The University of Michigan

MICHIGAN MEMORIAL – PHOENIX PROJECT
PHOENIX MEMORIAL LABORATORY FORD NUCLEAR REACTOR
ANN ARBOR, MICHIGAN 48109-2100

Office of the Director

August 11, 2000

Mr. Theodore S. Michaels
Senior Project Manager
Non-Power Reactors & Decommissioning Project Directorate
Division of Regulatory Improvement Programs
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Dear Mr. Michaels:

Enclosed please find a copy of the FY99 annual report for the Michigan Memorial Phoenix Project (MMPP), which operates the Ford Nuclear Reactor (FNR) and associated facilities in the Phoenix Memorial Laboratory (PML) at the University of Michigan. The annual report summarizes recent activities of the MMPP in support of its mission to promote peaceful uses of nuclear science and technology. In preparing the report this year, we have made particular effort to highlight key research programs at the PML, including neutron activation analysis, geological dating, materials science testing, neutron radiography, cobalt irradiation, radiopharmaceutical production, and radiation detector development.

I hope the enclosed MMPP publication provides you with a synopsis of current activities at the PML. I would like to take this opportunity to thank you for providing continued oversight and support of the FNR, which allows us to carry on its mission as a World War II memorial. All of us at the Phoenix Memorial Laboratory feel proud to make contributions to the nuclear science and technology program of the United States.

Sincerely,

John C. Lee
Interim Director and
Professor of Nuclear Engineering

Enclosure

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Michigan Memorial Phoenix Project

Ford Nuclear Reactor
Phoenix Memorial Lab

Annual Report, 1998-1999

Michigan Memorial Phoenix Project

Ford Nuclear Reactor
Phoenix Memorial Laboratory

Address
2301 Bonisteel Blvd.
North Campus, The University of Michigan
Ann Arbor, MI 48109-2100

Hours of Operation
Monday - Friday 8:00 a.m. - 5:00 p.m.
Facilities can be made available 24 hours a day, if required.

Tours
Monday - Friday 9:00 a.m. - 3:30 p.m.
Tours should be scheduled at least 48 hours in advance.

Project Staff

Interim Director	John C. Lee	(734) 764-6215
Associate Director	David K. Wehe	(734) 764-5225
Reactor Manager	Christopher W. Becker	(734) 764-6224
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Assistant Manager, Research Materials Science Testing Radiochemical Production	Philip A. Simpson	(734) 764-6221
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Senior Research Associate Neutron Activation Analysis	Leah D. Minc	(734) 936-1584
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Michigan Memorial Phoenix Project:

Ford Nuclear Reactor
Phoenix Memorial Lab

A

Summary of

Research

and

Educational

Activities,

1998-1999

Michigan Memorial Phoenix Project

Summary of Research and Educational Activities, 1998-1999

Research Highlights:

List of Tables:

Foreword: Looking to the Future....

In 1948, students at the University of Michigan called for a living memorial to World War II veterans - a memorial dedicated to a better and more enlightened world where the technology which had helped end the war could be turned to peaceful applications in the name of those who had fought and died. The University chose to honor those who died by *looking to the future*, and created the Michigan Memorial Phoenix Project.

With the intention of preserving this legacy by *looking to the future*, all of us at the Michigan Memorial Phoenix Project (MMPP) have worked together during this past year to examine our capabilities, to determine where enhancements and improvements can be made, and to open new areas. Several facility-wide efforts mark our progress:

> **Strategic Plan Development** - The entire staff participated in workshops and in-house seminars to review the objectives of the Project and develop specific strategies for the enhancement of research productivity, instructional outreach and support, and facility operations.
>
> **Research Advisory Committee Review** - The inaugural meeting of the Committee was held to assess research programs and their utilization, and to provide counsel on research directions and focus. Chaired by Dr. Michael Rowe (Director, NIST Center for Neutron Research), the Committee will also provide guidance and oversight for developing research programs in the future.
>
> **Phoenix 50th Anniversary Symposium** - In recognition of 50 years of scientific and technical contributions of the MMPP and the Ford Nuclear Reactor, we hosted a two-day symposium celebrating past, current, and future applications of nuclear science and technology in the fields of nuclear power, engineering, space exploration, medicine, and environmental and life sciences. Over 80 alumni and friends of the MMPP participated in the symposium and 33 papers were presented. A panel discussion at the end of the symposium provided suggestions for future MMPP directions.
>
> **Engineering Open House** - Interdisciplinary research within the College of Engineering was promoted to faculty, staff, and graduate students of the College through a series of displays and presentations featuring our major research programs and capabilities.

The Research Advisory Committee indicated that they were impressed with the performance of the facility, and encouraged the MMPP to become more outward focused and entrepreneurial. They strongly endorsed current programs, and noted that a focused effort would enhance these programs. Finally, they expressed their confidence that the Strategic Plan would lead to even higher utilization of this unique research facility.

Thus, in the coming year we will continue to pursue enhancements and improvements to research productivity, instructional outreach and support, and operations. Planned additions to the research and technical staff, funding sources to facilitate upgrades to research equipment (such as the state-of-the-art large-format neutron imager), and facilities upgrades (including the control-room upgrade and fire protection improvements) demonstrate our commitment to the future and will ensure that the Phoenix legacy leads to tomorrow's discoveries.

John C. Lee, Interim Director

Michigan Memorial Phoenix Project :

Dedicated to the peaceful applications of nuclear science and technology...

Founded in 1948 as a World War II memorial, the Michigan Memorial Phoenix Project (MMPP) is dedicated to encouraging and supporting peaceful applications of nuclear science and technology for the benefit of humankind. In pursuit of that mission, the Ford Nuclear Reactor and associated facilities in the Phoenix Memorial Laboratory support academic research, teaching, and service in a broad range of disciplines within the University of Michigan and other academic institutions, and provide contract services to government agencies, hospitals, and industry.

Research facilities at MMPP feature the Ford Nuclear Reactor (FNR) with a licensed power of 2.0 MW, which provides in-core and ex-core neutron irradiations within the reactor pool and offers facilities for neutron beam experiments. The Cobalt Irradiator Facility (CIF), housed in the Phoenix Memorial Lab (PML), also plays a key role as a source of intense gamma rays. In addition, the PML offers a number of specialized laboratories that allow for the analysis and handling of radioactive samples under a safe and controlled environment.

MMPP supports the peaceful applications of nuclear science through service to the public and academic communities in four key areas:

- ***Academic Research*** involving college and university students, faculty, and staff.
- ***Teaching and Training*** for college and university students as part of formal courses.
- ***Public Outreach Education*** for non-collegiate groups and professional organizations.
- ***Applied Research and Development*** for industrial and governmental organizations.

Ford Nuclear Reactor
Phoenix Memorial Laboratory

"...a vital facility with current programs that are worthy of the illustrious past of the Phoenix Memorial Laboratory."
David M. Gilliam, Group Leader
Neutron Interactions and Dosimetry, NIST

"...critically important to the research conducted by faculty and students in our department."
David K. Rea, Chair
Dept. of Geological Sciences

"...a tremendous research asset that we enjoy at the University of Michigan."
John O'Shea, Former Director
Museum of Anthropology

"...the future success of the Nuclear Engineering and Radiological Sciences Department is dependent on this facility."
Stephen W. Director, Dean
College of Engineering

"...a critical component of not only our research, but also the national (and indeed international) effort to understand and mitigate neutron irradiation embrittlement of [nuclear power plant] structural steels."
G. Robert Odette, Chair
Department of Mechanical & Environmental Engineering, UC-Santa Barbara

"...a unique educational experience for students who would otherwise never have the chance to go into a real nuclear science laboratory."
Katrine Klaphake, Education Coordinator
Ann Arbor Hands-On Museum

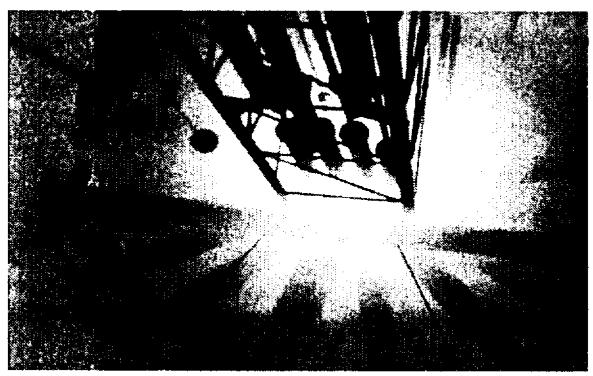
... providing research and educational opportunities for the University, the public, and industry for over 40 years.

The Ford Nuclear Reactor

The Ford Nuclear Reactor is a two-megawatt MTR-type research reactor immersed in a 50,000-gallon open pool of demineralized water. When operating at maximum power, the reactor produces a peak thermal flux of approximately $2x10^{13}$ neutrons/cm^2·sec. Among the 12 university research reactors currently operating in the U.S. with a power rating of 1.0 MW or higher, the 2-MW FNR is regarded as one of three leading facilities, together with the 10.0-MW University of Missouri reactor and 5.0-MW Massachusetts Institute of Technology reactor.

The FNR operates on a schedule of ten days at full power followed by four days of shutdown and maintenance, for an average of 120 hours of operation per week. The 10-day operating cycle provides long irradiation periods, which are desirable in many material studies, and offers experimental uses of the facilities for approximately 65% of the calendar year.

As an instrument of MMPP's mission, the FNR provides safe and reliable operation of the facility for the purposes of academic research, teaching, and service for the University of Michigan, other educational institutions, government agencies, and industry. The Ford Nuclear Reactor serves as a source of neutrons for materials irradiations; radiation damage studies; neutron activation analysis; radioisotope production; beam extraction experiments such as neutron radiography and neutron scattering; and teaching and laboratory experiments related to reactor physics, radiation safety, and materials analysis.



Technical Information

Neutron Physics Characteristics

- 2 MW steady-state
- 1.5×10^{13} n/cm^2/s peak thermal flux
- 5.0×10^{12} n/cm^2/s peak fast flux (E > 1 MeV)

Irradiation Testing Capabilities

In-Core/Ex-Core Irradiation Facilities

- In-core irradiation facilities (2.75" dia.; thermal flux: 7×10^{12} n/cm^2/s; fast flux: 5×10^{12} n/cm^2/s)
- Core-face locations with low flux gradient (thermal flux: 8×10^{12} n/cm^2/s; fast flux: 3×10^{12} n/cm^2/s)
- Large experimental grids in water reflector regions for long-term irradiation of samples
- Heavy-water reflector tank (thermal flux: 1×10^{11} n/cm^2/s - 1×10^{12} n/cm^2/s; Cd ratio: ~ 70)
- Pneumatic tube system (average thermal flux: 3×10^{12} n/cm^2/s; average fast flux: 6×10^{11} n/cm^2/s)

Beam Facilities

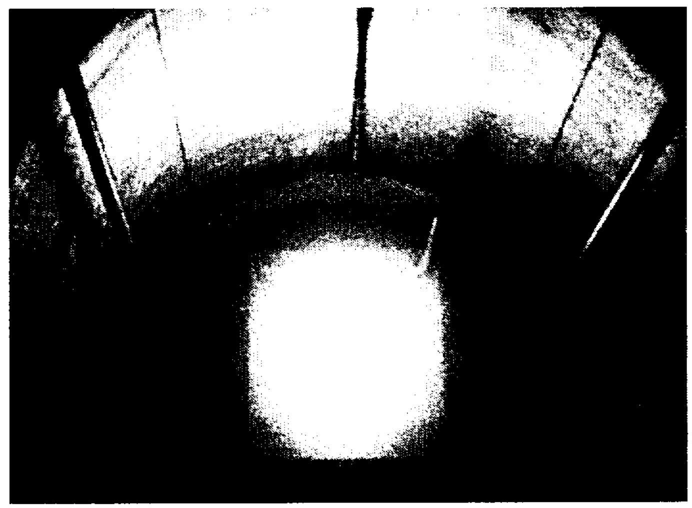
- One horizontal beam port dedicated to short-lived fission product characterization, where products released from fission targets are transported for chemical enhancement and subsequent gamma spectrometry via a carrier gas.
- Two horizontal ports providing monoenergetic, low-gamma thermal neutron beams for detector testing, neutron dosimeter studies, and material attenuation measurements.

Neutron Radiography and Radioscopy Facilities

- Large format (entrance dia.: 12.7 cm; L/D radioscopy imaging plane: 55.2; L/D film imaging plane: 62.4; thermal flux: 3.2×10^6 neutrons/cm^2/s; cadmium ratio: ~ 47).
- High-resolution (entrance dia.: 2.06 cm; L/D lower imaging plane: 326; L/D upper imaging plane: 407; thermal flux: 2.3×10^6 neutrons/cm^2/s; cadmium ratio: ~ 200).

Gamma Irradiation Facility

The Cobalt Irradiator Facility was constructed in 1958 and has served as a major gamma irradiation facility in the U.S. for sterilization of human tissue for reconstructive surgery and for studies of radiation effects on various materials. The CIF source consists of 9 rods, each a stainless steel tube approximately one-half inch in diameter and 13 inches long, that contains inch-long pellets of radioactive ^{60}Co. The nine rods are arranged in a circular array, providing irradiation locations within the center or around the periphery. The source rides on an elevator platform; the ^{60}Co rods are stored 12 feet under water to provide radiation shielding and are raised above water for sample irradiations. With the CIF licensed to 25 kCi of ^{60}Co in rods, the facility offers higher gamma dose rates than usually available in larger production facilities. The CIF is available 24 hours per day, seven days a week.



Electrons traveling faster than the speed of light create a blue glow.

Technical Information

Irradiation Parameters

- Peak exposure rate: ~ 1.5×10^6 rad per hour
- Minimum exposure rate: ~ 5×10^3 rad per hour
- Typical exposure time: 1-12 hours

Sample Handling Capabilities

- Sample irradiation using dry ice or liquid nitrogen (limited use).
- Spore Strip Testing is performed to ensure quality of sterilization process.
- Maximum sample size for peak exposure rates is limited to 8 cm dia. by 33 cm tall (center well).
- Maximum sample size is limited to 95 cm by 220 cm by 55 cm.

Typical Applications

- Sterilization of tissue for human grafts and transplants; lab equipment; soil, growth media, etc.
- Environmental qualification of electronic and reactor components for the nuclear power industry and satellites for the space industry.
- Studies of the effect of radiation on chemical systems, polymers, plastics, foods, seeds, etc.

Other Facilities Available

- ***Shielded hot caves*** for remote examination and handling of radioactive materials. One hot cave is connected to the reactor pool by a water lock system allowing the transfer of irradiated material from the pool directly to the hot cave.

- ***Radiochemistry laboratories*** equipped with walk-in hoods that exhaust through specialized particulate filters, pneumatic-tube connections to the reactor core, and drains for radioactive fluids to retention tanks.

- ***Machine and electronics shop*** providing the in-house capability for design, construction, and maintenance of customized irradiation facilities and handling equipment.

Facility Organization

The Ford Nuclear Reactor and Phoenix Memorial Laboratory are operated by the Michigan Memorial Phoenix Project of the University of Michigan under the Office of the Vice President for Research. Oversight and direction are provided by the MMPP Faculty Executive Committee, while the operation and safety of the Ford Nuclear Reactor are regularly reviewed by the Safety Review Committee. The members of these committees are:

Faculty Executive Committee
Prof. Mary L. Brake
(Nuclear Engin. & Radiological Sciences)
Prof. Billy J. Evans
(Department. of Chemistry)
Prof. David W. Gidley
(Department of Physics)
Prof. Nicholas H. Steneck
(Historical Center for Health)
Prof. Richard L. Wahl (Internal Medicine)
Prof. Gary Was
(Nuclear Engin. & Radiological Sciences)
Prof. Robert Whallon
(Museum of Anthropology)
Prof. Charles F. Yocum
(Department of Biology)

Safety Review Committee
Prof. Henry C. Griffin (Dept. of Chemistry)
Prof. John S. King, ***Interim Chair***
(Nuclear Engineering & Radiological Sciences)
Prof. James E. Martin
(Environmental & Industrial Health)
Prof. William R. Martin (*since Sept., 1999*)
(Nuclear Engineering & Radiological Sciences)
Prof. Massoud Kaviany
(Mechanical Engineering & Applied Mechanics)
Prof. Fredrick C. Neidhardt (*until Dec., 1998*)
(Vice President for Research)
Prof. Richard E. Robertson (*since Sept., 1999*)
(Material Science and Engineering)
Prof. Fawwaz T. Ulaby (*since January, 1999*)
(Vice President for Research)
Mr. Douglas Wood (V.P., Advent Engineering)
Mr. Mark Driscoll, *ex officio* (Rad. Safety Officer)
Mr. Christopher W. Becker, *ex officio* (FNR)

MMPP Staff

The total number of full-time personnel employed by the Michigan Memorial Phoenix Project is currently 24. The interim Director and Associate Director hold split appointments between the MMPP and Department of Nuclear Engineering and Radiological Sciences (NERS). The Nuclear Reactor Laboratory Manager reports to the Director and Associate Director, and supervises three assistant managers covering MMPP activities in three areas: Reactor Operations, Research Support Activities, and Laboratory Operations.

A total of 13 staff members, including the three assistant managers, currently hold U.S. Nuclear Regulatory Commission (NRC) licenses, either as a Reactor Operator or Senior Reactor Operator. To maintain around-the-clock operations, a number of staff members with primary responsibilities in other areas serve as relief operators at regular intervals.

Performing in-house research and providing research support are two Ph.D. staff members and two laboratory technicians. Two engineering technicians and one electronics engineer perform machine shop and electronics repair services and also work as relief FNR operators. Two administrative associates and three secretarial staff provide administrative support for the reactor and laboratory operations as well as for the MMPP administration. Two Health Physics personnel provide health physics surveillance and support for the diverse irradiation and laboratory facilities.

Research and Scholarship Activities

The Ford Nuclear Reactor and Phoenix Memorial Lab serve as valuable resources at the University, state, and national levels. Although our primary purpose is to provide the University with special facilities needed for nuclear science research and teaching, MMPP also participates in a broad range of programs that extend our mission well beyond the University of Michigan community. Academic service activities cover three main areas: (1) academic research involving college and university students, faculty, and staff; (2) teaching and training for college and university students as part of formal courses; and (3) public outreach education for non-collegiate groups and professional organizations.

Support for Academic Research

University students, faculty, and staff utilize the Reactor through active research programs involving neutron activation analysis, irradiations for geochronology, neutron radiography, materials science testing through accelerated neutron aging, and radioisotope production. The Cobalt Irradiator provides a unique research facility for sterilization of human, animal, and plant tissues, and also contributes to material science testing as a source of intense gamma irradiation.

Utilization of MMPP facilities by researchers and educators is fostered and encouraged through a variety of research support services. The success of our research support program is demonstrated by several factors:

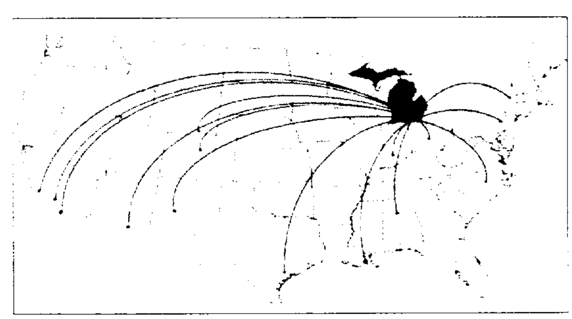
- **University researchers supported:** during the past year, *40 faculty researchers* and *60 student researchers* working on advanced degrees at the University of Michigan utilized research facilities and services at MMPP.

- **Volume of irradiation services:** the Ford Nuclear Reactor provided over *13,500 experiment hours* for academic research during 1998-1999.

- ***Pro bono* services:** more than *$200,000* in irradiation and analytical services were provided at no cost to University faculty for research and teaching during the 1998-1999 academic year. An additional *$280,000* of support was provided in the form of laboratory and office space.

- **Research dollars facilitated**: grants and awards brought into the University over the past two years by faculty and students whose research is significantly based on access to facilities and services at PML or FNR exceeded *4.8 million dollars*. In many cases, MMPP services work as matching funds in securing these outside grants.

- **National contribution to research:** MMPP serves a diversity of other colleges and universities other than the University of Michigan. In the past academic year alone, FNR benefitted *120 faculty* and *over 100 student researchers* from 18 other academic institutions across the country.



Researchers across the country conduct experiments and analyses at the Ford Nuclear Reactor.

Support for Teaching and Training

MMPP directly benefits University of Michigan students through a variety of formal courses, and offers educational opportunities for college students enrolled at other institutions as well. At the University of Michigan, 18 regularly offered courses incorporate the Ford Nuclear Reactor into their curriculum through tours, labs, lectures, and research projects. Key instructional areas include nuclear engineering, physics, and analytical chemistry, but also include such diverse disciplines as art and archaeology, geology, and biology. Training programs are offered in neutron activation analysis, neutron radiography, and reactor operations and instrumentation.

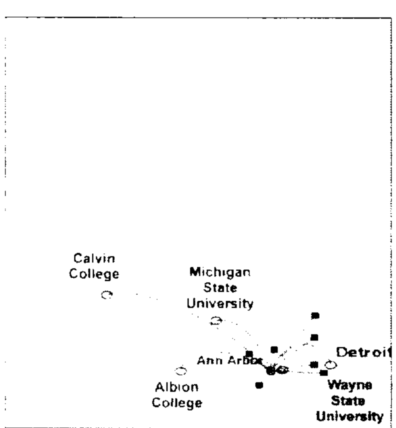
During the academic year 1998-1999, the FNR provided instructional opportunities for:

- Over 70 students in Nuclear Engineering & Radiological Sciences.
- Nearly 50 students from 10 other University departments.
- More than 100 students from other academic institutions.

Public Outreach Education

MMPP provides a public educational service by offering reactor tours, lectures, and demonstrations to school children, high school students, professional groups, and the public at large (Table 1). Pre-college physics and chemistry classes visited the facility for an introduction to reactor physics, nuclear chemistry, radioisotopes, and determinative methods such as neutron activation analysis. Professional groups visiting the facility included high school science teachers working on advanced degrees, and local fire-fighters receiving training in the handling of radioactive materials. During the past year (1998-1999):

- More than 1250 visitors toured FNR and PML facilities.
- Over 500 high school and middle school students visited FNR for science instruction.



Colleges (circles) and high schools (squares) utilizing the Ford Nuclear Reactor.

Table 1. Visitors to the Ford Nuclear Reactor, 1998-1999

Type of Visitor	Groups	Visitors
University of Michigan		
Faculty and Staff	2	33
Students	19	234
Other college students	2	63
High school students	16	345
Middle school students	4	196
Elementary school students	3	99
Adult/Professional	8	143
Adult/Family Public	23	220
Total	77	1270

Research Programs and Services

The Ford Nuclear Reactor and Phoenix Memorial Laboratory facilities provide irradiation and analytical services, some not available from any other source, to the University of Michigan, to other universities, and to government and industrial users. Major service areas include:

- ***Instrumental Neutron Activation Analysis.*** INAA provides sensitive, high-precision characterization of elemental composition (in ppm or ppb) of many types of materials through the creation of radioisotopes and measurement of their subsequent decay. Over the past decade, FNR has irradiated more than 32,000 samples for researchers representing nearly a hundred universities and colleges in the U.S. in such disciplines as art history and archaeology, chemical engineering, environmental science, geology, medicine, and zoology.

- ***Ar-Ar Dating.*** Mass spectrometric measurement of the concentrations of ^{39}Ar (produced through neutron irradiation of ^{39}K) and of ^{40}Ar (formed through natural decay of ^{40}K) yields the age of geological samples. Mineral samples are irradiated in-core at FNR and then returned to geochronology laboratories for analysis. FNR's dedicated irradiation facility (featuring a low flux gradient, high fast-to-thermal neutron ratio, and a favorable J-factor of 2×10^{-4}/hour) provided 2145 hours of in-core irradiation for ten major geochronology labs world wide in 1998-1999.

- ***Neutron Radiography and Radioscopy Program.*** Neutron radiography provides a nondestructive method to image light materials (particularly hydrogenous fluids) contained within dense, opaque, metallic structures, using a beam of neutrons in a manner analogous to X-ray radiography. In addition to high-resolution photographic systems, real-time neutron imaging (neutron radioscopy) systems allow studies of dynamic phenomena. Under the full-time direction of a Ph.D. research scientist, the neutron radiography program has contributed to such projects as high-resolution radiography of coking in fuel injectors in a jet aircraft turbine engine and lubricant movement in operating engines and transmissions.

- ***Neutron Irradiation and Materials Science Testing Program.*** Neutron irradiations for dosimetry and for materials damage studies are available both in-core and in the pool with fluence rates as high as 10^{13} n/cm^2-s. Accurate, NIST-certified dosimetry is provided through the Materials Dosimetry Reference Facility (MDRF). Designed and constructed by NIST, the MDRF provides a high-intensity neutron reference spectrum similar to that experienced by nuclear power plant reactor structural materials and pressure vessels. This characteristic makes the MDRF a valuable national resource for the calibration of neutron dosimeters.

