part of the beam design, we have investigated a new approach to imaging based on coded sources where images from multiple pinhole sources are combined to form a three dimensional image. If practical, this will greatly enhance sensitivity for the use of radiography in small reactors and perhaps even allow the use of portable neutron sources for high-resolution imaging.

A.4 Nanofluid Applications in Nuclear Energy Systems

A.4.1 Research Innovations

Dispersions of nano-sized (1-100 nm) particles in water or other base fluid are known as nanofluids. Nanofluids are attractive because the presence of the nanoparticles enhances energy and mass transport considerably. In particular, the heat transfer coefficient increases appear to go beyond the mere thermal-conductivity effect, and cannot be predicted by traditional pure-fluid correlations. Pool-boiling studies show that water-based nanofluids with low concentrations (<0.001% vol.) of nanoparticles can have significantly higher critical heat flux (CHF) than pure water. Personnel who participated in the nanofluid research include: Lin-wen Hu (Research Staff, NRL); Jacopo Buongiorno (Assistant Professor, NSE); Wesley Williams (grad student, PhD candidate); Sung Joong Kim (graduate student, PhD); Eric Forrest (undergraduate); Bao Troung (undergraduate). The INIE funding allocated for the nanofluid program in FY 2005 was used to purchase parts/equipments for the following experiments:

a) ***Title: Single-phase heat transfer loop***

Objective: This is a pressurized forced convection loop which is designed and constructed by MIT student and staff to investigate nanofluid heat transfer and pressure drop characteristics in laminar and turbulent flow regimes.

Status: Continuing

Explanation: Construction of this loop is near completion.

b) ***Title: Critical Heat Flux (CHF) loop***

Objective: The CHF facility is being constructed to obtain CHF data for different types of nanofluids which do not currently exist in the literature.

Status: Continuing

Explanation: Since CHF is significantly affected by the heated surface, actual Zircaloy cladding specimens are provided by PWR vendors for this experiment. This loop is under construction and is expected to be completed by the end of the year.

c) ***Title: Pool boiling screening experiment***

Objective: This apparatus was initially put together for a class room demonstration of pool boiling.

Status: Continuing.

Explanation: It was modified to test the pool boiling enhancement using nanofluids. Initial results were obtained for alumina nanofluid.

A.5 Advanced Materials/In-Core Loops

The NRL has a strong materials and in-core loop program that supports research in the areas of advanced materials and advanced fuels which are necessary for both existing and Gen-IV reactors. The MITR offers a unique technical capability that involves the use and installation of in-core loops that replicate PWR/BWR conditions to study the behavior of both advanced materials and micro-particles of advanced fuels for Gen-IV reactors.

The MITR is arguably the best suited university reactor for carrying out such basic studies because of its relatively high power density (similar to an LWR), the capability to control the chemistry and thermal conditions to reflect prototypic conditions, its easy-access geometric configuration, and space for up to three independent irradiation tests. While similar studies could in principle be carried out at certain national laboratory reactors such as the ATR, the costs would be far greater. The reason is that large national laboratory reactors are optimized for large scale, fully integrated tests and not the smaller scale, faster turnaround basic studies needed at the earlier stages of research. Access to the high flux in the core is also much more difficult in the larger reactors because of pressurization of the core. The MITR is unpressurized and the core is only about 12 feet below the lead reactor lid.

A.5.1 Research Innovations

(a) ***Title: Advanced Materials Testing Facility (AMTF):***

Objective: INIE continues to contribute significantly to the design and formation of a new state-of-the-art in-core advanced materials test facility at the MITR that supports essential research for the development of the next generation of power nuclear reactors known as Gen-IV reactors. This facility will analyze the:

- The lifetime behavior of certain materials, such as those used for cladding and structural purposes, which are immersed in a radiation environment is critical in determining the ultimate desirability of several proposed reactor concepts.

- The robustness and structural integrity of certain advanced fuels, such as the particles in pebble bed reactor pellets, need to be characterized in detail before such fuels are deemed desirable and acceptable for a next generation reactor.

- New materials and new fuel types are required that have not as yet been fully characterized with respect to various performance criteria.

Status: Continuing.

Explanation: The combination of the AMTF and MITR will be ideal for carrying out the more basic components of the research on materials in a radiation environment. The MITR offers good geometric access and room for up to three independent irradiation tests, it has a sufficiently high in-core flux to simulate accurately the radiation environment in PWR/BWR power reactors, and there is an ability to control the chemistry and thermal fields to reflect prototypic conditions. A facility such as this would complement the testing capabilities of large national laboratory reactors such as the Advanced Test Reactor (ATR), which are best suited for fully integrated experiments. In most cases the MIT Advanced Materials Test Facility would be relatively inexpensive for basic research projects, saving a factor in the range of 3 – 10 in cost over doing the same type of basic research at a large national laboratory reactor. On the other hand, the large reactors are essential for the integrated testing because those types of experiments cannot be carried out at a university research reactor.

(b) ***Title: High Temperature Irradiation Facility:***

Objective: This project is under the direction of Professor Ronald Ballinger, Professor Mujid Kazimi, and Dr. Gordon Kohse. The high temperature irradiation facility is designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs.

Status: Continuing

Explanation: This facility will be a valuable test facility for high temperature resistant materials research. Design work for this loop has been completed as part of the INIE program. Approval of the Reactor Safeguards Committee was received in May, 2005. Construction of this facility is near completion and the in-core irradiation is planned. Two types of materials will be tested during the initial irradiation – Graphite and SiC composite specimens provided by KAPL, and non-fueled coated particles from a gas reactor fuel manufacturer.

An initial run is planned to test the facility and verify the temperatures that can be achieved at the sample positions. If the projected temperatures are reached, the irradiation will continue for approximately eight weeks with a variety of silicon carbide and non-fueled TRISO particles specimens at temperatures from about 1000 to 1400 ºC.

(ORNL is currently developing a similar facility at their test reactor HFIR). Researchers from national laboratories, such as the INL, have expressed interests in using this facility, if it is demonstrated successfully.

(c) ***Title: High Performance Fuel Design for Next Generation PWRs:***

Objective: The goal of this project is to develop and optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins. It is under the direction of Professor Mujid Kazimi, Professor Pavel Hejzlar, and Dr. Gordon Kohse. Several students from the Nuclear Science and Engineering Department engaged in work at the NRL or in analysis related to this project. These include four undergraduates, David Carpenter, Dwight Chambers, Philip Dawson, and Kareem Reda as well as five graduate students, Zhiwen Xu, Yi Yuan, Paolo Morra, Dandong Feng, and Tyler Ellis.

Status: Continuing.

Explanation: This year, the INEI funding was used to equip a new hot cell at the lab to enable the examination of the results of irradiation of innovative fuel design for PWRs. The irradiation of two annular segments of uranium dioxide in the reactor was undertaken during the year. The 7 cm segments were irradiated for up to 5 MWd/kg HM then pulled out and allowed to cool off. They were transported from the storage location to the hot cells, one at a time, and inserted in a specially built shielded collimator. Measurements of 24 emitted gammas enabled the characterization of the degree of fuel swelling and fission gas release. The annular fuel operates at very low temperatures compared to the current PWR solid cylindrical fuel. However, the fuel is manufactured by vibrational packing of powder, which may increase the ability to relocate and to release fission gases. Thus the measurements would help in the assessment of the suitability of this manufacturing process for commercial deployment in the future in PWRs. The annular fuel geometry, if fuel performance is judged satisfactory, would enable raising the power density in the fuel, thus allowing more power to be extracted from the core.

This is the first time that a new fuel design is examined in a university research reactor. The established of this research capability enables future examinations of advanced fuels to be done, with benefits to the national industry and to the government program on advanced fuel cycles (AFCI).

(d) Title: Shadow corrosion experiment

Objective: To investigate corrosion mediated by a radiation field. This project is under the direction of Professor Ronald Ballinger.

Status: Completed.

Explanation: Fuel cladding corrosion and subsequent hydrogen pickup are among the most critical phenomena that limit in-reactor exposure. As fuel burnup is pushed to higher levels, general and localized corrosion phenomena have assumed an even more important role. A localized corrosion phenomenon, labeled "shadow corrosion," is the most recent type of corrosion to be recognized as a significant concern. Several occurrences of local corrosion enhancement of zirconium-base alloys in proximity to other components have been observed. This corrosion enhancement comes in the form of a shadow of the metal component in proximity, hence its name, "shadow effect."

(e) ***Title: Advanced Light-Water Reactor Fuel Cladding Development***

Objective: Investigation of the corrosion behavior of both pre-irradiated and unirradiated cladding as well as a study of corrosion rate laws and hydrogen pickup kinetics. The project is under the direction of Professor Ronald Ballinger.

Status: Continuing

Explanation: Existing light-water reactors use zircalloy clads. Research is ongoing to identify improved alternatives. One possibility is ceramic cladding. Another is Zr-Nb based materials. These may offer an advantage in reducing shadow corrosion. Research would focus on developing corrosion and hydrogen pickup models under conditions of high fuel burnup.

(f) ***<u>Title:</u>* *Investigation of Electro-Chemical Potential (ECP) Effect on Shadow Corrosion***

<u>Objective:</u> To measure the electro-chemical potential (ECP) difference between Zircaloy and Inconel under neutron and gamma irradiation conditions. This project is under the direction of Professor Ronald Ballinger.

<u>Status:</u> Continuing

<u>Explanation:</u> This loop was installed and operated in June 2004 and was removed in July 2004. This experiment is the continuation of the shadow corrosion study performed previously.

A.5.2 Infrastructure Improvements

(a) Title: Post-Irradiation Examination Facility

<u>Objective:</u> To support the MITR's Advanced Materials Test Facility

<u>Status</u>: Continuing

<u>Explanation:</u> Construction of the PIE facilities include the following: two top-entry hot cells with manipulators (1000 Ci capacity each), a lead shielded hot box (20 Ci capacity) with manipulators, an overhead crane at 3-ton and 20-ton capacity, and several transfer casks. There is also a fracture toughness testing capability available to support irradiation testing. Hot cell facilities are available that can accommodate a Charpy testing machine that could be used for on-site testing of irradiated materials. The PIE facilities are currently being refurbished with DOE's INIE funds. Additional equipment upgrade/purchase to support PIE, such as manipulators, alpha detectors, ventilation, etc., are also being funded by DOE's INIE.

A.5.3 Partnerships with DOE labs, colleges, universities, utilities, and other public/private entities

(a) Title: SiC Duplex Clad Irradiation

<u>Objective:</u> This project, which is under the direction of Dr. Gordon Kohse and Professor Mujid Kazimi, involves the production and testing of candidate duplex SiC/SiC composite cladding materials for Light Water

Reactors (LWRs). These materials have potential advantages over conventional metal alloy cladding materials in both improved safety margin and higher burnup. Irradiation testing in prototypical PWR and BWR coolant conditions will be performed at the MITR. Post-Irradiation Examination (PIE) is planned to measure weight loss, thermal conductivity changes, mechanical property tests and scanning electron microscopy. The irradiation testing and some of the PIE are planned for the MIT-NRL using the MITR's in-core loop facilities and hot cells.

<u>Status</u>: Continuing

<u>Explanation</u>*:* Although this project was not initially funded or supported by INIE, it does represent a significant leveraging effect because of the increased capabilities resulting from the upgrades to the MITR and the Advanced Material Testing Facility that made it possible for the research to be done at the NRL**.** A workshop on SiC cladding applications for advanced nuclear reactors was held on May 5, 2005, to present initial out-of-pile testing results of SiC cladding development, and to discuss the future testing development. This workshop was sponsored by Gamma Engineering Inc., Westinghouse Electric, Nova Tech, and co-hosted by MIT Center for Advanced Energy Systems (CANES) and Oak Ridge National Laboratory.

Initial funding has been received to design and plan for the upcoming irradiations. Funding for the initial 3-month irradiation has been allocated and additional funding is being sought to extend the irradiation test to 12 months. The SiC cladding irradiation is scheduled to begin in December 2005.

A.6 Rhode Island Nuclear Science Center (RINSC)

A.6.1 <u>Research Innovations</u>

(a) ***Title: Gadolinium Cancer Research Project***

<u>Objective</u>: This program activity addresses the critical need for a better delivery agent for neutron capture treatment of brain tumors. All research reactors would benefit from a successful protocol for treatment of such tumors. Dr. Leith and Dr. Williard have been investigating this problem for several years and have completed trials using tumor cells provided by Dr. Practer. The next step includes animal trials which will be conducted at MIT. Dr. Norman Holden and his group from Brookhaven National Laboratory have been of great assistance in characterizing the thermal column and providing technical support for the project. Dr. Carl Ott of Purdue University has spent the last eight years designing a new NCT epithermal filter for the RINSC reactor thermal column with the technical assistance of Argonne National Laboratory. He is currently completing the construction plans for this filter which would be a significant infrastructure improvement.

Status: Continuing

Explanation: From these results will derive response curves on the dose-dependent changes in these endpoints. The data on radiation effects on dispersing cells will be compared to results from the primary tumor. From the data obtained, data will be derived on the relative biological effectiveness of thermal neutron irradiation as compared to photon irradiation for the migration, proliferation, tumor volume, hypoxia, and tumor cell survival endpoints. Implanted 9L/LacZ and C6/LacZ neoplasms will be treated with Gd-Pc at a given time post-implantation using a known Gd-Pc concentration as previously determined. As the extent of tumor cell dispersal in the brain, the proliferative and hypoxic status of these dispersing cells as well as the growth rate of the primary tumor and the clonogenic cell survival of tumor cells have previously been defined. These studies will determine if Gd-Pc affects cell dispersal rates, cell proliferation, cell hypoxia, and growth or cell survival of tumor cells *in vivo* throughout the brain. In this regard, it is noted that it is already determined that Gd-Pc decreases the cell migration rates *in vitro*. Also note that these studies do not involve thermal neutron irradiation. Then, adding thermal neutron and photon doses already studied in tumor-bearing animals, thermal neutron irradiation with Gd-Pc will be combined to investigate potentiation of these biological effects by the decay of ^{157}Gd-Pc. The data will be used to determine a dose modification factor for Gd-Pc. Animals that survive implantation of brain tumors with subsequent treatment (neutrons, photons, with and without gadolinium-phthalocyanine application) will be kept for 6 months posttreatment to assess "late" effects.

(b) Title: Environmental Modeling Project

Objective: New activities for this year include an aerosol analysis program based on extensive field samples. Between July 6 and August 4, 2005 aerosols less than 2.5 micrometers in diameter (PM2.5) were collected during 53 12-hour periods at sampling sites on Appledore Island, ME and in rural Durham, NH. The 2.5 micrometer size limit is important because it is the approximate "cut size" of the human respiratory system. Particles larger than this approximate size are removed in the mouth and throat. Only the smaller ones can make it into the lungs where they can potentially be trapped and cause problems. (Cancer, for example, if the particles contain carcinogens.)These samples and associated blanks and standards will be analyzed for approximately 25 elements by neutron activation at RINSC starting in September. The resulting elemental compositions will be analyzed with multi-variate statistical techniques to "fingerprint" and thereby assess the origins of the aerosols.

Status: Continuing

Explanation: The previous years sample analysis program resulted in valuable data on how halogens influence the chemistry of North American pollutant outflow. Specifically, the base model for ozone depletion has a much closer fit to observed data when the halogen depletion corrections are applied. RINSC has a long history of environmental research using neutron activation analysis for highly accurate, multi-element analysis of air, water and soil samples. INIE funding was utilized to upgrade the center's counting systems to handle the massive number of environmental samples processed last year. This year's work requires additional upgrades to automate a counting system to handle long counting times. Over thirty years of environmental NAA research has resulted in the URI Graduate School of Oceanography awarding many advanced degrees in atmospheric chemistry, geology, and ocean engineering. These graduates utilized the reactor in their research and they return to RINSC with their students to continue using NAA for new research initiatives.

(c) Weapons of Mass Destruction and Environmental Pollution Sensor Research

Objective: Dr. Alfred Hanson of the URI Graduate School of Oceanography is utilizing six of his graduate students from the Chemical Oceanography Department in the research and development of underwater sensors at RINSC.

Status: Continuing.

Explanation: There are two general applications for the submersible chemical analyzers that are the focus of the research effort:

- **Environmental Pollution:** Water quality monitoring of chemical and biological contaminants such as nutrients, trace metals, coliform bacteria, and radiochemicals (NOAA, EPA, ONR).

- **Coastal Security – Ocean Observation Systems:** Detection, tracking and source localization for chemicals associated with weapons of mass destruction (WMD) submerged in coastal waters. These WMD chemicals include those leaking from unexploded ordinance (i.e. submerged mines leaking TNT) and radiological isotopes associated with submerged nuclear devices or contamination (i.e. uranium series nuclides, alpha, beta, gamma radiation). (DOD, NAVY, NUWC, USCG)

A.7 University of Massachusetts – Lowell

A.7.1. Education Enhancements

(a) Title: Virtual Console

<u>Objective</u>: UMass Lowell plans to establish a virtual console that will be integrated with the digital neutron radiography facility.

Status: New project.

<u>Explanation</u>: The virtual console will allow students and researchers to engage in digital neutron imaging without entering the research reactor. This initiative therefore will reduce security concerns and eliminate personnel radiation exposures. The project will begin in the final year of funding.

A.7.2. Research Innovations

(a) ***Title: Investigation of CMOS Line Camera***

<u>Objective</u>: UMass Lowell has collaborated with *Envision Corporation* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate a CMOS line camera that contains the inorganic scintillator gadolinium-oxysulfide for use in neutron radiography.

<u>Status</u>: Ongoing project.

<u>Explanation</u>: The CMOS line camera as manufactured by *Envision* originally was designed for x-ray imaging. Upon investigation, we have determined that the camera is suitable for neutron imaging also. We currently are considering incorporating a CMOS line camera into the digital neutron radiography facility.

(b) ***Title: Dual X-Ray and Neutron Imaging Capability***

<u>Objective</u>: UMass Lowell has plans to investigate the efficacy of combining x-ray capabilities into the digital neutron radiography facility.

<u>Status</u>: New project.

<u>Explanation</u>: We are considering adding an x-ray imaging capability to provide an additional investigative tool for conducting research in imaging. The contrast of both x-ray and neutron produced images may prove useful for assessing object properties. The x-ray imaging component also would provide infrastructure improvement.

A.7.3. Infrastructure Improvements

(a) ***Title: Digital Neutron Radiography Facility***

<u>Objective</u>: UMass Lowell planned to establish a reliable digital neutron radiography facility.

<u>Status</u>: Completed project.

<u>Explanation</u>: The infrastructure for the digital neutron radiography facility has been completed. The existing facility is adjacent to the thermal column on the first floor of the research reactor, and constitutes the major infrastructure improvement for this research. It is noteworthy that essentially all of the components that comprise the digital neutron radiography facility, exclusive of the thermal column, were fabricated or acquired using INIE funding.

A.7.4. Intra-Consortium Integration

(a) **Title:** Regional Neutron Radiography

Objective: UMass Lowell will provide its digital neutron radiography capability to consortium members, businesses, and other research institutions in the northeast region.

Status: New project.

Explanation: UMass Lowell's digital neutron radiography capability is unique in the northeast region. Therefore, we plan to make that capability available to other consortium members, as well as regional businesses and research institutions. This activity also supports UMass Lowell's mission of providing the University's expertise to enhance the regional economy.

B. Funding Allocation and Execution

Tables I.A and I.B summarize generally and program specific how the MIT INIE funds were expended during the third year of this program.

Table I.A
Oct 1'04 - Aug 30 '05

	ACTUALS TOTAL	PROJECTED SEPT.	TOTAL YEAR
Personnel	138,341	12,576	150,917
RA (grad)	46,243	4,560	50,803
Undergrad	-		-
eb	43,086	3,917	47,003
Travel	4,500	409	4,909
M&S	33,302	3,027	36,329
Rx Use	41,425	54,000	95,425
Equip	221,415	20,000	241,415
Tuition	29,920	3,948	33,868
UML/RINSC	139,938	12,722	152,660
Subtotals	**698,170**	**115,160**	**813,330**

Table I.B: INIE REPORT FOR YEAR 3 OCT 1, 2004 - SEPT. 30, 2005

	NRL Gen. (6894190) Bernard	Pumping Sys. (6896109) Bernard	In-Core Mat. & Chem (6894191) Ballinger	Fabr. Eq. High Temp (6896729) Ballinger	Advanced Fuels (6894192) Kazimi	Neutron Interferometry (6894194) Cory	Phase Contrast Imaging (6894195) Lanza	Fabr. Eq. Beam Plug (6896216) Lanza	NCT (6894196) Harling	Fabr. Eq. Lithium Filter (6895664) Harling	Fabr. Eq. Basement (6896361) Harling	Fabr. Eq. Irradiation Jig (6898559) Harling	Nano Fluid Heat Transfer (6896898) Hu	Fabr. Eq. In-Core Loop (6896974) Hu	Fabr. Eq. In-Core Loop (6897388) Hu	Fabr. Eq. Transient Hot Wire Probe (6898593) Hu	TOTAL
Cumulative spending as of 9/30/04																	
Personnel	1,512		71,388		41,589		22,199		119,146								255,834
RA						46,963	38,775		40,775								126,513
Undergrad							354		45								399
eb	486		20,629		12,198		6,542		28,649								68,504
Travel						4,909	1,476		1,772								8,157
M&S	1,999		1,116		1,741	275	562		49,324								55,017
Rx Use						1,553	759		43,142								45,454
Equip	91,279	8548	18,006				105,139	5,815	90,403	12,526	529						332,245
Tuition						21,971	15,195		17,065								54,231
UMR/RINSC	227,215																227,215
			111,139														111,139
Cumulative spending as of 8/30/04																	
Personnel	1,512		100,511		76,498		39,031		176,623								
RA						69,466	38,775		64,515								
Undergrad							354		45								
eb	486		30,248		23,670		12,198		44,988								
Travel	4,500					4,909	1,476		1,772								
M&S	10,161		5,567		2,628	275	571		67,055				2,062				
Rx Use			4,900			1,553	759		79,667								
Equip	126,979	8,548	24,372	99,540			105,549	29,566	111,991	12,526	10,923		1,670	15,157	6,839		
Tuition						36,931	15,195		32,025								
UMR/RINSC	367,153																
subtotals	*510,791*	*8,548*	*165,598*	*99,540*	*102,796*	*113,134*	*213,908*	*29,566*	*578,681*	*12,526*	*10,923*	*-*	*3,732*	*15,157*	*6,839*		
YR 3 11 months, Oct 1'04 - Aug 30 '05																	
Personnel	-	-	29,123	-	34,909	-	16,832	-	57,477	-	-	-	-	-	-	-	138,341
RA	-	-	-	-	-	22,503	-	-	23,740	-	-	-	-	-	-	-	46,243
Undergrad	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
eb	-	-	9,619	-	11,472	-	5,656	-	16,339	-	-	-	-	-	-	-	43,086
Travel	4,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4,500
M&S	8,162	-	4,451	-	887	-	9	-	17,731	-	-	-	2,062	-	-	-	33,302
Rx Use	-	-	4,900	-	-	-	-	-	36,525	-	-	-	-	-	-	-	41,425
Equip	35,700	-	6,366	99,540	-	-	410	23,751	21,588	-	10,394	-	1,670	15,157	6,839	-	221,415
Tuition	-	-		-	-	14,960	-	-	14,960	-	-	-	-	-	-	-	29,920
UMR/RINSC	139,938	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	139,938
Subtotals	**188,300**	**-**	**54,459**	**99,540**	**47,268**	**37,463**	**22,907**	**23,751**	**188,360**	**-**	**10,394**	**-**	**3,732**	**15,157**	**6,839**	**-**	**698,170**

II. Cumulative Report

1. Massachusetts Institute of Technology

A. Statistics

Massachusetts Institute of Technology	**ACADEMIC YEAR**				
STATISTICS	04 - 05	03-04	02-03	01-02	00-01
Education Related					
Tenure track faculty (FTE's)	15	14	16	16	17
BS enrollment	49	35	26	18	18
MS enrollment	14	21	23	27	35
PhD enrollment	86	90	84	80	82
BS graduates	9	4	5	6	2
MS graduates	26	23	15	17	17
PhD graduates	15	13	15	11	20
Research Related					
Research faculty (FTE	15	14	16	16	17
Technical support staff (FTEs)					
Refereed publications (number)					
Non-INIE research expenditures	$6.2M	$6.9M	$4.9M	$4.3M	$3.5M
Non-INIE research awards					
Reactor Related					
Capacity (total potential hours)	8760	8784	8760	8760	8760
Actual Capacity (4.5 MW hrs)	6123	4237	6448	7067	7738
Utilization – education (total hours)	652	393	526	404	546
Utilization – research (total hours)	3062	2569	3224	3534	3869
Utilization – training (total hours)	2449	1695	2579	2827	3095
Utilization – commercial (total hours)	6123	4237	6448	7067	7738

Note: MIT INIE funds are primarily used for research projects being conducted by faculty, researchers, and students from the MIT Nuclear Engineering and Science Department (NSE) ; however, there is new interest by MIT's Physics Department to utilize the MIT Nuclear Reactor Laboratory's 5 MW research reactor (MITR) and as a result of the funding opportunity provided by INIE, students from the Physics Department have and plan to conduct research utilizing this unique research facility.

B. Educational Enhancements

The first step towards strengthening university nuclear engineering programs across the U.S. is the education of the next generation of nuclear engineers and to this end INIE is proving to be a major catalyst in attaining that goal. This is evident by the influx of undergraduates enrolling in MIT's Nuclear Engineering and Science Department as well as the increased number of graduate students pursuing their MS and Ph.D. degrees. The following is a list of projects and student involvement:

- The INIE supported Neutron Capture Therapy User Center has enabled professors, post-doctoral research scientists and graduate students to carry out research in the field of neutron capture therapy for cancer. Table II.A provides a statistical summary of MIT education enhancement for a five year period, academic years 00-01 through 04-05. INIE support was essential for much of the education related research in 02-03 through 05-06.

- Several students from the Nuclear Science and Engineering Department engaged in work at the NRL or in analysis related to the High Performance Fuel Design for Next Generation PWRs project. These include four undergraduates, David Carpenter, Dwight Chambers, Philip Dawson, and Kareem Reda as well as five graduate students, Zhiwen Xu, Yi Yuan, Paolo Morra, Dandong Feng, and Tyler Ellis. The goal of this project is to develop and optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins and is under the direction of Professor Mujid Kazimi, Professor Pavel Hejzlar, and Dr. Gordon Kohse.

- Vivian Leung, a graduate student from the Nuclear Science and Engineering Department received support for her participation in the Phase Contrast Imaging project which is under the direction of Dr. Richard Lanza who is working on the development of the beam and detector system for producing phase contrast images using a cooled CCD imager combined with a neutron scintillator.

C. Research Innovations

The funds received through INIE have enabled several MIT Nuclear Science and Engineering Department faculty members and researchers to initiate new and expand upon existing research activities that would otherwise have not been able to be pursued, such as Phase Contrast Imaging being conducted Dr. Richard Lanza, materials and in-core loop research being conducted Professor Ronald Ballinger, Professor Mujid Kazimi's annular fuel studies, and the innovative nanofluid research initiated by Dr. Lin-Wen Hu and Professor Jacopo Buongiorno. As a result of the INIE Program, the MIT research reactor has seen a definite increase in utilization by faculty, researchers, and students within MIT, but has also allowed the NRL to offer its unique resources to support researchers across the country, such as those individuals utilizing the MIT NCT User Facility.

D. Infrastructure Improvements

Funds received under the INIE program have allowed the MIT Nuclear Reactor Laboratory (NRL) to make several necessary upgrades to its 5 MW research reactor but has also supported the design and implementation of several facilities that will greatly increase the NRL's research reactor's capability to support and conduct faculty and outside user research. These improvements include:

- Reactor Upgrades

  — Hot Cell Manipulator: One large through-wall telemanipulator assembly has been ordered from Central Research Laboratories. This system is currently being built and will be installed into the Hot Cell #1 facility to replace the existing manipulator system which has aged through many years of use and lacks key replacement parts.

  — Ventilation and HEPA Filter System Replacement for Hot Cells: The ventilation duct work and its HEPA filter assembly were replaced with upgraded units for operation of reactor Hot Cell #1 and #2.

  — Hot Box Assembly: This is a steel / lead hot box that was transferred from the DOE Brookhaven National Laboratory for use in post-irradiation analysis at the MIT Research Reactor. The INIE grant supported its transfer from Brookhaven and installation / assembly at the MIT reactor.

  — Manipulators for the Hot Box Assembly: Two sets of manipulator were rebuilt with new parts and components. They have been installed at the new Hot Box for handling of radioactive samples.

  — Hot Box Fire Alarm and Suppression Systems: The Hot Box interior was equipped with new fire detection (with local alarm and remote warning in the reactor control room) and fire suppression systems. The original assembly did not have these provisions. Since sample-cutting work is a key part of post-irradiation analysis, this fire system is a necessary feature.

  — Area Radiation Monitors: The Hot Cell #1 facility and the new Hot Box were equipped with new radiation monitors that provide both local and remote readouts and trip alarms. The INIE grant also supported their calibrations and cable installation by the reactor staff.

