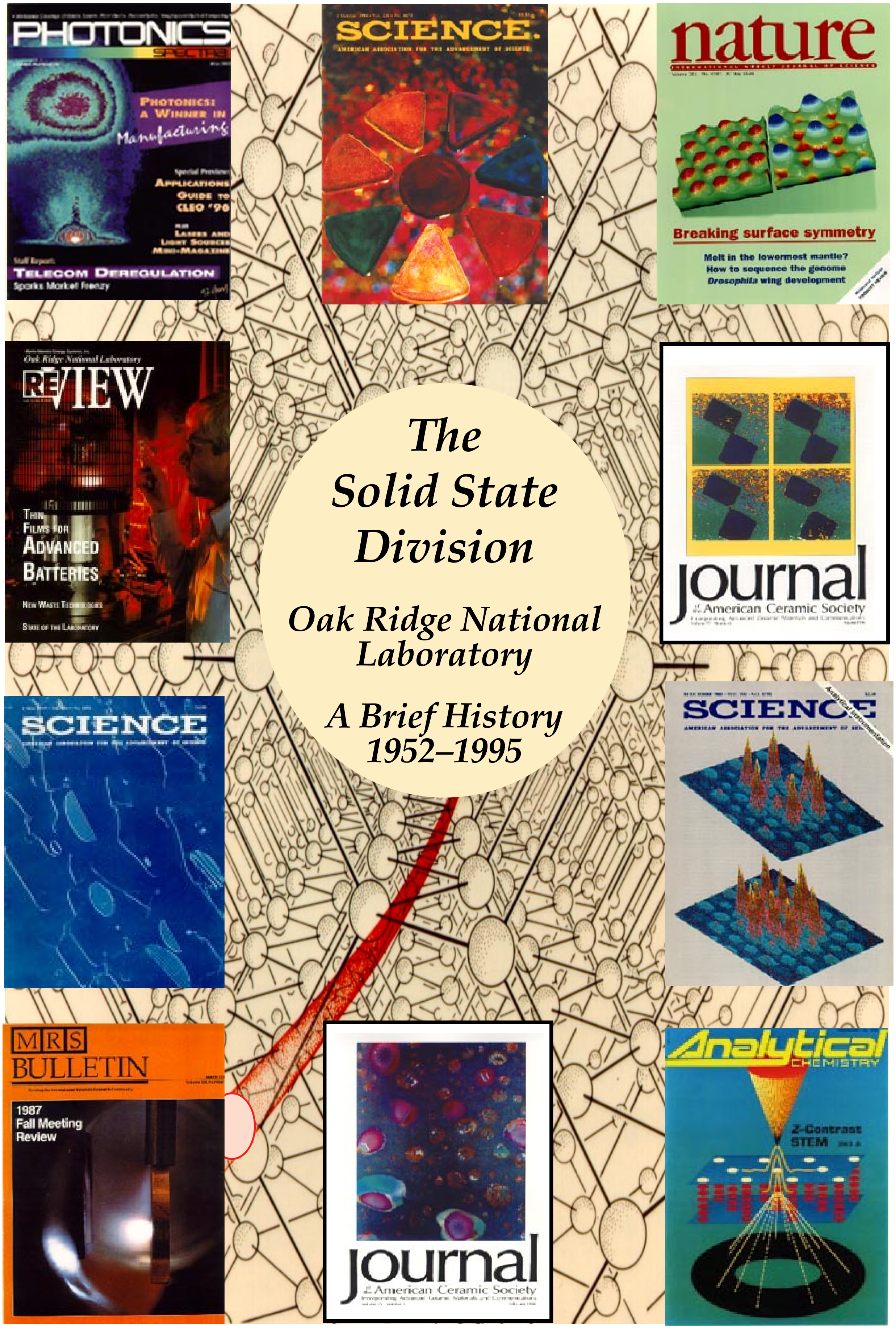
The Solid State Division

Oak Ridge National Laboratory

A Brief History
1952–1995



Cover: The trajectory of a "channeled" ion in a crystal surrounded by journal covers featuring other Solid State Division research. Clockwise from upper left: laser ablation, glass research, surface science, sintering, neutron scattering, Z-contrast electron microscopy, ion implantation, superconductivity, laser annealing, and thin-film batteries.

Foreword

For more than four decades, the Solid State Division at Oak Ridge National Laboratory has been at the forefront of interdisciplinary research in condensed matter science and materials physics. This brief history chronicles the development of the division and its major scientific and technological contributions from 1950 to 1995. During this period, the division evolved from a small institute devoted to the new field of radiation effects to the broad, multidisciplinary materials physics effort which exists today. This evolution was shaped by the missions of the Department of Energy and its predecessor organizations, by the advanced research facilities available at the Laboratory, but mostly by the talent and creativity of the people of the Solid State Division.

Compiled by Mike Wilkinson, director of the Solid State Division from 1972 to 1986, the history provides a broad overview of the division and its place in the scientific community. This is a daunting task. There is no way to include every significant contribution nor to properly assess the impact of the more recent research. An honest attempt has been made to include the more important events, but names and contributions have undoubtedly been missed. We sincerely regret any oversights.

I congratulate Mike for producing a thoughtful and balanced history of the division. I would also like to thank Phyllis Green, who patiently prepared the numerous drafts of the history, and Lynn Boatner, John Cooke, Ben Larson, Ralph Moon, Dick Wood, and David Zehner, who contributed to various sections of the final document.