- ***Radioisotope Production.*** Preparation and custom labeling with radioisotopes are available for biological, medical, and industrial research.

- ***Cobalt Irradiation Program.*** The cobalt irradiator is used in a large number of applications requiring a high dose rate of gamma radiation. Typical applications include sterilization of bone and cartilage for human grafts and transplants, sterilization of growth media for biomedical research, and studies of radiation effects.

- ***Radiopharmaceutical Program.*** Radioiodine compounds are synthesized for clinical studies on a regular basis for distribution to 60 hospitals in the United States and Canada.

Research Advisory Committee Review

In February, 1999, the Michigan Memorial Phoenix Project established a strategic plan for the future of the project. To accomplish long-term enhancement of MMPP research productivity and to determine future directions for focused research activities this plan called for a Research Advisory Committee (RAC) to provide an in-depth discussion and exchange of ideas with experts in a few selected areas of direct relevance to MMPP research programs. The RAC would be charged with (1) evaluation of the quality of the technical staff and research and service programs, and the utilization of MMPP facilities; (2) provide advice and counsel to the Phoenix Project on its research directions and focus; (3) provide support, within and outside the University, for the mission and programs of the Phoenix Project; and (4) serve as an expert resource for developing MMPP research programs, as appropriate. With the concurrence of the MMPP Executive Committee and the Vice President for Research, the Director assembled the committee:

J. Michael Rowe
Committee Chair
Director, NIST Center for Neutron Research
(General reactor utilization, neutron scattering)

Robert Brugger
Former Director, University of Missouri Research Reactor Center
(General reactor utilization, neutron scattering, BNCT)

John I. Sackett
Deputy Assoc. Laboratory Director, Argonne National Lab-West
(Reactor utilization, reactor physics/safety)

Jacob I. Trombka
Senior Fellow, Goddard Space Flight Center
(Radiation measurements, space applications)

G. Robert Odette
Chair, Mechanical & Environmental Engineering, UC- Santa Barbara
(Radiation effects, materials science)

John S. King
Professor, Nuclear Engineering & Radiological Sciences, UM
(Reactor utilization, reactor physics, neutron scattering)

On August 13th, 1999, the Director hosted the first RAC meeting. The staff made presentations on the current programs and facilities at MMPP and planned facilities enhancements:

Current programs and facilities:

Ar/Ar geological dating
Neutron activation analysis
Pressure vessel steel/ materials science testing
Neutron radiography and radioscopy
Cobalt irradiator
Nuclear medicine
GaAs(B-10) neutron detectors /
Spent fuel imaging program

Planned facilities enhancements:

Pneumatic tube system replacement
Dedicated Ar/Ar irradiation facility
Prompt gamma activation analysis
Silicide fuel
Pressure vessel steel handling & testing facility
Reactor control room upgrade
Radiation effects on zeolites

The committee noted that many of the reactor facilities which supported the initial development and application of nuclear technology are being lost. This is due in part to a shift in emphasis for reactor-based research, which is moving away from reactor development and towards the application of nuclear technology to a broad range of technologies. Collaboration with researchers in these broader fields is essential to success of MMPP. They recommended seeking opportunities for collaboration within the university, with other universities, national labs, industry and foreign interests. This collaboration should be sought through a combination of marketing and joint proposal development. MMPP must first and foremost become more outward focused and entrepreneurial in approach. Opportunities for expansion are there, but it is up to the staff to develop them. However, efforts should not attempt to duplicate existing capabilities that exist elsewhere, by placing too much emphasis on one strategy. Rather, they felt that efforts should identify unique strengths and capabilities at UM, such as the area of neutron dosimetry. The committee made specific recommendations in several major program areas.

Research Advisory Committee Recommendations

Instrumental Neutron Activation Analysis (INAA): INAA is a major part of MMPP both at present and as seen for the future. Although the quality of instrumentation is adequate, the reliance on a single pneumatic tube irradiation location is a situation that must be addressed as soon as possible. The design of a replacement pneumatic tube system must carefully consider neutron spectrum, intensity, and reproducibility. Additionally, increasing competition from new techniques makes expansion of the user base (through better publicity and aggressive contact with a variety of users not currently familiar with INAA) critical.

Materials Science Testing: MMPP is currently playing a crucial role in the field of irradiation effects on materials that is critical to a number of technologies, including the reliability of aging nuclear power plant structures, safe isolation of nuclear wastes, development of fusion energy, space science, radiation detection, and semiconductor device processing. MMPP has facilities that are unique on a worldwide basis, including the hot cells to conduct low-to-intermediate flux irradiations of materials. The current showcase project is the poolside IAR/IVAR irradiation facilities. The value of these facilities lies in their flexibility to vary the neutron exposure conditions and the ability to insert and remove large-volume irradiation capsules routinely in a cost effective manner. More direct participation of staff is necessary to exploit these opportunities and develop closer connections with the physical and intellectual infrastructure at UM and partnerships with researchers at other institutions in both the national and international arenas. Additionally, the development of a higher flux in-core facility is important to cement MMPP's position as a world leader in material irradiations.

Argon/Argon Dating: FNR's in-core irradiation facility (combined with UM's geochronology program) provides an Ar/Ar dating capability that is probably foremost in the U.S. The scientific research level and intra-UM interest is strong. The current FNR facility is not optimized and could become more competitive internationally. A fully optimized facility could be provided for a relatively small investment and would solidify UM's position as one of the foremost Ar/Ar dating facilities in the world.

Neutron Radiography: This program could potentially be world-class in its capabilities, but needs improved visibility in the areas of research and technical development. This could be best accomplished by writing up each new technical development for publication in peer-reviewed journals. Collaboration with other researchers in the field would also be beneficial.

Nuclear Medicine: Interactions between MMPP and the nuclear medicine community at UM is hindered by the fact that there is no staff member within MMPP that has research experience in the application of radioisotopes in nuclear medicine.

Cobalt Irradiation Facility: This facility provides MMPP with an important resource providing a competitive edge in several fields of research. Opportunities to expand the research role of this facility, especially in the area of radiation effects, must be pursued with collaborations within UM.

Overall, the Committee was impressed with the performance of MMPP but encouraged a more outward focus that is entrepreneurial in its approach. Current programs received a strong endorsement, but the Committee noted that sustained effort over several years would be required to build programs to their fullest.

Recent Enhancements and Improvements

With guidance from the RAC review, MMPP is continuing its pursuit of enhancements and improvements to the areas of research productivity, instructional outreach and support, and operations. Recent and on-going enhancements include:

Reactor Control-Room Upgrade: The whole-scale replacement for the original reactor instrumentation system has begun with funding from the U.S. Department of Energy ($85,000) and the University ($25,000). This is the first of a series of steps to upgrade the entire reactor control system, much of which is still original. We will being by replacing the annunciator, reactor scram, and rod control systems. This project will continue through the next several years and will provide much needed documentation to support reactor relicensing.

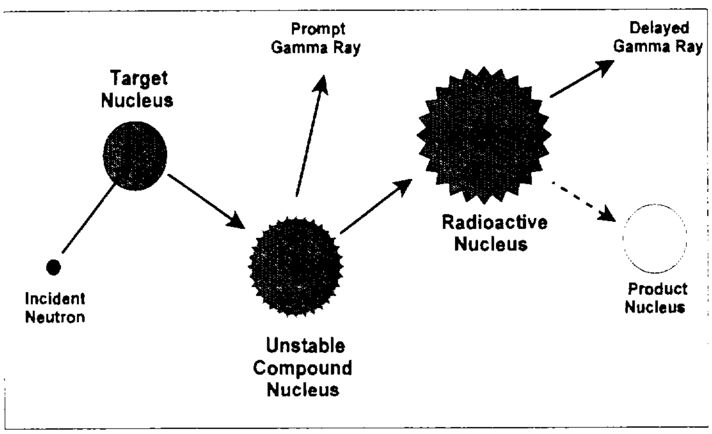
Neutron Radioscopy Facilities: A new, large-format analog neutron imaging camera was recently made possible through the generous gift of $57,000 from the Ford Motor Company.

Pneumatic Tube System Replacement: A new and innovative ptube systems will be designed in stages utilizing the expertise of senior Mechanical Engineering students in UM's Capstone design course (ME450). This collaborative effort both upgrades FNR research facilities, and extends the teaching and training mission of MMPP.

Additional Research and Technical Staff: An important factor influencing MMPP research productivity is the availability of research and technical support staff. Over time, the number of administrative positions will be decreased and the number of research staff positions increased. In addition, existing technical staff with sufficient experience will be elevated to research status, thereby improving MMPP's capability for contributing to the richness of scholarship and creative activity.

Instrumental Neutron Activation Analysis Program

Instrumental Neutron Activation Analysis (INAA) is a highly sensitive analytical technique for identifying and measuring trace quantities in samples from a broad range of scientific fields. Sixty-seven common and rare earth elements become radioactive when exposed to the neutron flux in a reactor. As the activated nuclei decay, they produce gamma radiation at energies (measured in keV) characteristic of each element. Measurement of the gamma radiation permits both isotopic identification and provides high-precision determination of elemental concentrations, often in parts per million or even in parts per billion.



At the base of INAA is the sequence of events termed "thermal neutron capture" or the (n,γ) reaction, a common type of nuclear reaction that occurs when a target or sample material is placed within a beam of neutrons generated by a nuclear reactor. When a "slow" or thermal neutron collides with a nucleus of the target material via a non-elastic collision, a compound nucleus forms in an excited state. This compound nucleus almost instantaneously deexcites into a more stable configuration through emission of one or more prompt gamma rays. The technique known as prompt-gamma neutron activation analysis utilizes these instantaneous decays.

In some cases, this new configuration will be stable. More commonly, the resulting configuration is a radioactive nucleus which further de-excites (or decays) by emission of one or more characteristic delayed gamma rays. This decay takes place at a much slower rate than the prompt gammas, according to the unique half-life of the radioactive nucleus. INAA utilizes the characteristic energy and unique half-life of this decay to identify isotopes present in the target material.

INAA is an important analytical tool in many fields, owing to the accuracy, low detection limit, and number of elements that can be identified simultaneously. The technique is heavily utilized by archaeologists and geologists for multi-element analysis of mineral samples. Archaeologists characterize the trace-element composition of artifacts to source the raw materials, while geologists examine rock minerals to reconstruct ancient marine environments or evaluate plate tectonics. INAA is also used to analyze contaminants in environmental samples and tracers in industrial samples for quality control.

Gamma-ray spectrometry facilities in PML's Counting Room include three High Purity Germanium (HPGe) detectors, two of which are connected to automated sample changers. Data reductions utilize Canberra Nuclear Products Group "Genie Workstation" software operating on two Digital Equipment Corporation VAX computers.

Future plans for the Counting Room include the near-term acquisition of two additional HPGe detectors coupled with automatic sample changers, effectively doubling the through-put capacity of the INAA lab. This will significantly reduce the turn-around time during periods of peak

demand for INAA services. Longer-term plans include up-grading the VAX to a Windows NT-based system.

The INAA program is available as a turnkey service performed by the PML staff. The irradiated samples may also be returned to researchers for their own analyses using their own equipment or PML facilities. Researchers utilizing the INAA program come from the UM Museum of Anthropology, and from the departments of Geological Sciences, Chemistry, and Chemical Engineering, as well as from other universities and research institutions in the United States. The U.S. Department of Energy (DOE) Reactor Sharing program has provided resources to subsidize the use of INAA facilities by scientists from other universities, both U.S. and overseas.

Over 2000 samples were irradiated and analyzed for trace-element composition at the facility and by the facility staff (Table 2). Roughly 45% of these samples were submitted by researchers at the University of Michigan. Samples were also irradiated and analyzed for researchers at eight other colleges and universities, under the DOE's Reactor Sharing program. A sampling of recent projects utilizing INAA follows by discipline.

Table 2. Neutron Activation Analysis Summary, 1998-1999

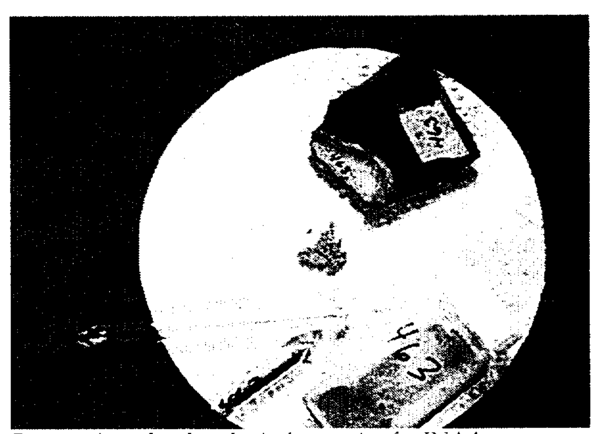
Organization	Number of Samples	Irradiation Time (hrs.)
University of Michigan		
Anthropology	574	204
Chemical Engineering	214	36
Nuclear Engineering	128	32
School of Dentistry	16	10
School of Public Health	6	20
Subtotal	***938***	***302***
Colleges, Universities, & Other Public Institutions		
Calvin College	27	20
Eastern Michigan University	3	6
Indiana University	283	142
Michigan State University	90	41
SUNY-Albany	452	84
University of California-San Diego	32	25
University of Colorado	8	20
Wayne State University	3	1
Subtotal	***898***	***339***
Federal and Industrial Research		
NSF International	72	29
Natural Systems, Inc.	14	40
XRAL	115	32
Subtotal	***201***	***101***
Total	**2032**	**742**

INAA Studies in Archaeology

Prof. Richard Ford (***University of Michigan, Museum of Anthropology***) and Ph.D. candidate Sunday Eiselt are utilizing INAA to characterize micaceous clays and pottery from central New Mexico. The goal is to compare the trace-element composition of archaeological pottery with the geochemical signature of historically-utilized clay mines in the same area, to determine the source of distinctive prehistoric ceramic traditions.

Dr. Kostalena Michelaki, a recent Ph.D. recipient (***University of Michigan, Museum of Anthropology***), investigated aspects of ceramic technology within Early Bronze-age communities of SE Hungary. Ms. Michelaki is using multi-element INAA of ceramics from archaeological sites along the Maros River to examine aspects of raw material procurement and processing as part of her study into the environmental, technological, and social factors constraining pottery production.

The first phase of neutron activation analyses for the Joint Armenian-American Project for the Archaeology and Geography of Ancient Transcaucasian States (Project ArAGATS) headed by Dr. Adam Smith (***University of Michigan, Department of Anthropology***) was initiated this year. ARAGATS is an international collaborative research program dedicated to investigating the initial emergence of socio-political complexity in Caucasia from the late 3rd to the early 1st millennia B.C. Field research began in 1998 with a systematic archaeological survey of the northern slope of Mt. Aragats and the southern Tsakahovit Plain (emerging from an unsystematic architectural survey made of the Ararat and Shirak plains in 1995). The goal of the survey was to document and collect surface materials from all major habitation sites in the region (primarily large cyclopean stone masonry fortresses) and to define the inter-site archaeological landscape. As part of this study, samples of clays from currently known sources were collected, and an initial round of both clay and ceramic samples have been submitted for INAA. The goal in using this technique is to establish a model for the movement of finished products and raw materials within the immediate region of the Tsakahovit Plain. The orienting hypothesis is that the emergence of increasingly complex social hierarchies capped by bureaucratic political institutions transformed the way basic raw materials moved across the landscape. With the emergence of a true political economy, access to resources such as clay deposits may have been regulated in new ways leaving a unique signature in the finished ceramics. Dr. Smith has recently moved to the ***University of Chicago***, but research in the area will continue over the next 3 years, amplifying the sample size of clays and ceramics in order to detect patterns in the links between sources and finished ceramics.



Preparation of archaeological ceramics for INAA.

Ph. D. student William Griffin (***University of Michigan, Museum of Anthropology***) has initiated a study to determine the feasibility of INAA for sourcing artifacts of soapstone (chlorite schist). While the use of INAA to successfully source pottery has become somewhat routine over the past few decades, in many parts of the world people first carved pots and vessels from soapstone or other soft stone before they adopted the practice of making earthenware ceramics. The ability of INAA to source these earlier vessels has not been adequately demonstrated, and the purpose of this project is to explore its usefulness with a collection of early stone vessels from Madagascar. The majority of the samples used in this analysis were collected in 1999 through archaeological survey and excavation on Madagascar's southeast coast A pilot study of 24 samples compared stone artifacts from Madagascar's southeast and northeast coasts with quarry samples recovered from the central east coast. The initial analyses indicate that trace-element analyses can successfully discriminate between these regions, though the sample size is still too small to be statistically significant. The continuation of this project will increase the sample size from both the east coast and other regions of Madagascar using samples donated by the Museé d'Art et d'Archéologie, Antananarivo, Madagascar. The significance of this research will be both methodological, in helping to verify the usefulness of this technique for the study of early soapstone vessels, and substantive, in helping to trace out the regional trade relations on pre-colonial Madagascar and in the wider Indian Ocean.

Dr. Leah Minc (***University of Michigan, Museum of Anthropology***) has been conducting a series of tests to characterize the trace-element composition of New Ohio Red Clay, a standard reference material commonly used by archaeologists when analyzing ancient ceramics. Accurate characterization of this material will facilitate inter-lab calibrations and enable researchers who conduct INAA at FNR to compare their results with data produced at other facilities.

Prof. Clarence Menninga (***Calvin College, Department of Geology***) is utilizing INAA to examine the chemical composition of samples of ancient pottery from an archaeological site in Northern Jordan. The ceramic samples were collected during excavation of the ancient city of Abila, a city of the Decapolis. The city was occupied during various periods of history ranging from the Early Bronze Age through the Ayyubid/Mamluk Period of Islamic history. The goal of the study is to characterize the sources of clay used in the manufacture of pottery found at Abila during various periods of its occupation. In addition to the pottery samples, samples of clay from various locations in the region are being collected for comparison with the trace-element patterns found in the pottery.

Tarascan polychrome "duck" pot, Mexico.

Prof. Helen Pollard and Ph.D. student Amy Hirshman (***Michigan State University, Department of Anthropology***) are utilizing INAA to characterize archaeological ceramics and clay samples as part of their on-going

research into the emergence of the Tarascan state. Recent research in the Lake Patzcuaro Basin, Michoacan, Mexico, has directly inquired into the formation of the Tarascan state and the role which sumptuary goods played in defining elite social status and political power. One such high-status item is the polychrome pottery produced for elite household and state ritual use. Previous analyses of the sherds and clays samples from the archaeological site of Urichu - a secondary center owing allegiance to the Tarascan capital - have isolated three clay composition groups and allowed the identification of polychrome ceramics produced locally and those imported from other parts of the basin. The imported sherds primarily date to after the formation of the Tarascan state, and suggest a major increase in the quantity of state-associated polychrome ceramics, as well as shifts in the proportions of various locally made pottery types, with incorporation into the Tarascan state economy. On-going research is extending this chemical analysis to ceramics and clays from the Tarascan capital at Tzintzuntzan, with the goal of identifying vessels made within this political center. The results of this study will enable specific hypotheses regarding the relationship between state emergence and ceramic production and distribution to be evaluated, and will contribute to regional database on ceramic clay composition.

Prof. Michael Smith and Ph.D. candidate Timothy Hare (***State University of New York - Albany, Department of Anthropology***) are continuing with a study of Aztec-period ceramics from Morelos, Mexico, one of the first regions incorporated into the expanding Aztec empire. Utilizing INAA to source decorated archaeological ceramics, these researchers will examine the organization of ceramic production and exchange systems before and after incorporation into the Aztec empire, with the goal of understanding how political consolidation affected economic interactions between the two polities. Mr. Hare's thesis, entitled *Postclassic and Colonial Political Boundaries and Market Systems in the Yautepec Valley, Morelos, Mexico,* will summarize the results of these analyses.

The impact of Aztec conquests over neighboring states will be explored through trace-element studies of ancient ceramics.

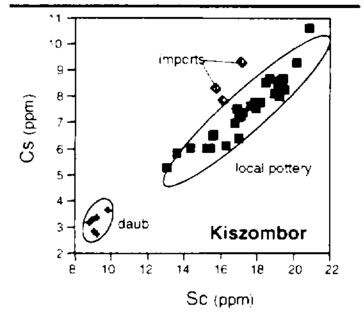
Household Ceramic Economies Among the Maros Villagers of Bronze Age Hungary

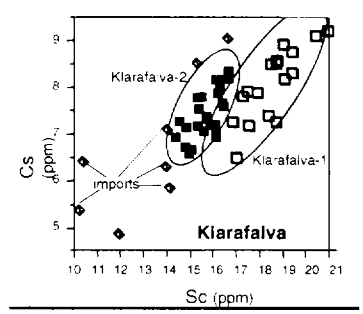
Kostalena Michelaki

Museum of Anthropology, University of Michigan

This dissertation research project focused on the analysis of ceramic material from two Bronze Age settlements--Kiszombor-Új-Élet (2700-2000 BC cal) and Klárafalva-Hajdova (2000-1650 BC cal). These settlements belonged to the Maros Group, who lived in small (40-60 people), politically autonomous villages at the confluence of the rivers Tisza and Maros, around the borders of modern Hungary, Romania and Yugoslavia. The Maros lived in simple extended family households, and exploited both domestic and wild plants and animals. They also made ceramics, stone, bone, bronze, and copper tools and ornaments, and wove textiles. The goal of this project was to contribute to our understanding of the social life of the Maros, by focusing on the way they made and used their ceramics.

While technological choices and the organization of production activities are indisputably material in character, they are also intrinsically social phenomena. Nevertheless, several alternative approaches can be used to carry out any particular technological process, such that the particular approach chosen is laden with cultural meaning and reflects not only the conscious decision of an individual, but also the abstract cultural rules behind them. To be able to examine both the material and the social dimensions of the Maros ceramic technology, I had to document a broad range of activities, from raw material procurement to vessel forming to firing methods, using a variety of techniques, including instrumental neutron activation (INAA), petrographic analyses, scanning electron microscopy (SEM), and X-ray diffraction (XRD).





Trace-element analysis using INAA indicated that the Maros were using local clays in the manufacture of their ceramics. At Kiszombor, multivariate analysis of constituent elements revealed that the bulk of the ceramic samples represent a single compositional group. At Klárafalva, two closely linked compositional groups can be identified; both appear as part of a larger compositional continuum and are about equally abundant in the sample. It is thus possible that they both represent local clay sources. In both sites, the ceramic samples differed from the architectural clay samples in their calcium concentrations suggesting that clays with shell (the primary source of Ca in the architectural daub) were avoided for pottery manufacture. Petrographic analysis of ceramic thin sections revealed that the Maros potters crushed other ceramics to create temper for their new vessels. At Kiszombor, potters created two distinct sizes of temper and used the large inclusions for their thick vessels and the small ones for their thin vessels. In contrast, potters at Klárafalva consistently varied the amount of inclusions added (rather than the size), perhaps using a standardized measurement, such as a handful.

After they had prepared their raw materials, Kiszombor potters built simple, mainly undecorated vessels with surfaces that were either roughened or burnished. At Klárafalva, however, more than 90% of the vessels were burnished and most of them have complex shapes and decoration. SEM and XRD showed that the Maros potters fired their pots under 800°C, without kilns. Their choice of relatively low firing temperatures was wise, since at higher temperatures their vessels would deform and be rendered useless. Again, in Klárafalva we can detect greater consistency in firing, and fewer firing mistakes.

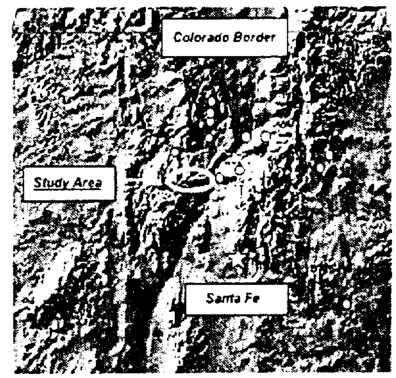
Considering all the stages of ceramic production we see that while no dramatic changes occurred in ceramic technology from the Early to the Late Maros, the focus of the potters shifted from what cannot be seen (raw material preparation) to what is most evident about a vessel (its shape, color and texture). In Late Maros, potters skipped important steps in temper preparation and instead put their time into making more complex shapes and burnishing and decorating their vessels. This change reflects the changing role of pottery in the Maros communities through time. In Early Maros Kiszombor social inequality was not evident in settlements and differences in social status were only expressed in death, through grave goods placed in burials. In the latter Klárafalva, however, social inequalities were expressed during life, through the display of food consumption and subsistence wealth. Eating and drinking vessels, along with storage vessels, were central in such displays.

Through this detailed examination of ceramic technology, made possible by powerful analytical methods such as INAA and SEM, it was possible to document a change in the Maros society, which was on its way to a more complex political organization.