— Reactor Primary Pump (x2): The two main reactor primary coolant pumps were replaced with two new variable speed pumps. The new pumps are controlled via variable frequency drives (VFDs) for improved energy efficiency and performance. All associated piping, some valves and some pressure gages were also replaced for conformance to new ANSI standards.

— Reactor Secondary Pump (x2): The two main reactor secondary coolant pumps were replaced with two new variable speed pumps. This upgrade replaced the old secondary pumps in service for many years. These new pumps are also controlled via variable frequency drives (VFDs) for improved energy efficiency and performance. All associated piping, some valves and some pressure gages were also replaced for conformance to new ANSI standards. The replacement of the secondary coolant pumps was timed together with the replacement of the primary pumps to ensure system flow / pressure balance during operation.

— Upgrade of the Inductively-Coupled Plasma (ICP) Analyzer: The reactor's ICP Analyzer was upgraded for post-irradiation sample analyses.

— Upgrade of Control Room Shim Blade Position Indicators: The position indicator system for the six reactor control shim blades and for the regulating rod will be replaced. The original units were surplus equipment from the DOE and have been in service since 1958. Spare parts are no longer manufactured and components replacement has been impossible. The upgrade will provide better response and user-friendly indication for the console operator.

— Multi-Channel Reactor Temperature Data Acquisition and Analysis System: This data-conditioning analyzer will be installed in the control room for use with the reactor multi-point temperature recorder. It will replace the use of paper charts and printing supplies for reactor temperature recording and storage.

- **BNCT User Facility**

  INIE funds:

  — Provided a significant fraction of the cost for upgrading and modernizing the NCT thermal neutron irradiation facility at the MITR.

— Supported the design and construction of the Lithium-6 filter system at the epithermal neutron beam at MIT.

— Were used to purchase major optical equipment, computer hardware and software, a freezer to store tissue sections and a cryogenic microtome needed for the MIT graduate thesis project in high-resolution quantitative autoradiography, (HRQAR).

— Paid for the refueling of the fission converter.

— Allowed the purchase of signal processing electronics that are part of control systems for two neutron beam lines as well as ionization chambers and other equipment for mixed-field dosimetry.

- **Neutron Interferometry:**

  INIE provided funds to support the purchase and installation of equipment necessary for research being conducted by Professor David Cory, these include:

  — Shutter, collimator, and shielding were installed at 4DH4.

  — Primary monochrometer (graphite crystal) was installed.

  — Measurements of alignment and Bragg peak in progress.

  — Secondary monochrometer, polarizer, and interferometer placement pending.

- **Phase Contrast Imaging**: This portion of the MITR INIE program is under the direction of Dr. Richard Lanza. The MITR staff person who interfaces with this project is Mr. Edward Lau. The following is a list of activities supported by INIE:

  — Calibration of cooled CCD Camera.

  — Initial data acquisition software.

  — Acquired and tested imaging plate system for neutron imaging.

  — Awaiting delivery of amorphous silicon imager.

— Redesign of new beam port using pinhole collimator with Bi and sapphire filters.

- **Materials/In-Core Loops**:

  — Design and construction of a post-irradiation examination facility (PIE) for in-core irradiations of both advanced fuels and materials.

  — Funds were used to equip a new hot cell to enable the examination of the results of irradiation of innovative fuel design for PWRs.

  — Design of a very high temperature loop that will allow studies related to GEN-IV fuel and materials design. INIE funds were used to partially support Dr. Il Soon Huang, an MIT PhD. with considerable industrial experience, to assist with loop design.

  — Design and construction of a single-phase heat transfer loop to investigate nanofluid heat transfer and pressure drop characteristics in laminar and turbulent flow regimes.

  — Design and construction of a Critical Heat Flux (CHF) Facility. This loop will be used to obtain CHF data for different types of nanofluids which do not currently exist in the literature.

  — Modification of the pool boiling screening facility that was initially used for classroom demonstration of pool boiling in order to test the pool boiling enhancement using nanofluids.

E. Partnerships with DOE labs, colleges, universities, utilities, and other public/private entities

- **Neutron Capture Therapy**

  Through the INIE supported NCT User Center, collaborative research activities have been established with 10 university research groups that are engaged in NCT research. A collaboration in the NCT area with consortium partner RINSC is currently under development. Collaborations have also been developed with clinical researchers at two Boston area hospitals. Currently this collaboration is focused on the evaluation of clinical BNCT worldwide and on the development of new BNCT clinical trials using the specialized medical irradiation facilities at MITR. One collaboration has been developed with private industry and one with a DOE national laboratory to support DOE-sponsored SBIR grants. Table II.A is a summary of academic, research staff and students at other institutions (besides MIT) supported by experiments performed at the NCT User Center. The research of these groups and individuals depends on the availability of the NCT User Center.

- **Materials/In-Core Loops**

  Research being conducted for the high performance fuel design for next generation PWRs is the first time that a new fuel design is examined in a university research reactor. Establishment of this research capability enables future examinations of advanced fuels to be done, with benefits to the national industry and to the government program on advanced fuel cycles (AFCI).

- **Nanofluid Research**

  As a collaborator with MIT, University of Florida is assessing the challenges related to chemical and physical stability of nanofluids in prototypical PWR water chemistry. (funded by Framatome-ANP). In addition, Idaho National Lab is setting up an experimental facility to evaluate the heat transfer enhancement of carbon nanotubes in gas for Very High Temperature Reactor (VHTR) and Gas Fast Reactor (GFR) applications.

  This is the first time that a new fuel design is examined in a university research reactor. The established of this research capability enables future examinations of advanced fuels to be done, with benefits to the national industry and to the government program on advanced fuel cycles (AFCI).

F. Commitment

Massachusetts Institute of Technology continues to provide the resources necessary to operate its 5 MW research reactor. The funding provided by INIE reinforces the university's commitment to its research reactor and nuclear engineering and science programs.

G. Leveraging

MIT had traditionally operated the MIT Research Reactor on a five-year rolling commitment. That changed in the mid-1990s when questions arose about the long-term survivability of nuclear engineering as a distinct discipline of study. The MITR was then operated on a one-year cycle which made long-rang planning difficult. The INIE

Table II.A

Researchers and Student Numbers that Received Significant Support from the NCT User Center at MITR (2004)

Researcher	Institute	Undergrad	Graduate	Post-Doctoral
Prof. Werner Tjarks	OSU	2	1	4
Prof. Rolf Barth	OSU	-	-	2
Prof. Fred Hawthorne	UCLA	2	2	2
Prof. Stephen Kahl	UCSF	-	-	3
Prof. Graca Vincente	LSU	-	3	1
Prof. George Kabalka	UT	2	1	1
Dr. Henry Smilowitz	Uconn	-	1	-
Prof. Jeffrey Coderre	MIT	-	3	-
Prof. Otto Harling	MIT	2	1	
Dr. Stead Kiger	BIDMC	-	1	-
Dr. Joseph Backer	SibTech Inc.	-	-	-
Others awaiting funding				
Dr. Michi Miura	BNL	1	-	1
Dr. Naren Ramakrishna	B&W Hospital	-	-	2

program was created, at least in part, as one aspect of a national effort to stem the decline in university research reactors. In this respect, INIE has been a success. MIT recently reverted to the policy of a five-year rolling commitment. INIE was one factor in that decision and this is the principal leveraging effect. Other fators wererenewedstudent interest in nuclear engineering, MIT partnership with Battelle Energy Alliance that now operates INL., and growing public realization that nuclear power is essential to the assurance of a benign and stable energy supply.

The New England INEA consortium has also either produced or benefited from relative with other programs. Please see Appendix A for additional information (outlines, tables, and where practical, dollar amounts) on leveraging activities for the New England INIE Consortium.

H. Minority Student Involvement in INIE

MIT does not keep statistics of this type for individual projects such as BNCT, in-core experiments, beam port usage, etc. Statistics are kept for student enrollment as a whole, and we note that the involvement in each INIE activity is typical of the student body. Figures for 2004 are furnished here.

	Male (%)	Female (%)	Minority (%)
Undergraduate	**57**	**43**	**47**
Graduate	**70**	**30**	**16**

I. INIE Impact

Although funding was considerably less than originally anticipated, INIE has provided a definite impact to the nation's nuclear engineering and nuclear research reactor community. It has carried this out in two ways: 1) underscoring national interest in maintaining the U.S. position as a leader in nuclear science and engineering; and 2) providing much needed funding to support that goal. At MIT, it has provided the motivation as well as the momentum to rethink the university's vision of how it can contribute to the needs of future generations in the area of nuclear science and engineering. As a result, existing research programs have been expanded upon and new research projects have been initiated.

Overall, this program has started the process of revitalizing nuclear science and engineering at MIT which is evidenced by the increase in:

a) overall student enrollment in the Nuclear Science and Engineering Department and the increased utilization of faculty and researchers;

b) the number of faculty and researchers utilizing the MIT Nuclear Reactor Laboratory; and

c) the number of students who wish to participate in the MIT Nuclear Reactor Laboratory's Student Reactor Operator Training Program.

In addition, INIE funds have been used in support of graduate students, infrastructure improvements, and the purchase of new equipment in support of existing and new research programs. It has also supported significant upgrades and necessary improvements to the MIT Nuclear Reactor Laboratory's equipment and instrumentation.

Finally, in order to achieve the goals originally set out by INIE, this program must continue.

2. Rhode Island Nuclear Science Center (RINSC)

A. Statistics

Rhode Island Nuclear Science Center	ACADEMIC YEAR				
STATISTICS	04 - 05	03-04	02-03	01-02	00-01
Education Related					
Tenure track faculty (FTE's)					
BS enrollment					
MS enrollment	2	4	2	0	0
PhD enrollment	1	2	2	0	0
BS graduates					
MS graduates	2	0	0	0	0
PhD graduates	1	0	0	0	0
Research Related					
Research faculty (FTE	1	1	1	0	0
Technical support staff (FTEs)	1	1	0	0	0
Refereed publications (number)					
Non-INIE research expenditures	110K	85K	60K	25K	25k
Non-INIE research awards	2	2	1	1	1
Reactor Related					
Capacity (total potential hours)	1600	1600	1600	1600	1600
Utilization – education (total hours)		50	50	150	150
Utilization – research (total hours)		400	100	100	100
Utilization – training (total hours)		25	25	25	25
Utilization – commercial (total hours)		325	225	225	225

B. Educational Enhancements

The opportunity for graduate students in ocean engineering, chemical oceanography, and atmospheric chemistry to work in such areas as the CHAIOS project and the sensor projects at RINSC will strengthen a long tradition of marine scientists in the nuclear field. Due to its location at the URI Graduate school of Oceanography, RINSC has a long history of educating graduate students in the fields of neutron activation analysis, neutron scattering, and radiation studies for use in environmental and marine applications. The INIE grant has enabled RINSC to improve the service and facilities available to these students and will ensure that another generation of graduates has these skills.

C. Research Innovations

- **Atmospheric Research**

  The INIE grant has enabled RINSC to support the large scale atmospheric research effort of UNH and the other members of the CHAIOS group. The initial sample analysis at RINSC proved to be very successful and has resulted in more samples and analysis to further refine basic pollution outflow model parameters. The ability of the center to analyze a large number of samples for multiple elements with great accuracy was due to INIE support for new equipment to accomplish this work.

- **Cancer Research**

  The INIE grant has enabled Dr. Leith and Dr. Willard to develop a pure gadolinium-porphrin compound for use in neutron cancer treatment(NTC). Testing in the reactor at the cellular level has been promising and current efforts center on animal testing to verify the compound's effectiveness . The filter designed by Dr. Ott shows great promise for providing a pure epithermal beam for use in NTC.

- **Sensor Research**

  Dr. Hanson's students have designed underwater sensor for several applications and these devices have been tested by the United States Navy, several government agencies and even foreign governments.

D. Infrastructure Improvements

Funds from the INIE grant have been utilized to significantly upgrade the center's nuclear counting system. A Data Acquisition System was purchased for use in collection and analysis of reactor parameters. This system will also support maintenance, calibration and testing. A new rod position indication system was purchased which provides inputs to the data acquisition system. A dual ion chamber detection system for mixed beam dosimetry is being purchased to support the cancer research. A TLD Reader was purchased to support the dosimetry for this research and several other pieces of laboratory equipment were purchased to support the cell analysis efforts.

INIE funds freed up other funds for several important infrastructure improvements. After the interior walls of the reactor building were patched and painted, the reactor room floor was refurbished by removing asbestos tiles and applying epoxy. Numerous security enhancements have been installed including a new security camera system and vehicle barriers around the reactor building.

The biggest recent infrastructure improvement was the completion of the new sensors building on the South lab wing of the reactor complex. The project was totally financed by outside funding including state grants for technology and research. The total value of the project is in excess of one million dollars. The added capabilities of this facility will be of long term benefit to RINSC.

E. Partnerships with DOE labs, colleges and universities and other private/ public entities.

The cancer research group has partnered with MIT, Brookhaven National Lab, Brown University, The University of Rhode Island and The University of Connecticut. Dr. Ott has partnered with Argonne National Lab in the development of his filter. The atmospheric Chemistry group is part of the CHAIOS Group that includes UNH, MWO, UVA, UCSD, UCLA, Heidelberg and SML.

RINSC has two other private entities who make extensive use of the facility. BioPhysics Assay Laboratory, Inc. (BioPAL) specializes in high-precision alternatives to traditional, radiolabeled life science products. Their products are labeled with stable (nonradioactive) isotopes and are used in an analogous fashion to their radioactive counterpart. The analysis of stable tracer(s) in samples of interest is performed by BioPAL using neutron activation technology at RINSC In many cases, this approach provides information with improved sensitivity and specificity well beyond that achievable by optical markers and traditional radiolabels. Microinorganics Inc. does analytical consulting in the areas of trace metal analysis of water columns. This company has done extensive work for the Rhode Island Department of Health, the Narragansett Bay Commission and various other state and federal agencies. It has done analytical work on numerous rivers and other bodies of water such as the Narragansett Bay to determine trace contaminant concentrations at levels much below that normally achievable. RI Consultants LLC also has a laboratory at RINSC for the development of custom radio-nuclides. It has been successful in developing a P-32 stint for angioplasty and p-33 labeled drugs.

F. University Commitment

RINSC is the only state operated research reactor. As such, it serves the educational, research and commercial sectors of the entire state of Rhode Island and the

Northeast region. Its oversight body is the Rhode Island Atomic Energy Commission that is composed of a member from the University of Rhode Island, Providence College, Brown University, the Massachusetts Institute of Technology, and the Army research Center, Nedik, Massachusetts. The state legislature has shown continued commitment to the center by approving annul budgets that provide for over 80% of the cost of operating the facility. The state has also supported a strong five year capital budget which has funded several major projects including new roofs, air conditioning systems, outside building preservation, parking lots and asbestos abatement. This capital budget includes a 30 million dollar unfunded line item for decommissioning the reactor which is reviewed by the legislature every year. The reactor was converted to LEU fuel in 1993. As part of this conversion, a new compact core was installed which required the Department of Energy to supply new primary pumps, heat exchangers and associated piping. Subsequent DOE reactor instrumentation grants have resulted in new electronic instrumentation for the reactor. As a result of an extensive repair and replacement program, the reactor and the entire facility are in excellent material condition and ready to perform well for another licensing period. The RIAEC has applied to the Nuclear Regulatory Commission to re-license the reactor for an additional 20 years.

G. Leveraging

Leveraging information (outlines, tables, and where practical, dollar amounts) for the New England consortium can be found in Appendix A.

3. University of Massachusetts – Lowell Radiation Laboratory

A. Statistics

UMass Lowell Radiation Laboratory	Academic Year				
Statistics	**04 - 05**	**03 - 04**	**02 - 03**	**01 - 02**	**00 - 01**
Education Related[1]					
Tenure-track faculty (FTEs)	1	1	1	1	1
BS enrollment (total)					
Minorities					
Females					
MS enrollment (total)					
Minorities					
Females					
PhD enrollment (total)					
Minorities					
Females					
BS graduates (total)					
Minorities					
Females					
MS graduates					
Minorities					
Females					
PhD graduates	1	3	3	2	1
Minorities	0	0	1	1	0
Females	0	1	2	1	0
Research Related[2]					
Research faculty (FTEs)	7	7	7	7	7
Technical support staff (FTEs)	5	5	5	5	5
Refereed publications (number)	12	9	11	9	21
Non-INIE research expenditures ($)	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$
Non-INIE research awards ($)	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$
Reactor Related[3]					
Capacity (total potential hours)	1500	1500	1500	1500	1500
Educational use (total hours)	76	71	62	46	49
Research use (total hours)	102	95	83	62	65
Training use (total hours)	51	48	42	31	32
Commercial use (total hours)	25	24	21	15	16

Notes:
1) The Radiation Laboratory is a research center used by multiple departments, and therefore does not have enrollments.
2) Research Faculty: the PI's who use or have used the reactor in research.
3) Reactor Related – Capacity based upon 6 hour shift 5 days 50 weeks; and usage hours based upon a percentage of critical hours (respectively 30, 40, 20, 10).

B. Educational Enhancements

Title: Virtual Console
Description: UMass Lowell plans to establish a virtual console that will be integrated with the digital neutron radiography facility. The virtual console will allow students and researchers to engage in digital neutron imaging without entering the research reactor. This initiative therefore will reduce security concerns and eliminate personnel radiation exposures.
Impact on Nuclear Science Education Programs: This initiative is expected to enhance interest in nuclear science by making neutron radiography potentially accessible to all interested students.

C. Research Innovations

Title: Investigation of CMOS Line Camera
Description: UMass Lowell has collaborated with *Envision* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate a CMOS line camera that contains the inorganic scintillator gadolinium-oxysulfide for use in neutron radiography.
Impact on Nuclear Science Education Programs: This innovation is expected to encourage additional research support in the area of neutron radiography.

Title: Dual X-Ray and Neutron Imaging Capability
Description: UMass Lowell plans to investigate the efficacy of combining x-ray capabilities into the digital neutron radiography facility.
Impact on Nuclear Science Education Programs: This innovation will provide the combination of both x-ray and neutron produced images that may prove useful for assessing object properties, and thus encourage additional research support.

D. Infrastructure Improvements

Title: Digital Neutron Radiography Facility
Description: UMass Lowell has established a reliable digital neutron radiography facility.
Impact on Nuclear Science Education Programs: The UMass Lowell digital neutron radiography facility is unique in the northeast region, and therefore offers students the potential to use non-destructive testing in research.

E. Partnerships

UMass Lowell has partnered with *Envision Corporation* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate an x-ray CMOS line camera for use in neutron radiography. This partnership is expected to encourage additional research support in the area of neutron radiography, and to foster partnerships with other businesses involved in digital imaging.

F. University Commitment

UMass Lowell continues to provide the resources necessary to operate its radiation laboratory. The funding provided by INIE reinforces the University's commitment to its research reactor and nuclear science programs.

G. Leveraging

Leveraging information (outlines, tables, and where practical, dollar amounts) for the New England consortium can be found in Appendix A.

H. Minority Student Involvement in INIE

UMass Lowell Radiation Laboratory	04 - 05	03 - 04	02 - 03
BS Students	0	0	N/A
Minorities			
Females			
MS Students	0	0	N/A
Minorities			
Females			
PhD Students	1	0	N/A
Minorities			
Females	1		

I. INIE Impact

The impact of even modest DOE funds (See Table II.C) made available to UMass Lowell through the INIE program is considerable. The money provided by DOE has created a regional digital neutron radiography facility at UMass Lowell; has helped to improve the chances of attaining tenure for a UMass Lowell assistant professor; has created research assistantships for graduate students in an environment where student funding is declining; has enhanced the reputation of the UMass Lowell Radiation Laboratory by its ability to secure DOE funding for research; has provided the impetus for establishing a collaboration with a business that manufactures imaging devices; and has gained notoriety for the UMass Lowell Radiation Laboratory through its collaboration with the Nuclear Laboratory at MIT. It is also speculated that the INIE funding will increase the probability that UMass Lowell will obtain additional DOE funding for future research projects. The current infrastructure established by the INIE funding will be potentially available as a research facility to all interested students. Continued DOE funding for the digital neutron radiography facility also will ensure its longevity, and should increase the probability that UMass Lowell will attract more students interested in nuclear science research. Furthermore, the virtual console will help to integrate this facility into more classrooms. The concept of a virtual console also could be expanded to include various reactor experiments, thus potentially familiarizing a variety of students with the research reactor and nuclear science in general.

Table II.C: RINSC: Funding Allocation And Execution

FY03-$100,000 (budgeted and expended)

Personnel $45,160.50
Reactor use Charges $64,618.75
Laboratory use charges $4,724.50
Materials and supplies $10,534.84
RINSC cost share $25,464.59

FY04-$100,000(budgeted and expended)

Personnel $8,514
Equipment $32,000
Reactor use charges $58,282.50
Laboratory Use charges $3612.00
Materials and Supplies $9,733
RINSC Cost Share $12,141.50

FY05- (budgeted and spent)

Personnel $48,325.50
Equipment $46,000.00
Reactor Use Charge $20,000.00
Laboratory use Charge $24,50.00
RINSC Cost Share $16,775.50

II. <u>Notable Accomplishments</u>

A. Massachusetts Institute of Technology

1. Title: MIT Neutron Capture Therapy User Center

<u>Description:</u> With INIE support MIT has established a neutron capture therapy user center to meet the needs of all U.S. researchers in this field.

<u>Explanation:</u> With the closure of the Brookhaven Medical Research Reactor (BMRR), the MIT neutron facilities for NCT research are the only ones in the USA capable of supporting a full range of research from pre-clinical to clinical irradiation studies. Currently the MIT NCT User Center is essential to the research activities of a number of university, industry and hospital-based NCT research groups and meets or exceeds the capabilities that once existed at BMRR. Activities under the NCT User Center have grown during each of the three years of INIE funding measured by the numbers of experiments and users supported.

INIE has supported a significant part of the upgrade of the MITR based NCT thermal neutron irradiation facility. This includes automated beam shutters, improved shielding in the medical room in preparation for new clinical studies. INIE support has also made possible the implementation of a Lithium-6 filter for the epithermal neutron (FCB) medical irradiation facility. This enhancement to the FCB significantly improves the useful penetration of this epithermal neutron beam.

All the necessary technology, pre-clinical studies and approvals (11 separate approvals from government entities and local review boards) were obtained to allow initiation of clinical studies of NCT. Several phase I and phase I/II have been carried out at the MITR in recent years. Control of melanoma metastases was observed in a significant fraction of the patients with this type of cancer. Further clinical studies are planned and INIE support will be essential to these studies

2. *<u>Title: High Performance Fuel Design for Next Generation PWRs:</u>*

<u>Description:</u> The objective of this project is to develop and optimize the design of internally and externally cooled annular fuel to achieve a significant increase of core power density while improving safety margins.

<u>Explanation</u>: This will appreciably reduce capital cost per installed kW as well as operating and fuel cycle cost per unit energy produced. In addition, core design and fuel performance analyses will be performed to maximize fuel burnup utilizing the benefits of very low operating fuel temperature and wetter lattices to further improve fuel cycle economics. While aimed at new Generation IV reactor applications, a retrofit version for current PWRs will also be examined. All current PWR units worldwide employ fuel of very similar design: cylindrical pins of about one centimeter diameter in a lattice with a water-to-fuel volume ratio of about 1.7. Evolutionary improvements have been implemented over the past decades, but with small incremental benefits. The concept proposed for investigation here, however, would provide substantial safety improvements: for example, a 1000 ˚C reduction in peak fuel temperature at the hot spot and a very mild fuel response in LOCA, while simultaneously allowing an appreciable increase of power density (by 30% or more) and significant economic benefits.

MIT is the lead organization for this research, which is funded via the DOE-NERI Program. It is planned to demonstrate and evaluate fuel using an in-core loop in the MITR. Collaborating organizations include Gamma Engineering Corporation (fuel fabrication), Westinghouse Electric Corporation (quality and cost of fabrication), and Duke Engineering (safety margins).

3. *Title: Nanofluid Applications in Nuclear Energy Systems*

Description: The major task during this year has been the construction of the Single-Phase Heat Transfer Loop and the Critical Heat Flux (CHF) Loop.

Explanation: The single-phase loop is close to completion. It has been pressure tested to 10 bars, the operating pressure, and the signal acquisition has been tested. The system is being setup in order to test deionized water under laminar and turbulent flow conditions. The data will be compared with the expected behavior (as predicted by the Dittus-Boelter & Gnielinski correlations) and all of the remaining troubles within the system, if any, will be worked out. The loop should be capable of achieving heat fluxes up to 100 kW/m^2 by design and measurable flows of Reynolds numbers from high laminar to turbulent 50,000. The maximum operating temperature will be maintained below 180°C in order to prevent steam formation in the system. A large stainless steel accumulator (6 liter) is used as a pressurizer and a point to fill the loop with coolant. The accumulator has a flow through gas/liquid interface in order to help remove gas from the system during operation.

Currently Nyacol alumina-water nanofluid is selected as the first nanofluid coolant to be tested in the loop after it has been fully characterized with water. The coolant will most likely be added to an empty system and diluted with water in order to achieve the desired volumetric loading. The volumetric loading can then be modified through bleed and feed operations in order to step through the various desired test points. Figures 1-2 are photographs showing the single-phase nanofluid loop.

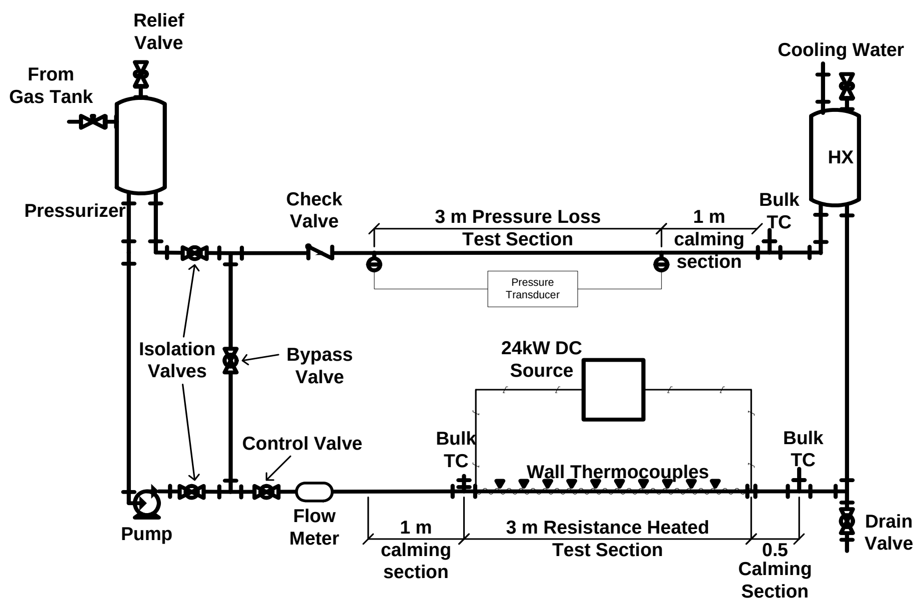

Figure 1. Schematic of the single-phase convective heat transfer loop.

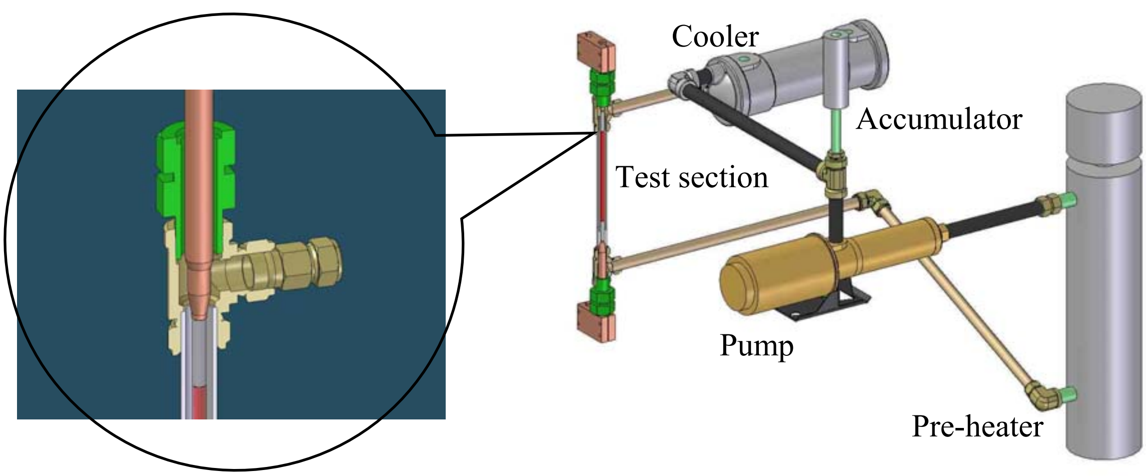

Figure 2. The CHF nanofluid flow loop.

The CHF facility is being constructed to obtain CHF data for different types of nanofluids which do not currently exist in the literature. Since CHF is significantly affected by the heated surface, actual Zircaloy cladding specimens are provided by PWR vendors for this experiment.

