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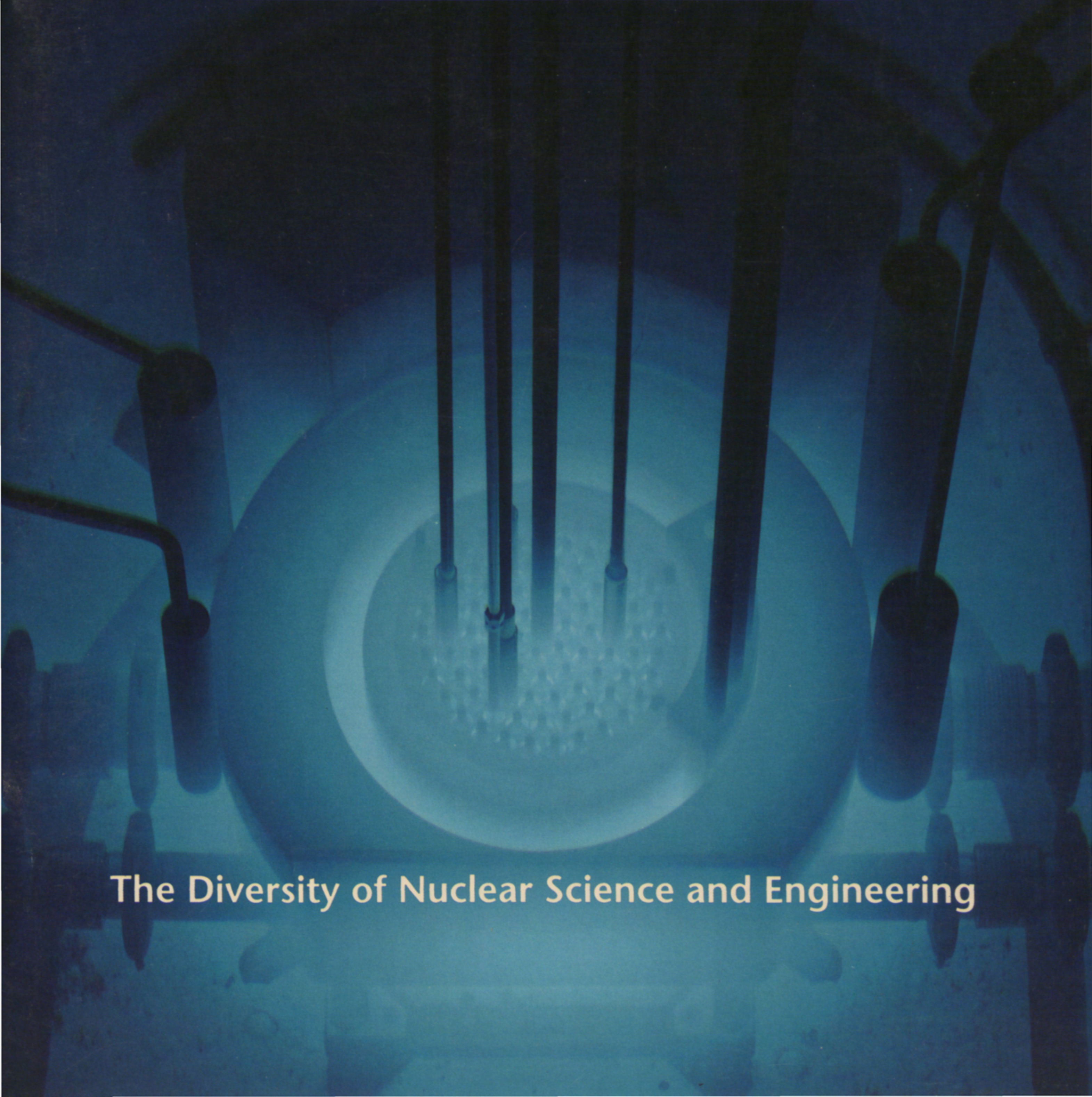

The Diversity of Nuclear Science and Engineering

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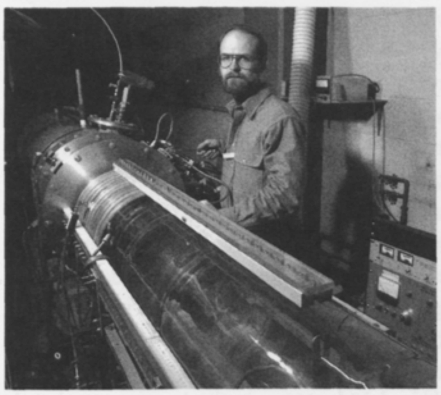

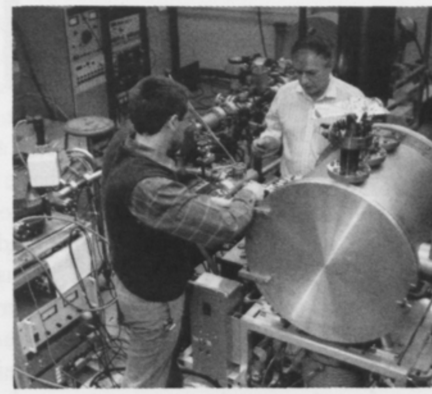

Cover: Cherenkov radiation from the core of Cornell's TRIGA reactor.

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THE NUCLEAR FRONTIER
Cornell's Program of Basic and Applied Research

by David D. Clark

"Both reactors reached criticality . . . just twenty years after Enrico Fermi's first reactor went into operation."

The Program in Nuclear Science and Engineering at Cornell is an interdisciplinary field that encompasses a wide range of research. Some faculty members and graduate students are working on the basic physics of nuclei, plasmas, and atoms, while others are investigating the interaction of radiation with matter and the basic mechanisms of radiation-induced failure in microelectronic devices. Some are developing new research techniques based on nuclear and atomic interactions, and others are adapting nuclear methods such as activation analysis to research in geology, biology, and archaeology. Some are investigating advanced types of ion and electron beams, while yet others are improving the generation of power from fission and seeking to generate it from fusion.

The Background of Nuclear Science and Engineering at Cornell

Cornell's involvement in nuclear science dates back to the 1930s, when Lloyd P. Smith, M. S. Livingston, and Hans Bethe joined the faculty of the physics department. In 1954, T. R. Cuykendall, of the School of Applied and Engineering Physics, offered Cornell's first course in nuclear engineering. An interdepartmental nuclear power option was set up shortly thereafter with courses from engineering physics, mechanical engineering, and chemical engineering. The Program in Nuclear Science and Engineering was organized as a separate administrative unit in 1977 by Dean Edmund T. Cranch.

Ward Laboratory, which serves as headquarters for the program, was constructed in 1960–61. It is named for J. Carlton Ward, Jr., a mechanical engineering alumnus, class of 1914, who was an active Cornellian and an ardent supporter of nuclear power. Ward served on the Engineering College Council and the university's Board of Trustees, where he was instrumental in securing approval for the construction of the laboratory. Vitro Corporation, which he headed, designed and en-

Ward Laboratory is the home of Cornell's Program in Nuclear Science and Engineering.

gineered the building on a nonprofit, expenses-only basis. Ward later provided funding for the laboratory, and an endowment that became available after his death in 1989 supports a professorship and defrays some of the cost of the laboratory's operation. The first J. Carlton Ward Professor of Nuclear Energy Engineering is David Hammer.

Facilities for Research and Teaching in Ward Laboratory and Upson Hall

Three of the five specialized facilities that support the Program in Nuclear Science and Engineering were proposed by a faculty study committee in 1957 and underwritten by grants from the Atomic Energy Commission and the National Science Foundation. These are a 500-kilowatt TRIGA reactor, a 100-watt "zero-power reactor" (ZPR), and a gamma irradiation cell. Subsequently, an electron-beam ionization source was added to Ward Laboratory, and a light-ion fusion facility was installed in Upson Hall.

Both reactors reached criticality in 1962, just twenty years after Enrico Fermi's first reactor went into operation. The TRIGA (an acronym for "training reactor, isotopes" and the name of the manufacturer, General Atomics) is an open-pool reactor using fuel elements made of uranium zirconium hydride clad with stainless steel and arranged in five concentric circles. The fuel is 8 percent uranium by weight, enriched in U-235 to 19 percent, and there are 1.7 hydrogen atoms per zirconium atom. Because of this fuel design, the TRIGA can deliver power and radiation in pulses reaching a peak of 1,000 megawatts and lasting several hundredths of a second. The four control rods contain boron carbide in aluminum sleeves and are positioned by drives located above the pool. The fuel, control rods, and neutron monitors are supported in an aluminum structure located more than eighteen feet below the water surface. The pool contains 20,000 gallons of deionized water, which acts as a moderator, biological shield, coolant, and reservoir for the heat produced.

Cornell's zero-power reactor, the first on a university campus, was expressly designed for research in reactor physics—the study of chain-reacting systems and the behavior of neutrons in bulk media. Although it is no longer useful for research in reactor physics, which now requires more sophisticated equipment, it has, over the years, supported research for a number of master's and doctoral theses, as well as design projects in the Master of Engineering program. It is still a useful facility for teaching students the important properties of chain-reacting systems.

The gamma cell is a small, heavily shielded room used to irradiate samples with intense fluxes of gamma rays. Up to ten thousand curies of cobalt-60 may be used. The cobalt is encapsulated in stainless steel "pencils" that can be manipulated by electromechanical arms controlled by an operator who views the process through a three-foot-thick leaded glass window. Examples of projects using the gamma cell include calibration and seasoning of radiation detectors and sterilization of soil for experiments in agronomy. The gamma cell has also been used for chemical engineering experiments in polymerization and in processing by radiation.

The electron-beam ion source (EBIS) was developed at Ward Laboratory by Vaclav Kostroun in 1982 with support from the Department of Energy. One of only two in the United States, the EBIS facility is used in atomic physics and plasma-related studies.

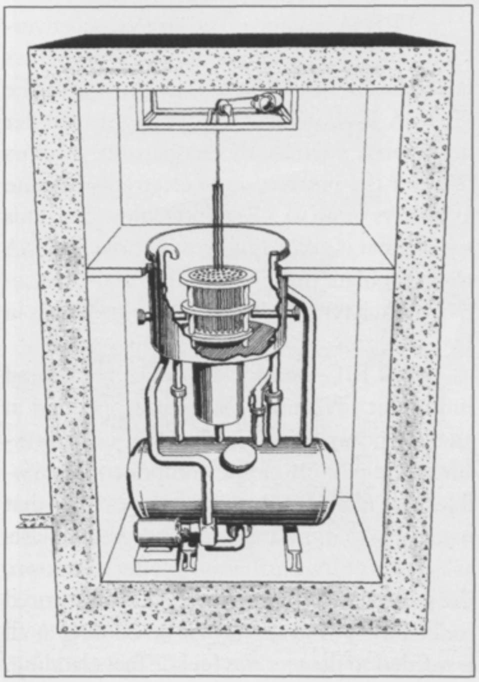
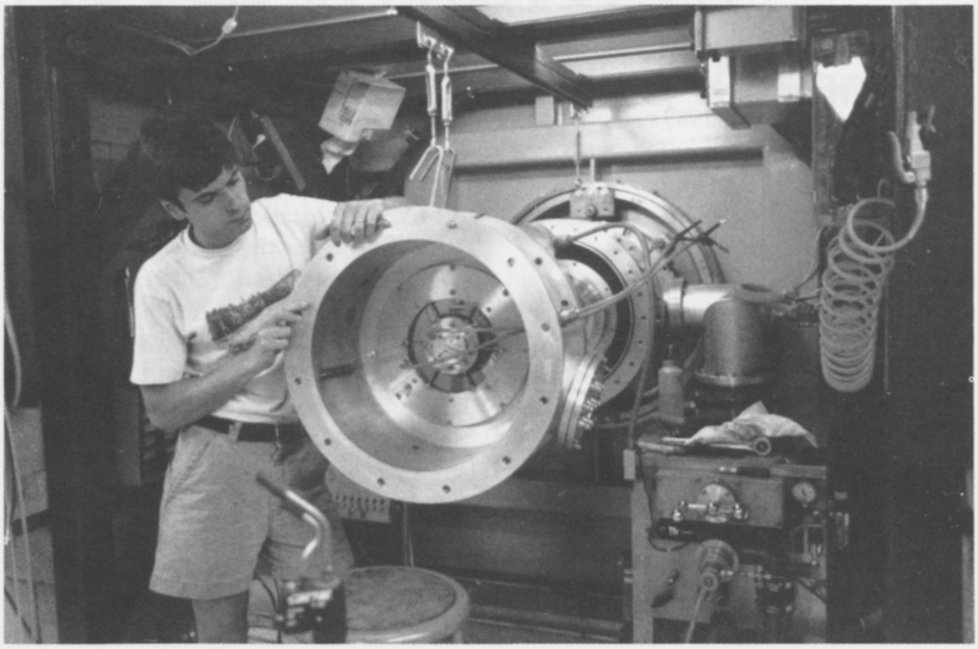


Figure 1. An artist's rendering of the zero-power reactor, drawn at the time of its installation.

Graduate student Conrad Struckman works with the light-ion fusion facility.



The light-ion fusion facility (LION) was provided to Cornell by Sandia National Laboratories in 1981 for collaborative research on the production and focusing of ion beams. It is the most powerful pulsed-power generator (10^{12} watts) available at any university in the United States.

The TRIGA Reactor: A Facility with Many Uses

The TRIGA reactor is the largest, most versatile, and most widely used of the program's facilities. At 500 kilowatts, the power of the TRIGA is about that of two eight-cylinder automobile engines. By comparison, reactors used for the production of electricity operate at powers of up to 3.8 million kilowatts. This means that it takes a full year for the TRIGA to accumulate the amount of stored radioactivity that a typical power reactor produces in two minutes.

The TRIGA's moderate power has several important advantages. Since it is operated in an open pool of water instead of a sealed pressure vessel, the important components are visible. The fuel cannot reach a temperature that would make the water boil, and the fuel lasts at least ten years. Furthermore, after shutdown, the self-heating of fuel elements due to stored radioactivity is so slight that no cooling at all is needed to protect the fuel or fuel cladding. In all of these respects, the TRIGA provides an ideal teaching environment.

The TRIGA is used for a broad range of research involving irradiation of samples or targets by neutrons. Irradiation tubes that extend from the pool top to positions next to the core make it possible to expose small samples to a neutron flux without getting them wet. Larger samples may be lowered into air-filled movable standpipes or, in some cases, lowered directly through the water. Additional access to the neutron flux is provided by eight horizontal beam ports and the graphite thermal column, all of which penetrate the concrete biological shield at core level. The beam ports can be used to let neutron beams pass through the shield when experimental apparatus requires more space.

The TRIGA sometimes provides support services to industry and to other research efforts. The reactor can be used, for example, to test and calibrate radiation detectors and associated electronic instrumentation. In addition, the facility provides radionuclides for research elsewhere on the campus. Cornell maintains about 150 laboratories that use radioactive tracers for research in biology, biochemistry, or other areas. Occasionally these laboratories need a short-lived tracer or a particular compound that is not commercially available, but can be made through irradiation with the TRIGA. A recent example is a compound labeled with P-32 that was produced for Professor Gerald Feigenson in the Section of Biochemistry, Molecular and Cell Biology.

A Staff with a Wide Range of Research Interests

The diversity of interests and areas of expertise is illustrated in this issue of *Cornell Engineering Quarterly*, which contains articles by the program's five faculty members as well as the reactor supervisor and the assistant manager of experimental facilities at Ward Laboratory.

Tim Z. Hossain, the new assistant manager, presents three examples of work involving neutron activation analysis. David A. Hammer, who specializes in high-power electron- and ion-beam physics, explains the relevance of his work on inertial confinement to the prospect of power from controlled nuclear fusion. K. Bingham Cady, whose field is nuclear engineering and fission reactor physics—with special emphasis on the modeling of accident transients, writes on the issue of safety in nuclear reactors used for power generation. Vaclav O. Kostroun, who specializes in the interaction of radiation and matter, atomic and molecular-collision physics, and EBIS sources, has contributed a paper on the status of research on atomic processes in ionized matter. Howard C. Aderhold, the reactor supervisor, describes the principles and the potential applications of neutron radiography. Stephen C. McGuire, who is interested in relativistic nucleus-nucleus collisions and radiation effects on microelectronic devices, has sketched the major concerns and practical implications of this area. My own areas of interest are nuclear physics, activation analysis, prompt-gamma analysis, and radiation measurement, and I have written a few pages on the development of cold-neutron-beam capability at Ward Laboratory.

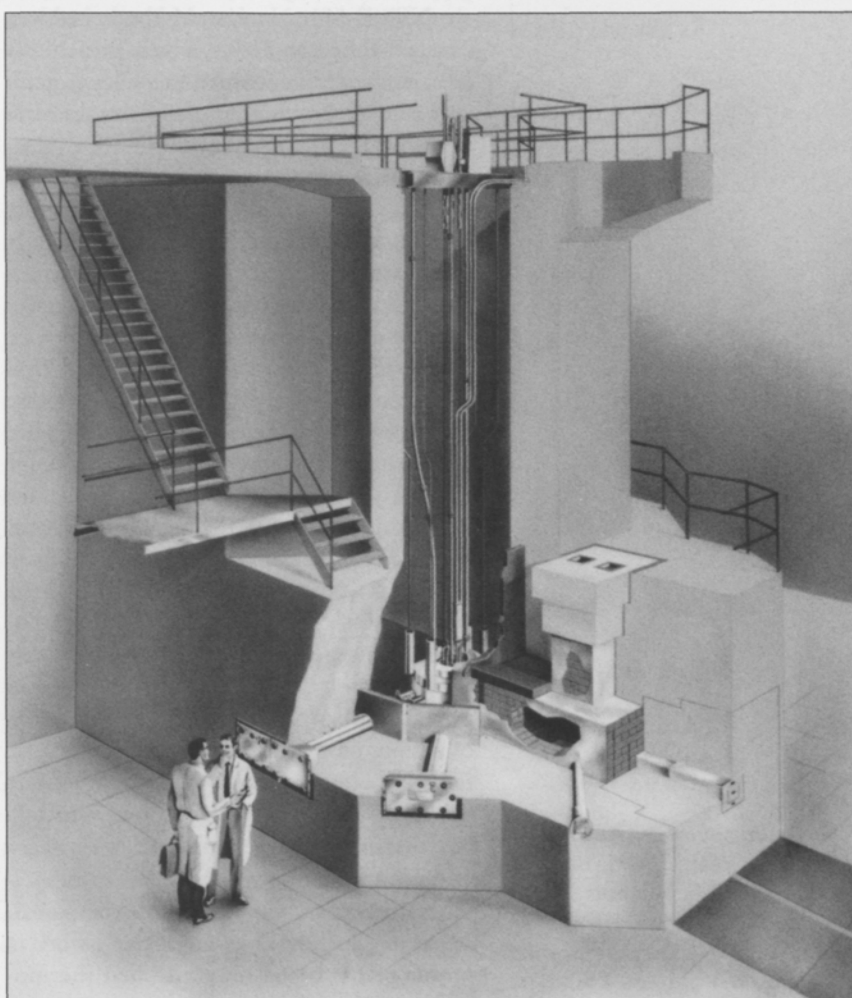
Members of other schools and departments who have made substantial contributions to the Program in Nuclear Science and Engineering, either by chairing the special committees of doctoral students or by teaching NS&E courses are Hans H. Fleischmann of applied and engineering physics, Charles B. Wharton of electrical engineering, George Morrison of chemistry, and Che-Yu Li of materials science and engineering.

Academic Programs in Nuclear Science and Engineering

Much of the program's mission is in education, and Cornell offers Master of Engineering, Master of Science, and doctoral degrees in nuclear science and engineering. Several courses are given at the undergraduate level, but there is no undergraduate major.

Current offerings include one freshman-level introductory course and two junior/senior courses, Introduction to Nuclear Science and Engineering, and Introduction to Controlled Fusion. Four graduate courses are given directly by the Program in Nuclear Science and Engineering, and five are offered by the program's faculty through the School of

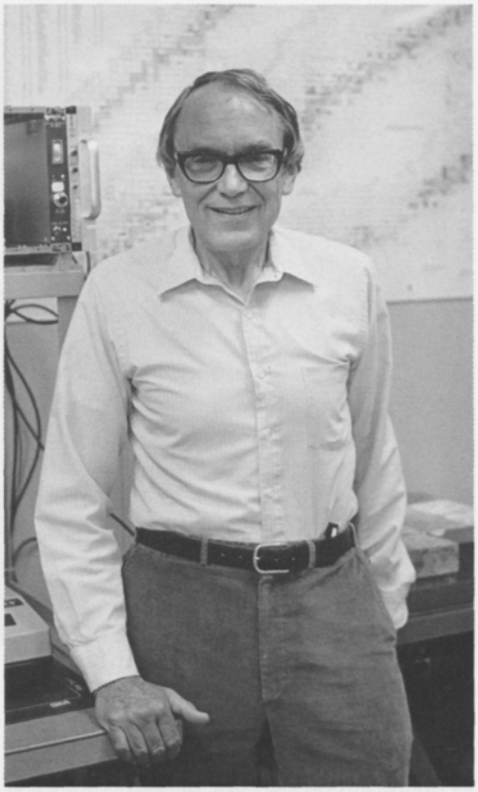
Figure 2. A cut-away view of the TRIGA reactor, showing details of its construction.



Applied and Engineering Physics. These nine courses cover low-energy nuclear physics, fission-reactor theory and engineering, laboratory methods of nuclear measurement, pulsed electron and ion beams, plasma diagnostics, and radiation effects in microelectronics. Several of the core courses in the doctoral program, such as those in plasma physics, quantum physics, and thermal hydraulics, are offered through other departments.

As the Program in Nuclear Science and Engineering has grown and matured, the relative emphasis given to subfields within the discipline has changed. In the early years, equal attention was given to fission power and nuclear science. Today, however, nonpower applications, atomic physics, and fusion power form an increasingly large part of the teaching and research programs. Three of the graduate courses illustrate this shift in emphasis. NS&E 551, Nuclear Methods in Non-Nuclear Research Fields, which I teach, is a laboratory course intended to convey to graduate students from other disciplines the skills in activation analysis and other nuclear techniques that are used in their research areas. NS&E 621, Radiation Effects in Microelectronics, taught by Stephen McGuire, is a seminar course on the effects of radiation on devices used in space exploration and in the vicinity of accelerators and fusion reactors. NS&E 504, Fission and Fusion Energy Systems, taught by David Hammer, is a course for Master of Engineering students enrolled in the energy engineering option.

