Phoenix Memorial Laboratory
Ford Nuclear Reactor

Annual Report
1997-1998

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

Director (until July, 1998)	Ronald F. Fleming	(734) 647-9661
Interim Director (since August, 1998)	John C. Lee	(734) 764-6215
Reactor Manager	Christopher W. Becker	(734) 764-6224
Assistant Manager, Operations	Bernard P. Ducamp	(734) 764-6222
Assistant Manager, Research Neutron Activation Analysis Materials Science Testing Radiochemical Production	Philip A. Simpson	(313) 764-6221
Assistant Manager, Laboratory ^{60}Cobalt Irradiator Radiopharmaceutical Production	Robert B. Blackburn	(734) 936-1582
Senior Research Associate Neutron Radiography	John T. Lindsay	(734) 936-1583
Information and Tours		(734) 764-6220
Fax Number		(734) 936-1571

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

April, 1999

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Annual Report, 1997-1998

Research Highlights

Overview

Founded in 1948 as a World War II memorial, the Michigan Memorial Phoenix Project is dedicated to encouraging and supporting peaceful applications of nuclear energy and technology. In pursuit of that mission, the **Ford Nuclear Reactor** (FNR) and associated facilities in the **Phoenix Memorial Laboratory** (PML) 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 and Education Facilities

Research facilities at MMPP feature the FNR with a licensed power of 2.0 MW, which provides incore and excore neutron irradiations within the reactor pool and offers facilities for neutron beam experiments. The Cobalt Irradiator Facility (CIF), housed in the 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 safe controlled environment. A brief review of the MMPP facilities follows.

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 2×10^{13} neutrons/$cm^2 \cdot$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 achieved initial criticality in 1957 and operated with varying operating cycles and with high enrichment uranium (HEU) fuel until 1981, when it served as the whole-core demonstration facility for low enrichment uranium (LEU) fuel for research reactors. Since 1984, the FNR has utilized LEU fuel and currently operates ten days at full power followed by four days of shutdown and maintenance, offering experimental uses of the facilities for 65% of the calendar year.

Key experimental facilities for the FNR include:

- In-core irradiation facility for short- and long-term irradiation of samples in high neutron flux regions.

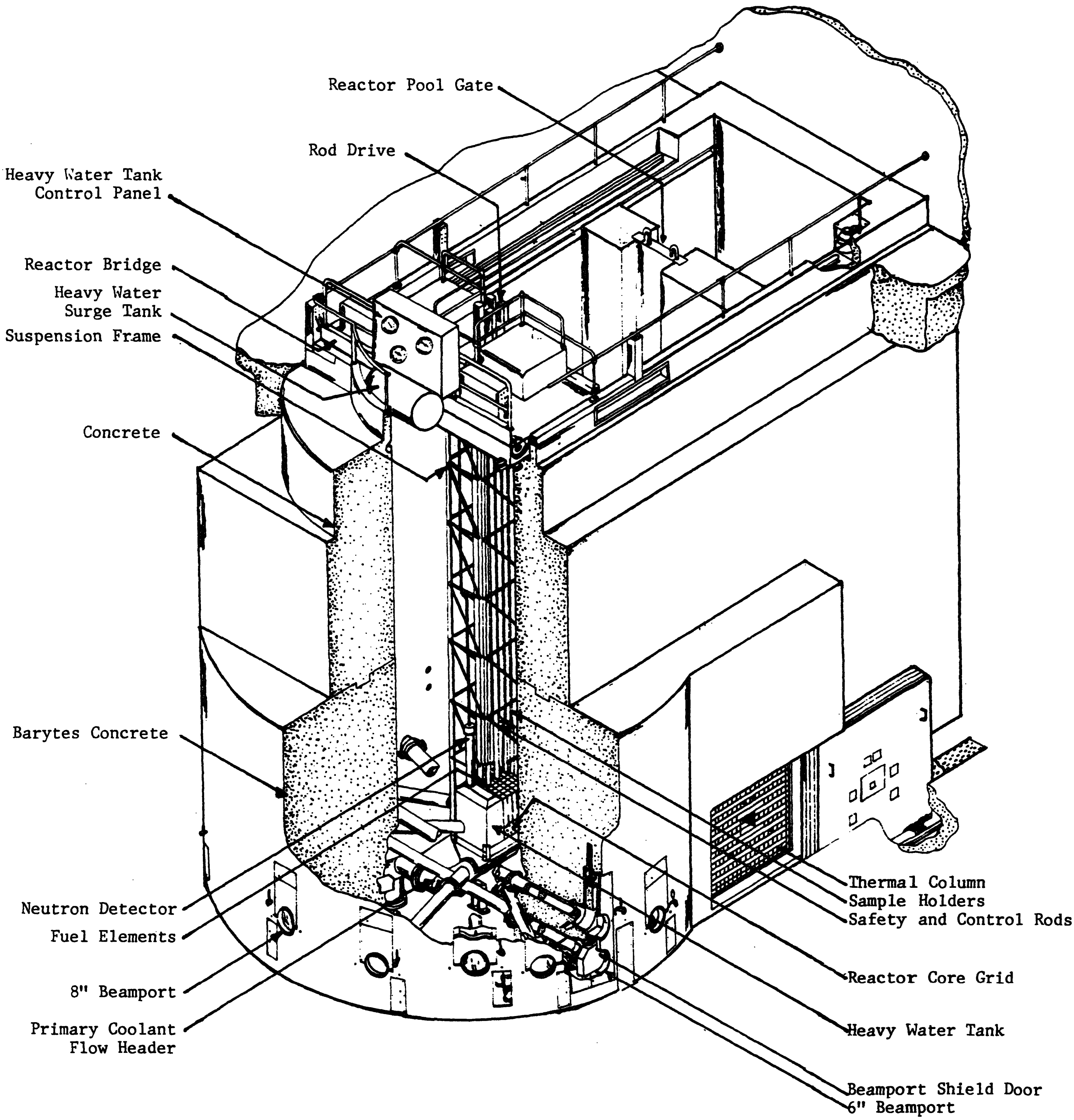
- Large experimental grids in water reflector regions for long-term irradiation of samples, including the Materials Dosimetry Reference Facility, which is calibrated and maintained by the National Institute of Standards and Technology.

- One horizontal pneumatic tube (P-tube) system to transfer small samples from a remote laboratory to the reactor core. The system is of special use in short half-life activations.

- Eight horizontal beam ports and one vertical beam port for experiments requiring neutron beams, such as neutron radiography and spectroscopy.

- Two 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.

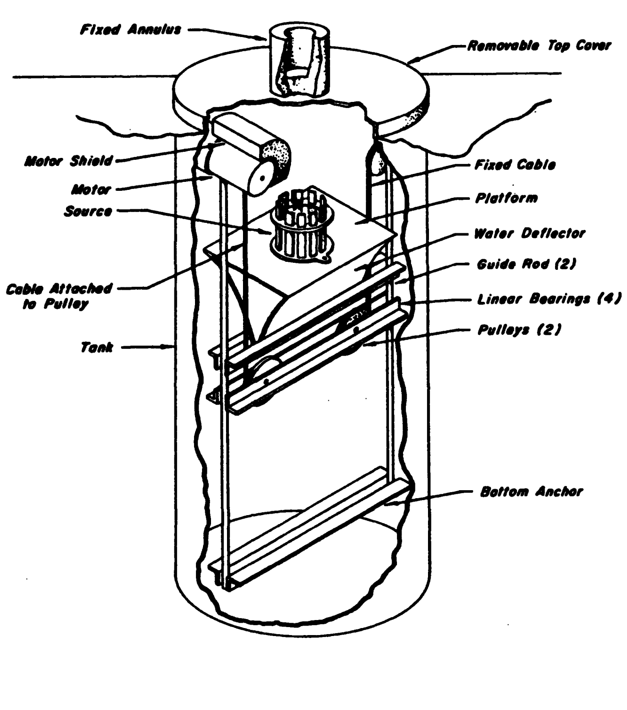
The Ford Nuclear Reactor serves as a source of neutrons for materials irradiations; radiation damage studies; neutron activation analysis; radioisotope production; beam extraction experiments such as neutron radiography and neutron spectroscopy; neutron depth profiling; and teaching and laboratory experiments related to reactor physics and operations. The megawatts of power generated by the reactor is not put to



Isometric view of the Ford Nuclear Reactor.

practical use, but is dissipated to the atmosphere through a heat exchanger and cooling tower system.

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. 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. Typical sterilization doses are $2x10^6$ rad. Most of the irradiation projects at the CIF are usually accomplished in irradiation times ranging from an hour to a half day. The ^{60}Co rods are stored 12 feet under water to provide radiation shielding and are raised above water for sample irradiations.



The Cobalt Irradiator Facility (CIF).

Specialized Laboratory Facilities. The PML offers a number of specialized laboratory facilities that allow the analysis of irradiated samples, production of radiopharmaceuticals, and nondestructive testing and imaging of various material. Key facilities include:

- Neutron activation analysis laboratory providing high-resolution measurement of gamma and X-rays for identification of trace quantities of elements in a variety of samples.

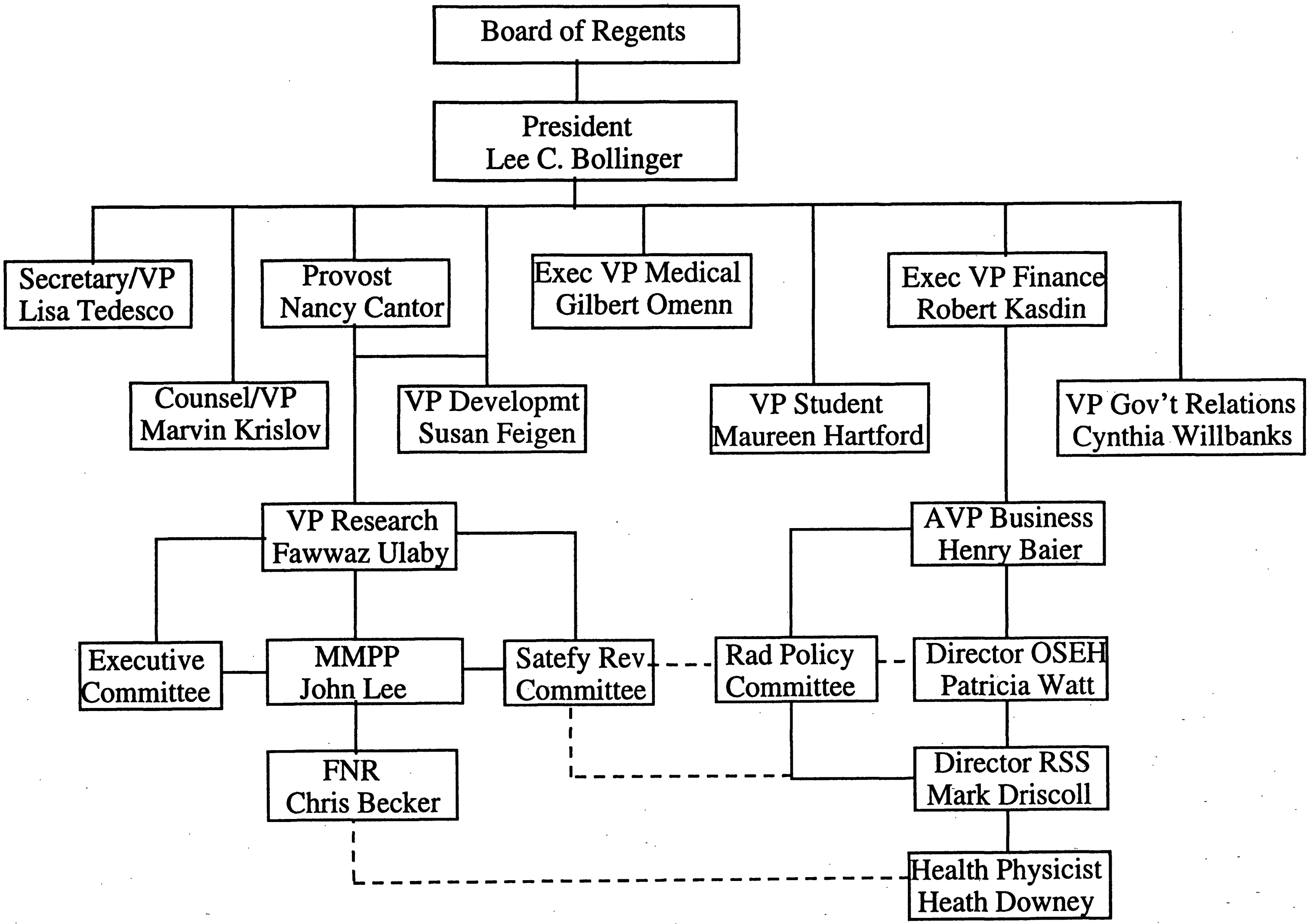
- Radiochemistry laboratories equipped with drains for radioactive fluids to retention tanks and hoods that exhaust through specialized particulate filters. Two laboratories have walk-in hoods and P-tube connections to the reactor core.

- Neutron radiography facilities providing a nondestructive method to image light materials contained within dense materials. In addition to high-resolution photographic systems, real-time neutron imaging (neutron radioscopy) systems allow studies of dynamic phenomena.

Located also in the PML are a machine shop and an electronics shop, providing the in-house capability for much of the maintenance and repair of reactor systems and laboratory equipment.

Facilities Organization and Staff

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:



Position of Michigan Memorial Phoenix Project (MMPP) within the University of Michigan.

Faculty Executive Committee
Prof. Mary L. Brake
(Nuclear Engineering & Radiological Sciences)
Prof. David R. Engelke (*until June, 1998*)
(Biological Chemistry)
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 (*since July, 1998*)
(Nuclear Engineering & Radiological Sciences)
Prof. Robert Whallon (*since July, 1998*)
(Museum of Anthropology)
Prof. Charles F. Yocum
(Department of Biology)

Safety Review Committee
Prof. Dale E. Briggs (Chemical Engineering)
Prof. I-Wei Chen (*through February, 1998*)
(Materials Science & Engineering)
Prof. Henry C. Griffin (Dept. of Chemistry)
Prof. John S. King, Interim Chair (*since Aug., '98*)
(Nuclear Engineering & Radiological Sciences)
Prof. John C. Lee, Chair (*until July, 1998*)
(Nuclear Engineering & Radiological Sciences)
Prof. James E. Martin
(Environmental & Industrial Health)
Prof. Massoud Kaviany (*since March, 1998*)
(Mechanical Engineering & Applied Mechanics)
Prof. Fredrick C. Neidhardt (*until December, 1998*)
(Vice President for Research)
Prof. Fawwaz T. Ulaby (*since January, 1999*)
(Vice President for Research)
Mr. Douglas C. Wood (V.P., Advent Engineering)
Mr. Mark Driscoll, *ex officio* (Rad. Safety Officer)
Reactor Manager, *ex officio* (FNR)

MMPP Staff. The total number of personnel on the Michigan Memorial Phoenix Project is currently 24. The interim Director holds a split appointment between the MMPP and Department of Nuclear Engineering and Radiological Sciences (NERS), as has been the case for past directors. The Nuclear Reactor Laboratory Manager reports to the 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 three-shift 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 on the non-tenured research scientist track 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. The HPs report to the University's Radiation Safety Service, which ensures compliance with Occupational Safety and Environmental Health (OSEH) and NRC regulations regarding the handling, storage, shipping, and disposal of radioactive material.

Research and Service Programs

The primary purpose of the Ford Nuclear Reactor and Phoenix Memorial Laboratory is to provide University faculty with special facilities needed for nuclear science research and teaching. In addition, the facilities and services of the laboratory are available for use by other schools, colleges, and universities; by units of the federal and state government, industry, and electric utilities for research and teaching; and by hospitals for research and in connection with preparation of medical isotopes.

Scientific research and research support services at PML/FNR are organized into five programs that offer expertise and technical assistance to a diversity of research and educational activities:

• The **Nuclear Analysis Program** utilizes the FNR as a source of neutrons for three analytic techniques and service areas:

Instrumental Neutron Activation Analysis (INAA or NAA), a method of identifying and measuring trace quantities of elements in many types of materials through the creation of radioisotopes and measurement of their subsequent decay.

