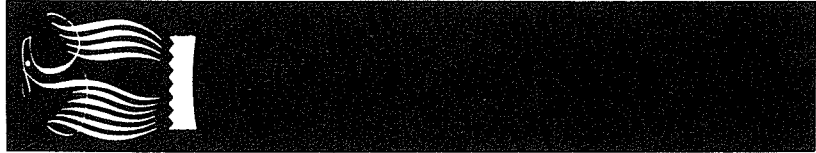

QUARTERLY REVIEW

FALL 1995

MICHIGAN MEMORIAL PHOENIX PROJECT
THE UNIVERSITY OF MICHIGAN

NUCLEAR REACTOR LABORATORY
FORD NUCLEAR REACTOR
PHOENIX MEMORIAL LABORATORY



North Campus
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QUARTERLY REVIEW

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Eighth Year, No. 23

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The Nuclear Reactor Laboratory Quarterly Review is published and distributed to University of Michigan faculty and staff members to inform them of the unique research capabilities provided by the Nuclear Reactor Laboratory and to make them aware of the types of research in progress.

The Michigan Memorial Phoenix Project was founded on May 1, 1948, as a memorial to the 585 University of Michigan alumni, students, faculty, and staff members who died in World War II. The Project is devoted to peaceful, useful, and beneficial applications and implications of nuclear science and technology to the welfare of the human race. Research support and services provided by the Nuclear Reactor Laboratory and a research grant program are the means by which the Project fulfills its mission.

NEW RESEARCH

FORD NUCLEAR REACTOR

University of Michigan

Chemistry

James Zimmerman, a doctoral candidate working with Professor Henry Griffin, 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.

Physics

Students and members of the Physics Department faculty are utilizing the reactors J beamport to polarize a neutron beam by transmission through a laser polarized helium-3 absorber. The neutron absorption cross section of helium-3 changes from almost zero for one "spin polarization" to a very large value for the opposite "spin polarization". Initially, Shenq-Rong Hwang is working on a master's thesis involving neutron time-of-flight measurements in the beam and setting up the experiment. Profes-

sor Timothy Chupp and Dr. Kevin Coulter are the advisors and principal investigators on the project.

School of Public Health

Chul Lee is a master's degree student working under the advisement of Professor James E. Martin. He is irradiating liquid nickel nitrate to produce radioactive nickel-65. The nickel is a short lived nuclide that is used as a substitute for 100-year-half-life nickel-63 in chemical separation processes of nickel-63 from reactor generated waste samples. The tracer is needed to determine the chemical recovery fraction in the separation process. The title of Mr. Lee's thesis is "Radiochemical Analysis of Nickel-63 in Reactor Waste Streams".

University of California, Santa Barbara

Chemical Engineering

For the past five years, Professor Gene E. Lucas has been conducting an extensive research program sponsored by the Department of Energy on radiation effects in pressure vessel and support structure steels under conditions of low neutron flux and temperature exposure. The results of this program have provided significant insight into the processes that are responsible for hardening and embrittlement of these steels under these conditions, and have helped to provide understanding of apparent accelerated embrittlement of the High Flux Isotope Reactor (HFIR) pressure vessel. This has significant implications not only for current operating reactors, but for the next generation of reactors.

The Ford Nuclear Reactor was selected for these irradiations after an extensive review of available facilities in the United States. It was the only facility that had the requisite combination of: (1) a set of irradiation positions with a range of neutron fluxes that matched the program needs; (2) low gamma heating rates at those positions; (3) a 24-hour-per-day operating schedule to minimize irradiation times; (4) a competent staff interested in meeting the needs of the program; and (5) a good operational record that minimized the risk of having the irradiation prematurely terminated.

A follow-on program has been started under sponsorship of the Nuclear Regulatory Commission in collaboration with Oak Ridge National Laboratory involving irradiations at elevated temperatures. The irradiation vehicle is being designed for the Ford Nuclear Reactor to perform these irradiations.

University of Manchester

Geology

A variety of terrestrial and extraterrestrial rock samples are routinely irradiated in the reactor for several days. The nuclear transmutations that result from the irradiation enable the ages of the samples and the elemental abundances of the halogens and other elements to be determined. This method has permitted models of the geochemistry of the elements in the earth's mantle to be developed, and both crystallization ages and eruption ages of diamondiferous deposits to be calculated.

Applied to meteoritic samples, highly precise ages from the very earliest period of Solar System history have been determined which enables models for the formation of planetesimals and their constituent parts to be delimited.

Samples irradiated at the Ford Nuclear Reactor have been utilized by over twenty individuals, including several from other European laboratories.