Thirty years ago, power from sustained nuclear fission seemed the wave of the future. But public mistrust has put the development of nuclear power in the United States on hold, and fewer of our students are learning to be nuclear engineers who design and manage nuclear power plants. Instead, much of our time is now spent on nonpower applications of fission, on plasma and atomic physics, on radiation effects, and on fusion. We look to the future with a degree of caution, but anticipate that in time the pendulum will swing back again to nuclear power. And perhaps, in another thirty years, Cornell will also be educating young engineers to go out and work in power plants based on controlled thermonuclear fusion.



David D. Clark, who heads the academic Program in Nuclear Science and Engineering, is a professor of nuclear science and engineering and of applied and engineering physics. He also directs the J. Carlton Ward, Jr. Laboratory of Nuclear Engineering.

Clark received the bachelor's degree in 1948 and the doctorate in 1953, both in physics, from the University of California at Berkeley. He was a research associate in physics at Brookhaven National Laboratory for two years before joining the Cornell faculty in engineering physics.

During sabbatical leaves, he has been a Euratom fellow at Ispra, Italy, a Guggenheim fellow at the Niels Bohr Institute in Copenhagen, a visiting professor at the Technical University in Munich, a visiting scientist at Brookhaven, and a guest scientist at the Center for Analytical Chemistry of the National Institute of Standards and Technology. He is a member of the American Physical Society and the American Nuclear Society.

NEUTRON ACTIVATION ANALYSIS

A Sensitive Test for Trace Elements

by Tim Z. Hossain

Neutron activation analysis (NAA) is an extremely sensitive technique for determining the elemental constituents of an unknown specimen. It was pioneered by George Hevesy and Hilde Levi in Copenhagen in 1936, but widespread use had to wait for the advent of nuclear reactors in the 1950s. George Morrison, of Cornell's Department of Chemistry, helped develop the new technique, and he used it to study lunar materials brought back by the Apollo missions. Currently, there are some twenty-five moderate-power TRIGA reactors scattered across the United States (fourteen of them at universities), and one of their principal uses is for NAA.

The Basic Elements of the Analytical Technique

NAA is procedurally simple. A small amount of the material to be tested (typically between one and one hundred milligrams) is irradiated for a period that varies from a few minutes to several hours in a neutron flux of around 10^{12} neutrons per square centimeter per second. A tiny fraction of the nuclei present (about 10^{-8}) is transmuted by nuclear reactions into radioactive forms. Subsequently, the nuclei decay, and the energy and intensity of the gamma rays that they emit can be measured in a gamma-ray spectrometer.

Each element (indeed, each isotope) has a gamma-ray spectrum that is as unique as a fingerprint, and can provide unambiguous identification. The mass of each element can also be deduced, either by measuring the intensity of the gamma rays with an efficiency-calibrated spectrometer (an absolute method), or by comparing the intensity of gamma rays from the sample with those from a prepared reference sample of known composition irradiated under the same conditions (a comparison method).

This simple two-step procedure is applicable to more than sixty elements that have gamma-emitting nuclides, although some elements, such as hydrogen, boron, carbon, nitrogen, and phosphorus, are excluded. Another important property of NAA is that it provides a bulk or average analysis because both incident neutrons and emergent gamma rays penetrate typical samples with negligible attenuation. In addition, the results are independent of the chemical and

"Each element (indeed, each isotope) has a gamma-ray spectrum that is as unique as a fingerprint. . . ."

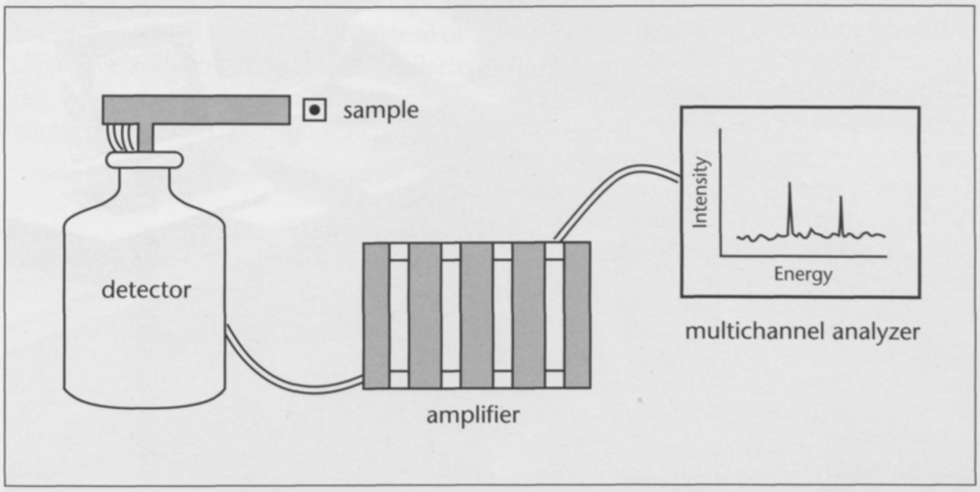


Figure 1. A schematic depiction of neutron activation analysis. After a sample has been irradiated, the gamma rays it emits are detected, electronically amplified, and plotted on a graph.

physical form of the constituents, because the activation and decay involve nuclear rather than atomic or molecular structure.

As an analytical technique, NAA is absolute, nondestructive, and simultaneous. Since it is carried out instrumentally, steps such as slicing, polishing, or chemical processing—which might inadvertently contaminate a sample—are kept to a minimum or omitted entirely. Because of its advantages, NAA is the method of choice for many areas of research. Three current projects illustrate its uses.

"...NAA is absolute, nondestructive, and simultaneous."

Neutron Activation Analysis in the Study of Plate Tectonics

Professor Robert Kay and his colleagues in the Department of Geological Sciences are engaged in an ongoing project to study the flow of mass in the earth's mantle. They are interested in the way energy is dissipated at subduction zones, where one tectonic plate pushes down under another. They are able to study the mechanics of subduction by paying attention to trace elements in material originating deep in the earth that is brought to the surface by volcanic eruptions.

Members of the team have traveled to some of the world's most remote land areas, in Alaska, Russia, the Philippines, and Argentina, and over a thousand samples have been analyzed. The technique can be illustrated with reference to the central portion of the Aleutian Islands, where a string of volcanoes forms an arcuate barrier that separates the basin of the North Pacific Ocean from that of the Bering Sea. The subduction of the Pacific Plate northward at an angle of about 45° under the Aleutian Islands and the Bering Sea is clearly delineated by a dipping earthquake zone. What is not clear is how much of the Pacific Plate is being subducted. This can be evaluated, however, with the aid of trace elements that appear in volcanic rocks.

The Pacific Plate consists of two parts—an igneous layer topped by a sedimentary layer. The igneous layer is a six-kilometer-thick mass of basalt that rides on mantle peridotite, and the sedimentary layer is a half-kilometer-thick veneer of clay that has washed off the adjacent continent. The cesium content of the two layers is very different, with only ten to twenty parts per billion in the basalt, but considerably more in the sedimentary material.

NAA was used to determine the cesium content of rock that had been brought to the

Graduate student Carol Ouellet examines a spectrum at one of the three facilities for neutron activation analysis in Ward Laboratory.

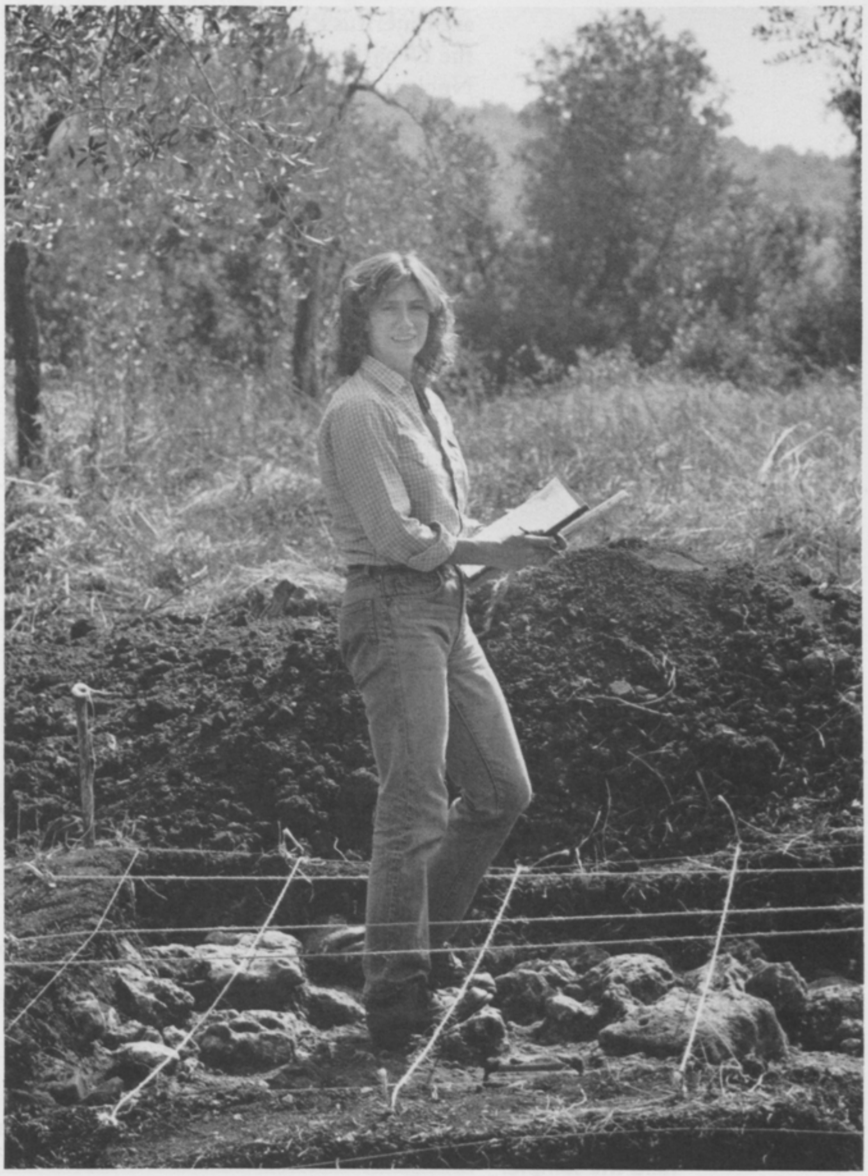
surface by the Aleutian volcanoes. The technique involves irradiating half a gram of rock powder sealed in a high-purity quartz tube. Eleven such samples and three in-house rock standards are irradiated together. After a week, and again after a month, the intensity of the gamma rays emitted by radioactive daughter nuclides in the samples and standards is measured.

This technique showed that the cesium content of lava from the Aleutian volcanoes ranged from 0.5 to 5 parts per million—twenty to fifty times higher than the cesium content of the igneous part of the oceanic crust. This strongly suggests that not only the basalt layer, but also sediment and perhaps sea water are being pushed down into the earth in the process of subduction.

Neutron Activation Analysis and the Provenience of Artifacts

One of the things that archaeologists want to know about the artifacts they dig up is where they originally came from. Archaeologists try to infer the nature of once-living societies from their enduring remains, and the provenience of objects made of clay, metal, or stone can give evidence of trade contacts or military conquests. Traditionally, the place of origin of artifacts has been determined by studying the details of style and craftsmanship. A place where a particular style predominates is assumed to be its place of origin, and artifacts of the same style found elsewhere are presumed to have been exported.

NAA can be used with a similar logic but considerably greater precision. Instead of a subjective assessment of stylistic similarity, the variety and proportion of chemical elements in the materials from which artifacts



Jane Whitehead, who is excavating an Etruscan site at La Piana, near Siena, Italy, uses neutron activation analysis to help determine the provenience of ceramic artifacts such as those pictured above.

are made can be determined and compared. This is the goal of a new program headed by Professor Jane Whitehead of the Department of Classics.

Whitehead has spent eight seasons excavating an Etruscan site located at La Piana, near Siena, Italy, which flourished from the fourth to the early first century B.C.E. Artifacts found at the site provide evidence of a thriving agricultural settlement. Contacts between the Etruscans, the Celts, the Carthaginians, and the Romans, as demonstrated by the distribution of pottery of known provenience, could cast new light on the turbulent history of those times.

Working on the project with Whitehead are Emeritus Professor Albert Silverman of the Department of Physics, David Clark of Nuclear Science and Engineering, and graduate student Carol Ouellet. The initial phase of the program involves finding the elemental composition of a large number of ceramic samples. This will make it possible, in principle, to determine their place of origin, since the clays from different sources have characteristic compositions. But first, it will be necessary to build up a database containing the elemental profiles of sources of raw materials and artifacts whose place of origin is known.

The Cornell effort will complement the work of two groups doing similar studies with artifacts from other Etruscan sites. One is headed by Theodore Peña of the State University of New York at Albany and the other by Shirley Schwartz of the University of Evansville. Both are working with James Blackman of the Smithsonian Institution, using the 20-megawatt reactor of the National Institute of Standards and Technology in Gaithersburg, Maryland. The three-way collaboration will speed the development of a database, and interesting results can be expected in the not-too-distant future.

Neutron Activation Analysis and Electronic Materials

Because of its great sensitivity, NAA is an ideal way to discover and quantify trace elements in electronic materials—both unwanted impurities and dopants. Professor Yosef Schacham-Diamand, of the School of Electrical Engineering, is collaborating with Professor Stephen McGuire, of Nuclear Science and Engineering, in a program to use this technique for the characterization of $Si_{1-x}Ge_x$

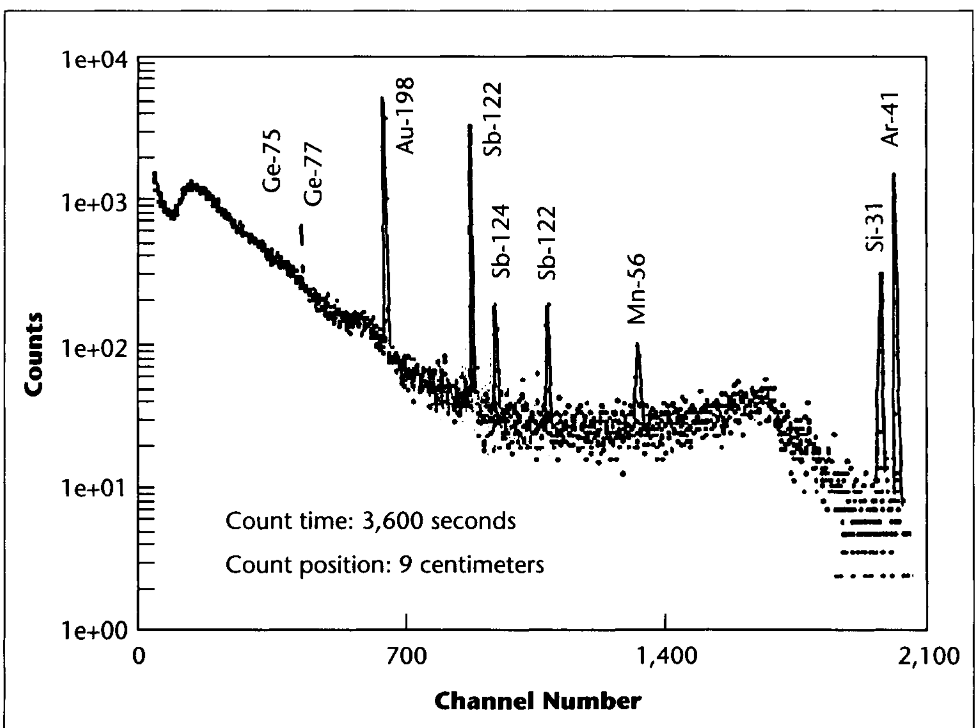


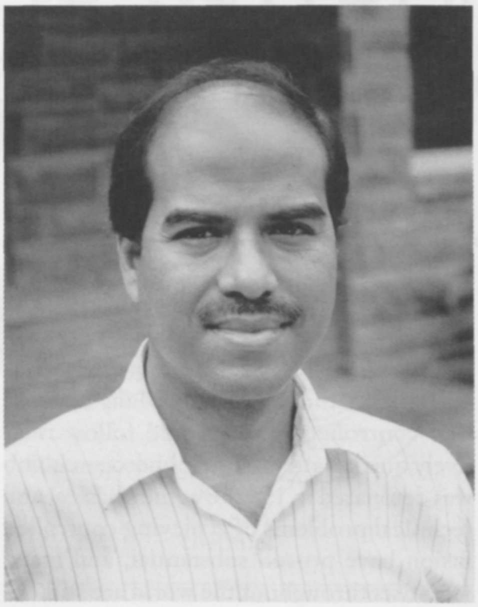
Figure 2. A spectrum showing trace elements in a specimen of silicon-germanium alloy. The technique is so sensitive that it shows a trace of Mn-56, which was not actually in the sample, but in the high-purity polyethylene container that held the sample.

alloys. Because of their reduced bandgap and enhanced carrier mobility, these materials are being employed in bipolar junction transistors (BJTs) and high-speed modulation-doped field-effect transistors (MODFETs) intended for VLSI technology. Both bandgap and mobility depend on the germanium fraction, which is typically between 5 and 20 percent. Analysis of gamma-ray spectra, such as that shown in Figure 2, has made it possible to determine the amount of germanium and of dopants such as antimony in silicon-germanium alloys.

New facilities will enhance Ward Laboratory's capabilities in the area of semiconductor materials characterization. A cold-neutron guide tube that is nearing completion will provide a low-background, moderate-intensity beam of subthermal neutrons (see article by David Clark, this issue). In addition, a neutron depth-profile facility is being designed. This will make it possible to identify and determine the spatial distribution of elements that emit a charged particle (such as an alpha particle or a proton) when they absorb a low-energy neutron. Some elements that do this are boron, nitrogen, beryllium, and oxygen—all important in the fabrication of semiconductor devices.

The Power of NAA As an Aid to Research

As the examples from geology, archaeology, and microelectronics show, NAA has great utility in a wide range of applications. While it is a fairly mature method, new variants and extensions are still being developed and reported. The Eighth International Conference on Modern Trends in Activation Analysis took place in Vienna in September 1991, and a ninth in the series is being planned, probably for 1994. Cornell has made significant contributions to the development and application of the technique, and this is expected to continue in the future.



Tim Z. Hossain received the Ph.D. in 1982 from the University of Kentucky, where he specialized in radionuclear chemistry. He then joined the Eastman Kodak Company in Rochester, New York as group leader of the neutron activation analysis section. He received Kodak's Team Achievement Award in 1989.

In 1989, he joined the Central Research Laboratory at Texas Instruments, Inc., in Dallas. He came to Cornell University in 1991 as assistant manager of experimental facilities at Ward Laboratory.

Hossain's research interests involve the use of neutron activation analysis in the characterization of materials. He is currently using trace analysis techniques to examine archaeological and semiconductor materials, as described in this article.

HOLDING A BIT OF THE SUN

Progress toward Inertial Confinement Fusion

by David Hammer

". . . energy from a virtually inexhaustible fuel that is readily available to all nations . . ."

The promise of useful energy from the fusion of light nuclei, the mechanism that powers the sun, has drawn the research efforts of many scientists since the early 1950s. Many believed that controlled fusion would follow relatively quickly after the first hydrogen bomb was detonated in 1952. But the physical and technical problems of achieving controlled fusion have proven substantial, and many scientists throughout the world are still engaged in addressing them. The promise of fusion is compelling: energy from a virtually inexhaustible fuel that is readily available to all nations, generated by a process that is inherently much safer than nuclear fission and does not cause air pollution or greenhouse gases.

The easiest fusion reaction to initiate, and the one that will probably be used in the first fusion reactors, involves two heavy isotopes of hydrogen: deuterium and tritium. A deuterium nucleus (one proton and one neutron) combines with a tritium nucleus (one proton and two neutrons), yielding an ordinary helium nucleus (two protons and two neutrons) plus one free neutron, and releasing 2.8×10^{-12} joules of energy (see Figure 1). Although this yield may not sound like very much, it is about four million times the energy released per carbon atom consumed when fossil fuel is burned.

Because nuclei are positively charged, inducing them to fuse means getting them to collide with enough energy to overcome their mutual electrostatic repulsion. This can be done for deuterium and tritium atoms by heating them to 50,000,000°C, a temperature at which they are broken up into their constituent electrons and nuclei. The challenge is how to hold this hot ionized gas, or plasma, which is like a small piece of the sun. If it is in contact with a material wall, either the wall will melt or the plasma will cool down—or both. Therefore, in addition to high temperature, a successful fusion reactor will require a way to keep the plasma away from the walls of the reactor vessel long enough for the energy generated by deuterium-tritium reactions to exceed the energy required to heat the plasma.

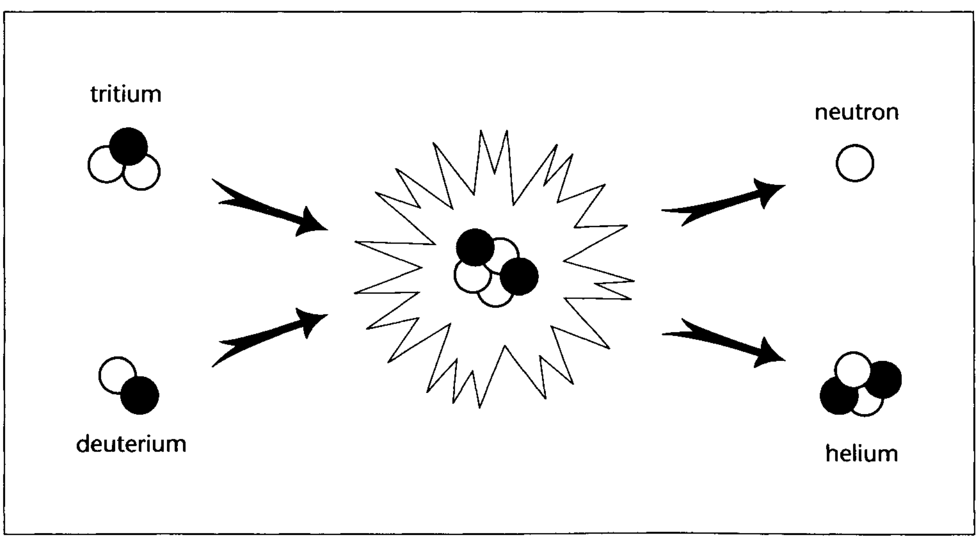


Figure 1. The basic fusion reaction. A deuterium nucleus (one proton and one neutron) fuses with a tritium nucleus (one proton and two neutrons) to yield a helium nucleus and a free neutron. The approaching particles must have enough kinetic energy to overcome their mutual electrostatic repulsion, but the reaction releases several hundred times the energy it takes to bring them together.