Initial pool boiling experiments were performed using alumina nanofluid. The current scope of the work is for screening purpose to see if there is any increase in pool boiling CHF in nanofluid. An increase in CHF of stainless steel wire was found ranging from 13 to 47% depending on the concentration of alumina and the ways the experiment were run. Ramping experiment shows a smaller increase in CHF comparing to slow experiments, which suggests that the increase in CHF is probably due to nanoparticle precipitating on wire. More work in this area is needed. Figure 6 is a Scanning Electron Microscope (SEM) image of a stainless steel wire showing alumina nanoparticles precipitation after it was used in a pool boiling experiment with 0.01 volume% of alumina nanofluid.

4. Title: High Temperature Irradiation Facility

Description: The major task was the design, construction, and installation in-core of a facility capable of testing Gen-IV materials at temperatures up to 1400 C. This facility became operational in mid-December 2005, which is after the period covered by this report. However, we briefly note its success here.

Explanation:

The HTIF was designed by MIT's Department of Nuclear Engineering (Prof. Ballinger, Dr.Kohse, Prof. Kazimi and others) for the purpose of providing the means to subject samples simultaneously to conditions of high neutron flux ($5x10^{13}$ thermal, $1x10^{14}$ fast) and temperature (1400°C). The design and its accompanying safety and control features were reviewed and approved by the MIT Committee on Reactor Safeguards. No unreviewed safety issues were identified. The facility consists of a tungsten thimble that is isolated from its environment by a gas gap. The thimble fits in a container that occupies one fuel element position. The gap may be filled with neon (low conductivity) or helium (somewhat higher conductivity). This limits heat removal to radiative and conduction. There is no convective heat removal. As the result of gamma heating of the tungsten, the thimble attains very high temperatures while the outer container remains at ambient (50°C).

The HTIF was installed last week and underwent extensive pre-operational testing to verify the effects of the neon and helium as well as to check all control and alarm features while at low power. A series of planned power increases were then conducted and we are now at 4 MW with the facility at 1400°C. We are irradiating some SiC samples. We anticipate achieving full power operation with the HTIF next week.

This facility, which as noted above, was built under the Department of Energy's Innovations in Nuclear Infrastructure and Education (INIE) program, represents a major achievement for the MIT Nuclear Reactor Laboratory. The HTIF provides a unique capability among university research reactors. It will be used to irradiate candidate GEN-IV materials. We look forward to contributing to the national research mission in nuclear energy through the use of this facility.

B. Rhode Island Nuclear Science Center (RINSC)

1. Title: Cancer Research Project

Description: INIE funding has enabled RINSC to bring together an eminent group of researchers to tackle the difficult task of developing an effective agent for use in neutron capture therapy of brain cancers. This treatment protocol utilizes the large aperture neutron beam capability of a research reactor to target the diffuse nature of certain brain cancers and has promise of treating other deep cancers. The RINSC team consists of Dr. Paul Willard, a noted chemist, Dr. John Leith, an experienced radio-biologist, Dr. Arvin Glicksman, an oncologist and Dr. Carl Ott, a nuclear engineer. The team has developed a gadolinium based compound and has conducted basic research starting at the cell level to prove the value of this protocol. Dr. Ott has designed a new filter that promises to improve the treatment protocol.

Explanation: INIE funding was critical to the development of this project since it takes time to put together a multi-disciplinary team and then apply for grants. Since RINSC is a state supported facility, there was no support available at the university level. Since the project has developed, it has received support from the legislature which has maintained the RINSC budget at a level adequate to support the project.

2. Title: Atmospheric Chemistry Project

Description: The CHAIOS Project achieved excellent results from last year's analysis efforts at RINSC. The large number of sample irradiations doubled the reactors utilization for the year. This year, the increased analysis program should provide even more detailed results regarding halogens and their role in the pollution outflow model for the Northeast United States. INIE funding of the improvements to the RINSC counting system was crucial to the success of the project and additional improvements are being installed with INIE funding to support this year's efforts.

Explanation: RINSC as a long history of environmental research utilizing Neutron Activation Analysis and the numerous graduates of the URI Graduate School of Oceanography continue to return to RINSC with the research projects. INIE funding has a large impact on our ability to support these research efforts by allowing us to maintain our equipment at a level necessary to support these efforts.

3. Title: Sensor Research Project

Description: Dr. Hanson's research into underwater sensors for environmental work and detection of weapons of mass destruction has coupled the unique capabilities of the marine scientists at URI with the capabilities of RINSC to create a very talented team of researchers with the facilities necessary to take on difficult problems. The large amount of state funding that has gone into completing his laboratory would not have been possible without the initial INIE support to move the project forward. The subsequent SBIR and other grants that have continued the research and the six graduate students that are supported by the research are the result of the initial INIE help.

Explanation: RINSC serves as an incubator for small businesses and researchers who have a good idea in the nuclear field but lack funding. Dr. Hanson's research efforts have lead to commercial success. BioPal and RI Consultants also fit the mold of small startup companies that benefit from the ability to use RINSC as a base while they develop their technology. INIE funding support of RINSC enables us to support innovative ideas in the area of nuclear science as they transition from theory to practice.

C. University of Massachusetts Lowell Radiation Laboratory

1. ***Title: Digital Neutron Radiography Facility***

Description: UMass Lowell has established a reliable digital neutron radiography facility using INIE funding.

Explanation: The UMass Lowell digital neutron radiography facility is unique in the northeast region, and therefore offers students, businesses, and other research institutions the infrastructure to use non-destructive testing in research. The facility did not exist before DOE funding.

2. ***Title: Research Assistantships***

Description: UMass Lowell is using INIE funding for research assistantships.

Explanation: The research assistantships established with DOE funding have made graduate study in nuclear science affordable for one of our female Ph.D. students. The research assistantships also increase the probability that UMass Lowell attracts competitive students interested in nuclear science.

3. ***Title: Industry Partnerships***

Description: UMass Lowell has partnered with *Envision Corporation* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate an x-ray CMOS line camera for use in neutron radiography.

Explanation: The collaboration with *Envision Corporation* proved fruitful in that the company realized the potential of a new customer base, namely those interested in neutron imaging. In addition, the present partnership has opened the door for future collaborations with *Envision Corporation* or other businesses involved in imaging, or who need non-destructive testing services to satisfy industry manufacturing, quality control, and quality assurance standards.

Appendix A

Leveraging

NEW ENGLAND CONSORTIUM LEVERAGING

1. MIT

- **In-Core Experiments (Prof. Kazimi, Prof. Ballinger, Dr. Khose)**

  The INIE funding enabled construction of a facility capable of testing the possibility of obtaining very high temperatures (close to 1400°C) in the reactor. It is expected that this will attract additional funding. While no funding has materialized yet, the ability to reach that temperature provides a unique opportunity for both industry and national laboratories to test the proposed materials for high temperature reactors.

  Earlier, the INIE funding helped expand NERI funding of the annular fuel project. In particular funds were used to construct the hot cell manipulators and collimeter to enable measurement of the fission gas gamma emissions from irradiated fuel samples. This allowed the NERI project to be extended for another year to conduct the examinations. That was a good reason to get one of the students a fellowship from the AFCI program.

  Also, a new project is planned with a private firm, Gamma Engineering, to continue evaluations of SiC clads.

- **National User Center for Neutron Capture Therapy (Prof. Harling, Prof. Ballinger)**

  The research supported by the User Center covers a wide range of pre-clinical and translational research in NCT. While INIE provides essential support for this research, most of the funding is derived from a broad range of private and government sources. Table A.1 provides information about the research and funding of the users of the NCT User Center as well as expected users. There were 13 research groups supported in this latest year compared to 9 in 2003-04 and four in 2002-03.

- **Nanofluid Applications in Nuclear Energy Systems (Prof. Buongiorno, Dr. Hu)**

  This program comprises the following activities, which are currently sponsored by the INL, AREVA, and the INIE program. There is enormous leverage in this project as illustrated by the multiplicity of sponsors.

— Procurement of water-based nanofluids (i.e., C, SiO_2, ZrO_2, Al_2O_3) from vendors (e.g., Sigma-Aldrich, Nycol, Applied Nanoworks).

— Nanofluid characterization with TEM (nanoparticle size and shape), neutron activation and ICP trace element analysis (nanoparticle loading and trace element composition).

— Property measurements: thermal conductivity (transient hot wire method) and viscosity (ultrasonic viscometer).

— Property modeling with Molecular Dynamics simulations.

— Single-phase heat transfer and pressure drop measurements in flow loop.

— Single-phase heat transfer modeling.

— Critical Heat Flux (CHF) measurements: experiments with heated wire, and in flow loop with PWR-equivalent annulus and Zircaloy heated surface.

— Nuclear applications: subchannel, safety and neutronic analyses of PWRs with nanofluid coolant.

- **Quantum Computing (Prof. Cory)**

  As a direct result of the INIE funds NIST has provided $75,000 in support to fund a postdoct on neutron interferometry. This has been awarded.

- **SiC Duplex Clad Irradiation (**Prof. Ballinger, Prof. Kazimi, Dr. Kohse.)

  Although this project which involves the production and testing of candidate duplex SiC/SiC composite cladding materials for Light Water Reactors (LWRs) was not initially funded or supported by INIE, it does represent a significant leveraging effect because of the increased capabilities resulting from the upgrades to the MITR and the Advanced Material Testing Facility that made it possible for the research to be done at the NRL. A workshop on SiC cladding applications for advanced nuclear reactors was held on May 5, 2005, to present initial out-of-pile testing results of SiC cladding development, and to discuss the future testing development. This workshop was sponsored by Gamma Engineering Inc., Westinghouse Electric, Nova Tech, and co-hosted by MIT Center for Advanced Energy Systems (CANES) and Oak Ridge

National Laboratory. Initial funding has been received to design and plan for the upcoming irradiations. Funding for the initial 3-month irradiation has been allocated and additional funding is being sought to extend the irradiation test to 12 months. The SiC cladding irradiation is scheduled to begin in December 2005.

Table II.B: Users of NCT User Center at MITR-II 2002-2005

NAME	INSTITUTE	PROJECT TITLE	DURATION	FUNDING SOURCE	AMOUNT
1. Prof. Rolf F. Barth	Ohio State University	a.“Molecular Targeting of EGF for the Treatment of Gliomas” b.“Combination Therapy of Primary and Metastatic Brain Tumors”	06/01/03 – 05/31/07	NIH funding 1R01 CA107367 -01A1 High probability for future NIH funding	$1,312,752
2. Prof. Werner Tjarks	College of Pharmacy, Ohio State University	a. “Synthesis of Boron and Gadolinium Containing Texaphyrins for NCT of Head and Neck Cancer” b. “Synthesis and Evaluation of Boron-Containing Nucleosides for BNCT	07/01/03 – 06/30/05 02/01/00 – 01/31/05	Funding from Ohio Cancer Research Associates DOE	$50,000 $1,344,432
3. Prof. Henry Smilowitz	University of Connecticut Health Center, School of Medicine	“The Combination of Radiation Therapy [BNCT] and Enhanced Gene-Mediated Immunoprophylaxis for Glioblastoma Multiforme”	04/01/99 – 12/31/04 02/01/04-12/31/04 08/01/04-02/01/05	funding from University of Bern NIH funding NIH funding	$44,000 $29,799 $34,000
4. Dr. Michiko Miura	Brookhaven National Laboratory	“ Targeted Ablation of Tumors by BNCT using Lipophilic Tetracarboranylphenyl Porphyrins”	09/01/04-08/31/05	DOE CRADA funding (possibly renewable for 2 subsequent years)	$210, 000
5. Prof. M. Frederick Hawthorne	Univ. of California, Los Angeles	“Liposome Delivery of Boron for BNCT”		NIH funding 1R01 CA97342-01A2	$1,726,536

Table II.B: Users of NCT User Center at MITR-II 2002-2005 (Continued)					
NAME	**INSTITUTE**	**PROJECT TITLE**	**DURATION**	**FUNDING SOURCE**	**AMOUNT**
6. Prof. George W. Kabalka	Univ. of Tennessee	"Boronated Amino Acids for NCT"		Private funding	
7.Prof. Maria da Graca Vicente	Louisiana State Univ.	"Tumor-targeting with New Boronated Porphyrins"	Apr. 2004 – March 2007	NIH funding1R01 CA098902	$595,350
8. Prof. Stephen B. Kahl	University of California, San Francisco	"Program for Development of BNCT Agents:	1999 – 2005	NIH funding 1RO1 CA82478 (no cost ext. filed for 2005; renewal to be submitted for $250k pa from 12/1/05)	$1,250,000
9. Prof. Jeffrey A. Coderre	MIT	a. "Mechanisms of High-LET Radiation Damage in Normal Lung" b. "Selective Irradiation of the Vascular Endothelium" c. "VEGF-based Delivery of Boron Therapeutics" d. "Liposome Delivery of Boron for BNCT"	08/9/01 – 8/8/05 07/01/04-06/31/05 06/27/03 – 06/26/05 08/03/04-07/31/08	DOE (OBER) funding DE-FG02-01ER63194 MIT Research funding, Dean of Engineering office, Westaway Memorial Fund DOE, Phase II SBIR subcontract NIH, NCI subcontract	$661,453 $50,000 $140,951 $465,880
10. Dr. W. Steadman Kiger	Beth Israel Deaconess Medical Center	"NCT Treatment Planning Intercomparison"	2002-2004	Harvard Joint Center for Radiation Therapy Foundation	$60,000
11. Dr. Joseph M. Backer	Sib Tech,Inc.	"VEGF-based Delivery of Boron Therapeutics:	6/27/03-6/26/05	DOE SBIR DE-FG02-02ER83520	$848,798

Table II.B: Users of NCT User Center at MITR-II 2002-2005 (Continued)					
NAME	**INSTITUTE**	**PROJECT TITLE**	**DURATION**	**FUNDING SOURCE**	**AMOUNT**
12. Dr. Jacek Capala	NCI	"Gadolinium Based Macromolecular MRI Contrast Agents for NCT"		NCI internal funding	
13. Prof Otto Harling	MIT	a. "BNCT Research Facility at MITR" b. "Reconstruction and Upgrade of the Thermal Neutron Irradiation Facility"	02/01/02-03/14/06 08/15/00-08/14/03	DOE (OBER) DE-FG02ER63358 DOE (OBER) DE-FG-00ER62983	$1,679,400 $292,155

2. Rhode Island Nuclear Science Center

SubChem systems received over $50,00 in state economic assistance to complete their of our nuclear capability and their work in developing weapons of mass destruction sensors (nuclear, chem biological) for underwater applications. BioPal Inc., has invested over $300,000 in specialized counting equipment at our facility because they can use the reactor for NAA of biological samples. The state of Rhode Island has recently invested over $50,000 in interior building upgrades and this is due to our increased activity. Another $50, is scheduled for outside improvements next year. R.I. Associates has proposed a hot cell for RINSC to do radio isotope development. The cost is not clear but probably greater than $50,000.

INIE Leveraging

Actual Expenditures	**source**	**amount**
Equipment	R.I. Cancer Council	$20,000
	NTC Company (Dr. Ott)	100,000
Facilities	State Economic Development	$1,200,000
	Grants and private funding	
Cost Share	State of Rhode Island	$ 54,381
Total		
		$1,374,381

In-Kind Contributions		
Personnel	CHAIOS Project-technician	$60,000
Equipment	Brookhaven National Laboratory	$125,000
Facilities	RI Consultants	$80,000
Analytical work	Argonne national laboratory	$600,000
Total		**$865,000**

3. UMass-Lowell (Professor Tries/Mr. Bobek)

Professor Mufeed MahD (UMass EE), who is the director of the UMass Biomedical Engineering program, and who also teaches a medical imaging course as well has having ties to UMass Medical has initiated work on developing neutron tomography at the UMass-Lowell Radiation Center with the expected outcome of generating some research grants. Work has also been done for two small Massachusetts companies. RMD (Watertown) and Nova Scientific (Sturbridge). Both companies do neutron imaging R&D.

RMD was just recently awarded a DOE SBIR Phase II grant for "New Ceramic Scintillator for Neutron Detection" The proposal included a description of the upgraded neutron radiography facility at UMASS. Under the award, they will perform testing here (funded). RMD also has submitted an SBIR Phase II under NIH for "Digital 2-D neutron Detector for Protein Function Studies" which is still under review. The initial Phase I tests (funded) were performed here.

Nova Scientific recently did some initial tests (unfunded) of a neutron scintillator that may be submitted as part of a new SBIR proposal.

Appendix B

Publications

MIT BNCT Program (Provided by Professor Otto Harling and Dr. Kent Riley)

Peer-reviewed journal articles

<u>2001</u>

1. O.K. Harling, K.J. Riley, T.H. Newton, B.A. Wilson, S. Sakamoto and B. Sutharshan (2001) The new fission converter based epithermal neutron irradiation facility for neutron capture therapy *Neutron News* **12 (1)** 24-26.

2. W.S. Kiger III, M.R. Palmer, K.J. Riley, R.G. Zamenhof, P.M. Busse (2001) A Pharmacokinetic Model for the Concentration of ^{10}B in Blood following Boronphenylalanine-Fructose Administration in Humans, *Radiat. Res.* **155** 611-618.

3. G.A. Santa Cruz, M.R. Palmer, E. Matatagui and R.G. Zamenhof (2001) A theoretical model for event statistics in microdosimetry; part I: uniform distribution of heavy-ion tracks *Med. Phys.* **28** 988-996.

4. G.A. Santa Cruz, M.R. Palmer, E. Matatagui and R.G. Zamenhof (2001) A theoretical model for event statistics in microdosimetry; part-II: Non-uniform distribution of heavy-ion tracks", *Med. Phys.* **28** 997-1005

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1. O.K. Harling, K.J. Riley, T.H. Newton, B.A. Wilson, J.A. Bernard, L-W. Hu, E.J. Fonteneau, P.T. Menadier, S.J. Ali, B. Sutharshan, G.E. Kohse, Y. Ostrovsky, P.W. Stahle, P.J. Binns, and W.S. Kiger III (2002) The Fission Converter-Based Epithermal Neutron Irradiation Facility at the Massachusetts Institute of Technology Reactor *Nucl. Sci. Eng.* **140** 223-240.

2. K.J. Riley, P.J. Binns, D. Greenberg and O.K. Harling (2002) A physical dosimetry intercomparison for BNCT, *Med. Phys.* **29** (5), 898-904.

3. T.H. Newton Jr., K.J. Riley, P.J. Binns, G.E. Kohse, L.W. Hu and O.K. Harling (2002) Startup of the fission converter epithermal neutron irradiation facility at the MIT reactor *J. Nucl. Technol.* **139** 175-183.

4. O.K. Harling, G. Kohse and K.J. Riley (2002) Irradiation performance of polytetrafluoroethylene (teflon) in a mixed fast neutron and gamma radiation field *J. Nucl. Mater.* **304** 83-85.

5. J.T. Goorley, W.S. Kiger III and R.G. Zamenhof (2002) Reference dosimetry calculations for neutron capture therapy with comparison of analytical and voxel models *Med. Phys.* **29** 145-156.

6. M.R. Palmer, J.T. Goorley, W.S. Kiger, P.M. Busse, K.J. Riley, O.K. Harling and R.G. Zamenhof (2002) Treatment Planning and Dosimetry for the Harvard-MIT Phase I Clinical Trial of Cranial Neutron Capture Therapy, *Int. J. Radiat. Oncol. Biol. Phys.* **53** (5) 1361-1379.

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8. A. Buffler, F.D. Brooks, M.S. Allie, P.J. Binns, V. Dangendorf, K.M. Langen, R. Nolte and H. Schuhmacher (2002) Measurement of neutron energy spectra from 15-150 MeV using stacked liquid scintillators, *Nucl. Instrum. Methods A* **476** 181-185.

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4. W.S. Kiger III, M.R. Palmer, K.J. Riley, R.G. Zamenhof and P.M Busse (2003) Pharmacokinetic modeling for boronophenylalanine-fructose mediated neutron capture therapy: ^{10}B concentration predictions and dosimetric consequences *J. Neuro-Oncol.* **62** 171-186.

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7. R.F.Barth, W. Yang and J.A. Coderre (2003) Rodent brain tumor models to assess the efficacy of Boron Neutron Capture Therapy: A critical evaluation. *J. Neuro-Oncol.* **62** 61-74.

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2. J.A. Coderre, J.W. Hopewell, J.C. Turcotte, K.J. Riley, P.J. Binns, W.S. Kiger III and O.K. Harling (2004) Tolerance of normal human brain to boron neutron capture therapy *Appl. Radiat. Isot.* **61** 1083-1088.

3. G.A. Santa Cruz and R.G. Zamenhof (2004) The microdosimetry of the 10-B reaction in boron neutron capture therapy: a new generalized theory *Radiat. Res.* **162** 702-710.

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1. P.J. Binns, K.J. Riley and O.K. Harling (2005) Epithermal neutron beams for clinical studies of BNCT: A dosimetric comparison of seven beams *Radiat. Res.* **164** 212-220.

2. Otto K. Harling, Kent J. Riley, Peter J. Binns, Hemant Patel and Jeffrey A. Coderre (2005) The MIT User Center for Neutron Capture Therapy Research, *Radiat. Res.* **164** 221-229.

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2. K. Hideghéty, W. Sauerwein, P. Busse, O. Harling, R. Zamenhof, A. Chanana and J. Coderre (2001) The intercomparison of three epithermal neutron-based clinical trials of BNCT Frontiers *Frontiers in Neutron Capture Therapy Vol. 1* eds Hawthorne et al (New York: Kluwer Academic/Plenum Publishers) pp 99-103.

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5. M.R. Palmer, C. Chuang, W.S. Kiger, P.M. Busse and R.G. Zamenhof (2001) Predicting B-10 Concentrations in Normal Brain and GBM from Blood Measurements *Frontiers in Neutron Capture Therapy Vol. 1* eds Hawthorne et al (New York: Kluwer Academic/Plenum Publishers) pp 243-247

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10. C. Chuang, M.R. Palmer, L. Tang, R.G. Zamenhof and P.M. Busse (2001) Time-Dependent Biodistribution of BPA-f in Normal & Tumor Brain Tissues in Mice *Frontiers in Neutron Capture Therapy Vol. 1* eds Hawthorne et al (New York: Kluwer Academic/Plenum Publishers) pp 965-971.

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5. K.J. Riley, P.J. Binns, B.A. Wilson and O.K. Harling (2002) A Digital Dose Monitoring System for Automated Control of High Intensity Neutron Beams *Research and Development in Neutron Capture Therapy* eds W. Sauerwein, R. Moss and A. Wittig, (Bologna: Monduzzi) pp 373-377.

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NCT Studies (Provided by Professor Jeffrey Coderre)

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Appendix D

MIT NRL INIE Annual Report 2005-2006

INIE ANNUAL REPORT

Period of Performance: 1 September 2005 - 30 September 2006

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I. Yearly Report

A. Program Activities

1. Educational Enhancements

Title: Neutron Spectrometer Experimental Facility (MIT)

Objective: The MIT Nuclear Reactor Laboratory (NRL) is designing and constructing a web-enabled neutron spectrometer experimental facility.

Status: Continuing. INIE support is being used for equipment procurement.

Explanation: Currently, the NRL's neutron spectrometer is a non-automated facility installed in the Research Reactor's 4DH1 beam port. Although this facility has been enhancing MIT undergraduate curriculums for the last twenty years, it is limited because it is only accessible on-site. In collaboration with MIT's iCampus program, the NRL plans to debut the first online, interactive, real-time neutron-based experiment this winter. Using a combination of LabVIEW software and a prototype iCampus-developed architecture, the MIT-NRL can provide educational opportunities to students nationwide and internationally that do not have the benefit of an on-site nuclear reactor or other neutron source

Title: Neutron Scattering User Facility (MIT)

Objective: Establishment of a user facility to allow users from outside of MIT to conduct early phases of some experiments saving on precious time at large facilities, and to test and develop new neutron optics components.

Status: New. INIE support is being used for equipment procurement.

Explanation: Neutron scattering and spectroscopy are among the pre-eminent tools for studying the structure and dynamics of matter at the atomic and molecular scale. A powerful new neutron facility is currently under construction in Oak Ridge National Lab, the Spallation Neutron Source (SNS), which is widely anticipated to revolutionize this field, and enable the US to regain leadership lost to Europe decades ago. The SNS will catalyze a new generation of instrument development, a new generation of neutron scientists, and therefore, a new generation of scientific research with neutrons. Plans are underdevelopment at the NRL to develop a cyber-infrastructure for SNS Remote Access. The MIT Nuclear Reactor Laboratory envisions the following programs:

- Education and training for students in basic concepts of neutron scattering;

- Enhanced production of new materials at MIT and elsewhere by allowing rapid evaluation by neutron scattering;

- Development of novel neutron optics components;

- Conceptual development of a new imaging instrument - a neutron microscope in absorption and phase-contrast, for future installation at SNS; and

- Establishment of a user facility to allow users from outside of MIT to conduct early phases of some experiments saving on precious time at large facilities, and to test and develop new neutron optics components.

Title: High Resolution Quantitative Autoradiography for Boron Neutron Capture Therapy (MIT)

Objective: To develop a method to image boron in cancerous and normal cells at concentrations relevant to boron neutron capture therapy (BNCT) for cancer and at spatial resolutions which allow the determination of concentrations at the sub-cellular level.

Status: Continuing. An MIT NS&E graduate student, Thomas Harris, worked on this research project for his MS thesis that was completed during the report period. The INIE program provided support for all equipment, supplies and services required for this project. After acquiring all the major capital equipment needed for this research he was able to perform a series of experiments that produced track etch images from thin tissue sections containing boron. These images were used to explain differences in therapeutic effect of two different boron (liposomes and BPA) delivery agents on a mouse tumor model.

Explanation: Of critical importance to the development of improved delivery agents for BNCT is a detailed knowledge of the microscopic distribution of B-10 in the tumor and normal cells. High Resolution Quantitative Autoradiography (HRQAR) is one of only a very few analytical techniques, which has the quantitative resolution combined with adequate spatial resolution to allow estimation of the effectiveness of a boron delivery agent in BNCT. In the last year it was possible to identify that boron delivered to tumors by small nano particles (liposomes) was not as homogeneously distributed as with BPA and that this lack of uniformity was correlated in a poorer tumor cure rate. It is for these reasons that we are placing a strong emphasis on developing HRQAR so that it can be used routinely for evaluating the expected effectiveness of boron delivery agents for BNCT. This capability is currently available to users. Further development is planned regarding post mortem boron migration with a view to improving spatial resolution at sub cellular dimensions.

Title: Liposome Delivery of Boron for Neutron Capture Therapy (MIT)

Objective: To evaluate and develop a new boron delivery compound based upon nano sized particles (liposomes) for neutron capture therapy.

Status: Continuing. An MIT NS&E graduate student Yonsun Chung, who is supported fully by INIE, has performed extensive in vivo experiments with two mouse tumor models to test the therapeutic efficacy of boronated liposomes. This is the last phase of this student's Ph.D. thesis research.

Explanation: The development of better compounds for the delivery of capture agents is on the critical path to success for NCT as a modality. Chemists nationwide are synthesizing new compounds for use in NCT but do not possess the experimental infra structure and radiobiology expertise to evaluate their formulations. This research project was undertaken to provide this capability for NCT researchers from all over the country at the INIE funded MIT NCT User Center.

Title: Selective Irradiation of Vascular Endothelium as a Tool for Elucidating the Mechanism of Radiation Induced Side Effects in Normal Tissues (MIT)

Objective: To determine if irradiation damage to normal tissue is caused by damage to the microvasculature or by direct damage to the clonogenic cells.

Status: Continuing. This Ph.D. thesis research is in progress. The student, Bradley Schuller, is using this work as part of his requirements for his Ph.D. thesis in the MIT NS&E Department. The INIE program provides essential irradiation and technical support for this work. The remaining financial support for this research is from the Westaway Family Memorial Fund at MIT and a subcontract of an NIH grant to the University of California at Los Angeles. Recent findings were published in the Proceedings of the National Academy of Sciences with the student as first author and a second manuscript has been submitted to another internationally peer reviewed journal. The use of the novel selective irradiation was extended to study the frequency of apoptosis (programmed cell death) and gene regulation in the propagation of radiation induced effects.

Explanation: One of the major unresolved issues in radiation is whether normal tissue damage is caused by damage to the microvasculature or by direct damage to clonogenic cells. Results obtained during the report year show that selective irradiation of the vascular endothelium has no effect on the induction of the GI syndrome.

Title: Biodistribution Studies to Determine Selective Boron Uptake for Newly Synthesized Compounds (MIT)

Objective: To quantify the selective uptake of boron delivered by newly formulated delivery agents in tumor relative to normal tissues in different animal tumor models.

Status: Continuing. An MIT NS&E graduate student Yonsun Chung, who is supported fully by INIE, has performed extensive in vivo experiments with the EMT-6 and SCCVII tumor lines in mice for 4 different compounds. This has required becoming familiar with the necessary analytical techniques associated with PGNAA as well as using the ICP-AES machine purchased last year with INIE funds. This work establishes the usefulness or otherwise of a particular capture compound and forms an integral part of this student's Ph.D. thesis research.

Explanation: A necessary requirement for a new boron delivery compound is to attain selective uptake in tumor compared to normal tissue; to be uniformly distributed in all tumor cells and to reach absolute concentrations in tumor in the 20-30 ppm range. These studies are aimed to optimize administration of the compound to determine how best to maximize these requirements and are a pre requisite for efficacy studies. This research project is conducted for NCT researchers from all over the country at the INIE funded MIT NCT User Center.