NEUTRON ACTIVATION ANALYSIS

University of Michigan

Anthropology

Jeffrey Bonevich is utilizing neutron activation analysis to measure trace elements in archaeological ceramics from sites in central and gulf coast Mexico. The analysis is being performed to determine whether variations in the chemical composition of ceramic paste exist on a locality basis within the Huasteca region during the late Postclassic era. Mr. Bonevich's advisor is Professor Jeffrey Parsons.

School of Public Health

Jason Eggart is utilizing neutron activation analysis on landfill leachate. Liquid samples take from simulated landfills are dried and activated to test for trace metals. Mr. Eggart is a master's degree candidate working for Professor James E. Martin. The title of his thesis is "Trace Metal Analysis of Lysimeter Leachate Using Neutron Activation Analysis".

Richard Porter and Julie Levin are utilizing neutron activation analysis on both the shells and soft tissue of Zebra Mussels in the Great Lakes. They and their advisor, Professor Jerome Nriagu, are developing alternative techniques for analyzing trace metals in biological samples from the Great Lakes.

University of Colorado

Geological Sciences

Professor Edwin Larson, two additional professors, and three graduate students utilized neutron activation analysis to obtain trace element and rare earth information on Miocene volcanic rocks from Oregon; Precambrian lavas from the Belt Supergroup, Montana; Eocene sediments from Wyoming; soils from several Pacific islands; late Paleozoic apatite material; Quaternary volcanic ash beds in Death Valley, California; and Front Range, Colorado, Paleocene alkaline intrusions.

University of Toledo

Geology

Professor James Harrell and a master's degree candidate, Steven Badger, are researching possible methods of handling the furnace dust created during electric arc steel making. The dust is classified as hazardous waste by the Environmental Protection Agency. The disposal cost is approximately \$200 per ton utilizing recycling or chemical fixation. Neutron activation analysis is being used to help characterize the dust which will, in turn, assist in the technical evaluation of alternative processing methods. The title of Mr. Badger's thesis is "Electric Arc Furnace Dust".

COBALT-60 IRRADIATOR

University of Michigan

Chemical Engineering

Professor David Mooney 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 the second experimental area: design devices to transplant cells and engineer new tissues. Tissue engineering may ultimately provide alternatives to whole organ or tissue transplantation. This work is motivated by the tremendous shortage of available tissues, and by the large number of people who either die or survive on sub-optimal therapies due to this shortage.

Medical School-Surgery/Orthopedic Surgery Section

Dr. James Carpenter, Laura Huston, and Jim Pribble are gamma irradiating human patella tendon allografts to determine whether there are significant reductions in viscoelastic properties at high irradiation doses. Conway et al. suggest that as much as 3.6 million rads of gamma radiation may be needed to inactivate all but one in a million HIV infected bone cells.

Aastrom Biosciences

Dr. Bernard Palsson and his associate, Matthew Heidmous, utilize the cobalt-60 gamma irradiator to sterilize polyethylene tubing for use in bone marrow transplant research.

NEUTRON RADIOGRAPHY

University of Michigan

Nuclear Engineering

Jiyoung Park is conducting various neutron radiography experiments using various scattering media to measure, model, and remove scatter from neutron radiographic images. Small amounts of helium-3, helium-4, aluminum, and cadmium are initially being used. Ms. Park is a doctoral candidate. Her advisors are Professor John Lee and Dr. John Lindsay. The title of her thesis is "Scatter Removal from Neutron Radiographic Images".