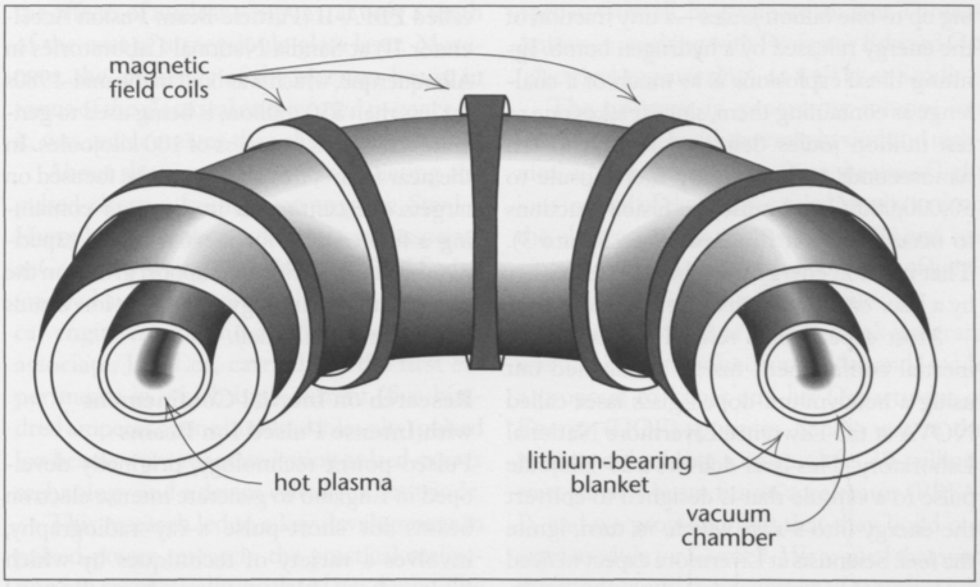


Figure 2. The tokamak consists of a toroidal magnetic field coil wrapped around a vacuum chamber in which the plasma is generated and confined. Another coil system (not shown) induces a current flow in the plasma to heat it as well as to help confine it. A lithium-bearing blanket around the vacuum chamber stops neutrons released by the fusion and breeds more tritium, which can serve as fuel.

Magnetic Confinement Approach to Controlled Fusion

There are two approaches to containing a plasma in which fusion can take place. One depends on the charge of the particles in the plasma, and the other depends on their mass.

The approach that has received the most attention so far is magnetic confinement. Since energetic charged particles move in circles perpendicular to a magnetic field, it is possible to confine them inside a magnet that is made in the shape of a hollow torus. The configuration of such a magnet means that the field lines go around in endless circles.

A variant of this concept was developed at Moscow's Kurchatov Institute in the 1950s and 1960s. Called a tokamak (an acronym for "toroidal magnetic chamber" in Russian), it makes use of magnetic fields generated both by currents in coils wrapped around the torus and by current flow in the plasma, as shown in Figure 2. The tokamak configuration for magnetic confinement has dominated fusion research for over twenty years.

The next step toward fusion power by the magnetic confinement approach is to design a toroidal demonstration power reactor. This is being undertaken as an international collaboration involving scientists from the United States, Japan, Russia, and Europe. Supporters believe the project will lead to an economically viable fusion reactor. But many other fusion scientists believe that a different configuration will have to be developed to make a magnetic fusion reactor practical. Alternate candidates are at various stages in the process of research and development.

Inertial Confinement Approach to Controlled Fusion

The other approach to plasma confinement is to make the fusion reactions occur so quickly that the fuel does not have a chance to fly apart before its energy is released. This approach is called inertial confinement because it is only the inertia of the reactants that keeps them together long enough for fusion to occur.

Practical power generation by inertial-confinement fusion will involve a rapid succession of micro-hydrogen bombs, each releas-

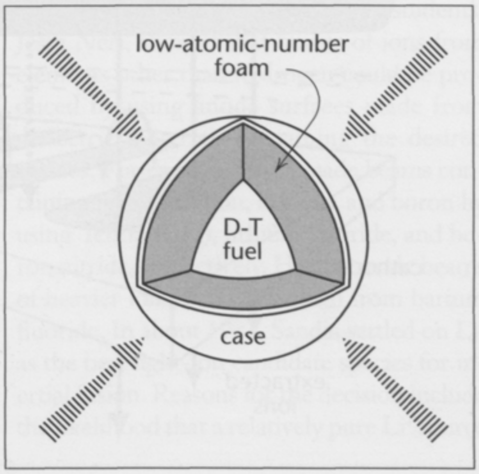


Figure 3. The basic configuration of a target for ion-beam-powered inertial-confinement fusion. The target is irradiated with ion beams from all sides and the low-atomic-number, low-density foam converts the energy into x-rays. These x-rays ablate the surface of the frozen deuterium-tritium fuel in the center, imploding it and heating it to the point at which fusion can occur.

ing up to one billion joules—a tiny fraction of the energy released by a hydrogen bomb. Igniting these explosions is as much of a challenge as containing them, since it takes one to ten million joules delivered in one to ten nanoseconds to heat a tiny fuel capsule to 50,000,000°C and cause the fusion reactions to occur before it flies apart (see Figure 3). That ignition energy must be supplied either by a laser or by a charged-particle beam.

Most experiments related to developing inertial confinement fusion are carried out using a neodymium-doped glass laser called NOVA at the Lawrence Livermore National Laboratory. This laser delivers a 25-kilojoule pulse to a capsule that is designed to convert the energy into x-rays which, in turn, ignite the fuel. Scientists at Livermore expect to need twenty to forty times more laser energy to release as much energy from fusion as they deliver in the laser beam. A glass laser this powerful would cost hundreds of millions of dollars. Therefore, an alternative way to ignite fuel capsules is being sought. One possible alternative is the krypton fluoride laser being developed at the Naval Research Laboratory. The other major contender is intense pulsed ion beams.

The advantage of the pulsed ion beams is that the technology to generate beams up to about one megajoule already exists. A device called PBFA-II (Particle Beam Fusion Accelerator II) at Sandia National Laboratories in Albuquerque, which was built in the mid-1980s for less than $50 million, is being used to generate ion beams in excess of 100 kilojoules. In the near future, this energy will be focused on targets one centimeter in diameter containing a fuel capsule for inertial fusion experiments. Sandia's principal support group on the physics and technology of intense ion beams is right here at Cornell.

Research on Inertial Confinement with Intense Pulsed Ion Beams

Pulsed-power technology, originally developed in England to generate intense electron beams for short-pulse x-ray radiography, involves a variety of techniques by which high-voltage, high-current, short electrical pulses are produced. (Voltages range from 100 kilovolts to 20 megavolts, current from 10 kiloamperes to 10 megamperes, and pulses from 0.01 to 10 microseconds.) Sandia National Laboratories has been among the leading developers of pulsed power since the early 1960s.

Led by former Cornellian Gerold Yonas (BEP '62), Sandia initiated an electron-beam fusion program in 1973. By then an intense electron-beam generator in the megajoule range had already been built, for simulating

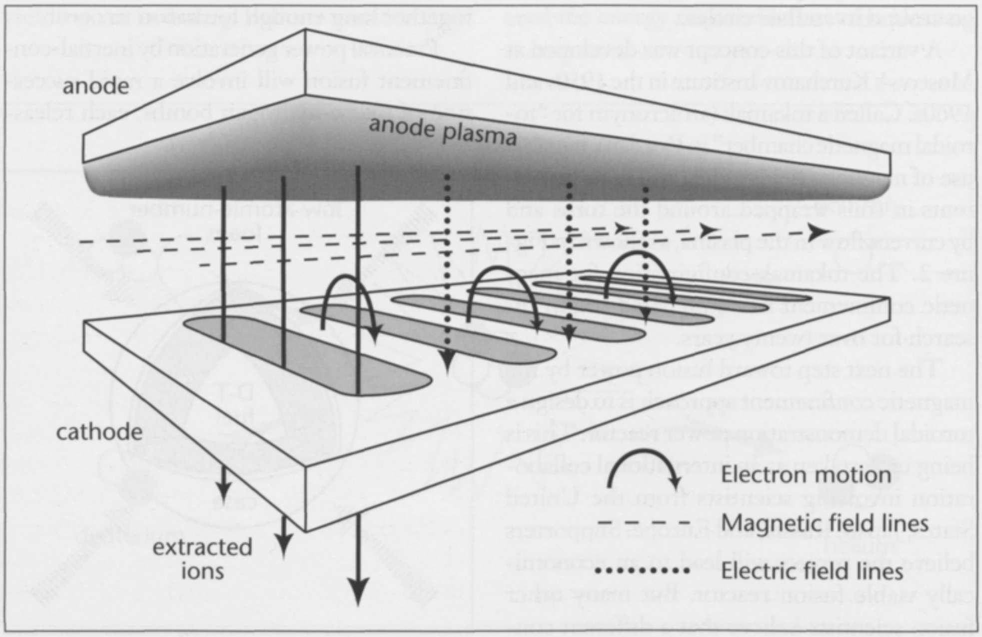


Figure 4. Schematic diagram of a magnetically insulated ion diode. Electrons leaving the cathode are returned to it by the magnetic field. Ions drawn from the plasma adjacent to the anode surface, being more massive, are minimally affected by the magnetic field. The electric field accelerates these ions toward the cathode, which has openings through which they are extracted.

the effects of nuclear weapons, at only a tenth of the cost of a megajoule glass laser. Moreover, the efficiency of the electron beam, in terms of the electrical energy used to generate it, was much greater than that of a laser.

About the time Sandia was initiating the pulsed-electron-beam fusion program, Stanley Humphries, Jr., then a postdoctoral associate at Cornell working with Professor Ravi Sudan (applied and engineering physics and electrical engineering), and another postdoctoral associate, J. J. Lee, carried out the first experiments in which high-current (five hundred amperes at one hundred kilovolts) pulsed ion beams were generated using pulsed-power technology and a device called a reflex triode.

This research led to a key development in pulsed-power research: the practical realization of a magnetically insulated ion diode. The theory (illustrated in Figure 4) was worked out in 1973 by Richard Lovelace, now a professor of applied and engineering physics, and Sudan. They calculated the magnetic field needed to prevent electrons from sapping virtually all the power from the pulser, so that an intense ion beam could be produced efficiently—assuming a suitable ion source was available at the anode. In 1975 Humphries, by then an assistant professor in the Department of Applied and Engineering Physics working with Sudan and graduate student Philip Dreike, succeeded in generating that ion source by mounting a plastic, such as polyethylene or Lucite, on the anode. Within a short time, Sandia successfully tested the magnetically insulated diode on one of their trillion-watt, thirty-nanosecond pulsers.

Another important advance was the extraction of an ion beam from a magnetically insulated diode through a "virtual cathode," consisting of an electron cloud formed on magnetic field lines, rather than a partially transmitting metal cathode. This development, made independently by Humphries, working with Sudan and graduate student Larry Wiley, and by Professor Hans Fleischmann (applied and engineering physics) and graduate student Stanley Luckhardt, in 1976, allowed accelerated ions to be efficiently extracted from the diode at high current density.

By 1979 more complete theories of the magnetically insulated diode had been developed at Cornell, by graduate student Thomas Antonsen working with Professor Edward Ott (electrical engineering), as well as at Sandia.

The progress in generating intense ion beams, together with several physical and technical advantages accruing from the use of light ions instead of electrons, caused Sandia to drop the electron-beam approach in 1980 and begin concentrating on the development of light-ion beams for igniting fuel capsules.

When it was clear that Sandia's program was moving in this direction, Sudan and I made a proposal to Yonas and his Department of Energy (DOE) sponsors. Sandia was in the process of building a 36-module, 30-trillion-watt particle beam fusion accelerator (PBFA-I), and we proposed that that they build one extra module for Cornell. We argued that with this module and their support of our research, we could help them overcome the problems of generating extremely high-current-density ion beams and focusing them on a centimeter-sized target in a twenty-nanosecond pulse. Sandia and DOE accepted our proposal, creating Cornell's Light Ion Fusion Facility (LION), and we have had a very fruitful and productive collaboration ever since.

"The Cornell research program in intense ion beams is by far the largest of its kind at any university in the world."

Important Contributions to Light Ion Research

The Cornell research program in intense ion beams is by far the largest of its kind at any university in the world. Our accomplishments include the invention of several of the major techniques used for intense-ion-beam generation, the development of novel diagnostic techniques, and the first intentional production of intense beams of ions heavier than protons.

In early experiments, one of my students, Jesse Neri, showed that beams of ions from elements other than hydrogen could be produced by using anode surfaces made from dielectric materials containing the desired species. For example, Neri made beams containing mostly carbon, lithium, and boron by using Teflon (CF_2), lithium fluoride, and boron nitride, respectively. He also made beams of heavier ions, such as barium from barium fluoride. In about 1983, Sandia settled on Li^+ as the best light-ion candidate species for inertial fusion. Reasons for the decision include the likelihood that a relatively pure Li^+ source

"... we initiated a program to probe magnetically insulated diodes using optical techniques...."

could be developed and that the high-voltage pulses necessary to give it an optimum range in an inertial fusion target capsule (15 to 30 million volts) could be generated. As of the end of 1991, Sandia's best results on Li^+-beam generation have been obtained with lithium fluoride anodes.

More recently, John Moschella, a graduate student working with Professor Bruce Kusse in the Department of Applied and Engineering Physics, demonstrated that obtaining a mostly-lithium beam from a lithium chloride anode was possible only if the anode surface was appropriately prepared and discharge-cleaned to eliminate water vapor and as many other sources of hydrogen as possible. Since proton contamination has proved to be the most difficult ion-source problem, procedures similar to Moschella's are now becoming standard practice in all experiments—at Sandia as well as at Cornell—in which beams other than hydrogen are being generated.

Using Optical Techniques To Probe Diodes

Since the application of any technology is facilitated by a better understanding of how it works, we initiated a program to probe magnetically insulated diodes using optical techniques such as emission spectroscopy and laser-induced-fluorescence spectroscopy. These techniques provide an ideal way to get data for comparison with analytic theory, computer simulations, and intuitive expectations, because they do not change the conditions around them, as a material probe would do. Much of the support for these experiments came from the Plasma Physics Division of the Naval Research Laboratory, which had other reasons to be interested in pulsed-power applications, but the experimental results are also relevant to the inertial-confinement fusion program.

Rabindranath Pal, a postdoctoral associate working with me, showed that the region from which the intense ion beam is extracted is actually about two millimeters in front of the plastic surface, that the anode plasma contains neutral atoms as well as ionized surface material, and that it takes only ten to twenty nanoseconds to form. The distance between the high-voltage plates in an ion diode, which form the gap across which ions are accelerated, may be as little as six to ten millimeters (see Figure 4). The rapid appearance of the anode plasma layer can have a significant effect on the size of the magnetic field needed to keep electrons from crossing this gap. Earlier experiments using laser interferometry done elsewhere had suggested the existence of such a layer. Then research associate John Greenly and visiting scientist Yoshiro Nakagawa inferred the presence of neutral atoms from measurements of energetic neutrals extracted from one of our magnetically insulated ion diodes that was being used for studies of magnetic fusion. But the location of the ion-emission surface had not been revealed by these earlier experiments.

Following Pal's work, visiting scientist (and then research associate) Yitschak Maron carried out an extensive series of experiments, assisted by visiting scientist Hansheng Peng, graduate student Michael Coleman, and me. We measured and analyzed the light emitted by ions in the anode plasma and in the ion-accelerating gap of a magnetically insulated diode. Because an electric field affects the wavelength of certain ion-emission lines, we were able to determine the electric field as a function of position in the ion-accelerating gap. We were also able to determine the distribution of ion velocities perpendicular to the direction of acceleration from the *width* of ion emission lines. This is very important in assessing how well the ion beam can be focused.

For his doctoral dissertation, Coleman used laser-induced fluorescence spectroscopy to measure the velocity of singly charged argon ions as they were being accelerated in a magnetically insulated diode. This was accomplished by tuning a dye laser near an ion absorption line and looking for re-emitted light at a different wavelength—that is, "fluorescence." The laser light is absorbed by argon ions moving toward the laser, at a wavelength that depends on the ion velocity—and ion velocity is a function of position in the ion-accelerating gap. By determining within a fraction of a millimeter where the laser light was absorbed, the argon-ion velocity at this position can be calculated. This velocity can then be converted to information on the electrostatic potential profile and electric field as a function of diode configuration and the initial density of the argon plasma at the anode.

Both the electric-field and potential-profile measurements showed the ion-accelerating gaps of magnetically insulated intense-ion-beam diodes to be more or less uniformly filled with electrons. This result was inconsistent with the predictions of analytic theory and computer modeling done in the 1970s and early 1980s, which assumed that electrons in a magnetically insulated diode existed in the form of a quiescent, well-confined cloud near the cathode. Michael Desjarlais, a graduate student working with Sudan, hypothesized that electron motion might include a stochastic element due, for example, to a lack of uniformity in the structure of the anode and/or cathode. According to this model, the electrons would tend to diffuse into the entire ion-accelerating gap. While agreement between theory and experiments was not quantitatively good, the theory and experiments together served to explain, phenomenologically, why ion beam experiments always seemed to show a higher ion current density and more leakage of electrons to the anode than expected, unless the magnetic field was much stronger than should have been necessary. These effects are

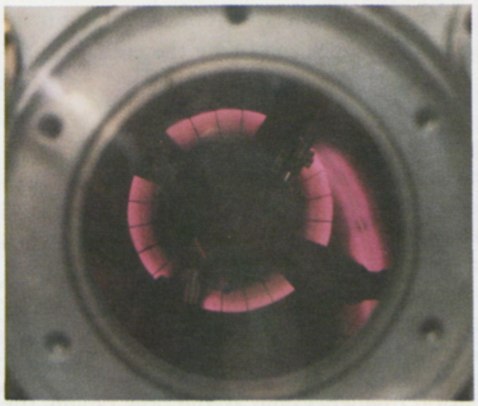


Figure 5. Exploding-metal-film anode mounted in the LION and undergoing low-pressure discharge cleaning.

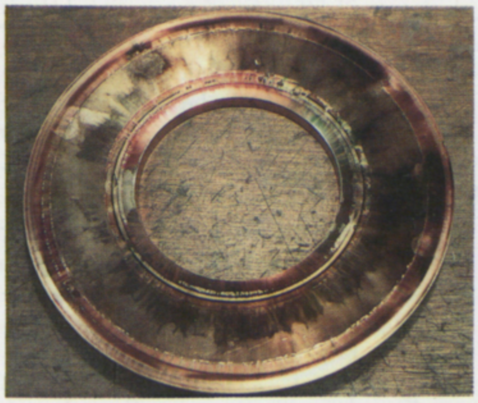


Figure 6. The anode after a pulse. The discolored epoxy substrate shows remnants of the aluminum film.

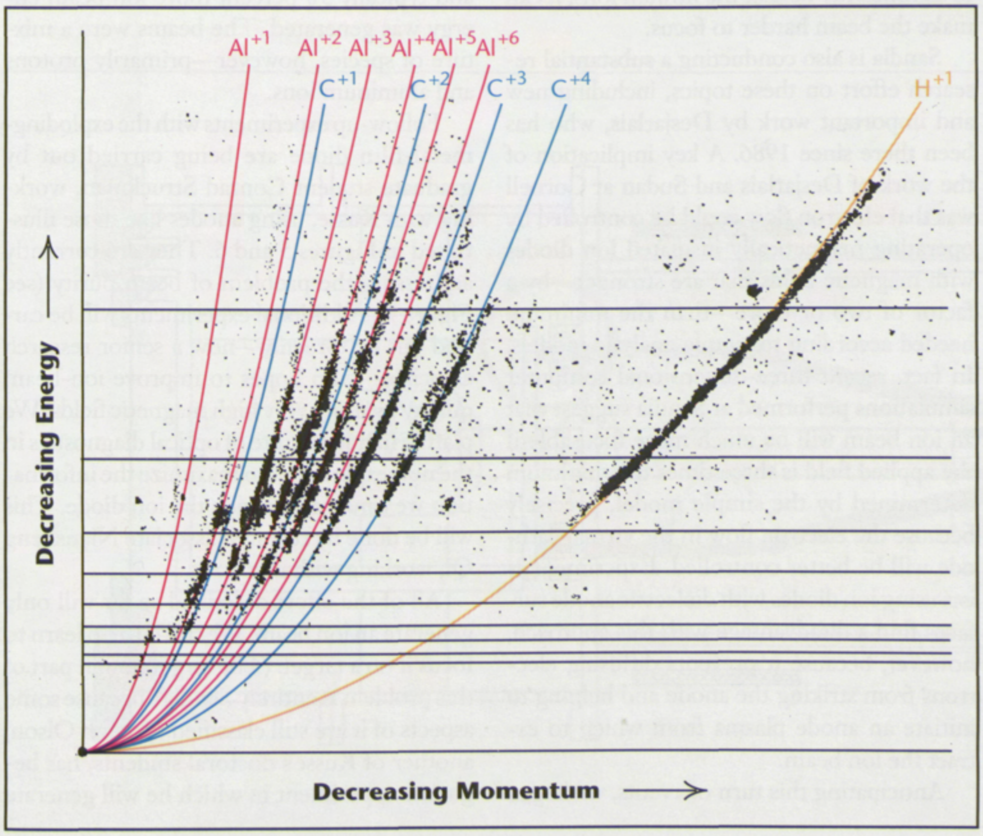


Figure 7. Ion species in a beam made from aluminum plated over epoxy. This plot was made with a Thomson parabola spectrometer, which separates ion species horizontally with a magnetic field and spreads them out vertically, according to their energy, with an electric field. The theoretical curves for the ion species are parabolas, with lower-energy ions further out along the curves.

This figure illustrates the difficulty of generating a beam that contains only one kind of ion. In addition to aluminum, ionized up to five times (Al^{+5}), the plot shows carbon and hydrogen ions, which are probably from the epoxy substrate.

both due to the electrons diffusing across magnetic field lines and filling the entire ion-accelerating gap.