Title: Hypoxic sensitizers as a boron delivery agent for neutron capture therapy (MIT)

Objective: To determine if boron containing pimonidazole can deliver boron to hypoxic tumor cells.

Status: Initiated this year. Radiobiology studies are being performed by Jugal Shah an MIT NSE undergraduate student. This research is being carried out as part of MIT's undergraduate research opportunity project (UROP). Tumor models developed in mice are being assessed for hypoxic fraction using immuno histological staining of tissue sections after injection with pimonidazole. Boron containing pimonidazole that was synthesized by an outside research group at McLean Hospital (Belmont, MA) has also been administered and the concentration of boron in liver and tumor are being quantified using ICP-AES and PGNAA. Substantial support was provided by INIE for this work.

Explanation: This work seeks to evaluate and develop a newly synthesized nitroimidazole-carborane as a prospective compound for boron neutron capture therapy (BNCT) in the treatment of cancer. The use of a hypoxia-targeted boron compound may provide a more selective and homogeneous distribution of boron in solid tumor than hitherto achieved with the FDA approved boronated amino acid boronophenylalanine (BPA). The hypothesis to be tested is that combining the boronated nitroimidazole with BPA will be more effective than employing BPA alone in destroying solid tumors with a significant hypoxic fraction during cancer therapy with BNCT. The purpose is to first demonstrate and then optimize delivery of boron to the hypoxic portion of a tumor in preparation for efficacy experiments.

Title: Experiments performed at the MIT NCT User Center during the report year 2005/2006 with reactor beams and staff assistance (MIT)

- A tumor growth delay study using (coated and loaded) liposome-mediated BNCT for mice bearing EMT-6 tumors (Prof Fred Hawthorne et al., UCLA)

- Two series of irradiations for a quantitative evaluation of a colorimetric assay to test efficacy of different boron containing compounds (Ms Yoonsun Chung Ph.D. candidate, Nuclear Science and Engineering)

- Uptake and biodistribution studies with two different formulations of boron containing liposomes in EMT-6 and SCCVII tumors and normal tissues (Prof Fred Hawthorne et al., UCLA)

- Selective irradiation of the vascular endothelium and a study on the survival of intestinal crypt stem cells in mice using BPA as a control (Prof Jeff Coderre, Nuclear Science and Engineering, MIT).

- To evaluate the efficacy of BNCT following convection enhanced delivery (CED) of the boronated porphyrins H_2TCP and H_2TBP with or without i.v. BPA in rats bearing intracerebral F98 gliomas (Prof Rolf Barth et al., Dept. of Pathology Ohio State University and Prof Maria da Graca Vicente Dept. of Chemistry, Louisiana State University)

- Determination of the dose response for vascular endothelial cell apoptosis with targeted irradiations in an epithermal neutron beam using boronated liposomes and BPA as a control (Prof Jeff Coderre, Nuclear Science and Engineering, MIT)

- A comparison of the effectiveness of boronated liposomes versus BPA in retarding the growth of SCCVII tumors hosted in mice. (Prof Fred Hawthorne et al., UCLA)

- Uptake studies and basic biodistribution investigations of boronated unnatural amino acids in tumor bearing mice using both PGNAA and ICP analyses (Prof George Kabalka, Dept of Chemistry, University of Tennessee)

- To evaluate the efficacy of BNCT following convection enhanced delivery (CED) of boronated monoclonal antibodies C225 and L8A4 in rats bearing intracerebral mixed $F98_{EGFRWT}$ and $F98_{EGFRvIII}$ gliomas (Prof Rolf Barth et al., Dept. of Pathology, Ohio State University)

- Evaluation of neuropathological effects of BNCT following CED of N5-2OH (Prof Rolf Barth et al., Dept. of Pathology, Prof Werner Tjarks et al., College of Pharmacy, Ohio State University)

- A series of nine (2 in the 3GV and 7 in the thermal neutron beam) irradiations of prepared tissue samples for developing HRQAR in the laboratory (Mr Tom Harris MS candidate, Nuclear Science and Engineering, MIT)

- Incidental boron assays of both biological specimens and compound formulations using the prompt gamma neutron activation analysis beam line for numerous users.

- Dosimetric measurements and calibration of the thermal neutron column at the RINSC to assist in the development of the facility for in-vitro studies of NCT (M. Middleton, Rhode Island Nuclear Science Center, RINSC)

- A pilot study to investigate the role that damage to the vascular endothelium plays in molecular and cellular signaling (via up regulation of TNF-alpha and ICAM-1 genes) in tissue following exposure to radiation. (Mr B. W. Schuller Ph.D. candidate, Nuclear Science and Engineering, MIT)

- To evaluate the efficacy of BNCT following convection enhanced delivery (CED) of boronated C225 in combination with either i.v. or i.c. administration BPA+BSH in rats bearing intracerebral $F98_{EGFR}$ gliomas.

Title: Distance Learning Capabilities (UMass-Lowell)

Objective: Goals for University of Massachusetts – Lowell (UML) Distance Education Initiative include:

- Provide a variety of educational resources to the nuclear engineering community (reactor physics, reactor operations, modeling & analysis examples, etc.)
- Provide a direct link to data from a real operating research reactor -- archival and real-time data.
- Share the unique capabilities of the UMLRR and the UML NE Program beyond the physical boundaries of UMass-Lowell.

Status: On-going

Explanation: Recent improvements to the UMass Lowell Distance Education Infrastructure have included the capability for real-time interaction using web-based browser type applications. Applications sharing has allowed for the infrastructure investments to be shared with users outside of the UMass-Lowell Research Reactor both on the UMass Campus and to the wider world.

Title: Virtual Radiography Console (UMass-Lowell)

Objective: Develop a virtual radiography console.

Status: Continuing

Explanation: UMass Lowell has developed a virtual console that integrates with the digital neutron radiography facility. The virtual console allows students and researchers to engage in digital neutron imaging without entering the research reactor. This initiative reduces security concerns and eliminates outside personnel radiation exposures. System has been demonstrated over broad geographical distances to be effective in allowing for remote radiography sample analysis and manipulation. Presented findings of the educational and research uses of remote digital neutron radiography at the IEEE Nuclear Science Symposium Farajdo, PR (Nov. 2005).

Title: Controls Development Training Kit (UMass-Lowell)

Objective: Help develop the content needed for training students to effectively utilize the UML Reactor Online.

Status: Continuing

Explanation: Students and faculty utilized the OPTO-22 Distance Educational Experimental Control Development tool kit over the course of the summer recess.

Title: Neutron Scattering Upgrade (RINSC)

Objective: Upgrade one goniometer Beam Port #2 in order to allow continued and improved student laboratories and research.

Status: Continuing

Explanation: Dr. Anthony Nunes of the URI Physics Department is responsible for upgrading one goniometer in Beam Port #2. A Undergraduate student from the Physics Department at URI will be completing the calibration of the unit and provide support as necessary to bring web based neutron scattering laboratory exercises to the Physics Department on the main campus. Preparation is underway to upgrade a second goniometer Beam Port #5. The second system will incorporate an existing 1-D Position sensitive (1 meter) He3 gas neutron proportional Detector. This project will significantly reduce collection time and make it more attractive to outside researchers.

2. Research Innovations

Title: Annular Fuel Project (MIT)

Objective: The purpose of this project was to develop and optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins by determining fission gas release rates and fuel dimensional and structural changes during irradiation by achieving a range of burnups to identify potential performance differences among the fuel types. The annular fuel specimens were designed so that, with the combination of enrichment, inner and outer annulus dimensions, and gap thermal properties, the fuel heat temperature would be similar to that of a reference reactor design. The project is under the direction of Professor Mujid Kazimi, Professor Pavel Hejzlar, and Dr. Gordon Kohse.

Status: Completed. INIE funds used for equipment.

Explanation: The annular fuel operates at very low temperatures compared to the current PWR solid cylindrical fuel. However, the fuel is manufactured by vibrational packing of powder, which may increase the ability to relocate and to release fission gases. Thus the measurements would help in the assessment of the suitability of this manufacturing process for commercial deployment in future

PWRs. This was the first time that a new fuel design was examined in a university research reactor.

Title: High Temperature Irradiation Facility (HTIF) (MIT)

Objective: The High Temperature Irradiation Facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials.

Status: Completed. Project completely supported by INIE.

Explanation: in November 2005, this in-core loop was installed in the MITR. A demonstration test was performed with temperatures up to 1600 °C. A variety of materials relevant to high temperature gas reactor design, including SiC, AGR matrix graphite and non-fueled coated particles, were irradiated. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs. This facility will be a valuable test facility for high temperature resistant materials research.

Title: Neutron Phase Contrast Imaging Project (MIT)

Objective: The Neutron Phase Contrast Imaging Project has the goal of providing the MIT reactor with a state-of-the-art neutron imaging system capable of exploiting the phase contrast edge enhancement effect. The project's aim is twofold: the imaging facility can be used for industrial and research purposes, notably in the study of materials; the system will provide great educational value, by giving insight on the experimental functioning of neutron phase contrast and by providing a facility to test new ideas.

Status: Continuing. INIE provides both equipment and student support.

Explanation: Phase contrast imaging uses the wave properties of neutrons to greatly increase spatial resolution and contrast in materials imaging. A beamline and detector system for implementing this technique was installed at the MIT Nuclear Reactor Lab. Recently a new approach is being examined which can lead to phase tomographic imaging which enables us to three-dimensional images to be produced of materials which cannot be distinguished by their density and absorption.

Title: International Dosimetry Exchange for Neutron Capture Therapy (MIT)

Objective: To compare and summarize the results of clinical BNCT from all clinical centers worldwide.

Status: Continuing. MIT has organized an international dosimetry change for the intercomparison of absorbed dose measurements at all NCT clinical centers, worldwide. Measurements have been completed at the two centers in the US, MIT and BNL, and at four clinical centers in Europe; Petten, Netherlands; Studsvik, Sweden; Espoo, Finland and Rez, Czech Republic. MIT measurements were completely analyzed and organized into a journal publication that identified differences in the absorbed dose measured at each center. The four European centers as well as Brookhaven National Laboratory (BNL) supplied treatment plans that corresponded to the MIT measurements. These data have been compared to derive normalizations for individual dose components so that dose specifications from all of the participating institutes can be consistently expressed in terms of the trials at MIT. The derived normalizations for BNL have been independently verified by applying them in a treatment plan of the MIT ellipsoidal water head phantom for which the resulting depth dose profiles agree well with the corresponding MIT measurements. The validated normalizations have been applied for all dose components in a retrospective analysis of BNL treatment plans to examine the incidence of somnolence amongst 81 patients irradiated at BNL and MIT. Similar validations are now in progress for the remaining European centers so that results from these centers can be included in the dose response analysis for somnolence as well as other adverse events. The International Dosimetry Exchange has also spawned other related activities such as an effort to develop NCT dosimetry standards and protocols for which the already acquired data should prove useful. INIE provides support for personnel.

Explanation: BNCT clinical trials are expensive and a pooling of worldwide clinical results would greatly accelerate the development of this new treatment modality. In order to utilize the clinical results and experience of all clinical centers, and, thereby, to obtain the largest possible data base for evaluation of BNCT clinical results it is necessary to develop a sound basis for inter-comparison of irradiation doses. Dosimetry in BNCT is complicated compared to photon therapy and there is no international standard for dosimetry practice. To help overcome these difficulties and allow a comparison of all clinical results, MIT has begun an international effort to compare dosimetric measurements made by the staff of the various clinical centers and to obtain complete dosimetric characterization of the epithermal neutron beams at all clinical centers. Most of the support for this research has come from the DOE OBER but INIE support was also needed to carry on this work.

Title: Basic Radiation Biology (MIT)

Objective: One of the major unresolved issues in radiation biology is the understanding of underlying mechanisms that produce normal tissue damage following radiation. One hypothesis tested is that damage to the micro-vasculature is the initiating event in tissue damage. It has long been assumed that early effects are due to damage to the rapidly dividing stem cell populations and that late effects are due to damage to the more slowly growing blood vessels. However, several recent, and controversial, reports have suggested that microvascular damage is causative in the acute radiation syndrome: the loss of intestinal crypt stem cells and the subsequent development of the gastrointestinal syndrome. Future studies will use the selective vascular approach to investigate the signaling pathways that lead to late effects in normal tissue months or years after irradiation.

Status: Continuing. A novel method has been developed for selective irradiation of the microvasculature that allows direct experimental testing of the role of the vasculature in normal tissue radiation response. A boron compound has been prepared that will remain inside the blood vessels. The short path length of the radiations from the boron neutron capture reaction allows irradiation of the blood vessel walls but not the surrounding functional cells.

Explanation: Consistently reproduced data indicate that damage to the blood vessels are not the cause of the gastrointestinal syndrome. These studies could have significant implications for the development of agents to protect normal tissues during radiation therapy or to treat normal tissues after accidental radiation exposure.

Title: Hypoxic sensitizers as a boron delivery agent for neutron capture therapy (MIT)

Objective: The hypothesis to be tested is that the use of nitroimidazole-carborane may provide a more homogeneous distribution of boron in tumor than the current clinically approved boron carrier and that improved biological efficacy in BNCT can be demonstrated using the combination of boron carriers. This is to be tested using a squamous cell carcinoma (SCCVII) in mice that is known to develop tumors with hypoxic.

Status: To determine if boron containing pimonidazole can deliver boron to hypoxic tumor cells.

Explanation: A limitation with tumor seeking agents is that drug delivery is dependent upon sufficient vascularization within the tumor itself. Yet the morphology of most tumors is associated with a dense necrotic and hypoxic core with limited vascularity. Thus, most anticancer agents cannot be effectively delivered into a necrotic region. This can be a major impediment to any treatment because some tumor cells in this hypoxic region drop out of the proliferation compartment. These G_0 cells are radio-resistant and thus capable of re-growth if the target atoms required for the binary therapy system are not delivered to these sites. In principal BNCT is well suited to treating poorly oxygenated tumors since the reduced radio-sensitivity in the absence of oxygen observed with photons is less pronounced for high LET radiations. However, to ensure a uniform absorbed dose in all parts of the tumor, there is a need to develop new boron carriers that are less dependent on good blood flow as for BPA and that are capable of delivering boron compounds to cells in the poorly vascularized and poorly oxygenated regions of the tumor.

Title: Determine and Validate Source Term for Treatment Planning System of MIT Epithermal Neutron Beam with Lithium-6 Filter (MIT)

Objective: To modify the treatment planning system (TPS) used for BNCT with the FCB to incorporate the use of ^{6}Li filtered fields.

Status: Completed. A ^{6}Li filter system was designed, constructed and fully characterized with INIE funds as described in last years report. The new beam characteristics with the filter installed were computationally modeled with MCNP and benchmarked by measurements. The computational aspects of this project were performed by Ray Albritton a PhD student in NSE working in the Department of Radiation Oncology at the Beth Israel Deaconess Medical Center.

Explanation: To implement the use of the new optional ^{6}Li beam filter for therapy, the treatment planning system used to calculate the dose prescription required modification. In particular MCNP calculations must determine a new source description for the filtered beam at the exit plane of the patient collimator. This source description is then transported into a realistic shaped phantom in which measurements have been performed. Scaling the calculations to the measured results effectively calibrates the TPS for therapy with the new beam configuration.

Title: Nanofluids (MIT)

Objective: The goal of this project is to investigate the heat transfer enhancement of water-based nanofluids.

Status: Continuing. INIE provides equipment and student support.

Explanation: Dr. Lin-Wen Hu and Professor Jacapo Buongiorno are pursuing an experimental study of water-based nanofluid heat transfer enhancement. Nanofluids are engineered colloids made of a base fluid and nanoparticles (1-100 nm) in various forms. The presence of the nanoparticles produces four major effects on the thermal-hydraulic behavior of the fluid. These are: increase of the thermal conductivity, increase of the viscosity, increase of the single-phase convective heat transfer, and increase of Departure from Nucleate Boiling (DNB) heat flux. The occurrence and magnitude of these effects depends on nanoparticle loading, material and shape, in ways that are not clear yet. Given their potential for superior heat removal performance, nanofluids are being investigated for numerous applications, including electronics, manufacturing, chemical processes, cosmetics, pharmaceuticals, power generation, etc. A research program was initiated as a collaboration between the NRL and NSE to assess the feasibility of nanofluids for nuclear applications. In principle, the use of water-based nanofluids could improve the performance of any water-cooled nuclear system that is heat removal limited. Potential applications include Pressurized Water Reactor (PWR) primary coolant, standby safety systems, accelerator targets, plasma diverters, etc. The program comprises the following activities, which are currently sponsored by the Idaho National Laboratory (INL), NRC, AREVA/Framatome and DOE's Innovations in Nuclear Infrastructure and Education (INIE) grant. Two out-of-pile loops are being built to investigate the nanofluids heat transfer enhancement.

- Procurement of water-based nanofluids, i.e., C, SiO2, ZrO2, Al2O3.
- Property measurements: thermal conductivity (transient hot wire method) and viscosity (ultrasonic viscometer).
- Property modeling with Molecular Dynamics simulations.
- Single-phase heat transfer and pressure drop measurements in flow loop.
- Single-phase heat transfer modeling, both conceptual and CFD.
- Critical Heat Flux (CHF) measurements: experiments with heated wire and in flow loop with PWR-equivalent annulus and Zircaloy heated surface.
- Nuclear application evaluations: subchannel, safety and neutronic analyses of PWRs with nanofluid coolant.

Title: Neutron Beam Line Optimization and Upgrade (UMass-Lowell)

<u>Objective</u>: Refurbishment of the neutron radiography collimator system to reduce scatter and increase the L/D of the thermal neutron beam.

<u>Status</u>: Continuing. INIE provides all support.

<u>Explanation</u>: These improvements include: evacuating both sections of the 8 meter beam line flight path to remove air scatter. In addition, MCNP modeling of the current facility is underway. This will allow for an optimized beam line configuration to be developed and benchmarked.

Title: Imaging Plate X-ray and Neutron Radiography (UMass-Lowell)

Objective: Encourage additional research support in the area of neutron and x-ray radiography at UMass-Lowell

Status: Continuing. INIE provides all support.

Explanation: UMass Lowell has developed a virtual console that integrates with the digital neutron radiography facility. The virtual console allows students and researchers to engage in digital neutron imaging without entering the research reactor. This initiative reduces security concerns and eliminates outside personnel radiation exposures. System has been demonstrated over broad geographical distances to be effective in allowing for remote radiography sample analysis and manipulation. Presented findings of the educational and research uses of remote digital neutron radiography at the IEEE Nuclear Science Symposium Farajdo, PR (Nov. 2005).

Title: Gadolinium Cancer Research Project (RINSC)

Objective: Determine the radiation responses of three brain tumor cell lines to single, graded doses of low linear energy transfer (LET) x-rays and to high LET neutrons. The cell lines are 9L/lacZ, C6/lacZ, and F98.

Status: Continuing. INIE provides all support.

Explanation: The main findings from this work are:

- The three cell lines differ in their responses to conventional x-ray treatment. They are all relatively radioresistant, as noted by their survival at a typical dose in radiation therapy of 2 Gy (SF_2). The average survival after x-irradiation in these 3 lines is 84.3%.

- The data implies that for x-ray therapy of brain tumors, that after 30 fractions, the resulting survival would be 0.006%. But, as brain tumors typically contain 10^9 or more cells, this would suggest that the survival of the entire brain tumor would be reduced to 6 x 10^6 cells. This is a far cry from the clinical need to reduce the number of surviving cells to less than one to produce a chance for a cure. Note, this illustration is simplistic: it neglects cell proliferation, cell hypoxia, and cell migration and invasion (see below), all of which modulate the resultant survival.

Table 1

Cell Line	Single-Hit, Multi-Target (SHMT) X-ray Response Parameters		
	Extrapolation Number (n)	**Quasi-Threshold Dose (D_q, Gy)**	**Inactivation Dose (D_0, Gy)**
9L/lacZ	5.0	4.2	2.6
C6/lacZ	3.5	2.6	2.1
F98	4.2	2.5	1.7

The SF_2 for the 9L/lacZ, C6/lacZ, and F98 cells are respectively 90, 90, and 73%

For thermal neutron irradiation, there is a marked decrease in survival due to the high LET nature of a neutron beam. The survival parameters are listed in the Table below.

Table 2

Cell Line	Single-Hit, Multi-Target (SHMT) X-ray Response Parameters		
	Extrapolation Number (n)	**Quasi-Threshold Dose (D_q, Gy)**	**Inactivation Dose (D_0, Gy)**
9L/lacZ	5.0	1.9	1.2
C6/lacZ	4.0	1.4	1.0
F98	3.0	1.0	0.9

The SF_2 for the 9L/lacZ, C6/lacZ, and F98 cells are respectively 42, 38, and 28%

The implications for the thermal neutron survival data are:

- The decreased survival is shown by the decrease in the extrapolation number (n), the reduced inactivation slope (D_0) and by the decrease in SF_2. Indeed, the average SF_2 is now 36% which is a reduction of about 57% from the x-ray data.

- A reduction of over 50% in the SF_2 by the high LET neutron irradiations would seem to be a worthwhile reduction in survival. However, comparing this to x-rays, this would reduce the percentage survival after 30 fractions of 2 Gy to 5.5 x 10^{-8}. Again, using a tumor containing 10^9 cells, this would suggest that about 55 cells would survive a multifraction treatment with neutrons. Again, this is markedly different from “less than one cell” as described above.

Title: Weapons of Mass Destruction and Environmental Pollution Sensor Research (RINSC)

Objective: Research and Development of underwater sensors at RINSC.

Status: Continuing. INIE provides all support.

Explanation: Dr. Alfred Hanson of the URI Graduate School of Oceanography is utilizing six of his graduate students from the Chemical Oceanography Department. in the research and development of underwater sensors at RINSC. There are two general applications for the submersible chemical analyzers that are the focus of the research effort:

- **Environmental Pollution:** Water quality monitoring of chemical and biological contaminants such as nutrients, trace metals, coliform bacteria, and radiochemicals (NOAA, EPA, ONR).

- **Coastal Security – Ocean Observation Systems:** Detection, tracking and source localization for chemicals associated with weapons of mass destruction (WMD) submerged in coastal waters. These WMD chemicals include those leaking from unexploded ordinance (i.e. submerged mines leaking TNT) and radiological isotopes associated with submerged nuclear devices or contamination (i.e. uranium series nuclides, alpha, beta, gamma radiation). (DOD, NAVY, NUWC, USCG)

For the last three years, the research focus for instrument development has become Coastal Security and we expect that emphasis will continue for several years. We are working on multiple NAVY projects that involve coastal security. We have had phase II (ONR) and phase III (NUWC) SBIR funding to develop a sensitive submersible sensor for trinitrotoluene (TNT) that can be deployed on a small autonomous underwater vehicle (AUV). We are also collaborating with URI and Nomadics, Inc. (Stillwater, OK) on a phase II STTR project for the development of a WMD sensor payload for the AUV. The WMD payload includes a TNT sensor, a radiological detector module and a sediment sample collection module. The WMD payload for the AUV is being designed to autonomously retrieve sediment and water samples that can subsequently be analyzed for radionuclides. During the next few years we expect to be developing and evaluating the radiological detectors and radiological sample collection modules for the AUV.

This emerging and very important aspect of Dr. Hansons' research requires collaborative consultation and the type of analytical and radiological source services that a facility like RINSC can provide. During the next couple of years he intends to apply for additional Federal grants for the further development of submersible radiological sensor technologies. These proposals would include requests for funds to compensate RINSC for professional consultation, reactor time, and radiological analytical services required for the development, testing and demonstration of the submersible radiological sensors.

In addition to providing opportunities for several graduate students in the field of nuclear chemistry, Dr. Hanson provided RINSC with a significant infrastructure improvement when he completed his laboratory building on the South Wing of the facility last year. This laboratory has state of the art facilities for sensor development and was constructed with the use of grants and other outside funding in excess of one million dollars.

3. Infrastructure Improvements

Title: MIT Nuclear Reactor Infrastructure Improvements

Objective**:** Improvements to reactor's infrasturcture in order to improve research and educational opportunities.

Status: Completed

Explanation:

- Completed installation of new manipulator in reactor floor hot cell #1.
- Repaired manipulators in hot cell #2
- Local and remote area radiation monitors for the hot cells are now functional.
- Parts for repair of shim blades/regulating and position indicators were purchased.
- New HPGe detector was received for NAA activities.
- Commissioning Treatment Planning System for the Fission Converter Facility with Lithium-6 Filtered Epithermal Neutron Beams
- Improved Shielding and Refueling of the Fission Converter
- High Resolution Quantitative Autoradiography
- Boron Analysis Using an Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES)
- Support Working Cell Culture Laboratory for Radiobiology Experiments

Title: University of Massachusetts – Lowell

Objective**:** Improvements to infrastructure in order to improve research and educational opportunities.

Status: Continuing

Explanation: UMass-Lowell has continued to refine and enhance their Digital Neutron Radiography Facility's capabilities. In addition, recent improvements to its Distance Education Program include:

- Centra Software
- Real-time interactivity within a web browser
- Voice over IP and Video
- Application sharing

Title: Rhode Island Nuclear Science Center (RINCS) Infrastructure Improvements

Objective: Improvements to infrastructure in order to improve research and educational opportunities.

Status: Continuing

Explanation:

- Purchased Reactor Control System automation software and hardware.
- RINSC plans to purchase the remaining hardware to implement the Process Control System automation this year. URI Senior Physics Department Student will assist in the implementation of the software and hardware for reactor control. This project's objectives have been approved for his senior project requirement.
- Purchase request of software and license to provide Web Based training to URI Physics Department and Providence College Physics Department is submitted into the RI state purchasing system. URI will be setup to do neutron scattering experiments and PC will be setup to do NAA experiments remotely.

- Work continues with the upgrade on the goniometer. Two new motors were purchased and installed to control the sample and detector swing arm. Plans to purchase new detectors and/or electronics as required this year. Another URI Senior Physics Department Student will assist in the upgrade and calibration of the goniometer. This project's objectives have been approved for his senior project requirement.

- Dr. Leith's work continues with Gd NCT. Dr. Leith will be publishing two papers in support of resubmitting the 3M NIH grant request in February 2007. RINSC has started collaborating with Albany Medical Center and associated private companies for Gd based radionuclides for medical purposes. RINSC is also collaborating with Dr. Willard of Brown University and Dr. Vittenberger of URI in applying for the Rhode Island Science and Technology Advisory Council, STAC grant through the RI Economic Development Corporation, RIEDC.

- Dr. Ott has hired Sargent and Lundy to complete the RINSC Thermal Column Filter and Medical Building design to be submitted to the NRC for design approval. RINSC and Dr. Ott are working with Dr. Glicksman of the RI Cancer Council to find financial backing for the project.

4. Intra-Consortium Integration

Title: MIT/Rhode Island Nuclear Science Center (MIT)

Objective: To assist RINSC in the development of a research program in neutron capture therapy.

Status -: The MIT neutron capture therapy research group visited RINSC and performed dosimetric measurements. with the intention of (i) demonstrating mixed field dosimetry in the thermal column where biological experiments will be performed (ii) ensuring proper set up and working of the newly acquired (using INIE funds) ionization chambers/electrometer to be used in future at RINSC, and (iii) to measure absorbed dose rates under conditions pertinent to previously performed biology experiments for future measurement comparisons by RINSC themselves.

Explanation: The Rhode Island Nuclear Center (RINSC) is developing an experimental irradiation facility for biological experiments at its nuclear reactor. The facility is a thermal neutron column that is dedicated to the development of better tumor seeking compounds for neutron capture therapy (NCT). As part of an inter consortium collaboration MIT is providing assistance to RINSC in developing the necessary skills and techniques to perform mixed field dosimetry to aid development of their nascent NCT irradiation facility. The BNCT research program at MIT is currently the leading US group in this field and with INIE support is in a position to assist RINSC with their efforts to develop a BNCT research program.

B. Funding Allocation and Execution

	NRL INIE Bernard	In-Core Mat. & Chem Ballinger	Fabr. Eq. High Temp Ballinger	Advanced Fuels Kazimi	Neutron Interfero metry Cory	Phase Contrast Imaging Lanza	NCT) Harling	Nano Fluid Heat Transfer Hu	Fabr. Eq. Pool Boiling Facility Hu	Fabr. Eq. Irradiation Jig Harling	Fabriction Lead Shield Bernard	INIE Education Bernard	Fabr. Eq. CHF In- Core Loop Hu	Fabr. Eq. Transient Hot Wire Probe Hu	Student Spectrometer Facility Bernard	TOTAL
Personnel	0	11,906	0	32,603	0	8,420	105,230	653	0	0		0	0	0	0	158,812
RA	0	0	0	0	29,499	25,400	27,680	4,856	0	0		0	0	0	0	87,435
Undergrad	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
Employee Benefitss	0	4,346	0	11,900	0	3,073	34,964	176	0	0		0	0	0	0	54,459
Travel	4,900	0	0	0	-686	503	6,959	0	0	0		0	0	0	0	11,676
M&S	47,838	227	841	0	272	1,493	18,073	657	4,475	576	13723	0	3,440	6,964	6,656	105,235
Rx Use	0	0	0	20,000	0	2,350	75,775	0	0	0		0	0	0	0	98,125
Equip	158,037	144	0	22,131	0	0	6,616	14,566	3,808	0	0	21,346	2	5,431	0	232,081
RA Tuition	0	0	0	0	17,638	15,743	17,705	498	0	0	0	0	0	0	0	51,584
UMass-Lowell*	93,036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	93,036
RINSC**	85,000	0	0	0	0	0	0	0	0	0		0	0	0	0	85,000
F&A	43,270	10,194	0	40,598	18,226	25,788	168,644	4,095	0	0		0	0	0	0	310,815
Total	432,081	26,817	841	127,232	64,949	82,770	461,646	25,501	8,283	576		21,346	3,442	12,395	6,656	1,288,258

II. Cumulative Report

B. Educational Enhancements

1. Title: Neutron Capture Therapy Center (MIT)

Description: The Neutron Capture Therapy User Center is comprised of several state-of-the-art neutron facilities for neutron capture therapy (NCT) research that have been developed and are in operation at the MITR.