Ar-Ar Dating, in which 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.

Radiochemical and Tracer Production, a service which produces radionuclides for use as tracers in various scientific and industrial research programs in UM departments, other universities, hospitals, and industrial laboratories.

• The **Neutron Radiography** program uses a beam of neutrons to create images of objects, in a manner analogous to X-ray radiography. Unlike X-rays, however, which are used for imaging dense materials, neutron radiography is an important non-destructive tool in constructing images of light materials, especially when contained within a dense material, such as water flow in soil, or oil flow in an engine or transmission.

• The **Materials Science Testing** program determines the effects of radiation, and in some cases temperature, on materials such as reactor vessel steels, insulation, and neutron shields used in nuclear reactors. Typical parameters measured include: hardness, tensile strength, impact strength, dimension changes, weight changes, and neutron attenuation. Neutron radiographs are frequently taken of target samples.

• The **Cobalt Irradiation Program** 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.

• The **Radiopharmaceutical Program** synthesizes three radioiodine compounds for clinical studies on a regular basis for distribution to 60 hospitals in the United States and Canada.

In addition, MMPP maintains collaborative programs with several departments within the University of Michigan. Support for these programs ranges from the provision of laboratory or office space, to joint research projects involving the expertise of MMPP staff:

- **Nuclear Engineering & Radiological Sciences**,
- **Nuclear Chemistry**,
- **Nuclear Medicine**,
- **Environmental & Industrial Health,**
- **Archaeometry**.

Staff at Phoenix Memorial Laboratory and Ford Nuclear Reactor welcome the opportunity to work with researchers from all UM departments and from other academic institutions.

Educational Activities at MMPP

MMPP also fulfills its mission through education of the academic community and general public on the peaceful applications of nuclear technology. FNR serves as a teaching facility for the University of Michigan, as well as other schools, colleges, and universities. Educational activities include university courses, as well as labs and lectures, in areas such as nuclear engineering, nuclear chemistry, and archaeometry. MMPP also maintains an active outreach program, providing facility tours to grade school, high school, community, and professional groups.

Facility Operations

Ford Nuclear Reactor

The reactor operates at a maximum power level of two megawatts which produces a peak thermal flux of approximately $2x10^{13}$ n/cm^2·s. A typical core configuration consists of approximately 43 plate-type fuel elements. Standard elements contain 167 grams of ^{235}U in eighteen aluminum-clad fuel plates. Control elements, which have central control rod guide channels, have nine plates containing 83 grams of ^{235}U. Overall fuel element dimensions are *ca.* 3 x 3 x 26 in.

Fuel elements are retired after burnup levels of approximately 35-40% are reached. Fuel burnup rate for the entire core is approximately 2.46 grams of ^{235}U per day at two megawatts. The operating and replacement schedule resulted in the use of eight standard and two control fuel elements during the year. The estimated value of this support from the United States Department of Energy (DOE) is $500,000 annually.

New fuel is manufactured by Babcock and Wilcox, Lynchburg, Virginia. No new fuel was received this year. Spent fuel is shipped periodically to the Westinghouse Company located at the Savannah River National Laboratory in Aiken, SC, for reprocessing. No spent fuel shipments were made this year.

The current operating schedule consists of ten days at full power followed by four days of shutdown for fuel loading and maintenance. The ten days of operation (from Tuesday afternoon of one week through Friday afternoon of the following week) result in approximately 230 continuous full-power operating hours per half-cycle or two-week period (Table 1).

The FNR has operated safely throughout the 40 years of its life, with repairs and refurbishment made to maintain the facility in safe, operating condition. Major system upgrades in recent years include the replacement of the old nuclear instrumentation modules with modern solid-state components and refurbishment of the shim safety rod system. Further upgrades to control room instrumentation that need to be addressed include (a) replacing current reactor control relays, annunciators, instrumentation, and alarm panels with modern solid-state devices in a new console, and (b) development of a fully functional Data Acquisition System incorporating digital display, monitor. and control capabilities. A proposal was submitted in January 1999 under the DOE University Reactor Instrumentation Program to acquire funds for these upgrades.

Table 1. Reactor Operation, 1997-1998

Operating Hours	5487.2
Operating Hours > 1.8 MW	5077.4
Accumulated Megawatt Hours	10190.0
Reactor Availability (% calendar yr)	58.1

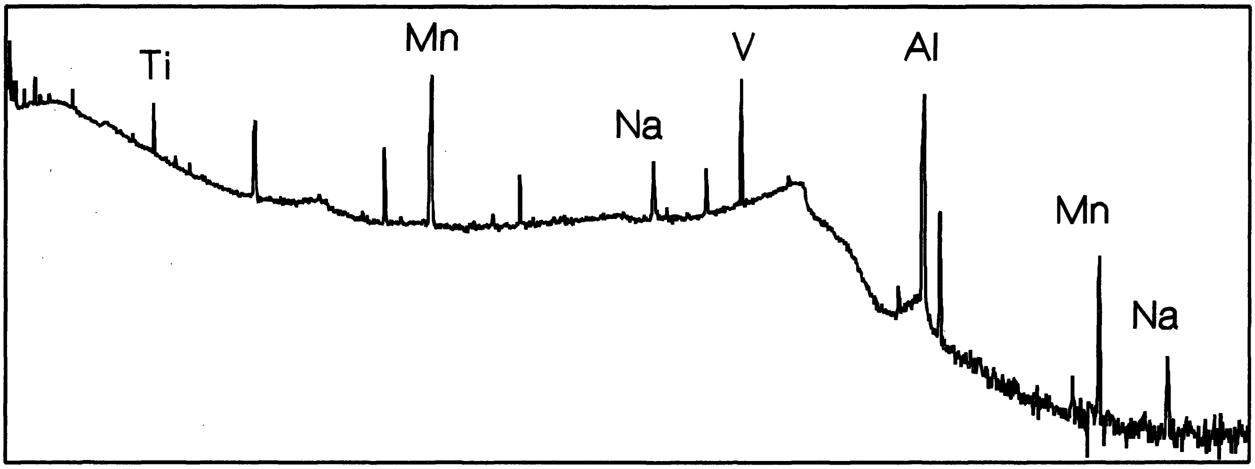
Cobalt Irradiation Facility

The Cobalt Irradiator source consists of 9 rods, each a stainless steel tube approximately one-half inch in diameter and 13 inches long that contains a thin ribbon 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.

The source rods were replaced most recently in 1996, and the source rod elevator system was refurbished in 1998. The CIF is expected to provide trouble-free operation for a long period of time, with the replacement of existing ^{60}Co rods in three years. Current plants are to install an improved indicator for the ^{60}Co irradiator position. Such an indicator will help us provide safer and more efficient gamma irradiation services.

The CIF is available 24 hours per day, seven days a week. During 1997-1998, the CIF was in use for 35.3% of calendar hours.

Instrumental Neutron Activation Analysis Program



Typical gamma-ray spectrum following irradiation for short-half life elements.

Instrumental Neutron Activation Analysis (INAA or NAA) is a method of identifying and measuring trace quantities of elements in many types of materials. 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. The INAA program is available as a 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.

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 Work-station" software operating on two Digital Equipment Corporation VAX station computers. An ethernet communication capability links research work-stations throughout the facility to networked data acquisition hardware. The laboratory is also connected globally via the Internet Network. Currently, users with access to the Internet can be allowed access to PML's VAX stations for direct analysis of their gamma spectrometry data.

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.

Nearly 2500 samples were irradiated and analyzed for trace-element composition at the facility and by the facility staff (Table 2). Roughly 65% of these samples were submitted by researchers at the University of Michigan. Samples were also irradiated and analyzed for researchers at ten 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, 1997-1998

Department/ Organization	Number of Batches	Number of Samples
University of Michigan		
Anthropology	29	873
Chemistry	3	214
Chemical Engineering	17	231
Geological Sciences	8	258
Subtotal	***57***	***1576***
Colleges, Universities, & Other Public Institutions		
Calvin College	1	24
Cincinnati University	2	58
Indiana University	6	142
Northern Illinois University	4	120
San Jose State University	2	40
University of Akron	2	40
University of Colorado	5	128
University of Maine	2	52
University of Nevada, Las Vegas	3	73
University of New Orleans	3	73
Subtotal	***28***	***750***
Federal and Industrial Research		
Department of Commerce (GLERL)	1	14
Ford Motor Company	2	16
NSF International	4	101
Subtotal	***7***	***131***
Total	**92**	**2457**

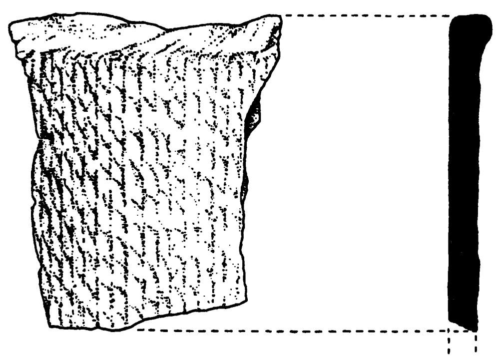
INAA Studies in Archaeology

Prof. Jeffrey Parsons and Research Scientist Dr. Leah Minc (***UM - Museum of Anthropology***) initiated a regional study of "Texcoco Fabric-Marked Pottery", a distinctive ceramic type associated with salt-production in the Valley of Mexico during Aztec times. The project identifies sources of salt production in the Aztec heartland and trace the flow of salt as it was distributed throughout the Aztec empire, based on the distinctive geochemical signatures of the ceramic shipping containers. The study is part of an on-going effort to elucidate economic organization and change under

INAA and the Aztec Salt Trade

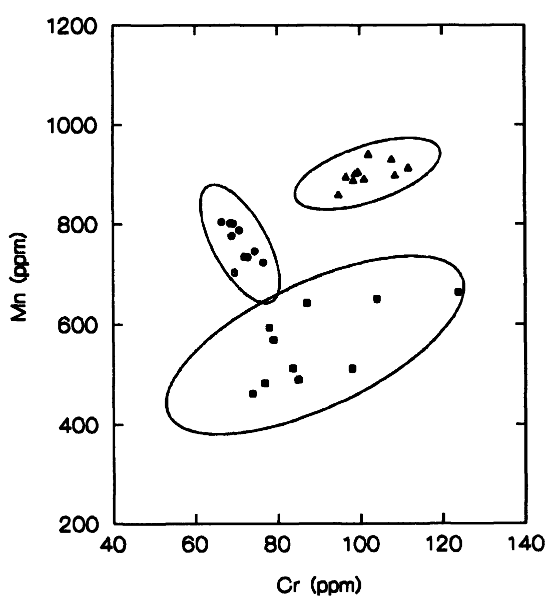
Leah Minc and Jeffrey R. Parsons
Museum of Anthropology, University of Michigan

Under Aztec rule (*ca.* 1350-1520 A.D.) salt-production emerged as a major, specialized industry in the Valley of Mexico. Salt was produced by mounding up salt-laden lakeshore soils which were flushed with water to leach out the salts and concentrate them in a brine solution. This brine was then reduced and dried through boiling and/or solar evaporation to produce hard loaves of dark salt which were widely traded throughout the Valley and beyond.



Texcoco Fabric-Marked pottery.

Although the salt is itself archaeologically invisible, a distinctive type of crudely made ceramic basin, termed "Texcoco Fabric-Marked pottery" is clearly associated with the salt industry. Fabric-marked pottery sherds are found in very high densities at ancient salt-making sites where these vessels were used as containers to boil and reduce the brine and to mold the salt into loaves. But Fabric-marked vessels were also used as the packaging in which salt was shipped, and trace amounts of this pottery type can be found at sites far from the lakeshore, indicating locations to which salt was traded.



Separation of three salt-making areas based on their chemical composition.

By examining both the chemical composition and distribution of the ceramic salt containers, we can monitor the spatial extent of the Aztec salt trade and provide insights into the distribution systems through which this important commodity moved. Over 320 sherds of Fabric-marked pottery (representing 17 different areas of salt production and 99 locations to which salt was traded) were selected for trace-element analysis through INAA at Phoenix Memorial Laboratory. Based on the distinctive geochemistry of their clays, the products of six different salt-producing regions can be distinguished, and connections between specific salt-producing areas and salt consumers can be mapped.

Overall, salt was widely traded within the Basin of Mexico, with salt consumers obtaining salt from a variety of sources, but typically from their closest (and most cost-effective) source. These distributional data support early historic documents, and indicate that salt moved through a combination of centralized market exchange in which salt was pooled at the main market for redistribution, and through a series of diadic exchanges in which producers supplied local markets directly. On-going research will extend the scope of our investigations to examine the trade in Aztec salt at the interregional level.

Minc, L. 1999. *The Aztec Salt Trade: Insights from INAA of Texcoco Fabric-Marked Pottery.* Paper presented at the 64th Annual Meetings of the Society for American Archaeologists, Chicago.

pressure of increasing political centralization within ancient empires.

Prof. Richard Ford (***UM - Museum of Anthropology***) is using INAA to compare the trace-element composition of archaeological pottery from New Mexico with the geochemical signature of historically-utilized clay mines in the same area, to determine the source of distinctive prehistoric ceramic traditions.

Ms. Kostalena Michelaki, Ph.D. candidate (***UM - Museum of Anthropology***), is investigating aspects of ceramic technology and economic organization 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 determine the degree of specialization (the number and distribution of ceramic producers as identified by their distinctive geochemical signatures) and exchange of ceramic vessels among these communities.

Prof. Adon Gordus (***UM - Chemistry***) has an on-going program assisting archaeologists and art historians from around the world in analyzing precious metal (primarily gold) artifacts using neutron activation analysis. In his work, rubbings are taken from the artifacts and analyzed. The level of minor and trace elements, particularly silver and copper in gold artifacts, provides clues to the source of the material. Such analyses can provide supporting evidence for the legitimacy of the artifacts. Most recently, Prof. Gordus has analyzed rubbings from early Persian (3rd-8th century AD) gold coins from the collections of the American Numismatic Society of New York City, the National Coin Collection in Paris, and the St. Petersburg Hermitage Museum. The compositional data are compared with that of coins recently appearing on the market which have been questioned as modern forgeries.

Dr. Clarence Menninga (***Calvin College - Dept. of Geology, Geography, and Environmental Sciences***) initiated a study utilizing INAA to assist in archaeological characterization of ancient pottery from the Abila excavation in northern Jordan.

Timothy Hare, a Ph.D. candidate (***State University of New York - Albany, Department of Anthropology***) working under the direction of Prof. Michael Smith, has initiated a study of Aztec-period ceramics from Morelos, Mexico, one of the first regions incorporated into the expanding Aztec empire. Utilizing multi-element INAA to source decorated archaeological ceramics, Mr. Hare 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 is entitled *Postclassic and Colonial Political Boundaries and Market Systems in the Yautepec Valley, Morelos, Mexico.*

Ms. Catherine Chmidling (***University of Maine- Institute for Quaternary Studies***), a Masters degree student working under the direction of Prof. Kristin Sobolik, completed a series of neutron activation analyses to assist her archeological research. Ms. Chmidling's thesis is on trade patterns and population movements in the northern Chihuahuan Desert in an area near what is now Big Bend National Park, Texas. INAA is being used to provide elemental signatures for known sources of lithic material which can be linked to archaeological artifacts found at various sites.

INAA Studies in Chemistry and Chemical Engineering

Prof. Levi Thompson (***UM - 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.

Graduate student Nopparat Tharapiwattananon and Post-Doctoral Researcher Richard Long (***UM - Chemical Engineering***) continue their work with Prof. Ralph Yang in the development of potential replacements for the 3-way catalysts used to reduce automotive emissions. The current catalysts use expensive precious metals such as platinum and rhodium. The research is directed at finding other combinations of less costly metals that would be similarly effective in reducing unburned hydrocarbons, carbon monoxide and nitrous oxides. Neutron activation analysis is being used to determine metal concentrations in the various experimental catalysts.

David Zaziski, an undergraduate student working with Prof. Anthony Francis (***UM - Department of Chemistry***), completed his analyses of five samples of silicate glass for the presence of first row transition metal impurities. The glasses were believed to contain iron in an unusual, never before seen coordination and spin state.