The Museum of Anthropology Micaceous Ceramic Project

Dr. Richard Ford and Sunday Eiselt
Museum of Anthropology, University of Michigan

This project combines INAA, archaeology, and history to shed light upon 19^{th} century Apache and Hispanic interactions in New Mexico. The geochemistry of micaceous clay mined historically for ceramic production by both groups is compared to ceramic sherds recovered from historic Apache and Hispanic archaeological sites. INAA is used to relate ceramic sherds to clay source locations, and it is used to characterize differences in ceramic production styles between Hispanic and Apache potters. This information is related to regional and localized distributions of ceramics, the patterning of which illuminates the role of women's domestic labor in the frontier economy of northern New Mexico.



Map of north-central New Mexico showing clay deposits sampled with reference to archaeological sites in the study area.

INAA results are integrated with other archaeological and historical data to develop theories regarding the effect of Euroamerican expansion among multiethnic frontier communities. This effect was variable, but largely negative in New Mexico. Although the U.S. introduced new infrastructure and access to eastern markets, it severely limited traditional New Mexican lifeways by abolishing Hispanic communal land grants, tethering nomadic Indian populations to the agency ration system, and devaluing locally produced household necessities such as ceramics.

Especially pertinent to this discussion is the transformation of women's labor as an indicator of a developing frontier system. Changes in women's economy and external trade relations are assessed through an analysis of the ceramics they produced and sold. INAA helps us to distinguish the makers of ceramics found at different households and archaeological sites. These differences illuminate production styles and ethnically distinctive practices that can be related to the frontier economy of New Mexico. The analysis of ceramics produced and traded by women of different ethnic backgrounds emerges as a proxy measure of changing land availability, seasonal mobility, and community-wide interethnic adaptations to U.S. policies. We're finding that although the Apache and Hispanics were economically marginalized by U.S. regulations, they sought new opportunities among each other at the same time. These labor interactions were facilitated through the sale or trade of items produced by Apache women and through the incorporation of Apache labor by disadvantaged Hispanic ranchers.

Traditional Hispanic and Apache potters assist us in the design and execution of our research. This strengthens our interpretation of INAA results. Mr. Felipe Ortega, a master potter in Hispanic and Apache traditions, has been the most ardent supporter of these efforts. He is instrumental in helping us to locate and sample high quality clays, and he oversees our efforts to understand the manipulation of clays from the potter's perspective. His involvement has a direct and positive impact on research by refining the methods we use to collect and prepare clay samples and analyze compositional results.


Felipe Ortega forming clay.

INAA is used to understand unwritten aspects of history that have direct relevance for descendant communities of the Jicarilla Apache and native Hispanics. These results support oral traditions regarding the historic use of particular clay pits and they establish Jicarilla and Hispanic ceramic practices as long-standing cultural traditions. Such traditions are intimately linked to sacred landscapes containing ancestral clay pits that are located on Federally protected lands.

Our efforts likewise focus on the distribution of results to relevant communities. Educational materials that teach INAA principles using historically relevant case studies are currently being developed for Apache high school science classes, and results are being used legitimize practicing micaceous potters who struggle for recognition in the competitive Santa Fe folk-art markets today. This research is supported in part through a Phoenix Faculty Research Grant.

INAA Studies in Geology

Recent research within the Economic Geology-Geochemistry Group (***Indiana University, Department of Geological Sciences***), under the direction of Prof. Edward Ripley, ranges from high-temperature magmatic deposits, through hydrothermal base and precious metals deposits, to low-temperature sedimentary rock-hosted ores. Virtually all of the projects involve studies of either magma-country rock or hydrothermal fluid-country rock interaction and deal with primary and secondary processes of element partitioning and redistribution. This past year, Ph.D. candidate Tim Johnson completed a detailed survey involving trace elements, fluid inclusions, and stable isotopes, to identify the processes responsible for (and the mode of emplacement of) hydrothermal beryllium mineralization at Spor Mountain, Utah. Paragenetic sequencing and stable isotope analysis of both whole-rock and mineral separates will be spatially correlated to trace element distributions. Fluid inclusions and secondary hydrous mineral pairs afford independent geothermometers for reconstructing the thermal regime. Other examples of current research include isotopic and petrologic studies of Cu-Ni-PGE and Ti-P mineralization in the Duluth Complex of Minnesota and geochemical studies of hydrothermal fluid flow and alteration in the North Shore Volcanic Group. Analyses which utilize FNR's program in INAA focus on the rare earth elements and platinum group elements. Current research involves two faculty members, two Ph.D. students and one Masters candidate.

Over the past several years, Dr. Michael Dorais and colleagues (***Indiana University, Department of Geological Sciences***) have undertaken a major study of the geochemistry of igneous and metamorphic rocks of New England with the intent to decipher the tectonic history of the region. As a result of the continental collisions that formed the Appalachian Mountains in New England, North America was juxtaposed against a fragment of north Africa called Avalon, which remained attached to North America with the opening of the Atlantic Ocean. The boundary between the original North American rocks and Avalon is now obscure in much of New England because the region is covered by allochthonous rocks that were thrust over this major boundary during continental collision. Current studies focus on granites that have intruded into the cover rocks with the supposition that the geochemical compositions of these granites serve as windows to the distinct North American versus Avalon basement in central New England. Based on trace element differences obtained through INAA, these researchers have observed that northern New England granites have two distinct geochemical signatures which are grouped by region, thus revealing the locations of the boundary between the original North American basement and the attached Avalon basement.

Researchers at the Analytical Geochemistry Laboratory (***Indiana University***), under the direction of Dr. Erika Elswick, employed INAA to determine the rare earth element content of various igneous rock samples. The results will be used to check the calibration of the Lab's ICP set-up.

Dr. Russell Vernon (***University of California-San Diego, Department of Chemistry***) has utilized INAA to investigate materials of possible extra-terrestrial origin,

based on the relative abundance of natural (stable) isotopes, particularly those of silicon. In terrestrial materials, the relative abundance of the primary silicon isotopes, ^{28}Si and ^{29}Si, is 92.2% and 4.7%, respectively. Previous analyses of reportedly meteoric samples using SIMS indicated that the relative abundance of ^{28}Si and ^{29}Si varied markedly from this earthly norm, supporting an extra-terrestrial origin. However, re-analysis using INAA concluded that the silicon isotopic ratios were consistent with materials of terrestrial origin.

Under the direction of Prof. David Budd (***University of Colorado, Department of Geological Sciences***), Ms. Terry Church completed a project to assess palaeo-oceanographic events that may have led to the demise of coral-stromatoporoid fauna at the end of the Frasian (Late Devonian). Geochemical analyses of limestone samples spanning two separate mass-extinction events (the end-biostrome of the Late Devonian and the Frasian-Fammennian boundary) yielded distinctly different signals, indicating that very different mechanisms were responsible for the two extinctions. Ms. Church's research was supported by the McNair Scholars Program.

INAA Studies in Chemistry and Chemical Engineering

Prof. Levi Thompson (***University of Michigan, Chemical Engineering***) is using neutron activation analysis to determine the metals content of early transition metal carbide and nitride catalysts. These catalysts are being developed for use in hydrocarbon conversion, water-gas shift and steam reforming reactions. The latter two reactions are used to convert hydrocarbons into hydrogen for use in fuel cells. Several of Prof. Thompson's students are also utilizing the INAA program at the FNR.

Under the direction of Prof. Thompson, Ph.D. student Chris Bennett (***University of Michigan, Chemical Engineering***) is conducting research involving the synthesis, characterization, and evaluation of novel materials for potential use as catalysts for several industrially important reactions. Since the optimization of a material for a particular catalytic application requires a detailed knowledge of the pertinent structure-function relationships, extensive characterization is performed. The characterization techniques utilized include numerous x-ray, electron, and sorption techniques to probe both the surface and bulk of the materials. A full understanding of the structure-function relationships also requires detailed analysis of the catalyst composition, which is accomplished via the combination of neutron activation analysis (performed at the FNR) and combustion analysis. The culmination of these investigations has elucidated the mechanisms by which these materials catalyze several key reactions.

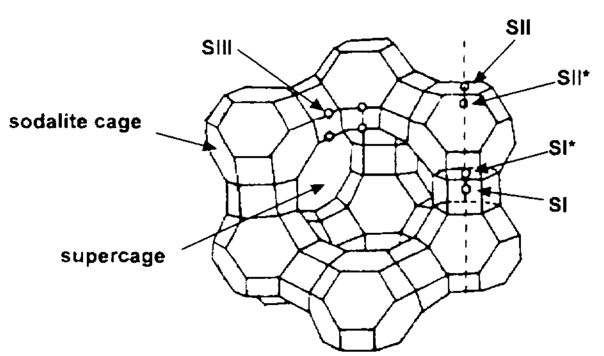
In a related project, Prof. Thompson and doctoral student Michael Neylon (***University of Michigan, Chemical Engineering***) are utilizing INAA to assess the metals content and purity of molybdenum carbide catalysts. Molybdenum carbide is synthesized from molyoxide by high temperature exposure to methane and hydrogen. These materials have high surface area and good activity towards many catalytic reactions. Synthesis and catalyst activity can lead to oxygen, excess carbon, and sulfur forming on the surface of the material. Understanding the relationship between composition (both bulk and surface), structure, and catalyst activity can lead to engineering better catalysts.

Prof. Ralph T. Yang and doctoral candidate Nick D. Hutson (***University of Michigan, Chemical Engineering***) have completed a study involving the characterization of the structure and adsorption characteristics of silver ion-exchanged zeolites. Silver is known to strongly affect the adsorptive properties of some zeolites,

Characterization of the Structure and Adsorption Characteristics of Silver Ion-Exchanged Zeolites Y, X and Low Silica X

Nick D. Hutson and Ralph T. Yang
Department of Chemical Engineering, University of Michigan

Silver is known to strongly affect the adsorptive properties of some zeolites. It is also known that thermal vacuum dehydration of some argentiferous zeolites leads to the formation of charged silver clusters within the zeolite. In this work we synthesized silver zeolites of the types Y, X and low silica X. The zeolites were treated in such a way as to promote the formation of intracrystalline charged silver clusters. Equilibrium room temperature isotherms were measured for adsorption of nitrogen for each of the zeolites after various heat treatments and dehydration. The materials were analytically characterized using neutron activation analysis at the Ford Nuclear Reactor. The materials were structurally characterized via Rietveld refinement of neutron powder diffraction patterns collected at the NIST Center for Neutron Research (NCNR) at the National Institute of Standards and Technology in Gaithersburg, MD. Color changes upon heat treatment and subsequent X-ray photoemission spectroscopy (XPS) confirmed some reduction of Ag^+ -> Ag^0. The effects of various dehydration conditions, including the time, temperature and atmosphere, on the room temperature adsorption of nitrogen were also characterized. Structural characterization, along with valence bond calculations, revealed the presence of cations in a novel site (called II*) which are more active in Ag-LSX samples which were vacuum dehydrated at 450°C as compared to those which were vacuum dehydrated at 350°C.



The faujasite (type Y and Z zeolite) unit cell.

The separation of air for the production of nitrogen and oxygen is a very important operation in the chemical processing industry. Historically, this separation has been done mostly using cryogenic distillation. However, as adsorption systems have become more efficient and new, more effective sorbents have been synthesized, separation by adsorption processes (*e.g.*, pressure swing adsorption (PSA), and vacuum swing adsorption (VSA)) have become increasingly competitive and are already favorable for small-to-medium scale operations. Currently, approximately 20% of air separations are done using adsorption technologies. Li ion-exchanged low silica X zeolite (Si/Al ≅ 1.0) is currently the best adsorbent for use in the separation of air by adsorption processes.

We have synthesized type X zeolites containing varying mixtures of Li and Ag. The addition of very small amounts of Ag and the proper dehydration conditions resulted in the formation of a material with enhanced adsorptive characteristics and increased energetic heterogeneity as compared to those of the near fully exchanged Li-zeolites. The performance for air separation by the best of these sorbents, containing, on average, only one Ag per unit cell, was compared to that of the near fully Li ion-exchanged zeolite using a standard PSA cycle by numerical simulation. The results showed that the new adsorbent provides a significantly higher (>10%) product throughput, at the same product purity and recovery, when compared to that of the near fully Li ion-exchanged zeolite.

The location of the extraframework silver in relation to the aluminosilicate framework is of primary importance for elucidating the effect of silver clustering on the adsorptive characteristics of the zeolite. The silver contents of the mixed Li/Ag-zeolites were determined using INAA at the Ford Nuclear Reactor. The materials were structurally characterized via Rietveld refinement of neutron powder diffraction patterns collected at the NCNR. Structural characterization, again, confirmed the presence of cations in a novel site (called II*). Silver in this site boosts the adsorption capacity of the mixed Li/Ag-zeolites over that of the near fully Li ion-exchanged zeolite.

with thermal vacuum dehydration of some argentiferous zeolites leading to the formation of charged silver clusters within the zeolite. In this work, silver zeolites of the types Y, X and low silica X were synthesized and treated in such a way as to promote the formation of intracrystalline charged silver clusters. The materials were analytically characterized using neutron activation analysis at the FNR.

In a second study under the direction of Prof. Ralph T. Yang, Ph.D. student Richard Long (***University of Michigan, Chemical Engineering***) is employing INAA in their study of elective catalytic reduction of nitric oxide. Selective catalytic reduction (SCR) of nitric oxide with hydrocarbon and ammonia in the presence of excess oxygen is an efficient way to abate NO emission. These researchers investigated a series of metal ion-exchanged pillared clay, MCM-41 and ZSM-5 catalysts for this reaction. The catalysts were prepared according to the conventional ion-exchanged method in aqueous solution. The content of metal was measured by neutron activation analysis at the Ford Nuclear Reactor. The element concentrations of Cu, Fe, Al, Na and Rh were determined through direct comparison with the standard reference materials. The data provided important information for searching and modifying catalysts because the metal ion concentrations of the catalysts are critical for the SCR reaction.

At ***Eastern Michigan University***, the Ford Nuclear Reactor and Phoenix Memorial Laboratory facilities were used for teaching a number of analytical chemistry classes (Chem. 381 and Chem. 481); nearly fifty students were introduced to neutron activation analysis through a lab on sample irradiation and gamma spectrometry.

NAA in Health Science Fields

Dr. William O'Brien and undergraduate research assistant Irina Elterman (***University of Michigan, School of Dentistry***) used INAA to evaluate the ^{238}U content of dental porcelains to assess their conformity with ISO specifications. The ^{238}U radioactivity in dental porcelains results from the minerals used in their formulation, but total activity cannot exceed 0.1 Beq/g.

In an innovative study supported in part by a Phoenix Faculty grant, Drs. David Hamby and Srinantha Kannan (***University of Michigan, Environmental Health Sciences***) are monitoring the biodistribution of minerals in plant-based food products using radioactive tracers. The FNR facility has enabled them to combine features of INAA, biokinetic modeling of minerals, and food processing to develop and to test the feasibility of this novel application of the isotopic tracer technique. In a recently completed experiment, naturally occurring iron (^{58}Fe) in dried black beans was activated to create the radioactive tracer ^{59}Fe. Approximately 3 weeks following irradiation, the activated bean products were fed to animals (Sprague Dawley rats). In order to study absorption of the mineral, loss of mineral in the feces was monitored by counting the amount of ^{59}Fe in fecal samples using the PML low background gamma spectrometer. A control group of rats was fed the non-radioactive diet and rat tissues were activated to further trace the retention of the mineral in rat bones using INAA.

INAA in Nuclear Engineering & Radiological Sciences

Doctoral candidate Binxi Gu, working under the direction of Research Scientist Dr. Lumin Wang ***(University of Michigan, Nuclear Engineering and Radiological Sciences)***, is utilizing INAA to examine ion exchange solutions from zeolites and to compare with the results obtained from atomic absorption analysis. The main elements of interest are strontium and cesium. Their research is part of a long-term project to identify materials appropriate for

high-level radioactive waste storage. For further details, see project description under *Materials Science Testing Program.*

INAA for Industrial Applications

National Sanitation Foundation International of Ann Arbor utilized INAA to verify the trace-element composition of polyethylene plastics. A suite of six elements are added to the plastics in different combinations, and used as tracers to identify the products of specific batches for quality control.

Natural Systems, Inc., an environmental consulting firm in Muskegon, Michigan, approached the FNR's INAA program about assessing soil samples for metal contamination. Soils from both allegedly contaminated and non-contaminated sites were analyzed for antimony, selenium, barium, and vanadium content.

XRAL Activation Services Incorporated operated a neutron activation analysis program headquartered at the Ford Nuclear Reactor to serve geologists and the mining industry. The XRAL program utilized laboratory and reactor space; samples were irradiated in the reactor and analyzed by XRAL employees.

Ar-Ar Geological Dating Program

Another active research program at the Ford Nuclear Reactor is geological dating through the determination of potassium isotopic concentrations in mineral samples. Rocks have a natural isotopic ratio between ^{39}K and ^{40}K of 7971:1. However, ^{40}K is radioactive and decays to ^{40}Ar with a half-life of about 1.28 billion years. Determination of the amount of ^{40}K that remains and performance of radioactive decay calculations permit the determination of a rock's age.

The reactor is used to assist in determining the amount of ^{40}K that remains in a rock. High energy neutrons from the reactor convert some of the ^{39}K to ^{39}Ar, by the reaction $^{39}K(n,p)^{39}Ar$. After irradiation, vacuum extraction of both isotopes of argon is conducted, and the isotopes are quantified by passing the extracted gasses through a gas chromatograph. The argon isotope ratio permits determination of the potassium isotope ratio, which in turn yields the age of geological samples.

For example, based on the half-life of 1.28 billion years, if the sum of the amount of ^{40}K that has decayed and the current amount in a rock were determined to be 1,000 atoms and the current number of atoms were 500, half the atoms present would have decayed (one half-life), and the rock would be 1.28 billion years old. If the current number of atoms were 250, two half-lives would have passed, and the rock would be 2.56 billion years old. The data are then used to interpret a variety of geological problems, including the tectonic evolution of mountain belts, the volcanic history and potential hazards of particular volcanic fields, and the potential for the production of hydrocarluene in sedimentary basins.

The Ford Nuclear Reactor offers one of the best facilities in the U.S. for the irradiation of rock and mineral samples for $^{39}Ar/^{40}Ar$ dating. FNR's dedicated irradiation facility provides a highly desirable low flux gradient, high fast-to-thermal neutron ratio, and a favorable J-factor of 2×10^{-4} /hour. Equally important, our operation schedule permits the long irradiation times required for dating samples of extreme age (such as lunar and Martian samples) with great precision.

To date, the FNR has provided irradiation services only. However, we have recently established a collaborative program with the University of Michigan's Argon Geochronology Lab, to offer $^{39}Ar/^{40}Ar$ dating directly to interested geologists. In this arrangement, irradiations will be performed at FNR; the samples will then be analyzed by Dr. Chris Hall (Argon Geochronology Lab) for mass spectrometric measurement of the concentrations of ^{39}Ar and of ^{40}Ar to determine the age of geological samples. This service will be of particular interest to geologists interested in dating clays, an area in which Dr. Hall has pioneered the vacuum encapsulation technique.

The primary users of the $^{39}Ar/^{40}Ar$ dating services come from the University of Michigan's Department of Geological Sciences, as well as from other research institutions in the United States, western Europe, and New Zealand. In 1998-1999, FNR's dedicated irradiation facility provided nearly 1500 hours of in-core irradiation for ten major geochronology labs world wide (Table 3).

The geologic research that is supported by access to the Ford Nuclear Reactor is diverse and covers a range of applications:

At the ***University of Michigan***, the argon dating facility within the Department of Geological Sciences is involved in a large number of collaborative studies with investigators both at UM and at other universities. In the recent past, researchers have conducted projects ranging from tectonic studies aimed at working out the histories of mountain belt formation and uplift, to studies combining the dating precision of Ar-Ar dating with excellent stratigraphic control possible with deep sea sediments to confirm recent astronomically based time-scales, which had assumed that variations in oxygen isotopes (associated with temperature and glacial ice volume changes) are caused by astronomical forcing. In a pioneering effort, UM researchers developed a reliable way to "vacuum encapsulate" samples, enabling researchers to date fine-grained minerals, like clays. Clays are useful in working out sedimentary basin histories, and they are frequently the only datable minerals in economically important ore deposits. Ar-Ar dating of clays has also helped in interpreting the weathering environment during the recent ice ages.

Current projects include (but are not limited to): testing a model of preservation of an unusually old near-surface gold deposit in Cuba; doing the first large-scale spatial and temporal estimate of volcanic eruption rates in a subfunction related zone in Mexico; finding the timing of rapid motion along deep faults using argon dating of rock melted along faults during earthquakes (pseudotachylites); extending the use of argon dating as a geochemical tracer in oceanographic studies; using argon dating of clay mixtures in the rock "flour" found in active faults (fault "gouge") to estimate the timing and duration of near surface fault motion.

Researchers at the ***University of Houston's Thermochronology Laboratory*** utilize Ar-Ar dating to determine: (1) the precise dating of volcanic eruptions to provide chronologic constraints on magmatic and eruptive processes; (2) the timing and rates of uplift of rocks in the Himalaya and other mountain ranges to provide information on orogenic events caused by continent-continent collision; (3) relative movements of continental and oceanic plates by combining age constraints with palaeomagnetic work; and (4) the thermal history of sedimentary basins with a focus on implications for development of oil and gas deposits.

Geologists at the ***University of Manchester*** and their collaborators are investigating: (1) the age of mare volcanism on the Moon to establish a timescale of basaltic volcanism on the moon and the relationships between mare-filling and earlier basin formation events; (2) the geochronology of martian meteorites by dating separated mineral components, providing information on the formation of martian atmosphere and the possible existence of life on Mars; (3) the chronology of diamonds through Ar-Ar dating of silicate inclusions to determine whether populations of diamonds crystallized continuously or at distinct time intervals; and (4) the determination of the halogen content of the mantle through time through analysis of diamonds of different age and depth of formation, using an extension of the Ar-Ar method.

The ***Institute of Geological & Nuclear Sciences*** in New Zealand utilizes FNR irradiation facilities for (1) geological dating programs related to orogenic, tectonic and volcanic histories in various geological terrains of New Zealand and the southwest Pacific region; and (2) neutron irradiation of very small (0.01g) silicate mineral samples to maintain incremental heating and laser heating variants of noble-gas mass spectrometric analytical techniques.

Ar Dating of Near-Surface Faulting - A Project Summary

Chris M. Hall and Ben A. van der Pluijm
Argon Geochronology Lab, University of Michigan

Radiometric dating of ductile shear zones has revolutionized our understanding of fault evolution and deep-crustal processes. However, the timing of shallow faulting has primarily been constrained using stratigraphic and other indirect dating techniques. One of the major problems at near-surface conditions is the presence of mineral phases that are both detrital (primary) and authigenic (secondary) in origin. Therefore, radiometric dating of such rocks typically reflects a mix between these mineral populations. We are proposing $^{40}Ar/^{39}Ar$ vacuum-encapsulation geochronology to accurately date clay-bearing fault rock that resolves the inherently mixed origin of clay minerals in fault rocks. Mineral characterization and modeling of X-ray diffraction patterns, supported by microscopic characterization, allow quantification of the percentages of detrital vs. authigenic phases through their characteristic crystal structures or polytypes. Ages of samples that contain known authigenic/detrital ratios allow us to extrapolate these 'mixed ages' to their detrital and authigenic end members. The advantages of our Ar encapsulation technique over traditional K-Ar ages are small sample size (1-2 orders of magnitude less), simple chemical preparation, detailed information through degassing steps (total gas and retention ages, and mineral/chemical heterogeneity) and improved precision (>1 order of magnitude greater). The likelihood for success of the method is shown by preliminary data on clay gouge from the Lewis Thrust in the southern Canadian Rockies. We propose further testing and development of standard procedures for this work, which includes comparison with traditional K-Ar dating. The second component of the project involves field application of our method in three structural settings and with variable mineralogies: a section across the southern Rockies, dating of normal faulting in Utah (Moab), dating of gouge along the San Andreas Fault (Punchbowl). We anticipate that, once fully developed, this method of radiometric fault dating will see widespread application in regional geology/tectonics.

Researchers at ***Lehigh University*** use Ar-Ar dating in a large number of studies, including the geochronology of metamorphism in the Pakistan Himalayas; the geochronology of detrital mica from Early Paleozoic sedimentary rocks of the Appalachian foreland; thermochronology of K-feldspars of eastern Maine; the geochronology and thermal evolution of Kinya Konga peak, China; recycling of subducted sediments in Tertiary volcanics, Nicaragua; geomorphic evolution of the forearc region, Costa Rica; dating of Neogene tuffs from NW Argentina, cooling history of Late Paleozoic granitics, southern Appalachian Piedmont; timing of ultrahigh-pressure metamorphism, China; chronostratigraphic of the Fort Union Formation, North American mid-continent; and the age of late hydrothermal alteration, Adirondack Mountains, New York.

At the ***Universite Blaise Pascal, Ferraud, France,*** Ar-Ar dates are used (1) to analyze the driving mechanisms of mountain building through thermochronology; (2) for the dating of volcanism, especially young volcanism in various geodynamical settings; and (3) to monitor and model argon loss to assess the physical background of argon diffusion in glass and silicates.