Impact on Nuclear Engineering Education: More than 25 students have been supported as a result of research activities made possible by INIE. The INIE supported NCT Center has enabled professors, post-doctoral research scientists and graduate students to carry out research in the field of NCT for cancer. INIE support was essential for much of the education related NCT research from 02-03 through 05-06.

2. Title: Annular Fuel Project (MIT)

Description: The goal of this project was to develop and optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins.

Impact on Nuclear Engineering Education:

As a result of this INIE funded project, several MIT Nuclear Science and Engineering students had the opportunity for hands-on participation in cutting edge research related to the High Performance Fuel Design for the Next Generation of PWRs Project.

3. Title: SiC Duplex Advanced Clad Irradiation (ACI):

This project is under the direction of Dr. Gordon Kohse and Prof. Mujid Kazimi. This project involves the production and testing of candidate duplex SiC/SiC composite cladding materials for Light Water Reactors (LWRs). These materials have potential advantages over conventional metal alloy cladding materials in both improved safety margin and higher burnup. Irradiation testing in prototypical PWR and BWR coolant conditions began in May 2006 and will continue until the end of the year. Post-Irradiation Examination (PIE) is then planned to measure weight loss, thermal conductivity changes, mechanical property tests and scanning electron microscopy. The irradiation testing and some of the PIE are being conducted at NRL using the MITR's in-core loop facilities and hot cells.

4. Title: Ocean Engineering, Chemical Oceanography, and Atmospheric Chemistry (RINSC)

Description: The opportunity for graduate students in ocean engineering, chemical oceanography, and atmospheric chemistry to work in such areas as the CHAIOS project and the sensor projects at RINSC will strengthen a long tradition of marine scientists in the nuclear field. Due to its location at the URI Graduate school of Oceanography, RINSC has a long history of educating graduate students in the fields of neutron activation analysis, neutron scattering, and radiation studies for use in environmental and marine applications.

Impact on Nuclear Engineering Education: The INIE grant has enabled RINSC to improve the service and facilities available to these students and will ensure that another generation of graduates has these skills.

The opportunity for students in the physics department to work in the area of neutron scattering will be strengthen. The automated control system will allow for more detailed and interesting work to be undertaken. RINSC has a past history of numerous neutron scattering projects. The INIE grant has enabled RINSC to improve these facilities and make them more attractive to graduate students interested in pursuing a graduate degree in this area.

5. Title: Distance Learning Capabilities (UMass-Lowell)

Description: Recent improvements to the UMass Lowell Distance Education Infrastructure have included the capability for real-time interaction using web-based browser type applications. Applications sharing has allowed for the infrastructure investments to be shared with users outside of the UMass Lowell Research Reactor both on the UMass Campus and to the wider world.

Impact on Nuclear Science Education Programs: This remote teaching and research capability is now available to educational users with simple browser based web access.

6. Title: Virtual Radiography Console (UMass-Lowell)

Description: UMass Lowell has developed a virtual console that integrates with the digital neutron radiography facility. The virtual console allows students and researchers to engage in digital neutron imaging without entering the research reactor. This initiative reduces security concerns and eliminates outside personnel radiation exposures. System has been demonstrated over broad geographical distances to be effective in allowing for remote radiography sample analysis and manipulation. Presented findings of the educational and research uses of remote digital neutron radiography at the IEEE Nuclear Science Symposium Farajdo, PR (Nov. 2005).

Impact on Nuclear Science Education Programs: This initiative is expected to enhance interest in nuclear science by making neutron radiography potentially accessible to any interested students who possess an internet connection.

7. Title: Controls Development Training Kit (UMass-Lowell)

Description: Students and faculty utilized the OPTO-22 Distance Educational Experimental Control Development tool kit over the course of the summer recess to help develop the content needed for training students to effectively utilize the UML Reactor Online (Nuclear101.com).

Impact on Nuclear Science Education Programs: Students and faculty members were provided experiment and classroom tools that will help to develop additional materials and training content for our Distance Education Programs

C. Research Innovations

1. Title: Annular Fuel Project (MIT)

Description: In February 2004, a new type of in-core experiment was installed to test performance of an innovative annular fuel designs as a part of the Generation-IV power reactor research effort by the MIT Nuclear Engineering Department. This experiment continued into FY2005. It is the first irradiation of a fueled test capsule at the MIT reactor, and one of very few undertaken at any university reactor.

Impact on Nuclear Engineering Education: The Annular Fuel Project was very successful and the new internally and externally cooled annular fuel captured the interest of the industry and media. At the ANS conference in Reno in June 2006, the Westinghouse presentation at the special plenary session on Innovation in Nuclear Technologies by Senior Vice President and Chief Technology Officer, Regis Matzie, was fully devoted to the new annular fuel proposed by MIT and Westinghouse is putting some of their own funding into further development of this fuel. In September, Reuters published an article “Scientists Develop More Powerful Nuclear Fuel.”

2. Title: Nanofluids (MIT)

Description: Dr. Lin-Wen Hu (MIT NRL) and Professor Jacapo Buongiorno MIT NSE) are conducting research to assess the feasibility of water-based nanofluids for nuclear reactors. The potential reactor applications include advanced coolants and safety systems, as well as reactor cavity flooding for in-vessel retention during severe accidents.

Impact on Nuclear Engineering Education: This project is a perfect example of how INIE has and can impact nuclear engineering in the U.S. The research being conducted on this project is cutting edge and as a result has several undergraduates and graduate students working along side Dr. Hu and Professor Buongiorno. However, on a much larger scale, it is also attracting a lot of attention among nuclear engineering students across the country and the nuclear engineering community.

3. Title: Investigation of CMOS Line Camera (UMass-Lowell)

Description: UMass Lowell has collaborated with *Envision* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate a CMOS line camera that contains the inorganic scintillator gadolinium-oxysulfide for use in neutron radiography.

Impact on Nuclear Science Education Programs: This innovation is expected to encourage additional research support in the area of neutron radiography.

4. Title: Dual X-Ray and Neutron Imaging Capability (UMass-Lowell)

Description: UMass Lowell plans to investigate the efficacy of combining x-ray capabilities into the digital neutron radiography facility.

Impact on Nuclear Science Education Programs: This innovation will provide the combination of both x-ray and neutron produced images that may prove useful for assessing object properties, and thus encourage additional research support.

5. Title: Neutron Beam line Optimization and Upgrade

Description: The existing UMass Lowell neutron radiography collimator system has been refurbished and upgraded to reduce scatter and increase the L/D of the thermal neutron beam. These improvements include: evacuating both sections of the 8 meter beam line flight path to remove air scatter. In addition, MCNP modeling of the current facility is underway. This will allow for an optimized beam line configuration to be developed and benchmarked.

Impact on Nuclear Science Education Programs:
These innovations are expected to encourage additional research support in the area of neutron and X-Ray radiography at UMass Lowell.

6. Title: Imaging Plate X-ray and Neutron Radiography

Description: Utilizing INIE funding, a Fuji BAS 5000 Imaging Plate and Reader system was procured and installed. This system allow for both neutron and x-ray images to be read into the same formats. Using our upgraded beam line and an existing X-Ray exposure unit at UMass Lowell, preliminary studies have been performed as to the X-Ray and neutron sensitivity of the new system.

Impact on Nuclear Science Education Programs: These innovations are expected to encourage additional research support in the area of neutron and X-Ray radiography at UMass Lowell.

D. Infrastructure Improvements

1. Title: MIT Neutron Capture Therapy User Center

Description: INIE has supported a significant part of the upgrade of the MITR based NCT thermal neutron irradiation facility. This includes automated beam shutters, improved shielding in the medical room in preparation for new clinical studies. INIE support has also made possible the implementation of a Lithium-6 filter for the epithermal neutron (FCB) medical irradiation facility. This enhancement to the FCB significantly improves the useful penetration of this epithermal neutron beam.
All the necessary technology, pre-clinical studies and approvals (11 separate approvals from government entities and local review boards) were obtained to allow initiation of clinical studies of NCT. Several phase I and phase I/II have been carried out at the MITR in recent years. Control of melanoma metastases was observed in a significant fraction of the patients with this type of cancer. Further clinical studies are planned and INIE support will be essential to these studies

Impact on Nuclear Engineering Education: With INIE support MIT has established a neutron capture therapy user center to meet the needs of all U.S. researchers in this field. With the closure of the Brookhaven Medical Research Reactor (BMRR), the MIT neutron facilities for NCT research are the only ones in the USA capable of supporting a full range of research from pre-clinical to clinical irradiation studies. Currently the MIT NCT User Center is essential to the research activities of a number of university, industry and hospital-based NCT research groups and meets or exceeds the capabilities that once existed at BMRR. Activities under the NCT User Center have grown during each of the three years of INIE funding measured by the numbers of experiments and users supported as well as the number of undergraduate and graduate students who have benefited from the support provided by these funds.

2. Title: Nanofluid Program

Description: The INIE funding allocated for the nanofluid program in FY 2005 was used to purchase parts/equipments for the experimental facilities listed below. These facilities and associated instrumentations are now part of a Thermal Hydraulics Laboratory supported jointly by the Nuclear Science and Engineering Department and the Nuclear Reactor Laboratory. These facilities can be utilized for future research projects in general heat transfer and two-phase flow research as well as teaching at both undergraduate and graduate levels.

b) ***Single-phase heat transfer loop*:** This is a pressurized forced convection loop which is designed and constructed by MIT student and staff to investigate nanofluid heat transfer and pressure drop characteristics in laminar and turbulent flow regimes. Initial experiments of DI water and alumina and zirconia nanofluid experiments were completed.

c) ***Title: Critical Heat Flux (CHF) loop:*** The CHF facility is being constructed to obtain flow CHF data for different types of nanofluids which do not currently exist in the literature. The design of the heated section was modified this year and is currently under pure water testing.

d) ***Title: Pool boiling Facility**:* This apparatus is designed to understand the fundamental CHF mechanism. This facility is equipped with a thin Indium-Tin-Oxide (ITO) heater deposited over a sapphire substrate to provide a direct bottom-up view of the boiling phenomena on the heater surface, and an optical probe for measuring bubble size distribution. Initial tests are being conducted to verify the performance of the facility and the optical probe.

Impact on Nuclear Engineering Education: These facilities can be utilized for future research projects in general heat transfer and two-phase flow research as well as teaching at both undergraduate and graduate levels.

3. Title: Advanced Materials Testing Facility (AMTF):

Description: In 2001, MIT recognized the need for an Advanced Materials Test Facility (AMTF) and proposed the assembly of such a facility at the MITR under INIE. Procurement and installation of equipment for this state-of-the-art facility is on-going and includes upgrades to the MITR's existing hot cells which are used to support in-core experiments. The combination of the AMTF and MIT Research Reactor (MITR) will be ideal for carrying out the more basic components of the research on materials in a radiation environment. The AMTF offers good geometric access and room for up to three independent irradiation tests, it has a sufficiently high in-core flux to simulate accurately the radiation environment in PWR/BWR power reactors, and there is an ability to control the chemistry and thermal fields to reflect prototypic conditions.

Impact on Nuclear Engineering Education: The establishment of this research capability enables future examinations of advanced fuels to be done, with benefits to the national industry and to the government program on advanced fuel cycles (AFCI) with the added benefit of student participation in research that will affect the design the next generation of PWR reactors.

4. Title: Reactor Upgrades

Description: Funds received under the INIE program have allowed the MIT Nuclear Reactor Laboratory (NRL) to make several necessary upgrades to its 5 MW research reactor but has also supported the design and implementation of several facilities that will greatly increase the NRL's research reactor's capability to support and conduct faculty and outside user research. These improvements include:

- Hot Cell Manipulator: One large through-wall telemanipulator assembly has been ordered from Central Research Laboratories. This system is currently being built and will be installed into the Hot Cell #1 facility to replace the existing manipulator system which has aged through many years of use and lacks key replacement parts.

- Ventilation and HEPA Filter System Replacement for Hot Cells: The ventilation duct work and its HEPA filter assembly were replaced with upgraded units for operation of reactor Hot Cell #1 and #2.

- Hot Box Assembly: This is a steel / lead hot box that was transferred from the DOE Brookhaven National Laboratory for use in post-irradiation analysis at the MIT Research Reactor. The INIE grant supported its transfer from Brookhaven and installation / assembly at the MIT reactor.

- Manipulators for the Hot Box Assembly: Two sets of manipulator were rebuilt with new parts and components. They have been installed at the new Hot Box for handling of radioactive samples.

- Hot Box Fire Alarm and Suppression Systems: The Hot Box interior was equipped with new fire detection (with local alarm and remote warning in the reactor control room) and fire suppression systems. The original assembly did not have these provisions. Since sample-cutting work is a key part of post-irradiation analysis, this fire system is a necessary feature.

- Area Radiation Monitors: The Hot Cell #1 facility and the new Hot Box were equipped with new radiation monitors that provide both local and remote readouts and trip alarms. The INIE grant also supported their calibrations and cable installation by the reactor staff.

- Reactor Primary Pump (x2): The two main reactor primary coolant pumps were replaced with two new variable speed pumps. The new pumps are controlled via variable frequency drives (VFDs) for improved energy efficiency and performance. All associated piping, some valves and some pressure gages were also replaced for conformance to new ANSI standards.

- Reactor Secondary Pump (x2): The two main reactor secondary coolant pumps were replaced with two new variable speed pumps. This upgrade replaced the old secondary pumps in service for many years. These new pumps are also controlled via variable frequency drives (VFDs) for improved energy efficiency and performance. All associated piping, some valves and some pressure gages were also replaced for conformance to new ANSI standards. The replacement of the secondary coolant pumps was timed together with the replacement of the primary pumps to ensure system flow / pressure balance during operation.

- Upgrade of the Inductively-Coupled Plasma (ICP) Analyzer: The reactor's ICP Analyzer was upgraded for post-irradiation sample analyses.

- Upgrade of Control Room Shim Blade Position Indicators: The position indicator system for the six reactor control shim blades and for the regulating rod will be replaced. The original units were surplus equipment from the DOE and have been in service since 1958. Spare parts are no longer manufactured and components replacement has been impossible. The upgrade will provide better response and user-friendly indication for the console operator.

- Multi-Channel Reactor Temperature Data Acquisition and Analysis System: This data-conditioning analyzer will be installed in the control room for use with the reactor multi-point temperature recorder. It will replace the use of paper charts and printing supplies for reactor temperature recording and storage.

5. Title: High Temperature Irradiation Facility (HTIF) (MIT)

Description: The High Temperature Irradiation Facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials and in November 2005, this in-core loop was installed in the MITR. A demonstration test was performed with temperatures up to 1600 °C. A variety of materials relevant to high temperature gas reactor design, including SiC, AGR matrix graphite and non-fueled coated particles, were irradiated.

Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs.

Impact on Nuclear Engineering Education: This INIE funded facility represents a major achievement for the MIT Nuclear Reactor Laboratory. The HTIF provides a unique capability among university research reactors. It will be used to irradiate candidate GEN-IV materials and will contribute to the national research mission in nuclear energy through the use of this facility. This facility will not only be a valuable test facility for high temperature resistant materials research but will also be an important teaching facility for both undergraduate and graduate students.

6. Title: Digital Neutron Radiography Facility

Description: UMass Lowell has continued to refine and enhance their digital neutron radiography facility's capabilities. Improvements have been instrumental in developments that will lead to a Level 1 neutron radiography capacity at UMass Lowell.

Impact on Nuclear Science Education Programs: The UMass Lowell digital neutron radiography facility is unique in the northeast region, and therefore offers students the potential to use non-destructive testing in research.

Title: Distance Learning Infrastructure

Description: Recent improvements to the UMass Lowell Distance Education Infrastructure include the following:

- Uses Centra Software
- Real-Time interactivity within a web browser
- Voice Over IP and Video
- Application sharing

Impact on Nuclear Science Education Programs: These infrastructure improvements have helped to facilitate INIE Inter-Consortium collaboration. An example of this was demonstrated on 5/5/06 when NE students from Univ. Illinois were able to participate in an "approach to criticality" laboratory with UMass Lowell students.

E. Partnerships with DOE labs, colleges and universities, utilities, and other public/private entities

MIT

Through the INIE supported NCT User Center, collaborative research activities have been established with 10 university research groups that are engaged in NCT research. A collaboration in the NCT area with consortium partner RINSC is currently under development. Collaborations have also been developed with clinical researchers at two Boston area hospitals. Currently this collaboration is focused on the evaluation of clinical BNCT worldwide and on the development of new BNCT clinical trials using the specialized medical irradiation facilities at MITR. One collaboration has been developed with private industry and one with a DOE national laboratory to support DOE-sponsored SBIR grants. Table III is a summary of academic, research staff and students at other institutions (besides MIT) supported by experiments performed at the NCT User Center. The research of these groups and individuals depends on the availability of the NCT User Center.

UMass-Lowell

UMass Lowell has partnered with *Envision Corporation* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate an x-ray CMOS line camera for use in neutron radiography.

RINSC

The cancer research group has partnered with MIT, RI Cancer council, Brookhaven National Lab, Brown University, The University of Rhode Island and The University of Connecticut. Dr. Ott has partnered with Argonne National Lab in the development of his filter. The atmospheric Chemistry group is part of the CHAIOS Group that includes UNH, MWO, UVA, UCSD, UCLA, Heidelberg and SML.

RINSC has two other private entities who make extensive use of the facility. BioPhysics Assay Laboratory, Inc. (BioPAL) specializes in high-precision alternatives to traditional, radiolabeled life science products. Their products are labeled with stable (nonradioactive) isotopes and are used in an analogous fashion to their radioactive counterpart. The analysis of stable tracer(s) in samples of interest is performed by BioPAL using neutron activation technology at RINSC In many cases, this approach provides information with improved sensitivity and specificity well beyond that achievable by optical markers and traditional radiolabels. Microinorganics Inc. does analytical consulting in the areas of trace metal analysis of water columns. This company has done extensive work for the Rhode Island Department of Health, the Narragansett Bay Commission and various other state and federal agencies. It has done analytical work on numerous rivers and other bodies of water such as the Narragansett Bay to determine trace contaminant concentrations at levels much below that normally achievable. RI Consultants LLC also has a laboratory at RINSC for the development of custom radio-nuclides. It has been successful in developing a P-32 stint for angioplasty and p-33 labeled drugs.

F. University Commitment

Massachusetts Institute of Technology and the UMass-Lowell continue to provide the resources necessary to operate their university research reactors. The funding provided by INIE reinforces these universities' commitment to their research reactors and nuclear engineering and science programs.

RINSC is the only state operated research reactor. As such, it serves the educational, research and commercial sectors of the entire state of Rhode Island and the Northeast region. Its oversight body is the Rhode Island Atomic Energy Commission that is composed of a member from the University of Rhode Island, Providence College, Brown University, the Massachusetts Institute of Technology, and the Army research Center, Natick, Massachusetts. The state legislature has shown continued commitment to the center by approving annul budgets that provide for over 80% of the cost of operating the facility. The state has also supported a strong five year capital budget which has funded several major projects including new roofs, air conditioning systems, outside building preservation, parking lots and asbestos abatement. This capital budget includes a 30 million dollar unfunded line item for decommissioning the reactor which is reviewed by the legislature every year. The reactor was converted to LEU fuel in 1993. As part of this conversion, a new compact core was installed which required the Department of Energy to supply new primary pumps, heat exchangers and associated piping. Subsequent DOE reactor instrumentation grants have resulted in new electronic instrumentation for the reactor. As a result of an extensive repair and replacement program, the reactor and the entire facility are in excellent material condition and ready to perform well for another licensing period. The RIAEC has applied to the Nuclear Regulatory Commission to re-license the reactor for an additional 20 years.

G. Leveraging

As a result of INIE, MIT has been able to expand as well as extend its services to countless number of scientists, researches, private industry, national laboratories, and nuclear engineering students. Further, several research projects would never have had the opportunity to go forward had it not been for the funds that INIE provided. A sampling of projects that have had significant resulted in significant leveraging are listed below:

- Annular Fuel. The purpose of this project which was to develop and to optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins and will assist the research for the next generation of research reactors. This was the first time that a new fuel design was examined in a university research reactor. Additional testing will now be completed at Idaho National Laboratory.
- High Temperature Irradiation Facility. This facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs. This facility will not only be a valuable test facility for high temperature resistant materials research but will also be an important teaching facility for both undergraduate and graduate students.
- Nanofluid Applications in Nuclear Energy Systems. This program comprises the following activities, which are currently sponsored by the INL, AREVA, and the INIE program. There is enormous leverage in this project as illustrated by the multiplicity of sponsors.
- The NCT User Center. This project has given researchers across the country an opportunity to pursue very specialized neutron capture cancer research; advancement opportunities in the area of material science which includes utilizing MIT's in-core loop abilities. (See Table III for scope of leveraging resulting from this project.)
- SiC Duplex Clad Irradiation. Although his project which involves the production and testing of candidate duplex SiC/SiC composite cladding materials for Light Water Reactors (LWRs) was not initially funded or supported by INIE, it does represent a significant leveraging effect because of the increased capabilities resulting from the upgrades to the MITR and the Advanced Material Testing Facility that made it possible for the research to be done at the NRL. A workshop on SiC cladding applications for advanced nuclear reactors was held on May 5, 2005, to present initial out-of-pile testing results of SiC cladding development, and to discuss the future testing development. This workshop was sponsored by Gamma Engineering Inc., Westinghouse Electric, Nova Tech, and co-hosted by MIT Center for Advanced Energy Systems (CANES) and Oak Ridge National Laboratory.

H. Minority Student Involvement in INIE

MIT does not keep statistics of this type for individual projects such as BNCT, in-core experiments, beam port usage, etc. Statistics are kept for student enrollment as a whole, and we note that the involvement in each INIE activity is typical of the student body. Figures for 2004 are furnished here.

	Male (%)	Female (%)	Minority (%)
Undergraduate	**57**	**43**	**47**
Graduate	**70**	**30**	**16**

UMass Lowell Radiation Laboratory	05-06	04 - 05	03 - 04	02 - 03
BS Students	2	0	0	N/A
Minorities	1			
Females	1			
MS Students	0	0	0	N/A
Minorities				
Females				
PhD Students		1	0	N/A
Minorities				
Females		1		

RINSC	05-06	04 - 05	03 - 04	02 - 03
BS Students	2	0	0	0
Minorities	0	0	0	0
Females	0	0	0	0
MS Students	2	1	1	1
Minorities	0	0	0	0
Females	0	0	0	0
PhD Students	2	2	2	2
Minorities	0	0	0	0
Females	0	0	0	0

I. INIE Impact

MIT

The first step towards strengthening university nuclear engineering programs across the U.S. is the education of the next generation of nuclear engineers and to this end INIE is proving to be a major catalyst in attaining that goal.

INIE has provided a definite impact to the nation's nuclear engineering and nuclear research reactor community. It has carried this out in two ways: 1) underscoring national interest in maintaining the U.S. position as a leader in nuclear science and engineering and 2) providing much needed funding to support that goal. At MIT, it has provided the motivation as well as the momentum to rethink the university's vision of how it can contribute to the needs of future generations in the area of nuclear science and engineering. As a result, existing research programs have been expanded upon and new research projects have been initiated.

Overall, this program has started the process of revitalizing nuclear science and engineering at MIT which is evidenced by the increase in:

- Overall student enrollment in the Nuclear Science and Engineering Department and the increased utilization of faculty and researchers;
- The number of faculty and researchers utilizing the MIT Nuclear Reactor Laboratory; and
- The number of students who wish to participate in the MIT Nuclear Reactor Laboratory's Student Reactor Operator Training Program.

In addition, INIE funds have been used in support of graduate students, infrastructure improvements, and the purchase of new equipment in support of existing and new research programs. It has also supported significant upgrades and necessary improvements to the MIT Nuclear Reactor Laboratory's equipment and instrumentation.

Finally, in order to achieve the goals originally set out by INIE, this program must continue.

UMass-Lowell

The impact of even modest DOE funds (See Table II.C) made available to UMass Lowell through the INIE program remains considerable. The money provided by DOE has created and upgrade a state-of-the-art regional digital neutron radiography facility at UMass Lowell; has helped to improve the chances of attaining tenure for a UMass Lowell assistant professor; has created research assistantships for graduate students in an environment where student funding is declining; has enhanced the reputation of the UMass Lowell Radiation Laboratory by its ability to secure DOE funding for research; has provided the impetus for establishing a collaboration with a business that manufactures imaging devices; and has gained notoriety for the UMass Lowell Radiation Laboratory through its collaboration with the Nuclear Laboratory at MIT.

The INIE funding has also provided the seed for further enhancements in our overall Distance Education and Research Initiative (DERI). Communications and interaction in the greater INIE community has lead to the development of inter-consortium collaboration with University of Illinois. This funding will help to broadcast the educational and research capabilities of UMass Lowell to the broader engineering community. Schools that do not possess an operating Research reactor will be capable of performing remote laboratory experiments from within the walls of their own schools.

It is also speculated that the INIE funding will increase the probability that UMass Lowell will obtain additional DOE funding for future research projects. The current infrastructure established by the INIE funding will be potentially available as a research facility to all interested students. Continued DOE funding for the digital neutron radiography facility also will ensure its longevity, and should increase the probability that UMass Lowell will attract more students interested in nuclear science research. Furthermore, the virtual reactor accessible from Nucelar101.com will help to integrate the UMass Lowell Research Reactor into more classrooms. The concept of a virtual console also could be expanded to include various reactor experiments, thus potentially familiarizing a variety of students with the research reactor and nuclear science in general.

IIII. Notable Accomplishments

1. Title: The MIT NCT User Center

Objective: The development and operation a user center at the MIT Research Reactor to provide BNCT type neutron irradiations and technical support to MIT as well as non-MIT researchers who do not have access to neutron beams. Status: Continuing. This center has continued successful operation in this last project year. Small animal and cell culture irradiations were performed in 15 different experiments that usually involve multiple runs. Mixed field dosimetry measurements and computations as well as assistance with experiment design and execution was also provided to the users of the NCT User Center.

Explanation: Specialized neutron facilities for neutron capture therapy irradiations are generally only available in a few locations. With the closure of the Brookhaven Medical Research Reactor a number of BNCT researchers were left without neutron irradiation facilities required for their research in radiobiology and capture compound development. To meet this need, the MIT BNCT research group has established an NCT User Center to assist MIT as well as non-MIT researchers who require specialized neutron irradiations, mixed field dosimetry and experimental design support. The INIE project has provided support needed to operate this center. (See Table III for list of researchers and activities).

2. Title: High Temperature Irradiation Facility (HTIF) (MIT)

Description: The High Temperature Irradiation Facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials and in November 2005, this in-core loop was installed in the MITR. A demonstration test was performed with temperatures up to 1600 °C. A variety of materials relevant to high temperature gas reactor design, including SiC, AGR matrix graphite and non-fueled coated particles, were irradiated. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs.

Explanation: This INIE funded facility represents a major achievement for the MIT Nuclear Reactor Laboratory. The HTIF provides a unique capability among university research reactors. It will be used to irradiate candidate GEN-IV materials and will contribute to the national research mission in nuclear energy through the use of this facility. This facility will not only be a valuable test facility for high temperature resistant materials research but will also be an important teaching facility for both undergraduate and graduate students.

3. Title: Nanofluids (MIT)

Description: Dr. Lin-Wen Hu (MIT NRL) and Professor Jacapo Buongiorno MIT NSE) are conducting research to assess the feasibility of water-based nanofluids for nuclear reactors. The potential reactor applications include advanced coolants and safety systems, as well as reactor cavity flooding for in-vessel retention during severe accidents.

Explanation: This project is a perfect example of how INIE has and can impact nuclear engineering in the U.S. The research being conducted on this project is cutting edge and as a result has several undergraduates and graduate students working along side Dr. Hu and Professor Buongiorno. However, on a much larger scale, it is also attracting a lot of attention among nuclear engineering students across the country and the nuclear engineering community.

4. Title: Digital Neutron Radiography Facility (UMass-Lowell)

Description: UMass Lowell has upgraded and enhanced their distance education capabilities using INIE funding. These efforts will be further enhanced in the coming years to allow for a broad range of experimental facilities at UMass to be made available to the broader Nuclear Engineering community.