INAA Studies in Geology

Susannah Duly (***UM - Geological Sciences***) completed her analyses of iron and copper-iron pyrites for gold, arsenic, antimony, thallium, and selenium. The latter are gold followers found along with gold in mineral deposits. The work was associated with her master's degree thesis under the direction of Prof. Steven Kesler.

Prof. Robert Owen (***UM - Geological Sciences***) has had a number of graduate student researchers working on projects looking into the geochemistry of submarine sediments to understand palaeo-oceanic environments. Neutron activation analysis is used extensively to characterize ancient ocean sediments and the prevailing conditions under which they formed. Current students actively involved with PML's INAA facilities are Egon Weber and Lisa Kraemer.

Prof. James Brophy (***Indiana University - Department of Geological Sciences***) has initiated a study involving multi-element INAA of geological samples from the South Sister volcano in the Oregon Cascades to understand the physical nature of fractional crystallization mechanisms within orogenic (calc-alkaline) magma systems from "fractionation-generated" composition gaps. Two apparent composition gaps are being evaluated using trace-element data to verify that they result from fractional crystallization rather than alternative processes such as lower crustal melting.

Several students working under Dr. Brophy had INAA performed as part of their graduate research. Matthew Paige is investigating samples of layered gabbros and granophyre from the calc-alkaline Guadalupe Complex in Catheys Valley, California, for his thesis *Evaluation of Magmatic Processes: Guadalupe Complex, Catheys Valley CA.* Michael Dorais is studying the trace-element composition of metaigneous rock samples from the Massabesic Gneiss Complex, New Hampshire, to determine the tectonic setting in which the magmas originated.

Robert Ward, a doctoral candidate (***Northern Illinois University - Department of Geology***) working with Prof. James Walker, completed his dissertation research into deep crystal growth and modification beneath the Trans-Pecos Volcanic Province in Southwest North America. Mr. Ward had samples analyzed for trace and rare earth elements at PML to help unravel the geochemistry and thus the crystal growth rates in the region during the Cenozoic.

Prof. Ellen Metzger (***San Jose State University - Department of Geology***) has utilized the facilities at PML for a series of projects over the years. Most recently she has been investigating trace-element concentrations in metamorphic rocks of the northern Cascades. The rock samples represent an affiliate complex formed on the ocean floor; ratios of the rare-earth elements assist in understanding ocean basin conditions at the time the sediments were laid down.

Geochemical Signals at the Cessation of a Late Devonian Stromatoporoid-Dominated Biostrome in Southern Nevada

Terry A. Church and David A. Budd
Department of Geological Sciences, University of Colorado, Boulder

High diversity coral-stromatoporid biostromes, which dominated the Late Devonian tropical and subtropical continental shelves, underwent an abrupt global-scale disappearance in the fossil record roughly one million years before the Frasnian and Famennian (F-F) boundary. Their demise is considered the first major step in the Late Devonian mass extinction, a step-wise, global scale event that spanned over one million years and culminated at the F-F boundary. The entire extinction episode is the third largest known and eliminated over 80% of tropical and subtropical shallow marine water species.

This study examines the geochemistry, sedimentology, and conodont biostratigraphy of a well-exposed section of Late Devonian date in the Golden Gate Range, SE Nevada. This relatively offshore outer shelf section records separately both extinction events: (1) the loss of stromatoporoid biostrome-producing organisms near the end of the Late Frasnian, and (2) the over-lying final step in the F-F mass extinction. Geochemical analyses included selected major, minor, trace, and rare earth elements (REE), together with measurements of carbon and oxygen isotopes, to detect any evidence for major changes in palaeo-oceanic conditions. Neutron activation analysis played a key role in the determination of REE.

Analyses of transition-metal content were used to evaluate possible stratigraphic changes in palaeo-oceanic composition. Such changes in near-shore marine environments typically suggest violent and/or abrupt overturn of oceanic bottom waters into near-shore realms. Prior studies have implicated F-F enrichments as evidence of oceanic overturn resulting from an abrupt change in climate (from a greenhouse to an icehouse environment) or from an oceanic disturbance such as a bolide impact. This study found:

- only mild enrichments at the biostrome cessation interval, indicating that acute upwelling of ocean bottom waters onto near-shore reals did not occur, and that a violent or abrupt oceanic overturn event can be ruled out.

- a significant enriched in these elements at the F-F boundary, indicating a possible flux of accumulated elements onto the near-shore realm, that may support the theory of abrupt oceanic overturn as the result of either climate change or bolide impact.

The relative concentrations of rare-earth elements (Z=57 to 71) are sensitive indicators of palaeo-oceanic conditions. In particular, the ratio of light rare earth elements (LREE) to the heavy rare earth elements (HREE) reflect the degree to which ocean masses mixed sufficiently to keep the REE of different atomic weights in balance. In modern oceans, shallow-water environments ($\leq$. 5 km of water depth) have a consistently higher concentration of LREE to HREE. Examination of the LREE to HREE pattern at Golden Gate revealed:

- LREE to HREE ratios rise sharply at the biostrome cessation interval and remain elevated until the F-F boundary, signaling a period of less ocean mixing or reduced interaction between near-shore and deep-ocean waters.

- a subsequent reduction in LREE back to baseline even coincident with the F-F boundary, suggesting that ocean mixing became relatively more dynamic once again. The distinctive geochemical signals at the two intervals suggest that the direct and/or ultimate causal mechanisms responsible for these two extinction steps may have been significantly different.

In light of these preliminary data, future interpretations of the F-F and other stepwise mass extinctions should continue to address the potential for multiple and distinct mechanisms driving individuals steps of the larger extinction episode.

Church, T.S., J.R. Morrow, and D.A. Budd. 1998. *Distinct Geochemical Signals within Stepwise Mass Extinction, F-F (Mid-Late Devonian) Boundary, Southern Nevada.* Paper presented at the Geological Society of America Meetings.

Prof. Lingren Chyi (***University of Akron - Department of Geology***) has used the INAA services of PML/FNR for many projects over the years. He is currently working on a long-term research into using the coherent triad of elements aluminum, lanthanum, and scandium found in geological systems to develop discrimination diagrams. The concept of discrimination diagrams is not new but applying this particular triad of elements which are easily determined by INAA is a new development. Dr. Chyi has also advised numerous graduate students that have used the reactor's INAA services in their research projects. Lawrence Antonnelli, who completed his degree in December, 1997, examined trace-elements in groundwater with emphasis on the Al-La-Sc coherent triad. Robert Kowalkoski is investigating trivalent cations in groundwater.

Maria Prokopenko, a Masters student (***University of Cincinnati - Department of Geology***) is studying the geochemistry of K-bentonites from the Precordillera, Argentina which represent altered volcanic ash. The goal of her project is to reconstruct the development of the magmatic source of these ashes and establish a reliable pattern for using the K-bentonites as a tool for regional stratigraphic correlations based on their trace-element composition.

A number of graduate students working with Prof. Edwin Larson in the Department of Geological Sciences (***University of Colorado***) have utilized neutron activation analysis to determine the trace element and rare earth element composition of various rocks. Most recently, Ralph Klinger examined a series of volcanic ash deposits, and Ms. Lupe Maldonado examined mineralized ore-deposits.

Abbas Sharaky, Ph.D. Candidate (***University of Colorado - Department of Geological Sciences***), is examining the relationship between porphyry (high temperature, subvolcanic stocks) and epithermal (low temperature) deposits at Jamestown, Colorado. The porphyry is believed to be the main source for the ore-forming fluids. Different methods to test this relationship include an assessment of the geochemistry (major, trace, and REE elements) of the porphyry, the surrounding veins and main ore deposits using INAA.

Under the direction of Prof. David Budd (***University of Colorado - Department of Geological Sciences***), Ms. Terry Church initiated 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 is supported by the McNair Scholars Program.

For many years, researchers from the ***University of Nevada, Las Vegas, Department of Geoscience*** have been performing rare-earth analyses to support non-funded research of the origin of volcanic and plutonic rocks in selected areas of the southern Great Basin of Nevada and Arizona. Most recently, Prof. Terry Spell and Masters student Leigh Justet have been investigating rock samples from the Bearhead Rhyolite, a sequence of volcanic rocks from the Jemez Volcanic Field in New Mexico. These rocks are unique in that they potentially represent low-volume effusive eruption of rhyolitic magma from a single large magma chamber instead of the more typical large-scale explosive eruptions associated with this type of volcanism. Thus, their chemistry may hold important clues for understanding volcanic hazards.

Prof. William Simmons (***University of New Orleans - Department of Geology and Geophysics***) conducted several exploratory studies at PML facilities, including a joint project with Prof. Alexander Falster and graduate student Philip Richardson on the origin of Wisconsin pegmatltes, and an on-going study on the mineralogy and geochemistry of Tourmaline from central Siberia.

Ms. Brenda Yawn, a graduate student working under the direction of Prof. Simmons and Dr. Karen Webber, is investigating the geochemistry and mineralogy of volcanic rocks from Death Valley, California, in order to relate volcanisms and tectonics in the region.

INAA Studies in Nuclear Engineering & Radiological Sciences

Doctoral candidate Binxi Gu, working under the direction of Research Scientist Dr. Lumin Wang ***(UM - Nuclear Engineering & 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 Sr and Cs. Their research is part of a long-term project to identify materials appropriate for high-level radioactive waste storage.

Prof. Marty Ludington (***Albion College - Physics Department***) spent his sabbatical leave from Albion College conducting research at PML. His research activities centered on expanding the high accuracy calibration of germanium detectors for relative efficiency; this work follows up on that initiated by Dr. Ayman Hawari (***UM - Nuclear Engineering & Radiological Science***). The calibrations were tested using scandium and silver sources fabricated at the Reactor and utilized the new low-background level detector system. The resulting data confirm that the calibration method works for two different detectors of quite different size.

INAA for Environmental Studies

Great Lakes Environmental Research Laboratory (Department of Commerce) submitted sediment samples from the Florida Everglades and Lake Okeechobee for analysis. The results will assist in determining the impact past and present human activities have had on these environments.

INAA for Industrial Applications

Ford Motor Company has utilized neutron activation analysis to identify trace and rare earth elements in various glass and base materials.

National Sanitation Foundation International of Ann Arbor initiated a program using 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.

Thermo Analytical Inc. is an analytical consulting laboratory which utilizes neutron activation analysis as one of the powerful tools in analyzing metals and halogens in practically any type of material. Using the Ford Nuclear Reactor as the neutron source for activation, Thermo Analytical has successfully completed several projects for complete or partial scan of all the elements that can be analyzed using this method. This group has been particularly involved in the analysis of environmental samples such as soil, vegetation, and water for trace elements by neutron activation.

XRAL Activation Services Incorporated operates a neutron activation analysis program headquartered at the Ford Nuclear Reactor to serve geologists and the mining industry. The XRAL program includes use of laboratory and reactor space. Samples are irradiated in the reactor and analyzed by XRAL employees.

Relative Full Energy Peak Efficiency Curve of HPGe Detectors

Martin A. Ludington
Department of Physics, Albion College

Ronald F. Fleming
Nuclear Engineering & Radiological Sciences, UM

Over the past year, we have been developing a method which will allow for the accurate determination of the relative full energy peak efficiency of a High Purity Germanium (HPGe) detector. The first stage of the project was carried out by Ayman Hawari (1995, 1997), who was able to predict the relative efficiency to within ± 0.1% over most of the energy range from 702 keV to 1333 keV. NIST standard sources were also used to obtain absolute efficiencies by normalizing the relative efficiency curve.

After the completion of Hawari's work, we decided to test the universality of the method by applying it to a second detector of significantly larger volume than the 93.6 cm^3 that Hawari calibrated; accordingly, we utilized PML's low background gamma ray detector (owned by David Hamby of UM School of Public Health) with an active volume of approximately 280 cm^3. The results were comparable to those Hawari obtained in terms of precision and accuracy. At the same time, they repeated the measurements of the efficiency of the 93.6 cm^3 detector to see how it had changed with time, and found that the shape of the efficiency curve was the same to within the experimental uncertainties after a period of 3 years. This suggests that these detectors are more stable than many people may believe.

The second phase of the study involved extending the energy range of the calibration both to higher and lower energies. The method relied on using two nuclides with very well-known gamma ray emission ratios: ^{108m}Ag and ^{24}Na, both of which have cascading E2 transitions with minimal feeding to the intermediate state. Using the 434, 614, and 723 keV gamma rays of ^{108m}Ag, and the 1368 and 2754 keV gamma rays of ^{24}Na, we found that with this larger energy range (from 434 keV to 2754 KeV) the two-parameter least-square fit did not give the kind of precision obtained for the narrower range. Accordingly, a 3-parameter model was employed and resulted in a fit with a χ^2 probability well within acceptable range.

The third phase of this study is being conducted in collaboration with Richard G. Helmer of the Idaho National Engineering Laboratory, who has carried out a series of calculations of peak efficiency by means of a Monte Carlo electron and photon transport code, Cyltran. The accuracy of the code was tested by comparing the efficiency ratios calculated by Monte Carlo to those measured with the gamma-ray sources at PML. The ratios were in agreement within a range of 0.03-0.28% for the various nuclides. After the fitting procedure, the agreement between the fit values and the Monte Carlo values was found to be in agreement within a range of 0.03-0.31%. Given the good agreement at these energies, efficiencies were calculated at intermediate energy values in order to have additional data points for the interpolation function. The resulting ratios from the fit are in agreement with the Monte Carlo ratios to within a range of 0.004% to 0.25%. Results of the high accuracy calibration over the wider energy range and the comparison and use of the Monte Carlo values have been submitted to *Nuclear Instruments and Methods* for review.

Hawari, A.I. 1995. *High accuracy determination of relative full energy peak efficiencies for high resolution gamma-ray spectrometry*. Ph.D. Dissertation, University of Michigan, Ann Arbor.

Hawari, A.I., R.F. Fleming, M.A. Ludington. 1997. High-accuracy determination of the relative full energy peak efficiency curve of a coaxial HPGe detector in the energy range 700-1300 keV. *Nuclear Instruments and Methods A* 398(2-3):276-286.

Ar-Ar Geological Dating Program

Another technique closely related to the NAA program 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 primary users of the $^{39}Ar/^{40}Ar$ dating services come from the UM Department of Geological Sciences, as well as from other universities and research institutions in the United States, western Europe, and New Zealand. Irradiated $^{39}Ar/^{40}Ar$ samples are typically returned to users for their own analyses, or analysis can be arranged through the University's Department of Geological Sciences.

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

At ***UM Department of Geosciences***, researchers have conducted a wide range of projects utilizing Ar-Ar dating, including tectonic studies aimed at working out the histories of mountain belt formation and uplift, and 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 recent years, UM researchers have 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 tremendously in interpreting the weathering environment during the recent ice ages.

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.

Cenozoic Eolian Dust Deposition in the North Central Pacific: Assessing Source Indicators and Palaeoclimate Proxies

Thomas Pettke, Alex N. Halliday, David K. Rea, and Chris M. Hall
Department of Geological Sciences, University of Michigan

Records of eolian dust deposition preserved in deep-sea sediments, continental loess, and ice cores can provide important information on palaeoclimate and the geochemistry of continental crust exposed to weathering, averaged over large areas. Physical parameters of eolian dust records are the best proxy indicator of continental climates and atmospheric transport processes in the geological past. The Eolian Mass Accumulation Rate (EMAR, a true measure for the eolian dust input to oceans) and the grain size distribution of the dust (a measure of the energy of the transporting winds) provide independent information on the aridity - humidity pattern of the source region and the vigor of atmospheric circulation. Geochemical and Nd and Sr isotopic data from eolian dust complement those of river-suspended and river-dissolved loads in representing the mean characteristics of erosional source terrains. This has led to the tracing of the source(s) of eolian dust recovered from modern pelagic sediments, modern loess, and ice cores using Nd and Sr isotopes.