Understanding Electron Diffusion From First Principles

A topic of current research for Sudan and graduate students Bryan Oliver and Bruce Church is to understand the diffusion from first principles. One aspect of their work involves assuming the existence of a plasma instability that will cause a certain effective collision frequency, and asking how rapidly the electrons will diffuse across magnetic field lines as a function of magnetic field strength and other parameters of a diode. Such a calculation is relevant to both the enhancement of ion current density and the efficiency of generating an ion beam. A second goal is to determine what mechanism generates that effective collision frequency. In addition to driving the diffusion of electrons into the gap, the same physical mechanism may also influence the quality of the ion beam. For example, if the electric field from the instability is of large enough amplitude and low enough frequency to significantly deflect the lithium ions, it can make the beam harder to focus.

Sandia is also conducting a substantial research effort on these topics, including new and important work by Desjarlais, who has been there since 1986. A key implication of the work of Desjarlais and Sudan at Cornell was that electron flow could be controlled by operating magnetically insulated ion diodes with magnetic fields that are stronger—by a factor of two or more—than the minimum needed according to simple analytic models. In fact, recent three-dimensional computer simulations performed at Sandia suggest that an ion beam will be much more focusable if the applied field is three times the minimum determined by the simple model, precisely because the electron flow in the virtual cathode will be better controlled. Experimentalists using ion diodes with dielectric anode surfaces find a disadvantage with this approach, however, because it prevents diffusing electrons from striking the anode and helping to initiate an anode plasma from which to extract the ion beam.

Anticipating this turn of events, we began looking into the possibility of independently generating a plasma at the anode. Greenly began developing an active anode plasma source as part of our magnetic fusion research in the early 1980s. This process involves breaking down a gas puff to form a plasma about three centimeters from the anode and moving that plasma into position by a rapid (0.3 to 0.5 microsecond) change in the magnetic field in the diode. Graduate student Mario Ueda completed the development of the ion diode under Greenly's direction.

To meet the stringent requirements of inertial confinement fusion, Gary Rondeau, our laboratory engineer (who was working for a Ph.D. in the employee degree program), developed, with Greenly, an exploding-metal-film anode. By clever routing of LION's high-current pulse through an aluminum film deposited on plastic on the anode surface, the film can be vaporized and converted into a plasma by the beginning of the power pulse—ready to supply ions exactly when needed. Rondeau's experiments were successful in the sense that ion beams were extracted earlier in the power pulse than with dielectric anodes, and typically 50 percent more ion beam energy was generated. The beams were a mixture of species, however—primarily protons and aluminum ions.

Follow-up experiments with the exploding-metal-film diode are being carried out by graduate student Conrad Struckman, working with Kusse, using anodes like those illustrated in Figures 5 and 6. They are currently addressing the problem of beam purity (see Figure 7). Additional experiments will be carried out by Greenly—now a senior research associate—who hopes to improve ion-beam quality by using very high magnetic fields. We plan to include a suite of optical diagnostics in the new experiment to maximize the information we can obtain inside the ion diode. This will be done by research associate Niansheng Qi, working with me.

All of the effort described so far will only generate an ion beam. We still have to learn to focus it on a target. (The target design part of this problem is entirely Sandia's because some aspects of it are still classified.) Joseph Olson, another of Kusse's doctoral students, has begun an experiment in which he will generate

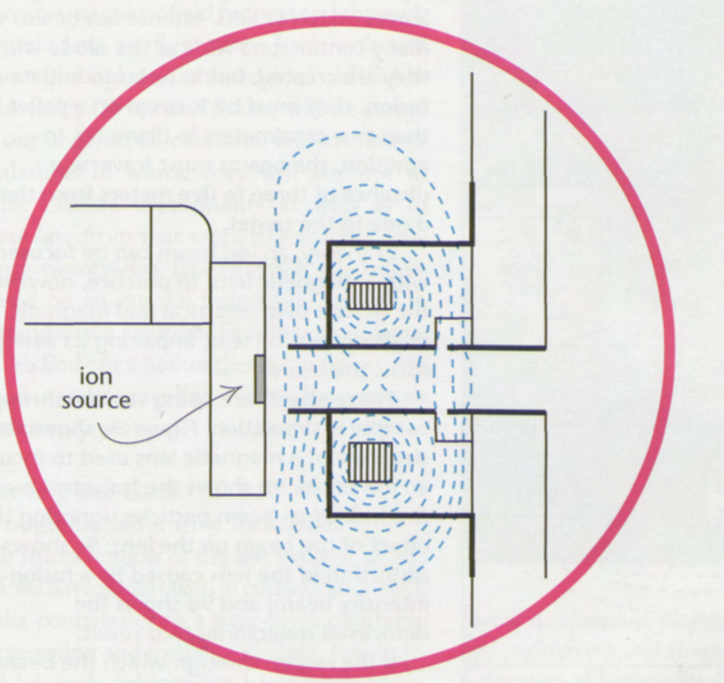
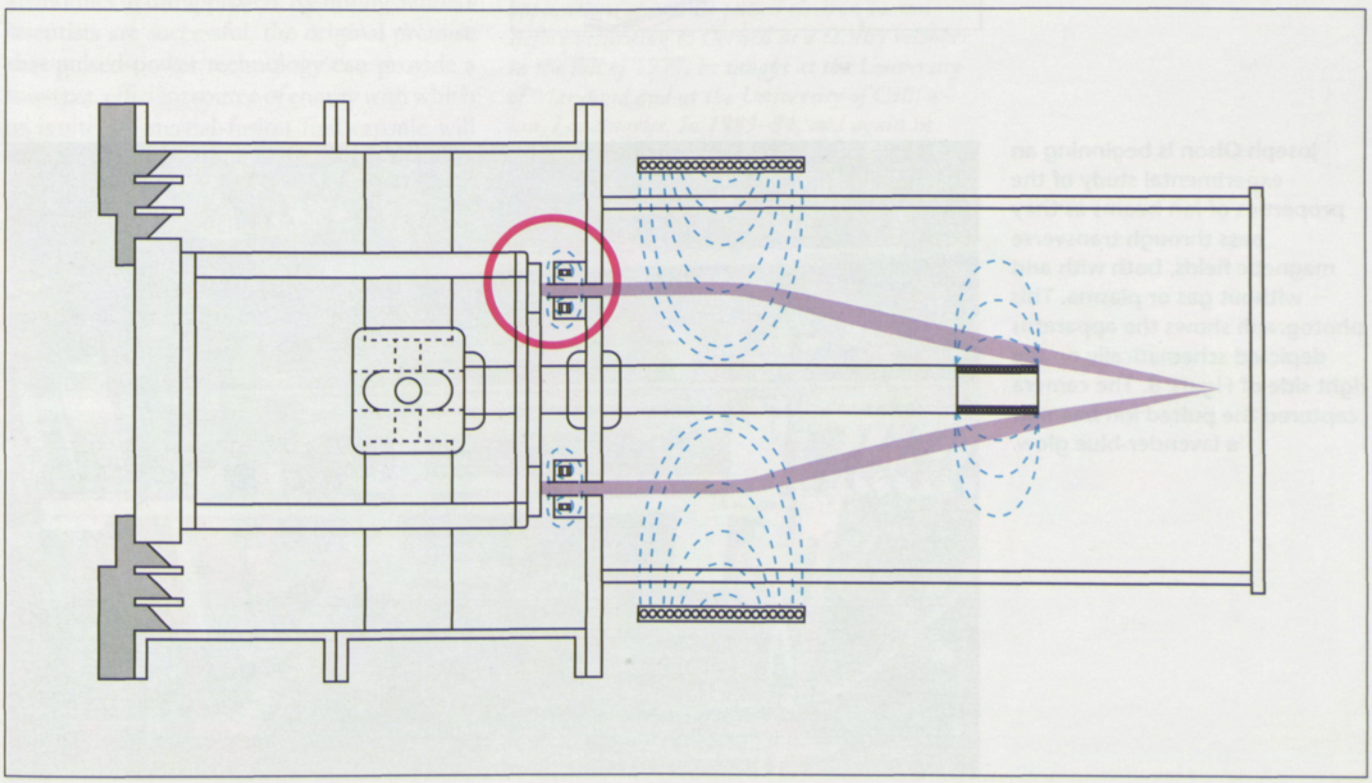


Figure 8. Focusing ion beams with magnetic lenses. In order to deliver several intense ion beams to an inertial-fusion fuel capsule, all at the same time, an efficent focusing method must be perfected. One possibility is to use a combination of magnetic lenses. In the left side of the apparatus shown below is an evacuated chamber where a high-voltage pulse produces an ion beam. On the right side, this beam is focused by a pair of magnetic lenses. The enlarged detail of the region in which the ion beam is generated shows the magnetic-field configuration that allows ions to be extracted while preventing electron flow. Efficient ion-beam propagation may require puffs of plasma or gas in each of the three regions where there are strong magnetic fields, in order to prevent the buildup of an electric charge.



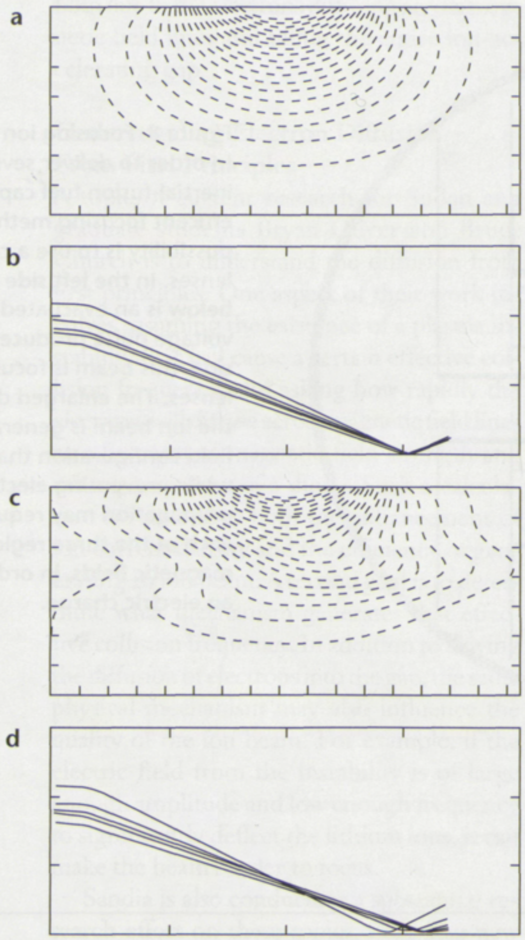
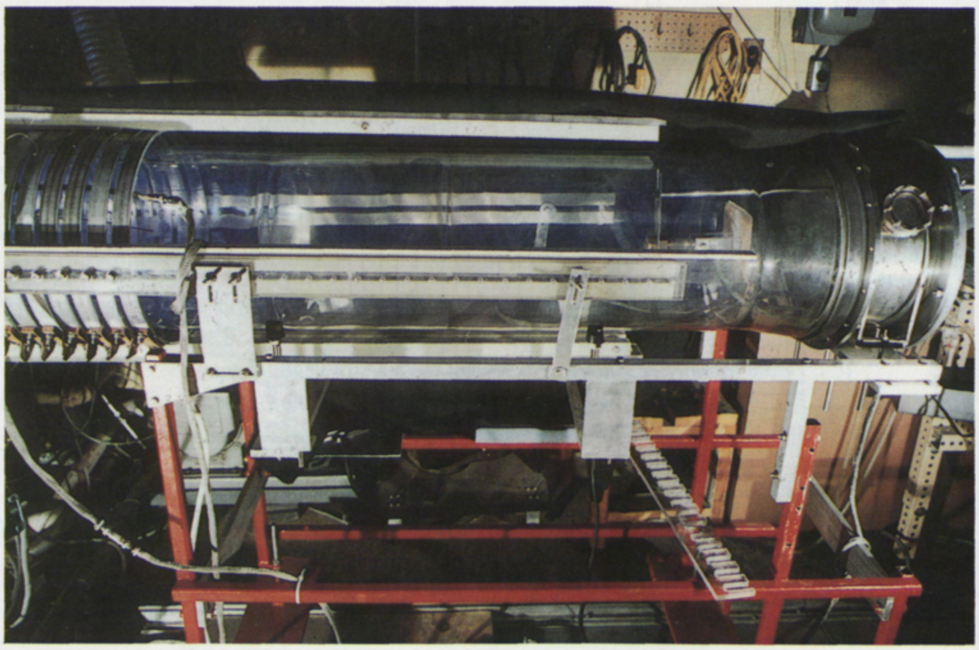


Figure 9. Simulating the effect of magnetic lenses on ion beams. Intense ion beams are many centimeters wide at the diode where they are created, but in order to initiate fusion, they must be focused on a pellet less than two centimeters in diameter. In addition, the beams must traverse a distance of three to five meters from the diode to the target.

In theory, an ion beam can be focused with a magnetic lens. In practice, however, the beam's own electrical and magnetic fields distort the lens, impairing its ability to focus the beam.

These effects are being studied through computer simulation. Figure 9a shows the structure of a magnetic lens used to focus an ion beam; 9b shows the trajectories of five individual beam particles, ignoring the effect of the beam on the lens; 9c shows the distortion of the lens caused by a fusion-intensity beam; and 9d shows the defocused trajectories that result.

If the region through which the beam passes is filled with plasma, distortion of the magnetic lens is minimized, and the trajectories in 9b are recovered.

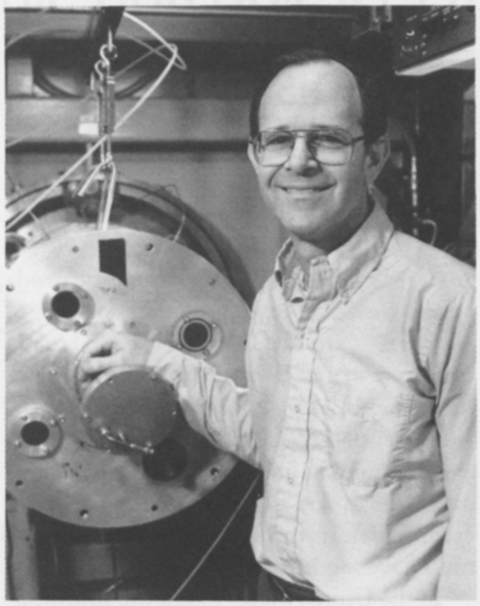


Joseph Olson is beginning an experimental study of the properties of ion beams as they pass through transverse magnetic fields, both with and without gas or plasma. This photograph shows the apparatus depicted schematically on the right side of Figure 8. The camera captured the pulsed ion beam as a lavender-blue glow.

an ion beam and study its properties through transverse magnetic field regions and through magnetic lens configurations both with and without gas or plasma in the regions with fields. Meanwhile, Oliver and Sudan will be carrying out analytic calculations and computer simulations in which they will attempt to model Olson's experiments as well as to extrapolate from that work to a reactor containing twenty-five 100-kilojoule ion beams focused on an inertial fusion fuel capsule in the middle of a chamber five meters in diameter. To find out whether these simulations are a good match for reality, we may have to wait some twenty years.

Achieving the Goal Through Collaborative Research

With the exception of the last project, all the work we have undertaken in collaboration with Sandia contributes to a near-term capability of generating and focusing a single, few-hundred-kilojoule lithium-ion beam onto an inertial fusion capsule located in the middle of the single, huge pulsed-power device, PBFA-II. While achieving this goal is only one step on the path to useful power by inertial confinement fusion, it will be a major one in the economics of the approach. Assuming Sandia's scientists are successful, the original premise that pulsed-power technology can provide a low-cost, efficient source of energy with which to ignite an inertial-fusion fuel capsule will have been demonstrated. Cornell's contributions to that success include not only the theoretical and experimental results already described but also the students who have gone on to work at Sandia. Their expertise in light-ion-beam technology and physics has enabled them to begin making major contributions from the moment they join the Sandia staff.



David A. Hammer, professor of nuclear science and engineering and director of Cornell's Laboratory of Plasma Studies, received the B.S. degree in 1964 from the California Institute of Technology and the Ph.D. in 1969 from Cornell University.

Hammer worked for several years as a research physicist at the Naval Research Laboratory, investigating the physics and applications of intense pulsed electron beams. Before returning to Cornell as a faculty member in the fall of 1977, he taught at the University of Maryland and at the University of California, Los Angeles. In 1983–84, and again in 1991, he was a visiting senior fellow at Imperial College in London, under the joint sponsorship of the National Science Foundation and the Science and Engineering Research Council.

Hammer's current interests are in plasma physics, nuclear fusion, and high-power ion-beam physics.

SAFE NUCLEAR POWER

Better Design and Simulation Diminish the Liabilities

by K. Bingham Cady

A country's gross domestic product depends on its supply of energy. Energy is needed to extract raw materials and produce manufactured goods. More energy is needed to provide essential services such as transportation and communications, as well as to air-condition, heat, and maintain buildings. To be competitive in the world market, a nation must have access to abundant, cheap energy.

In the United States today, the consumption of electricity is growing by an annual rate of about 3 percent—7 percent in the manufacturing sector. Modernizing the nation's manufacturing capability, which is the best way to fuel America's economic growth, will require a sharply increased use of electricity. The energy to generate this electricity cannot come from water power without serious environmental consequences, as the controversy over the proposed James Bay project is making clear. It cannot come from petroleum without making the United States yet more dependent on foreign oil. It cannot come from coal without exacerbating the problems of air pollution, acid rain, and global warming.

The only clean, readily available, and relatively abundant source of energy for electric power is uranium. Other industrialized countries know this. Germany, Japan, Taiwan, and South Korea all depend on nuclear power more heavily than the United States, and over 75 percent of the electricity produced in France is from uranium. Canada has recently embarked on an ambitious plan to increase its nuclear generating capacity from the current 20 percent to over 50 percent by the year 2010.

Nearly 22 percent of the electricity generated in the United States already comes from nuclear power plants, but no new plants have been ordered since 1978. The problems that stand in the way of further development have to do with complexity and perceived risk. Licensing, construction management, and waste disposal are complex matters, and the possibility of accident has alienated a significant portion of the public. But a national poll conducted by Bruskin/Goldring at the beginning of February shows that opposition to nuclear energy is softening. Sixty percent of the American people support (strongly or moderately) the use of nuclear power, and 18 percent moderately oppose it. Only 15 percent remain obstinately opposed. Perhaps they are not aware of recent advances in reactor technology.

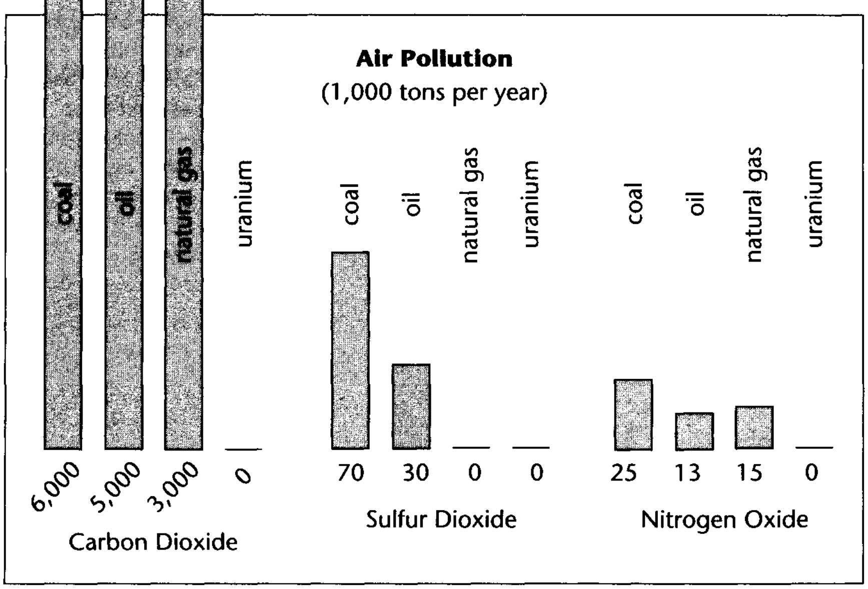


Figure 1. Fossil fuels and uranium as sources of pollution. Because nuclear power plants do not burn anything, they do not pollute the air, and the radiation for which they are responsible is far less damaging than air pollution. The uranium fuel cycle, from mining through disposal, accounts for less than one percent of the radiation to which the general public is exposed. In contrast, air pollution from fossil fuels is implicated in thousands of deaths per year and pervasive environmental degradation.

Figure 2. Nuclear power plants in the United States. Black dots mark the 111 units currently in operation and white dots show eight more that are under construction. The low cost of transporting nuclear fuel, compared to the higher cost of transporting fossil fuels, makes it possible to locate plants near centers of population, where demand for electricity is greatest. *(Source: U.S. Council for Energy Awareness)*

The Trend toward Passively Low-Risk Nuclear Power Plants

The economic disaster at Three Mile Island and the environmental tragedy at Chernobyl illustrate the need for passively low-risk nuclear power plants. When accidents occur, damage control should rely, wherever possible, on gravity, pressure differences, heat capacity, and natural circulation instead of electricity or the actions of human operators. For example, the fission products released from the Three Mile Island core were contained, as intended, by the building surrounding the reactor system. The accident showed, however, that electrical instrumentation and operator action could not be relied upon to protect the reactor's primary coolant system.

The nuclear power industry is now designing plants that are passively low-risk in a number of ways. The Westinghouse Corporation, for example, has developed the AP-600 (advanced, passive, 600-megawatt reactor). This design features natural circulation to remove heat from the core and to cool the reactor-containment building. It has passive core-flooding capability and control rods that drop into the core automatically upon loss of power. These design features seek to minimize the possibility of damage to the core through the use of passive systems, but the overall concept requires a lower-power reactor than those currently in use.

In addition to Westinghouse's AP-600, General Electric has developed the advanced safety boiling-water reactor (ASBWR), and other vendors—Combustion Engineering and Babcock & Wilcox—are following their lead. None of these reactors has been ordered for the United States market, although General Electric is building two advanced boiling-water reactors in Japan.

The Safe Disposal of Nuclear Wastes

The biological effects of ionizing radiation are better understood than the biological effects of many inorganic and organic chemicals, such as asbestos, mercury salts, lead salts, PCBs, dioxin, and benzene. The reason is straightforward: the effects of ionizing radiation are

Sources of Energy for Electricity in the United States, 1991
(percent)

Coal	54.8
Uranium	21.8
Water power	9.9
Gas	9.3
Oil	3.8
Other	0.4
Total	100.0

Coal is the main source of electrical energy in the United States, followed by uranium. Water power, which ranks third, is clean and renewable, but is environmentally unsound and has limited potential for further development.

"Even if a spill should somehow occur, the material . . . would be relatively easy to clean up."

essentially the same, regardless of the source, while each chemical toxin has a different biological effect. Critics of nuclear power mistakenly suppose that because there is some uncertainty about what level of exposure will cause harmful effects, *any* level should be regarded as dangerous. This does not follow, however. If maximum permissible exposure is uncertain to, say, a factor of two, a factor of ten will provide a margin of safety that is more than adequate.