The *New Mexico Geochronology Research Lab (NMGRL)*, under the direction of Prof. Matt Heizer, conducts a broad range of Ar-Ar dating projects, with support for the Ford Nuclear Reactor. Recent key projects include:

Yucca Mt. Project. The NMGRL performed an extensive geochronological study of the Lathrop Wells volcanic center near the proposed high-level radioactive test site at Yucca Mt., Nevada. This young volcanic center has a very controversial geochronology database which directly impacted probability calculations for volcanic risk assessment at Yucca Mt. Numerous samples were irradiated at the Ford Reactor for the dating at Lathrop Wells volcanic center. Their analyses strongly suggested the volcanic center to be 75,000 years old and a single eruptive event, thereby providing significant data to constrain volcanic hazard models for the repository at Yucca Mt.

Rocky Mt. Project A grant from the NSF continental dynamics program to study the Rocky Mts. and other regions of the western U.S. has been underway for about 1.5 years. The project is very large and dozens of scientists and students from several universities are participating. The project requires a significant component of argon geochronology and to date, more than 100 samples have been irradiated at the Ford reactor for this project.

Trans-Hudson Orogeny Project. Principle investigators K. Condie, M. Heizler, S. Kelley (New Mexico Tech.) and P. Bickford (Syracuse) have recently been awarded a grant from the NSF tectonics division to study the Trans-Hudson Orogeny of Central Canada. Over 100 samples were collected during the 1998 field season and approximately 150 minerals have now been irradiated at the FNR from these samples. The project is supporting a MS student at NMT and a Post-doc at Syracuse and preliminary results were recently presented at the 1999 GSA meeting in Denver, CO.

In addition to these large, highly visible projects, 33 other NMGRL projects required irradiation of samples at the Ford Nuclear Reactor. These projects involved mostly geological research conducted by students or colleagues at many universities. Overall, NMGRL supported in excess of one million dollars in research, involving 20 faculty members and 13 graduate students.

Table 3. Summary of Irradiations for Ar-Ar Dating, 1998-1999

University or Institution	Irradiation Time (hrs)
University of Michigan	247
Inst. of Geological & Nuclear Sciences, New Zealand	120
Lehigh University	50
New Mexico Institute of Mining & Technology	422
Ohio State University	242
Universite Blaise Pascal	84
University of Arizona	15
University of California, Los Angeles	180
University of Manchester, UK	111
Total	1471

Neutron Radiography Program

Neutron radiography is analogous to X-ray radiography in that a beam of radiation is used to create images of objects. However, while X-rays interact with electrons in the atomic shell and cannot penetrate dense materials, neutrons interact with the atomic nucleus, and hence can penetrate dense materials. This makes neutron radiography an important nondestructive tool in constructing images that are complementary to X-ray radiography. Materials with a high Z, such as lead, titanium, and steel, readily stop X-rays but are in turn penetrated to a certain extent by neutrons. Materials with a low Z, such as water, oil, and human tissue, which are essentially transparent to X-rays are on the other hand easily imaged using neutrons. The difference in interaction between neutrons and X-rays allows the imaging of phenomena that is impossible with X-rays.

The neutron radiography facility at the FNR provides services for (a) high-resolution film radiography, where a neutron beam interacts with a neutron-absorbing screen to produce secondary radiation and exposes a photographic film and (b) real-time radiography or radioscopy, which converts optical images from the neutron beam into digital images.

Recent applications of PML neutron radiography facilities include (a) high-resolution radiography of coking and debris deposition in fuel injectors in an automobile engine, (b) radioscopy of lubricant movement in operating engines and transmissions, and (c) radioscopy study of two-phase flow and fluid flow in porous structures. Solid-state GaAs(^{10}B) detectors have been developed for neutron radiography and tomography applications and will be used in a three-year DOE research project to measure key characteristics of spent nuclear fuel elements.

Neutron Radiography Techniques

In film neutron radiography a screen is used to convert the modulated neutron beam, which is itself non-ionizing, into an ionizing form to expose the film. The type of screen and film used is dependent on the level of resolution that is desired in the image. The most common form of screen is 25 μm thick gadolinium metal vapor-deposited on an aluminum backing and covered with 25 nm of sapphire to protect the gadolinium from moisture in the air. This screen converts the neutron into electrons which are then used to expose the film and gives the highest resolution available. If a lower resolution image is sufficient, then a gadolinium oxysulfide rare earth phosphor screen is used. This screen converts the neutron image into a light image which can then expose the film in the same manner as regular photography. These films are then developed in a similar fashion to X-ray films. Film neutron radiography is used when the image is static and not changing with time.

If the object or phenomenon being imaged is moving or changing with time, neutron radioscopy is used. Once again, a gadolinium oxysulfide screen is used to convert the neutron image into a light image and is then intensified and viewed with a TV camera. The output from the TV camera is then input into a computerized image processing system. This allows enhancement of the images and/or information retrieval by computer from the images. These neutron radioscopy images are then stored on video tape in real time at a framing rate of 30 frames (or new images) per second.

Neutron Radiography Facilities

Neutron radiography at MMPP utilizes the Ford Nuclear Reactor as a source of neutrons. Neutron beams are extracted via the heavy water tank located along the north side the reactor, resulting in a very low energy neutron beam which in turn yields a very high sensitivity to most materials.

Two radiography beams are used at the Phoenix Memorial Laboratory. The first beam is a vertical beam with L/D, or collimator ratio, of 340 to 450 and a beam diameter of 2.8" used for high resolution film neutron radiography, neutron radioscopy, and neutron tomography. The second beam is a horizontal beam with a L/D of 50 and a beam diameter of 12" used for imaging large objects and smaller objects where high resolution is not needed.

Two neutron radioscopy imaging systems are used as well. The first is a LIXI-NID manufactured by LIXI, Inc. of Downers Grove, Illinois. This system uses a 2" gadolinium oxysulfide screen which is coupled by fiber optics to a micro-channel plate image intensifier to provide dynamic images. This imaging system is then viewed with an extended red neuvicon camera. The second imaging system is a Thompson, CSF, 9" Neutron Imaging System. This imaging system uses a gadolinium oxysulfide screen to convert the neutron beam to a light image. The output screen is then viewed with a Neuvicon camera.

Recent Applications

Coking and Debris Deposition in Fuel Injectors. An issue of concern in the gas turbine industry is fuel injector nozzle blockage resulting from build-up of hydrocarbon deposits, called coking, and other foreign matter. Coking and debris in a fuel injector can cause problems with the combustion in the gas turbine engine and can lead to a reduction in or loss of power and increased maintenance. Previous methods used to study coking of fuel injectors involved sectioning nozzles suspected of coking problems and visually inspecting the sectioned nozzle. However, sectioning the nozzle dislodges a considerable amount of the coking, and accurate assessment of its location prior to sectioning becomes impossible. High resolution, film neutron radiography can be used to image coking and foreign matter inside nozzles used in gas turbine engines without disturbing the nozzle or the internal deposits.

During the past year efforts have been ongoing to study the effect of neutron beam energy on coking determination. Radiographs have been made using reactors around the world and papers presented on the results. In addition, work is ongoing to assist other neutron radiography facilities to enhance the capability for coking imaging.

Lubrication Studies. Neutron radioscopy has been used to image the lubrication of several automotive transmissions. Verification of the presence or absence of lubrication was performed and where absent, neutron radioscopy was used to track down the obstruction or design fault. After modifications were made, neutron radioscopy was performed to verify that the problem was corrected and the modifications did not adversely affect other locations in the transmissions. In addition, neutron radioscopy has been used to image the lubrication in operating engines, lubrication of bearings, lubrication of valve guides, lubrication movement in pre-loaded bearings, lubrication of combustion chambers and piston rings, and many other applications where determination of lubrication presence, absence, or amount is required.

An Application in Transmission Lubrication Studies

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Neutron radioscopy can be a powerful tool for studying the internal fluid flow in a metallic structure whether that be a transmission, an engine, or any other structure. This is because neutrons can penetrate high-Z materials (such as lead, titanium, and steel), but are stopped by low-Z materials (such as water, oil, and human tissue). As an example of this capability, we will look at the role of neutron radiography in resolving a recent transmission lubrication problem, in which internal transmission parts were experiencing significant damage due to lack of lubrication.

In this case, the transmission was experiencing catastrophic failure of internal parts caused by overheating due to lack of lubrication. "In house" measurements indicated sufficient lubrication was reaching the appropriate circuits: according to analyses in the dynamometer labs (Fig. 1), everything was working correctly inside the transmission and the oil flow patterns were "as expected". The "in house" method of determining whether the correct amount of oil was getting to the correct circuits was to attach hoses to the various outlet tubes (seen on the bottom of the test fixture, Fig. 1) and measure the volume of transmission fluid as a function of time. The critical assumption was that the various drain tubes only drained "their assigned circuits" and there was no crossing of transmission fluid between the various circuits. Using neutron radioscopy to image the internal flow of lubricant, the true source of the problem was revealed.

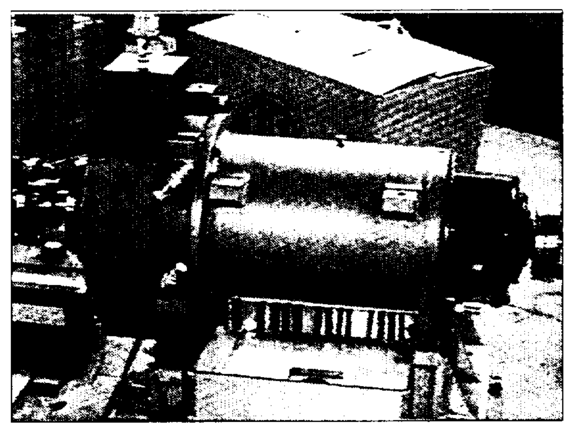


Fig. 1. Lubrication test stand.

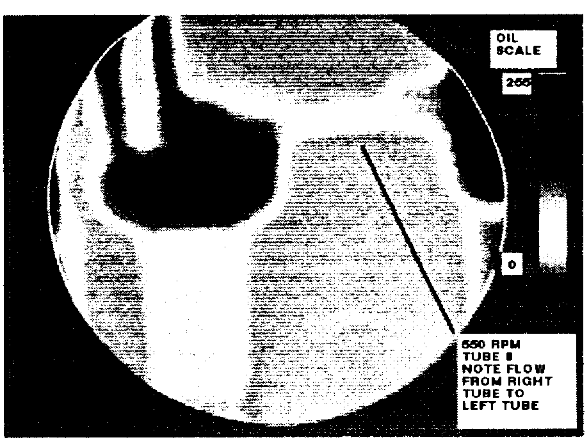


Fig. 2. Leakage between drainage tubes.

The flow of oil through two drainage tubes is shown in neutron radioscopy mask subtracted image (Fig. 2), made by taking an image of the hardware (in this case the test rig and drain tubes), and digitally subtracting it from the real time neutron radioscopic image, thereby showing only the movement of the transmission fluid. The image shows the oil drainage from the pinion area, and reveals that flow is occurring *between* the two drainage tubes, because a single tube is not big enough to handle all of the flow. This non-stability indicates the source of the problem, and demonstrates the power of neutron radioscopy to provide significant information for non-destructive testing of materials, processes, and models.

The past year has seen continued use of a dedicated transmission test stand designed for and with Ford Motor Company with full motoring and loading capabilities. The new test stand is able to drive any current transmission manufactured by Ford Motor Company while providing a dynamometer for loading the transmission. Flow rates in various circuits, as well as pressure and temperature control, is also available. This test stand enhances FNR ability to respond quickly to production problems in the automotive transmission field. During the past year this test stand was used to solve a critical "neutraling out" problem. Dr. John Lindsay received a special achievement award for his work from Ford Motor Company. In addition, the facility received an equipment grant to purchase a Precise Optics imaging system as a "thank you award" from Ford Motor Company for the fast, efficient use of neutron radioscopy to solve their problem.

Liquid Spray Imaging. Neutron radioscopy has also been used to image different types of sprays and spray phenomena inside metallic structures. These include: (1) diesel fuel spray injection in an operating, single-cylinder diesel engine; (2) differences in spray density profiles as a function of pressure and orifice type; wall wetting in combustion chambers and injection ports; (3) imaging the flow characteristics of the Space Shuttle Main Engine preburner injectors; and (4) the imaging of steady state sprays in a 3-D tomographic manner.

Oil Recovery Methods. Different acidizing methods are used in oil bearing limestone to increase oil recovery in shale. Real time neutron radiography has been utilized to image the acid-produced capillary structure in limestone without destroying the structure itself. Standard methods of imaging the capillaries, called worm holes, involve filling them with molten Wood's metal and dissolving the limestone from around the metal after it has solidified. A great deal of the structure, which is quite fine, is lost. Radiographic imaging permits the entire capillary system to be observed without destroying the limestone. One Ph.D. degree was obtained in Chemical Engineering during the past year using neutron radiography.

Fluid Flow in Porous Structures. Neutron radioscopy has also been used to study flow in porous structures. These include organic and inorganic contaminant flow in soils, water flow in soils, oil flow in various shales, gas/water flow in filters, and many other applications where it is desired to image the flow of hydrogenous fluids in porous structures.

Additional Applications. Film and real time neutron radiography have been used to study many additional phenomena including: (1) monitoring of plastic injection molding and lost wax castings; (2) imaging of remaining wax in turbine engine blades as a standard quality control measure; (3) the study of miscible and immiscible flow in porous media; (4) the study of gas flooding and recovery in porous media; (5) the development of fingers in the flow of ground water through soil (important in the prediction of ground water contamination modeling); (6) observation of the progression of a layer of moisture ahead of the moving front of burning material in a lighted cigarette; (7) determination of the crack growth rates in powder metal components; (8) measurement of the presence and size of air bubbles in titanium ingots; and (9) imaging cavitation induced in pumps by injection of air in pump suction lines.

New Detector Development. New, solid state GaAs(^{10}B) neutron imaging detectors have been developed recently. The new detectors are radiation hard, easy to construct, self discriminating to gammas, and provide the

ability to be pixilated for imaging purposes. This is very important due to the decreased availability of cameras that can withstand a high neutron radiation field. This work is on-going with the assistance of Dr. Douglas McGregor (***University of Michigan, Nuclear Engineering & Radiological Sciences***). This past year has seen further construction of a new design, demonstration of the gamma/neutron differentiation, and further radiation hardness testing of the concept. By the end of this year, two and three-dimensional images will have been developed using these new detectors on test objects. The next year will see these detectors used to image spent fuel at FNR.

Neutron Radiography Program Summary

A summary of neutron radiography performed at PML during 1998-1999 is provided in Table 4 by organization. A total of 275 radiographs were imaged, involving 1250 researcher man hours. Within the University of Michigan, one department (NERS) utilized the neutron radiography services, as did two outside customers (NIST and Ford Motor Company). In addition, training in neutron radiography and radioscopy was provided for researchers from Bangladesh, Japan, and Brazil. A description of research projects follows.

Table 4. Neutron Radiography Summary, 1998-1999

Department/Organization	Research Man-Hours	Number of Radiographs
University of Michigan		
Nuclear Engineering & Radiological Sciences	280	183
FNR-Research	870	86
Subtotal	***1150***	***269***
Federal and Industrial Research		
National Inst. of Standards & Technology	20	6
Ford Motor Company	80	0
Subtotal	***1 00***	***6***
Total	**1250**	**275**

Neutron Radiography for University of Michigan Departments

Jiyoung Park (***University of Michigan, Nuclear Engineering & Radiological Sciences***) has finished her Ph.D. thesis titled *Neutron Scattering Correction Functions for Neutron Radiographic Images*. She is currently teaching at the Catholic University of Korea, Research Institute of Biomedical Engineering, Seoul, Korea. Her advisors were Prof. John Lee and Dr. John T. Lindsay.

As part of her thesis research, Ms. Park developed an image reconstruction algorithm that involves the point spread functions (PSFs) to account for image degradations due to neutron scattering and due to image system unsharpness. The algorithm is based on a modulation transfer function approach and uses a maximum likelihood method that iteratively estimates the scattering effects and hence the unknown geometry. Inherent fluctuations in the experimental data are represented through a Kalman filtering algorithm. A number of neutron radiographs were obtained with collimated thermal neutrons at the Vertical Beam Port of the Ford Nuclear Reactor and the images were reconstructed through the scattering and system PSFs explicitly utilized. The scatter-correction algorithm determines neutron scattering components based on the best estimates of the scattering functions and removes the scattering effects in reconstructing neutron radiographic images. Clear enhancements in the reconstructed images were obtained in an idealized experiment involving two paraffin disks.

Neutron Radiography for Federal and Industrial Research Organizations

A new $310,000 contract with ***Ford Motor Company*** has resulted in the second use of the transmission test stand developed earlier. The project was the "Neutraling Out" problem for which FNR and Dr. Lindsay won two awards. This also resulted in the awarding of the equipment grant mentioned above that was used to obtain the Precise Optics Neutron Imaging Device.

A new project is being considered by Daimler-Chrysler to use neutron radioscopy to study the root cause in catalytic failures in current models. This work will be performed with Automotive Testing Technologies, Inc.

Neutron Radiography Training for International Laboratories

Mr. Nurul Islam of the ***Bangladesh Institute of Nuclear Science and Technology*** (INST) of the Atomic Energy Commission in Dhaka, Bangladesh, finished a six-month International Atomic Energy Agency training fellowship in neutron radiography at the FNR last year and is currently applying for further IAEA support for FNR's assistance in training additional personnel and assisting in the establishment of their neutron radioscopy program. Mr. Islam over sees the neutron radiography program at INST TRIGA reactor

Mr. M. Matsubayashi of the ***Japan Atomic Energy Research Institute (JAERI)***, Tokai Research Establishment, Japan, who recently completed a one-year training fellowship at FNR in neutron radiography, is currently in charge of the JAERI neutron radiography program. In particular, the work performed with the JRR-3 research reactor. He is continuing the work he started at FNR on neutron tomography, computerized image processing, and high resolution film radiography.

Dr. H. Kobayashi, at ***Rikyo University*** in Japan, has proposed a new neutron effective energy measuring device. We are currently assisting Dr. Kobayashi in testing this devise at various research reactor neutron beams.

Dr. Reynaldo Publiesi of the ***Supervisao de Fisica Nuclear-TFF*** of Sao Paulo, Brazil spent two weeks visiting the neutron radiography facility at FNR during the previous annual report time frame and has sent Mr. Mario de Menezes (his Ph. D. student) for training in neutron radioscopy this year. Next year he has requested a reciprocal visit from FNR personnel to assist in setting up their facility.

Materials Science Testing Program

The FNR and associated facilities have been extensively used in recent years for material testing programs. Included are neutron and gamma radiation damage studies of various materials and components performed in the FNR core, in spent fuel storage, and in the ^{60}Co irradiation facility. Neutron spectrometers at selected beam ports and neutron radiography facilities are used to perform neutron attenuation tests for shielding materials as part of the quality assurance and materials testing process. Currently, substantial service is provided in certification of Boral or Boraflex materials, utilized extensively in spent fuel pools at nuclear power plants.

Significant effort has been underway at the FNR, for a number of years, to study the effects of long-term neutron and gamma irradiation on materials, as part of collaborative research with national laboratories and federal agencies. Current collaboration involves Oak Ridge National Laboratory and the University of California at Santa Barbara, in a four-year program initiated in 1997 and funded by the U.S. Nuclear Regulatory Commission (NRC). The material testing program focuses on establishing the integrity of pressurized steel vessels that play a crucial role in ensuring the safety of nuclear power plants around the world. Considerable investments have been made in equipment and facilities in the FNR to capitalize on the stable, long irradiation periods of the FNR cycle. Both incore and excore irradiation sites have been developed and are utilized by a number of investigators. More detailed descriptions of these projects follow.

Academic Research

Materials Dosimetry Reference Facility (MDRF). Designed and constructed by the National Institute of Standards and Technology (NIST) in cooperation with FNR, the MDRF provides a high-intensity neutron fluence similar to that experienced by nuclear power plant reactor structural materials and pressure vessels. This characteristic makes the MDRF a valuable national resource for the calibration of neutron dosimeters and, in particular, those used for monitoring neutron exposure of power plant reactor structural materials. Accurate dosimetry is vital to properly assessing the neutron damage experienced by these materials.

Basically, the facility design is a steel cylinder (15 cm o.d., 5 cm i.d.) wrapped in cadmium and mounted in the pool close to the core of the Ford Nuclear Reactor. An irradiation thimble, inserted from the top of the reactor pool, locates passive or active detectors at the core midplane. Alternative thimbles provide two spectrum options for investigating detector response characteristics and validating dosimetry measurement methods. The standard thimble generates a reference spectrum with a near-1/E distribution below 0.1 MeV down to the cadmium cut-off at 0.4 eV. In contrast, a ^{10}B liner truncates the spectrum at 4 keV.

The nominal MDRF fast neutron fluence rate (E>1 MeV) is 2.8×10^{11} $cm^{-2} \cdot s^{-1}$. Certified fast-neutron fluences are established with $^{58}Ni(n,p)^{58}Co$ activation detector monitors calibrated by means of neutron fluence transfer from the NIST ^{252}Cf Fission Neutron Irradiation Facility.

The development and characterization of the MDRF was a joint project of the FNR and NIST, with major support and funding provided by the Nuclear Regulatory Commission (NRC). The NRC interest in such a facility was based on their need to be able to assess the quality of fluence measurement data presented to them, as by a utility wishing to gain NRC approval for a reactor license extension. In this example, parallel sets of fluence monitors are irradiated at the utility and in the MDFR, along with a NIST nickel foil. Based on their count of the ^{58}Co activity in the nickel foil and from their knowledge of the shape of the neutron energy spectrum, NIST scientists can assign an accuracy value to the MDRF irradiation and counting, as done by the utility.

Cooperation between the University and the government's measurement laboratory - NIST- has provided the nuclear utilities and the Nuclear Regulatory Commission with an objective measure of measurement quality.

University of California Santa Barbara (UCSB). Specimen irradiation for a multi-year research project sponsored by the Nuclear Regulatory Commission and the Mechanical and Environmental Engineering Department of the University of California Santa Barbara, investigating neutron radiation damage in iron alloys is continuing. The project is examining the fundamental mechanisms behind atom displacement damage caused by fast neutron interactions and the resulting degradation in the mechanical properties of iron alloys.

Approximately 40,000 specimens will be irradiated to a variety of total neutron exposures at differing exposure rates and temperatures. To date, irradiations are complete for almost 10,000 specimens. The specimens are model alloys that have been spiked to differing levels with elements that are known to be "bad actors" - elements that seem to enhance neutron damage. The specimens are in the form of miniature mechanical test specimens that will be examined for hardness, yield and tensile strength and fracture toughness. Selected specimens will also undergo an extensive examination of their microstructure.

The objective of the program is to unravel how alloy composition, temperature, irradiation rate, and total neutron exposure cause observed changes in mechanical properties. The irradiation facility for this project was designed and fabricated by Oak Ridge National Laboratory with the consultation of UCSB and FNR staff.

Heavy Section Steel Irradiation (HSSI). Test specimen irradiation for the NRC sponsored HSSI Program at Oak Ridge National Laboratory takes place in temperature-controlled irradiation facilities (IAR) developed for FNR by Oak Ridge National Laboratory. The IAR facilities are designed to straddle each side of the UCSB irradiation facility. In this program, specimens of actual reactor pressure vessel steels are being examined to investigate the damage response of these materials through accelerated neutron aging.

This program is directed at one of the major re-licensing issues facing currently operating pressurized water nuclear reactors: Can we restore the neutron damaged mechanical properties of existing reactor pressure vessels such that they can be relied upon to safely operate an additional ten years or more beyond their current licensed lifetime? The answer to this question may lead to a substantial reduction in the cost of generating electricity by nuclear power. But, more importantly, the answer will have a broad impact on the major environmental issues of global warming, acid rain, and greenhouse gases.

Heavy-Section Steel Irradiation Program

T. M. Rosseel, Manager
Oak Ridge National Laboratory

The objective of the Heavy-Section Steel Irradiation (HSSI) Program, a major safety program sponsored by the U.S. Nuclear Regulatory Commission (NRC) at Oak Ridge National Laboratory (ORNL), is to provide a thorough, quantitative assessment of the effects of neutron irradiation on the material behavior, particularly the fracture-toughness properties, of typical pressure-vessel steels as they relate to light-water reactor pressure vessel (RPV) integrity. The program centers on experimental assessments of irradiation-induced embrittlement augmented by detailed examinations and modeling of the accompanying microstructural changes. Effects of specimen size; material chemistry; product form and microstructure; irradiation fluence, flux, temperature, and spectrum; and post-irradiation heat treatment are being examined on a wide range of fracture properties. Fracture toughness (KIc and JIc), crack-arrest toughness (KIa), ductile tearing resistance (dJ/da), Charpy V-notch (CVN) impact energy, drop-weight (DWT) nil-ductility transition (NDT), and tensile properties are included. Models based on molecular dynamics simulations and observations of radiation-induced microstructural changes using the atom-probe field-ion microscope (APFIM) and the high-resolution transmission electron microscope (TEM) are being developed to provide a firm basis for extrapolating the measured changes in fracture properties to wide ranges of irradiation conditions. Archival storage and disbursement of correlation monitor materials provide support for commercial light-water reactor (LWR) irradiation surveillance programs. Collaborative research activities with other domestic and foreign research programs provide a wider experimental base for understanding embrittlement effects.