A yet unexplored aspect of the potential of eolian dust records for palaeoclimatic studies is the connection between the records of physical data, EMAR and grain size distributions, and corresponding mineralogy and radiogenic isotope data such as Nd, Sr, Pb, Hf. For example, to what extent do climatic changes as recorded by the EMAR and grain size distributions alter the radiogenic isotope signatures of Sr, Pb and Nd? Can we use Nd isotope systematics of eolian dust to trace its source and the corresponding Sr isotope composition as an isotopic proxy for the continental weathering regime prevailing immediately prior to dust uptake by wind? And, as a consequence, what are the potential inferences Sr, Nd, Pb and Hf isotopic compositions of eolian dust may allow us to draw on the evolution of these isotopic systems in seawater through time? Yet another unknown issue of eolian dust records is the time when its mineralogy and isotopic signature has been established. Was it immediately prior to dust uptake by wind (hence directly comparable with the EMAR and grain size data of the record), or are the mineralogy and isotopic signatures a source signal, or neither of both?

The great potential of eolian dust records for monitoring the global evolution of palaeoclimate and crustal geochemistry is now being realized through recent advances in analytical techniques and the understanding of clay mineral $^{40}Ar/^{39}Ar$ incremental heating age spectra that allow the mean age of a bulk clay mineral assemblage to be determined. This provides the only direct evidence on the time at which the mineral assemblage has been established, and after which the system remained closed with respect to K-Ar, and, by inference, to mineralogical transformations and isotopic exchange for Sr, Pb and Nd.

Here we present the first age-resolved record of Nd, Sr and Pb isotopic compositions and abundances of Sm, Nd, Rb, Sr, U and Pb of eolian dust deposition in the north central Pacific at ODP sites 885/886 extending from the present day back to 11 Ma. We relate these data to dust mineralogy, flux (EMAR) and grain size distributions. This enables us to confine the source terrain of the dust precisely. Incremental heating $^{40}Ar/^{39}Ar$ age spectra of bulk dust samples selected on the basis of the Sr, Nd and Pb isotopic data then allow to assess the "age" of the mineralogical and geochemical signal of the dust. It permits us to quantify the effects of the continental weathering regime prevailing immediately prior to dust uptake by wind on the mineralogy and isotope geochemistry of the dust. Consequently, the validity of the currently inherent assumption that down-core changes in dust mineralogy are a monitor of climate-driven changes in continental weathering over time, given that there is positive evidence for source constancy, can be critically tested. Finally, we evaluate the relationships between established palaeoclimatic proxies such as EMAR and dust grain size distributions and dust geochemistry and isotopic signatures, which, in the past, have been inferred to yield valuable information on past climate changes.

T. Pettke, D.K. Rea, A.N. Halliday, and C.M. Hall, "Geochemistry, mineralogy and flux of Cenozoic eolian dust to the North Pacific: Source indicators, palaeoclimate proxies, or both?" *EOS Trans. Am. Geophys. U.*, 79, F442 (1998).

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 crystallised 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.

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 fore-arc 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.

Overall, 1400 hours of irradiation time were provided for Ar-Ar dating at FNR, benefitting research efforts at 24 universities (Table 3). A list of universities, principal investigators, and collaborating researchers utilizing the FNR for Ar-Ar dating is presented in Table 4.

Table 3. Summary of Irradiations for Ar-Ar Dating, 1997-1998

University or Institution	Irradiation Time (hrs)
University of Michigan	550
New Mexico Institute of Mining & Technology	249
Ohio State University	206
University of Manchester, UK	111
University of California, Los Angeles	110
Inst. of Geological & Nuclear Sciences, New Zealand	60
Universite Blaise Pascal	56
Lehigh University	48.5
University of Arizona	20
Total	**1410.5**

Table 4. Researchers and Institutions Utilizing the FNR for Ar-Ar Dating

University of Michigan

Research and Teaching Staff	*Graduate Students*	*Outside collaborators*
Prof. John Christensen	Dan Barfod	Rudy Boer (Witswatersraand Univ.)
Prof. Eric Essen	Karen Boven	Bill Hames (Auburn University)
Res. Sci. Chris Hall	Hailiang Dong	Jerry Magloughlin (Colrado St. Univ.)
Prof. Alex Halliday	John Fortuna	Robert Merriman (British Geo. Survey)
Prof. Stephen Kesler	John Harris	Matt Nyman (New Mexico Tech.)
Prof. Rebecca Lange	Gregory Simon	Bill Parry (University of Utah)
Prof. Sam Mukasa	Margaret Streepey	Greg Snyder (Univ. of Tennessee)
Prof. Donald Peacor	Eric Tohver	
Prof. Thomas Pettke		
Prof. David Rea	*Undergrad. Students*	
Prof. Damon Teagle	Shelly Erikson	
Prof. Ben van der Pluijm	Rachel WIlborn	
Prof. Youxue Zhang		

Lehigh University

Research and Teaching Staff	*Outside collaborators*
Prof. Bruce Idleman	Dr. C. Page Chamberlain (Dartmouth College)
Prof. Peter Zeitler	Dr. Teresa Jordan (Cornell University)
	Dr. Peter Copeland (University of Houston)
	Colgate University
	Penn State University
	Queens College, CUNY
	Rutgers University
	Syracuse University
	Trinity University
	University of Chicago
	University of Kansas
	University of North Carolina, Charlotte
	University of Tucuman, Argentina

New Mexico Institute of Mining & Technology

Research and Teaching Staff	*Outside collaborators*	
Prof. Matthew Heizler	Brigham Young University	Univ. of California, Davis
	Idaho State University	Univ. of Colorado, Boulder
	Iowa State University	University of Florida
	N. Arizona University	University of Iowa
	N. Illinois University	University of Maine
	Navajo Comm. College	University of Nebraska
	New Mexico Tech.	Univ. of Nevada, Reno
	New Mexico St. University	University of Utah,
	Princeton University	Utah State University
	Purdue University	Vanderbilt University
	U.S. Geological Survey	Victoria Univ., New Zealand
	Univ. of Calgary, Canada	W. Washington Univ.

New Zealand Institute of Geological & Nuclear Sciences

Research and Teaching Staff	*Outside collaborators*
Dr. Christopher Adams, Geochronology Group	Earth science departments at four New Zealand universities.
Nuclear Science Group	
Geophysical Group	
Volcanological Group	

Table 4. Researchers and Institutions Utilizing the FNR for Ar-Ar Dating (cont.)

Institution		
Ohio State University		
Research and Teaching Staff Dr. Fritz Hubacker Prof. Ken Foland Dr. David Elliot Dr. Thomas Fleming ***Graduate students*** Zhang Xifan Shi Jianyou	***Outside collaborators*** Bob Speed (Northwestern University) Peter Dahl (Kent State University) David Holm (Kent State University) Greg Areahrt (University of Nevada, Reno) Dan Murray (Rhode Island University) Alan McGrew (Dayton University) Bob Nickelson (Brown University) Steve Bergman (ARCO Oil & Gas Co.)	
University of Arizona		
Research and Teaching Staff Prof. Suzanne Baldwin Prof. Timothy Swindle Prof. Marek Zreda Res. Assoc. Paul Fitzgerald Sr. Research Spec. Bin Li		
Universite Blaise Pascal		
Research and Teaching Staff Dr. Nicolas Arnaud Dr. Raymond Montigy		
University of California, Los Angeles		
Research and Teaching Staff Prof. Jo-Anne Wartho Dr. Marty Grove		
University of Houston		
Research and Teaching Staff Prof. Peter Copeland Prof. Terry Spell		
University of Manchester		
Research and Teaching Staff Dr. R. Burgess Prof. G. Turner Dr. I. Lyon Dr. J.D. Gilmour Dr. J.A. Whitby Dr. D.A.C. Manning Dr. G.T.R. Droop Dr. R.A.D. Pattrick Dr. P. Harrop ***Graduate students*** Ms. L.H. Johnson Mr. M. Kendrick Ms. I. Nardini Mr. C. Thrower	***Outside collaborators*** Dr. J.W. Harris (University of Glasgow, UK) Dr. J.H. Milledge (Univ. College London, UK) Dr. D.P. Mattey (Royal Holloway Univ., UK) Dr. P. Nixon (Univ. of Leeds, UK) Prof. C.T. Pillinger (Open Univ., UK) Dr. M. Grady (Natural History Museum, UK) Dr. J. Bridges (Natural History Museum, UK) Dr. M. Genge (Natural History Museum, UK) Dr. R. Davies (Macquaire Univ., Australia) Dr. W. Griffin (Macquaire Univ., Australia) Dr. R. Ash (Carnegie Institute of Washington, USA) Dr. M. Prinz (Am. Mus. of Natural History, USA) Dr. O. Navon (Hebrew Univ., Israel)	

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 UM departments, other universities, hospitals and industrial laboratories (Table 5). Recent activities in tracer applications include:

- ^{82}Br-labeled hydrocarbons for the study of oil consumption in automotive engines;
- ^{24}Na-labeled sodium carbonate for process testing in chemical and petrochemical plants; and
- ^{134}Cs-labeled cesium carbonate for studies of adsorption and de-adsorption in Great Lakes sediments.

Radiochemical Production for Academic Research

Prof. Henry Griffin (***UM - Chemistry***) has initiated 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.

Dr. Roule Wapnir, at the ***North Shore University Hospital*** in Manhasset, NY, is researching intestinal transport. Dr. Wapnir is using ^{24}Na produced at the Ford Nuclear Reactor as a radioactive tracer in his studies using laboratory animals.

Dr. Howard Fuqua and Research Fellow Dr. Michael Banish at the ***Center for Microgravity and Materials Research, University of Alabama*** in Huntsville are investigating the diffusion coefficients for atom species in binary systems. Diffusion coefficients measured on earth are affected by gravity and are not the "true" atom diffusion coefficients for the system. Dr. Fuqua and Dr. Banish are designing experiment packages to measure diffusion coefficients that will be taken aloft in the Space Shuttle where the effects of gravity are minimal. The experiments involve diffusing one atom species tagged with radioactive tracer atoms into the second atom species of the binary system. The Phoenix Memorial Laboratory is providing radioactive tracers for these experiments. In addition, 35 mg of 93% ^{113}In were irradiated to produce a calibration source of ^{114m}In.

Dr. John Robbins (***Great Lakes Environmental Research Laboratory, Dept. of Commerce***) and fellow researcher, Nancy Moorehead, produced ^{134}Cs in the compound, cesium carbonate (Cs_2CO_3), in the reactor. The ^{134}Cs is used as a radioactive tracer for studies of adsorption and de-adsorption in sediment and to study the redistribution of contaminants in a calcite enriched environment.

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.

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 ***IC Tracerco*** and ***Tru-Tec Services Division of Koch Industries***. Both firms are service providers to the oil and petro-chemical 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, 1997-1998

Department /Organization	Number of Irradiations	Number of Samples
University of Michigan, Nuclear Engineering & Radiological Sciences	5	6
North Shore University Hospital	1	1
General Motors Technical Center	15	15
IC Tracerco	10	20
Total	**31**	**42**

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 PML 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. The Phoenix Memorial Laboratory is the world leader in both neutron radioscopy and high resolution neutron radiography.

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 © 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 vapor deposited 25 μm thick gadolinium metal 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 inches 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 inches 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 inch 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 an extended red neuvicon camera.

Recent Applications of Neutron Radiography

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. During the past year the McClellan Neutron Radiography Facility has been certified for coking determination.

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, and/or amount is required.

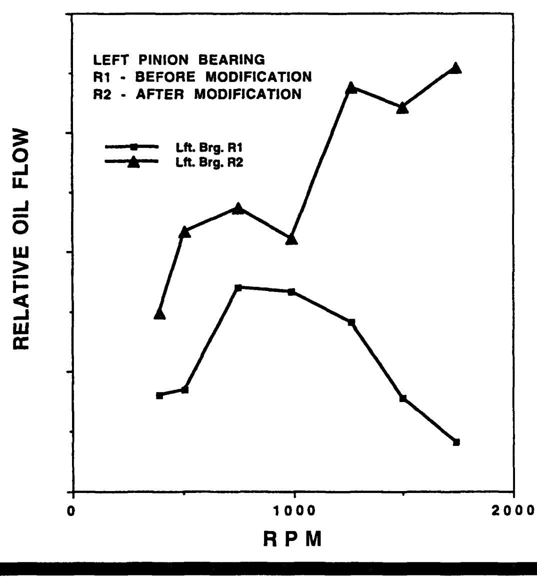
The past year has seen the construction of a dedicated transmisssion test stand with full motoring and loading capabilities. The new test stand is able to drive any current transmission manufactured by Ford Motor Company while providing a dynamometer for loading the transmission. Flow rates in various circuits, as well as pressure and temperature control, is also available. This test stand enhances PML ability to respond quickly to production problems in the automotive transmission field. During the past year this test stand was used

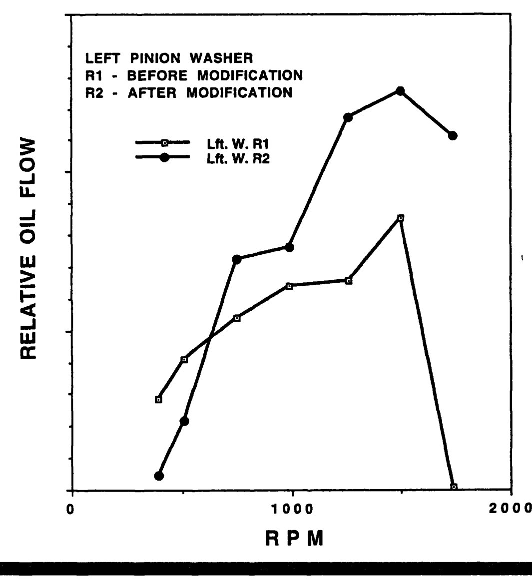
Neutron Radioscopy and Ford Transmission Bearing Lubrication

John T. Lindsay[1], Peter Schoch[2], and James Gooden[3]

The industrial utility of neutron radioscopy was recently demonstrated in a joint project with Ford Motor Company designed to monitor lubrication flow within the low planet pinion gear assembly of the 5R50/ 5F50 transmission. Insufficient lubrication flow was resulting in failure of pinion bearings and heat distress of surrounding components, even though standard industrial tests to measure oil (the Transmission Lubrication Flow Test Fixture or "Lube Pig") indicated that lubrication to that gear set appeared adequate. Collaborative efforts between Ford Motor Co., PML, and Hallick Hydraulic led to the development of a test stand, consisting of an electric motor to drive the transmission, a water break dynamometer to provide loads for the transmission, and a complex hydraulic system capable of controlling the temperature, pressure, and flow rate in the four lubrication circuits in the transmission. The test stand also incorporated the ability to modify all operating conditions as well as monitor the relevant experimental parameters.

Neutron radiographic images of the lubrication flow were made of selected areas (left and right pinion washers and gears) inside the transmission at various speeds and loads using the current design. The transmission was then rebuilt using modifications designed to improve the lubrication in the target areas. The transmission was re-imaged and improvements in the lubrication documented. The first run of experiments was terminated when the transmission emitted loud clunking noises; disassembly of the unit revealed that the bronze pinion washers were fragmented and the planetary gear set and surrounding parts were heat stained. The second run of experiments duplicated the first run. With increased lubrication in the area of interest, however, no further noises were heard. Upon disassembly, some of the same failures were found, but to a lesser extent. Clearly, the modifications suggested by neutron radiography increased the amount of oil reaching these areas.





Relative oil amounts as a function of transmission RPM within two target locations, before and after modifications suggested by neutron radiographic images of lubrication flow. In all cases, after modification, the amount of lubrication increased at higher RPM's.

Lindsay, J.T., P. Schoch, and J. Gooden. 1998. *Neutron Radioscopy Applications in Transmission Lubrication.* Paper presented at the 4th International Topical Meeting on Neutron Radiography, Lucerne, Switzerland.

[1]Phoenix Memorial Laboratory; [2] Hallock Hydraulic, Ann Arbor; [3] Ford Motor Company.

to solve a critical "neutraling out" problem. Dr. John Lindsay received a special achievement award for his work from Ford Motor Company.

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; well 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. and two Master's degrees were 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. One Ph.D. degree was obtained in Civil Engineering this year using neutron radioscopy of flow in porus media.