Reactors produce fission products such as iodine-135, xenon-135, strontium-90, and cesium-137, as well as transuranic nuclei such as plutonium-239 and neptunium-237, all of which emit ionizing radiation. These products must be carefully contained in the core of the reactor, cooled, and shielded when they leave the reactor as spent fuel.

Some transuranic elements pose a special threat because of their long half-lives and high toxicity. A novel way to deal with these actinides has been proposed. Before they are disposed of, they can be run through the reactor a second time. This will convert them, almost entirely, into fission products with much shorter half-lives.

Eventually, spent reactor fuel must be shipped to a reprocessing plant, a retrievable storage facility, or a disposal facility. This sounds like a dangerous step, but by taking the worst-case scenario into account, it can be done quite safely. The fuel is shipped in an insoluble, cladded form, inside a shielded cask that is strong enough to resist crash and fire. Even if a spill should somehow occur, the material could not dissolve and penetrate the ground, so it would be relatively easy to clean up. In comparison, chlorine tank cars, propane tanks, insecticide vessels, and gasoline trucks are far more dangerous.

The final disposal of wastes, after they have been reprocessed, calcined, and vitrified, requires little in the way of sophisticated engineering. Ingots of glassy fission-product oxides clad in stainless steel can be dropped into deep holes drilled in the earth in places where water will not contact the waste and return to the biosphere for centuries to come. The search for an appropriate location is currently underway, and a monitored surface-storage facility is being designed. Federal land in Yucca Mountain, Nevada, is under consideration as a permanent repository.

When nuclear power plants become old and inefficient, or threaten to become dangerous, they are decommissioned. A number of reactors have already been successfully decommissioned, including those at Shippingport, Pennsylvania, and Elk River, Minnesota. The process involves decontamination, mothballing, and eventual disposal or entombment. The state and the power company have to make some decisions that are specific to each case. For example, what should be done with radioactive pipes and pumps? Decontamination and ten years or so of radioactive decay will eliminate most of the radiation, because the major source of radioactivity in these installations is cobalt-60, which has a half-life of five years. At this point, the pipes and pumps can either be entombed at the reactor site or shipped to a specialized landfill. The choice is mainly determined by economics.

Using Computer Simulations to Understand How Accidents Happen

A nuclear power plant is a complex system consisting of thousands of components, including vessels, pipes, pumps, heat exchangers, motors, electrical controls, and human operators. Much can be learned about how this system will respond in a severe accident by modeling it as a set of equations and computing its behavior numerically. This effort forces those who undertake it to examine a whole range of physical possibilities, to search for ways to simplify the model, to find mathematically stable computational algorithms, and to compute the behavior in a reasonable amount of time. It requires a collaboration among physicists, engineers, systems modelers, computer scientists, programmers, and a smart coordinator. The plant's engineers must help with parameter selection. To keep everybody honest and provide input from all possible directions, there must be a peer review board, watchdogs from the Nuclear Regulatory Commission, and even the occasional doubting environmentalist.

But how can we be sure that the results of a computer simulation are realistic—or for that matter, how do we know which set of initiating events to start from, when they lead to

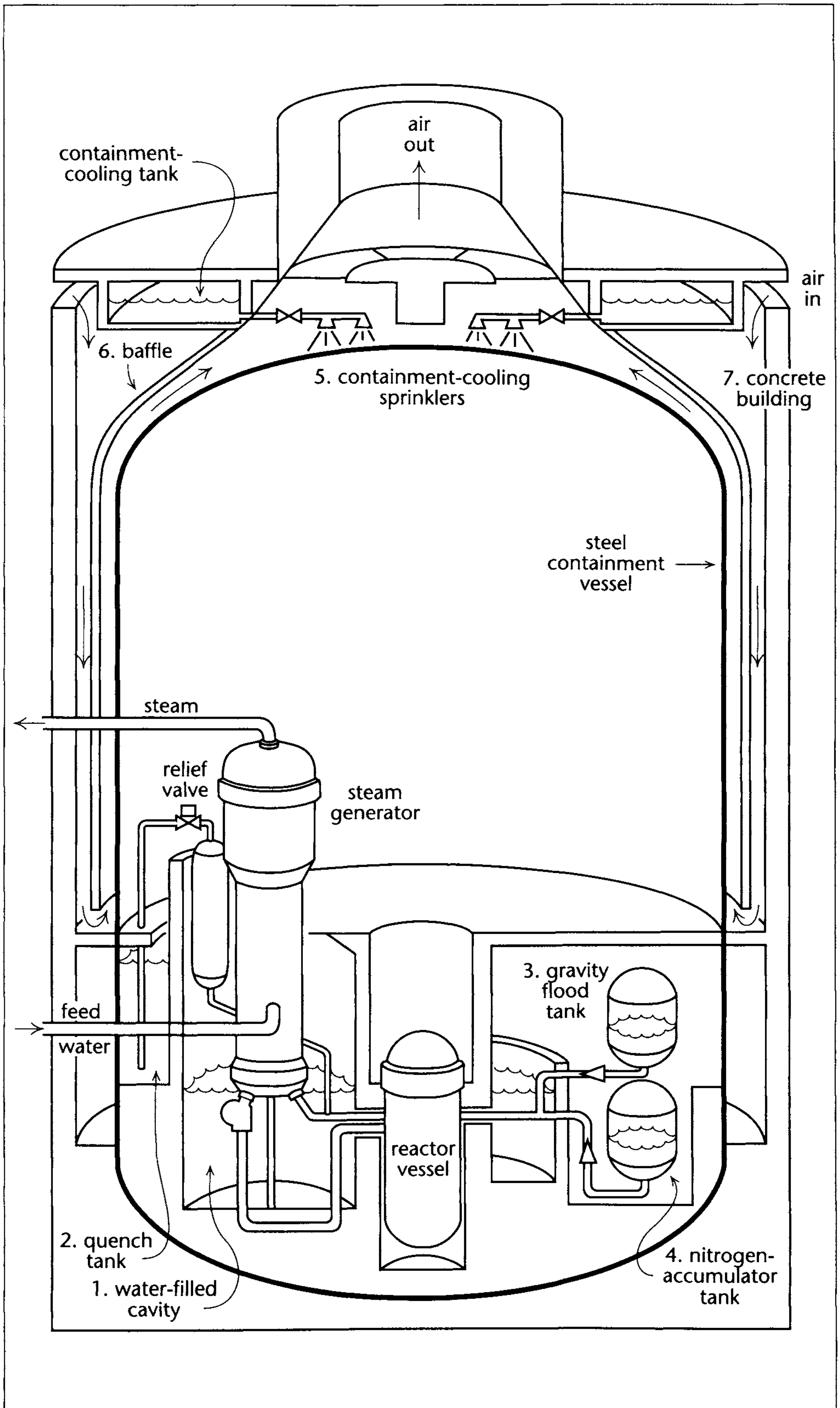


Figure 3. A Westinghouse pressurized water reactor. This design incorporates a number of features that passively minimize risk:

1. **a reactor vessel whose pumps and piping are submerged in a water-filled cavity;**
2. **automatic depressurization through a water-filled quench tank;**
3. **a gravity-operated flooding tank that pours cooling water into the core in the event of an emergency;**
4. **a nitrogen-filled, pressurized accumulator tank that injects cooling water into the reactor core in the event of an emergency;**
5. **a gravity-fed sprinkling system to cool the containment vessel;**
6. **a system that cools the containment vessel by natural convection; and**
7. **a twelve-inch-thick reinforced concrete building.**

Each of these features is effective without decisions by human operators—and even remains effective during a loss of electrical power.

Many countries are more committed to nuclear energy than the United States, and several of them are major industrial competitors. ***(Source: U.S. Council for Energy Awareness)***

International Reliance on Uranium for the Generation of Electricity

	percent
France	75
Belgium	60
Hungary	51
South Korea	49
Sweden	46
Switzerland	43
Spain	38
Taiwan	38
Finland	35
Bulgaria	35
West Germany	33
Czechoslovakia	28
Japan	26
United States	22
United Kingdom	21

countless possible accident scenarios? The answers to these questions are not simple. All important physical phenomena must be modeled and verified in the laboratory. Film boiling, hydrogen diffusion, jet entrainment, pump cavitation, aerosol formation, two-phase flow and heat transfer, concrete ablation, and explosions must be studied by highly educated specialists. These people must have cross-disciplinary training at an advanced level in physics, engineering, and computer science. Once the physical phenomena have been successfully modeled and their performance expressed as logical parameters, the information can be used to represent components in a model of the reactor plant as a whole.

This involves large systems of differential equations governing the conservation of mass, momentum, and energy; explicit and implicit algebraic and transcendental equations; and logical expressions governing events and decisions that occur during the accident scenario. There are two steps to this synthesis. In the first, the physics of each submodel is systematically differentiated from the mathematics of its computation. In the second, larger and larger subsystems are modeled, each with its own equations, data, and algorithms. The challenge is to keep the complexity and error patching from taking over the computational model. Indeed, most large computational modeling efforts have a finite lifetime, which ends when the cost of patching errors starts to exceed the value of correction.

How can we tell whether a simulation faithfully represents a full-blown reactor accident? It is not prudent to create severe accidents just to test modeling capability, so one must resort to real accidents, such as the one at Three Mile Island. Parameters chosen to represent the plant where the accident happened are entered into the computerized model, and the program is permitted to run. The result is a faithful representation of the transient behavior up to a point, and then something unexpected happens—for instance, a relief valve opens or fails to open. From then on, the computational model diverges from reality in a way that an adequate relief-valve model would have prevented.

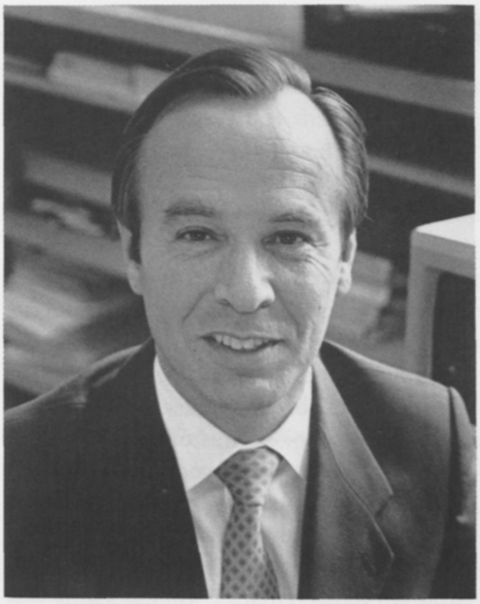
Interpreting the results of a simulation is yet another complex problem. Plots of dozens or even hundreds of flow rates, mass inventories, and temperatures as a function of time are likely to be a meaningless mess without careful editing. But the Nuclear Regulatory Commission is beginning to trust computer modeling, as demonstrated by a warning notice it recently issued to owners of licensed nuclear power plants, informing them of an error in simulation code. Prior to this, the NRC had restricted warning notices to malfunctions in real equipment.

The Future of Nuclear Fission As a Source of Power

As a way to generate electricity, nuclear fission has many advantages over fossil fuels. At current rates of extraction, petroleum will be prohibitively expensive in about thirty years; natural gas will be virtually exhausted in about sixty years, and coal in somewhat over two hundred years. In contrast, the world's supply of uranium can be expected to last for a long time—exactly how long is hard to say, because so much energy can be gotten from so little uranium that it is feasible to mine relatively poor ores. Uranium is cheap; reactors may be expensive to build, but the cost of transporting nuclear fuel is negligible and the energy released in fission is enormous. Today, France, with its many nuclear power plants, has the cheapest electricity in Europe (except for a few places in Scandinavia that are blessed with convenient hydropower). Nuclear power is clean. While no industry is entirely without environmental consequences, nuclear power plants are much less polluting than coal-fired power plants, which promote strip mining and spew into the air particulate matter, nitrogen oxides, sulfur dioxide (which contributes to acid rain), and carbon dioxide (which may cause global warming).

The weapons-grade uranium and plutonium that have become available in the aftermath of the Cold War are an unexpected resource. These materials can be reprocessed and recycled for use as fuel in nuclear power plants. There is no better way to dispose of them than to fission them into needed energy, and the process is far safer than the use for which they were originally intended.

Controversy over nuclear power has spurred nuclear engineers to design passively low-risk reactor plants and develop a modeling capability that makes it possible to predict and avoid accident transients. Further progress can be expected in the development of more standardized designs, the manufacture of more components in factories (rather than in the field), the development of better ways to manage complex projects, and the establishment of simpler procedures for licensing and public intervention. These steps should lead to greater confidence, and this, in turn, should result in the backing that the nuclear power industry needs in order to move forward.



K. Bingham Cady, a professor of nuclear science and engineering and of applied and engineering physics, serves the College of Engineering as associate dean. He received the S.B. in naval architecture and marine engineering in 1956, and the Ph.D. degree in nuclear engineering in 1962, both from the Massachusetts Institute of Technology.

While an undergraduate, Cady worked for the Moore McCormack Steamship Company, and after receiving his degree he worked for the Shipbuilding Division of the Bethlehem Steel Company. Later, while pursuing his doctorate, he worked part-time for the engineering firm of Jackson and Moreland, Inc. He joined the Cornell faculty in 1962.

Cady is an author of several of the large modeling codes used to evaluate transients and accidents in nuclear reactor systems. He is a consultant to many companies and national laboratories and is past president of the Niagara–Finger Lakes section of the American Nuclear Society.

He has held several scholarships and fellowships, including a Ford Foundation Pre-Induction Scholarship, a Woodrow Wilson Fellowship, and a U.S. Atomic Energy Commission Fellowship in Nuclear Science and Engineering.

"As a way to generate electricity, nuclear fission has many advantages over fossil fuels."

Atomic Processes in Ionized Matter

by Vaclav O. Kostroun

"While decades of research have contributed to an understanding of neutral atoms, the investigation of ionized matter still has a long way to go."

Almost all the matter with which we are familiar, here on Earth, exists as neutral atoms in the solid, liquid, or gaseous states. But most of the matter in the universe—perhaps more than 95 percent—is in the plasma state. It exists as a mixture of ions, free electrons, and electromagnetic radiation. While decades of research have contributed to an understanding of neutral atoms, the investigation of ionized matter still has a long way to go.

Ions are atoms that carry a positive or negative charge because they have a different number of electrons than protons. The properties and behavior of ions are of interest to astronomers and astrophysicists because stars consist of plasmas and stellar processes take place in the plasma state. In the solar corona, for example, the temperature is on the order of 2×10^6 °K. Here, the light elements have all their electrons removed, so that they are completely ionized, while calcium, iron, and nickel lack from nine to fifteen of their electrons. In solar flares, where the temperature is around 2×10^7 °K, iron and nickel are fully ionized.

The study of ionized matter has practical as well as theoretical implications because efforts to derive commercial energy from a self-sustaining nuclear fusion reaction (see article by David Hammer, this issue) depend on a detailed understanding of what happens in plasmas. In tokamak fusion reactors, for example, the plasma often contains atoms of chromium, iron, nickel, molybdenum, and tungsten. These elements enter the plasma as a result of sputtering on walls and diverters, and they have deleterious consequences for the operation of the reactors. They become very highly ionized and give rise to discrete and continuous electromagnetic radiations which, upon escaping from the plasma, cool it and prevent it from reaching the temperatures needed for nuclear fusion.

The need for a better understanding of the atomic processes that take place in astrophysical and thermonuclear fusion plasmas has long been recognized, and my students and I form just one of many groups around the world that are measuring and calculating relevant atomic properties. The behavior of ionized matter is very complicated and many phenomena involve nonlinear collective interactions of charged particles with one another and with electromagnetic fields. But atomic processes, which involve individual particles, are also important. For example, the heating and cooling rates of a plasma are determined by atomic processes, and photons (quanta of electromagnetic radiation) emitted by excited ions can yield useful information. Photons are emitted when ions collide with other ions, neutral atoms, electrons, or other photons. From an analysis of the photons that are emitted, one can deduce the elements present in the plasma, their degree of ionization, their relative abundance, the local electron density, ion velocities, how the ions were excited, and the strength of local electric and magnetic fields.

Much information about astrophysical and thermonuclear fusion plasmas can be obtained from a spectral analysis of the electromagnetic radiation emitted by individual ions. Teasing out the component parts of this complex system is not easy, however, and studying the interaction of particular ions with other ions, neutral atoms, electrons, and electromagnetic radiation requires observations made under carefully controlled laboratory conditions.

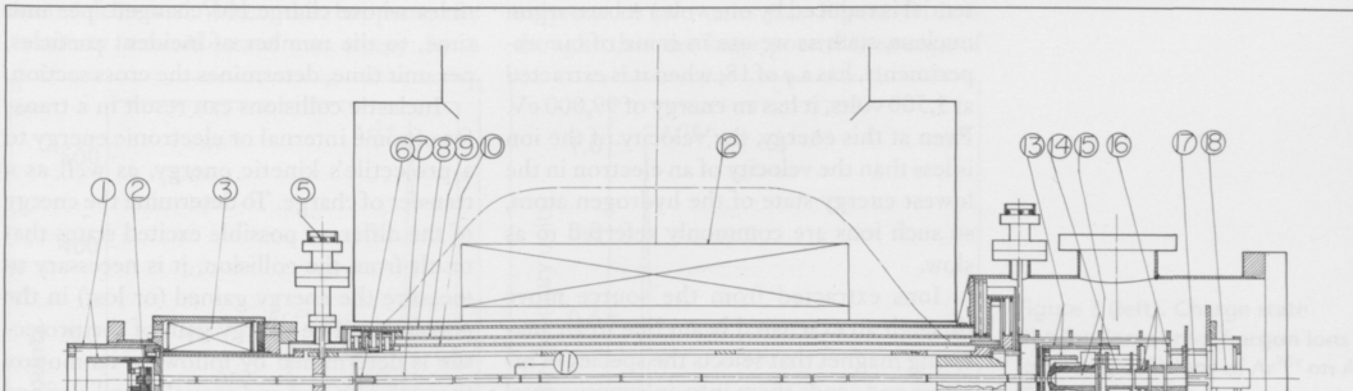
Developing an Ion Source for Laboratory Experiments

The first requirement for studying many of the atomic processes that occur in plasmas is a facility capable of producing beams of the low-energy, highly charged species found in ionized matter. It is not easy to produce such beams in the laboratory, and a good part of our effort, over the last few years, has gone into the design and construction of a suitable source. The two basic types of ion source that we had to choose from are the electron cyclotron resonance ion source (ECRIS) and the electron-beam ion source (EBIS). Both of these were developed in France and the old Soviet Union to extend the usefulness of existing large-proton synchrotrons by converting them into heavy-ion accelerators, and both are unusually sophisticated devices. For technical reasons, we chose to build an EBIS.

In our EBIS, shown in Figure 1, an electron gun produces a beam that is launched along the magnetic field axis of a 30,000-gauss superconducting solenoid that is 80 centimeters long. The strong magnetic field focuses the beam to a diameter of less than 100 microns and helps keep it confined as it propagates along the length of the solenoid. In this manner, electron-beam densities of several hundred amperes per square centimeter can be obtained. When atoms are introduced into this beam, the impact of the electrons converts them into highly charged ions. These ions are contained radially by an attractive potential well that results from the electron beam's negative charge, and they are contained axially by an appropriate potential distribution produced by a series of cylindrical electrodes that encircle the beam. After a predetermined confinement time, the axial trap potential is modified, which allows ions to be expelled from the source. When the kinetic energy of the bombarding electrons is sufficiently high and the containment time is sufficiently long, very highly charged ions can be produced and extracted.

Our EBIS was designed and built at Ward Laboratory, with the participation of Ebrahim Ghanbari and Edward Beebe, graduate students in nuclear science and engineering, Ren Yao in applied and engineering physics, and Siegfried Janson in mechanical engineering. There are other facilities of this type in Sweden, Germany, Russia, Japan, and elsewhere in the United States, but ours is the only one designed and built entirely at a university. It is capable of producing all degrees of ionization, including bare nuclei, of elements up to argon, as well as ions of krypton and xenon with charges up to Kr^{30+} and Xe^{44+} (a krypton nucleus with only 6 electrons instead of the usual complement

Figure 1. Schematic diagram of Cornell's cryogenic, superconducting, solenoid EBIS. Numbered features are: 1) magnetic shield for electron gun, 2) electron gun, 3) entrance solenoid, 4) gun-end vacuum-chamber linear positioner, 5) gun-end drift-tube positioners, 7) drift tube, 8) main vacuum chamber, 9) 77°K thermal shield, 10) 4.3°K copper cryopanel, 11) gas inlet, 12) 3T main solenoid, 13) electron-collector magnetic shield, 14) electron collector, 15) ion extractor, 16) Einzel lens, 17) time-of-flight chopping plates, 18) horizontal deflection plates, 19) cryopump, 20) collector-end vacuum-chamber linear positioner.



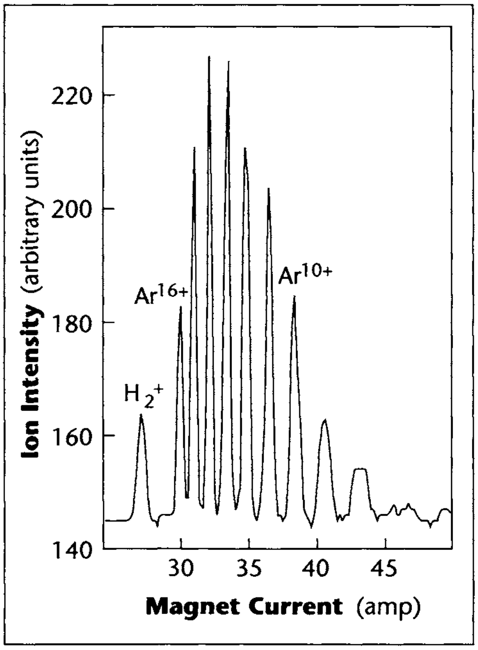


Figure 2. Charge spectrum of argon ions extracted at 3,000 *q* eV from the EBIS. The ions were produced by a 4.5-kiloelectron-volt, 17-milliampere electron beam in a confinement time of 40 milliseconds. They were analyzed by a 90° analyzing magnet and detected using a Faraday cup.

of 36, or a xenon nucleus with 10 electrons instead 54). The kinetic energy of the ions extracted from the source can be varied between 1,500 and 5,500 q eV. (The degree of ionization, q, is equal to the number of electrons that have been lost. An electron volt—eV—is an amount of energy equal to that gained by one electron when its electric potential is reduced by one volt.) A bare argon nucleus, such as we use in some of our experiments, has a q of 18; when it is extracted at 5,500 volts, it has an energy of 99,000 eV. Even at this energy, the velocity of the ion is less than the velocity of an electron in the lowest energy state of the hydrogen atom, so such ions are commonly referred to as slow.