Results from the HSSI studies are used to help resolve major regulatory issues facing the NRC. Those issues involve RPV irradiation embrittlement such as pressurized-thermal shock, operating pressure-temperature limits, low-temperature overpressurization, and the specialized problems associated with low upper-shelf (LUS) welds. Together, the results of these studies also provide guidance and bases for evaluating the overall aging behavior of light-water RPVs.

This program is coordinated with those of other government agencies and the manufacturing and utility sectors of the nuclear power industry in the United States and abroad. The overall objective is the quantification of irradiation effects for safety assessments of regulatory agencies, professional code-writing bodies, and the nuclear power industry. All HSSI irradiations are performed at the University of Michigan's Ford Nuclear Reactor (FNR). HSSI accomplishments include:

- Fabrication, installation, and testing of the Irradiation, Anneal, and Reirradiation (IAR) Facility, with dual reusable capsules, at the FNR. The IAR facility has been designed to maintain specimen temperatures at 288° C within ± two degrees during irradiation. The facility has operated successfully for *ca.* 5500 effective full power hours.

- Characterization of the neutron field in the HSSI reusable irradiation facilities at the FNR. Using TORT, a 3-D neutron-transport code, measurements of radiometric monitors, and the FNR core power distribution, the exposure parameter distribution and displacements per atom (dpa) rate in iron were calculated.

- Atom Probe Tomographic characterization of the solute distribution in a neutron-irradiated and annealed pressure vessel steel weld. The size of the neutron-induced, Cu-enriched precipitates increased and the number density decreased upon isothermal annealing. The precipitates were also found to be enriched in Ni and Mn at the precipitate-matrix interface.

- Completion of a major irradiation campaign at the FNR using a German high-copper weld to evaluate curve-shape effects and the assumption of constant shape of the fracture-toughness transition-temperature region. This is an important test of the fracture-toughness, master-curve method.

- Completion of a major irradiation campaign to (1) evaluate the effects of temper embrittlement on the coarse-grained, heat-affected zone in RPV steels and (2) examine the effects of reirradiation on KJc and KIa in order to evaluate the relative changes in the recovery and reembrittlement between CVN and fracture-toughness properties and a detailed examination of the reembrittlement rates.

Pressure Vessel NDE. In a program indirectly related to the HSSI program, the NRC has contracted PML/FNR to act as a host site for a comparison of non-destructive evaluation techniques that could be applied to nuclear reactor pressure vessels. This program seeks a quantitative relationship between properties that can be non-destructively measured, such as ultrasound transmission or magnetic acoustic emission, and mechanical properties such as ductile-brittle transition temperature, yield and tensile strength, and fracture toughness of irradiated steels. The ultimate goal is to find NDE techniques that can reliably predict the mechanical condition of the pressure vessel at the time of testing.

The NRC is making a set of very well characterized unirradiated and irradiated pressure vessel steel specimens available for testing. The specimens will give research groups a chance to apply their NDE techniques to a standard set of specimens. The program also provides the NRC with the opportunity to independently evaluate the current NDE state of the art. While the NRC is particularly interested in the development of NDE techniques for testing pressure vessels, any advances in this area will have much broader application in the overall arena of non-destructive testing.

The PML/FNR will be providing a temporary home and the hot cell facilities for handling and measuring the radioactive specimens. Staff and logistics support for visiting research teams will also be provided.

Dr. Brian Roe (***University of Michigan, Physics***) has been testing the irradiation hardness of aerogel, a material of potential interest in the development of particle detectors for use in the particle accelerator at Argonne National Lab near Chicago.

Commercial Testing

During the year, material testing and neutron radiography of Boral coupons was performed for ***AAR Advanced Structures*** as part of their quality assurance program. This testing included visual inspection of the specimens, neutron attenuation measurements, and dimensional measurements. This testing is performed to quantify boron content in the plates to ensure it exceeds the minimum specification for use in the spent fuel pools. Similar testing was conducted for ***Pacific Gas and Electric***.

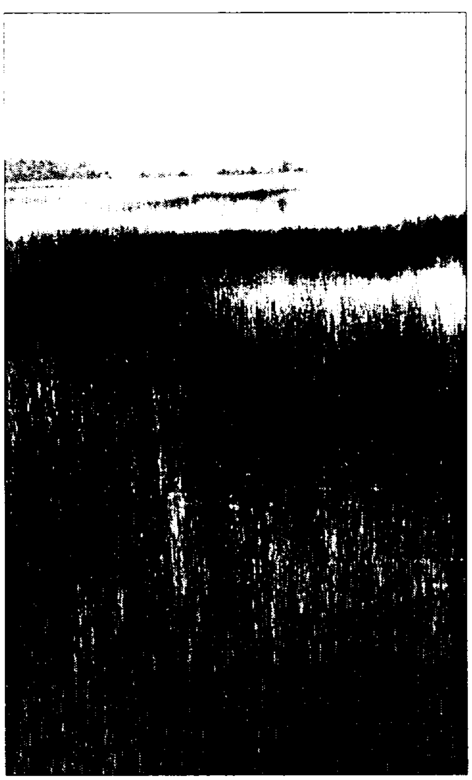
Radiochemical and Tracer Production Program

A number of radioisotopes for academic and industrial research are produced by neutron irradiation in the FNR, followed by processing in the PML hot cells. These radionuclides are typically used as tracers in various scientific and industrial research programs in University of Michigan departments, other universities, and industrial laboratories (Table 5). Recent activities in tracer applications include:

- ^{82}Br-labeled hydrocarbons for the study of oil consumption in car engines;

- ^{24}Na-labeled sodium carbonate for process testing in chemical and petrochemical plants; and

- ^{59}Fe tagged compounds for studies of sediment mixing and burial for use in modeling Great Lakes environments.



Mechanisms of sediment burial in Great Lakes coastal wetlands are being investigated by GLERL.

Radiochemical Production for Academic Research

Drs. Peter Landrum and John Robbins (***Great Lakes Environmental Research Laboratory, Department of Commerce***) have initiated a project to monitor rates of mixing and burial of sediments by sediment-dwelling organisms through use of a gamma scanning system. Test sediments are doped with variable amounts of toxic organic compounds in the lab, and the mixture is monitored through the addition of the radioisotopic tracer ^{59}Fe. FNR is producing a gamma tracer (^{59}Fe) used in a gamma scanning system.

Prof. Henry Griffin (***University of Michigan, Chemistry***) is continuing radiation trials looking into the feasibility of producing radioactive mercury that could be used as a tracer for process and inventory control at plants processing metallic mercury.

Radiochemical Production for Industrial Research

^{82}Br labeled motor oil is routinely produced for ***General Motors Research Laboratories*** in Warren, Michigan. The tracer-labeled motor oil is used at the analytical laboratories to test oil consumption in automotive engines. Engine exhaust is analyzed for the radioactive tracer while the motor is put through its paces on a dynamometer. On average, two shipments of tracer labeled oil are prepared per month. The General Motors R&D radiometric method for measuring engine oil consumption is a key tool for the development of prototype engines and for resolution of field problems. During 1999, radiometric oil consumption

measurements were employed in a number of proprietary projects to reduce exhaust emissions and improve product performance.

In a new study initiated this year, ***General Motors R&D*** developed a radiotracer method to measure piston ring wear during engine operation. Piston rings coated with molybdenum were irradiated to produce ^{99}Mo-tagged components. Initial measurements show that the sensitivity of the technique is sufficient to measure wear rates at all engine operating conditions. Current work is aimed at the effects of lubricant formulation and lubricant condition on engine wear.

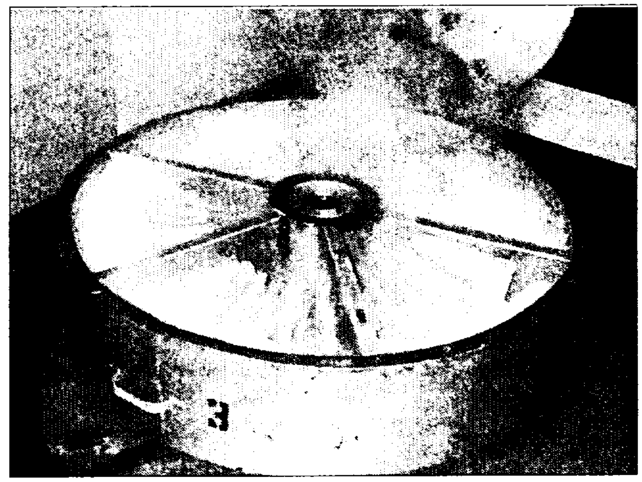
Hydrocarbon-based tracers labeled with radioactive ^{82}Br, ^{140}La labeled hydrocarbon cracking catalysts, and sodium carbonate tracers labeled with radioactive ^{24}Na were produced for ***ICI Tracerco*** and ***Tru-Tec Services Division of Koch Industries***. Both firms are service providers to the oil and petrochemical industry and are involved in analyzing problems and improving the efficiency of refinery processes. Short-lived radioactive tracers and sources produced at FNR are injected into refinery process streams at various points and can be followed to test the operation of the process. Short-lived, high energy, high activity sources are used with gamma detection equipment to perform radiography of catalytic cracking columns.

Table 5. Radiochemical Production Summary, 1998-1999

Department / Organization	Irradiation Time (hrs)
UM - Dept. of Chemistry	1
G.L. Environmental Research Lab	1
General Motors Research Lab	225
ICI Tracerco	1
TruTec	35
Total	**263**

Cobalt Irradiation Program

With a maximum ^{60}Co activity of 25 kCi, the Cobalt Irradiator Facility (CIF) is used in a large number of applications requiring a high dose rate of gamma radiation. The most common applications are the sterilization of bone and cartilage for human grafts and transplants. Other uses include high doses of gamma irradiation for the sterilization of soil; mutation of cells; and studies of radiation effects on chemical systems, polymers, plastics, electronic and reactor components, satellite components, food, seeds, plants, and parasites.



Human tissues are kept frozen with dry ice during gamma irradiation in the Cobalt Irradiator Facility.

Irradiation services at the facility are available to UM hospital and departments, other universities, hospitals, and federal and industrial laboratories, 24 hours per day, seven days a week. The CIF has been in use 35% of calendar hours in this past fiscal year.

Irradiation services provided by the Cobalt Irradiator for the University of Michigan and for outside institutions are summarized in Table 6. Over the past year, over 31,000 samples were irradiated; of these, the vast majority were for medical facilities and bio-medical research. Pall Gelman Laboratories and Northern California Transplant Bank are two major users of the facility in recent years, accounting for over 83% of samples irradiated. Other major research areas include studies in environmental sciences, physics, and industrial materials testing.

Hospitals and Tissue Banks

LifeNet. Frozen and freeze dried human bone grafts are gamma sterilized for reconstructive surgery and transplantation.

Michigan Regional Tissue Bank. Large quantities of bones, bone grafts, and cartilage are sterilized by irradiation in the Cobalt Irradiator. Most samples are double sealed in plastic or aluminum packs, but some are wrapped in plastic and irradiated while frozen on dry ice. A typical radiation dose is $1.8x10^6$ rad administered over 8-16 hours. Tissue is dispensed from the tissue bank to doctors and hospitals throughout the state and the nation for human transplant and reconstructive plastic surgery.

Northern California Transplant Bank. Large quantities of bones, bone grafts, and cartilage are sterilized by irradiation in the Cobalt Irradiator. Most samples are double sealed in plastic or aluminum packs and irradiated freeze-dried at room temperature or while frozen on dry ice, but some, cartilage in particular, are sealed in glass jars with 0.9% saline solution. A typical radiation dose for freeze-dried or frozen materials is $1.8x10^6$ rad, while a dose for cartilage is $2.5x 10^6$ rad administered over 8-16 hours.

Table 6. Cobalt Irradiator Utilization Summary, 1998-1999

Department/Organization	Number of Irradiations	Number of Samples
University of Michigan		
Atmospheric & Oceanic Science	3	9
Biology	2	212
Chemical Engineering	37	528
Civil & Environmental Engineering	13	342
Dentistry	1	48
Phoenix Project, Michigan Memorial	27	979
Physics	11	107
University Hospital/Medical School		
Internal Medicine	4	69
Orthopedic Research	6	17
Subtotal	***104***	***2341***
Other Colleges, Hospitals, & Institutions		
LifeNet	1	112
Michigan Regional Tissue Bank	3	742
Michigan State University	5	1149
Northern California Transplant Bank	123	14092
St. Luke's Hospital	1	6
Sparrow Hospital	1	21
University of California-Davis	2	19
Subtotal	***136***	***16141***
Federal and Industrial Research		
Aastrom Biosciences, Inc.	3	27
Dow Corning	1	24
Eastman Kodak	1	5
Pall Gelman Sciences Inc.	51	12285
Montana Biotech Corporation	7	527
New Waste Concepts	2	40
Pelorus Enbiotech Corporation	1	5
Raven Biological Laboratories, Inc.	2	176
SoloHill Engineering, Inc.	1	50
USDA Forest Service, Forest Products Lab	1	90
Subtotal	***70***	***13229***
Total	310	31711

Tissue Banks International

Northern California Tissue Bank
Multi-Tissue Operations, National Processing Center
San Rafael, California

Tissue Banks International (TBI) was founded in 1962 as a non-profit, non-governmental network of 40 tissue banks, which includes but is not limited to musculoskeletal and eye banking activities in the US and overseas. The TBI National Processing Center (TBI/NPC), located in San Rafael, California, is the central processing facility for Multi-Tissue Operations for TBI in the United States.

The TBI National Processing Center was established in 1968 as the Northern California Transplant Bank (NCTB), a hospital based program to provide human allograft tissues for transplantation, research, and medical training. A pioneer in encouraging multi-tissue donation and procurement by a single donor, NCTB promoted the awareness that one tissue donor could provide a wide variety of grafts to benefit as many as 60 individuals in need of transplants. NCTB is fully accredited by the American Association of Tissue Banks (AATB).

Under its Ocular Division's VisionGraft service, TBI provides corneas and other eye tissues, while the Multi-Tissue Division of TBI provides tissues such as bone, skin, sclera, cartilage, pericardium, heart valves, and saphenous veins to surgeons throughout the US and abroad. Many of these allografts are distributed from TBI's National Processing Center through its TranZgraft tissue service. Other allografts, through strong partnerships, may be provided by the Center to biotechnology companies, a practice which enables patients to benefit from their proprietary innovations. These TranZgraft allografts and innovative tissues are used for spinal, knee, hip, and other orthopedic sports injuries, tumor resection, oral, dental, maxillofacial, urological and other reconstructive procedures. Last year alone, TBI provided approximately 1100 multi-tissue donors, which resulted in many thousands of allografts restoring health and mobility to grateful recipients.

Today, TBI/NPC processes, stores, and distributes a wide range of human allograft tissues to physicians, hospitals, and surgical centers from its state-of-the-art facility. Multi-tissue donors recovered at all TBI-affiliated tissue banks are directed to its National Processing Center for allograft preparation and distribution. A strict protocol is followed for each tissue to ensure quality, sterility, strength, and safety. Several different preservation processes are used to satisfy the diverse requirements of transplant and other surgeons. Freeze drying, ultra-low freezing, demineralization, and preservation in sterile solution or other media are alternative ways of preparing tissue for surgery. Tissue is then directed to the Phoenix Memorial Lab for gamma irradiation in the ^{60}Co irradiator facility to assure a final level of safety prior to transplantation to the patient. Quality control is strictly and methodically observed; along with thorough reviews of medical and social histories, numerous tests for infectious diseases and rigorous standards are stringently enforced to ensure patients throughout the United States and abroad a safe, high-quality tissue for their surgical procedures.

TBI/NPC has had a long, well established relationship with the Phoenix Memorial Lab, extending well over 14 years. Utilizing very controlled systems of sterilization for target dosage for TBI/NPC allografts, Phoenix Memorial Lab shares our commitment to "*Do no harm*" to the patients we serve, and enables TBI/NPC to provide the ultimate safety and sterility in allografts.

Saint Luke's Hospital. Small quantities of frozen femoral head bones are sterilized in the Cobalt Irradiator while frozen on dry ice. Talc is also irradiated and sterilized for use in the operating room.

Sparrow Hospital. Brian Sklapsky is sterilizing operating room pens and pencils.

Academic Biomedical Research

Deborah Cieslinski, the laboratory director for Dr. H. David Humes (***University of Michigan, Internal Medicine***), is growing endothelial cells on polysulfone hollow fibers in order to study their permeability characteristics under perfusion conditions. The single hollow fibers are irradiated in the Cobalt Irradiator to sterilize them prior to cell inoculation.

Steven A. Goldstein, Ph.D. (***University of Michigan, Orthopedic Research***) is investigating the role of a single dose gene therapy on bone repair in a critical defect. The primary experiment consists of four groups of eight animals each. Each animal will undergo bilateral defects. One side will be treated with a gene therapy and the other side will be filled with cancellous allograft. Five animals in each group will be used for biomechanical torsion testing, and the remaining three will be used for histologic analysis. Long term evaluation will consist of eight dogs undergoing the identical surgical procedure. Four dogs will remain post-operative for 32 weeks and four will continue for 52 weeks.

Prof. David Mooney (***University of Michigan, Chemical Engineering***) is sterilizing polymer sponges that are used in experiments with cultured mammalian cells and as vehicles for cell transplantation. He is studying how the function of mammalian cells is regulated by signals present in their micro environment (for example, adhesion to specific materials). This understanding is utilized in a second experimental area: design of devices to transplant cells and engineer new tissues. Tissue engineering may ultimately provide alternatives to whole organ and tissue transplantation. The work is motivated by the tremendous shortage of available tissues and by the large numbers of people who either die or survive on sub-optimal therapies due to the shortage.

Dr. Seth M. Feder (***University of Cincinnati, Biomechanics***) has been investigating the effects of ionizing radiation on the mechanical and material properties of collagenous tissues used in orthopaedic reconstructive procedures. This research is both timely and important because gamma irradiation is currently being used by surgeons and tissue banks to sterilize transplant tissues, yet the effects of the radiation on the tissues is not well documented.

Bruce Rutherford and Paul Krebsbach (***University of Michigan, School of Dentistry***) sterilized a synthetic polymeric non-woven "cloth" (polyglycolic acid) from a commercial source. Cells derived from tissue biopsies are propagated *in vitro* and adhered to the cloth to construct tissue graft substitutes for implantation *in vivo.*

Biomedical Research Organizations

Aastrom Biosciences. Dr. Bernard Palsson and his associate, Matthew Heidmous, utilize the Cobalt Irradiator to sterilize polyethylene tubing, bioreactors, and other materials for use in bone marrow transplant research.

Montana Biotech. Fred Albert and Joan Combie irradiated microorganisms to identify radiation resistant strains isolated from extreme environments. They are irradiated, cultured, and cell viability determined.

Pall Gelman Sciences. Gelman has utilized the Cobalt Irradiator to sterilize various experimental medical devices such as microfunnels and filters. The effects of radiation on the materials of these devices are being observed.

Pelorus Enbiotech Corporation. William R. Mahaffey, Ph.D., sterilized soil and ground water by gamma irradiation to be used as controls for studying the capacity of microorganisms to degrade organic and inorganic compounds by natural assimilation and biodegradation.

Raven Biological Laboratories. *Bacillus pumilus* spore strips are being irradiated in the Cobalt Irradiator to determine the lethal gamma dose value for various *Bacillus pumilus* lots. Long term lethal dose values of some older lots are being studied to determine shelf-life of spore strips. The laboratory will also sterilize culturing strips that will be used in a new culturing technique which Raven Biological is developing. Various materials used in this new culturing system will be irradiated to study the effects of gamma sterilization.

Solo Hill Engineering. Gamma sterilization was conducted on callogen micro carrier beads used in producing cell cultures.

Biological Studies and Instruction

Prof. Ruthann Nichols (***University of Michigan, Biology***) and Keri Paisley are researching a peptide that inhibits heart rate in fruit flies (*Drosophilamelangaster*). They are using gamma irradiation mutagenesis to generate deletions of the peptide gene in the fruit fly, and then monitoring the effect of eliminating the peptide in an attempt to understand the physiological function of this peptide in the whole animal.

Prof. Robert Helling (***University of Michigan, Biology***) irradiated soybeans from low to high gamma doses for use in Biology 301 class projects.

Environmental Studies

Alex Orlov, Hildegard Selis, and others (***University of Michigan, Civil & Environmental Engineering***) are sterilizing soil with ^{60}Co gamma radiation for Dr. Walter Weber. They are investigating the bio-availability of organic pollutants from various soil materials. Their studies include long term adsorption and desorption studies of toluene and correlating these with biodegradation rates. They need sterile soil that has not been sterilized chemically or heat sterilized. First, they will assess the influence irradiation may have on the sorption properties of the contaminants due to effects on the soil by the irradiation. Second, they will test for bacterial spore survival in the soil after sterilization.

Xianda Zhao, a research assistant working for Prof. Thomas C. Voice (***Michigan State University, Civil & Environmental Engineering***), is gamma sterilizing biofilm-coated granular-activated-carbon (GAC). He is testing a pilot scale fluidized bed system used to treat ground water contaminated with three milligrams of toluene per liter of water. The GAC is used as the carrier media for microbial growth. The biofilm-coated GAC is taken from the system each month and sterilized. The sterilized GAC is used in an adsorption isotherm experiment to determine the remaining adsorption capacity.

Rod Venterea (***University of California at Davis, Land, Air and Water Resources***), is using soils in studies to examine biological and chemical transformations of a wide range of organic and inorganic chemicals in natural, agricultural and polluted environments. The

sterilized soils are used as controls in biodegradation experiments to assess the importance of abiotic transformation processes.

Alex Chow (***University of California at Davis, Land, Air and Water Resources)*** sterilized peak soil to serve as a control in a study that examines peat soils at various incubation temperatures and at various moisture contents. He looked at the wet-dry cycle effects on the quality and quantity of dissolved organic carbon production.

Physics Research

Bruce Block (Sr. Engineer, ***Atmospheric and Oceanic Science/ Space Physic Research Lab***) is studying the effects of gamma irradiation on silicon microcircuits. Analog device performance is characterized before and after each gamma exposure up to an exposure that disables them.

Neville Wadia and Prof. Byron Roe (***University of Michigan, High Energy Physics***) are utilizing the Cobalt Irradiator to test a system of detectors for use in the proposed MiniBooNE experiment at the Fermi National Laboratory. MiniBooNE will utilize an 8GeV proton beam for the production of neutrinos; the UM researchers seek to monitor the secondary beam, produced after the protons strike a target. Materials used in the detector system need to be tested to ensure that they will function in the high radiation environment. The researchers will expose detector materials to fixed doses of gamma rays and later neutrons, checking for any changes in the refractive index of the materials after each dose in order to determine any radiation damage.

Drs. Tim Killeen and Heinz Grassi (***University of Michigan, Space Physics Research Lab***) investigated the radiation effects on the through-put of a flint glass optic assembly. It will be used in a satellite based doppler interferometer for wind and temperature measurements.

Dr. H. Richard Gustafson, an Associate Research Scientist (***University of Michigan, Physics***), is irradiating epoxy compounds and plastics with ^{60}Co gamma rays to observe radiation damage. The materials being irradiated will be used in the fabrication of electronics and detector components.

Industrial Research

Dow Corning Corporation. Kevin Hawes sterilized painted metal tubes used to contain adhesive. He is looking at the radiation effects on the adherence of the paint to the metal.

Eastman Kodak. A continuing goal of development work in diagnostic imaging equipment is to make devices light, lower in X-ray absorption, and stronger. David Steklenski is gamma irradiating an aluminum/polypropylene/aluminum composite called Hylite as a possible replacement for aluminum in several imaging applications. It has the strength of aluminum at a fraction of the weight. The major concern with the material are the effects of radiation, the stability of the polypropylene, and the polypropylene/aluminum bond.

New Waste Concepts. Tom Nachtman gamma-irradiated Instacote material at various doses for damage studies. The material is used as a coating for walls and items that are radioactively contaminated.

USDA Forest Products Lab. Simon Curling gamma sterilized wood to study the relationship between bending strength and chemical composition (hemi-cellulose chemistry) compared to steam sterilization. The wood is exposed to decay fungi after sterilization and the effect of decay monitored.

Radiopharmaceutical Program

Four radioiodine compounds are synthesized for clinical studies on a regular basis by the radiopharmaceutical program at PML using three iodine isotopes. Iodine-labeled radiopharmaceuticals are routinely analyzed for purity as part of the quality assurance program associated with their production.