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 pixellated for imaging purposes. This is very important due to the decreased manufacturing of cameras that can withstand a high neutron radiation field. This work is on-going with the assistance of Dr. Douglas McGregor (UM - Nuclear Engineering & Radiological Sciences). This past year a $550,000 research grant from DOE was obtained to further develop this detector for spent fuel analysis.

Neutron Radiography Program Summary

A summary of neutron radiography performed at PML during 1997-1998 is summarized in Table 6 by organization. A total of 214 radiographs were imaged, involving nearly 850 researcher man hours. Three UM engineering departments (Chemical Engineering, Civil Engineering, and Nuclear Engineering) utilized the neutron radiography services, as did three industrial customers (Ford Motor Company, Georgia Power, and Carolina Power & Light). In addition, training in neutron radiography and radioscopy was provided for researchers from Bangladesh, Japan, and Brazil. A description of research projects follows.

Table 6. Neutron Radiography, 1997-1998

Department/Organization	Research Man-Hours	Number of Radiographs
University of Michigan		
Chemical Engineering	0	38
Civil Engineering	10	0
Nuclear Engineering	97	8
PML-Research	490	158
Subtotal	***597***	***204***
Federal and Industrial Research		
Ford Motor Company	242	0
Georgia Power	4	8
Carolina Power & Light	2	2
Subtotal	***248***	***10***
Total	**845**	**214**

Neutron Radiography for University of Michigan Departments

Christopher N. Fredd (***UM - Chemical Engineering***) is utilizing neutron radiography as an analytical tool associated with his doctoral dissertation, *Stimulation of Ethylenediaminetetraacetic Acid (EDTA)*, completed this year under the guidance of Prof. Scott Fogler. Two visiting European scientists also received their Master's degrees in this program.

Fracture acidizing is a stimulation technique frequently used in the petroleum industry to improve well productivity in carbonate (limestone and dolomite) reservoirs. The process involves creating a fracture in the rock formation and injecting acid, usually hydrochloric. The acid dissolves the carbonate surfaces leaving a conductive channel through which reservoir fluids can flow. For an effective stimulation, live acid must penetrate as far down the fracture as possible. Unfortunately, significant fluid loss occurs normal to the fracture surface which reduces the penetration distance.

EDTA is being investigated as an alternative stimulation fluid. Experiments with carbonate cores indicate that EDTA may reduce the fluid loss by plugging fracture walls. The source of plugging is believed to be a precipitate that may be a dissolution product or an undissolvable component of the carbonate core. To determine the origin of this precipitate, samples of the carbonate and the precipitate are being analyzed through the aid of neutron activation. For further insight into the dissolution/precipitation in carbonates, images of treated cores have been obtained using neutron radiography. These tools are contributing to an understanding of the observed plugging and its usefulness in fracture acidizing.

Blake Tullis and his advisor, Prof. Steven Wright (***UM - Civil Engineering***), are using real time neutron radiography to study the role of fingering in water transport through soil. The purpose of this study is to investigate the role of fingering in the use of surfactants (detergents) to clean up petroleum spills and gasoline released from leaking underground tanks. Mr. Tullis has completed his Ph.D.

dissertation, entitled *The Role of Fingering During Aquifer Remediation with Surfactants*; a new student will continue his work.

Jiyoung Park (***UM - Nuclear Engineering & Radiological Sciences***) is conducting various neutron radiography experiments using various scattering media to measure, model, and remove scatter from neutron radiographic images. Small amounts of ^{3}He, ^{4}He, aluminum, and cadmium are initially being used. Ms. Park is a doctoral candidate. Her advisors are Prof. John Lee and Dr. John Lindsay. The title of her thesis is *Scatter Removal from Neutron Radiographic Images*.

Neutron Radiography for Federal and Industrial Research Organizations

Testing of Boral coupons used in spent fuel storage pools was performed for ***Carolina Power & Light*** and for ***Georgia Power***. 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.

A new $250,000 contract with ***Ford Motor Company*** has resulted in PML obtaining a test bench with driving motor and dynamometer for testing current and future transmission designs. In addition, PML has recently joined with Ford to develop better air conditioning subsystems for automobiles using the new non-chlorinated coolants.

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, recently finished a six-month International Atomic Energy Agency training fellowship in neutron radiography at the PML. Mr. Islam over sees the neutron radiography program at INST TRIGA reactor. During his stay, he concentrated on neutron radiography techniques and applications in industry, and he continued the research into water diffusion in epoxy.

Mr. M. Matsubayashi of the ***Japan Atomic Energy Research Institute (JAERI)***, Tokai Research Establishment, Japan, recently completed a one-year training fellowship at PML in neutron radiography. Mr. Matsubayashi is in charge of the JAERI neutron radiography program, in particular, the work performed with the JRR-3 research reactor. While at PML, he concentrated on neutron tomography, computerized image processing, and high resolution film radiography, and conducted a research project that involved the study of water diffusion through epoxies, an important research topic for the automotive industry for the prevention of corrosion in metallic structures sealed with epoxy. This work is ongoing to develop new standards for neutron 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 PML. He is planning on sending one student for training in neutron radioscopy next year and has requested a reciprocal visit from PML 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.

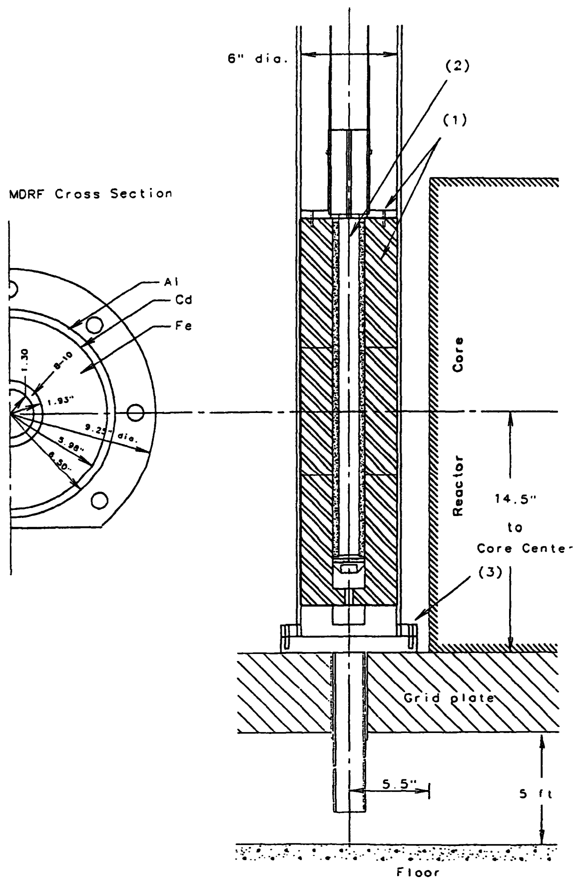
Significant effort has been underway at the FNR, for a number of years, to study the effects of long-term neutron and gamma irradiation on materials, as part of collaborative research with national laboratories and federal agencies. Current collaboration involves Oak Ridge National Laboratory and the 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.

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. 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, for example, 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.



The MDRF assembly in the water pool near the FNR reactor face. The outer aluminum pipe extends above the top of the pool. Sample irradiation thimbles, with active and/or passive detectors, are inserted from the top into the position shown. The entire assembly is transferred to a remote grid position when not in use.

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.

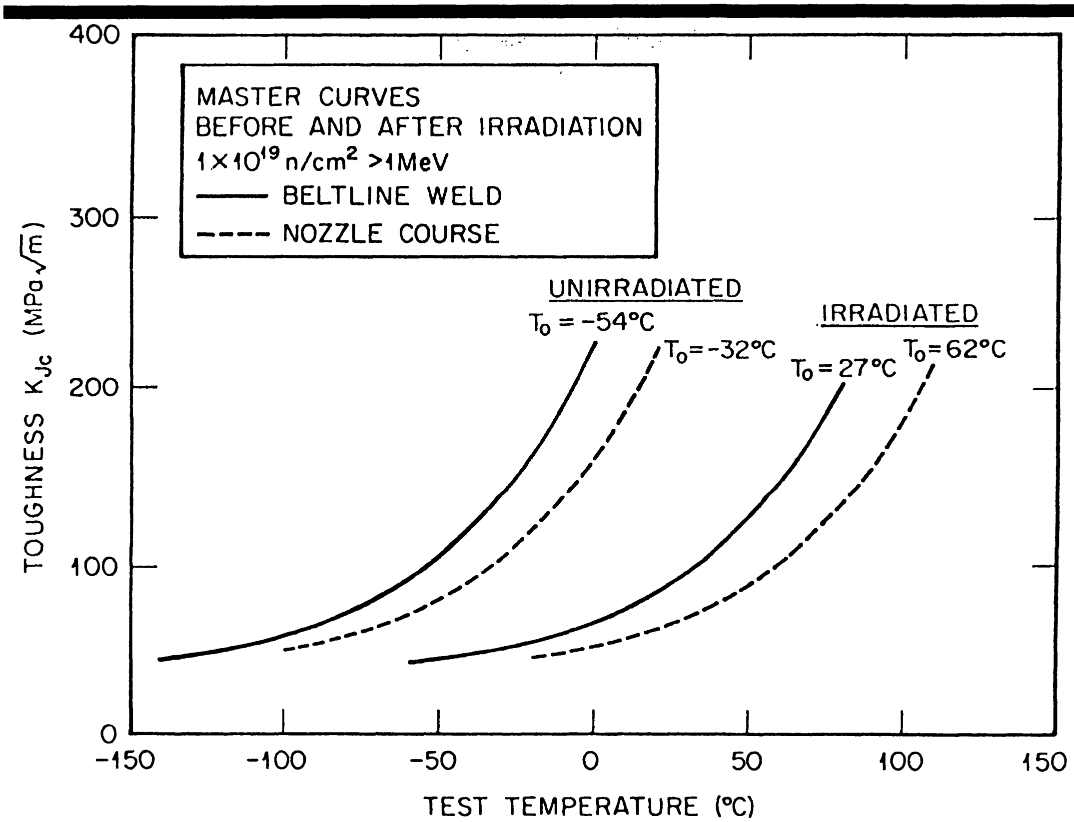
University of California Santa Barbara (UCSB). Specimen irradiation for a multi-year research project sponsored by the Nuclear Regulatory Commission at the Chemical and Nuclear Engineering Department of the University of California Santa Barbara, investigating neutron radiation damage in iron alloys 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. 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 PML/FNR staff.

Heavy Section Steel Irradiation (HSSI). Test specimen irradiation for the NRC sponsored HSSI Program at Oak Ridge National Laboratory are continuing at the Ford Nuclear Reactor. Two new, reusable irradiation facilities have been fabricated for the Irradiate - Anneal - Reirradiate, or IAR task of the HSSI Program. 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.

The objective is to determine what annealing conditions are required to achieve various degrees of recovery in the ductile-brittle transition temperature and fracture toughness of irradiated reactor pressure vessels currently in service. The rate at which irradiation induced degradation reoccurs in annealed, previously irradiated specimens is also being studied. A small preliminary set of test specimens for the IAR project are presently being irradiated in the UCSB facility.



Fracture-toughness curves generated with steel specimens taken from the unused Midland I reactor pressure vessel. Master curves reveal the temperature shift in toughness properties as a result of irradiation in the HSSI facility. Irradiated samples have a significantly higher temperature for the transition from the brittle to ductile fracture mode.

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 currently are performed at the Ford Nuclear Reactor. Recent HSSI accomplishments include:

- Completion of the 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 561 +/- 5 K during irradiation.

- Initiation of a major irradiation campaign using a 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.

- Initiation 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 thermal annealing and Reirradiation on K_{Jc} and K_{Ia} 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.

- Development of an irradiated-materials machining facility. This hot-cell based facility will permit the program to validate the assessment of the effects of neutron irradiation on the fracture-toughness properties of retired RPVs as well as typical RPV materials examined in previous HSSI studies.

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.

Pressure Vessel NDE. In a program indirectly related to the HSSI program, the Nuclear Regulatory Commission 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.

Researchers from the Japan Atomic Energy Institute and Ishikawajima - Havima Heavy Industries participated in the program in the fall of 1997.

Commercial Companies and Power Plants. During the year, materials testing was performed for the New York Power Authority and Omaha Public Power District. Additional testing was conducted for AAR Advanced Structures.

Material testing and neutron radiography of Boral coupons used in spent fuel storage pools was performed for Carolina Power & Light and for Georgia Power. 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.

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; sterilization of growth media; mutation of cells; and studies of radiation effects on chemical systems, polymers, plastics, electronic and reactor components, satellite components, food, seeds, plants, and parasites.

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 7. Over the past year, over 42,000 samples were irradiated; of these, the vast majority were for medical facilities and biomedical research. Michigan Regional Tissue Bank and Northern California Transplant Bank are two major users of the facility in recent years, accounting for over 75% of samples irradiated. Other major research areas include studies in environmental sciences, physics, and industrial materials testing.

Cobalt Irradiator Utilization by Hospitals and Tissue Banks

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 1.8×10^6 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 ^{60}Co Irradiator. Most samples are double sealed in plastic or aluminum packs and irradiated 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 cartilage is 1.8×10^6 to 2.5×10^6 rad administered over 8-16 hours.

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.

Cobalt Irradiator Utilization by Academic Biomedical Researchers

Deborah Cieslinski, the laboratory director for Dr. H. David Humes (***UM - 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 innoculation.

Steven A. Goldstein, Ph.D. (***UM - 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.

Table 7. Cobalt Irradiator Utilization, 1997-1998

Department/Organization	Number of Irradiations	Number of Samples
University of Michigan		
Atmospheric & Oceanic Science	1	3
Biology	5	712
Chemical Engineering	17	862
Civil & Environmental Engineering	21	159
Phoenix Project, Michigan Memorial	11	595
Physics	16	161
School of Natural Resources & Environment	3	163
University Hospital/Medical School		
Internal Medicine	10	87
Orthopedic Research	1	2
Subtotal	***85***	***2744***
Other Colleges, Hospitals, & Institutions		
Michigan Regional Tissue Bank	59	26011
Michigan State University	17	1358
Montana State University	1	8
Northern California Transplant Bank	83	8360
St. Luke's Hospital	3	56
Stanford University	1	758
University of California-Davis	1	106
University of Cincinnati-Biomechanics Lab	1	12
Subtotal	***166***	***36669***
Federal and Industrial Research		
Aastrom Biosciences, Inc.	26	393
Bionix	1	18
Dow Chemical	1	3
DowElanco	2	216
Eastman Kodak	2	13
Fermi National Lab	1	1
Ford Motor Co.	1	5
Gelman Sciences Inc.	26	1999
Ionics Inc.	1	48
LifeNet	5	335
Life Technologies, Inc.	13	118
New Waste Concepts	3	33
Promatec Technologies Inc.	1	4
Raven Biological Laboratories, Inc.	1	80
SoloHill Engineering, Inc.	1	30
Subtotal	***85***	***3296***
Total	**336**	**42709**

Prof. David Mooney (***UM - 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.

Previously, Dr. Feder completed a study in animals of the effects of two megarads of gamma radiation on patellar tendon allografts used to reconstruct the knee's anterior cruciate ligament (ACL). He was able to demonstrate that at this dose level, there were no differences between irradiated and non-irradiated allografts six months post-surgery. This project involved the work of two faculty members and a total of four students during the year.

These studies will evaluate higher irradiation levels. This is motivated by recent evidence suggesting that at least 3.6 megarads of radiation are required to kill all but one in a million AIDS infected cells in bone. Investigations of the effects of 4 megarads of gamma radiation on the initial mechanical and material properties of human patellar tendon allografts and continued animal implantation studies at this higher dosage are planned. These projects will involve two faculty members and six to eight students.

Dr. Dave Fredricks (***Stanford University***) is gamma irradiating water and buffer for use in a polymerase chain reaction assay designed to detect microbial DNR. They must start with DNR free reagents in order to prevent false positive results. "Sterile" water still contains microbial DNA that may interfere with the assay and they believe that gamma irradiation will destroy DNA in water rendering it non-amplifiable by PCR methods.

Cobalt Irradiator Utilization by 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.