Ions extracted from the source move through an evacuated beam line to an analyzing magnet that selects the species of interest and sends them into an experimental chamber. Along the way, several ion-optical elements focus and deflect the beam.

Techniques for Studying Charge Transfer

The basic atomic process that we are currently investigating is charge transfer. What happens when a bare nucleus of, say, oxygen collides with atomic hydrogen? There is a strong probability that the single electron in the hydrogen atom will jump over to the oxygen nucleus, leaving the hydrogen atom's nucleus as a lone proton, and forming a hydrogen-like oxygen ion in a very excited state. Several aspects of such a collision system are measurable. One is the probability that an electron will be captured as a function of the energy of the incident ion. Another is the energy of the different possible excited states of the hydrogen-like oxygen ion. Yet another is the relative population of ions in these excited states and the way they decay. Decay to a lower energy state involves the emission of a photon, and the energies and intensities of all possible emission lines are of interest.

The collision cross section, or probability that a collision between two atomic particles will have a particular outcome, is used to calculate how many reactions take place under given conditions. It can be measured by passing a well-collimated beam of projectile particles through a gas target whose density and length are known. The projectiles that undergo a charge transfer have their degree of ionization reduced by one (or more) and can be separated from the direct beam by the application of an electric field. The ratio of the number of particles whose charge has changed, per unit time, to the number of incident particles, per unit time, determines the cross section.

Inelastic collisions can result in a transfer of some internal or electronic energy to a projectile's kinetic energy, as well as a transfer of charge. To determine the energy of the different possible excited states that result from the collision, it is necessary to measure the energy gained (or lost) in the encounter. The energy gain of the projectile is determined by following its motion through a known and spatially well-defined electric field, which is formed between cylindrical or spherical electrodes. A barrier with a narrow slit is placed at the entrance to the electrical field, and a similar barrier is placed at its exit. By varying the strength of the field until a particle just makes it through the exit slit, one can measure its energy.

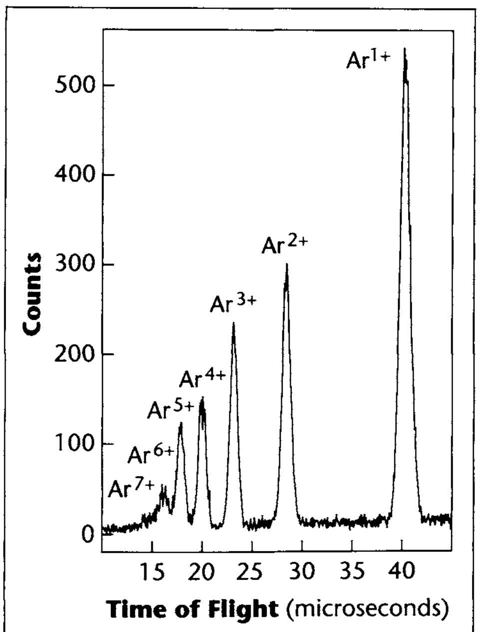
The photons emitted during the decay of excited states can be studied using standard spectroscopic techniques, which are available for the visible, vacuum-ultraviolet, and soft-x-ray regions of the electromagnetic spectrum.

The Current Status of Research on Charge Exchange

Initially, we tried using atomic hydrogen as a target because of its important role in astrophysical and laboratory plasmas. Unfortunately, however, there were no easy and reliable ways to define the extent of the target, the ratio of atomic to molecular hydrogen, or the target density, and so we switched to noble gases and the more common molecular gases, at least for the time being. We have designed a chamber for the target gas that allows us to measure the absolute pressure with an error of no more than a few percentage points in the range of 10^{-6} to 10^{-4} millibar. We have measured the cross section (probability of collision) for highly ionized argon projectiles striking a helium target at a given energy as a function of degree of ionization with an error of 5 to 7 percent. This is nearly three times more accurate than the measurements usually made with singly or doubly charged projectiles.

With elements other than hydrogen, it is possible for a projectile to capture two or more electrons. When this happens, the resultant excited state can decay by a nonradiative, Auger process in which an electron carries away the energy released in the transition. The kinetic energy of the emitted electron can range from a few electron volts to several hundred electron volts. We have measured the spectra of electrons emitted in the decay of highly charged argon ions formed through the capture of two electrons from helium, molecular hydrogen, and argon. But other experiments are needed to help us interpret these spectra, since virtually nothing is known about excited states of highly ionized atoms.

To help us understand the spectra of electrons emitted when Ar^{q+} ions (ions with a deficit of q electrons) strike an Ar target, we looked at the charge distribution of the recoil target ions using a time-of-flight spectrometer (see Figure 3). For incident projectiles with an ionization state q and 2,300 q eV kinetic energy, where q is greater than seven and less than seventeen, most recoil ions had positive charges of one to six, and a few had charges of seven and eight. This implies that up to eight electrons were removed from the targets during collision, although from separate experiments we know that the projectile charge changes by only one or two units (see Figure 4). It is thought that the large potential energy of



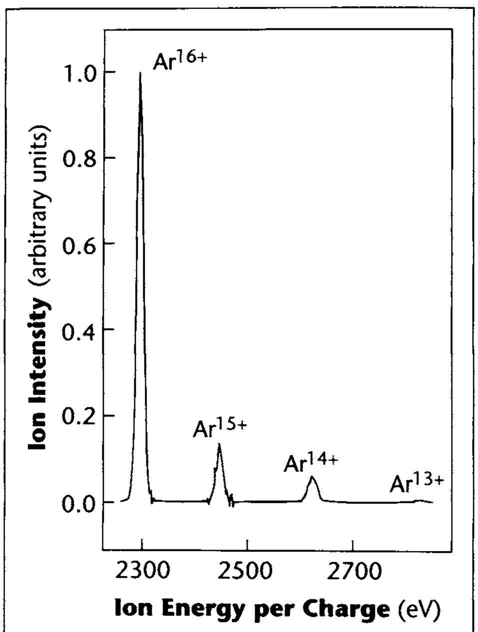


Figure 3 (left). Charge state distribution of recoil argon ions following collisions of Ar^{16+} on Ar. The distribution was measured by time-of-flight spectroscopy. Charge states up to 7+ are visible.

Figure 4 (right). Analysis of the charge state of the incident Ar^{16+} beam following collisions with neutral argon. In addition to the direct beam, argon projectiles that have captured one and two electrons can be seen.

the incident projectile, which is equal to the total binding energy of the q missing electrons, is used in such collisions to ionize the target. Our electron spectra for incident projectiles with different degrees of ionization are all quite similar and show little variation, however, implying little dependence on potential energy.

At present, the mechanism responsible for this phenomenon is not known. One possible explanation is that the least tightly bound electrons of the neutral argon target atom are shared with the projectile for a brief moment during the collision. Then a number of Auger transitions would get rid of most of these electrons, leaving the projectile, as it moves away from the target, with only one or two electrons—even though the target has lost as many as eight. We are currently investigating this possibility.

"Rydberg states provide a meeting ground between classical and quantum-mechanical models."

The way in which two or more electrons are removed from target atoms can also be investigated through energy-gain spectroscopy. This is difficult, however, because the energy difference between excited states may be only a tiny fraction of the incident kinetic energy of the projectile. Jan Vančura, a postdoctoral associate in our group, is currently attempting to measure the energy gain by slowing down the ions extracted from the EBIS to kinetic energies of 50 q eV or less. He is using two 180°, ten-centimeter-radius, spherical electrostatic analyzers, connected in series, to select a slice of the incident beam that is 0.1 q eV wide. A similar pair of analyzers, located after the gas target, is used to determine the energy of the projectiles that have undergone charge transfer.

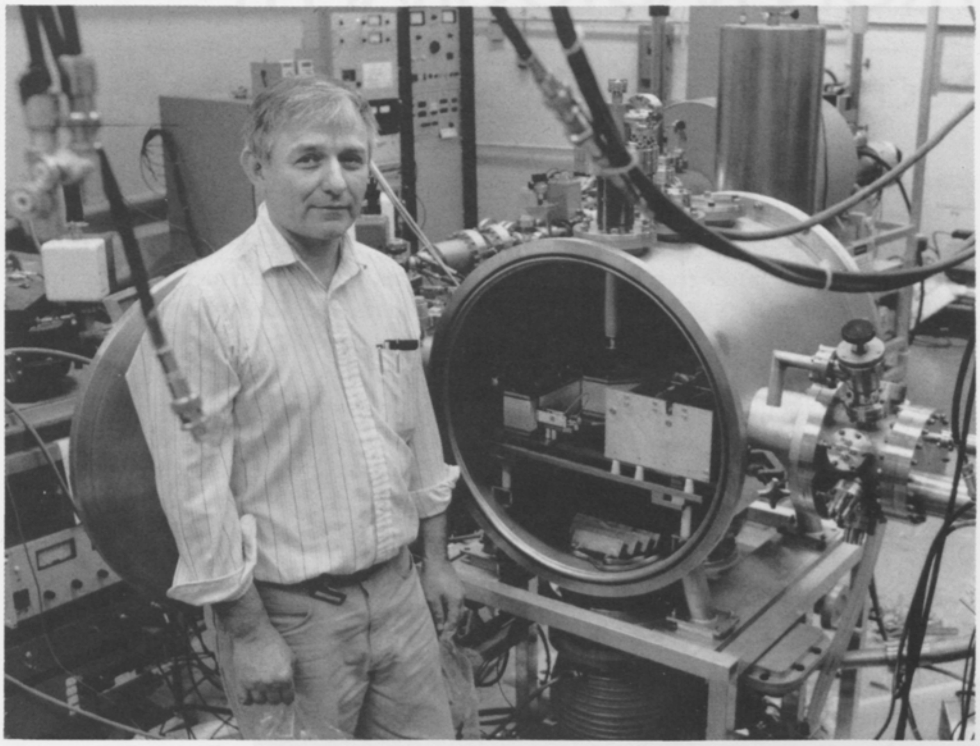
Other Plasma Processes Currently under Study

In addition to charge exchange, other atomic processes of interest to our group are radiative and dielectronic recombination. In radiative recombination, a free electron is captured by an ion and the energy released in capture is carried away by a photon. In dielectronic recombination, the same antecedent leads to the same consequence, but the process is different. The capture of a free electron pushes one of the ion's bound electrons to a doubly excited state, and a photon is emitted when it returns to a lower energy state. The distinction between the two processes may appear minor, but their spectral signatures are quite different. In both processes, however, the kinetic energy of electrons is converted into electromagnetic radiation, which can escape from the plasma.

Direct experimental measurement of these processes is complicated by the difficulty of producing low-energy electron-cloud targets of sufficient density. One possibility that we are investigating is to produce a relatively cold hydrogen plasma heated by radio-frequency or electron-cyclotron resonance. The free electrons in this plasma would then serve as target electrons, allowing us to determine radiative and dielectronic recombination rates averaged over a relatively small range of electron energy.

Another subject of interest concerns the implications of increasing quantum number, n, for electrons captured by highly charged ions. When one electron is captured by a highly charged projectile, it generally assumes an excited state whose energy is equal to its binding energy before capture. When, for example, a bare argon nucleus strikes an atom of hydrogen, it captures the hydrogen's lone electron into an excited state whose energy is close to 13.6 eV—the binding energy of a hydrogen atom's electron in its ground state. This corresponds to a principal quantum number of about 18. In a more highly charged nucleus such as Xe^{40+}, n would, correspondingly, be about 40.

Ions with an electron in such a high quantum-number state are known as Rydberg ions, and the captured electron is said to be in a Rydberg state. One of the interesting properties of Rydberg states is that as the principal quantum number increases, the difference between consecutive energy levels decreases, so that the system begins to approximate the gradualism expected in classical mechanics. Thus, Rydberg states provide a meeting ground between classical and quantum-mechanical models. If enough of the highly excited states formed at very low collision energies manage to survive, it



may be possible to trap Rydberg ions in a magnetic field to study them.

Finally, an area of research with clear practical implications is potential sputtering. Highly charged ions are very reactive, and their neutralization as they replenish their missing electrons releases a large amount of potential energy. When directed at the surface of materials such as insulators and semiconductors, low-energy, highly charged ions can remove several surface atoms per incident ion. It is possible to study this phenomenon of potential sputtering by slowing down the incident ions until the sputtering that results from their kinetic energy becomes negligible. We are just moving into this area of research, which may lead to new techniques for ion milling and other operations essential to the fabrication of microelectronic components.

Vaclav O. Kostroun, an associate professor of nuclear science and engineering and of applied and engineering physics, received the B.S. in 1961 from the University of Washington and the Ph.D. in 1968 from the University of Oregon.

Kostroun was a research associate in applied physics at Cornell for two years before joining the faculty in 1970. In 1977, he was a visiting scientist at the Laboratoire pour l'Utilisation du Rayonnement Electromagnetique (LURE), in Orsay, France, and a visiting professor at the Université de Paris VI. For several weeks in 1979–80 he was a visiting professor at the Pontífica Universidade Católica, in Rio de Janeiro, Brazil. He is a fellow of the American Physical Society and a member of the American Association for the Advancement of Science.

The work described in this article is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences.

NEUTRON RADIOGRAPHY

Key to Secrets That X-Rays Can't See

by Howard C. Aderhold

"The two types of radiography reveal different things. . . ."

Neutron radiography produces images that look much like x-rays. But what they reveal is, in many ways, just the opposite of what x-rays reveal. Neutron radiography cannot show coins inside a purse or bones concealed by flesh. But it can show a plastic toy behind an inch of lead, oil flowing through a valve, or tiny roots growing through soil.

The two types of radiography reveal different things because of a fundamental difference in the way x-rays and thermal neutrons interact with matter. X-rays interact with the electrons in the atoms of which a specimen is composed, and the higher the atomic number and the denser the specimen, the more the x-rays are attenuated. Thermal neutrons are unaffected by the specimen's electron content, since they have no charge. Instead, they interact with the specimen's atomic nuclei, and attenuation of the neutron flux depends on the way the nuclei deflect or absorb neutrons. This varies from one element to another, in ways that have nothing to do with atomic number, as shown in Figure 1.

Neutron radiography of a plastic toy gun behind an inch of lead shows a coil spring and other internal details.

The techniques for creating photographic images with the two kinds of radiography are also different. X-rays interact directly with a photographic plate, affecting it just as if it were exposed to visible light. For a neutron beam to produce a photographic image, an intermediate stage is necessary. The neutrons are absorbed by a screen made of the rare-earth metal gadolinium, which emits an electron for nearly every neutron absorbed, and it is these electrons that produce the photographic image. Since it is essential for the metal converter screen to be in close contact with the photographic film, a vacuum cassette is used.

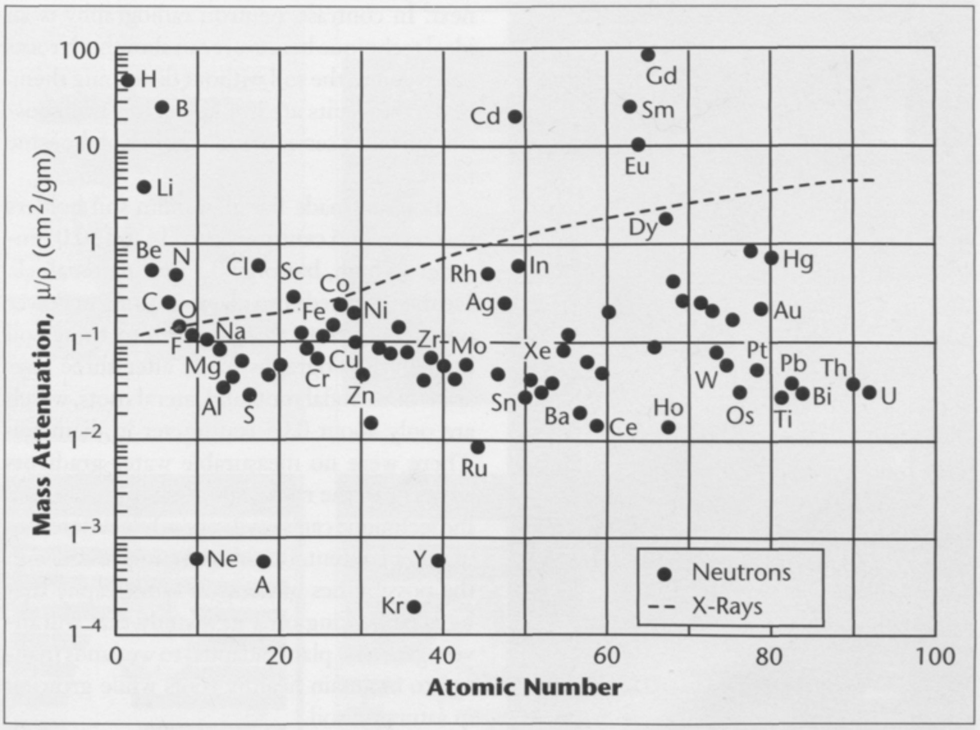


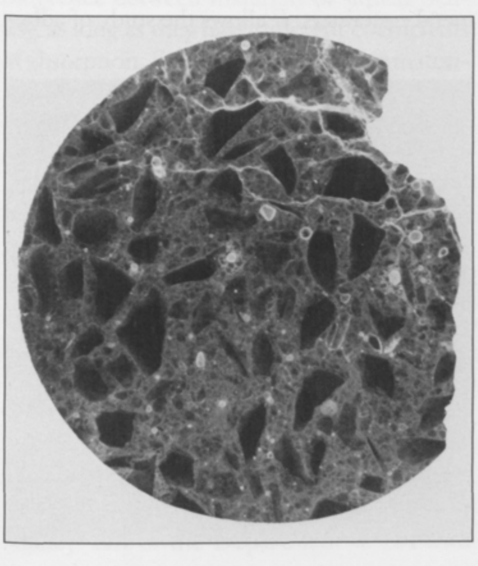
Figure 1. Neutron and x-ray attenuation coefficients as a function of atomic number. While the attenuation of x-rays rises with atomic number, the attenuation of neutrons shows no such correlation. In fact, the lightest element, hydrogen, has a very high attenuation coefficient.

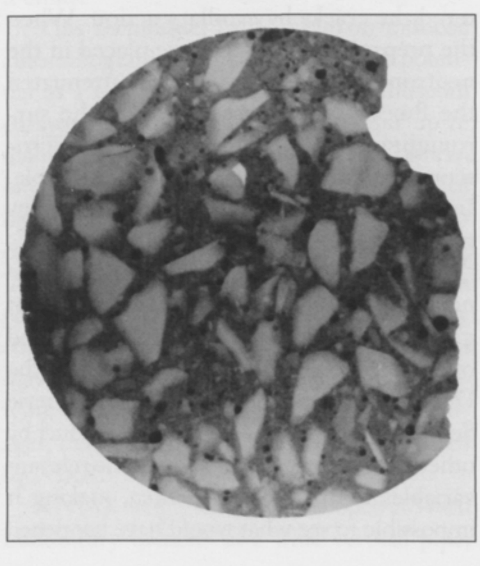
Two Projects Using Neutron Radiography

The potential of neutron radiography is illustrated by two projects carried out by Cornell researchers using the facilities at Ward Laboratory. One involves the growth of microcracks in concrete and the other involves the growth of roots on corn seedlings.

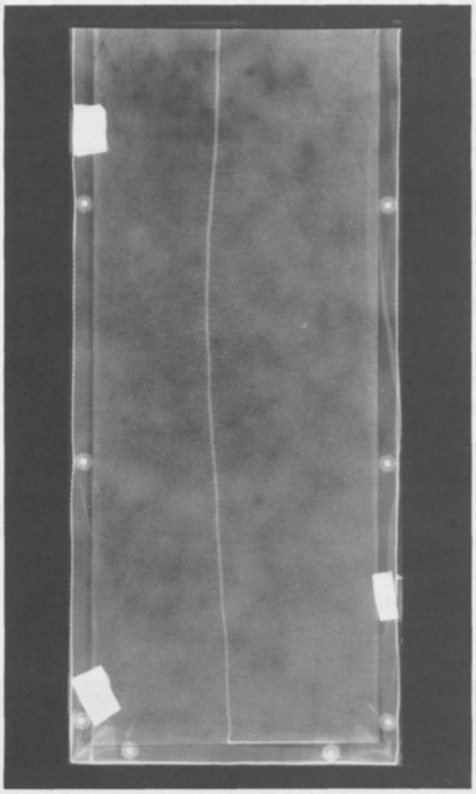
When concrete fails due to excessive loading, it first develops a network of tiny cracks. Since the failure of concrete members in large structures such as buildings and bridges can be catastrophic, engineers who specialize in concrete are seeking to understand how these microcracks form. Standardized specimens of concrete can be compressed in the laboratory until they are on the point of failure, but the microcracks are difficult to detect, even with magnification.

Professor Kenneth C. Hover and gradu-





Microcracks in concrete are revealed more clearly by neutron radiography (left) than by x-radiography (right). The specimen is a 0.38-centimeter-thick slice of a concrete cylinder that had been loaded to the point of fracture. Gadolinium nitrate was used as a contrast agent.



Neutron radiography reveals the tap root of a corn seedling growing in soil between two aluminum plates. Even the fine lateral roots can be seen.

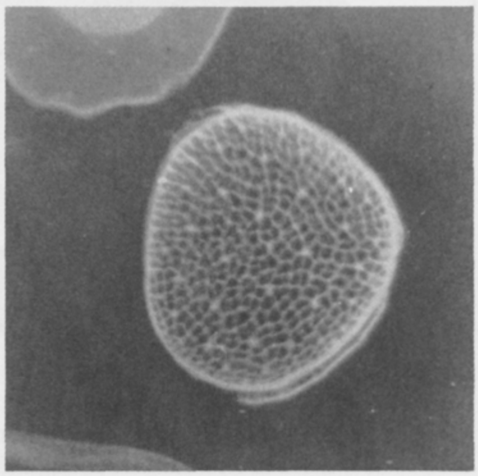
ate student Walid S. Najjar of the School of Civil and Environmental Engineering decided to try neutron radiography. They cast concrete in cylinders ten centimeters in diameter, then compressed them to varying degrees to create microcracks. Thin slices were cut, using a geological saw. After polishing, they were treated with an aqueous solution of gadolinium nitrate, which entered the cracks by capillary action. When the prepared specimens were placed in the neutron beam, the gadolinium attenuated the flux to a greater extent than the surrounding concrete, and networks of microscopic cracks were made clearly discernible. In comparison with x-ray techniques, neutron radiography proved far superior.