- NP-59, a derivative of cholesterol, is an adrenal scanning agent used in the detection of abnormalities in the adrenal gland. NP-59 is synthesized twice monthly for distribution.

- mIBG-123 diagnostic doses are synthesized twice monthly for the University of Michigan Hospital. MIBG-125 and 131 therapeutic doses are synthesized on demand.

- mIBG-therapeutic, a radioiodinated analog of guanethidine, an antihypertensive drug, is an adrenal medula scanning agent used in the detection and treating of disease in the adrenomedulla.

- IBVM-diagnostic is a structural analog of vesamicol, a compound that has been shown to bind to acetylcholine storage vesicles found within cholinergic nerve endings. It is theorized that a radio-labeled benzovesamicol might serve as a non-invasive *in vivo* marker for cholinergic nerve endings in the brain. Such a marker could potentially serve as an indicator of the damage that occurs in brain disorders such as Alzheimer disease. IBVM is being synthesized weekly for in house human studies. It may become a production compound in the near future.

Radiopharmaceuticals were synthesized 104 times and shipped to 46 hospitals in 23 states and the District of Columbia in the United States; and to three hospitals in Alberta, Ontario, and Saskatchewan, Canada.

A summary of therapeutic radiopharmaceutical production broken down by country, state, and hospital, is presented in Table 7. Table 8 is a similar listing for diagnostic radiopharmaceutical production. In general, therapeutic samples contain larger amounts of radioactivity than diagnostic samples.

Table 7. Therapeutic Radiopharmaceutical Production Summary, 1998-1999

Recipient Hospital		**mIBG-131 Injections**
California	City of Hope Nat'l. Medical Center, Ouarte	2
Georgia	Emory University, Atlanta	3
Michigan	University Hospital, Ann Arbor	3
Minnesota	Mayo Clinic, Rochester	1
North Carolina	Duke University, Durham	24
Tennessee	Vanderbilt Medical Center, Nashville	2
Total Number of Injections/Syntheses		**35/30**

Table 8. Diagnostic Radiopharmaceutical Production Summary, 1998-1999

Hospital		NP-59	mIBG-123	IBVM
Canada				
Alberta	Foothills Provincial General Hospital, Calgary	1		
Ontario	The Toronto Hospital, Toronto	1		
Saskatch.	Pasqua General Hospital, Regina	2		
United States				
California	VA Medical Center, Long Beach	1		
	University of California, Los Angeles	3		
	Kaiser Foundation Hospitals, Sacramento	1		
Conn.	University of Connecticut Health Center, Farmington	6		
D.C.	Georgetown University Hospital, Washington	5		
Florida	Jackson Memorial Hospital, Miami	2		
Illinois	Hines Veterans Administration Hospital, Hines	1		
	Michael Reese Hospital, Chicago	1		
	Northwestern Memorial Hospital, Chicago	2		
	Rush Presbyterian-St. Luke Medical Center, Chicago	1		
	Loyola University Medical Center, Maywood	3		
Indiana	Luthern Hospital of Indiana, Ft. Wayne	1		
	The Methodist Hospitals-Southlake Campus, Merillville	1		
Maryland	John Hopkins, Baltimore	2	0	2
	Walter Reed, Silver Spring	2		
Michigan	St. Joseph Mercy Hospital, Ann Arbor	2		
	University of Michigan's Hospital, Ann Arbor	86	68	38
	Henry Ford Hospital, Detroit	4		
	Saint John Hospital, Detroit	2		
	William Beaumont Hospital, Royal Oak	3		
N.J.	St. Barnabus Medical Center, Livingston	2		
New York	Mem. Sloan-Kettering Cancer Center, New York City	3		
	New York Hospital, New York City	2		
	St. Vincent's Hospital, New York City	2		
	SUNY University Hospitals, Stoney Brooke	1		
N.C.	North Carolina Baptist Hospital, Winston-Salem	2		
Ohio	University of Cincinnati, Cincinnati	1		
	Ohio State University Hospital, Columbus	1		

Table 8. Diagnostic Radiopharmaceutical Production Summary, 1998-1999 (cont.)

Hospital		NP-59	mIBG-123	IBVM
Okla.	University of Oklahoma, Oklahoma City	2		
Oregon	Sacred Heart General Hospital, Eugene	1		
Penn.	Lehigh Valley Hospital, Allentown	1		
	Hospital of the Univ. of Pennsylvania, Philadelphia	4		
R.I.	Rhode Island Hospital, Providence	2		
S.C.	Medical University of South Carolina, Charleston	4		
Tenn.	Baptist Memorial Hospital-Central, Memphis	1		
Texas	Hermann Hospital, Houston	1		
	University of Texas Medical Branch, Galveston	2		
	University of Texas System Cancer Center, Houston	1		
Virginia	University of Virginia Hospital, St. Louis	1		
Wash.	University of Washington, Seattle	8		
Wisc.	University of Wisconsin, Madison	4		
Total Radiopharmaceutical Production		178	68	40

Collaborative Programs

Phoenix Memorial Laboratory and Ford Nuclear Reactor welcome researchers from all disciplines. Five UM departments have established collaborative programs with MMPP involving dedicated laboratory facilities and/or office space, as well as the expertise of MMPP staff.

Nuclear Engineering & Radiological Sciences

A number of faculty members and research scientists in the Nuclear Engineering and Radiological Sciences (NERS) department have maintained long-term collaborations with the PML staff, essentially spanning all PML programs. In recent years, the collaborations have focused on the development of neutron and gamma detectors, study of radiation effects on nuclear waste materials, reactor physics analysis of the FNR core, and development of radiation imaging systems for robotics applications. Current collaborative projects between NERS and PML/FNR include:

Neutronic Analysis of the FNR Core for the Heavy Section Steel Irradiation Program: In support of the Heavy Section Steel Irradiation (HSSI) program sponsored by the U.S. Nuclear Regulatory Commission and Oak Ridge National Laboratory, effort has been underway to improve the reactor physics analysis capability for the Ford Nuclear Reactor. This project, developed by Prof. Ron Fleming, Philip Simpson, and Prof. John Lee, focuses on refining the assembly-level representation of FNR fuel elements using the WIMS-D4M collision probability code. Based on benchmark MCNP Monte Carlo calculations for control fuel elements, with a control rod guide occupying the central region of the assembly, a detailed discrete representation of fuel plates and guide regions has been developed. In addition, Monte Carlo neutron transport calculations have been performed to represent geometrical details of steel specimens, as well as boral plates used as thermal neutron shields for the steel specimens, in the HSSI program. Effort is made to combine the Monte Carlo results with global diffusion theory analysis to account for significant flux perturbations in the vicinity of the HSSI capsules. The project was supported by Lockheed Martin Energy Systems ($34,000/20 mo.)

Advanced Devices and Systems for Radiation Measurements: Under the direction of Prof. Glenn Knoll and Prof. Zhong He, this investigation focuses on new radiation detection techniques that could be applied in fieldable instrumentation in the monitoring of nuclear materials. A major emphasis is on the development of gamma ray spectrometers that combine good energy resolution with room temperature operation. These researchers have recently demonstrated excellent results using CdZnTe, a ternary semiconductor material with favorable properties. The current project is sponsored by the Nonproliferation and National Security Office of Research and Development of the U.S. Department of Energy ($950,000/3 yrs).

Robotic Systems for Hazardous Environments: The goal of this project, under the direction of Prof. David Wehe, is to

support DOE's Environmental Management Program in the development of mobile robotic devices needed for environmental assessment, decontamination, and decommissioning of DOE facilities. Within the NERS department, work has centered on developing portable gamma ray imaging sensors. The project is funded through the U.S. Department of Energy's Office of Environmental Management ($900,000/12 mo).

Research on Room Temperature Semiconductors for Radiation Spectroscopy: Developed by Prof. David Wehe and Dr. Douglas McGregor, this project is dedicated to material-related research to improve the characteristics of room temperature semiconductors. Much of the current work with room temperature semiconductors is limited by a lack of knowledge of the surface effects. While most current research examines effects in the bulk, their research shows that the major limitations occur near the surface. Recent work has involved development of boron-coated GaAs detectors for spent fuel assays. The project is supported by Argonne National Laboratory.

Improved Method for Determining Radionuclide Depth Distributions Using in situ Gamma-ray Spectrometry: The dissertation research of Roland Benke implemented a unique collimator design with conventional radiation detection equipment. Cylindrically symmetric collimators were fabricated to allow only those gamma-rays emitted from a selected range of polar angles (measured off the detector axis) to be detected. Positioned with its axis normal to surface of the media, each collimator enables the detection of gamma-rays emitted from a different range of polar angles and preferential depths. Based on the results of actual measurements, this method increases the potential of *in situ* gamma-ray spectrometry as an independent characterization tool in situations with unknown radionuclide depth distributions. The Ford Nuclear Reactor has been a primary producer of sources for project testing and development.

Development of a Hybrid Portable Gamma Camera: The doctoral research of Ph.D. recipient Eric Smith has involved the design, construction, and analysis of a hybrid portable gamma camera for industrial gamma ray imaging. In order to calibrate the camera and simulate object scenes in the typical industrial setting, gamma-emitting radionuclides of various energies and shapes were necessary. Over the past three years, the Ford Nuclear Reactor has been a primary producer of sources, including ^{60}Co, ^{198}Au, ^{203}Hg, and ^{58}Co in shapes and quantities that are not commercially available.

Radiation Effects on Materials in the Near-Field of a Nuclear Waste Repository: Researchers Dr. Lumin Wang and Prof. Rod Ewing are addressing the issue of long term radiation effects in materials related to nuclear waste disposal. Site restoration activities at DOE facilities and the permanent disposal of nuclear waste generated at DOE facilities involve working with various types and levels of radiation fields. Radionuclide decay and the associated radiation fields lead to physical and chemical changes that can degrade or enhance material properties. The principal sources of radiation at the DOE sites are the actinides and fission-products contained in high-level wastes currently in storage. Alpha-decay of the actinide elements and beta-decay of the fission products lead to atomic scale changes in the material structure (radiation damage and transmutation). During site restoration, materials will be exposed to radiation fields that exceed 10^4 rad/hr. The radiation exposure due to the release and sorption of long-lived actinides (e.g., ^{237}Np) and fission products (e.g., ^{137}Cs and ^{90}Sr) may cause changes in important properties (e.g., cation exchange capacity) in geological materials (e.g., clays and zeolites)

along transport pathways. The objective of this research program is to evaluate the long term radiation effects in the materials in the near-field of a nuclear waste repository with accelerated experiments in the laboratory using energetic particles (electrons, ions, and neutrons). Experiments on the microstructure evolution during irradiation of two important groups of materials, sheet silicates (e.g., clays) and zeolites, are being conducted using PML/FNR facilities (neutron irradiation and neutron activation); and studies of radiation-induced changes in chemical properties (e.g., cation exchange capacity) are underway. These research efforts are supported by the U.S. DOE's Environmental Management Science Program ($408,000/3 yrs).

Table 9. Recent NERS Doctoral Dissertation Research Projects Utilizing the FNR

Student	Thesis Title	Advisor
1999-2000		
Benke, Roland	*An Improved Method for Determining Radionuclide Depth Distributions Using in situ Gamma-Ray Spectrometry*	K. Kearfott
Park, Jiyoung	*Neutron Scattering Correction Functions for Neutron Radiographic Images*	J. Lee, J. Lindsay
1998-1999		
LeBlanc, James W.	*A Compton Camera for Low Energy Gamma Ray Imaging in Nuclear Medicine Applications*	D. Wehe
Smith, L. Eric	*Design, Modeling and Performance of a Hybrid Portable Gamma Camera*	D. Wehe
1997-1998		
Stuenkel, David	*Measurement of Dose Equivalent Rate in Mixed Fast Neutron-Gamma Ray Fields*	G. Knoll
1996-1997		
Christodoulou, Emmanuel G.	*Measurements of the Differential Cross Sections for Elastic and Inelastic Scattering of 14 MeV Neutrons in Natural Chromium, Iron, and Nickel*	G. Knoll
Gormley, Jerome E.	*Experimental Comparison of Electrical and Mechanical Gamma-Ray Collimation*	D. Wehe
Miyamoto, Jun	*A Study of Micro-Strip Gas Chambers for the Measurement of Ionizing Radiation*	G. Knoll
1995-1996		
Guru, Shankar	*Mechanically Collimated High Energy Gamma Ray Imagers*	D. Wehe
Hawari, Ayman	*The High Accuracy Determination of HPGe Detector Relative Full Energy Peak Efficiencies for Gamma-Ray Spectrometry*	R. Fleming
Venkatarman, Ramkumar	*The Measurement of Photofission Interference in Fission Detector Results*	R. Fleming

Design, Modeling, and Performance of a Hybrid Portable Gamma Camera

L. Eric Smith
Department of Nuclear Engineering & Radiological Sciences, University of Michigan

The combination of a mechanically-collimated gamma-ray camera with an electronically-collimated gamma camera offers both the high efficiency and good angular resolution typical in a mechanically-collimated camera for lower photon energies and the uncoupling of spatial resolution and efficiency provided by an electronically-collimated camera at higher energies. The design, construction, performance modeling and measured performance of the Hybrid Portable Gamma Camera (HPGC) are developed. Intended for industrial use, the HPGC offers good angular resolution and efficiency over a broad energy range (50 keV to 2 MeV) by combining a MURA coded aperture camera with a Compton scatter camera in a single system. The HPGC consists of two detector modules: 1) a NaI(Tl) scintillator with Anger logic readout and 2) a CsI(Na) pixellated crystal viewed by a position-sensitive photomultiplier tube. The imaging characteristics of the two individual modules operating independently are shown in Figures 1 and 2.

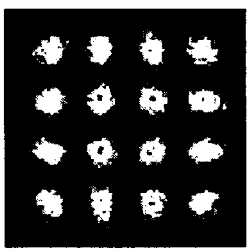


Figure 1. 16-position point source image reconstruction using the HPGC first detector module and a maximum likelihood position estimation algorithm, using an Au-198 point source with an activity of approximately 500 μCi.

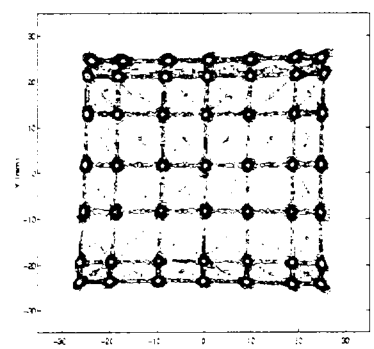


Figure 2. Flood field irradiation of the HPGC second detector module. The pixellation of the detector crystal provides well-resolved pixel interaction positions, despite the nonlinearity of the PSPMT

Analytical calculations of angular resolution components and efficiency for the HPGC were compared to Monte Carlo calculations of the same quantities. The predicted angular resolution performance for on-axis point sources, a central scattering angle of 45° and a detector separation distance of 35 cm ranges from 3.5-6° FWHM over the sensitive energy range. The mechanical collimation intrinsic efficiency for energies up to 800 keV varies from 0.50 to 0.05 while the electronic collimation intrinsic efficiency for energies above 400 keV is 7.0×10^{-4} to 5×10^{-5}. The experimentally measured angular resolution and efficiency values show good agreement with the modeling predictions for incident energies of 412 keV and 662 keV.

Although work has been done on mechanical collimation cameras and electronic collimation cameras operating independently, no truly hybrid imaging system has been constructed that uses the same gamma ray for both mechanical collimation and electronic collimation information. This work compares the relative information per photon for three imaging modalities: mechanical collimation, electronic collimation and hybrid collimation. The analysis is done for point sources at two incident energies (412 keV and 662 keV) in the medium energy range of operation for the HPGC (400 keV to 800 keV) where neither mechanical collimation nor electronic collimation performs particularly well acting independently. A tool from estimation theory called resolution-variance analysis is used to compare the three modalities. Results show that hybrid collimation is superior to mechanical and electronic collimation at both 412 keV and 662 keV over the resolution range likely to be used for such a camera.

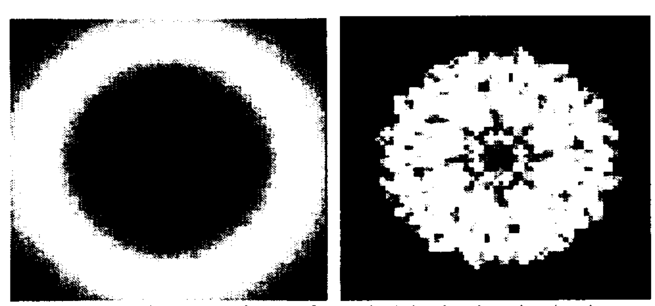


Figure 3. Unfiltered (left) and filtered (right) backprojection image of a 36 cm diameter Au-198 ring source at 1.6 meters from the front face of the HPGC. This image was produced using electronic collimation information from the HPGC.

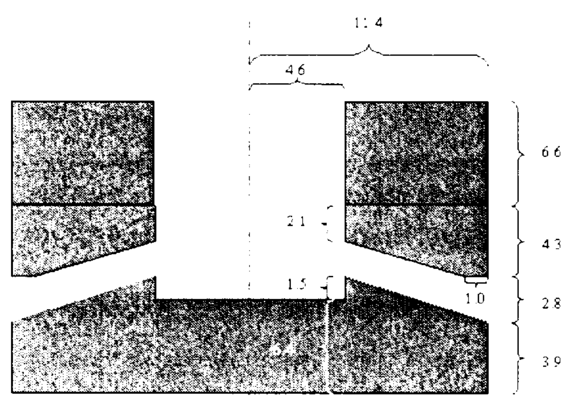
An Improved Method for Determining Radionuclide Depth Distributions Using *In Situ* Gamma-ray Spectrometry

Roland R. Benke
Department of Nuclear Engineering & Radiological Sciences, University of Michigan

In principle, *in situ* gamma-ray spectrometry determines the quantities of radionuclides in some medium with a portable detector. The main limitation of *in situ* gamma-ray spectrometry lies in determining the depth distribution of radionuclides. This limitation is addressed by developing an improved *in situ* method for determining the depth distributions of gamma-ray emitting radionuclides in large area sources.

This project implements a unique collimator design with conventional radiation detection equipment. Cylindrically symmetric collimators were fabricated to allow only those gamma-rays emitted from a selected range of polar angles (measured off the detector axis) to be detected. Positioned with its axis normal to surface of the media, each collimator enables the detection of gamma-rays emitted from a different range of polar angles and preferential depths. This work also involves sectioning the measured media into several independent depth layers. For this work, a uniform radionuclide distribution was assigned to each depth layer.

From the *in situ* measurements of a particular source medium, the photopeak count rates acquired with several different collimators were described by a system of equations that incorporate the activity concentrations in the independent depth layers with the counting efficiencies of each depth layer. Solution of the system of equations yielded the activity concentration of radionuclides in each depth layer.



Cross-sectional diagram of the 60-70° collimator developed for this study (all measurements are in cm).

Previous *in situ* methods require *a priori* knowledge of the depth distribution shape. However, the absolute method developed in this study determines the depth distribution as a histogram and does not rely on such assumptions. Other advantages over previous *in situ* methods are that this method only requires a single gamma-ray emission, provides more detailed depth information, and offers a superior ability for characterizing complex depth distributions. Applications of this method for radionuclide contamination in soil and activated concrete in decommissioned nuclear reactors are being investigated. Collimated spectrometer measurements of buried area sources demonstrated the capability of the method to yield accurate depth information for both experimental and Monte Carlo calibrations. Based on the results of actual measurements, this method increases the potential of *in situ* gamma-ray spectrometry as an independent characterization tool in situations with unknown radionuclide depth distributions.

Self-Biased GaAs Diodes for Thermal Neutron Detection

Douglas S. McGregor, Holly K. Gersch, and David K. Wehe
Nuclear Engineering & Radiological Sciences

Stan Vernon
SPIRE Corporation

Thermal neutron detection devices based on ^{10}B-coated high-purity GaAs films are being investigated in a collaborative effort between the University of Michigan and Spire Corporation. The fundamental device consists of high-purity v-type epitaxial GaAs films grown onto n-type GaAs substrates. Two different blocking contact adaptations were applied to the high-purity v-type GaAs regions: 2000 Å thick *p*+ GaAs contacts and 200 Å thick Schottky blocking contacts.

The v-type GaAs active layers range between 1 μm and 5 μm in thickness. The device sensitive areas were 3mm x 3mm, each of which was coated with a 1.5 mm diameter film of 98% enriched high-purity ^{10}B. The built-in potential of the blocking contact interface is sufficient to operate the devices, and *no* external voltage bias is necessary to operate the detectors.

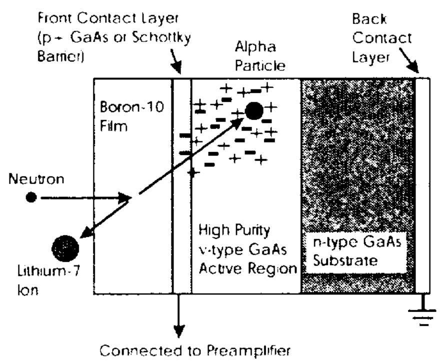


Fig. 1: The basic construction of a ^{10}B-coated self-biased high-purity epitaxial GaAs neutron detector. Neutrons interact in the ^{10}B film, thereby releasing an alpha particle and a ^{7}Li ion in opposite directions, one of which can enter the detector. The built-in potential at the p-v junction supplies enough voltage to operate the device.

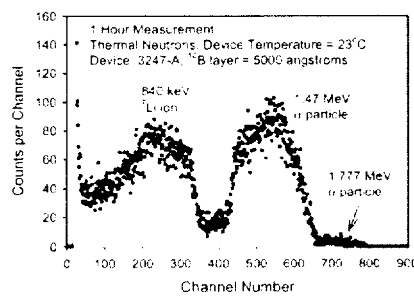


Fig. 2: Pulse height spectrum of thermal neutron reactions taken with a ^{10}B-coated self-biased GaAs detector. All major charged-particle reaction product energies are apparent. No voltage was applied to the device during the measurements.

Experimental measurements on intrinsic detection efficiency yield values between 1.6% and 2.6%. Theory shows that the efficiency can be tripled for a single device, and stacked devices can yield as high as 20% thermal neutron detection efficiency, all in a package that is only a few mm in thickness.

The self-biased detector design offers a straightforward method to produce low-cost, lightweight, compact and low-power neutron detectors for remote deployment. Future devices will have thicker ^{10}B films to increase neutron detection efficiency closer to the theoretical maximum.

Detectors from various sample sets are presently being irradiated with gamma rays, fast neutrons and thermal neutrons from the Ford Nuclear Reactor. The radiation hardness and the limiting radiation doses through which the different diode configurations may survive are under investigation.

Nuclear Chemistry

Prof. Henry C. Griffin heads a joint program linking FNR to UM's Department of Chemistry. Current research projects include a collaborative project with Prof. James Martin and research associate Chul Lee (School of Public Health), aimed at refining the use of radioactive materials to keep track of a hazardous industrial material used in the production of chlorine and sodium hydroxide (NaOH). Both chlorine and NaOH are among the top ten chemical products in terms of tonnage; both products can be made by electrolytic decomposition of NaCl solutions. The purest NaOH is made in cells in which one electrode is liquid mercury, and production plants utilizing this method might have a million pounds of the metal on site. The cells for electrolytic decomposition of NaCl solutions are complex, and the amount of mercury in a given cell can be difficult to determine. One solution is to add a small amount of radioactive "tracer" which mixes with all of the mercury in a cell, and serves as a reference by which the amount of mercury in the entire system can be monitored. Current research at PML concentrates on how to improve the accuracy of the technique. In particular, these researchers are analyzing the significance of how the radioactive material is added to the cells, when samples of mixed mercury are taken, and how the samples are counted.

Prof. Griffin also works with a group of undergraduate students as part of the Undergraduate Research Opportunities Program (UROP) to develop chemical procedures for isolating thorium (Th) from uranium (U). The first step in the decay of ^{238}U produces ^{234}Th; gram amounts of U produce nanogram amounts of Th, but the rate of decay of the two substances is the same. That rate can be determined by weighing the uranium, and if the chemical procedure is "quantitative" (i.e., all of the thorium is isolated), the rate of decay of the thorium will be known. This thorium sample becomes a standard for radioactivity that is available to anyone who has a balance for weighing and a known chemical form of uranium (e.g., uranium nitrate). This ^{234}Th is particularly useful as a standard for low energy radiations (gamma rays and X-rays) and can be used to determine how efficiently radiation detectors can detect low energy (5-100 keV) radiations.

Another important collaborator in the Nuclear Chemistry team has been Prof. Krish Rengan (***Department of Chemistry, Eastern Michigan University***). Prof. Rengan has conducted extensive ion-exchange studies, particularly on the chelating resins used in radiochemical separations and for pre-concentration of trace-elements prior to analysis. The properties of these resins are not well characterized, and the EMU Radiochemistry Laboratory has initiated a program to systematically study the property of these resins. Distribution co-efficients have been measured between aqueous solutions of several elements and the resins; the measurements are performed with radioactive tracers produced at FNR. Earlier work has been published as an article in *Radioanalytical and Nuclear Chemistry* in 1999.