Bionix Development Corporation. Bionix product development manager, David Kinsel, is gamma irradiating medical device plastics at sterilizing and greater doses. Bionix will compare the color and tensile properties to non-irradiated controls.

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 also will be sterilizing media that will be used for culturing strips in a new culturing technique Raven Biological is developing. Various materials such as the plastics that will be 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.

Cobalt Irradiation and Growth of Micro-Fungi

P.A. Volz[1], N. Rosenzweig[1], R.B. Blackburn[2], S.P. Wasser[3], and E. Nevo[4]

Eleven micro-fungal species were isolated from both north-facing slope (NFS) and south-facing slope (SFS) positions of Evolution Canon, Lower Nahal Oren, Israel, and their growth rates were examined before and after exposure to ^{60}Co irradiation. Earlier studies have shown that radiation can affect the growth dynamics of micro-fungi. When exposed to the irradiations of space, for example, certain yeasts were stimulated to increase growth and respiration rates. Other studies have shown, however, that the rate of survival and recovery of individual species can vary by phenotype according to previous environmental exposure.

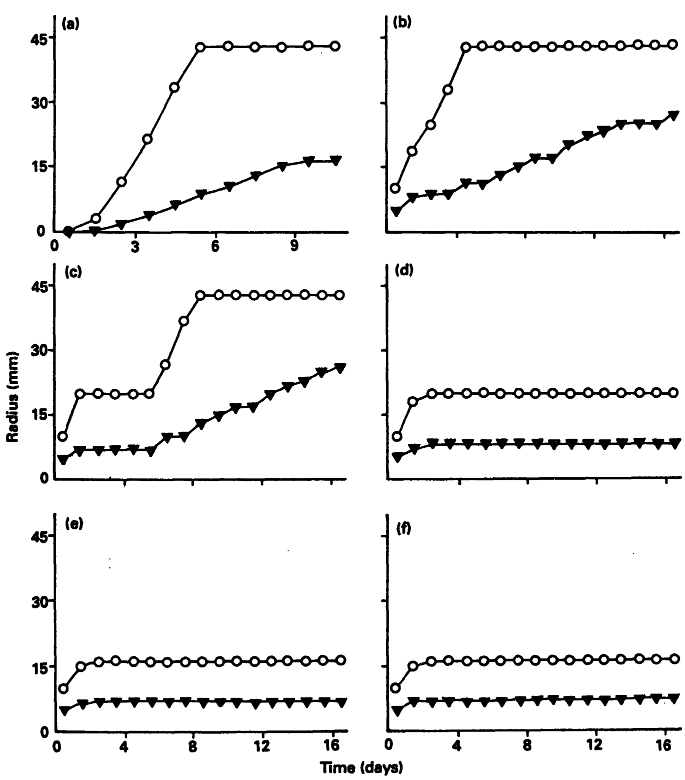
This study examined that hypothesis that isolates of the same micro-fungal species would exhibit differential response to radiation, based on their evolution in sites perennially exposed to different levels of solar radiation. Specifically, it was anticipated that isolates of the same micro-fungal species, recovered from opposing slopes of a canyon, would show variation in recovery time, growth dynamics, and physiology according to species and the direction of radiation received in north or south facing slope positions.

Soil samples were collected from the NFS and SFS of Evolution Canyon, for the isolation and characterization of micro-fungal species inhabiting the regions. Pure cultures of 11 species (each collected from both slopes) were made, and actively growing stock cultures were maintained on dextrose agar.

Before irradiation, growth rates varied for the same species according to whether it had been isolated from the NFS or SFS of the canyon. Certain species (including *Alternaria*, *Aspergillus*, *Humicola*, *Oidiodendron*, and *Staphylotrichus*) grew faster in isolates from SFS, while others (including *Fusarium*, *Sodaria*, and *Stachybotrys*) had faster growth rates in NFS isolates.

The eleven species were then subjected to ^{60}Co irradiation, with exposures levels ranging from 40K rads up to 4 x 10^6 rads ^{60}Co. After exposure, all isolates were monitored for growth patterns and variations, and isolates from NFS and SFS of the same species compared.

Most species of micro-fungi experienced greater growth rates when isolated from the SFS of Evolution Canyon than when isolated from the NFS. In addition, more micro-fungi manifested a greater response from SFS than the NFS when further subjected to various level of ^{60}Co irradiation. *Staphyotrichum coccosporum* demonstrate the greatest variation in growth rates between isolates from opposite slopes.



Growth rates of *S. coccosporum* isolated from the NFS (▼) and the SFS (o) of Evolution Canyon following exposure to ^{60}Co irradiation. (a) control isolates (no exposure); (b) 40,000 rads exposure; (c) 400,000 rads exposure; (d) 1 x 10^6 rads exposure; (e) 2 x 10^6 rads exposure; and (f) 4 x 10^6 rads exposure.

Volz, P.A., N. Rosenzweig, R.B. Blackburn, S.P. Wasser, and E. Nevo. 1997. Cobalt-60 radiation and growth of eleven species of micro-fungi from Evolution Canyon, Lower Nahal Oren, Israel. ***Microbios*** 91: 191-201.

[1]EM Mycology Associates, Ann Arbor; [2]Phoenix Memorial Laboratory; [3]N.G. Kholodny Institute of Botany, Kiev, Ukraine; [4]Institute of Evolution, Haifa, Israel.

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 is being observed.

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

Life Technologies. Richard Fike is studying the effects of various gamma irradiation doses on various salt solutions and growth/culture media that Life Technologies produces. They are hoping to decrease the bioburden of their products using gamma irradiation without causing toxicity problems or changes in the products that would render them useless for the original application.

Cobalt Irradiator Utilization for Biological Studies and Instruction

Prof. Ruthann Nichols (***UM - 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 (***UM - Biology***) irradiated soybeans from low to high gamma doses for use in for Biology 301 class projects.

Cobalt Irradiator Utilization for Environmental Studies

Undergraduate Shawn Bobick (***UM - School of Natural Resources & Environment)*** is sterilizing soil for a research project to identify the potential for abiotic fixation of nitrogen in soil. He is comparing levels. of abiotic fixation with levels of biotic fixation by soil micro-organisms. The research is part of the NSF Research Experience for Undergraduates program, under the supervision of Prof. Don Zak and Post-doctoral Fellow Greg Zogg.

Astrid Hillers, Michael McCormick, and others (***UM - Civil & Environmental Engineering***) are sterilizing soil with ^{60}Co gamma radiation for Dr. Peter Adriaens. 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.

Prof. Ernesto Franco ***(Michigan State University - Biology)*** is utilizing ^{60}Co gamma to sterilize soil with a five megarad dose. He then adds phanerochaete chrysosporium to the sterile soil to observe its growth. Phanerochaete chrysosporium is a lignin degrading basidiomycete capable of utilizing a wide range of environmental pollutants in pure culture. However, the ability of this fungus to grow and compete in the soil environment is relatively uncharacterized. The proposed experiment will compare the growth of phanerochaete chrysosporium in sterile soils with its growth in competition with the native soil microflora.

Gary Icopini (***Michigan State University - Geological Sciences/ Center for Microbial Ecology***) is irradiating samples as part of an ongoing research project to assess the mobility of chromium in a wetland environment. Samples will be used to determine if microbial processes influence chromium mobility. Treatment fluids will be pumped through four sets of soil samples. Two sets of samples will be treated with chemicals that enhance microbial growth. The other two sets will have a simulated rain water treatment applied to them and are considered to be the controls for the experiment. One of the controls will be the samples he is irradiating.

At ***University of California at Davis - Land, Air and Water Resources***, soils are used in studies examining 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.

Erica Miller (***Montana State University Bozeman***) sterilized soil contaminated with small amounts of pentachlorophenol wood preservative solution in the Cobalt Irradiator. She studied the effects on the preservative and then added microbes to the soil to test their ability to clean the soil of the preservative.

Mr. Robert West (***Dow Chemical***) is sterilizing soil samples for the environmental toxicology and chemistry research laboratory. He then tests the samples to find the extent and rate of degradation of pesticides in the soil. He is trying to determine what is responsible for the degradation of pesticides in soil.

Sandra Byrne (***Dow Elanco***) sterilizes soil samples. She then tests the samples to determine the extent and rate of degradation of pesticides in the soil. She is attempting to evaluate the cause of degradation of pesticides in soil.

John Phillips (***Ford Motor Company***) gamma sterilized soil for use in experiments involving addition of various organic compounds to the soil. Ford is working on ways to remove contaminants from soil.

Cobalt Irradiator Utilization for Physics Research

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

Dr. H. Richard Gustafson, an Associate Research Scientist (***UM - 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.

Prof. Martin R. Marcin (***UM - Physics***) is irradiating fused silica fibers (optical fibers). They transmit ultraviolet light primarily in the blue range and are used for laser calibration of scintillator tiles on a calorimeter. The fibers are subjected to various doses of ^{60}Co irradiation up to $1x10^6$ rad to study the changes in their transmission capabilities.

Cobalt Irradiator Utilization for Industrial Research

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.

Fermi National Accelerator Lab. Jay Hoffman is irradiating epoxy adhesives in the Cobalt Irradiator to a level of one mega-rad. The adhesives are used to bond aluminum and steel to lead in a radiation environment.

Promatec Technologies Incorporated. Promatec is gamma irradiating to 200 Mrad 3M Interam™ E50 series E54C flexible fire wrap to design basis accident conditions. The fire wrap is used in light-water nuclear power plants for the separation and protection of redundant cables and equipment.

Ionics, Inc. Bernie Mack gamma irradiated ethylene vinyl acetate (EVA) to various doses to possibly change the melting point and flow characteristics of the material after an initial manufacturing step.

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.

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 was 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 radiolabeled 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's disease. IBVM is being synthesized weekly for in house human studies. It may become a production compound in the near future.

Radiopharmaceuticals were shipped to 60 hospitals in 25 states and the District of Columbia in the United States; and to four hospitals in Alberta, Manatoba, Ontario, and Saskatchewan, Canada.

A summary of therapeutic radiopharmaceutical production broken down by country, state, and hospital, is presented in Table 8. Table 9 is a similar listing for diagnositc radiopharmaceutical production. In general, therapeutic samples contain larger amounts of radioactivity than diagnostic samples.

Table 8. Therapeutic Radiopharmaceutical Production Summary, 1997-1998

Recipient Hospital		mIBG-131 Injections
Georgia	Emory University, Atlanta	3
Kansas	University of Kansas, Kansas City	1
Michigan	University Hospital, Ann Arbor	1
North Carolina	Duke University, Durham	14
Pennsylvania	Childrens Hospital of Philadelphia, Philadelphia	2
Tennessee	Vanderbilt Medical Center, Nashville	2
Total Number of Injections/Synthesis		**23/22**

Table 9. Diagnostic Radiopharmaceutical Production Summary, 1997-1998

Hospital		NP-59	mIBG-123	IBVM
Canada				
Alberta	Foothills Provincial General Hospital, Calgary, ALB	1		
	Health Sciences Centre, Winnepeg, MAN	1		
	The Toronto Hospital, Toronto, ONT	3		
	Pasqua General Hospital, Regina, SAS	2		
United States				
Arizona	University Medical Center-Arizona, Tucson	1		
California	St. Agnes Medical Center, Fresno	1		
	University of California, Los Angeles	2		
	VAMC West Los Angeles Medical Center, Los Angeles	1		
	Sutter Community Hospital, Sacramento	1		
	University of California, San Francisco	1		
	South Coast Nuclear Med. Group, Inc., Santa Barbara	1		
Conn.	University of Connecticut Health Center, Farmington	8		
D. C.	Georgetown University Hospital, Washington	3		
Florida	Jackson Memorial Hospital, Miami	2		
	Tampa General Hospital, Tampa	3		
Illinois	Michael Reese Hospital, Chicago	3		
	Northwestern Memorial Hospital, Chicago	1		
	Rush Pres.-St. Luke Medical Center, Chicago	4		
	Loyola University Medical Center, Maywood	4		
Indiana	Luthern Hospital of Indiana, Ft. Wayne	2		
	The Methodist Hospitals-Southlake Campus, Merillville	1		
Kansas	University of Kansas Medical Center, Kansas City	2		
	Christie Hospital, Witchita	1		
Louisiana	Tulane University Hospital, New Orleans	1		
	Overton Brooks VA Medical Center, Shreveport	1		
Maryland	John Hopkins, Baltimore	0	0	1
Mass.	Boston University Hospital, Boston	1		
	New England Medical Center, Boston	5		
	Univ. of Massachusetts Medical Center, Worcester	2		
Michigan	St. Joseph Mercy Hospital, Ann Arbor	2		
	University of Michigan's Hospital, Ann Arbor	73	72	36
	Oakwood Hospital, Dearborn	2		
	Henry Ford Hospital, Detroit	6		
	Saint John Hospital, Detroit	2		
	William Beaumont Hospital, Royal Oak	2		
Missouri	Cox Medical Center-North, Springfield	4		
	St. Johns Mercy Medical Center, St. Louis	2		
N.J.	St. Barnabus Medical Center, Livingston	2		

Table 9. Diagnostic Radiopharmaceutical Production Summary, 1997-1998 (cont.)

Hospital		NP-59	mIBG-123	IBVM
New York	Mem. Sloan-Kettering Cancer Center, New York City	3		
	New York Hospital, New York City	2		
	St. Lukes/Roosevelt Hospital, New York City	2		
	St. Vincents Hospital, New York City	1		
	VA Medical Center, Northport	1		
N. C.	Medical University of South Carolina, Charleston	1		
	North Carolina Baptist Hospital, Winston-Salem	2		
Ohio	University of Cincinnati, Cincinnati	1		
	Ohio State University Hospital, Columbus	2		
	Riverside Methodist Hospital, Columbus	1		
	Summa Health Systems, Uniontown	1		
Okla.	University of Oklahoma, Oklahoma City	3		
Oregon	Sacred Heart General Hospital, Eugene	1		
Penn.	Lehigh Valley Hospital, Allentown	3		
	Allegheny University of Health Sciences, Philadelphia	0	6	
	Hospital of the Univ.of Pennsylvania, Philadelphia	4		
R. I.	Rhode Island Hospital, Providence	1		
S. C.	Medical University of South Carolina, Charleston	1		
Tenn.	Baptist Memorial Hospital-Central, Memphis	1		
Texas	Hermann Hospital, Houston	3		
Wash.	University of Washington, Seattle	7		
Wisc.	Univ. of Wisconsin, Madison	3		
	St. Luke's Medical Center, Milwaukee	4		
Total Radiopharmaceutical Production		**202**	**78**	**37**

Collaborative Programs with Academic Departments

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. In addition, MMPP has close research ties with scientists from Eastern Michigan University and Albion College.

Nuclear Engineering & Radiological Sciences (NERS)

A number of faculty members and research scientists in the NERS department have maintained long-term collaborations with the PML staff, essentially spanning the entire 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 is supported by Lockheed Martin Energy Systems ($34,000/20 mos.)

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 disposed of in nuclear waste repositories. Site restoration activities at DOE facilities and the permanent disposal of nuclear waste generated at DOE facilities involve working with and within various types and levels of radiation fields. Once the nuclear waste is incorporated into a final form, radioactive decay will decrease the radiation field over geologic time scales, but the α-decay dose for these solids will still reach values as high as 10^{18} α-decay events/gm in periods as short as 1,000 years. This dose is well within the range for which important chemical (e.g., increased leach rate) and physical (e.g., volume expansion) changes may occur in crystalline ceramics. Release and sorption of long-lived actinides (e.g., ^{237}Np) can provide a radiation exposure to backfill materials, and changes in important properties (e.g., cation exchange capacity) may occur. 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 microstructural evolution during irradiation of two important groups of materials, sheet silicates (e.g., clays) and zeolites, are being conducted at PML/FNR facilities; 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).