FEATURE ARTICLE

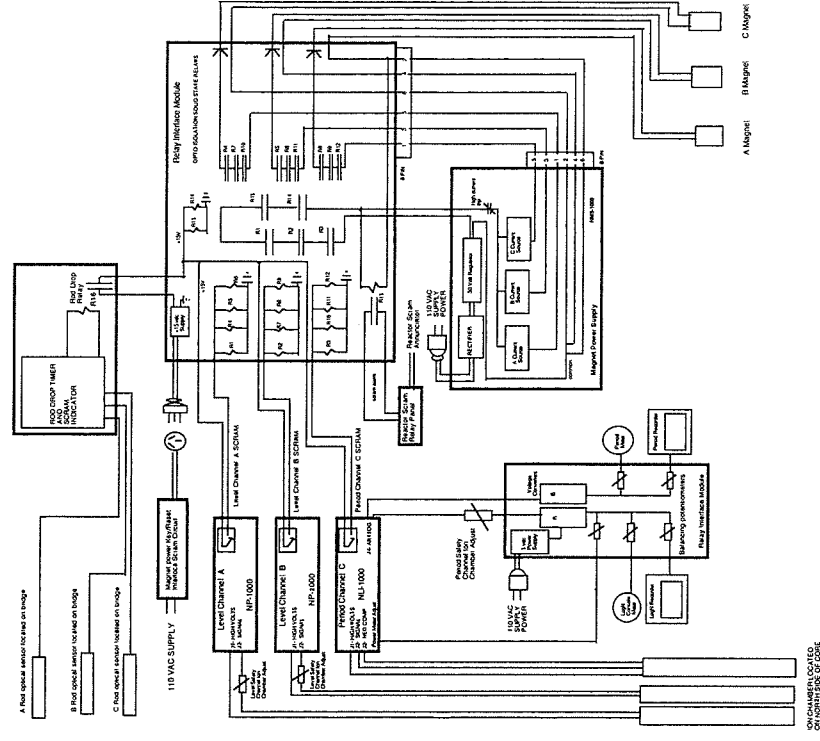
KEEPING UP WITH THE TIMES: RECENT AND PROPOSED UPGRADES TO THE FORD NUCLEAR REACTOR

Reactor Safety System Instrumentation

The reactor safety system monitors power level and automatically shuts down the reactor if power increases from the normal 2 megawatt operating level to 2.45 megawatts. A 1950s-vintage, tube-driven composite safety amplifier (CSA) system originally installed in the Ford Nuclear Reactor was replaced in the early 1980s by a solid-state system obtained from the Lawrence Livermore Laboratories reactor when it shut down. That system served the reactor until 1994, when it was upgraded with one-for-one replacement modules purchased from General Atomics with funds provided by the Department of Energy's Research Reactor Instrumentation Upgrade program.

The reactor safety system consists of three separate channels: power level A and Power level B that initiate a reactor shut down (scram) at 2.45 megawatts and period C that initiates a scram for a rapid rate of change of power. Reactor power level signals are transmitted to the safety system from three neutron detectors, one for each channel. When a scram is initiated, the current to the magnets that hold up the reactor's three shim-safety rods is turned off and all three rods drop into the core in less than half a second.

Figure 1
Reactor Safety System



The upgraded system, in addition to being state-of-the-art, has three outstanding new features. The power supply for the magnets contains three identical, individual current supplies, one for each magnet. In the Livermore system, the maximum holding current was 60 milliamperes, just enough to latch and hold the rods. The upgraded system has a current capacity of 150 milliamperes which is far more than needed to firmly latch and hold the rods.

A rod release and drop timer is incorporated into the safety system to permit verification of the half second drop time. When a scram push button is depressed, a scram is initiated and a timer starts. As a falling rod approaches its lower limit, the magnet armature attached the top of the rod extension clears an optical sensor and a resultant voltage transition output from the sensor stops the timer. Prior to the upgrade, drop times were measured with an acoustic coupler that "heard" the rod as it slammed into the reactor core. Setting up the coupler and associated electronics often required the better part of a maintenance day. The optical system is permanently installed and is locked in and out of the system with an enable key. Performance of rod drop time measurements now takes a few minutes.

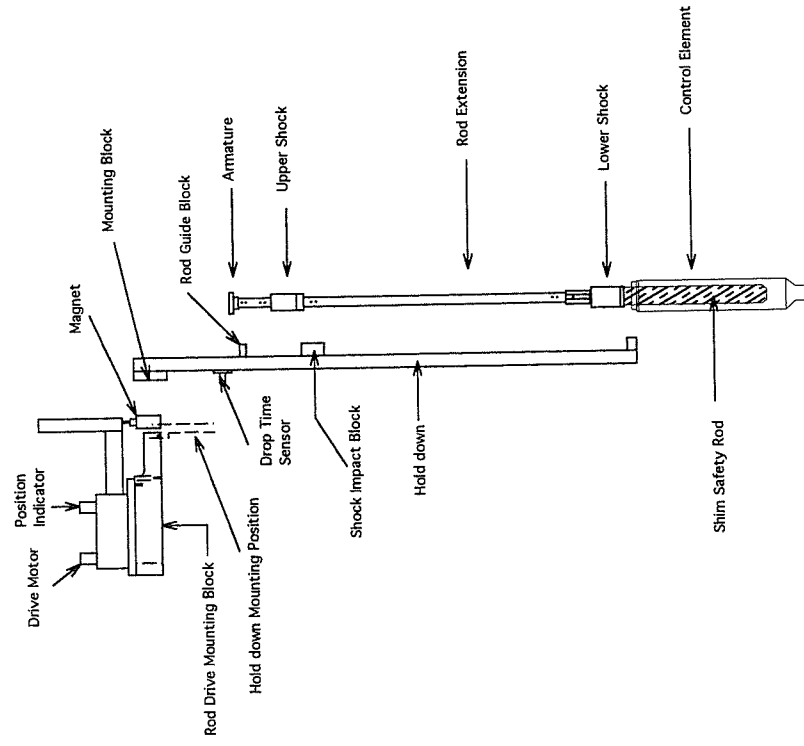
Reactor power is determined at the beginning of each operating cycle by a calorimetric method. In the past, the four main power level indicating instruments were adjusted to match true thermal power by mechanically adjusting their respective detectors closer to or farther from the reactor core, a very sensitive procedure. As part of the upgrade, electronic adjustment potentiometers were installed in the reactor control room to replace the need for mechanical adjustments.