Explanation: The UMass Lowell online reactor and neutron radiography facilities are unique in the northeast region, and therefore offers students, businesses, and other research institutions the infrastructure to use remote teaching and research. INIE funding is critical to help establish these facilities to there full potential.

5. Title: Research Assistantships (UMass-Lowell)

Description: UMass Lowell is using INIE funding for research assistantships.

Explanation: The research assistantships established with DOE funding have made graduate study in nuclear science affordable for several students. The research assistantships also increase the probability that UMass Lowell attracts competitive students interested in nuclear science.

6. Title: Cancer Research Project (RINSC)

Description: INIE funding has enabled RINSC to bring together an eminent group of researchers to tackle the difficult task of developing an effective agent for use in neutron capture therapy of brain cancers. This treatment protocol utilizes the large aperture neutron beam capability of a research reactor to target the diffuse nature of certain brain cancers and has promise of treating other deep

TABLE III

NAME	INSTITUTE	PROJECT TITLE	DURATION	FUNDING SOURCE	AMOUNT
1. Prof. Rolf F. Barth	Ohio State University	a. "Molecular Targeting of EGF for the Treatment of Gliomas" b. "Carboranyl Nucleosides as Delivery Agents for Neutron Capture Therapy of Gliomas"	06/01/03 – 05/31/07 4 years	NIH 1R01 CA107367 - 01A1 Submitted to NIH Feb 2006	$1,312,752
2. Prof. Werner Tjarks	College of Pharmacy, Ohio State University	a. "Synthesis of Boron and Gadolinium Containing Texaphyrins for NCT of Head and Neck Cancer" b. "Synthesis and Evaluation of Boron-Containing Nucleosides for BNCT	07/01/03 – 06/30/05 02/01/00 – 01/31/05	Ohio Cancer Research Associates DOE	$50,000 $1,344,432
3. Dr. Michiko Miura	Brookhaven National Laboratory	" Targeted Ablation of Tumors by BNCT using Lipophilic Tetracarboranylphenyl Porphyrins"	09/01/06-08/31/08	DOE CRADA (with Morvus Technology)	$210,000
4. Prof. M. Frederick Hawthorne	University of California, Los Angeles	"Liposome Delivery of Boron for BNCT"	08/03/04-07/31/08	NIH funding 1R01 CA97342-01A2	$1,726,536
5. Prof. George W. Kabalka	University of Tennessee	"Boronated Amino Acids for NCT"		Private funding	
6.Prof. Maria da Graca Vicente	Louisiana State University	"Tumor-targeting with New Boronated Porphyrins"	Apr. 2004 – March 2007	NIH funding1R01 CA098902	$595,350

7. Prof. Stephen B. Kahl	University of California, San Francisco	"Program for Development of BNCT Agents"	2006 – 2011	NIH 1RO1 CA82478 (submitted for $250k pa from 12/1/05)	$1,250,000
8. Prof. Jeffrey A. Coderre	MIT	a. "Selective Irradiation of the Vascular Endothelium" b. "Liposome Delivery of Boron for BNCT"	07/01/04-06/31/05 08/03/04-07/31/08	Westaway Memorial Fund, MIT NIH, NCI subcontract	$50,000 $465,880
9. Dr. W. Steadman Kiger	Beth Israel Deaconess Medical Center	"NCT Treatment Planning Intercomparison"	2005-2006	Harvard Joint Center for Radiation Therapy Foundation	$45,000
10. Dr Peter Binns	MIT	"Hypoxic sensitizers as a boron delivery agent for neutron capture therapy"	03/01/06-02/28/07	David H Koch Cancer Research Fund (MIT)	$100,000
11. Prof David Lee	McLean Hospital, Harvard Medical School	"Synthesis of nitroimidazole carborane as a boron delivery agent"		Private funding	
11. Dr Stuart Green	University of Birmingham, UK	"Radiobiology studies for the evaluation of epithermal neutron beams used for BNCT"	09/01/06-08/31/09	Engineering & Physical Sciences Research Council, UK	$650,000

cancers. The RINSC team consists of Dr. Paul Willard , a noted chemist, Dr. John Leith, an experienced radio-biologist, Dr. Arvin Glicksman, an oncologist and Dr. Carl Ott, a nuclear engineer. The team has developed a gadolinium based compound and has conducted basic research starting at the cell level to prove the value of this protocol. The team is investigating the Wortmannin with the Gd compound to inhibit repair of DNA double strand breaks produced by exposure to ionizing radiation. Dr. Ott has designed a new filter that promises to improve the treatment protocol.

Explanation: INIE funding was critical to the development of this project since it takes time to put together a multi-disciplinary team and then apply for grants. Since RINSC is a state supported facility, there was no support available at the university level. Since the project has developed, it has received support from the legislature which has maintained the RINSC budget at a level adequate to support the project.

7. Title: Atmospheric Chemistry Project (RINSC)

Description: The CHAIOS Project achieved excellent results from last year's analysis efforts at RINSC. The large number of sample irradiations doubled the reactors utilization for the year. This year, the increased analysis program has added additional sampling sites, thus providing a more national result regarding halogens and their role in the pollution outflow model for the United States. INIE funding of the improvements to the RINSC counting system was crucial to the success of the project.

Explanation: RINSC as a long history of environmental research utilizing Neutron Activation Analysis and the numerous graduates of the URI Graduate School of Oceanography continue to return to RINSC with the research projects. INIE funding has a large impact on our ability to support these research efforts by allowing us to maintain our equipment at a level necessary to support these efforts.

8. Title: Sensor Research Project (RINSC)

Description: Dr. Hanson's research into underwater sensors for environmental work and detection of weapons of mass destruction has coupled the unique capabilities of the marine scientists at URI with the capabilities of RINSC to create a very talented team of researchers with the facilities necessary to take on difficult problems. The large amount of state funding that has gone into completing his laboratory would not have been possible without the initial INIE support to move the project forward. The subsequent SBIR and other grants that have continued the research and the six graduate students that are supported by the research are the result of the initial INIE help.

Explanation: RINSC serves as an incubator for small businesses and researchers who have a good idea in the nuclear field but lack funding. Dr. Hanson's research efforts have lead to commercial success. BioPal and RI Consultants also fit the mold of small startup companies that benefit from the ability to use RINSC as a base while they develop their technology. INIE funding support of RINSC enables us to support innovative ideas in the area of nuclear science as they transition from theory to practice.

Appendix D

MIT NRL INIE Annual Report 2005-2006

INIE ANNUAL REPORT

Period of Performance: 1 September 2006 - 30 September 2007

(DE-FG07-02ID14420)

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I. Yearly Report

A. Program Activities

1. Educational Enhancements

Title: Neutron Spectrometer Experimental Facility (MIT)

Objective: The MIT Nuclear Reactor Laboratory (NRL) is designing and constructing a web-enabled neutron spectrometer experimental facility.

Status: Continuing. INIE support is being used for equipment procurement.

Explanation: One of the initiatives during the past year has been to improve the NRL's infrastructure by upgrading and web-enabling an existing neutron spectrometer system. This program is an important educational outreach activity for the NRL. The objective is to refurbish a neutron time-of-flight spectrometry experiment that is installed on one of the thermal neutron beams at the MITR, with the addition of capability to operate the experiment interactively over the Internet as part of MIT's iLabs program. An initial implementation of the LabView controlled experiment was installed and tested during the spring semester of 2006/2007. Student response was positive, and hardware and software upgrades are currently underway to improve reliability and add functionality in preparation for putting the experiment online. Experiments online will be adapted for students at the high school, undergraduate and graduate levels.

Title: Neutron Scattering User Facility (MIT)

Objective: Establishment of a user facility to allow users from outside of MIT to conduct early phases of some experiments saving on precious time at large facilities, and to test and develop new neutron optics components.

Status: New. INIE support is being used for equipment procurement.

Explanation: Although neutron scattering had a long and distinguished history at the NRL, it was not actively pursued after the retirement of Professor Cliff Shull. However, a revitalization of the NRL's neutron scattering program was initiated two years ago under the direction of Professor David Moncton with the assistance of Dr. Boris Khaykovich. As a result of their efforts, this project (which includes installation of new neutron scattering instruments; a neutron diffractometer with polarizing capabilities; and a neutron optics test station) is now nearing completion. Initial tests and first experiments are expected to start by the end of 2007.

Neutron scattering and spectroscopy are among the preeminent tools for studying the structure and dynamics of matter at the atomic and molecular scales. A powerful new neutron facility, the Spallation Neutron Source (SNS), is currently under construction at the Oak Ridge National Laboratory, and it is widely anticipated to revolutionize this field and enable the United States to regain leadership lost to Europe decades ago. The SNS will catalyze a new generation of instrument development, a new generation of neutron scientists, and therefore scientific research with neutrons.

The NRL envisions the following programs resulting from this initiative: education and training for students in basic concepts of neutron scattering; enhanced production of new materials at MIT and elsewhere by allowing rapid evaluation via neutron scattering; development of novel neutron optics components; conceptual development of a new imaging instrument—a neutron microscope in absorption and phase contrast—for future installation at the SNS; and establishment of a user facility designed to allow users from outside of MIT to conduct early phases of some experiments more quickly than at large facilities and to test and develop new neutron optics components.

Title: Radiation Effects on the Blood-Brain Barrier (MIT)

Objective: To demonstrate that selective irradiation of the blood vessels using boron confined to the blood stream produces localized radiation damage in the endothelial cells of vasculature and to quantify the effect.

Status: Completed. An MIT NS&E graduate student Rebecca Raabe performed and completed the required studies in the report year using the laboratory and neutron irradiation facilities supported by the INIE program. Radiation damage to the vasculature following injection of boron carrying BSH and thermal neutron irradiations produced a measurable disruption of the blood brain barrier in 12 week old BALB/C mice. This allowed blood stained with a dye to enter the brain that was quantified using the spectrophotometer purchased previously by INIE. The assay was established and a dose response relationship was demonstrated. A M.S. thesis was written and has been submitted. Her thesis advisor was Prof. J A Coderre.

Explanation: This experiment provided corroborating evidence that the selective vascular irradiation methodology utilizing boron containing compounds confined to the blood in combination with neutron beam irradiations produces direct damage to endothelial cells. The method was successfully tested although the assay proved not to be particularly sensitive.

Title: High Resolution Quantitative Autoradiography for Boron Neutron Capture Therapy (MIT)

Objective: To develop a method to image boron in cancerous and normal cells at concentrations relevant to boron neutron capture therapy (BNCT) for cancer and at spatial resolutions which allow the determination of concentrations at the sub-cellular level.

Status: Continuing. An MIT NS&E undergraduate student Sharat Alankar, worked on this research for a Undergraduate Research Opportunities Project (UROP) project in this report period. The INIE program provided support for all supplies and services required for this project as well as purchase of Zeiss Axio

Imager M1 optical microscope with precision automated stage as well as image acquisition and processing software. Experiments that produced track etch images from thin tissue sections containing boron are being performed. These images are used to investigate uptake of different boron delivery agents. During the last year uptake studies of boronated liposomes from single and double injections on a mouse tumor model were studied as was use of a hypoxic sensitizer as a possible delivery agent. Software to provide microdosimetric parameters based upon the recorded track distributions is being developed and evaluated.

Explanation: Of critical importance to the development of improved delivery agents for BNCT is a detailed knowledge of the microscopic distribution of B-10 in the tumor and normal cells. High Resolution Quantitative Autoradiography (HRQAR) is one of only a very few analytical techniques, which has the quantitative resolution combined with adequate spatial resolution to allow estimation of the effectiveness of a boron delivery agent in BNCT. In the last year it was possible to compare the patterns of boron delivered to tumors by small nano particles (liposomes) and to see how these related to tumor cure rate. It is for these reasons that we are placing a strong emphasis on developing HRQAR so that it can be used routinely for evaluating the expected effectiveness of boron delivery agents for BNCT. This capability is currently available to users. Further development is planned regarding post mortem boron migration with a view to improving spatial resolution at sub cellular dimensions. A microdosimetric analysis of track density seeks to provide a correlation between dose and tumor response to a BNCT irradiation.

Title: Liposome Delivery of Boron for Neutron Capture Therapy (MIT)

Objective: To evaluate and develop a new boron delivery compound based upon nano sized particles (liposomes) for neutron capture therapy.

Status: Completed. An MIT NS&E graduate student Yoonsun Chung, was supported fully by INIE, has performed extensive in vivo experiments with two mouse tumor models to test the therapeutic efficacy of boronated liposomes. The experimental work concluded with investigating dual injection doses as a means of improving boron uptake within the tumor. The INIE program provided essential irradiation and technical support for this work that augmented financing from a subcontract of an NIH grant to the University of Missouri. A Ph. D. thesis was written and has been submitted. Thesis advisors were Professors Jeffrey Coderre and Otto Harling.

Explanation: The development of better compounds for the delivery of capture agents is on the critical path to success for NCT as a modality. Chemists nationwide are synthesizing new compounds for use in NCT but do not possess the experimental infrastructure and radiobiology expertise to evaluate their formulations. This research project was undertaken to provide this capability for NCT researchers from all over the country at the INIE funded MIT NCT User Center.

Title: Selective Irradiation of Vascular Endothelium as a Tool for Elucidating the Mechanism of Radiation Induced Side Effects in Normal Tissues (MIT)

Objective: To determine if irradiation damage to normal tissue is caused by damage to the microvasculature or by direct damage to the clonogenic (stem) cells.

Status: Completed. This Ph.D. thesis research finished during the year. The student, Bradley Schuller, utilized this work as part of the requirements for his Ph.D. thesis in the MIT NS&E Department. The INIE program provided essential irradiation and technical support for this work. The remaining financial support for this research is from the Westaway Family Memorial Fund at MIT and a subcontract of an NIH grant to the University of Missouri. The use of the novel selective irradiation was extended to study the frequency of apoptosis (programmed cell death) and gene regulation in the propagation of radiation induced effects. This was reported in another peer reviewed journal earlier in the year. A Ph. D. thesis was written and submitted in August. (Thesis advisor Professor Jeffrey Coderre).

Explanation: One of the major unresolved issues in radiation biology is whether normal tissue damage is caused by damage to the microvasculature or by direct damage to clonogenic cells. Results obtained during the report year confirmed those from earlier experiments and showed that selective irradiation of the vascular endothelium has no effect on the induction of the GI syndrome.

Title: Biodistribution Studies to Determine Selective Boron Uptake for Newly Synthesized Compounds (MIT)

Objective: To quantify the selective uptake of boron delivered by newly formulated delivery agents in tumor relative to normal tissues in different animal tumor models.

Status: Completed. An MIT NS&E graduate student Yonsun Chung, was supported fully by INIE, has performed further in vivo experiments with the EMT-6 tumor line in mice trying different injection routes and schedules for intravenous injections. This used the PGNAA facility as well as the ICP-AES machine purchased previously with INIE funds. This work helps optimize the dosing schedule for a particular capture compound and formed an integral part of this student's Ph.D. thesis research.

Explanation: A necessary requirement for a new boron delivery compound is to attain selective uptake in tumor compared to normal tissue; to be uniformly distributed in all tumor cells and to reach absolute concentrations in tumor in the 20-30 ppm range. These studies are aimed to optimize administration of the compound to determine how best to maximize these requirements and are a pre requisite for efficacy studies. This research project is conducted for NCT researchers from all over the country at the INIE funded MIT NCT User Center.

Title: Hypoxic Sensitizers as a Boron Delivery Agent for Neutron Capture Therapy (MIT)

<u>Objective:</u> To determine if boron containing pimonidazole selectively delivers boron to hypoxic tumor cells.

<u>Status</u>: Continuing. Radiobiology studies were performed by Jugal Shah an MIT NSE undergraduate student with guidance from Yoonsun Chung. This research is being carried out as part of MIT's undergraduate research opportunity project (UROP). Tumor models developed in mice were first shown to contain hypoxic fraction using immuno histological staining of tissue sections after injection with pimonidazole. Uptake of boron containing pimonidazole that was synthesized by an outside research group at McLean Hospital (Belmont, MA**)** directed by Dr. David Lee, was quantified using ICP-AES. HRQAR images were also obtained to illustrate localized concentrations of boron in tumor. Additional biodistribution studies were performed with F98 brain tumors in rats in collaboration with Dr W Yang and Prof Barth (Ohio State University). Substantial support was provided by INIE for this work.

<u>Explanation:</u> This work seeks to evaluate and develop a newly synthesized nitroimidazole-carborane as a prospective compound for boron neutron capture therapy (BNCT) in the treatment of cancer. The use of a hypoxia-targeted boron compound may provide a more selective and homogeneous distribution of boron in solid tumor than hitherto achieved with the FDA approved boronated amino acid boronophenylalanine (BPA). The hypothesis to be tested is that combining the boronated nitroimidazole with BPA will be more effective than employing BPA alone in destroying solid tumors with a significant hypoxic fraction during cancer therapy with BNCT. The purpose is to first demonstrate and then optimize delivery of boron to the hypoxic portion of a tumor in preparation for efficacy experiments.

Title: The MIT NCT User Center (MIT)

<u>Objective:</u> To develop and operate a user center, at the MIT Research Reactor, which provides BNCT type neutron irradiations and technical support to MIT as well as non-MIT researchers who do not have access to neutron beams.

<u>Status</u>: Continuing. This center has continued successful operation in this last project year. Small animal and cell culture irradiations were performed in numerous different experiments that usually involve multiple runs. Mixed field dosimetry measurements and computations as well as assistance with experiment design and execution was also provided to the users of the NCT User Center.

<u>Explanation:</u> Specialized neutron facilities for neutron capture therapy irradiations are only available in a few locations. With the closure of the Brookhaven Medical Research Reactor a number of BNCT researchers were left without neutron irradiation facilities required for their research in radiobiology and capture compound development. To meet this need, the MIT BNCT research group has established an NCT User Center to assist MIT as well as non-MIT researchers who require specialized neutron irradiations, mixed field dosimetry and experimental design support. The INIE project has provided support needed to operate this center. The following is a list of experiments performed utilizing the MIT NCT User Center during the report year 2006/2007 with reactor beams and staff assistance

- A continued investigation into the role that damage to the vascular endothelium plays in molecular and cellular signaling (via up regulation of TNF-alpha and ICAM-1 genes) in tissue following exposure to radiation. (B. W. Schuller, Ph.D. candidate, Nuclear Science and Engineering, MIT)
- Biodistribution investigations in tumor-bearing mice to study the effectiveness of delivering boronated liposomes via different administration routes. (Prof. Hawthorne, University of Missouri)
- A tumor cure/growth delay study to evaluate the efficacy of BNCT following convection enhanced delivery (CED) of the boron containing nucleoside, N5-2OH in rats bearing intracerebral (i.c.) rat RG2 gliomas. (Profs. Rolf Barth and Werner Tjarks, Ohio State University)
- HRQAR was also performed on biodistribution samples to determine the uniformity of tumor boron uptake. (Prof. Hawthorne, University of Missouri)
- Optimization of the effectiveness of boronated liposomes given in a double administration versus BPA in retarding the growth of EMT-6 tumors hosted in mice. (Prof Fred Hawthorne, University of Missouri)
- A series of four experimental runs to quantify the damage to blood vessels in the mouse brain and determine the RBE for selective irradiating blood vessels using boron neutron capture. (Rebecca Raabe, M. S. candidate Nuclear Science and Engineering, MIT)
- Boron quantification in newly synthesized boronated metalloporphyrin compounds as possible tumor targeting agents for BNCT. (Dr. Michi Miura, Brookhaven National Laboratory)
- Dosimetry experiments were performed by the NRL BNCT dosimetry group at the RA-6 reactor in Bariloche, Argentina as part of the International Dosimetry Exchange for BNCT that is led by MIT. This is a collaboration with Drs Sara Liberman and Herman Blaumann from the CNEA in Argentina.
- Biodistribution experiments including HRQAR to investigate the ability of boronated nitroimidazoles to target hypoxic regions of SCCVII and EMT-6 tumors for 3 different formulations of compounds (Dr. Peter Binns, Dr. Kent Riley, MIT and Prof. David Lee, Harvard Medical School)
- Studies to test the feasibility of using boron-containing carbon nanotubes as radiation detectors. (Prof. Timothy Swager, MIT)

- Preliminary studies to apply a newly developed peptide that selectively targets tumor acidosis as a possible agent for BNCT. (Prof. Yana Reshetnyak, University of Rhode Island and Prof. Don Engelman, Yale University)
- Incidental boron assays of both biological specimens and compound formulations using the prompt gamma neutron activation analysis beam line for numerous users.
- Testing neutron and photon sensitivities of different detectors and irradiation geometries for neutron radiography.

Title: DOE Nuclear Summer Institute 2007 (MIT)

Objective: A one-week course, "Thermal Hydraulic Experiments for Nuclear Engineers" was held at the MIT NRL. Twenty-one students from Texas A&M, Kansas State, Ohio State, Oregon State, Univ. of Florida, Univ. of Wisconsin-Madison, Univ. of Michigan, Univ. of Missouri, North Carolina State Univ., MIT, UMass Lowell, and UC Berkeley participated in this course. The course co-directors were Dr. Lin-Wen Hu of the MIT Nuclear Reactor Lab and Prof. Jacopo Buongiorno and Dr. Tom McKrell of MIT's Nuclear Science and Engineering Department.

Status: Completed.

Explanation: This year's Nuclear Summer Institute was held at MIT from June 25-29. This one-week course, "Thermal Hydraulic Experiments for Nuclear Engineers," combines experiments with theories that cover a wide range of fluid dynamics and heat transfer topics that are relevant to nuclear reactor design and safety analysis. Four hands-on experiment segments on measurements of fluid thermal physical properties, single-phase heat transfer and viscous pressure loss, pool boiling and critical heat flux measurements, and flow boiling two-phase heat transfer measurements; four demonstrations on hydraulic loop, optical probe, flow instability, air-water two-phase flow dynamics; and seven lectures were given throughout the week. The experimental facilities and associated instrumentation available for the summer course were funded primarily through DOE's Innovations in Nuclear Infrastructure and Education (INIE) grant and are part of a Thermal Hydraulics Laboratory established jointly by MIT's Nuclear Science and Engineering Department and Nuclear Reactor Laboratory. This summer course provided the students with a unique and rewarding experience in applying what they learn in the classroom to real-world applications. The students also toured the 5-MW MIT Research Reactor and learned about various ongoing research programs in particular the in-core experiment program and advanced fuel and materials testing.

Title: Network Improvements (UMass-Lowell)

Objective: To improve the quality and bandwidth of distance education.

<u>Status</u>: Ongoing

<u>Explanation</u>: INIE funds were used to purchase components that will improve the quality and bandwidth of distance education between the reactor and the UMass network. This improvement will be used in the implementation of a Nuclear Engineering Minor through the Department of Chemical Engineering. The operability of the improved system was presented as the "*Innovative Use of a Research Reactor for Interdisciplinary Engineering Education*," at the 2007 Annual Conference of the American Society for Engineering Education (Honolulu, Hawaii), and as "*Reactor Operations Training via Web-Based Access to the UMass Lowell Research Reactor*," at the 2007 American Nuclear Society Conference on Nuclear Training and Education (Jacksonville, Florida).

Title: Neutron Scattering Upgrade (RINSC)

<u>Objective</u>: Upgrade two goniometer at Beam Ports L2 & R2 in order to allow continued and improved student laboratories and research.

<u>Status:</u> Continuing

<u>Explanation:</u> Dr. Anthony Nunes of the URI Physics Department is responsible for upgrading two goniometers in Beam Ports L2 & R2. An undergraduate student from the Physics Department at URI has completed the calibration of the L2 unit. He has also worked out the software and method to bring web based neutron scattering laboratory exercises to the Physics Department on the main campus. Efforts are underway to upgrade the second goniometer at Beam Port R2. The motion controllers, detectors and electronics are being upgraded as was done for the L2 unit. These upgrades have allowed us to propose and obtain a NERI-C Readiness Grant to further upgrade the two units with '8-Pack' Linear Detectors. These are the state of art detectors used by Oak Ridge National Laboratories. These detectors will increase the system sensitivity by two orders of magnitude and will provide opportunities for additional research opportunities. A URI Physics Graduate Student and a URI Chemical Engineering Undergraduate Student are planning projects to take advantage of these two units.

2. Research Innovations

Title: Neutron Phase Contrast Imaging Project (MIT)

<u>Objective</u>: The Neutron Phase Contrast Imaging Project has the goal of providing the MIT reactor with a state-of-the-art neutron imaging system capable of exploiting the phase contrast edge enhancement effect. The project's aim is twofold: the imaging facility can be used for industrial and research purposes, notably in the study of materials; the system will provide great educational value, by giving insight on the experimental functioning of neutron phase contrast and by providing a facility to test new ideas.

Status: Continuing. INIE provides both equipment and student support. One major problem that is being addressed is the contamination of a beam line with gammas. The imaging plate detector and amorphous silicon detector are especially sensitive to this and as a result, the contrast is significantly reduced. The CCD imager was upgraded to use a LiF-ZnS scintillator designed by the neutron imaging group at PSI which reduced the gamma sensitivity by at least one order of magnitude.

Explanation: Phase contrast imaging uses the wave properties of neutrons to greatly increase spatial resolution and contrast in materials imaging. A beamline and detector system for implementing this technique was installed at the MIT Nuclear Reactor Lab. Recently a new approach is being examined which can lead to phase tomographic imaging which enables us to three-dimensional images to be produced of materials which cannot be distinguished by their density and absorption.

Title: International Dosimetry Exchange for Neutron Capture Therapy (MIT)

Objective: To compare and summarize the results of clinical BNCT from all clinical centers worldwide.

Status: Continuing. MIT has organized an international dosimetry change for the intercomparison of absorbed dose measurements at all NCT clinical centers, worldwide. Measurements have been completed at the two centers in the US, MIT and BNL, and at four clinical centers in Europe; Petten, Netherlands; Studsvik, Sweden; Espoo, Finland and Rez, Czech Republic. To these were added results from MIT's visit to the RA-6 reactor in Bariloche, Argentina during the report year. A dosimetric characterization of the hyperthermal neutron beam used for melanoma clinical trials was performed in addition to comparative dosimetry measurements between the two groups. The results showed excellent agreement between the two dosimetry groups. Funding for travel costs were provided by the DOE sister laboratory program (DE-AC02-06CH11357).

Validations of the treatment planning system dose specification are in progress for Argentina and the remaining European centers so that results from these centers can be included in dose response analyses. Further reports in the form of manuscripts for publication in international journals are being prepared.

Explanation: BNCT clinical trials are expensive and a pooling of worldwide clinical results would greatly accelerate the development of this new treatment modality. In order to utilize the clinical results and experience of all clinical centers, and, thereby, to obtain the largest possible data base for evaluation of BNCT clinical results it is necessary to develop a sound basis for inter-comparison of irradiation doses. Dosimetry in BNCT is complicated compared to photon therapy and there is no international standard for dosimetry practice. To help overcome these difficulties and allow a comparison of all clinical results, MIT has begun an international effort to compare dosimetric measurements made by the staff of the various clinical centers and to obtain complete dosimetric characterization of the epithermal neutron beams at all clinical centers. Most of the support for this research has come from the DOE OBER but INIE support was also needed to carry on this work.

Title: Basic Radiation Biology

Objective: One of the major unresolved issues in radiation biology is the understanding of underlying mechanisms that produce normal tissue damage following radiation. One hypothesis tested is that damage to the micro-vasculature is the initiating event in tissue damage. It has long been believed that early effects are due to damage to the rapidly dividing stem cell populations and that late effects are due to damage to the more slowly growing blood vessels. However, several recent, and controversial, reports have suggested that microvascular damage is causative in the acute radiation syndrome: the loss of intestinal crypt stem cells and the subsequent development of the gastrointestinal syndrome. Future studies will use the selective vascular approach to investigate the signaling pathways that lead to late effects in normal tissue months or years after irradiation.

Status: Completed. A method was developed for selective irradiation of the microvasculature that allows direct experimental testing of the role of the vasculature in normal tissue radiation response. A boron compound has been prepared that will remain inside the blood vessels. The short path length of the radiations from the boron neutron capture reaction allows irradiation of the blood vessel walls but not the surrounding functional cells.

Explanation: Consistently reproduced data indicate that damage to the blood vessels are not the cause of the gastrointestinal syndrome. These studies could have significant implications for the development of agents to protect normal tissues during radiation therapy or to treat normal tissues after accidental radiation exposure.

Title: Determine and Validate Source Term for Treatment Planning System of MIT Epithermal Neutron Beam with Lithium-6 Filter (MIT)

Objective: To modify the treatment planning system (TPS) used for BNCT with the FCB to incorporate the use of ^{6}Li filtered fields.

Status: Completed. A ^{6}Li filter system was designed, constructed and fully characterized with INIE funds as described in last years report. The new beam characteristics with the filter installed were computationally modeled with MCNP and benchmarked by measurements. The computational aspects of this project were performed by Ray Albritton a PhD student in NSE working in the Department of Radiation Oncology at the Beth Israel Deaconess Medical Center.