Single Carrier Charge Sensing HgI_2 Radiation Detectors: Professors Zhong He and David Wehe continue their semiconductor detector development program with HgI_2. With a high atomic number, high density, and wide band gap, HgI_2 is very attractive as a high efficiency semiconductor gamma-ray detector which can be operated at room temperatures. However, due to the poor carrier collection, the induced charge on a conventional planar electrode is not directly proportional to the gamma-ray energy deposited in detector volume, but rather is a function of the interaction depth between the cathode and the anode. This makes it impossible to determine the gamma-ray energy from the amplitude of the induced pulse and prohibits the material from being used as a spectrometer. This project explores the possibility of applying the new single carrier charge sensing technique on HgI_2 detectors. This method, which has worked on other materials with similar problems, produces an induced pulse amplitude which is only proportional to the number of electrons arriving on the anode surface. Since the charge transport properties of electrons are much better than that of the holes, the new technique should enhance the gamma-ray spectroscopic performance of HgI_2 detectors significantly. The challenge is to design and fabricate an effective electrode pattern which will efficiently collect the electrons only. This project is supported by Constellation Technolog Corporation, an established firm specializing in the development of HgI_2 radiation detectors ($38,532/9 mos).

Development *of Gamma-Ray Compton Imagers Using Room-Temperature 3-D Position Sensitive Semiconductor Detectors:* Under the direction of Professors Zhong He, David Wehe, and Glenn Knoll, this project explores gamma-ray imaging devices which use the newly developed 3-dimensional position-sensitive room temperature semiconductor CdZnTe (CZT) gamma -ray spectrometers. Previous efforts fabricated two fully functional 3-dimensional position sensitive CZT semiconductor gamma -ray detectors. These detectors show 1.7% FWHM energy resolution and 0.7x0.7x0.5 mm position resolution for 662 keV incident gamma-ray energies on both of the 1x1x1 cm cube CdZnTe crystals. These performance values are significantly better than the ~6-7% FWHM energy resolution and ~3 mm FWHM position resolution values common to the standard 2-dimensional position sensitive scintillation detectors currently used for most gamma-ray imaging applications. Thus, the new detectors are expected to have a significant impact in gamma-ray imaging. The project is supported by the U.S. Department of Energy's NEER program ($496,309/3 yrs).

Non-Destructive Spent Fuel Characterization with Semiconducting Gallium Arsenide Neutron Imaging Arrays: This project, developed by Dr. John Lindsay, Dr. Doug McGregor, and Prof. John Lee, incorporates the use of ^{10}B coated bulk GaAs Schottky barrier neutron detection arrays in conjunction with a Sb/Be 24 keV neutron source to measure the fissile content of spent nuclear fuel. The goal of the overall project is to fabricate, test, and demonstrate a relatively portable device capable of characterizing and produced tomographic images of spent fuel elements. Reactor physics calculations for FNR fuel elements are underway and measurements of spent fuel characteristics will be performed in PML hot caves. This research effort is supported by the U.S. Department of Energy ($534,821/3 yrs).

Advanced Devices and Systems for Radiation Measurements: Under the direction of Prof. Glenn Knoll and Prof. David Wehe, 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).

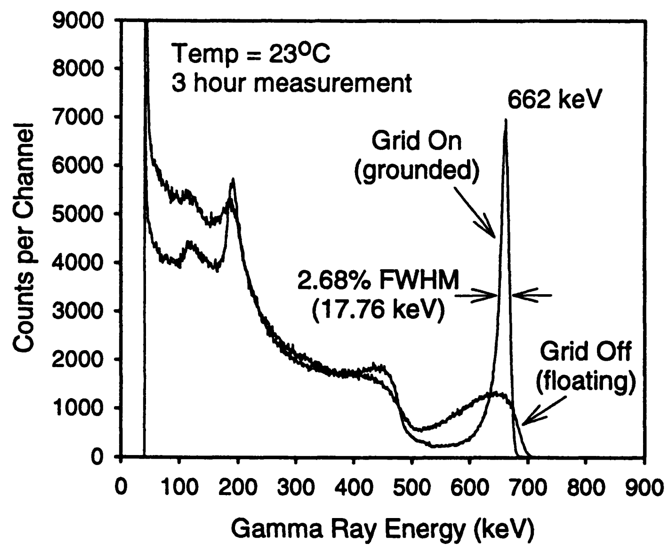
Radiation Detector Development at PML

Douglas S. McGregor and John T. Lindsay
Nuclear Engineering & Radiological Sciences

Semiconductor-based radiation detection devices are being developed and characterized at the Phoenix Memorial Lab and Ford Nuclear Reactor. The goal of this work is to develop radiation detectors that have the excellent energy resolution offered by a semiconductor, but without the limitations of low effeciency and cryogenic cooling required by conventional Ge and Si materials. New devices that detect charged particles, gamma rays, and thermal neutrons have shown very promising results. For example, fundamental ground breaking work on the physics of semi-insulating bulk GaAs as a radiation detector led to the world's record for room temperature alpha particle energy resolution for bulk GaAs being set, 2.5% FWHM at 5.5 MeV. The "truncated electric field effect" in bulk GaAs diodes was discovered at PML, and fundamental theories as to the cause for the effect were introduced.

Building upon this work, a new project was initiated last year to develop GaAs Thermal Neutron Detectors. The first GaAs-based boron coated thermal neutron detectors have been partially fabricated and demonstrated at the PML/FNR. The devices consist of 5 x 5 arrays of 1 mm^2 pixels, each coated with ^{10}B. Thermal neutrons react with the ^{10}B to produce charged particles, which are then detected in the GaAs detector. The "truncated electric field effect" plays a major part in the device operation. Preliminary tests demonstrated thermal neutron efficiency of 2% for a single 300 μm thick device with only a thin 0.4 μm ^{10}B layer. 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 millimeters thick. This GaAs thermal neutron work is being extended through an SBIR collaboration with SPIRE Corporation. In this work, an alternative design is being investigated for the ^{10}B coated GaAs device. GaAs based pin diodes are being fabricated at SPIRE and coated with ^{10}B and tested in the neutrons beam ports at the PML/FNR.

While GaAs is being developed for thermal neutron detection, CdZnTe has demonstrated good energy resolution for gamma rays, as described in the previous section. Unfortunately, fundamental understanding of the material is largely lacking and results in costs of ~$20K/$cm^3$ when suitable material can even be found. The designs described in the previous section, such as co-planar grids and drift diodes, use complex electrode patterns and sophisticated electronics to achieve their superor results. Recognizing the need for simpler designs, special geometrically-weighted CdZnTe crystals were cut from a raw ingot, and lapped and polished into trapezoid prisms to enhance their performance. Evaporating external grids on the trapezoid sides and grounding the grids with respect to the anode and cathode yielded devices with good energy resolution, but requiring only simple commercial electronics. While these devices are useful for a variety of applications, we are developing an understanding of the surface chemistry that will be useful as we begin a more thorough study into the growth and processing of this unique material.



Sample spectra for 662 keV gamma rays from ^{137}Cs, in which 2.68% FWHM energy resolution was achieved at room temperature using CdZnTe Frisch grid gamma ray detector. Also shown is the resolution difference when the Frisch grid is disconnected.

Robotic Systems for Hazardous Environments: The goal of this project, under the direction of Prof. David Wehe, is to support DOE's Robotics Technology Development 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 most recent camera developed by Prof. Wehe's team -- the Hybrid Portable Gamma Camera -- uses a coded aperture (16 element URA mask) for imaging gamma rays of low energy and, at higher energies where the mask becomes translucent, a second detector array for Compton imaging from first array scattered gamma rays. The project is funded through the U.S. Department of Energy's Office of Environmental Management ($860,000/12 mo).

Research on CZT 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, our research shows that the major limitations occur near the surface. The project is supported by Sandia National Laboratory ($276,000/12 mos).

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 graduate student 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 signiicance 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 microgram 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 (***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.

In a new project, the UM and EMU Nuclear Chemistry teams will be collaborating to assist in updating the *Heath Gamma-Ray Catalog*. This project will involve obtaining gamma-ray spectra for nuclides produced at FNR, especially those involving radiochemical purification. As a start, the team is investigating means to obtain clean ^{49}Ca gamma -ray spectra and developing appropriate radiochemical procedures to remove contamination. Later efforts will focus on developing the necessary chemical separation procedures for obtaining the gamma-ray spectra of certain strontium and yttrium nuclides produced in fission.

In addition, several UM Chemistry graduate students have recently conducted research at FNR. James Zimmerman, a doctoral candidate, irradiated small quantities of uranium in liquid and solid form to produce mixed fission products for use in the study of chemical and physical properties of individual fission product nuclides. In addition, Mr. Zimmerman irradiated small quantities of selenium and zinc metal to make low energy X-ray calibration standards by neutron activation. The metals were thin foils of very low mass that were irradiated for a prolonged period. Some radiochemical purification was utilized to improve the quality of the sources.

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 center on the development of radiotracers for diagnostic imaging. Research efforts include the development of:

- mIBG, radioiodinated analogs of anti-hypertensive drugs;
- adrenal scaning agent NP-59; and
- radiolabeled marker IBVM for the study of brain disorders such as Alzheimer's disease.

In Nuclear Medicine imaging procedures, the *in vivo* localization of an administered radiolabeled compound (radiopharmaceutical) 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 MMPP's Nuclear Medicine laboratory studies. Sympathetic neurons synthesize and store norepinephrine, the endogenous neurotransmitter of the sympathetic nervous system. Animal studies have shown that tritiumlabeled norepinephrine and related analogs are sequestered within sympathetic neurons upon intravenous administration. This sequestration occurs by a high affinity, low capacity uptake process via a specific protein (the norepinephrine transporter). At MMPP, 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 *meta*hydroxyephedrine, [^{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 MMPP 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 Michigan to assess its utility in imaging the extent of cholinergic neuronal impairment in patients with Alzheimer's disease.

Department of Environmental and Industrial Health (EIH)

EIH, in collaboration with Phoenix Memorial Laboratory, has established a low background gamma spectrometer at PML. The facility is intended primarily for quantifying gamma emitting isotopes in environmental samples. Prof. David Hamby has an on-going project examining the uptake and retention of cesium in bluegill fish from the Savanna River, near the large DOE nuclear waste storage and processing facilities. The fish, which had been previously exposed to ^{137}Cs from site operations, were further dosed with ^{134}Cs to determine whether the retention rate of ^{137}Cs in internal organs is the same for chronically vs. acutely exposed fish. Cesium is one of the more prominent nuclides from DOE sites owing to its long half-life, and it contributes the largest dose to the public.

Museum of Anthropology Program in Archaeometry

A new educational initiative that is just getting underway involves PML research scientist Dr. Leah Minc, who is an archaeologist by training. She is teaching a course on INAA applications under a "Problems in Archaeology" structure in the Department of Anthropology for Winter 1999. The course attempts to make 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.

Comparison of Cesium Retention Kinetics in Bluegill Following Acute and Chronic Dosing

David M. Hamby
Department of Environmental and Industrial Health

A critical aspect of the environmental restoration and remediation process is understanding contaminant fate sufficiently well as to permit prediction of potential human and environmental risks. The proximity of most nuclear reactors to aquatic systems has required that hydrospheric pathways be considered as potentially significant sources of human exposure. A major contributor to human dose from these pathways is the consumption of contaminated fishes. Of the radionuclides characteristic of these releases, radiocesium (i.e., ^{137}Cs) is of particular interest due to its long radiological half-life, high fission yield, and ready biological availability. From a human health perspective, ^{137}Cs concentrates in the edible muscle of animals, and consumption of contaminated animals can be a significant source of exposure. For these reasons, cesium is a contaminant of concern to current decision-making regarding the fate of radiologically-contaminated sites which seek to balance cost analyses of cleanup efforts with the desired benefits of that restoration.

Most previous studies of radiocesium elimination from fishes have been based on acute introduction, either orally through gavage or by labeling the food with the nuclide. While such procedures are useful in predicting the immediate impact of a recent release, evidence suggests that it is possible that these results may not be reliable predictors of the long-term kinetics of fishes in equilibrium with their environment, as is the case in most radiocesium-contaminated sites. Moreover, acute dosing is subject to a number of artifacts (e.g. unrealistic presentation of the isotope in the form and quantity of natural diets), and thus may be deficient in explaining the internal distribution processes that occur within biota over a lifetime of exposure.

This study is designed to directly compare the elimination kinetics and compartmentalization of radiocesium in bluegill (*Lepomis macrochirus*) following both acute dosing and chronic uptake. Also, cesium distribution within the organs of these fish as a function of time is being investigated. We are comparing dosing techniques within the same fish by using a two-isotope method, thus avoiding statistical variance due to individual differences. Fish were collected from a ^{137}Cs-contaminated reservoir. This contamination occurred long enough ago that cesium concentrations in the fish population and the environment are at equilibrium. These fish provide the population for an acute-dosing study using ^{134}Cs. Two isotopes of the same element with such a small difference in atomic weight will act identically under the same biological influences. Any difference in the retention of these two isotopes will, then, illustrate variability due to the uptake mechanism. Following the individual organ burdens of each of these isotopes throughout the study provides more direct evidence of these differences.

Whole-body burdens of ^{134}Cs and ^{137}Cs in live fish were measured at two-week intervals using a 3x3 NaI(Tl) detector (Canberra) with a multi-channel analyzer. Cohorts of 6 fish were sacrificed at 10-day intervals to allow for organ burden measurements. Following whole-body measurements, these fish were carefully dissected, and separate organs (or aliquots of skin, white muscle, heart, kidney, liver, stomach, stomach contents, and gills) were measured for burdens of ^{134}Cs and ^{137}Cs using the high-purity germanium detector located in PML for comparison with standards of known activity. The entire specimen (organs and remaining carcass) is then homogenized and analyzed.

The work described herein is ongoing. Approximately half of the fish and organ samples have been analyzed to date. A preliminary analysis of the data shows that the elimination rates are statistically similar, regardless of chronic or acute dosing regime.

Phoenix Grants for Faculty Research

Phoenix grants support faculty research involving the peaceful applications and the social implications of nuclear science and technology. Requests for $6,000 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. Applications from faculty who have substantial outside support or who have received significant Phoenix support previously will be given lower priority and will be required to demonstrate the pressing need for these additional Phoenix funds.

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). Part-time faculty, Research Investigators, Instructors, and Lecturers with 50 percent or greater appointments, who are required to conduct research as part of their University duties, also are eligible to apply. Clinical staff members are eligible only if they have an additional appointment as a regular teaching and/or research faculty member and are required to conduct research or teach formal University courses. Doctoral students are not eligible.

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 applicant should designate the Divisional Review Board which it is felt would most knowledgeably review the application. Where appropriate, more than one Board may be designated. The Divisional Review Boards are:

I. Biological and Health Sciences
II. Physical Sciences and Engineering
III. Social Sciences and Education
IV. Humanities and Arts

The budget period is for one year. Allowable expenses include equipment, expendable supplies and services, travel, and salaries and benefits for research assistants. The Phoenix Project will not pay the salary of the principal investigator, nor will it pay publication expenses. A list of awards made during Fall Term, 1997, follows (Table 10).

Table 10. Phoenix Faculty Research Grants Awarded Fall Term, 1997

Director & Department	Project Title
Siew-Ging Gong Pediatric Dentistry	*Isolate, Characterization and Functional Analysis of the Xenopus msx2 Gene*
David C. Kohrman Otolaryngology/Kresge Hearing Research Institute	*High Resolution Genetic Analysis of the Mouse Deafness Mutant 'Spinner'*
Richard H. Moseley Internal Medicine	*Characterization of the Functional Defect in Wilson's Disease*
Ayylusamy Ramamoorthy Chemistry/Biophysics Research Division	*Structure Determination of the Second Transmembrane Peptide Fragment of Human* a_2*-GABA*$_A$ *Receptor Using Solid-State NMR Spectroscopy*
Shiyong Wu Radiation Oncology	*The Role of Daxx in Gamma-Radiation-Induced Apoptosis*
Fred D. Becchetti Physics	*Teaching Simulations for Topics in Nuclear Medicine*
Lu-Min Wang Nuclear Engineering and Radiological Sciences	*Transmission Electron Microscopy Study of Radiation Effects of Actinide Containing Minerals and Neutron Irradiation Ceramic Materials*
Zhi Chen Internal Medicine	*Analysis of Function of Transcription Enhancer Factor One in Heart Formation*

D.O.E. Reactor Sharing Program

The U.S. Department of Energy provides support to MMPP through its 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 granting period September, 1997 to September, 1998, DOE provided $35,000; this amount has been increased to $50,000 for the granting period August, 1998 to August, 1999.