In an on-going collaborative project, the UM and EMU Nuclear Chemistry teams are joining forces to generate a reference gamma spectrum for ^{49}Ca. Most radioactive materials can be recognized by their gamma-ray spectra, that is, the characteristic energies and intensities of the gamma rays emitted in their decay. These are nuclear "fingerprints". This project contributes to a standard reference book and CD of spectra (the *Heath Gamma-Ray Catalogue*), beginning with a high quality spectrum for the decay of ^{49}Ca. High quality entails not only using pure sources of ^{49}Ca, but counting for a sufficient period of time so that the spectrum is well-defined. Because ^{49}Ca disappears rather quickly (with a half-

life of 8.7 minutes), the pneumatic transport system of the Ford Nuclear Reactor is used to make a new sample every 10-20 minutes for several days. Students in the Undergraduate Research Opportunity Program (UROP) are important members of the team, operating the transfer system and the detectors using the extended counting.

In addition, during 1999 the necessary chemical separation procedures for obtaining the gamma-ray spectra of some strontium and yttrium nuclides produced in fission have been developed. The methods will be used in the coming months to obtain gamma-ray spectra of these nuclides for publication in *Heath Gamma-Ray Catalogue* as well.

Future collaborative research efforts will utilize the gas jet system installed in a beam port of FNR to characterize the nature of other volatile fission product species. Results from previous research in this area, performed over the last several years, were presented in three papers in *Nuclear Instruments and Methods in Physics Research*. Current plans include using the gas jet to obtain enriched samples of ^{91}Sr by sweeping fission krypton and allowing ^{92}Kr to decay in delay line before collection of ^{91}Kr and its decay products. At present one graduate student is finishing her thesis work in this area, and additional students (graduate or undergraduate) are expected to join this project during the coming year.

Nuclear Medicine

The nuclear medicine group comprises five staff members, under the overall direction of Prof. Donald M. Wieland of the Department of Internal Medicine. Research programs in nuclear medicine at the PML focus on the development of radiotracers for diagnostic imaging. Research efforts include the development of:

- mIBG, a radioiodinated analog of catecholamines for adrenal tumor imaging;
- adrenal scanning agent NP-59; and
- radiolabeled marker IBVM for the study of brain disorders such as Alzheimer and Parkinson disease.

In Nuclear Medicine imaging procedures, the *in vivo* localization of an administered radiolabeled compound (radio-pharmaceutical) is monitored externally by detection and measurement of the emitted gamma radiation using specialized cameras. Unlike competing modalities such as MRI and CT, Nuclear Medicine imaging provides functional information on *in vivo* biochemical and physiological processes.

Radiopharmaceuticals for diagnostic imaging are commonly labeled with either single photon emitting radioisotopes [e.g. ^{99m}Tc ($t_{1/2}$ = 6 h), ^{123}I ($t_{1/2}$ = 13.5 h)] or positron emitting radioisotopes [e.g. ^{11}C, ($t_{1/2}$ = 20 min), ^{18}F ($t_{1/2}$ = 110 min)]. The vast majority of clinical radiodiagnostic procedures utilize radiopharmaceuticals labeled with ^{99m}Tc.

Development of radiopharmaceuticals for studying the function of the cardiac sympathetic nervous system in health and disease is a major focus of PML's Nuclear Medicine laboratory studies. Sympathetic neurons synthesize and store norepinephrine, the endogenous neurotransmitter of the sympathetic nervous system. Animal studies have shown that tritium-labeled norepinephrine and related analogs are sequestered within sympathetic neurons upon intravenous administration. This sequestration occurs by a high affinity uptake process via a specific protein (the norepinephrine transporter). At PML, the approach has been to utilize synthetic analogs of norepinephrine that are high affinity substrates for this uptake process.

Thus, several structural analogs of norepinephrine were synthesized and radiolabeled with either ^{11}C or ^{18}F. Rat biodistribution and dog imaging studies were also conducted with these radiotracers to determine their localization in tissues displaying high sympathetic neuronal innervation such as the heart and spleen.

These studies led to the selection of ^{11}C labeled metahydroxyephedrine, [^{11}C]HED as an *in vivo* imaging agent for cardiac sympathetic neurons. Numerous positron emission tomography (PET) studies have been conducted with [^{11}C]HED at Michigan and several other institutions around the world. [^{11}C]HED has provided noninvasive assessment of the integrity of the cardiac sympathetic nervous system in the normal and transplanted human heart and in disease states such as acute myocardial infarction and diabetic neuropathy.

Another focus of the Nuclear Medicine research program concerns the development of radiotracers for the external imaging of tumor metastases in prostate cancer (PC). The appropriate treatment strategy for PC (surgical or hormonal therapy) critically depends on its accurate staging (presence or absence of tumor metastases). Current screening techniques for PC detection (including the prostate specific antigen test) fail to reliably distinguish clinically-localized disease from metastatic disease. A reliable imaging technique for the detection of PC metastases would therefore be of immense value to the clinician to determine the appropriate treatment plan and/or confirm or monitor disease progression.

Most prostate tumor cells express androgen receptor proteins in their cell nuclei. These receptor proteins specifically recognize and bind circulating steroidal androgens such as testosterone and dihydrotestosterone. Radiolabeled non-steroidal androgen analogs are being developed at PML for targeting prostate tumor cells for imaging. These radiotracers will be labeled with ^{11}C, ^{18}F, or ^{123}I and evaluated for their imaging potential in a mouse model of human prostate cancer.

Nuclear Medicine researchers at PML have also successfully developed a gamma-emitting radiotracer (5-[^{123}I]Iodobenzovesamicol, 5-IBVM) for imaging cholinergic neurons in the brain. Clinical trials with 5-IBVM are currently being conducted at the University of Michigan to assess its utility in imaging the extent of cholinergic neuronal impairment in patients with Alzheimer and Parkinson disease.

Differential IBVM binding in human brain tissue showing neural impairment in Parkinson disease patient.

Department of Environmental and Industrial Health (EIH)

EIH, in collaboration with Phoenix Memorial Laboratory, operates a low background gamma spectrometer at PML. The facility is intended primarily for quantifying gamma emitting isotopes in environmental samples. In an innovative study supported in part by a Phoenix Faculty grant, Dr. David Hamby and Dr. Srinantha Kannan (Department of Environmental Health Sciences, University of Michigan) are monitoring the biodistribution of minerals in plant-based food products using radioactive tracers. The FNR facility has enabled them to combine features of instrumental neutron activation analysis, biokinetic modeling of minerals, and food processing to develop and to test the feasibility of this novel application of the isotopic tracer technique. In a recently completed experiment, naturally occurring iron (^{58}Fe) in dried black beans was activated to create the radioactive tracer ^{59}Fe. Approximately 3 weeks following irradiation, the activated bean products were fed to animals (Sprague Dawley rats). In order to study absorption of the mineral, loss of mineral in the feces was monitored by counting the amount of ^{59}Fe in fecal samples using the PML low background gamma spectrometer. A control group of rats was fed the non-radioactive diet and rat tissues were activated to further trace the retention of the mineral in rat bones using INAA. Similar mineral biodistribution studies are planned for the year 2000. It is anticipated that results from these experiments and others can be used to set the micronutrient reference intakes and to improve the mineral status of individuals.

Museum of Anthropology Program in Archaeometry

An educational initiative linking PML and the Museum of Anthropology is the program in material science in archaeology, or archaeometry. PML research scientist Dr. Leah Minc, an archaeologist by training, has developed a course on INAA applications entitled *Neutron Activation Analysis in Archaeology*, offered through the Department of Anthropology. The course makes the technical field of INAA accessible to social scientists, and covers irradiation procedures, gamma-ray spectrometry, and quantitative analysis of compositional data. The MMPP also currently shares with the Museum of Anthropology the support for a graduate student research assistant, who works under the supervision of Dr. Minc, to extend the collaboration between the two units.

Research Support and Funding Programs

Utilization of MMPP facilities by researchers and educators is fostered and encouraged through a variety of research support services. In addition, research is supported directly through two granting programs. Phoenix Faculty grants support innovative research by University of Michigan faculty. Through the Department of Energy (DOE) Reactor Sharing Program, the Ford Nuclear Reactor and Phoenix Memorial Laboratory provide research opportunities, analytical services, and teaching facilities to other universities and institutions.

Research Support for UM

MMPP provides research support for the University of Michigan in the form of *pro bono* services: irradiation and analytical services provided a no cost to University faculty and students. Frequently utilized services include INAA, irradiations for Ar-Ar dating, radiotracer production, and irradiation damage studies. During the 1998-1999 academic year, more than $200,000 in *pro bono* services was provided to University faculty for research and teaching, and to graduate students for research leading to an advanced degree. An additional $280,000 of support was provided to researchers in the form of laboratory and office space.

In many cases, MMPP services serve as matching funds in securing outside funding. Over the past two years, grants and awards brought into the University by faculty and students whose research is significantly based on access to facilities and services at PML or FNR exceeded *4.8 million dollars* (see Table 10). For example:

- Researchers within the ***Department of Nuclear Engineering and Radiological Sciences*** were awarded 6 grants totaling over 2.7 million dollars for projects directly involving the Ford Nuclear Reactor and Phoenix Memorial Laboratory.

- The ***Department of Chemical Engineering*** obtained nearly 1.5 million dollars through 9 separate grants; research conducted at FNR is a critical component in each project.

- Over $500,000 was awarded to researchers in the ***Department of Geological Sciences*** for Ar-Ar dating studies that will be initiated at the FNR.

Table 10. Recent Grants to UM Departments for Research Utilizing PML/FNR

Anthropology		
A. Darling	*INAA of Obsidian: A Test using Old Data.*	$8,725 (pending)
S. Fowles	*Regional mobility and the development of segmentary structures: a case study from the prehistory of the Taos District, NM.*	$10,286
W. Griffin	*African Initiative Fellowship, Ph.D. dissertation research in Madagascar.*	$2,800
Anthropology Subtotal		$21,811
Geological Sciences		
C.M. Hall, S. Kesler	*Test of a Model for Formation and Preservation of an Ancient Late State Epithermal Precious Metal Deposit.*	$49,765/12 mo
C.M. Hall, B. Van de Pluijm	*Argon Dating of Near-Surface Faulting.*	$131,894/30 mo
R. Lange, C.M. Hall	*Quantification of the Erupitve Flux along the Western Mexican Volcanic Arc.*	$264,862 / 24 mo
C.M. Hall	*Applying Argon Dating of Fine-Grained Sediments as a Geochemical Tool for Marin Sediments.*	$74,602/24 mo
Geological Sciences Total		***$521,123***
Nuclear Engineering and Radiological Science		
R. Fleming, P. Simpson, and J. Lee	*Neutronic Analysis of the FNR Core for the Heavy Section Steel Irradiation Program.*	$34,000/20 mo
L. Wang, R. Ewing	*Radiation Effects on Materials in the Near-Field of a Nuclear Waste Repository.*	$408,000/36 mo
G. Knoll, D. Wehe	*Advanced Devices and Systems for Radiation Measurements.*	$900,000/12 mo
D. McGregor, J. Lindsay, J. Lee	*Non-Destructive Spent Fuel Characterization with Semiconducting Gallium Arsenide Neutron Imaging Arrays.*	$534,821/36 mo
D. Wehe, D. McGregor	*Room Temperature Semiconductors for Radiation Spectroscopy.*	Argonne Nat'l. Lab support
D. Wehe	*Robotic Systems for Hazardous Environments.*	$900,000/12 mo
Nuclear Engineering and Radiological Sciences Subtotal		***$2,776,821***

Table 10. Recent Grants for Research Utilizing PML/FNR (cont.)

Chemistry		
H. Griffin	*Gamma-ray Spectroscopy of Chemically Isolated Radionuclides.*	$41,745/9 mo
	Precision Isotope Dilution Analysis	$19,000/12 mo
Chemistry Subtotal		$60,745
Chemical Engineering		
R. Yang, et al.	*New Sorbents for Gas Separation by pi-Complexation (National Science Foundation, CTS-9520328)*	$204,506/36 mo
	New Sorbents for Gas Separation by p-Complexation, National Science Foundation, supplement to CTS-9520328 for Impact of Research.	$25,000/12 mo
	Pillared Clays as Superior Catalysts for Selective Catalytic Reduction of NO by Hydrocarbons, U.S. Department of Energy.	$199,992/36 mo
	Separations Using Chemical Complexation Adsorbents, Chevron Research & Technology Company, Richmond, CA.	$240,000/36 mo
	New Adsorbents Development for Olefin- Paraffin Separations, UOP, Des Plaines, IL.	$50,000/18 mo
	High-Activity Pillared Clay Catalysts for NO Reduction by Ammonia, Electric Power Research Institute, Palo Alto, CA.	$265,939/24 mo
	Support for Sorbent Studies, NGK Insulators, LTD, Nagoya, Japan.	$40,000/18 mo
	New Sorbents for Separations and Purifications by Weak Chemical Bonds, National Science Foundation, CTS-9819008.	$200,000/36 mo
	Air Separation by Pressure Swing Adsorption Using Superior Sorbents, U.S. Department of Energy, DE-FG26-98FT40115.	$200,000/36 mo
Chemistry and Chemical Engineering Subtotal		$1,467,182
TOTAL		**$4,847,682**

Phoenix Grants for UM Faculty Research

Phoenix grants support faculty research involving the peaceful applications and the social implications of nuclear science and technology. Requests for $10,000 or less are considered appropriate for research in the fields of Biological and Health Sciences, Physical Sciences and Engineering, Social Sciences and Education, and Humanities and Arts.

Priority for awards are given to projects in which the applicants demonstrate a direct relevance of the research to peaceful uses of nuclear science and technology; special consideration is given to proposals for innovative (high risk) research. Among equally rated proposals, preference for awards will go to (1) new faculty, particularly to those who need funding in order to seek research support from outside agencies, and (2) established faculty who need assistance in opening a new area of research. Consideration may be given to multi-year proposals that are directly related to the development and enhancement of Phoenix programs.

To be eligible, the applicant must be a member of the University's regular teaching and/or research faculty (including Assistant, Associate, and Full Professors and Research Scientists; Librarians; Curators; and Archivists). All applications are referred for evaluation to a Rackham Divisional Review Board which submits recommendations to the Faculty Executive Committee of the Phoenix Project for final decision. The budget period is for one year. A list of awards made during the 1998-1999 academic year follows (Table 11).

Table 11. Phoenix Faculty Research Grants Awarded 1998-1999

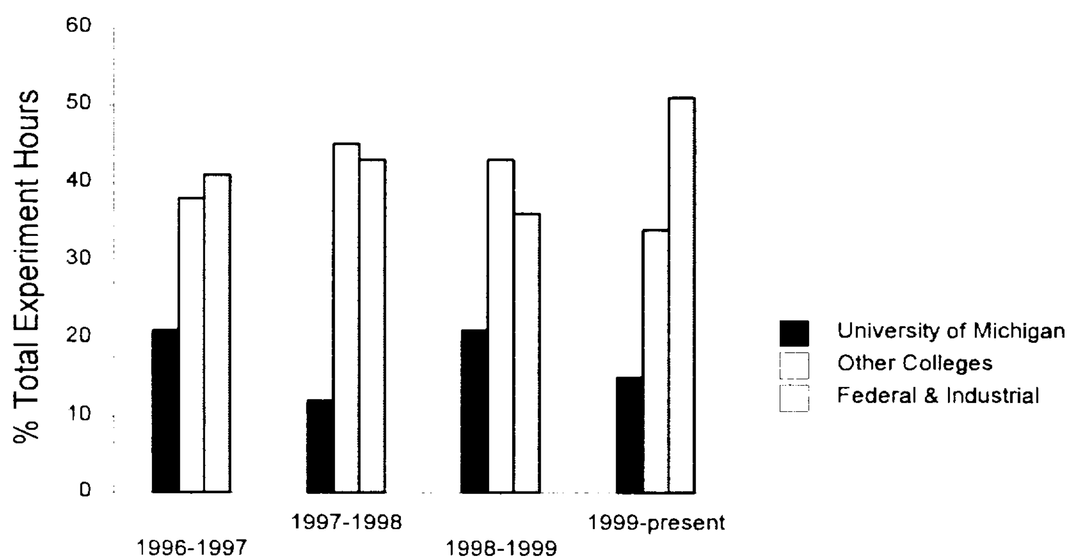
Director & Department	Project Title
Kenneth Cadigan Biology	*Analysis of Tissue-Specific Intercellular Signaling in Drosophila*
David M. Hamby Environmental & Industrial Health	*Neutron Activation Analysis to Trace the Fate of Iron in Processed Foods: A Feasibility Study*
Jesse C. Hay Biology	*Protein Interactions Controlling ER to Golgi Vesicle Transport*
Marci M. Lesperance Otolaryngology (Head & Neck Surgery)	*Mapping a Gene Responsible for Dominant Nonsyndromic Hearing Impairment*
Jianming Li Biology	*Identification of Novel Components of the Brassinosteroid Signaling Pathway*

D.O.E. Reactor Sharing Program

MMPP serves a diversity of colleges and universities other than the University of Michigan. Over the past four years, in excess of 35% of total reactor experiment hours have been devoted to research and teaching activities for other colleges and universities.

Services to other colleges and universities are made possible through the U.S. Department of Energy Reactor Sharing Program which exists to improve the accessibility of university research reactor facilities to non-reactor-owning colleges and other academic institutions. Under this program, FNR provides free or low cost irradiations to other (non-UM) academic users, in exchange for financial support from DOE. During the current granting period (September, 1998 to September, 1999), DOE provided $50,000; this amount has been increased to $67,000 for the granting period August, 1999 to August, 2000.

Projects supported by the Reactor Sharing Program involve researchers from numerous universities utilizing the INAA and Ar-Ar program facilities. Most projects involve research in the fields of geology and archaeology (Table 12).



Irradiation services provided to other colleges and universities under the DOE Reactor Sharing Program typically account for more than 35% of total FNR experiment hours.

Table 12. Research Projects Supported by DOE Reactor Sharing Program, 1998-1999

INAA Studies in Archaeology	
Dr. Clarence Menninga, Calvin College	Characterization of ancient pottery from Abila excavation, Jordan.
Prof. Michael Smith, SUNY - Albany	Sourcing Aztec-period ceramics from Morelos, Mexico, based on their geochemical signature, to examine ceramic production and exchange systems.
Amy Horseman and Prof. Helen Pollard, Michigan State University	Characterize trace-element composition of clays and polychrome ceramics from Tarascan archaeological sites, Mexico.
INAA Studies in Geology	
Tim Johnson & Prof. Edward Ripley Indiana University	Trace elements analysis to identify processes responsible for hydrothermal beryllium mineralization at Spor Mountain, Utah.
Dr. Michael Dorais, Indiana University	Determination of the tectonic setting of magmas of Massabesic Gneiss Complex, NH, from metaigneous rock samples.
Dr. Erika Elswick Indiana University	Rare earth element quantification of various igneous rock samples to check the calibration of the Lab's ICP set-up.
Terry Church & Prof. David Budd, University of Colorado	Assessment of palaeo-oceanic events that may have led to the demise of coral-stromatoporoid fauna at the end of the Frasnian (Late Devonian) based on geochemical analyses of limestone samples from SE Nevada.
Dr. Vernon RussellClark Univ. of Cal., San Diego	Investigate materials of possible extra-terrestrial origin, based on the relative abundance of silicon isotopes.
INAA Studies in Nuclear Chemistry	
Prof. Krish Rengan Eastern Michigan Univ.	Irradiation of pure sources of ^{49}Ca to generate a reference gamma spectrum for inclusion in the *Heath Gamma-Ray Catalogue*.
Prof. Ellene Contis, Eastern Michigan Univ.	Irradiations for analytical chemistry classes, including an introduction to neutron activation analysis and gamma spectrometry.

Table 12. Research Projects Supported by DOE Reactor Sharing Program (cont.)

Ar-Ar Dating for Geochronology	
Lehigh University	Studies of tectonic evolution of mountain belts, both active and ancient, in the Himalayas and Appalachians; evolution of Andean and Central American subduction systems.
New Mexico Institute of Mining & Technology	Investigations of volcanism and mineralization in the western U.S.A., Central and South America, and Antarctica.
New Zealand Institute of Geo. & Nuclear Sciences	Geological dating programs relating to the orogenic, tectonic, and volcanic histories in various geological terraines of New Zealand and the southwest Pacific region.
Ohio State University	Geothermal histories for the Adirondack Mountains of New York, the Black Hills of North Dakota, North Atlantic sea-bed cores, SE Asia, and Argentina.
Universite Blaise Pascal	Analysis of the driving mechanisms of mountain building through thermochronology; the dating of volcanism, especially young volcanism in various geodynamical settings; and monitoring and modeling argon loss to assess the physical background of argon diffusion in glass and silicates.
University of Arizona	Noble gas analysis of irradiated rocks and minerals to provide ages and geothermal histories.
University of California, Los Angeles	Analysis of irradiated rocks and minerals to provide ages and geothermal histories.
University of Houston	Studies into the thermal and tectonic history of samples from Nepal, China, Korea, Bolivia, Argentina, Grenada, and the U.S.
University of Manchester	Investigations into: the geochemistry of halogens in the Earth's mantle; chronology of diamonds; age of mare volcanism on the moon; geochronology of martian meteorites; and ancient mineralizing fluid systems.

Teaching and Training Activities at MMPP

University Labs and Lectures

The Phoenix Memorial Laboratory provides facilities for courses that are conducted by faculty members from the University of Michigan (Table 13). In addition, a number of classes and labs are taught by laboratory staff members for the benefit of students from other colleges and universities and high schools. Overall, 200 college students attended classes at the FNR, while more than 500 high school students participated in short-courses and labs during the past academic year (Table 14).

The ***Nuclear Engineering and Radiological Sciences Department*** (NERS) uses the laboratory and reactor for a number of formal University courses, and conducts extensive, on-going research projects in the areas of neutron spectroscopy, radiation effects in materials, and cross section measurements.

Within the NERS department, the Nuclear Reactor Laboratory (NERS 445) often serves as one of the senior year Capstone courses, allowing the student an opportunity to integrate the understanding gained in previous courses. The use of an actual research reactor - the FNR - presents the students with a direct comparison of experimental results with the analytical and computational models they have been taught.

The class investigates several aspects of reactor engineering and physics, challenging the assumptions of the theory with careful measurement. The determination of the reactor thermal power in the megawatt range uses the thermal-hydraulic characteristics of the system as a simple calorimeter. The relationship between the reactivity of the system and its time-dependence is investigated in two experiments addressing FNR steady-state behavior, as well as the response to both positive and negative reactivity insertion. The non-fission neutron source provided by the heavy water tank on the north face of the FNR makes this study much more valuable. The use of radio-activation and gamma spectrometry to gain insight into both the spatial and the energy dependence of the neutron flux in the reactor. A simple gold foil activation provides experience in the measurement of the intensity and dose of a neutron beam. The irradiation of an iron wire extending vertically through a fuel element provides an axial flux distribution used to access the space-dependent aspects of the reactor behavior.

The overall insight into the FNR as a reactor is best gained through two comprehensive measurements which exploit the entire system: the critical loading experiment and the investigation of the ^{135}Xe reactivity transient after shutdown from full power. The loading to critical duplicates the first measurement on any reactor, and for many of our students is their only opportunity to have this experience. The xenon measurement is a 24-hour measurement of the vital signs of the FNR following shutdown, and is designed to provide the student with insight into the space and time variation of a complicated system.

The Nuclear Reactor Laboratory course has been taught since the reactor was built and has evolved with the FNR and the NERS department. The FNR provides an ideal teaching tool for this purpose.

In addition to serving as the focal point for NERS courses, FNR facilities and staff

provide opportunities for students from other departments and from other colleges to gain first-hand experience with topics such as nuclear chemistry, instrumental neutron activation analysis, and reactor operations.

The University of Michigan's ***Department of Chemistry*** utilizes the facilities at FNR for upper-level undergraduate courses in nuclear chemistry taught by Prof. Henry C. Griffin. Students in Dr. Griffin's submit samples containing a variety of elements for irradiation. The students perform their own subsequent analysis. Dr. Griffin has also been actively involved in the UROP program, introducing undergraduate students both to the Reactor and the rigors of nuclear chemistry research.

In the ***Department of Geological Sciences***, Geology 455 introduces students to neutron activation analysis and gamma-ray spectrometry. The ***Department of Anthropology*** now offers a course (Antho. 589) on the use of neutron activation analysis in the analysis of archaeological materials, including ancient pottery, stone tools, and objects of metal.