Another recent project that makes use of neutron radiography is a study of root growth and soil moisture that was carried out by Professor David R. Bouldin, of the Department of Soil, Crop, and Atmospheric Sciences. Such studies are hard to conduct by other means, since observation of the relevant variables destroys the specimen, making it impossible to see what would have happened next. In contrast, neutron radiography is an ideal technique because it can show both roots and water in the soil without disturbing them. Since the plants are not killed, it is even possible to take a series of radiographs of the same plant.

Bouldin made flat aluminum soil holders that were 11.5 centimeters wide and 30.0 centimeters high, but only 0.3 centimeter thick. He then induced corn plants growing in flower pots to infiltrate their roots into these soil holders. Radiographs made after three days show both nodal roots and lateral roots, which are only about 0.05 centimeter in diameter. There were no measurable water gradients adjacent to the roots, although it is clear that the technique can reveal very subtle differences in water content. Bouldin is so impressed with the possibilities of neutron radiography that he is embarking on a new study that will investigate how plants adapted to wetlands manage to maintain healthy roots while growing in saturated soil.

Other Potential Uses of Neutron Radiography

Neutron radiography has a wide variety of other applications. One of its most salient properties is the ability to show details of light materials, especially hydrogenous materials such as plastics, oil, and water, even when they are surrounded by dense materials such as steel and lead. This makes it possible to view lubricants and other fluids in metal assemblies, and to assess the moisture content of materials in metal containers. It allows the study of adhe-



Right column. A neutron radiomicrograph showing a root in cross section reveals details of the vascular structure.

For purposes of experiment, W. Stanley Taft made a small painting with three separate layers. The naturalistic nude shown at upper left was painted over with an abstract design in red, blue, and black, and this, in turn, was covered with a painting of draped fabric. Following activation with neutron radiation, a series of autoradiographs were made. The difference in what they show depends on the elapsed time between activation and exposure of the photographic film. This interval is shortest for the image at bottom left, and longest for the one at bottom right.

sives used in bonding composites to metals and the inspection of electrical relays in metal housings. It can even be used to help detect corrosion in aluminum aircraft structures.

Neutron radiography can also detect the difference between materials of similar density, as long as they have different coefficients of absorption. For example, soldering materials containing silver, cadmium, or boron can be distinguished from the metals on which they are used.

Because neutron radiography depends on the interaction of neutrons with atomic nuclei, it is sensitive to the difference between isotopes of the same element. Thus, it can be used to distinguish between ordinary hydrogen and deuterium or tritium, and between isotopes of boron, cadmium, or uranium.

Neutron-Induced Autoradiography

A project being conducted by Professor W. Stanley Taft of the Department of Art uses the neutron source in a different way. Instead of sending neutrons through a specimen to produce an image on a piece of film behind it, the specimen itself is made slightly radioactive, and film is then exposed to the radiation it emits.

This technique, called neutron-induced autoradiography (NIAR), holds great potential as a tool for art historians and museum curators. Paintings are typically built up in many layers. Underpainting, which follows an initial drawing, sets out the arrangement of lights and darks, models the forms, and indicates the general position of various colors. The drawing and underpainting are then painted over and, in many cases, are completely covered up. As the work progresses, the artist may change color and form, sometimes modifying the entire composition. But earlier images, called pentimenti, can often be revealed by NIAR.

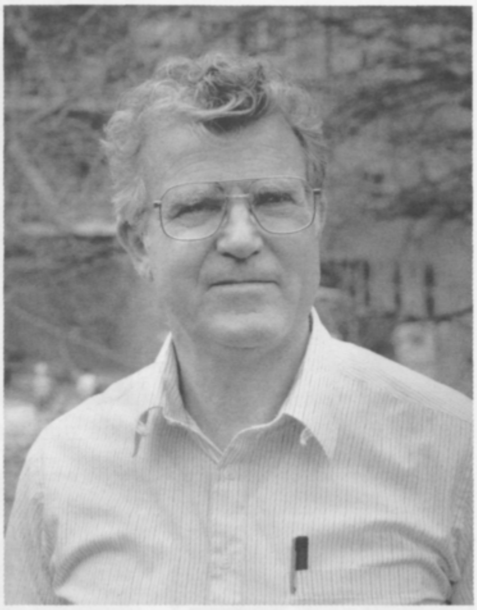
A NIAR facility recently developed at Ward Laboratory consists of a wide vertical pipe, closed at the bottom and placed near the core of the TRIGA reactor. Small paintings lowered into this pipe on a nylon string come to rest on an aluminum pedestal that holds them in proper alignment. A radiation beam stop is then inserted into the top of the pipe, and the paintings are activated in a thermal neutron environment of 10^9 neutrons per square centimeter per second for a period of twenty minutes. Following activation, the paintings, now radioactive, are removed and placed in direct contact with photographic film. The film is exposed by beta emission from radioisotopes in the pigments, and a sequence of autoradiographs is made. Since different radioisotopes have different half-lives, radiographs made at different times in the sequence reveal the presence of different elements. Manganese-56, for example, will betray the presence of raw umber even if it is painted over with cobalt blue.

The use of NIAR can reveal much about the methods used by a particular painter—the gesture of the brush stroke, the choice of color, the consistency of the paint. It can also help pinpoint the time when a painting was made. Cadmium red, for example, only came on the market in 1907, and will not be found in older paintings unless they have been restored. NIAR is especially useful in detecting forgeries, since forgers seldom leave pentimenti and often use anachronistic pigments.

A Tool for Research in Many Fields

Neutron radiography can aid research in a wide variety of areas in engineering and the physical sciences, medicine and the biological sciences, as well as other fields such as archaeology. It also has a place in industry, where it holds great promise as a tool for detecting flaws and assuring quality.

The neutron radiography facility in Ward Laboratory is available for research conducted in any of the academic departments at Cornell University. Arrangements are relatively informal; while funded projects usually make a contribution to help defray the costs of running the reactor, there is no set fee. The techniques are still being improved, and finding out all the things that neutron radiography can do is, in itself, a kind of research.



Howard C. Aderhold, who trained at Williamsport Technical Institute in Pennsylvania, is reactor supervisor at Ward Laboratory, responsible for all day-to-day operations at the laboratory. Before coming to Cornell in 1962, he worked in reactor design and operation at Curtiss-Wright Corporation, where he supervised the startup of reactors at Watertown, Massachusetts and at the University of Missouri at Rolla, as well as a reactor in Bangkok. He was also in charge of the startup of the Zero Power Reactor(ZPR)at Cornell.

Aderhold has been largely responsible for the procurement of up-to-date instrumentation for teaching and research in the area of radiation detection and neutron activation analysis. He planned the design and supervised the construction of Cornell's facilities for neutron radiography and for neutron-induced autoradiography. He holds senior reactor operator licenses on both the TRIGA and the ZPR.

The author of several papers, Aderhold has been invited to lecture at this year's summer meeting of the American Nuclear Society.

CHIPS IN SPACE

Developing Microelectronic Structures that Tolerate Ionizing Radiation

by Stephen C. McGuire

Microelectronic components that would function reliably at ground level may fail, with disastrous consequences, when used in a spacecraft or communications satellite. Outside the earth's atmosphere, ionizing radiation can make minute electronically active structures perform unreliably or break down completely. This was discovered in the early 1960s, when the first geosynchronous satellites were placed in orbit, and the effects of radiation on electronic components has been an important area of research ever since.

Together with a team of graduate students, I am investigating the fundamental mechanisms by which energetic radiation affects the behavior of microelectronic structures. Our approach involves three steps, each of which plays an essential role in the development of radiation-tolerant devices. First, we investigate the characteristics of relevant radiation sources, then we examine the ways in which radiation interacts with the materials employed in particular electronic devices, and finally, we measure and interpret the response of these devices to the radiation field. The effort is interdisciplinary, involving nuclear science, space science, solid-state physics, and microelectronics.

Sources of Radiation in Different Environments

Microelectronic components must perform reliably in nuclear reactors, particle accelerators, aircraft flown at high altitudes, satellites in near-earth orbits, and exploratory spacecraft whose electronic systems are expected to operate without interruption for years. Each of these environments is subject to its own characteristic type of radiation. Nuclear reactors produce neutrons with energies measurable in the thousands of electron volts, and they emit gamma rays from the decay of activation products. Electronic devices operated near a particle-accelerator beam must be resistant to bombardment with charged particles and neutrons. High-altitude aircraft are exposed to neutrons produced in the spallation collisions between protons or cosmic rays and air molecules in the upper atmosphere. Orbiting spacecraft are subject to especially severe radiation, and their electronic systems must withstand charged-particle bombardment from the earth's trapped proton and electron belts, cosmic-ray nuclei whose energy extends to 10^{19} electron volts, and intense electromagnetic radiation.

Radiation used in the fabrication of electronic components also needs to be considered. Low-energy, highly focused electron beams may be used to carve circuit patterns on silicon wafers, and a plasma of molecular ions is sometimes employed to etch away surface layers. While these processes, known as electron-beam lithography and reactive-ion etching, do not make use of penetrating radiation, the transfer of momenta between incident particles and the surfaces being treated does lead to displaced atoms.

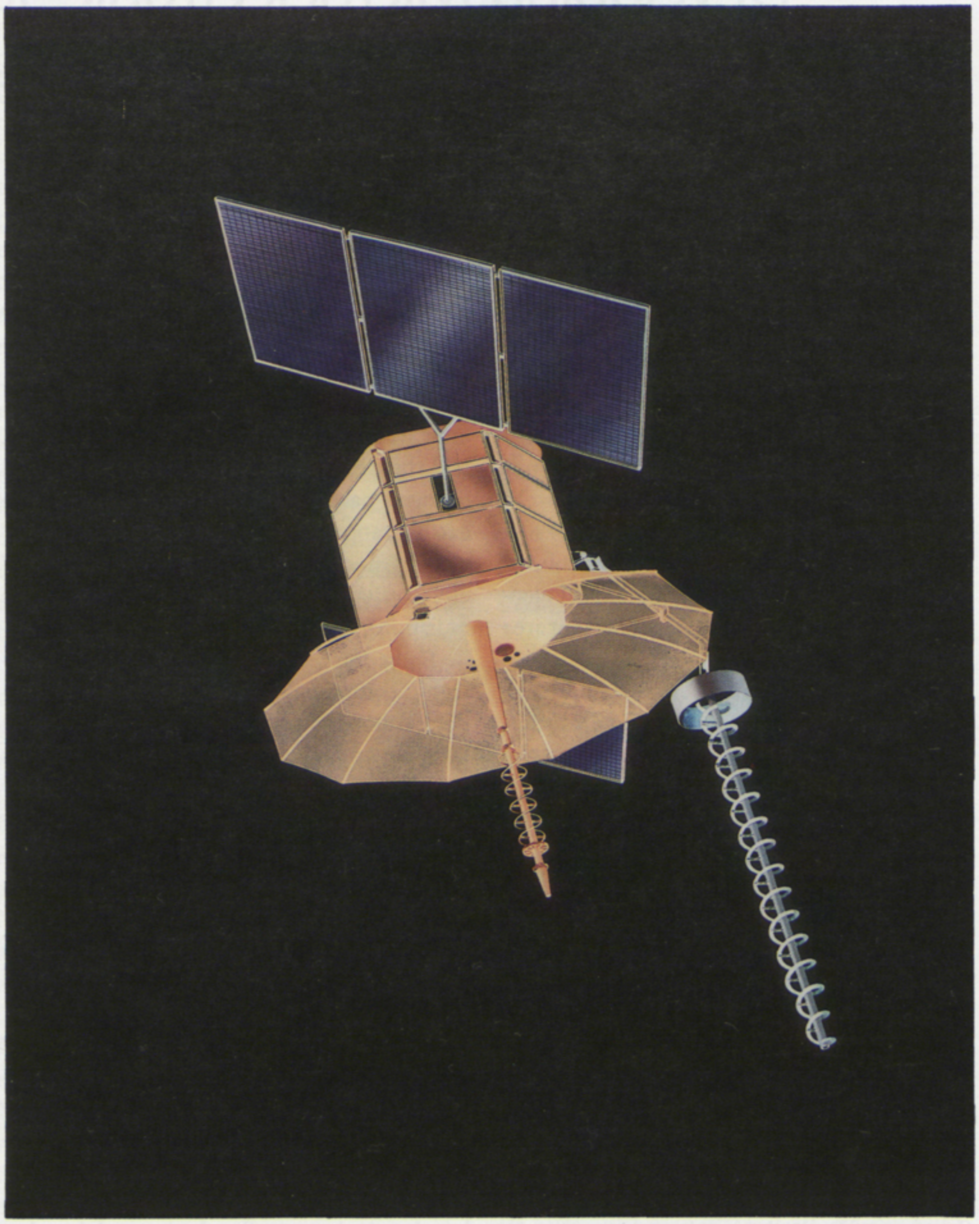
The most widely used semiconductor materials—crystalline silicon, silicon dioxide, and silicon alloys—are subject to two different effects, both of which involve absorption of energy from the incident radiation. One results in atoms being displaced from their normal locations in the crystalline lattice, and the other results in unwanted electronic excitation and ionization. Depending on the particle type and its energy, and the intensity of incident radiation, either or both of these effects may occur.

Total-Dose Damage from Ionizing Radiation

Long-term exposure to ionizing radiation can eventually modify the electrical properties of a device and cause it to fail. This problem is especially acute for circuitry fabricated with complementary-metal-oxide-semiconductor (CMOS) technology. CMOS devices, such as the metal-oxide-semiconductor field-effect

"Long-term exposure to ionizing radiation can eventually modify the electrical properties of a device and cause it to fail."

Three tracking data and relay satellites, like the one pictured here, are currently circling the earth in geosynchronous orbits. They are used by NASA for communicating scientific data. (*Courtesy of TRW Inc.*)



transistor (MOSFET, shown in Figure 1), contain n-type and p-type semiconductors in contact with oxide layers. When the gates used in MOSFETs are maintained at a positive voltage during exposure to a field of ionizing particles, released electrons are rapidly swept out of the oxide, leaving behind a distribution of fixed positive charges. These induce a negative image charge in the semiconductor, which then acts as a conducting channel between the source and the drain even when no gate voltage is applied. The negative shift in threshold voltage is accompanied by an increase in leakage current, and this can lead to electrical burnout of the circuit.

This effect was demonstrated recently in work done by Master of Engineering student John R. Mercier. A group of field-programmable gate arrays (FPGAs) were irradiated using Ward Laboratory's cobalt-60 gamma cell, in an experiment designed to test their suitability for use in satellites. The circuits were fabricated with the CMOS process, and contained 1,200 available gates that formed a system of logic modules. They showed monotonic increases in leakage current with doses of radiation up to about 12 kilorads, and then a rapid increase with additional radiation up to the point of failure, which was typically around 17 kilorads. This performance indicated that they would not be good candidates for use in space applications.

Further work in this area is being conducted in Cornell's Materials Science Center, where a scanning transmission electron microscope (STEM) can be used to obtain high-resolution cross-sectional views of multilayered circuit structures. This makes it possible to determine the precise geometry of oxide layers in CMOS circuits.

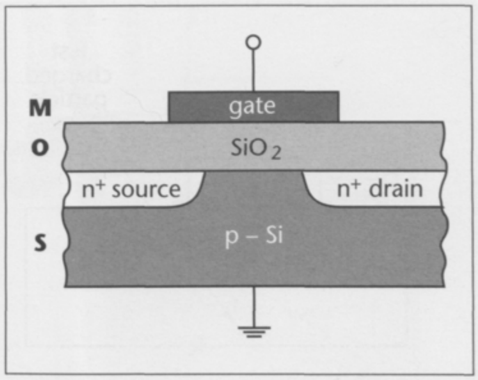


Figure 1. Cross-sectional view of a p-channel metal-oxide-semiconductor field-effect transistor (MOSFET). Features shown are the metal gate contact, the SiO_2 insulating oxide layer, source and drain structures, and the p-type silicon substrate.

Single-Event Upset: A Transient Response to Radiation

Damage to electronic devices need not be massive to adversely affect performance. A single charged particle can cause ionization that will change the electronic state of a circuit. This results in a temporary malfunction called a single-event upset (SEU) or a "soft fail." While an SEU does not involve permanent damage to the device, it can cause "bit flips" in digital logic circuits, adversely affecting the computer memory of telecommunications satellites and other electronic systems used in space.

SEUs occur when a charged particle penetrates the active region of a reverse-biased junction between two semiconductor materials. Dynamic random access memories (DRAMs), which store bits of information as charges on capacitors, contain many such junctions. Also vulnerable are the source, gate, and drain terminals of the field-effect transistors (FETs) that make up the bistable memory-circuit cells of static random-access memories (SRAMs).

Charged particles can affect these sensitive areas in two ways. In one case, a particle traversing a junction produces a dense plasma of electron-hole pairs along its track. In the other case, an energetic proton hits a silicon nucleus, generating several recoiling charged-particle fragments, and each creates its own track of electron-hole pairs. (A single proton can produce 1.4×10^6 electron-hole pairs.) In both cases, a number of electron-hole pairs are produced in the region in and near the junction. Ambipolar drift, which is influenced by the prevailing electric fields, combines with the process of diffusion to collect these electron-hole pairs, generating a transient current pulse at the junction (see Figure 2).

The entire sequence of events takes no more than a few nanoseconds. The region near the junction where the charges are generated constitutes a sensitive volume that is usually modeled in a quantitative description. Modeling this volume is especially important in cases in which multiple tracks are produced by recoil fragments in nuclear spallation.

An SEU does not occur until a certain amount of ionization, the critical charge (Q_{crit}), has collected at the junction. According to our measurements, critical charges for DRAM and SRAM circuits are in the range of 0.1 to 10 picocoulombs, where one picocoulomb (10^{-12} coulomb) corresponds to 6×10^6 electron-hole pairs. When cosmic rays induce SEUs that manifest themselves as bit flips in memory, they can adversely affect the performance of computers responsible for controlling the motion of a spacecraft, running on-board equipment, or conducting scientific experiments.

Research Aimed at Minimizing Single-Event Upsets

A device's susceptibility to SEU can be assessed by exposing it to a beam of ions whose intensity, charge state, mass, and energy are known, and measuring the number of upsets that occur. The ratio of upsets to incident ions per unit area provides a measure of the device's sensitivity. Also important are the beam's angle of incidence and the rate at which it loses energy along its path through the device. These variables can be measured quite easily, although they must be interpreted with care.

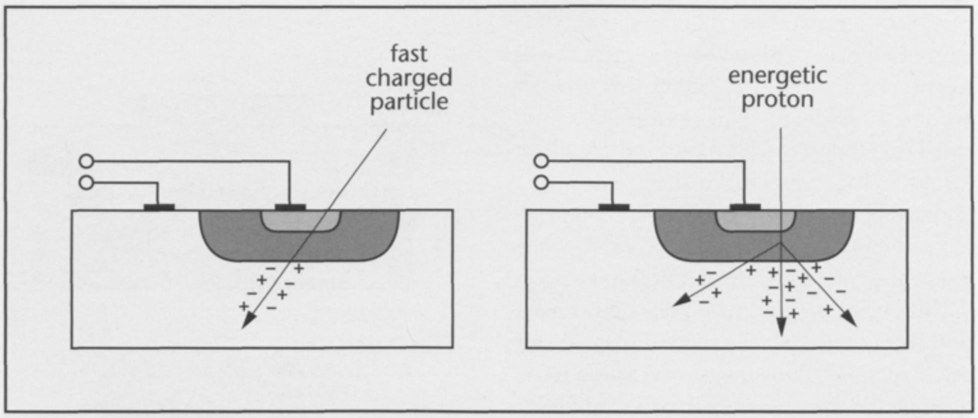


Figure 2. Two paths to a single-event upset. At left, an incident ion traverses the junction, producing a dense plasma of electron-hole pairs along its track. At right, an energetic proton strikes a silicon nucleus, generating several charged particles, each of which creates its own track of electron-hole pairs.

The resulting SEU cross-section measurement can be used to design devices that are more tolerant to radiation.

A far subtler source of charged-particle radiation is the trace amount of uranium and thorium that may contaminate the ostensibly pure materials used in electronic packaging. A few parts per million of these naturally occurring isotopes can sometimes be found in gold-plated metal lids, plastic packages, quartz fillers, and alumina. Although the quantities are miniscule, the effects can be substantial. Uranium-238 emits eight alpha particles when it decays to lead-206, and thorium-232 emits six alpha particles in becoming lead-208. The alpha particles, which are doubly-charged helium nuclei whose energy ranges from 3.95 to 11.65 million electron volts, can cause problems such as transient changes in computer-memory content unless sensitive components are shielded or radioactive trace elements are entirely removed from packaging materials.

Since the natural decay of these elements results in the emission of alpha particles that can cause soft fails, it is important to know the potential for this occurrence before a device is used in a particular application. Neutron activation analysis can quantitatively identify impurities in the parts-per-billion range, and this technique is especially useful for finding the traces of uranium and thorium that contaminate electronic packaging materials. Currently, Professor Che-Yu Li and research support specialist Boris Yost, of the Electronic Packaging Alliance, are using neutron activation analysis to study radioactive impurities in aluminum oxide as well as newly developed aluminum nitride ceramics.