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 11).

Table 11. Research Projects at FNR Supported by DOE Reactor Sharing Program

INAA Studies in Archaeology

Dr. Clarence Menninga, Calvin College	Characterization of ancient pottery from Abila excavation, Jordan.
Timothy Hare, SUNY - Albany	Sourcing Aztec-period ceramics from Morelos, Mexico, based on their geochemical signature, to examine ceramic production and exchange systems.
Catherine Chmidling, University of Maine	Identification of elemental signatures for lithic raw material sources, which can be linked to artifacts from sites in the northern Chihuahuan Desert, to examine trade patterns and population movements.

INAA Studies in Geology

Prof. James Brophy, Indiana University	Fractional crystallization mechanisms within orogenic (calc-alkaline) magma systems, South Sister Volcano, Oregon Cascades.
Mathew Paige, Indiana University	Evaluation of magmatic processes in the calc-alkaline Guadalupe Complex, Caatheys Valley, CA.
Michael Dorais, Indiana University	Determination of the tectonic setting of magmas of Massabesic Gneiss Complex, NH, from metaigneous rock samples.
Robert Ward, N. Illinois University	Deep crystal growth and modification beneath the Trans-Pecos Volcanic Province in southwest North America in rock samples of Cenozoic age.
Prof. Ellen Metzger, San Jose State University	Investigation of ocean basin conditions based on rare-earth element concentrations in metamorphic rocks of the northern Cascades.
Prof. Lingren Chyi, University of Akron	Development of discrimination diagrams based on the triad of aluminum, lanthenum, and scandium.
Lawrence Antonelli, University of Akron	Examination of trace-elements in groundwater, with emphasis on the Al-La-Sc coherent triad.
Robert Kowalkoski, University of Akron	Evaluation of trivalent cations in groundwater.
Maria Prokopenko, University of Cincinnati	Research on the geochemistry of K-bentonites from the Precordillera, Argentina, which represent altered volcanic ash.
Abbas Sharaky, University of Colorado	Examination of the relationship between porphyry (high temperature, subvolcanic) and epithermal (low temperature) deposits at Jamestown, Co, based on geochemistry of ore deposits and surrounding veins.
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.
Lupe Maldonado, University of Colorado	Determination of the geochemistry of mineralized ore-deposits.

Table 11. Research Projects at FNR Supported by DOE Reactor Sharing Program (cont.)

INAA Studies in Geology (cont.)

Ralph Klinger, University of Colorado	Examination of the trace-element composition of a series of volcanic ash deposits.
Dr. Terry Spell & Leigh Justet Univ. of Nevada - Las Vegas	Investigation of potential low-volume effusive eruption of rhyolitic magma, based on a sequence of volcanic rocks from the Jemez Volcanic Field, New Mexico.
Prof. Wm. Simmons, Univ. of New Orleans	Researching the origin of Wisconsin pegmatites, and an on-going study on the geochemistry and mineralogy of tourmaline from Siberia.
Brenda Yawn & Prof. Karen Webber, Univ. of New Orleans	Investigation into the mineralogy and geochemistry of volcanic rocks from Death Valley, CA, in order to relate volcanisms and tectonics in the region.

Ar-Ar Dating for Geochronology

Lehigh University	Studies of tectonic evlution 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 mineralising fluid systems.

Educational 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 (Tables 12 and 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.

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.

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.

Within the University of Michigan, the Department of Chemistry utilizes the facilities at FNR for upper-level under-graduate 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.

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

Chemistry students from Eastern Michigan University utilized the facility for a one-day introductory lab to neutron activiation analysis. A similar short-course was presented to chemistry classes from Carrol High School, Ft. Wayne, IN. Over the summer, young scientists took full advantage of the Ann Arbor Hands On Museum's summer program to get an in-depth view of reactor physics and radiation science.

A total of 36 professionals from around the world participated in a one-day workshop at PML/FNR, as part of the International Atomic Energy Agency (IAEA)'s three-week course entitled *Regulatory Aspects and Safety Documentation of Nuclear Research Reactors.* Visitors toured the PML/FNR facilities, and participated in presentations on technical specifications, conduct of operations, practices, and documentation, and safety analysis.

Public Tours

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 year, approximately 813 people participated in 59 tours.

Table 12. 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 new 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 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.

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.

Table 12. University of Michigan Courses Utilizing PML/FNR (cont.)

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.

Table 13. Reactor Teaching and Training for UM Departments, 1995-1998

Department	Course	Number of Students	Number of Classes
Archaeology		5	3
CEW Interns		2	1
Chemical Engineering		9	2
Chemistry		5	2
College of Engineering		109	3
Dearborn Campus		6	2
Geological Sciences	Various	34	5
	Geology 455	7	2
Minority Engineering Office		48	3
Nuclear Engineering & Radiological Sciences	NERS 211	44	3
	NERS 311	34	2
	NERS 312	28	3
	NERS 315	58	3
	NERS 400	62	6
	NERS 441	27	1
	NERS 442	14	2
	NERS 445	15	2
	NERS 462	14	3
	NERS 490	46	3
	NERS 499	2	1
	NERS 515	54	3
	NERS 543	11	1
	NERS 561	4	1
	NERS 590	16	1
	NERS 599	7	6
	NERS 599	14	5
	NERS 990	7	4
	NERS 995	20	6
Nuclear Medicine		12	1
Physics		5	1
School of Public Health		15	3
UM Total		**734**	**84**

Researchers and Students Utilizing PML/FNR, 1997-1998

UM Researchers

Block, Bruce	Atmospheric, Oceanic, and Space Sciences
Kennedy, Tim	Atmospheric, Oceanic, and Space Sciences
Helling, Robert	Biology
Nichols, Ruthann	Biological Chemistry
Fogler, Scott	Chemical Engineering
Mooney, David	Chemical Engineering
Thompson, Levi	Chemical Engineering
Yang, Ralph	Chemical Engineering
Francis, Anthony	Chemistry
Gordus, Adon	Chemistry
Griffin, Henry	Chemistry
Weber, Walter	Civil and Environmental Engineering
O'Brien, William	Dentistry
Rutherford, Bruce	Dentistry
Drexler, John	Earth Sciences-Geochronology
Miklos, Joseph	Environmental & Industrial Health
Halliday, Alex	Geological Sciences
Hubacker, Fritz	Geological Sciences
Kessler, Steve	Geological Sciences
Mukusa, Sam	Geological Sciences
Owen, Robert	Geological Sciences
Cieslinski, Deborah	Internal Medicine
Humes, David	Internal Medicine
Ford, Richard	Museum of Anthropology
Minc, Leah	Museum of Anthropology
O'Shea, John	Museum of Anthropology
Smith, Adam	Museum of Anthropology
Wright, Henry	Museum of Anthropology
Fleming, Ronald	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
Goldstein, Steve	Orthopedic Surgery
Debano, Chris	Orthopedic Research
Gustafson, Dick	Physics
Marcin, Marty	Physics
Roe, Byron	Physics
Zak, Don	School of Natural Resources & Environment
Killeen, Tim	Space Sciences Research Lab

Researchers and Students Utilizing PML/FNR, 1997-1998 (cont.)

Researchers from Other Universities

Ludington, Marty	Albion College	Physics
Falconer, Steve	Arizona State	Anthropology
Srinivasan, V.S.	Bowling Green St. University	Chemistry
Menninga, Clarence	Calvin College	Geol, Geogr., & Environ. Studies
Yogodzinski, Gene	Dickinson College	Geology
Contis, Ellene T.	Eastern Michigan University	Chemistry
Rengan, Krish	Eastern Michigan University	Chemistry
Barth, Andrew	Indiana University	Geological Sciences
Brophy, James	Indiana University	Geological Sciences
Ripley, Edward	Indiana University	Geological Sciences
Adams, C.	Inst. of Geol. & Nuclear Sci. Ltd.	Nuclear Science
Zeitler, Peter K.	Lehigh University	Earth Sciences
Pollard, Helen	Michigan State University	Anthropology
Voice, Thomas	Michigan State University	Civil & Environmental Engineering
Franco, Ernesto	Michigan State University	Biology
Peters, Lisa	New Mexico Inst. Mining & Tech.	Geosciences
Wapnir, Raul	North Shore University Hospital	Pediatrics
Duebendorfer, Ernie	Northern Arizona University	Geology
Walker, James	Northern Illinois University	Geology
Foland, Ken	Ohio State University	Geological Sciences
Kelley, Simon	Open University	Earth Sciences
Metzger, Ellen	San Jose State Univ.	Geology
Fredricks, David	Stanford University Medicine,	Div. of Infectious Diseases
Smith, Michael	SUNY Albany	Anthropology
Chyi, Lin	University of Akron	Geology
Baldwin, Suzanne	University of Arizona	Geosciences
Arnaud, Nicolas	Université Blaise Pascal	Groupé de Geochronologie Ar-Ar
Wartho, Jo-Anne	Univ. of California, Los Angeles	Geology
Lucas, Glenn E.	Univ. of Calif., Santa Barbara	Chemical Engineering
Odette, G. Robert	Univ. of Calif., Santa Barbara	Chemical Engineering
VernonClark, Russell	Univ. of Calif., Santa Barbara	Chemistry and Biochemistry
Huff, Warren	University of Cincinnati	Geology
Kilinc, Attila	University of Cincinnati	Geology
Budd, David	University of Colorado, Boulder	Geological Sciences
Copeland, Peter	University of Houston	Geosciences
Walker, J.D.	University of Kansas	Geology
Burgess, Ray	University of Manchester	Earth Sciences
Turner, Grenville	University of Manchester	Earth Sciences
Smith, Eugene	Univ. of Nevada, Las Vegas	Geoscience
Falster, Al	University of New Orleans	Geology and Geophysics
Harrell, James	University of Toledo	Geology
Bonivich, Jeff	Wayne State University	Detroit Surgery
Chandrasekhar, Kota	Wayne State University	Radiation Oncology
Lucas, Charles	Wayne State University	School of Medicine

Researchers and Students Utilizing PML/FNR, 1997-1998 (cont.)

Researchers from Other Institutions

Kinsel, David	Bionix Development Corporation	
Steklenski, David	Eastman Kodak Company	Diagnostic Imaging
Pla-Dalmau, Anna	Fermilab	
Gooden, John	Ford Motor Co.	
Sinclair, Art	Gelman Sciences	
Schneider, Eric	General Motors Co.	R&D and NAO Planning
Lechman, D. C.	General Motors Co.	
Reising, R. R.	General Motors Co.	
Albert, Fred	Montana Biotech Corporation	Microbiology
Forsell, James	Northern California Transplant Bank	
Brown, Allen	Northern California Transplant Bank	
Crockett, Don	Novi High School	
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
Russell, K.F.	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	Nat'l. Inst. Standards & Techology	Materials Reliability Division
Kyle, Jeff	Pall Gelman Sciences	Medical Filtration
LaCoe, Scott	Pall Gelman Sciences	Medical Filtration
McDonough, David	Pall Incorporated	
Carroll, Pat	St. Luke's Hospital	
Kotowicz, Ellie	St. Luke's Hospital	
Hillegas, William	SoloHill Engineering, Inc.	
Sklapsky, Brian	Sparrow Hospital	
Fredd, Christopher N.	Technology Center of the Americas	
Yusuf, Siaka O.	Gamma Metrics, Inc.	
Smith, R. Mike	Delphi Energy and Engine Management Systems	
Brevick, J.E.	Ford Motor Co.	
Helmer, R.	Idaho National Engineering and Environment Laboratory	
Hawari, A.	ABB Combustion Engineering	
Mare, W. H.	St. Louis, MO	

Researchers and Students Utilizing PML/FNR, 1997-1998 (cont.)

UM Students

Paisley, Keri	Biology
Bennett, Chris	Chemical Engineering
Brenner, Jim	Chemical Engineering
Csera, Petra	Chemical Engineering
Johnson, Wes	Chemical Engineering
Long, Richard	Chemical Engineering
Nikolovski, Janet	Chemical Engineering
Rowley, John	Chemical Engineering
Siripen, Mala	Chemical Engineering
Tharapwattananon, N.	Chemical Engineering
Busby, Bruce	Chemistry
Espinosa, Chris	Chemistry
Zaziski, David	Chemistry
Zimmerman, Jim	Chemistry
Johnson, Marty	Civil and Environmental
Orlov, Alex	Civil and Environmental
Dickens, Gerald	Geological Sciences
Duly, Susannah	Geological Sciences
Johnson, Marcus	Geological Sciences
Kraemer, Lisa	Geological Sciences
Zhou, Pinbo	Geological Sciences
Eiselt, Sunday	Museum of Anthropology
Fogelin, Lars	Museum of Anthropology
Griffin, Will	Museum of Anthropology
Michelaki, Kostalena	Museum of Anthropology
Shaffer, Bret	Museum of Anthropology
Gu, Binxi	Nuclear Engineering and Radiological Sciences
Park, Jiyoung	Nuclear Engineering and Radiological Sciences
Smith, Leon Eric	Nuclear Engineering and Radiological Sciences
Stuenkel, David	Nuclear Engineering and Radiological Sciences
Zogg, Greg	School of Natural Resources & Environment

Researchers and Students Utilizing PML/FNR, 1997-1998 (cont.)

Students from Other Colleges

Bradley, Ryan	Arizona State University	Botany
Suponcic, Sonya	Arizona State University	Anthropology
Dorais, Paige	Indiana University	Geological Sciences
Dreher, Scott	Indiana University	Geological Sciences
Johnson, Tim	Indiana University	Geological Sciences
Hirshman, Amy	Michigan State University	Anthropology
Zhao, Xianda	Michigan State University	Civil & Environ. Engineering
Icopini, Gary	Michigan State University	Geological Sciences
Ward, Robert	Northern Illinois University	Geology
Linder, Jeff	Ohio State University	Geological Sciences
Parent, Laura	San Jose State University	Geology
Hare, Timothy	State University of New York Albany	Anthropology
Purcell, Geoffrey	State University of New York Albany	Anthropology
Olson, Jan	State University of New York Albany	Anthropology
Grove, Marty	University of California, Los Angeles	Geology
Gerke, Tammie	University of Cincinnati	Geology
Prokopenko, Maria	University of Cincinnati	Geology
Welch, Raelyn	University of Cincinnati	Geology
Church, Terry	University of Colorado, Boulder	Geological Sciences
Klinger, Ralph	University of Colorado, Boulder	Geological Sciences
Maldonado, Lupe	University of Colorado, Boulder	Geological Sciences
Sharaky, Abbas	University of Colorado, Boulder	Geological Sciences
Aanson, Sarah	University of New Orleans	Geology and Geophysics
Simmons, William	University of New Orleans	Geology and Geophysics
Yawn, Brenda	University of New Orleans	Geology and Geophysics
Burmeister, Jay	Wayne State University	Radiation Oncology

Students from High Schools

Demashkieh, Lena	Port Huron Northern High School
Goode, Whitney	Port Huron Northern High School

Recent Publications and Papers Related to Research at PML/FNR

Archaeology

K. Michelaki, "Pottery production in Bronze Age Hungary: Keeping metallurgy in the picture," paper presented at the 64th Annual Meetings of the Society for American Archaeologists, Chicago (1999).

L.D. Minc, "The Aztec salt trade: Insights from INAA of Texcoco Fabric-Marked Pottery," paper presented at the 64th Annual Meetings of the Society for American Archaeologists, Chicago (1999).

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J.R. Parsons, and L.D. Minc, "Changing political economy of salt in the Valley of Mexico: Ethnographic/Ethnohistorical/Archaeological Perspectives," paper presented at the 61st Annual Meeting of the Society of American Archaeologists, New Orleans.

Biological and Environmental Sciences

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Geological Sciences

K. A. Boland and E. I. Smith, "The petrogenesis of andesites produced during crustal extension," *Geological Society of America Abstracts with Programs*, v. 28, no. 5, 51 (1996).

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Nuclear Medicine

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