Above Surface Shim-Safety Rod Magnets

The upgrade from subsurface to above surface shim-safety rod magnets was implemented to: (1) improve reliability when compared to subsurface magnets; (2) reduce radiation exposure during repair to the activated subsurface magnets and associated magnet contact switches; (3) reduce radiation exposure during shim-safety rod inspections; (4) reduce radiation exposure by having a single top for control rod elements that enable them to be used under rods and in other core locations; and (5) absorb the impact of scrambled shim-safety rods in the rod holddown device rather than the control fuel element; reducing the possibility of element damage.

Figure 2 is a diagram of the Ford Nuclear Reactor shim-safety rod drive system. A shim-safety rod assembly includes the shim-safety rod surmounted by a hydraulic shock absorber, a rod extension, an upper hydraulic shock absorber, an additional rod extension, and a ferromagnetic armature. Rods insert into guide channels in control fuel elements located in the core interior. Rods are driven by electric drive motors; drive motor speed is reduced through reduction gears. The drive motor drives a circular pinion gear which drives a vertical rack gear to which the rod magnets are attached. A holddown prevents inadvertent lifting of a fuel element from the core should a rod become bound in a control element guide channel. The holddowns were converted from closed cylinders to open channels to permit visual observation of the rods during operation and ease of removal for refueling and periodic inspections. As part of this upgrade, the holddown has a square guide at the bottom for positioning on the control element top block, a rod guide clock near the top to align

Figure 2
Shim-Safety Rod Drive and Holddown Assembly



the armature with its magnet, a shock impact block, and a mounting block at the top. In the event of a reactor scram, the upper shock on the rod assembly impacts on the shock impact block slightly before the lower shock impacts on the element top block; thus the momentum of the descending rod is absorbed on the holddown rather than on the control element. The drive motor and reduction gears are mounted on a massive aluminum mounting block. An arm extends from the drive motor mounting block out over the core. The holddown mounting block has a rectangular slot near the top that slides over the arm. When in place, the holddown is vertically free of the control element by approximately 0.125 in. This ensures that the impact of a dropping rod is totally absorbed by the holddown. The optical rod drop sensor is installed in the holddown just above the lower limit of armature travel.

The top blocks of control fuel elements also were redesigned as part of the project. In the original design, a guide cylinder was bolted to the top block of each element to align the underwater magnet above the element. In addition, the cylinder was slotted to permit handling the element with a hook tool. Removal and replacement of the guide cylinder during inspections and refueling was a significant source of radiation exposure. The guide cylinder was no longer necessary with above surface magnets. Handling slots were cut into control element side plates as integral parts of the elements.