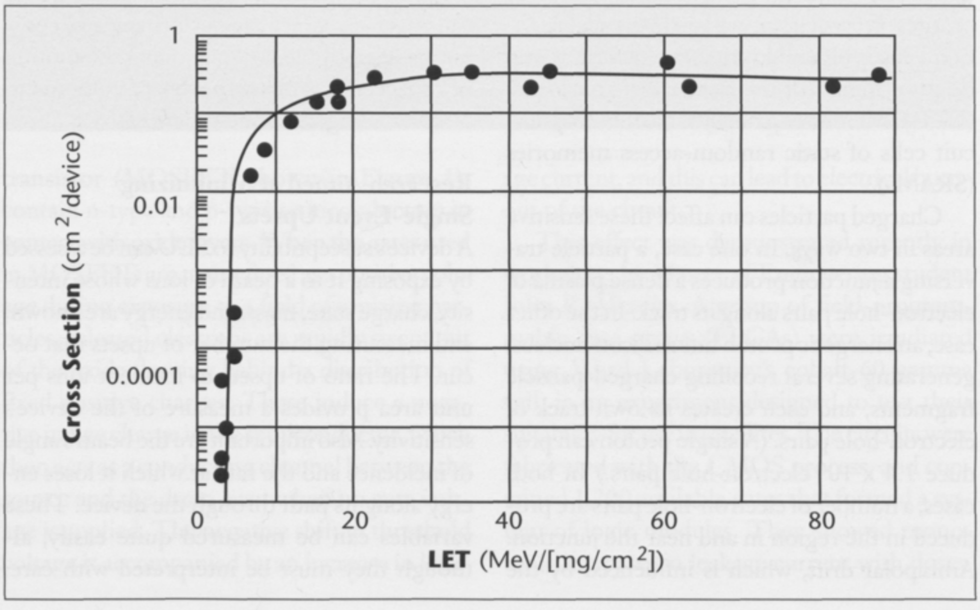
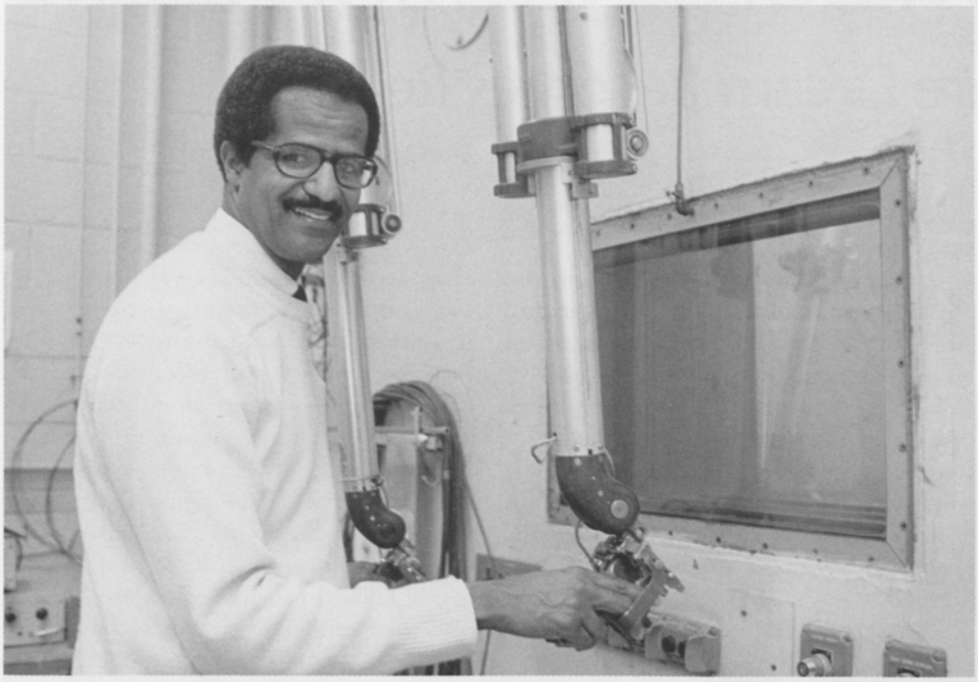


Figure 3. Variation in single-event-upset cross section with linear-energy transfer (LET) of the incident ion. Characteristic features are a rapid increase above the LET value at which SEUs approach saturation.



“. . . *new devices with smaller dimensions, based on new materials, must take radiation response into account.*”

Effects of Radiation on New Materials

As the microelectronics industry evolves, so do the principles upon which devices are based. Devices do not just get smaller and smaller. The ability to fabricate at the nanometer level has led to the creation of quantum devices that are fundamentally different from semiconductor junction devices. And devices based on high-temperature superconductors are also coming into their own. As these new technologies appear, we must continue to develop a fund of basic knowledge that is relevant to the design, fabrication, and application of electronic devices intended for use in environments with penetrating ionizing radiation.

Modern society has become dependent on satellites that relay telephone and television signals, provide meteorological information, and serve as navigational aids. In addition, space-shuttle missions and unmanned satellites are used for a wide variety of scientific experiments and have potential applications in national defense. In all of these contexts electronic components must perform reliably, and new devices with smaller dimensions, based on new materials, must take radiation response into account.

Stephen C. McGuire is an associate professor of nuclear science and engineering. He received the B.S. in 1970 from Southern University, the M.S. in 1974 from the University of Rochester, and the Ph.D. in 1979 from Cornell University.

McGuire's undergraduate studies were supported by a Crown Zellerbach Foundation fellowship, and as a doctoral candidate, he held a John McMullen graduate fellowship. While a graduate student, he was an invited lecturer at the Stanford Linear Accelerator Center.

McGuire spent four years as a staff scientist at Oak Ridge National Laboratory, where he worked on the production of transuranic isotopes in the laboratory's high-flux isotope reactor and helped develop national strategies for disposal of high-level nuclear waste. Subsequently he taught for six years at Alabama A&M University where he began research with the National Aeronautics and Space Administration on the interactions of charged-particle cosmic rays with emulsions and semiconductor electronics. In 1987 he received NASA's Office of Technology Utilization Research Citation Award. He joined the Cornell faculty in 1989.

BUILDING A COLD NEUTRON BEAM

A Pure Dream Becomes Reality

by David D. Clark

"It will be the first such facility in a university reactor. . ."

My first experiences with cold neutron sources and neutron guides, during a sabbatical leave spent at Munich and Grenoble in 1976, were exhilarating. Here were beams of slow neutrons that were almost entirely free of fast neutrons and gamma rays. Research that depended on the unique properties of neutrons could be conducted without confusing and frustrating background noise. It was like listening to a CD instead of a scratchy 78-rpm record.

At the time, building a cold neutron source and guide at Cornell was an impossible dream. The technology of the day involved using liquid hydrogen or deuterium close to the core of a nuclear reactor, and only large, national laboratories could support sufficient staff to meet the necessary safety standards. It was highly unlikely that the Nuclear Regulatory Commission would allow a reactor on a university campus to have such a source.

But technological improvements have removed the danger and reduced the cost, and a cold neutron beam facility at the Cornell TRIGA reactor is now nearing completion. It will be the first such facility in a university reactor, and only the second one in the United States. (The first is at the National Institute of Standards and Technology, in Gaithersburg, Maryland.) It will significantly upgrade the research capabilities of the Cornell reactor by providing a low-background, highly pure beam of cold neutrons.

Neutron Scattering: Characteristics and Consequences

How does a neutron interact with matter and what makes it a useful experimental probe? Apart from very small or rare effects, neutrons interact only with nuclei and only via the nuclear force. A neutron does not ionize the atoms along its path, and it penetrates matter readily, keeping the same velocity until it interacts with a nucleus, where it is either deflected or absorbed. Quantum mechanics predicts probabilistically both the distance traveled before an interaction and whether deflection or absorption will occur. Both processes have important roles.

Neutrons are released in nuclear fission at energies in the millions of electron volts, and they lose energy by deflection, scattering in billiard-ball-like collisions with the nuclei of moderators such as hydrogen. When their kinetic energy is reduced to the same level as the thermal-motion energies of the moderator atoms, they are as likely to gain energy as lose it in any given collision. The distribution of their kinetic energies then reaches an equilibrium that is close to the Maxwellian energy distribution of the moderator atoms at the temperature of the medium, and they are called thermal neutrons.

But this description of scattering is not complete. Particles also have a wave nature, with a de Broglie wavelength that is given by Planck's constant divided by their momentum. When a particle's wavelength and the dimensions of the system in which it is interacting are of the same order, wave properties dominate. This is the case for thermal neutrons interacting with atoms in molecules, liquids, and solids. When a thermal neutron strikes such a target, it encounters many nuclei simultaneously and scat-

Opposite page: The cold-source beam plug is being assembled prior to insertion into a beam port in the TRIGA's shielding. It rests on an I-beam that will support the neutron guide as it crosses Ward Laboratory's reactor bay from the beam port to the target chamber beyond the far wall.

“*If the guide is curved, even radiation that travels in a straight line . . . can be eliminated.*”

ters coherently, showing wave interference effects—intense scattering at the angles for constructive interference, and no scattering into the destructive angles. Since these angles are functions of both the interatomic spacing and the wavelength (read energy) of the neutrons, thermal neutrons in a beam aimed at a regular array of atoms such as a crystal are reflected at different angles depending on their energy. A crystal can thus be used as a monochromator to select monoenergetic neutrons out of a polyenergetic beam.

When such neutrons penetrate a sample, they scatter from its nuclei and emerge at different angles—and possibly with different energies. The angles reveal the spatial structure of the sample and the changes in energy give a picture of the interatomic potential wells that hold atoms in a crystalline array and create the states of motion (energy levels) of the atoms in those wells. Many neutron-beam studies are done by physicists, chemists, and biologists to analyze crystalline structures and their dynamics through coherent scattering effects, using triple-axis spectrometers and small-angle neutron scattering systems at large, high-flux reactors.

Another consequence of the wave nature of neutrons is the type of coherent scattering known as refraction. When a neutron passes from one medium into another medium that has a smaller index of refraction, it is reflected with one-hundred-percent probability, so long as its glancing angle is less than the critical angle. This property of total reflection makes it possible to create guides that conduct neutrons in exactly the same way that fiber-optic cables or light pipes transmit ordinary light.

Neutron Absorption: Implications and Applications

When a neutron interacts with a nucleus, the alternative to deflection is absorption. The nucleus of mass A becomes a “compound nucleus” of mass A + 1 in an excited state, which quickly undergoes one of several possible changes.

One form of de-excitation involves the emission of one or more “prompt” or “neutron-capture” gamma rays. Nuclear physicists can interpret the energies and intensities of these gamma rays to reveal the energy-level structure of the product nuclide. Applied scientists, on the other hand, can treat the gamma-ray spectrum as known and use it to identify the species in the target. This method is called prompt-gamma neutron-activation analysis (PGNAA). It is similar to ordinary neutron activation analysis (NAA, described on page 7), except that it involves gamma rays produced at the time of irradiation rather than those produced later by the decay of residual radioactive nuclei. An important difference between the two kinds of analysis is that all elements emit prompt gamma rays, whereas most but not all form the radioactive daughters that make NAA possible. Those not seen in NAA include hydrogen, boron, carbon, nitrogen, phosphorus, and sulfur.

Another form of de-excitation of the compound nucleus involves the emission of a proton or an alpha particle rather than gamma rays. This effect is used in neutron depth profiling (NDP), a technique for determining the depth and thickness of subsurface layers in multilayered objects such as semiconductor microchips. If a layer contains boron, for example, neutron absorption results in the emission of a monoenergetic alpha particle. Since this particle loses energy at a known rate as it ionizes the atoms along its path, its energy on emerging from the surface is directly related to the depth from which it comes. NDP is not applicable to all elements, but it is very effective for boron and one or two other light elements that emit suitable particles.

Neutron Beams from Nuclear Reactors

Most research reactors have channels or beam ports through the dense concrete that shields their core, so that streams of radiation can be made available for experimental and analytical purposes. Reactor beams differ from accelerator beams in two significant respects.

First, the fact that neutrons have no charge means that they cannot be steered like charged particles. Consequently, the

Several graduate students have been involved in the cold neutron beam project. Lydia Young designed, built, and tested a prototype cold source. Takashi Emoto modified and tested it together with a short neutron guide. His trial runs, which briefly produced a cold neutron beam, provided the performance data needed to decide on final design parameters. Currently, Alexander Atwood, Carol Ouellet (seen at left with David Clark), and Stuart Spern are working on the final system. Most of the Monte Carlo simulation program was written by J. Scott Berg while he was an undergraduate majoring in engineering physics. Staff members at Ward Laboratory have also contributed to the project and the comments of colleagues at other reactor laboratories have been useful.

A nuclear engineering grant from the U.S. Department of Energy has provided partial support for the past two years.

intensity and divergence of the flux at the exit of a beam port is determined solely by its length and diameter. For example, in a typical beam port that is 300 centimeters long and has a 10-square-centimeter opening, the inverse square law reduces the flux at the exit to only 9×10^{-6} of the isotropic flux at the entrance.

Second, the radiation spectrum from a nuclear reactor is very complex. Although the thermal neutrons that one wishes to use are the principal component of the radiation stream, fast neutrons and gamma rays of many energies are present as well. These components form a background that is a decided nuisance at best, and can, at worst, totally obscure the processes in which a researcher is interested.

Various filters have been devised to eliminate fast neutrons and gamma rays. The best is a neutron guide, which acts as a filter because the critical angle for total reflection is proportional to a neutron's de Broglie wavelength, which is inversely proportional to the square root of its energy. For thermal neutrons the angle is small, but for fast neutrons and gamma rays it is essentially zero—so only thermal neutrons are transmitted by reflection. If the guide is curved, even radiation that travels in a straight line from the core toward the exit of the beam port can be eliminated.

Unfortunately, the neutron guide's value as a filter is diminished by the way it attenuates the flux. For the usual nickel reflecting surface and a neutron energy of 0.025 electron volt, which is typical for a 300°K thermal spectrum, the critical angle is 3.1 milliradians. As a consequence, only 3.1×10^{-6} of an isotropic 0.025-electron-volt flux that enters the guide is within the critical angle and is transmitted.

This situation can be greatly improved, however. Since the transmission is proportional to the solid angle defined by the square of the critical angle, it is inversely proportional to the energy of the neutrons. This means that when the temperature of the incident neutrons is reduced from 300°K to 30°K, the efficiency of the transmission is increased by a factor of ten. The result is a relatively strong beam of pure, cold neutrons.

A further advantage of cold neutrons is rooted in quantum mechanics: a neutron's probability of absorption is inversely proportional to its velocity. Thus, neutrons at 30°K react with a target at a rate that is greater, by the square root of ten, than neutrons at 300°K.

> *". . . we optimized the size and shape [of the cold source] through a Monte Carlo simulation of a very large number of neutron histories. . . ."*

Designing and Building the Cold Neutron Source

The feasibility of building a cold neutron beam facility became apparent to the team at Cornell only gradually. First, we learned that a material called mesitylene (1,3,5-trimethylbenzene) had been used in a cold source in Japan. Unlike liquid hydrogen, it is nonexplosive and liquid at room temperature. Second, we found that the daunting task of fabricating meters of neutron guide to optical accuracies could be avoided by ordering prefabricated sections from a small company in Munich. Third, we thought up the concept of cooling the cold source by conduction through solid copper rods attached to a cryogenic refrigeration source, so that cryogenic gases or liquids would not have to be circulated close to the reactor core. Finally, we figured out how to fit all the necessary components into an existing beam port, so that we would not have to modify the structure of the reactor.

Mesitylene is an effective absorber of kinetic energy from thermal neutrons because it has a low-lying quantum level at 0.007 electron volts due to rotational motion of the methyl radicals on alternate corners of its benzene ring. Neutrons can excite this motion relatively easily because methyl contains hydrogen nuclei. (Many hydrogenous materials are not good cold moderators, however, because they do not have low-lying quantum levels in which the hydrogen participates.)

The cold source itself is 120 grams of frozen mesitylene in a disk-shaped aluminum container located 17 centimeters from the edge of the core. The size and shape of the mesitylene affect its function as a cold source. The larger it is, the more neutrons are absorbed, and the fewer make it through to the neutron guide. The smaller it is, the fewer collisions occur, and the fewer neutrons are brought into the 30°K range. To get the most favorable compromise, we optimized the size and shape through a Monte Carlo simulation of a very large number of neutron histories, using the probabilities of change in the neutrons' direction and kinetic energy at each collision.

When the reactor is at its full power of 500 kilowatts, the aluminum chamber is subjected to a thermal-neutron flux of about 1,012 neutrons per square centimeter, a fast-neutron flux of about 4×10^{10} neutrons per square centimeter, and a gamma-ray field of about 460 rads per second. The thermal flux is what we want, but we must also cope with the fast neutrons and gamma rays, which heat the chamber and the mesitylene at a level of about 1.5 watts. To maintain the temperature of the source near 30°K requires conducting that heat to a refrigerator that maintains a temperature of about 25°K, outside the shielding. A 99.999-percent-pure copper rod is used, because it has the highest thermal conductivity of any commercially available rod of the required length and diameter.

Radiation from the reactor's core not only heats the components; it also causes radiation damage that reduces the copper rod's conductivity by a significant factor during even a few weeks' operation. Fortunately, if the copper is brought up to room temperature periodically, almost all the conductivity is restored by thermal annealing. The radiation also causes a slight radiolysis of the mesitylene, but the products can be drawn off and released, or retained and recombined, when the system is brought to room temperature. We anticipate doing this routinely, every two weeks or so.

The Neutron Guide and the Experimental Chamber

The neutron guide consists of an evacuated rectangular glass tube that is 2 centimeters wide, 5 centimeters high, and nickel-plated on the inside. It has thirteen elements, each one meter long. The entrance to the guide is about 30 centimeters from the downstream surface of the cold source. The first three elements are mounted in a beam plug along with the cold source, the copper rod, heat shields, temperature and pressure sensors, a shutter upstream of the guide entrance, and shielding to attenuate the neutrons and gamma rays from the core. Downstream from the beam plug and the reactor shielding wall, the guide is shielded with borated plastic and lead, which form a tunnel, supported by an I-beam, that leads through a concrete wall to a target area. The guide elements form a polygonal approximation to a circular curve of 500-meter radius. This displaces the guide exit 18.2 centimeters from a straight line extrapolated along the beam-port axis.

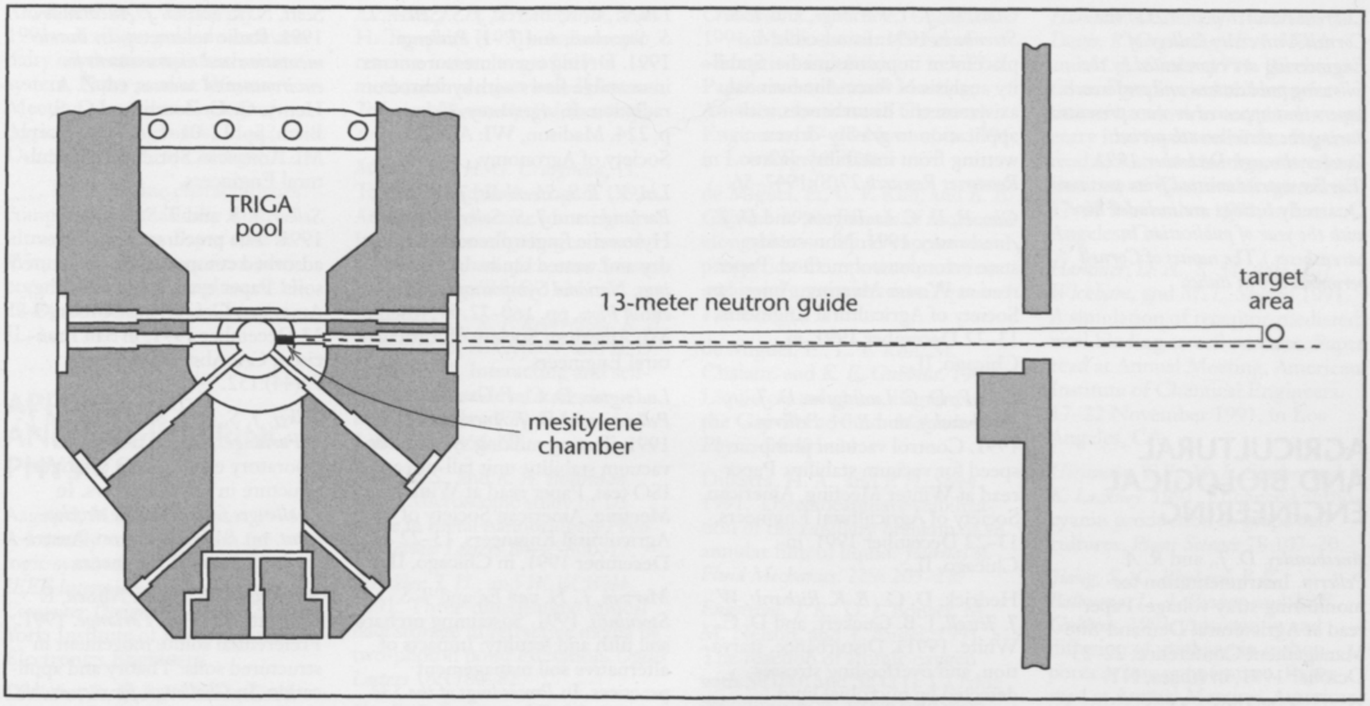


Figure 1. The cold neutron source and guide that is currently being installed at Cornell's TRIGA reactor. The mesitylene chamber is 17 centimeters from the edge of the core, and the 13-meter guide approximates the curve of a circle with a 500-meter radius, displacing the guide exit 18.2 centimeters from a straight line drawn through the axis of the beam port.

A chamber will be located at the end of the guide to accommodate targets and detectors for various experiments. Downstream from the chamber will be a beam stop to absorb neutrons that do not react in the target. As this magazine goes to press (mid-May 1992), the beam-plug shell is complete, all of the internal components are on hand or being fabricated, the cryogenic refrigerator is installed on its mounting, and the section of the I-beam in the reactor bay is in place.

Applied and Basic Research with the Cold Neutron Source

Several uses for the cold neutron source are planned. The primary analytical use will be for prompt-gamma neutron-activation analysis (PGNAA). This will complement our established programs in delayed neutron activation analysis, since it can detect elements like hydrogen, boron, and carbon—which NAA cannot. Another use of the source will undoubtedly be for neutron depth profiling.

We hope, however, that much of the use will be directed toward extending analytical capabilities by improving existing methods and developing new ones. One project might involve development of depth profiling with conversion electrons instead of alpha particles. Conversion electrons are monoenergetic and are emitted by many elements with an atomic number greater than 25, and their penetrating power is greater than alpha particles of similar energy. Therefore, conversion-electron depth profiling would be applicable to a greater range of elements and for greater depths than the present technique.

Another project might involve adapting techniques from nuclear physics, such as coincidence counting and multiparameter data acquisition, to analytical problems. It would also be interesting to exploit the special properties of cold neutrons, such as the possibility of focusing them by total reflection from curved surfaces.

Basic studies of nuclear energy levels and neutron optics should also have a place in the research schedule. These phenomena might be explored with the Bonse-Hart single-crystal interferometer, a device originally invented for x-rays that has been used for neutrons at several different laboratories. It was developed here at Cornell many years ago, and perhaps it is time to bring it back home.

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period October through December 1991. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

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