Explanation: To implement the use of the new optional ^{6}Li beam filter for therapy, the treatment planning system used to calculate the dose prescription required modification. In particular MCNP calculations must determine a new source description for the filtered beam at the exit plane of the patient collimator. This source description is then transported into a realistic shaped phantom in which measurements have been performed. Scaling the calculations to the measured results effectively calibrates the TPS for therapy with the new beam configuration.

Title: Thermophysical Properties and Heat Transfer Characteristics of Nanofluids (MIT)

Objective: The goal of this project is to investigate the heat transfer enhancement of water-based nanofluids.

Status: Continuing. INIE provides equipment and student support.

Explanation: Dr. Lin-Wen Hu and Professor Jacapo Buongiorno are pursuing an experimental study of water-based nanofluid heat transfer enhancement. Nanofluids are engineered colloids made of a base fluid and nanoparticles (1-100 nm) in various forms. The presence of the nanoparticles produces four major effects on the thermal-hydraulic behavior of the fluid. These are: increase of the thermal conductivity, increase of the viscosity, increase of the single-phase convective heat transfer, and increase of Departure from Nucleate Boiling (DNB) heat flux. Given their potential for superior heat removal performance, nanofluids are being investigated for numerous applications, including electronics, manufacturing, chemical processes, cosmetics, pharmaceuticals, power generation, etc. A research program was initiated as a collaboration between the NRL and NSE to assess the feasibility of nanofluids for nuclear applications. In principle, the use of water-based nanofluids could improve the performance of any water-cooled nuclear system that is heat removal limited. Potential applications include Pressurized Water Reactor (PWR) primary coolant, emergency core cooling systems and in-vessel retention for severe accident mitigation, etc. The program comprises the following activities, which are sponsored in 2006-2007 by the Idaho National Laboratory (INL), AREVA and DOE's Innovations in Nuclear Infrastructure and Education (INIE) grant. Three out-of-pile loops are completed to investigate the nanofluids heat transfer characteristics for laminar convective flow, turbulent convective flow, and two-phase boiling and critical heat flux enhancement. In addition, three pool boiling facilities were built to support this research.

- Procurement of water-based nanofluids, i.e., C, SiO_2, ZrO_2, Al_2O_3, TiO_2.
- Property measurements: thermal conductivity (transient hot wire method) and viscosity (capillary viscometer).
- Single-phase heat transfer and pressure drop measurements for laminar and turbulent flow in flow loops.
- Single-phase heat transfer modeling, both conceptual and CFD.
- Two-phase flow experiments for Critical Heat Flux (CHF) measurements:

- Pool boiling measurements to study the CHF hydrodynamics

Two new projects were started in early 2007 which are sponsored by Electric Power Research Institute (EPRI) and King Abdulaziz City for Science & Technology (KACST) Saudi Arabia through a collaborative research agreement.

Also worth noting is that the flow loops and equipments in the nanofluids lab were used in a one-week Nuclear Summer Institute course "Thermal Hydraulic Experiments for Nuclear Engineers" which 21 students from 13 universities participates. The NSI is sponsored by DOE university program.

Title: Neutron Tomography (UMass-Lowell)

Objective: To establish tomographic and 3-D imaging capabilities using the neutron radiography facility.

Status: Ongoing

Explanation: INIE funds have been used to purchase an improved neutron scintillation system from RCTritec (Switzerland), and to purchase 3-D imaging software from Octopus 8 Creations (Hawaii). These tools will be used to develop and implement neutron tomography and 3-D imaging using the existing neutron radiography facility.

Title: Gadolinium Cancer Research Project (RINSC)

Objective: Continue research into the radiosensitization of brain tumor cells afforded by Gadolinium (Gd-tetraphenyl porphine sulfonate). In the past year, we have completed one paper which is under revision to the journal *Radiation Research*, and we are in the process of submitting two other papers to *Radiation Research*. Below are summaries of these three papers.

Status: Continuing

Explanation: C6/lacZ, 9L/lacZ, and F98 tumor cell survival was determined after exposure to 250 kVp x-rays or reactor generated thermal neutrons to define the relative biological effectiveness (RBE). RBE values at the 10% survival level were respectively 2.42, 2.60, and 2.07. We then defined the dose-modifying factor or compound biological effectiveness (DMF, CBE) produced by neutron activation of gadolinium-tetraphenyl porphine sulfonate (GdTPPS, 15.65% ^{157}Gd, 200 μg/ml). These three lines had respectively 3.71, 3.70, and 3.77 x 10^5 ^{157}Gd atoms per μm^3 of cell volume at the time of irradiation, and the DMFs were respectively 1.88, 1.86, and 1.83. Using single-hit, multitarget parameters, the thermal neutron alone cell survival curve showed a reduction in the quasithreshold dose (D_q) to 50% of that seen with x-rays, and for the thermal neutrons plus GdTPPS, the D_q was reduced to 22% of the x-ray value. These data indicate that thermal neutrons plus ^{157}gadolinium produces a significant additional amount of cell killing, but that there is also still a "shoulder" of about 22% of the control value left on the survival curve. Linear-quadratic analysis of the data showed that addition of GdTPPS to thermal neutron irradiated tumor lines increases α by about 32% while increasing the β parameter by about 68%.

Further, using an *in vitro* 2-dimensional assay, we determined the dispersal rates and survival of dispersing C6/lacZ brain tumor cells. Mortality from Grade III/IV brain tumors is caused by both the primary neoplasm and dispersing cells in about equal percentages. However, relatively little has been published on the radiation and relevant cellular biology of the dispersing fraction of tumor cells. At 25 days post-seeding, C6/lacZ cells formed colonies of approximately 5 mm in diameter, and cells had dispersed to a distance of about 9 mm from the primary colony yielding an apparent dispersal rate of about 8.3 μM/hour. The number of dispersing cells semi-logarithmically decreased to about 10% (at 5 mm distance) of that seen at 1 mm away from the edge of the colony. Also, the BrdUrd labeling index decreased continually from the edge of the colony (20% at 1 mm to 5% at 8 mm), indicating that the dispersing cells were less proliferative as they dispersed from the primary colony. In contrast, the apoptotic percentage increased with distance from the colony edge indicating the the most dispersive cells also had the highest apoptotic index.

We have also studied the relationship between PLDR and cell dispersal using agents which either inhibited or stimulated potentially lethal damage recovery (PLDR). The agents chosen were used at a concentration producing 0 to 10 percent cell kill. An x-ray dose sufficient to reduce immediate survival to 10% was used, and cells were examined for PLDR expression.

PLDR expression was inhibited in the following manner: misonidazole (stimulates glucose utilization, inhibits lactate production, inhibits DNA synthesis, probably acts by fixing the target radical damage produced by x-rays) < caffeine (increased numbers and decreased length of replicons in DNA; may activate the ubiquitin system leading to inhibition of DNA synthesis) < leupeptin (inhibits proteases involved in protein degradation; does not induce DNA damage, nor interferes with DNA repair or replication) < wortmannin (inhibits repair of radiation produced DNA double strand breaks) < campothecin (an inhibitor of topoisomerase I) < nigericin < β-ara A (a DNA synthesis inhibitor) < etoposide (an inhibitor of topoisomerase II) < leptomycin B (an inhibitor of nuclear protein export). These data show that leptomycin B (LPM) is the most effective inhibitor of PLDR found in this study. Indeed, LPM was 200 times more effective per unit concentration than was the next most potent inhibitor, etoposide. This finding implies that the reduction of PLDR by LPM is associated with LMP binding to CRM1, a nuclear export protein. LPM binding inhibits CRM1, thereby inhibiting nuclear export.

In contrast, for agents which stimulate PLDR, we found that phorbol 12-myristate-13-acetate (PMA); < MIF, macrophage migration inhibitory factor (MIF); < gastrin < sodium butyrate (NAB); These agents as a group may act via their stimulation of protein kinase C. (i.e., PMA, MIF, ethanol, and gastrin). An agent which has been shown to increase PLDR, but has not been studied for its effects on cell dispersal is NAB (1 mM; Arundel and Leith, 1987). We have found that butyrate sensitized cells to graded single doses of 250 kVp x-rays by an increased α value in the linear-quadratic equation. But, butyrate also increased the expression of PLDR while decreasing the expression of SLDR (Arundel, Glicksman, and Leith, 1986). This change in α and in PLDR in butyrate treated cells appears, on the cellular level, to be consistent with the changes in the control population of dispersing cells (i.e., increased α and PLDR).

In summary, to date we have found the following facts about dispersing brain tumor cells:

- they are the most radiosensitive to both x-rays and neutrons when assayed acutely.
- addition of gadolinium (in the form of Gd-tetraphenyl porphine sulfonate) produces about an extra 50% cell kill with neutron irradiation.
- dispersing cells express a continually increasing amount of apoptosis the farther they are from the edge of the primary colony.
- they do not express sublethal damage repair.
- they do however, express the greatest amount of potentially lethal damage repair.
- In regard to the expression of PLDR, we have found that such repair may be completely inhibited by a extremely low (nM) concentration of leptomycin B.
- Leptomycin B produces complete inhibition of PLDR at a concentration 200 x less than that of the next most potent inhibitor. Future work will include placing a Gd^{3+} atom on the LPM molecular structure to further sensitize tumor cells to neutron irradiation.

Title: Weapons of Mass Destruction and Environmental Pollution Sensor Research (RINSC)

Objective: Research and Development of underwater sensors at RINSC.

Status: Continuing. INIE provides all support.

Explanation: Dr. Alfred Hanson of the URI Graduate School of Oceanography is utilizing six of his graduate students from the Chemical Oceanography Department. in the research and development of underwater sensors at RINSC. There are two general applications for the submersible chemical analyzers that are the focus of the research effort:

- **Environmental Pollution:** Water quality monitoring of chemical and biological contaminants such as nutrients, trace metals, coliform bacteria, and radiochemicals (NOAA, EPA, ONR).
- **Coastal Security – Ocean Observation Systems:** Detection, tracking and source localization for chemicals associated with weapons of mass destruction (WMD) submerged in coastal waters. These WMD chemicals

include those leaking from unexploded ordinance (i.e. submerged mines leaking TNT) and radiological isotopes associated with submerged nuclear devices or contamination (i.e. uranium series nuclides, alpha, beta, gamma radiation). (DOD, NAVY, NUWC, USCG)

For the last four years, the research focus for instrument development has become Coastal Security and we expect that emphasis will continue for several years. We are working on multiple NAVY projects that involve coastal security. We have had phase II (ONR) and phase III (NUWC) SBIR funding to develop a sensitive submersible sensor for trinitrotoluene (TNT) that can be deployed on a small autonomous underwater vehicle (AUV). We are also collaborating with URI and Nomadics, Inc. (Stillwater, OK) on a phase II STTR project for the development of a WMD sensor payload for the AUV. The WMD payload includes a TNT sensor, a radiological detector module and a sediment sample collection module. The WMD payload for the AUV is being designed to autonomously retrieve sediment and water samples that can subsequently be analyzed for radionuclides. During the next few years we expect to be developing and evaluating the radiological detectors and radiological sample collection modules for the AUV.

This emerging and very important aspect of Dr. Hansons' research requires collaborative consultation and the type of analytical and radiological source services that a facility like RINSC can provide. During the next couple of years he intends to apply for additional Federal grants for the further development of submersible radiological sensor technologies. These proposals would include requests for funds to compensate RINSC for professional consultation, reactor time, and radiological analytical services required for the development, testing and demonstration of the submersible radiological sensors.

In addition to providing opportunities for several graduate students in the field of nuclear chemistry, Dr. Hanson provided RINSC with a significant infrastructure improvement when he completed his laboratory building on the South Wing of the facility last year. This laboratory has state of the art facilities for sensor development and was constructed with the use of grants and other outside funding in excess of one million dollars.

3. Infrastructure Improvements

Title: MIT Nuclear Reactor Infrastructure Improvements

- New manipulator in reactor floor hot cell #1.
- Hot cell #2 manipulators repaired.
- Local and remote area radiation monitors for hot cells now functional.
- Parts purchased for repair of shim blades/regulating and position indicators.
- New HPGe detector for NAA activities.

Title: **Neutron Beam-Line Improvements (UMass-Lowell)**

Objective: To improve the quality of the thermal neutron beam used for radiography.

Status: Ongoing

Explanation: Recent improvements to the neutron radiography beam include increased neutron and gamma ray shielding, as well as a reduction in the scattered neutron component. These improvements will be especially useful when the UMass Lowell Research Reactor increases its power level from 1 MW to 2 MW, and for neutron tomography research.

Title: Rhode Island Nuclear Science Center Infrastructure Improvements (RINCS)

Objective: Improvements to infrastructure in order to improve research and educational opportunities.

Status: Continuing

Explanation:

- The Reactor Control System automation software and hardware upgrade has been installed. Additional hardware has been purchased to replace old equipment, such as chart recorders. A Power Conditioning UPS has been purchased and installed to improve the systems reliability.
- RINSC plans to purchase the remaining hardware to implement the Process Control System automation this year.
- RINSC has received a License Agreement with InduSoft to provide Web Based training to URI Physics Department and Providence College Physics Department. URI will be setup to do neutron scattering experiments and PC will be setup to do NAA experiments remotely.
- RINSC has purchase and installed the Canberra Genie 2000 VB programming Libraries. This upgrade was required to allow NAA experiments to use the Web Based Remote Training software. This software will allow RINSC and its users to develop custom NAA experiments and results.
- Work continues with the upgrade on the goniometer. All the motors, detectors and electronics have been purchased for the Unit at Beam Port L2. Efforts to purchase motors, new detectors and electronics for the Unit at Beam Port R2 are underway.

- Additional cameras were added to our video surveillance system. These new cameras cover the Reactor Floor where the two goniometers installed in Beam Ports L2 & R2 are located.
- Replacement/backup detectors and electronics for the Reactor Floor and Stack Air monitors are being purchased to increase our system reliability. Both systems must be working to startup the reactor. The two units were purchased last year, replacing forty-year-old equipment with monies from a Reactor Instrumentation Grant.

4. Intra-Consortium Integration

Title: MIT/Rhode Island Nuclear Science Center (MIT)

<u>Objective</u>: To assist RINSC in the development of a research program in neutron capture therapy.

<u>Status</u>: The MIT neutron capture therapy research group visited RINSC and performed dosimetric measurements. with the intention of (i) demonstrating mixed field dosimetry in the thermal column where biological experiments will be performed (ii) ensuring proper set up and working of the newly acquired (using INIE funds) ionization chambers/electrometer to be used in future at RINSC, and (iii) to measure absorbed dose rates under conditions pertinent to previously performed biology experiments for future measurement comparisons by RINSC themselves.

<u>Explanation</u>: The Rhode Island Nuclear Center (RINSC) is developing an experimental irradiation facility for biological experiments at its nuclear reactor. The facility is a thermal neutron column that is dedicated to the development of better tumor seeking compounds for neutron capture therapy (NCT). As part of an inter consortium collaboration MIT is providing assistance to RINSC in developing the necessary skills and techniques to perform mixed field dosimetry to aid development of their nascent NCT irradiation facility. The BNCT research program at MIT is currently the leading US group in this field and with INIE support is in a position to assist RINSC with their efforts to develop a BNCT research program. This assistance has helped RINSC obtain the data necessary to help Dr. Leith's publish his work and allow him to apply for additional NIH grants.

	Inie Summer Course: Thermal Hydraulics Education **Hu**	Innovations In Nuclear Infrastructure and Education **Bernard**	Task 1: In-Core Material And Chemistry **Ballinger**	Task 2: Advanced Fuels **Kazimi**	Task 5.1: Neutron Inter-ferometry **Cory**	Task 5.2: Phase Contrast Thermal Neutron **Lanza**	Task 6: Neutron Capture Therapy **Harling**	Nano-Fluid Heat Transfer **Hu**	Fabrica-tion: Pool Boiling Facility **Hu**	Nuclear Reactor Upgrade **Harling**	Inie – Education **Bernard**	Student Spectro-meter Facility **Bernard**	Diffracto-meter **Bernard**	Total
Personnel	18,247			60,692		36,118	106,455				1,383		10,928	233,824
RA	2,200			1,215	7,386	7,226	26,170	14,404						58,601
Student Salaries-Hourly		0						2,263						2,263
Employee Benefits	4,246			21,695		19,174	36,542				503		3,835	85,996
Travel	6,082	1,500				1,417	5,213	814						15,025
M&S	12,960	649	4,800	12	-1,231	25,190	8,342	3,324	4,743			17,671		76,459
Reactor Use		0				1,800	11,300	1,400						14,500
Equipment		23,912	0			589	61,028	4,054	0					89,583
RA Tuition				1,046	8,223	10,339	16,359	17,872						53,839
Subcontracts		166,945												166,945
F&A	15,060	1,397	3,120	54,349	4,801	59,101	128,954	14,788		1,128	1,226		9,596	293,520
Total	58,794	194,404	7,920	139,010	19,178	160,953	400,363	58,919	4,743	1,128	3,112	17,671	24,360	1,090,55 4

Subcontracts	
UMASS	**81,945**
RINSC	**85,000**
	166,945

II. Cumulative Report

A. Statistics

MIT	Academic Year				
STATISTICS	**06-07**	**05-06**	**04 - 05**	**03-04**	**02-03**
Education Related					
Tenure track faculty (FTE's)	16.5	16.5	15	14	16
BS enrollment	46	55	49	35	26
MS enrollment	25	20	14	21	23
PhD enrollment	82	80	86	90	84
BS graduates	20	16	9	4	5
MS graduates	25	20	26	23	15
PhD graduates	12	20	15	13	15
Research Related					
Research faculty (FTE	16.5	16.5	15	14	16
Non-INIE research expenditures	$5.2M	$6.7M	$6.2M	$6.9M	$4.9M
Reactor Related					
Research faculty (FTEs)	1	1	1	1	0
Technical staff/technical support staff (FTEs)	15	15	15	15	15
Capacity (total potential hours)	8760	8760	8760	8784	8760
Actual Capacity (4.5) MW hrs)	5950	4888	6123	4237	6448
Utilization – education (total hours)			652	393	526
Utilization – research (total hours)			3062	2569	3224
Utilization – training (total hours)			2449	1695	2579
Utilization – commercial (total hours)	5950	4888	6123	4237	6448

UMass Lowell Radiation Laboratory	Academic Year				
Statistics	06 - 07	05 - 06	04 - 05	03 - 04	02 - 03
Education Related[1]					
Tenure-track faculty (FTEs)	1	1	1	1	1
BS enrollment (total)					
Minorities					
Females					
MS enrollment (total)					
Minorities					
Females					
PhD enrollment (total)					
Minorities					
Females					
BS graduates (total)					
Minorities					
Females					
MS graduates					
Minorities					
Females					
PhD graduates	1	1	1	3	3
Minorities	0	0	0	0	1
Females	0	0	0	1	2
Research Related[2]					
Research faculty (FTEs)	7	7	7	7	7
Technical support staff (FTEs)	5	5	5	5	5
Refereed publications (number)	4	6	12	9	11
Non-INIE research expenditures ($)	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$
Non-INIE research awards ($)	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$	$5.16x10^6$
Reactor Related[3]					
Capacity (total potential hours)	1500	1500	1500	1500	1500
Educational use (total hours)	80	79	76	71	62
Research use (total hours)	106	105	102	95	83
Training use (total hours)	53	53	51	48	42
Commercial use (total hours)	27	26	25	24	21

Notes:
1) The Radiation Laboratory is a research center used by multiple departments, and therefore does not have enrollments.
2) Research Faculty: the faculty who use or have used the reactor in research projects.
3) Reactor Related: *Capacity* is based upon 6 hour shifts, 5 days per week, 50 weeks per year; and usage hours are based upon a percentage of critical hours (respectively 30, 40, 20, 10).

B. Educational Enhancements

Title: Neutron Capture Therapy Center (MIT)

Description: The Neutron Capture Therapy User Center is comprised of several state-of-the-art neutron facilities for neutron capture therapy (NCT) research that have been developed and are in operation at the MITR.

Impact on Nuclear Engineering Education: More than 25 students have been supported as a result of research activities made possible by INIE. The INIE supported NCT Center has enabled professors, post-doctoral research scientists and graduate students to carry out research in the field of NCT for cancer. INIE support was essential for much of the education related NCT research from 02-03 through 05-06.

Title: Annular Fuel Project (MIT)

Description: The goal of this project was to develop and optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins.

Impact on Nuclear Engineering Education: As a result of this INIE funded project, several MIT Nuclear Science and Engineering students had the opportunity for hands-on participation in cutting edge research related to the High Performance Fuel Design for the Next Generation of PWRs Project.

Title: SiC Duplex Advanced Clad Irradiation (ACI) (MIT)

Description: This project is under the direction of Dr. Gordon Kohse and Prof. Mujid Kazimi. This major in-core experimental activity was conducted in order to study the response of SiC/SiC composite materials to pressurized water reactor (PWR) conditions is the major in-core experimental activity. These materials have been proposed as a replacement for Zircaloy fuel cladding for PWRs in order to improve fuel performance in loss of coolant accidents and thus allow for increased reactor power and higher fuel burnup. A Phase I irradiation was completed in September 2006 and samples were removed for examination at MIT and mechanical property testing at Oak Ridge National Laboratory. A Phase II irradiation was started in December of 2006 containing some new specimens and some specimens continued from Phase I. Phase II is scheduled to continue through September 2007.

Impact on Nuclear Engineering Education: This project is supported by the Department of Energy and Westinghouse. Several graduate students have participated in both the experimental work and associated fuel/clad behavior modeling studies. The irradiation studies at MIT under realistic PWR in-core conditions have been key to the continued interest of DOE in this development.

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Title: Physics, Chemical Engineering, Ocean Engineering, Chemical Oceanography, and Atmospheric Chemistry (RINSC)

Description: The opportunity for graduate students in physics, Chemical Engineering, ocean engineering, chemical oceanography, and atmospheric chemistry to work in such areas as the CHAIOS project, Neutron Science and the sensor projects at RINSC will strengthen a long tradition of scientists in the nuclear field. Due to its location at the URI Graduate school of Oceanography, RINSC has a long history of educating graduate students in the fields of neutron activation analysis, neutron scattering, and radiation studies for use in environmental and marine applications.

Impact on Nuclear Engineering Education: The INIE grant has enabled RINSC to improve the service and facilities available to these students and will ensure that another generation of graduates has these skills. The opportunity for students in the physics department and chemical engineering to work in the area of neutron scattering will be strengthen. The automated control system will allow for more detailed and interesting work to be undertaken. RINSC has a past history of numerous neutron scattering projects. The INIE grant has enabled RINSC to improve these facilities and make them more attractive to graduate students interested in pursuing a graduate degree in this area.

Title: Distance Education and Research Initiative (DERI) (UMass Lowell)

Description: Recent improvements to the UMass Lowell Distance Education and Research Initiative (DERI) have included the capability for real-time interaction using web-based browser type applications. Applications sharing has allowed the infrastructure investments to be disseminated with users outside of the UMass Lowell Research Reactor both on the UMass Campus and to the wider scientific community. These improvements will be used in the implementation of a Nuclear Engineering Minor through the Department of Chemical Engineering. The capability of UMass Lowell's DERI was presented as the "*Innovative Use of a Research Reactor for Interdisciplinary Engineering Education*," at the 2007 Annual Conference of the American Society for Engineering Education (Honolulu, Hawaii), and as "*Reactor Operations Training via Web-Based Access to the UMass Lowell Research Reactor*," at the 2007 American Nuclear Society Conference on Nuclear Training and Education (Jacksonville, Florida).

Impact on Nuclear Science Education Programs: This remote teaching and research capability is now available to educational users with simple browser-based web access.

<u>Title:</u> Virtual Radiography Console (UMass Lowell)

<u>Description:</u> UMass Lowell has developed a virtual console that integrates with the digital neutron radiography facility. The virtual console allows students and researchers to engage in digital neutron imaging without entering the research reactor. This initiative reduces security concerns and eliminates outside personnel radiation exposures. The system has been demonstrated over broad geographical distances to be effective in allowing for remote radiography sample analysis and manipulation. The findings of the educational and research uses of remote digital neutron radiography were presented at the IEEE Nuclear Science Symposium, in Fajardo, Puerto Rico (2005).

<u>Impact on Nuclear Science Education Programs</u>: This initiative is expected to enhance interest in nuclear science by making neutron radiography potentially accessible to any interested students who possess an internet connection.

<u>Title:</u> Controls Development Training Kit

<u>Description:</u> Students and faculty utilized the OPTO-22 Distance Education Experimental Control Development tool kit over the course of the summer recess to help develop the content needed for training students to effectively utilize the UML Reactor Online (Nuclear101.com).

<u>Impact on Nuclear Science Education Programs:</u> Students and faculty members were provided experimental and classroom tools that will help to develop additional materials and training content for our Distance Education Programs.

C. Research Innovations

Title: Annular Fuel Project (MIT)

<u>Description:</u> In February 2004, a new type of in-core experiment was installed to test performance of an innovative annular fuel designs as a part of the Generation-IV power reactor research effort by the MIT Nuclear Engineering Department. This experiment continued into FY2005. It is the first irradiation of a fueled test capsule at the MIT reactor, and one of very few undertaken at any university reactor.

<u>Impact on Nuclear Engineering Education</u>: The Annular Fuel Project was very successful and the new internally and externally cooled annular fuel captured the interest of the industry and media. At the ANS conference in Reno in June 2006, the Westinghouse presentation at the special plenary session on Innovation in Nuclear Technologies by Senior Vice President and Chief Technology Officer, Regis Matzie, was fully devoted to the new annular fuel proposed by MIT and Westinghouse is putting some of their own funding into further development of this fuel. In September, Reuters published an article "Scientists Develop More Powerful Nuclear Fuel."

Title: High Temperature Irradiation Facility (HTIF) (MIT)

Objective: The High Temperature Irradiation Facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials.

Impact on Nuclear Engineering Education: In November 2005, this in-core loop was installed in the MITR. A demonstration test was performed with temperatures up to 1600 °C. A variety of materials relevant to high temperature gas reactor design, including SiC, AGR matrix graphite and non-fueled coated particles, were irradiated. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs. This facility will be a valuable test facility for high temperature resistant materials research.

Title: Nanofluids (MIT)

Description: Dr. Lin-Wen Hu (MIT NRL) and Professor Jacapo Buongiorno MIT NSE) are conducting research to assess the feasibility of water-based nanofluids for nuclear reactors. The potential reactor applications include advanced coolants and safety systems, as well as reactor cavity flooding for in-vessel retention during severe accidents.

Impact on Nuclear Engineering Education: This project is a perfect example of how INIE has and can impact nuclear engineering in the U.S. The research being conducted on this project is cutting edge and as a result has several undergraduates and graduate students working along side Dr. Hu and Professor Buongiorno. However, on a much larger scale, it is also attracting a lot of attention among nuclear engineering students across the country and the nuclear engineering community.

Title: Neutron Tomography (UMass-Lowell)

Description: UMass Lowell will use an improved neutron scintillation system from RCTritec (Switzerland), and 3-D imaging software from Octopus 8 Creations (Hawaii), to develop and implement neutron tomography and 3-D imaging using the existing neutron radiography facility.

Impact on Nuclear Science Education Programs: This new research area is expected to encourage additional research in the area of neutron imaging, and to foster collaborations with imaging specialists at UMass Lowell.

Title: Investigation of a CMOS Line Camera (UMass-Lowell)

Description: UMass Lowell has collaborated with *Envision* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate a CMOS line camera that contains the inorganic scintillator gadolinium-oxysulfide for use in neutron radiography.

Impact on Nuclear Science Education Programs: This innovation is expected to encourage additional research in the area of neutron radiography.

Title: Dual X-Ray and Neutron Imaging Capability

Description: Utilizing INIE funding, a Fuji BAS 5000 Imaging Plate and Reader system was procured and installed. This system allows for both neutron and x-ray images to be read into the same formats. Using our upgraded beam line and an existing x-ray exposure unit at UMass Lowell, preliminary studies have been performed as to the x-ray and neutron sensitivity of the new system.

Impact on Nuclear Science Education Programs: These innovations are expected to encourage additional research in the areas of neutron and x-ray radiography at UMass Lowell.

Title: Neutron Beam Line Optimization (UMass-Lowell)

Description: The existing UMass Lowell neutron radiography collimator system has been refurbished and upgraded to reduce scatter and optimize the thermal neutron beam for radiography. These improvements include evacuating both sections of the eight-meter beam-line flight path to remove air scatter. In addition, MCNP modeling of the current facility is underway. This modeling will allow for an optimized beam line configuration to be developed and benchmarked.

Impact on Nuclear Science Education Programs: These innovations are expected to encourage additional research in the area of neutron and x-ray radiography at UMass Lowell.

D. Infrastructure Improvements

Title: MIT Neutron Capture Therapy User Center (MIT)

Description: INIE has supported a significant part of the upgrade of the MITR based NCT thermal neutron irradiation facility. This includes automated beam shutters, improved shielding in the medical room in preparation for new clinical studies. INIE support has also made possible the implementation of a Lithium-6 filter for the epithermal neutron (FCB) medical irradiation facility. This enhancement to the FCB significantly improves the useful penetration of this epithermal neutron beam.