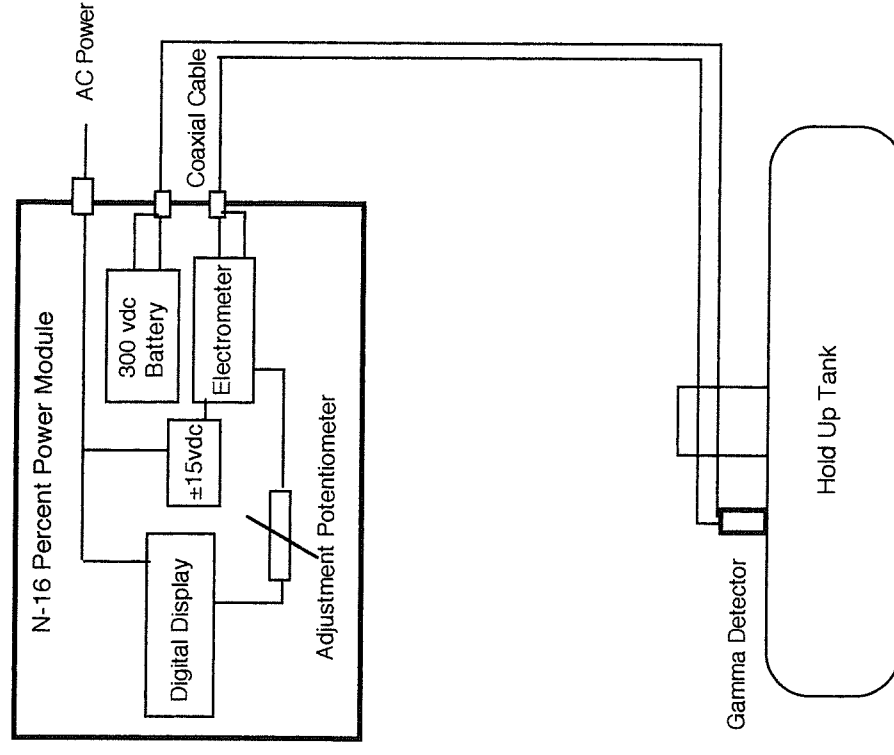
Nitrogen-16 Power Level Monitor

Core differential temperature is the final measure of steady-state power at the Ford Nuclear Reactor. During some evolutions, such as changing the number of cooling tower fans in operation, differential temperature undergoes a transient and does not provide an accurate measure of true power. A detector designed to detect gamma rays emitted by nitrogen-16 was installed to act as a power monitor and provide a more stable measure of power, even under transient conditions. Large amounts of nitrogen-16 are formed in reactor cooling water by a high energy neutron reaction with water: $^{16}\text{O}(n,p)^{16}\text{N}_7$; and the activity is directly proportional to power.

The detector is positioned adjacent to a 1200 gallon holdup tank in the reactor basement as shown in Figure 3. The tank is designed to receive primary coolant from the core exit for the purpose of permitting the decay of nitrogen-16 to limit personnel radiation exposures before the coolant continues on its flow path through the rest of the basement.

A variety of pre-operational tests were performed on the detector including: (1) determination that detector response was constant over an applied voltage range of 150 to 800 vdc; operating voltage is set at 300 vdc; (2) determination that detector output was unaffected by coolant flow rate; (3) verification that background radiation levels are a small fraction of operating levels in the detector location; (4) measurement of detector response for reactor scrams with and without coolant flow; and (5) verification of the correlation between steady-state core differential temperature and detector response over a prolonged oper-

Figure 3
Nitrogen-16 System Block Diagram



ating period. The detector performed as expected for each test.

Immediately following a startup, nitrogen-16 detector current was measured against indicated power from zero power to 2 megawatts on the Linear Level system, one of the reactor's power monitoring channels, as shown in Figure 4. The nitrogen-16 detector was linear over the entire range. Nitrogen-16 detector response also was shown to be linear with power for up and down power maneuvers during routine operation.

Proposed Replacement Shim-Safety Rods

The shim-safety rods in the Ford Nuclear Reactor core are borated stainless steel. The nuclide boron-10 (^{10}B) is a strong neutron absorber. The rods were installed in 1962. Rod reactivities have decreased in the 10 to 20 percent range over the intervening 33 years. Reactivity provides a measure of the ability of a rod to absorb neutrons and control the reactor. The reactor maintains a single spare rod. Replacement rods of essentially identical metallurgical composition are not available. Specialty metals companies that could produce borated stainless steel would have to make special runs and special molds to produce the material at a cost of hundreds of thousands of dollars. A boron-aluminum alloy, material used in spent fuel shipping and storage casks, was made available to the Ford Nuclear Reactor by Eagle-Picher, a leading supplier of boron enriched in ^{10}B . The boron-aluminum design is a single bar with overall dimensions the same as those of the present stainless steel rods: 0.875 in x 2.25 in x 30 in long. The original boron-stainless rods contain 1.75% natural boron. Natural boron is 20% ^{10}B and 80% ^{11}B . The replacement boron-aluminum alloy rods contain 1% boron enriched to greater than 95% in ^{10}B .