Students from outside the University of Michigan benefit from the Ford Nuclear Reactor, as well. Prof. James Johnson (***Dept. of Physics & Astronomy, Wayne State University***) incorporates a visit to the Ford Nuclear Reactor into his summer course on Modern Physics. The course is offered each year as part of the Summer Science Institute, a program which provides condensed science courses for middle school, high school, and community college teachers. This year, 30 teachers participated in a tour of the Reactor. In addition, samples were irradiated for use in a half-life experiment. In the future, the FNR will also become a regular feature of the new Modern Physics Laboratory course for undergraduate Physics majors.

At ***Eastern Michigan University***, the FNR and PML facilities were used for teaching a number of analytical chemistry classes (Chem. 381 and Chem. 481); this past year, nearly fifty students were introduced to neutron activation analysis (INAA). The use of Ford Reactor facility for these classes will continue. Four faculty members are involved in teaching these classes. In addition, a new course, *Introduction to Radiotracer Techniques* (Chem. 485), will be offered winter term, 2000. The course will use FNR for production of short-lived tracers as well as for NAA experiments.

A similar short-course on neutron activation analysis is presented annually to local high school senior chemistry classes. Participating high schools include the International Academy in Bloomfield Hills, Michigan, and Carroll High School, Ft. Wayne, Indiana.

Public Outreach Education

As part of MMPP's outreach and public education program, tours of the Nuclear Reactor Laboratory were provided to school children, university students, and the public at large. During the past year, over 1250 visitors viewed the facility as part of 77 public tours. These groups visit the Cobalt Irradiator Facility for an introduction to the importance of gamma irradiation in the sterilization of tissue transplants, and the Ford Nuclear Reactor, where reactor operations, nuclear power, and peaceful research applications of nuclear science are discussed.

Table 13. University of Michigan Courses Utilizing PML/FNR

Anthropology 589: Neutron Activation Analysis in Archaeology. Offered in cooperation with the University's Ford Nuclear Reactor, this course provides students with the fundamental principles and methods of neutron activation analysis (NAA), along with hands-on experience in utilizing NAA to determine the trace-element composition of archaeological materials. Irradiation procedures, gamma-ray spectrometry of trace-elements, quantitative analysis of NAA data, and the archaeological use and interpretation of NAA results are covered.

Geology 455: Determinative Methods in Mineralogical and Inorganic Materials. Introduction to the principal quantitative methods of characterizing the chemistry and structure of inorganic phases, including X-ray diffraction, XRF, microprobe, SEM, wet chemical, optical, resonance, and Mossbauer spectroscopy. Laboratory provides student with practical experience with principles covered in lectures. Designed for geologists, chemists, physicists, metallurgists, and materials scientists.

Chemistry 399: Undergraduate Research in Chemistry. Research procedures and applications in the area of Nuclear Chemistry.

Chemistry 480: Physical and Instrumental Chemistry. A laboratory exploration of methods for the measurement of physical and spectroscopic properties of substances and the application of these methods in instrumental analysis.

NERS 211: Introduction to Nuclear Engineering and Radiological Sciences. This course will discuss different forms of energy, the history of nuclear energy, the fundamentals of fission and fusion nuclear power, radiological health applications, and electromagnetic radiation in the environment. Current topics in the media such as radon, radioactive waste, and nuclear proliferation will also be covered.

NERS 311: Elements of Nuclear Engineering and Radiological Sciences I. Photons, electrons, neutrons, and protons. Particle and wave properties of radiation. Introduction to quantum mechanics and special relativity. Properties and structure of atoms and nuclei. Introduction to interactions of radiation with matter.

NERS 312: Elements of Nuclear Engineering and Radiological Sciences II. Production and use of nuclear radiation. Alpha-, beta- and gamma-decay of nuclei. Neutrons. Nuclear reactions. Elementary radiation interactions and transport.

NERS 315: Nuclear Instrumentation Lab. An introduction to the devices and techniques most common in nuclear measurements. Topics include the principles of operation of gas-filled, solid state, and scintillation detectors for charged particle, gamma ray, and neutron radiations. Techniques of pulse shaping, counting, and analysis by radiation spectroscopy. Timing and coincidence measurements.

NERS 400: Elements of Nuclear Energy. Ideas and concepts important to the development of nuclear energy for peaceful purposes -- intended for those in fields other than nuclear engineering. History of the nuclear energy program, elementary nuclear physics, fission and fusion reactors, radiological health physics, and nuclear medicine.

Table 13. University of Michigan Courses Utilizing PML/FNR (cont.)

NERS 441: Introduction to Nuclear Fission Reactors. An introduction to the theory of nuclear fission reactors including such topics as neutron diffusion, the one-speed theory of nuclear reactors, reactor kinetics, multigroup diffusion theory and criticality calculations, and neutron slowing down and thermalization.

NERS 442: Nuclear Power Reactors. Analysis of nuclear fission power systems including an introduction to nuclear reactor design, reactivity control, steady-state thermal-hydraulics and reactivity feedback, fuel cycle analysis and fuel management, environmental impact and plant siting, and transient analysis of nuclear systems. A semester-long design project of the student's choice.

NERS 445: Nuclear Reactor Laboratory. Measurements of nuclear reactor performance, activation methods, rod worth, critical loading, power and flux distributions, void and temperature coefficients of reactivity, xenon transient, diffusion length, pulsed neutrons.

NERS 462: Reactor Safety Analysis. Analysis of those design and operational features of nuclear reactor systems that are relevant to safety. Reactor containment, engineered safety features, transient behavior and accident analysis for representative reactor types; NRC regulations and procedures; typical reactor safety analyses.

NERS 543: Nuclear Reactor Theory II. A continuation of NERS 441 including neutron resonance absorption and variational methods, flux synthesis. Analytic and numerical solutions of the neutron transport equation including the S_n and B_n methods, collision probabilities and Monte Carlo methods.

NERS 551: Nuclear Reactor Kinetics. Derivation and solution of point reactor kinetics equations. Concept or reactivity, inhour equations and reactor transfer function. Linear stability analysis of reactors. Reactivity feedback and nonlinear kinetics. Space-dependent reactor kinetics and xenon oscillations. Introduction to reactor noise analysis.

NERS 590: Special Topics in Nuclear Engineering. Selected advanced topics such as neutron and reactor physics, reactor core design, and reactor engineering. The subject matter varies by term.

NERS 599: Master's Project. Individual or group investigations in a particular field or on a problem of special interest to the student. The course content will be arranged at the beginning of each term by mutual agreement between the student and a staff member. This course may be repeated for up to 6 credit hours.

University Course 280: Undergraduate Research (UROP). At FNR, research opportunities are provided for undergraduates in the areas of nuclear chemistry, radioisotopic tracers, and neutron activation analysis.

Table 14. Teaching and Research Utilization of FNR Facilities and Staff (1998-1999 Academic Year)

Institution/Department	Faculty & Staff Users	Student Users	Degrees Supported 1998-1999			Reactor Service Provided
			BS	MS	Ph.D.	
University of Michigan						
Anthropology	5	5	0	0	5	NAA
Classical Art & Arch.	2	0	0	0	0	NAA
Chemical Engineering	2	4	0	0	4	NAA
Chemistry[1]	2	11	3	0	0	NAA, Neutron Irradiation
Dentistry	1	1	0	0	0	NAA
Geological Sciences	13	11	2	5	3	Ar/Ar Dating
Environ. & Indust. Health[1]	4	2	0	0	2	NAA
History of Art	0	1	0	0	1	NAA
Mechanical Engineering	0	2	0	0	0	System Design
Nuclear Engineering & Radiological Sciences	9	73	33	16	24	Neutron Irradiation, NAA, Detector Testing
Physics	1	1	0	0	1	Beam Port
Zoology	1	8	0	0	0	Radioisotope Production
UM Total	***40***	***119***	***38***	***21***	***40***	
Other Colleges, Universities, and Academic Institutions						
Univ. of Arizona/ Geological Sciences	2	2	0	1	0	Ar/Ar Dating
U. of Cal., Sta. Barbara/ Mech. & Environ. Engin.	8	1	0	0	1	Materials Damage, Neutron Irradiation
U. of Cal., San Diego/ Chemistry	2	0	0	0	0	NAA
U. of Cal.- Los Angeles/ Geological Sciences	2	8	0	0	8	Ar/Ar Dating
Calvin College/ Geology	1	0	0	0	0	NAA
Univ. of Colorado/ Geological Sciences	1	1	1	0	0	NAA
E. Michigan University/ Chemistry	2	33	0	0	0	Beam Port, NAA, Radioisotope Production
University of Houston/ Geosciences	2	14	0	0	14	Ar/Ar Dating
Indiana University/ Geological Sciences	3	2	0	1	1	NAA
Inst. Geol. & Nuc. Sci./ New Zealand	18 (6)[2]	4	0	0	4	Ar/Ar Dating
Lehigh University/ Earth, Environ. Sciences	22	10	2	4	4	Ar/Ar Dating

Table 14. Teaching and Research Utilization of FNR (cont.)

Institution/Department	Faculty & Staff Users	Student Users	Degrees Supported 1998-1999			Reactor Service Provided
			BS	MS	Ph.D.	
Other Colleges, Universities, and Academic Institutions (cont.)						
Univ. of Manchester/ Geochemistry	8	4	0	0	1	Ar/Ar Dating
Michigan State Univ./ Anthropology	1	1	0	0	1	NAA
NM Institute of Mining & Technology	1 (24)[2]	18	0	10	4	Ar/Ar Dating
Ohio State University/ Geoscience	4 (8)[2]	2	0	0	2	Ar/Ar Dating
SUNY - Albany/ Anthropology	2	1	0	0	1	NAA
Blaise Pascal/ Earth Science	2	2	0	0	2	Ar/Ar Dating
Wayne State Univ./ Physics	1	0	0	0	0	Radioisotope Production
Other Colleges Total	***120***	***103***	***3***	***16***	***43***	
Government and Industry						
Brooks & Perkins	1	0	0	0	0	Beam Port
Dept. of Comm., GREL	2	0	0	0	0	Radioisotope Production
General Motors Corp.	8	0	0	0	0	Radioisotope Production
ICI Tracerco	6	0	0	0	0	Radioisotope Production, Neutron Irradiation
Natural Systems Inc.	2	0	0	0	0	NAA
NSF Int'l.	2	0	0	0	0	NAA
Nucl. Reg. Comm.	2	0	0	0	0	Material Damage
Pacific Gas & Electric	1	1				Neutron Radiography
Oak Ridge Natl. Lab.	14	0	0	0	0	Materials Damage, Neutron Irradiation
Tru-Tech	3	0	0	0	0	Radioisotope Production, Neutron Irradiation
Gov. and Industry Total	***41***	***1***	***0***	***0***	***0***	
Total	**201**	**223**	**41**	**37**	**83**	

[1]Includes UROP students involved in research sponsored by department.

[2]Numbers in parentheses indicate collaborators from other universities.

Researchers and Students Utilizing PML/FNR, 1998-1999[1]

UM Researchers (Faculty and Staff)

Smith, Adam	Anthropology
Grassi, Heinze	Atmospheric & Oceanic Science/Space Physics Research Lab
Killeen, Tim	Atmospheric & Oceanic Science/Space Physics Research Lab
Helling, Robert	Biology
Nichols, Ruthann	Biology
Mooney, David	Chemical Engineering
Thompson, Levi	Chemical Engineering
Yang, Ralph	Chemical Engineering
Gordus, Adon	Chemistry
Griffin, Henry	Chemistry
Weber, Walter	Civil and Environmental Engineering
Hamby, David	Environmental Health Sciences
Kannan, Srinantha	Environmental Health Sciences
Lee, Chul	Environmental Health Sciences
Martin, James	Environmental Health Sciences
Essene, Eric	Geological Sciences
Hall, Chris	Geological Sciences
Johnson, Marcus	Geological Sciences
Lange, Rebecca	Geological Sciences
Kessler, Steve	Geological Sciences
Rea, David	Geological Sciences
Van der Pluijm, Ben	Geological Sciences
Block, Bruce	High Energy Physics
Wadia, Neville	High Energy Physics
Cieslinski, Deborah	Internal Medicine
Humes, David	Internal Medicine
Van Dort, Marcian	Internal Medicine
Jung, Yong-Woon	Internal Medicine
Wieland, Donald	Internal Medicine
Herbert, Sharon	Kelsey Museum of Classical Art and Archaeology
Ford, Richard	Museum of Anthropology
Minc, Leah	Museum of Anthropology
O'Shea, John	Museum of Anthropology
Wright, Henry	Museum of Anthropology
Brake, Mary	Nuclear Engineering & Radiological Sciences
Ewing, Rod	Nuclear Engineering & Radiological Sciences
Fleming, Ronald	Nuclear Engineering & Radiological Sciences
He, Zhong	Nuclear Engineering & Radiological Sciences
Kearfott, Kimberly	Nuclear Engineering & Radiological Sciences
Kerr, William	Nuclear Engineering & Radiological Sciences
Knoll, Glenn	Nuclear Engineering & Radiological Sciences
Lee, John C.	Nuclear Engineering & Radiological Sciences
McGregor, Doug	Nuclear Engineering & Radiological Sciences
Wang, Lumin	Nuclear Engineering & Radiological Sciences
Wehe, David	Nuclear Engineering & Radiological Sciences
Wang, Shixin	Nuclear Engineering & Radiological Sciences (Research Fellow)
Wilderman, Scott	Nuclear Engineering & Radiological Sciences (Research Fellow)
Yi, Yongsung	Nuclear Engineering & Radiological Sciences (Research Fellow)
Goldstein, Steve	Orthopedic Surgery
Gustafson, Dick	Physics
Roe, Byron	Physics
O'Brien, William	School of Dentistry
Rutherford, Bruce	School of Dentistry
Krebsbach, Paul	School of Dentistry

[1]Includes individuals authorized to use FNR/PML facilities for research, teaching labs, and experiments, and researchers submitting materials for irradiation and/or analysis.

Researchers from Other Universities

Srinivasan, V.S.	Bowling Green St. University	Chemistry
Menninga, Clarence	Calvin College	Geology
Contis, Ellene T.	Eastern Michigan University	Chemistry
Rengan, Krish	Eastern Michigan University	Chemistry
Brophy, James	Indiana University	Geological Sciences
Dorais, Michael	Indiana University	Geological Sciences
Elswick, Erika	Indiana University	Geological Sciences
Ripley, Edward	Indiana University	Geological Sciences
Adams, Christopher	Inst. of Geol. & Nuclear Sci. Ltd.	Nuclear Science
Zeitler, Peter K.	Lehigh University	Earth Sciences
Idleman, Bruce	Lehigh University	Earth Sciences
Pollard, Helen	Michigan State University	Anthropology
Voice, Thomas	Michigan State University	Civil & Environ. Engineering
Heizler, Matt	New Mexico Inst. Mining & Tech.	Geosciences
Condie, K.	New Mexico Inst. Mining & Tech.	Geosciences
Kelley, S.	New Mexico Inst. Mining & Tech.	Geosciences
Wapnir, Raul	North Shore University Hospital	Pediatrics
Elliot, David	Ohio State University	Geological Sciences
Fleming, Thomas	Ohio State University	Geological Sciences
Foland, Ken	Ohio State University	Geological Sciences
Hubacker, Fritz	Ohio State University	Geological Sciences
Kelley, Simon	Open University	Earth Sciences
Kobayaski, H.	Rikyo University, Japan	Nuclear Sciences
Metzger, Ellen	San Jose State Univ.	Geology
Smith, Michael	SUNY Albany	Anthropology
Baldwin, Suzanne	University of Arizona	Geosciences
Swindle, Timothy	University of Arizona	Geosciences
Zreda, Marek	University of Arizona	Geosciences
Arnaud, Nicolas	Université Blaise Pascal	Centre Geochemique Ar-Ar
Montigy, Raymond	Université Blaise Pascal	Centre Geochemique Ar-Ar
Chow, Alex	University of California-Davis	Land, Air, &Water Resources
Venterea, Rod	University of California-Davis	Land, Air, &Water Resources
Wartho, Jo-Anne	Univ. of California, Los Angeles	Geology
Klingsmith, Doug	Univ. of Calif., Santa Barbara	Mech. & Environ. Engin.
Lucas, Glenn E.	Univ. of Calif., Santa Barbara	Mech. & Environ. Engin.
Odette, G. Robert	Univ. of Calif., Santa Barbara	Mech. & Environ. Engin.
Vernon-Clark, Russell	Univ. of Calif., San Diego	Chemistry and Biochemistry
Feder, Seth	University of Cincinnati	Biomechanics
Budd, David	University of Colorado, Boulder	Geological Sciences
Copeland, Peter	University of Houston	Geosciences
Burgess, Ray	University of Manchester	Earth Sciences
Turner, Grenville	University of Manchester	Earth Sciences
Johnson, James	Wayne State University	Physics and Astronomy

Researchers from Other Institutions

Schmidts, Ross	AAR Advanced Structures	
Palsson, Bernard	Aastrom Biosciences	
Heidmous, Matthew	Aastrom Biosciences	
Islam, Nurul	Bangladesh Inst. of Nucl. Sci. & Tech.	
Hawes, Kevin	Dow Corning Corp.	
Steklenski, David	Eastman Kodak Company	Diagnostic Imaging
Gooden, John	Ford Motor Co.	
Rosenburg, Stan	Ford Motor Co.	
Waterbury, Ed	Ford Motor Co.	
Yusuf, Siaka O.	Gamma Metrics, Inc.	
Blossfeld, Doug	General Motors Co.	R&D and NAO Planning
Lechman, D. C.	General Motors Co.	
Schneider, Eric	General Motors Co.	
Robbins, John	Great Lakes Environmental Research Lab	
Landrum, Peter	Great Lakes Environmental Research Lab	
Matsubayaski, M.	Japan Atomic Energy Research Institute	
Albert, Fred	Montana Biotech Corporation	Microbiology
Combie, Joan	Montana Biotech	
Nachtman, Tom	New Waste Concepts	
Forsell, James	Northern California Transplant Bank	
Brown, Allen	Northern California Transplant Bank	
Rosseel, Thomas	Oak Ridge National Laboratory	HSSI
Baldwin, C.A.	Oak Ridge National Laboratory	HSSI
Corwin, W. R.	Oak Ridge National Laboratory	HSSI
Heatherly, D.W.	Oak Ridge National Laboratory	HSSI
Iskander, S.K.	Oak Ridge National Laboratory	HSSI
McCabe, D.E.	Oak Ridge National Laboratory	HSSI
Miller, M.K.	Oak Ridge National Laboratory	HSSI
Nanstad, R.K.	Oak Ridge National Laboratory	HSSI
Remec, I.	Oak Ridge National Laboratory	HSSI
Sokolov, M.S.	Oak Ridge National Laboratory	HSSI
Stoller, R.E.	Oak Ridge National Laboratory	HSSI
Thoms, K.R.	Oak Ridge National Laboratory	HSSI
Igarashi, Brian	NIST	Materials Reliability Div.
Parker, Randy	Pacific Gas and Electric	
Sinclair, Art	Pall Gelman Sciences	
Kyle, Jeff	Pall Gelman Sciences	Medical Filtration
LaCoe, Scott	Pall Gelman Sciences	Medical Filtration
Mahaffey, William	Pelorus Enbiotech Corp.	
Nyberg, Russ	Raven Biological Laboratories	
Carroll, Pat	St. Luke's Hospital	
Kotowicz, Ellie	St. Luke's Hospital	
Hillegas, William	SoloHill Engineering, Inc.	
Sklapsky, Brian	Sparrow Hospital	
Publiesi, Reyanldo	Supervisao de Fisica Nuclear, Brazil	
Curling, Simon	USDA Forest Products Lab	

UM Students

Paisley, Keri	Biology
Bennett, Chris	Chemical Engineering
Hutson, Nick	Chemical Engineering
Long, Richard	Chemical Engineering
Neylon, Michael	Chemical Engineering
Selis, Hildegard	Civil and Environmental Engineering
Orlov, Alex	Civil and Environmental Engineering
Harris, John	Geological Sciences
Fortuna, John	Geological Sciences
Simon, Gregory	Geological Sciences
Tohver, Eric	Geological Sciences
Boven, Karen	Geological Sciences
Streepey, Margaret	Geological Sciences
Dong, Hailiang	Geological Sciences
Barfod, Dan	Geological Sciences
Ambrose, Kirk	History of Art
Paraventi, Denise	Material Science and Engineering
Eiselt, Sunday	Museum of Anthropology
Griffin, William	Museum of Anthropology
Gulick, Jennifer	Museum of Anthropology
Michelaki, Kostalena	Museum of Anthropology
Rupley, Eric	Museum of Anthropology
Alexandreanu, Bogdan	Nuclear Engineering & Radiological Sciences
Barrett, Carla	Nuclear Engineering & Radiological Sciences
Benke, Roland	Nuclear Engineering & Radiological Sciences
Bialik, Shawn	Nuclear Engineering & Radiological Sciences
Branch, Clair	Nuclear Engineering & Radiological Sciences
Brink, Jeffrey	Nuclear Engineering & Radiological Sciences
Brock, Kristy	Nuclear Engineering & Radiological Sciences
Busby, Jeremy	Nuclear Engineering & Radiological Sciences
Capell, Brent	Nuclear Engineering & Radiological Sciences
Chen, Chen	Nuclear Engineering & Radiological Sciences
Clarke, Geoffrey	Nuclear Engineering & Radiological Sciences
Daniels, Matthew	Nuclear Engineering & Radiological Sciences
Du, Yanfeng	Nuclear Engineering & Radiological Sciences
Gan, Jian	Nuclear Engineering & Radiological Sciences
Grambau, Benjamin	Nuclear Engineering & Radiological Sciences
Gu, Binxi	Nuclear Engineering & Radiological Sciences
Hammig, Mark	Nuclear Engineering & Radiological Sciences
Keyser, Marc	Nuclear Engineering & Radiological Sciences
Kim, Sung Hyun	Nuclear Engineering & Radiological Sciences
LeBlanc, James	Nuclear Engineering & Radiological Sciences
Li, Wen	Nuclear Engineering & Radiological Sciences
Lian, Jie	Nuclear Engineering & Radiological Sciences
Marcinkowski, Karin	Nuclear Engineering & Radiological Sciences
McAnallen, Julia	Nuclear Engineering & Radiological Sciences
Park, Jiyoung	Nuclear Engineering & Radiological Sciences
Patrick, Daniels	Nuclear Engineering & Radiological Sciences
Phillips, Michael	Nuclear Engineering & Radiological Sciences

Porter, Mark	Nuclear Engineering & Radiological Sciences
Reddy, Nishan	Nuclear Engineering & Radiological Sciences
Robinson, Duncan	Nuclear Engineering & Radiological Sciences
Seifert, Allen	Nuclear Engineering & Radiological Sciences
Selvaganapathy, P.	Nuclear Engineering & Radiological Sciences
Skrabis, Peter	Nuclear Engineering & Radiological Sciences
Smith, Leon Eric	Nuclear Engineering & Radiological Sciences
Tian, Huahang	Nuclear Engineering & Radiological Sciences
Wines, James	Nuclear Engineering & Radiological Sciences
Yang, Yonghong	Nuclear Engineering & Radiological Sciences
Yu, Qingkai	Nuclear Engineering & Radiological Sciences
Ashoak, Josh	UROP - School of Public Health
Perez, Ricardo	UROP - School of Public Health
Berebitsky, Daniel	UROP - Chemistry (Physics)
Gonzalez, Eric	UROP - Chemistry (Chemical Eng)
Gupta, Milan	UROP - Chemistry (Pre-Business)
Ries, Kelly	UROP - Chemistry (Chemical Engineering)
Degenhardt, James	UROP - Chemistry (Physics)
Yam, Ly	UROP - Chemistry (Computer Science)
Mansukhani, Surat	UROP - Chemistry (Undeclared)
Marsac, Patrick	UROP - Chemistry (Chemical Engineering)
Epp, Erik	UROP - Chemistry (Chemistry)
Trombley, John	UROP - Chemistry (Education)
Wong, Emma	UROP - Chemistry (Undeclared)

Students from Other Colleges

Paige, Matthew	Indiana University	Geological Sciences
Johnson, Tim	Indiana University	Geological Sciences
Hirshman, Amy	Michigan State University	Anthropology
Zhao, Xianda	Michigan State University	Civil & Environ. Engin.
Xifan, Zhang	Ohio State University	Geological Sciences
Jianyou, Shi	Ohio State University	Geological Sciences
Parent, Laura	San Jose State University	Geology
Hare, Timothy	State University of New York Albany	Anthropology
Church, Terry	University of Colorado, Boulder	Geological Sciences
Johnson, L.H.	University of Manchester	Earth Sciences
Kendrick, M.	University of Manchester	Earth Sciences
Nardini, I.	University of Manchester	Earth Sciences
Thrower, C.	University of Manchester	Earth Sciences

Recent Publications & Papers Related to Research at PML/FNR

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K. Michelaki, "Pottery making among the Maros villagers of Bronze Age Hungary: Considering the craft in its social and technical context ", paper presented at the Second Lampeter Workshop in Archaeology, Embedded Technologies: Reworking Technological Studies in Archaeology, Lampeter, Wales (1999).

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