All the necessary technology, pre-clinical studies and approvals (11 separate approvals from government entities and local review boards) were obtained to allow initiation of clinical studies of NCT. Several phase I and phase I/II have been carried out at the MITR in recent years. Control of melanoma metastases was observed in a significant fraction of the patients with this type of cancer. Further clinical studies are planned and INIE support will be essential to these studies

Impact on Nuclear Engineering Education: With INIE support MIT has established a neutron capture therapy user center to meet the needs of all U.S. researchers in this field. With the closure of the Brookhaven Medical Research Reactor (BMRR), the MIT neutron facilities for NCT research are the only ones in the USA capable of supporting a full range of research from pre-clinical to clinical irradiation studies. Currently the MIT NCT User Center is essential to the research activities of a number of university, industry and hospital-based NCT research groups and meets or exceeds the capabilities that once existed at BMRR. Activities under the NCT User Center have grown during each of the three years of INIE funding measured by the numbers of experiments and users supported as well as the number of undergraduate and graduate students who have benefited from the support provided by these funds.

Title: Nanofluid Program (MIT)

Description: The INIE funding allocated for the nanofluid program in FY 2005 was used to purchase parts/equipments for the experimental facilities listed below. These facilities and associated instrumentations are now part of a Thermal Hydraulics Laboratory supported jointly by the Nuclear Science and Engineering Department and the Nuclear Reactor Laboratory. These facilities can be utilized for future research projects in general heat transfer and two-phase flow research as well as teaching at both undergraduate and graduate levels.

- ***Single-Phase Heat Ttransfer Loop*:** This is a pressurized forced convection loop which is designed and constructed by MIT student and staff to investigate nanofluid heat transfer and pressure drop characteristics in laminar and turbulent flow regimes. Initial experiments of DI water and alumina and zirconia nanofluid experiments were completed.
- ***Title: Critical Heat Flux (CHF) Loop:*** The CHF facility is being constructed to obtain flow CHF data for different types of nanofluids which do not currently exist in the literature. The design of the heated section was modified this year and is currently under pure water testing.
- ***Title: Pool boiling Facility*:** This apparatus is designed to understand the fundamental CHF mechanism. This facility is equipped with a thin Indium-Tin-Oxide (ITO) heater deposited over a sapphire substrate to provide a direct bottom-up view of the boiling phenomena on the heater

surface, and an optical probe for measuring bubble size distribution. Initial tests are being conducted to verify the performance of the facility and the optical probe.

Impact on Nuclear Engineering Education: These facilities can be utilized for future research projects in general heat transfer and two-phase flow research as well as teaching at both undergraduate and graduate levels.

Title: Advanced Materials Testing Facility (AMTF):

Description: In 2001, MIT recognized the need for an Advanced Materials Test Facility (AMTF) and proposed the assembly of such a facility at the MITR under INIE. Procurement and installation of equipment for this state-of-the-art facility is on-going and includes upgrades to the MITR's existing hot cells which are used to support in-core experiments. The combination of the AMTF and MIT Research Reactor (MITR) will be ideal for carrying out the more basic components of the research on materials in a radiation environment. The AMTF offers good geometric access and room for up to three independent irradiation tests, it has a sufficiently high in-core flux to simulate accurately the radiation environment in PWR/BWR power reactors, and there is an ability to control the chemistry and thermal fields to reflect prototypic conditions.

Impact on Nuclear Engineering Education: The establishment of this research capability enables future examinations of advanced fuels to be done, with benefits to the national industry and to the government program on advanced fuel cycles (AFCI) with the added benefit of student participation in research that will affect the design the next generation of PWR reactors.

Title: Reactor Upgrades

Description: Funds received under the INIE program have allowed the MIT Nuclear Reactor Laboratory (NRL) to make several necessary upgrades to its 5 MW research reactor but has also supported the design and implementation of several facilities that will greatly increase the NRL's research reactor's capability to support and conduct faculty and outside user research. These improvements include:

Title: High Temperature Irradiation Facility (HTIF) (MIT)

Description: The High Temperature Irradiation Facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials and in November 2005, this in-core loop was installed in the MITR. A demonstration test was performed with temperatures up to 1600 °C. A variety of materials relevant to high temperature gas reactor design, including SiC, AGR matrix graphite and non-fueled coated particles, were irradiated. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs.

Impact on Nuclear Engineering Education: This INIE funded facility represents a major achievement for the MIT Nuclear Reactor Laboratory. The HTIF provides a unique capability among university research reactors. It will be used to irradiate candidate GEN-IV materials and will contribute to the national research mission in nuclear energy through the use of this facility. This facility will not only be a valuable test facility for high temperature resistant materials research but will also be an important teaching facility for both undergraduate and graduate students.

Title: Digital Neutron Radiography Facility (UMass-Lowell)

Description: UMass Lowell has continued to refine and enhance the capabilities of their digital neutron radiography facility. Improvements to the beam-line include increased neutron and gamma ray shielding, as well as a reduction in the scattered neutron component. These improvements will be especially useful when the UMass Lowell Research Reactor increases its power level from 1 MW to 2 MW, and for neutron tomography research.

Impact on Nuclear Science Education Programs: The UMass Lowell digital neutron radiography facility is unique in the northeast region, and therefore offers students the potential to use non-destructive testing in research.

Title: Distance Education and Research Initiative (DERI) (UMass-Lowell)

Description: Recent improvements to the infrastructure of Distance Education and Research Initiative (DERI) at UMass Lowell include the incorporation of Centra software, the capability for real-time interactivity within a web browser, voice over and video capability, and application sharing.

Impact on Nuclear Science Education Programs: These infrastructure improvements have helped to facilitate INIE Inter-Consortium collaboration. An example of this collaboration was demonstrated on 5/5/06 when nuclear engineering students from the University of Illinois were able to participate in an "approach to criticality" laboratory with UMass Lowell students.

E. Partnerships with DOE labs, colleges and universities, utilities, and other public/private entities

MIT: Through the INIE supported NCT User Center, collaborative research activities have been established with 10 university research groups that are engaged in NCT research. A collaboration in the NCT area with consortium partner RINSC is currently under development. Collaborations have also been developed with clinical researchers at two Boston area hospitals. Currently this collaboration is focused on the evaluation of clinical BNCT worldwide and on the development of new BNCT clinical trials using the specialized medical irradiation facilities at MITR. One collaboration has been developed with private industry and one with a DOE national laboratory to support DOE-sponsored SBIR grants. Table III is a summary of academic, research staff and students at other institutions (besides MIT) supported by experiments performed at the NCT User Center. The research of these groups and individuals depends on the availability of the NCT User Center.

UMass-Lowell: UMass-Lowell has partnered with General Electric (Lynn, MA) to perform neutron radiography of turbine blades that are used in helicopters.

RINSC: The cancer research group has partnered with MIT, RI Cancer council, Brookhaven National Lab, Brown University, The University of Rhode Island and The University of Connecticut. Dr. Ott has partnered with Argonne National Lab in the development of his filter. The atmospheric Chemistry group is part of the CHAIOS Group that includes UNH, MWO, UVA, UCSD, UCLA, Heidelberg and SML.

RINSC has two other private entities who make extensive use of the facility. BioPhysics Assay Laboratory, Inc. (BioPAL) specializes in high-precision alternatives to traditional, radiolabeled life science products. Their products are labeled with stable (nonradioactive) isotopes and are used in an analogous fashion to their radioactive counterpart. The analysis of stable tracer(s) in samples of interest is performed by BioPAL using neutron activation technology at RINSC In many cases, this approach provides information with improved sensitivity and specificity well beyond that achievable by optical markers and traditional radiolabels. Microinorganics Inc. does analytical consulting in the areas of trace metal analysis of water columns. This company has done extensive work for the Rhode Island Department of Health, the Narragansett Bay Commission and various other state and federal agencies. It has done analytical work on numerous rivers and other bodies of water such as the Narragansett Bay to determine trace contaminant concentrations at levels much below that normally achievable. RI Consultants LLC also has a laboratory at RINSC for the development of custom radio-nuclides. It has been successful in developing a P-32 stint for angioplasty and p-33 labeled drugs.

E. Intra-Consortium Integration

UMass-Lowell: Improvements in Distance Learning infrastructure enabled nuclear engineering students from the University of Illinois to participate in an “approach to criticality” laboratory with UMass Lowell students on 5/5/06. Future integration is anticipated.

F. University Commitment

MIT: Massachusetts Institute of Technology continues to provide the resources necessary to operate their university research reactor. The funding provided by INIE reinforces MIT's commitment to its research reactor and its nuclear engineering and science programs.

UMass-Lowell: The University of Massachusetts - Lowell continues to provide the resources necessary to operate its radiation laboratory. The funding provided by INIE reinforces the University's commitment to its research reactor and nuclear science programs.

RINSC: The Rhode Island Nuclear Science Center is the only state operated research reactor. As such, it serves the educational, research and commercial sectors of the entire state of Rhode Island and the Northeast region. Its oversight body is the Rhode Island Atomic Energy Commission that is composed of a member from the University of Rhode Island, Providence College, Brown University, the Massachusetts Institute of Technology, and the Army research Center, Natick, Massachusetts. The state legislature has shown continued commitment to the center by approving annual budgets that provide for over 80% of the cost of operating the facility. The state has also supported a strong five year capital budget which has funded several major projects including new roofs, air conditioning systems, outside building preservation, parking lots and asbestos abatement. This capital budget includes a 30 million dollar unfunded line item for decommissioning the reactor which is reviewed by the legislature every year. The reactor was converted to LEU fuel in 1993. As part of this conversion, a new compact core was installed which required the Department of Energy to supply new primary pumps, heat exchangers and associated piping. Subsequent DOE reactor instrumentation grants have resulted in new electronic instrumentation for the reactor. As a result of an extensive repair and replacement program, the reactor and the entire facility are in excellent material condition and ready to perform well for another licensing period. The RIAEC has applied to the Nuclear Regulatory Commission to re-license the reactor for an additional 20 years.

G. Leveraging

As a result of INIE, MIT has been able to expand as well as extend its services to countless number of scientists, researches, private industry, national laboratories, and nuclear engineering students. Further, several research projects would never have had the opportunity to go forward had it not been for the funds that INIE provided. A sampling of projects that have had significant resulted in significant leveraging are listed below:

- Annular Fuel. The purpose of this project which was to develop and to optimize the design of annular fuel to achieve a significant increase of core power density while improving safety margins and will assist the research for the next generation of research reactors. This was the first time that a new fuel design was examined in a university research reactor. Additional testing will now be completed at Idaho National Laboratory.

- High Temperature Irradiation Facility. This facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs. This facility will not only be a valuable test facility for high temperature resistant materials research but will also be an important teaching facility for both undergraduate and graduate students.
- Nanofluid Applications in Nuclear Energy Systems. This program comprises the following activities, which are currently sponsored by the INL, AREVA, and the INIE program. There is enormous leverage in this project as illustrated by the multiplicity of sponsors.
- The NCT User Center. This project has given researchers across the country an opportunity to pursue very specialized neutron capture cancer research; advancement opportunities in the area of material science which includes utilizing MIT's in-core loop abilities. (See Table III for scope of leveraging resulting from this project.)
- SiC Duplex Clad Irradiation. Although his project which involves the production and testing of candidate duplex SiC/SiC composite cladding materials for Light Water Reactors (LWRs) was not initially funded or supported by INIE, it does represent a significant leveraging effect because of the increased capabilities resulting from the upgrades to the MITR and the Advanced Material Testing Facility that made it possible for the research to be done at the NRL. A workshop on SiC cladding applications for advanced nuclear reactors was held on May 5, 2005, to present initial out-of-pile testing results of SiC cladding development, and to discuss the future testing development. This workshop was sponsored by Gamma Engineering Inc., Westinghouse Electric, Nova Tech, and co-hosted by MIT Center for Advanced Energy Systems (CANES) and Oak Ridge National Laboratory.

UMass Lowell has not contributed to INIE initiatives by direct cost-sharing.

H. Minority Student Involvement in INIE

MIT does not keep statistics of this type for individual projects such as BNCT, in-core experiments, beam port usage, etc. Statistics are kept for student enrollment as a whole, and we note that the involvement in each INIE activity is typical of the student body. Figures for 2004 are furnished here.

MIT	Male (%)	Female (%)	Minority (%)
Undergraduate	57	43	47
Graduate	70	30	16

UMass-Lowell	06-07	05 - 06	04 - 05	03 –04
BS Students	0	0	0	0
Minorities	0	0	0	0
Females	0	0	0	0
MS Students	0	0	0	0
Minorities	0	0	0	0
Females	0	0	0	0
PhD Students	1	1	1	3
Minorities	0	0	0	0
Females	0	0	0	1

RINSC	06-07	05 - 06	04 - 05	03 –04
BS Students	4	2	0	0
Minorities	0	0	0	0
Females	0	0	0	0
MS Students	3	2	1	1
Minorities	0	0	0	0
Females	0	0	0	0
PhD Students	2	2	2	2
Minorities	0	0	0	0
Females	0	0	0	0

I. INIE Impact

MIT: The first step towards strengthening university nuclear engineering programs across the U.S. is the education of the next generation of nuclear engineers and to this end INIE is proving to be a major catalyst in attaining that goal.

INIE has provided a definite impact to the nation's nuclear engineering and nuclear research reactor community. It has carried this out in two ways: 1) underscoring national interest in maintaining the U.S. position as a leader in nuclear science and engineering and 2) providing much needed funding to support that goal. At MIT, it has provided the motivation as well as the momentum to rethink the university's vision of how it can contribute to the needs of future generations in the area of nuclear science and engineering. As a result, existing research programs have been expanded upon and new research projects have been initiated.

Overall, this program has started the process of revitalizing nuclear science and engineering at MIT which is evidenced by the increase in:

- Overall student enrollment in the Nuclear Science and Engineering Department and the increased utilization of faculty and researchers;

- The number of faculty and researchers utilizing the MIT Nuclear Reactor Laboratory; and

- The number of students who wish to participate in the MIT Nuclear Reactor Laboratory's Student Reactor Operator Training Program.

In addition, INIE funds have been used in support of graduate students, infrastructure improvements, and the purchase of new equipment in support of existing and new research programs. It has also supported significant upgrades and necessary improvements to the MIT Nuclear Reactor Laboratory's equipment and instrumentation.

Finally, in order to achieve the goals originally set out by INIE, this program must continue.

UMass-Lowell: The impact of even modest DOE funds made available to UMass Lowell through the INIE program remains considerable. The money provided by DOE has created a state-of-the-art regional digital neutron radiography facility at UMass Lowell, with added x-ray imaging and virtual access capabilities; has helped a UMass Lowell assistant professor to obtain tenure; has created research assistantships for graduate students in an environment where student funding is declining; has enhanced the reputation of the UMass Lowell Radiation Laboratory by its ability to secure DOE funding for research; has provided the impetus for establishing a collaboration with a business that manufactures imaging devices; and has gained notoriety for the UMass Lowell Radiation Laboratory through its collaboration with the Nuclear Laboratory at MIT.

The INIE funding has also provided the seed for further enhancements in our overall Distance Education and Research Initiative (DERI). Communications and interaction in the greater INIE community has lead to the development of inter-consortium collaboration with the University of Illinois. This funding will help to broadcast the educational and research capabilities of UMass Lowell to the broader scientific community. Universities that do not possess an operating research reactor will be capable of performing remote laboratory experiments from within the confines of their own colleges.

It is also speculated that the INIE funding will increase the probability that UMass Lowell will obtain additional DOE funding for future research projects. The current infrastructure established by the INIE funding will be potentially available as a research facility to all interested students. Continued DOE funding for the digital neutron radiography facility also will ensure its longevity, and should increase the probability that UMass Lowell will attract more students interested in nuclear science research. Furthermore, the virtual reactor (accessible from Nucelar101.com) will help to integrate the UMass Lowell Research Reactor into more classrooms. The concept of a virtual console also could be expanded to include various reactor experiments, thus potentially familiarizing a variety of students with the UMass Lowell Research Reactor and nuclear science in general.

IIII. Notable Accomplishments

Title: The MIT NCT User Center

Objective: The development and operation a user center at the MIT Research Reactor to provide BNCT type neutron irradiations and technical support to MIT as well as non-MIT researchers who do not have access to neutron beams. Status: Continuing. This center has continued successful operation in this last project year. Small animal and cell culture irradiations were performed in 15 different experiments that usually involve multiple runs. Mixed field dosimetry measurements and computations as well as assistance with experiment design and execution was also provided to the users of the NCT User Center.

Explanation: Specialized neutron facilities for neutron capture therapy irradiations are generally only available in a few locations. With the closure of the Brookhaven Medical Research Reactor a number of BNCT researchers were left without neutron irradiation facilities required for their research in radiobiology and capture compound development. To meet this need, the MIT BNCT research group has established an NCT User Center to assist MIT as well as non-MIT researchers who require specialized neutron irradiations, mixed field dosimetry and experimental design support. The INIE project has provided support needed to operate this center.

Title: High Temperature Irradiation Facility (HTIF) (MIT)

Description: The High Temperature Irradiation Facility was designed to provide an environment appropriate for test irradiations of high temperature gas-cooled reactor materials and in November 2005, this in-core loop was installed in the

MITR. A demonstration test was performed with temperatures up to 1600 °C. A variety of materials relevant to high temperature gas reactor design, including SiC, AGR matrix graphite and non-fueled coated particles, were irradiated. Development and in-pile testing of high temperature resistant materials are essential for the Gen-IV reactor programs.

Explanation: This INIE funded facility represents a major achievement for the MIT Nuclear Reactor Laboratory. The HTIF provides a unique capability among university research reactors. It will be used to irradiate candidate GEN-IV materials and will contribute to the national research mission in nuclear energy through the use of this facility. This facility will not only be a valuable test facility for high temperature resistant materials research but will also be an important teaching facility for both undergraduate and graduate students.

Title: Nanofluids (MIT)

Description: Dr. Lin-Wen Hu (MIT NRL) and Professor Jacapo Buongiorno MIT NSE) are conducting research to assess the feasibility of water-based nanofluids for nuclear reactors. The potential reactor applications include advanced coolants and safety systems, as well as reactor cavity flooding for in-vessel retention during severe accidents.

Explanation: This project is a perfect example of how INIE has and can impact nuclear engineering in the U.S. The research being conducted on this project is cutting edge and as a result has several undergraduates and graduate students working along side Dr. Hu and Professor Buongiorno. However, on a much larger scale, it is also attracting a lot of attention among nuclear engineering students across the country and the nuclear engineering community.

Title: Digital Neutron Radiography Facility

Description: UMass Lowell has continued to refine and enhance the capabilities of their state-of-the-art regional digital neutron radiography facility. Recent improvements and added x-ray imaging and virtual access capabilities will lead to a sustained and versatile x-ray and neutron radiography capacity at UMass Lowell.

Explanation: Recent improvements to the neutron beam-line include increased neutron and gamma ray shielding, as well as a reduction in the scattered neutron component. These improvements will be especially useful when the UMass Lowell Research Reactor increases its power level from 1 MW to 2 MW, and for neutron tomography research. The UMass Lowell digital neutron radiography facility is unique in the northeast region, and therefore offers students the potential to use non-destructive testing in a variety of research areas.

<u>Title:</u> Distance Education and Research Initiative (DERI)

<u>Description:</u> Recent improvements to the UMass Lowell Distance Education and Research Initiative (DERI) have included the capability for real-time interaction using web-based browser-type applications. These efforts will be further enhanced in the coming years to allow for a broad range of experimental facilities at UMass Lowell to be made available to the broader nuclear engineering community.

<u>Explanation</u>: The UMass Lowell online reactor and neutron radiography facilities are unique in the northeast region, and therefore offer students, businesses, and other research institutions the infrastructure to make use of these research facilities. INIE funding is critical to help establish these facilities to their full potential.

<u>Title:</u> Research Assistantships

<u>Description:</u> UMass Lowell is using INIE funding for research assistantships.

<u>Explanation</u>: The research assistantships established with DOE funding have made graduate study in nuclear science affordable for one of our female Ph.D. students. The research assistantships also increase the probability that UMass Lowell attracts competitive students interested in nuclear science.

<u>Title:</u> Industry Partnerships

<u>Description:</u> UMass Lowell has partnered with *Envision Corporation* (a manufacturer of inorganic scintillators and x-ray imaging systems based in Anchorage, Alaska) to investigate an x-ray CMOS line camera for use in neutron radiography. UMass Lowell also has partnered with General Electric (Lynn, MA) to perform neutron radiography of turbine blades that are used in helicopters.

<u>Explanation:</u> The collaboration with *Envision Corporation* proved fruitful in that the company realized the potential of a new customer base, namely those interested in neutron imaging. In addition, the present partnership has opened the door for future collaborations with *Envision Corporation* or other businesses involved in imaging, or who need non-destructive testing services to satisfy industry manufacturing, quality control, and quality assurance standards.

Title: Cancer Research Project (RINSC)

<u>Description</u>: INIE funding has enabled RINSC to bring together an eminent group of researchers to tackle the difficult task of developing an effective agent for use in neutron capture therapy of brain cancers. This treatment protocol utilizes the large aperture neutron beam capability of a research reactor to target the diffuse nature of certain brain cancers and has promise of treating other deep cancers. The RINSC team consists of Dr. Paul Willard , a noted chemist, Dr. John Leith, an experienced radio-biologist, Dr. Arvin Glicksman, an oncologist and Dr. Carl Ott, a nuclear engineer. The team has developed a gadolinium based compound and has conducted basic research starting at the cell level to prove the value of this protocol. The team is investigating the Wortmannin with the Gd compound to inhibit repair of DNA double strand breaks produced by exposure to ionizing radiation. We have also found that dispersing cells from primary brain tumors repair the most amount of radiation induced damages. In this regard, we are also investigating an antifungal agent, leptomycin B, which is even more effective than wortmannin in inhibiting DNA repair. Dr. Ott has designed a new filter that promises to improve the treatment protocol.

Explanation: INIE funding was critical to the development of this project since it takes time to put together a multi-disciplinary team and then apply for grants. Since RINSC is a state supported facility, there was no support available at the university level. Since the project has developed, it has received support from the legislature, which has maintained the RINSC budget at a level adequate to support the project. We have also received support for the Cancer Project from the Rhode Island Cancer Council, Pawtucket, RI.

Title: Atmospheric Chemistry Project (RINSC)

Description: The CHAIOS Project achieved excellent results from last year's analysis efforts at RINSC. The large number of sample irradiations doubled the reactors utilization for the year. This year, the increased analysis program has added additional sampling sites, thus providing a more national result regarding halogens and their role in the pollution outflow model for the United States. This year also included sampling off the coast of Africa. INIE funding of the improvements to the RINSC counting system was crucial to the success of these project. The latest improvements to the system have doubled the throughput of samples and reduced manpower. The purchase of the Genie 2000 VB programming libraries will allow us to further improve this process.

Explanation: RINSC as a long history of environmental research utilizing Neutron Activation Analysis and the numerous graduates of the URI Graduate School of Oceanography continue to return to RINSC with the research projects. INIE funding has a large impact on our ability to support these research efforts by allowing us to maintain and improve our equipment at a level necessary to support these efforts.

Title: Sensor Research Project (RINSC)

<u>Description</u>: Dr. Hanson's research into underwater sensors for environmental work and detection of weapons of mass destruction has coupled the unique capabilities of the marine scientists at URI with the capabilities of RINSC to create a very talented team of researchers with the facilities necessary to take on difficult problems. The large amount of state funding that has gone into completing his laboratory would not have been possible without the initial INIE support to move the project forward. The subsequent SBIR and other grants that have continued the research and the six graduate students that are supported by the research are the result of the initial INIE help.

<u>Explanation</u>: RINSC serves as an incubator for small businesses and researchers who have a good idea in the nuclear field but lack funding. Dr. Hanson's research efforts have lead to commercial success. BioPal and RI Consultants also fit the mold of small startup companies that benefit from the ability to use RINSC as a base while they develop their technology. INIE funding support of RINSC enables us to support innovative ideas in the area of nuclear science as they transition from theory to practice.

TABLE III

NAME	INSTITUTE	PROJECT TITLE	DURATION	FUNDING SOURCE	AMOUNT
1. Prof. Rolf F. Barth	Ohio State University	a. "Molecular Targeting of EGF for the Treatment of Gliomas" b. "Carboranyl Nucleosides as Delivery Agents for Neutron Capture Therapy of Gliomas"	06/01/03 – 05/31/07 4 years	NIH 1R01 CA107367 -01A1	$1,312,752
2. Prof. Yana Reshetnyak	University of Rhode Island	"The self guided nanocompounds targeting breast cancer cells"	2007-2010	DOD BC061356	$431,995
3. Dr. Michiko Miura	Brookhaven National Laboratory	" Targeted Ablation of Tumors by BNCT using Lipophilic Tetracarboranylphenyl Porphyrins"	09/01/06-08/31/08	DOE CRADA (with Morvus Technology)	$210,000
4. Prof. M. Frederick Hawthorne	University of Missouri	"Liposome Delivery of Boron for BNCT"	08/03/04-07/31/08	NIH funding 1R01 CA97342-01A2	$1,726,536
5. Prof. George W. Kabalka	University of Tennessee	"Boronated Amino Acids for NCT"		Private funding	
6.Prof. Maria da Graca Vicente	Louisiana State University	"Tumor-targeting with New Boronated Porphyrins"	Apr. 2004 – March 2007	NIH funding1R01 CA098902	$595,350
7. Prof. Stephen B. Kahl	University of California, San Francisco	"Program for Development of BNCT Agents"	2006 – 2011	NIH 1RO1 CA82478 (submitted for $250k pa from 12/1/05)	$1,250,000
8. Prof. Jeffrey A. Coderre	MIT	"Liposome Delivery of Boron for BNCT"	08/03/04-07/31/08	NIH, NCI subcontract	$465,880
9. Dr. W. Steadman Kiger	Beth Israel Deaconess Medical Center	"NCT Treatment Planning Intercomparison"	2006-2007	Harvard JCRT Foundation	$45,000

Table III (Continued)					
NAME	**INSTITUTE**	**PROJECT TITLE**	**DURATION**	**FUNDING SOURCE**	**AMOUNT**
10. Dr Peter Binns	MIT	"Hypoxic sensitizers as a boron delivery agent for neutron capture therapy"	03/01/06-02/28/07	David H Koch Cancer Research Fund (MIT)	$100,000
11. Prof David Lee	McLean Hospital, Harvard Medical School	"Synthesis of nitroimidazole carborane as a boron delivery agent"		Private funding	
12. Prof Shih-Yuan Liu	University of Oregon	"Development of novel boron nitrogen heterocycles for BNCT"	2007-2008	Private funding	
12. Dr Stuart Green	University of Birmingham, UK	"Radiobiology studies for the evaluation of epithermal neutron beams used for BNCT"	09/01/06-08/31/09	Engineering & Physical Sciences Research Council, UK	$650,000

Appendix F

MIT NRL INIE Annual Report 2007-2008

Appendix F

MIT NRL INIE Annual Report 2007-2008

Appendix G

MIT NRL INIE Annual Report 2008-2009

Annual Report

Innovations in Nuclear Infrastructure and Education

DG-FG07-02ID14420

By

MIT Nuclear Reactor Laboratory
Cambridge, MA 02139

October 1, 2008 – September 30, 2009

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Annual INIE Report – MIT Nuclear Reactor Laboratory
October 1, 2008 – September 30, 2009

Summary: Funds totaling $136,458 were expended primarily on infrastructure improvements during this reporting period.

Details:

1. Cooling Tower Equipment - $73.8K was expended to upgrade/replace components of the reactor's cooling tower. This included:

    - Construction of shed to protect pumps, electronic controllers, and other sensitive equipment for cooling tower operation from exposure to the weather.

    - Procurement and installation of electric cables and wiring for instrumentation associated with operation of the cooling tower.

    - Procurement and installation of communications system between the shed and the reactor control room.

    - Installation of an A/C unit to improve operation of electronic controls in the shed building that houses these controls.

2. Neutron Diffractometer - $12.4K was expended to complete installation of a neutron diffractometer. This project is under the direction of Professor David Moncton and Dr. Boris Khaykovich. The diffractometer is now fully operational and being used for neutron scattering experiments.

3. Nano-fluid Heat Transfer - $2.4K was expended to defray salary costs of students involved with modifications to the various loops that comprise this facility. This project is under the direction of Dr. Lin-Wen Hu.

4. Advanced Fuels - $7.5K was expended to defray salary of those servicing the advanced fuels experiment and to repair several instruments associated with examination of the irradiated materials. This project is under the direction of Professor Mujid Kazimi and Dr. Gordon Kohse.

5. Reactor Instruments - $25.1K was expended to procure Keithley units to upgrade or replace existing instruments in the reactor's nuclear safety system. This project is under the direction of Dr. John A. Bernard.

6. U-Mass Lowell - $7.6K was expended by the University of Massachusetts – Lowell in conjunction with their INIE Program.

7. TRTR Meeting: A contribution of $7.5K was made by U.S. DOE through the INIE grant to support the 2008 annual meeting of the National Organization of Test Research and Training Reactors that was held in September 2008 in Yarmouth, MA. These funds were not part of the original INIE grant. There were 120 attendees at the meeting which provided both the U.S. Nuclear Regulatory Commission and the U.S. Department of Energy the opportunity to present their safety lessons and programs to the research reactor community.