Figure 4

Nitrogen-16 Detector Current Versus Linear Level Power

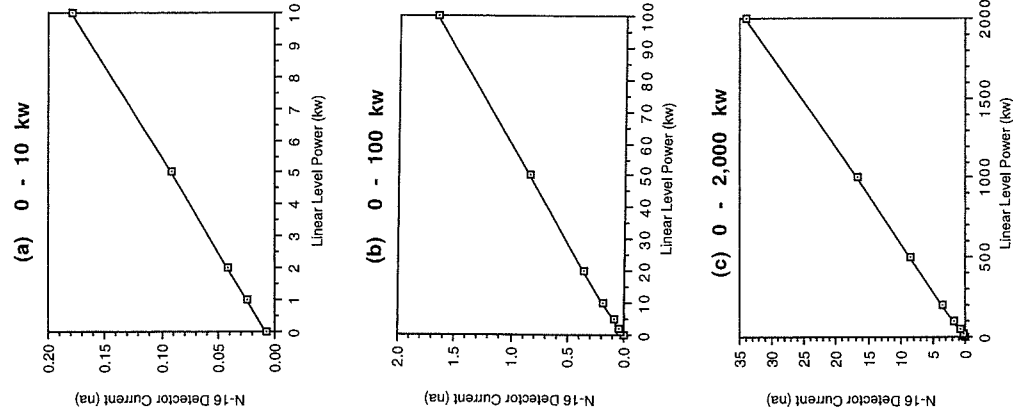
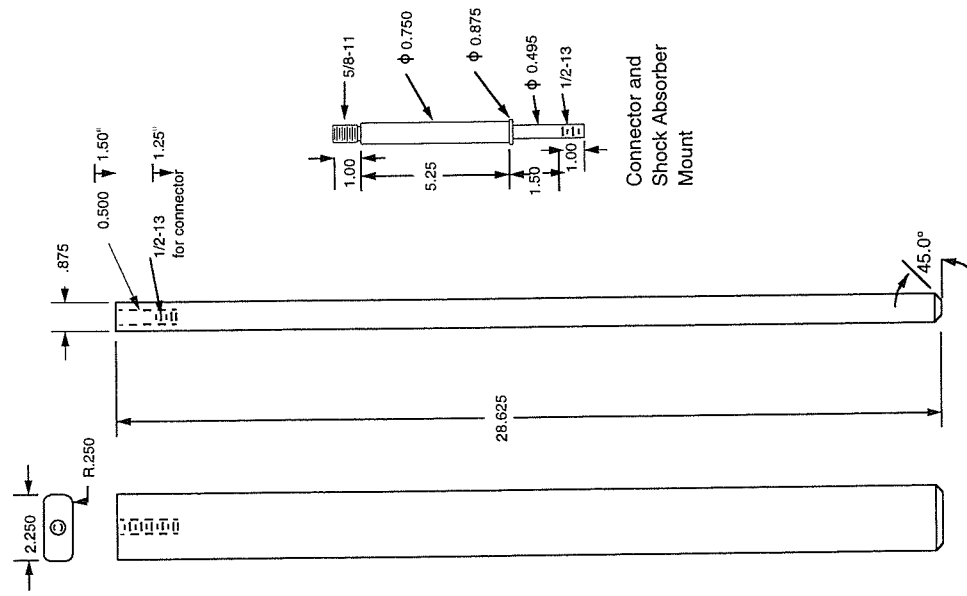


Figure 5 Shim Safety Rod



Miniature borated aluminum plates were inserted in the corner of the Ford Nuclear Reactor core and on a tray located near the south end of the pool more than a year ago. The aluminum has developed a tenacious oxide coating, but has shown no indication of physical deterioration. The in-core miniature plates are in a dead-ended sample holder with no water circulation, a much more severe environment than will exist with actual rods, but have shown no indication of excess temperature effects.

Reactivity comparisons were made between the new design and the spare stainless steel shim-safety rod of the old design. Measurements were made in a control element at the edge of the core. The boron-aluminum alloy rod was 10 to 20% more reactive than the boron-stainless rod.

Proposed Extended Life Reactor Fuel

Since 1984, the reactor has operated with low enriched ($<20\%$ ^{235}U) uranium aluminide (UAl_3) fuel. Elements are rectangular with 18 plates; each containing 167 grams ^{235}U . To extend fuel lifetime, it may be possible to utilize elements that contain up to 225 grams ^{235}U . Burnable poison may be needed to limit power peaking.

The proposed and existing fuel designs are geometrically similar. The active portion of each fuel plate is nominally 2.4 in wide by 24 in long. Overall plate thickness in aluminum fuel is 0.060 in; the aluminum clad is 0.015 in and the uranium-containing meat is 0.030 in. The proposed fuels have the same clad thickness, but the meat thickness is 0.020 in. Two burnable poison fuels under consideration are: (1) uranium silicide (U_3Si_2)

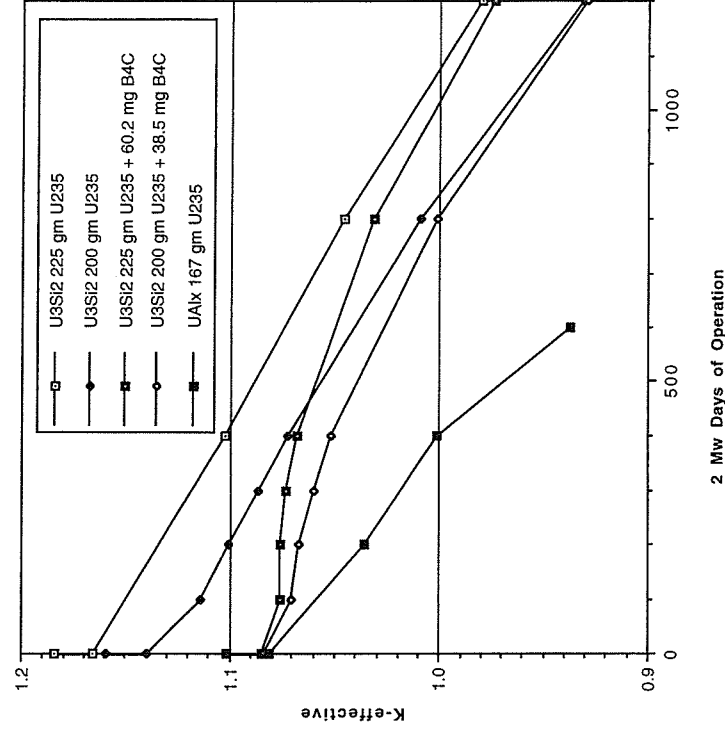
containing 200 grams ^{235}U in 18 fueled plates with 38.5 mg boron carbide (B_4C) per plate; and (2) U_3Si_2 containing 225 grams ^{235}U in 18 fueled plates with 60.2 mg B_4C per plate. In addition, both of these U_3Si_2 loadings are being considered without burnable poison.

Figure 6 is a plot of K_{eff} versus 2 Mw (full power) days for a 39-element core operating with UAl_3 fuel and operating with the more heavily loaded U_3Si_2 fuels with and without burnable poison. B_4C loadings in the 200 and 225 gram elements were chosen to produce an initial core reactivity that matched the reactivity of an all fresh element UAl_3 core.

There are two major advantages to using more heavily loaded fuel in the Ford Nuclear Reactor. The first is economic, resulting from the use of fewer elements; the second is reduced risk of radiation exposure, the result of reduced fuel handling and disposal.

Figure 6 shows that the in-core lifetime of the least heavily loaded of the proposed elements, 200 grams ^{235}U with burnable poison, is almost twice the lifetime of a UAl_3 element. The reactor currently uses approximately nine standard elements and two control rod elements per year. Decreasing the annual fuel element consumption from 11 to six elements, at a cost of approximately \$25,000 per element, would save \$125,000 per year. Roughly once every three years, a shipment of spent fuel is sent to Savannah River National Laboratory. Shipments made in the fall of 1992 cost approximately \$30,000 each; today's cost is probably closer to \$40,000. Extended life fuel would result in a savings of approximately \$40,000 over a six year operating

Figure 6
Burndown of Uranium Aluminide
and Proposed Uranium Silicide Fuel Designs



period. Savannah River estimates a spent fuel disposition cost of \$35,000 per element. Over a six year period, use of more heavily loaded fuels would reduce this cost by a minimum of \$840,000. Considering all costs, the use of more heavily loaded fuel elements would save a minimum of \$272,000 annually.

Fewer spent fuel shipments would reduce the potential for release of radioactive materials during cutting and preparation of fuel for shipment. Fewer shipments would reduce the probability of highway accidents. The risk of radiation exposure to the public from such accidents is extremely small because of current shipping cask design requirements. Spent fuel storage space at Savannah River is at a premium; extended life fuel would decrease the burden on that storage space.

Two potential problems of significance are associated with extended life fuel. First, the basis for limits on power peaking in the reactor core is prevention of nucleate boiling anywhere in the core. Even with burnable poisons, analyses show that the average power density in a single, fresh, heavily loaded element is from 13 to 18 percent greater than the average power density in a single UAl_3 element. However, these higher power densities in an equilibrium, 40-element core are lower than the average power densities in the 25-element core analyzed in the Safety Analysis. The Safety Analysis shows that boiling does not occur. Nevertheless, detailed core calculations are needed to provide assurance that boiling will not occur under any, possibly unforeseen circumstance.

Of greater concern is overall fuel management within the core. The standard refueling procedure in the reactor is insertion of a new element in the middle of the core, shuffling of partially expended elements toward the edge of the core, and removal of an expended element from the edge of the core. This peaks neutron flux in the center of the core where the rods are located and maximizes rod reactivity. The presence of burnable poison makes the initial reactivity of a heavily loaded element comparable to the reactivity of a UAl_3 element, as can be seen in Figure 6, but the B_4C burns out faster than the ^{235}U is consumed. The relative reactivity of the heavily loaded element increases with operating time relative to UAl_3 elements. Some thought has been given to cycling the heavily loaded elements to an intermediate position in the core, out of the center, but not on an edge. Since the heavily loaded elements have twice the in-core life of UAl_3 elements, two expended UAl_3 elements will ultimately be removed from the core for every one heavily loaded element that is inserted. The effect may be a gradual decrease in the size of the core, which is very undesirable because of a variety of experimental programs that rely on high leakage neutron flux around the periphery of the core.

A possible alternative is to achieve a greater burnup of fuel before it is removed from the core. This would apply to the UAl_3 fuel that is in the core during transition and to the more heavily loaded fuel once the core is fully converted. Once again, concern exists about the loss of leakage flux at the core edges and its effect on experimental programs.

Another concern cannot be solved analytically; the metallurgical aspects of longer life fuel. Presently, a UAl_3 element remains in the core for approximately two years. Over the past twenty years, the reactor has experienced two small fission product releases from fuel. The cause of the releases - tramp uranium, pinhole manufacturing leaks, or clad thinning due to corrosion - has never been determined. A longer life fuel element would remain in the reactor producing power for four or more years. Storage time prior to shipment as spent fuel also would be prolonged. Clad corrosion rates depend mostly on water quality, temperature, and time-integrated heat flux. Experience with lifetime cores and with other research reactors suggests that the possibility of radioactivity release from clad corrosion is very remote in the Ford Nuclear Reactor. However, additional corrosion resistance could be obtained by increasing fuel plate clad thickness from 0.015 in to 0.020 in so that the longer life U_3Si_2 fuel would have the same plate thickness as UAl_3 fuel. This will shorten life somewhat, but it has the benefit of reducing the peak power density by reducing the water gap between fuel plates. Calculations show that for a 225 gram element, the thicker plate decreases power density by nearly the same amount as the addition of burnable poison.

NUCLEAR REACTOR LABORATORY

Profile of Services

Neutron Irradiation Services

In-core, pneumatic tube, and beamport irradiations with high energy (fast) and low energy (thermal) neutrons. Thermal neutron range: 8×10^6 to 1.5×10^{13} n/cm²/sec.

Neutron Activation Analysis

Identification of trace quantities of sixty-two elements including most metals and rare earth elements utilizing a technique that is almost non-destructive and requires very small sample volumes.

Gamma Irradiation Services

Gamma irradiations utilizing a large cobalt-60 source to sterilize bone and cartilage for reconstructive surgery and to study radiation effects on materials.

Neutron Radiography

Radiographic imaging of low density materials such as plastic, oil, water, and gasoline contained in heavy materials and porous media that cannot be imaged with ordinary x-rays.

Radiopharmaceutical Preparation

Production and distribution of large quantities of investigational drugs containing iodine-123, iodine-125, and iodine-131 to more than 100 hospitals throughout the United States and Canada, as well as to medical research institutions for diagnosis and therapy of adrenal gland cancer and adrenomedulla diseases.

Radiochemical Production

Preparation of bromine-82 labeled motor oil for use in engine oil economy research programs; bromine-82 labeled toluene, sodium-24, lanthanum-140 for use in oil refinery flow tests; and other specialized radiochemicals.

Testing Programs

Accelerated neutron and gamma aging of reactor materials; fast neutron damage effects in reactor vessel steels; and quality assurance tests of irradiated materials including neutron attenuation properties, strength, gas evolution, radionuclide content, and changes in physical parameters.

Training

Neutron activation analysis and reactor operations laboratories for university students, advanced high school students, and electric utility engineers and reactor operators

NUCLEAR REACTOR LABORATORY DIRECTORY

Hours of Operation:

Monday-Friday 8:00 a.m.- 5:00 p.m.

Facilities can be made available 24 hours a day, if required.

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Tours should be scheduled at least 48 hours in advance.

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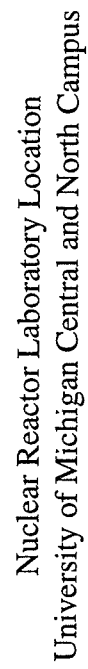
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