As a final note, I would like to thank Mike Wilkinson for over 45 years of outstanding service to the Solid State Division and Oak Ridge National Laboratory. Much of what is in this history would not have been accomplished without his leadership.

Jim Roberto, Director
Solid State Division
June 1996

Prologue

In early 1942, the Army Corps of Engineers designated a large section of land in East Tennessee as one of three sites in the United States that was needed for development of an atomic bomb. Part of this land, the X-10 site, was used for the construction of Clinton Laboratories, later designated the Oak Ridge National Laboratory. Construction of the Laboratory was begun in February 1943, only a couple of months after scientists had achieved the first nuclear chain reaction on a squash court under the University of Chicago football stadium at Stagg Field.

The Laboratory was built as a pilot plant for a large plutonium plant at Hanford, Washington, and the centerpiece of the X-10 site was the Oak Ridge Graphite Reactor (ORGR), which was larger and more advanced than the original Chicago pile. The initial missions of Clinton Laboratories were the production of small amounts of plutonium at the ORGR, the development of a chemical process for separating and purifying plutonium, and the evaluation of health hazards associated with processing and handling large amounts of radioactive materials. The early organization had divisions for chemistry, health, engineering, and accounting, with sections devoted to nuclear physics and radiation biology. Very little metallurgical research was performed, and there were no specific organizations to deal with metallurgy and the other solid state sciences.

In late 1946 and early 1947, the first reactor school was held at Clinton Laboratories. This school lifted the secrecy from portions of the atomic bomb project to enable the development of nuclear power for civilian use. Promising young scientists and engineers were selected by interested organizations and invited to attend this school. These participants were the skeletal structure for the nuclear industry that soon developed, and some of them became the seeds for future ORNL divisions (e.g., the Metallurgy Division and the Solid State Division).

Near the end of 1946, William Johnson, a participant in the reactor school from Westinghouse, was asked to organize a Metallurgy Division, and two of his first appointments were Doug Billington and Don Stevens, who were also reactor school participants from the Naval Research Laboratory. They were soon joined by additional reactor school participants and Laboratory staff members, including Larry Jetter, Ed Boyle, and Bill Pellini. Within several months following the conclusion of the reactor school, nearly all participants, including Johnson, Billington, and Stevens, returned to their home installations, and John Frye, Jr., was brought to the Laboratory to be the Director of the Metallurgy Division. Billington returned to the Laboratory in 1948 to lead a section in the Metallurgy Division involved with research on radiation effects. This section was later combined with a similar section in the Physics Division as the nucleus for a special institute that became the Solid State Division. Stevens returned to the Laboratory in 1951 to perform research for his Ph.D. thesis and then became a member of the Solid State Division for a brief period before joining the Atomic Energy Commission (AEC) in Washington, D.C.

Rootie Ti Toot, Rootie Ti Toot
We are the ones from the Institute
We work early, we work late,
Researching in solid state.

We won't let neutrons and their wiles
Prevent us from constructing piles.
Reports, papers, neutrons, piff!
We'll spend today just getting stiff!

PHYSICS OF SOLIDS INSTITUTE—An informal dedication ceremony of the new Physics of Solids Building was held by the individual group of the Physics of Solids Institute last Friday. The program was presented by J. C. Pigg, as follows: (1) presentation of a giant size key to Dr. D. S. Billington, Acting Director, which was presented by S. E. Dismuke; (2)christening of the building. Margaret Stewart broke the bottle which, by the way, did not consist of champagne but of talc (solids, you know); (3) presentation of symbols (Greek letter Psi) to all members of the Institute, and (4) Margaret Stewart led the group in a yell. (Just in case we promote a football team, we will need a pep yell—therefore, the bit of verse which appears above.)

(Reprinted from The ORNL News, December 22, 1950)

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The First Ten Years (1952–1962): *Foundations of Radiation Effects*

The Solid State Division actually had its beginning in November 1950, as the Physics of Solids Institute. This institute, with Doug Billington as Acting Director, was formed as a Section in the Metallurgy Division. It had a lifetime of slightly more than one year, becoming the Solid State Division on January 11, 1952, with Billington as the Division Director. Jim Crawford, Jr., was appointed Assistant Division Director in early 1953 and Associate Division Director in 1960. Hal Mate was the first division Administrative Assistant, and Frank Kocur was appointed to this position in 1961.

The Solid State Division was established with the primary mission of obtaining an understanding of the behavior of materials in an environment of nuclear radiation. It was known that radiation could markedly alter the physical properties of materials, frequently in a deleterious fashion, but almost nothing was known about the fundamental nature of the process. In order to protect materials from the effects of radiation and to develop radiation-resistant materials, an understanding of these effects was essential. Moreover, radiation damage experiments frequently yield significant information about the fundamental behavior of materials in the absence of radiation, and radiation can be used as a tool to study many physical properties of materials.

At the time that the Solid State Division and its predecessor, the Physics of Solids Institute, were formed, studies of radiation effects constituted one of the fastest growing areas of scientific research. Such growth was emphasized at ORNL by the complete inadequacy of space to house the scientists conducting this research. A new building, which is now known as the East Wing of Building 3025, was available for occupancy in December 1950, shortly after the Institute was formed. This building, which contained offices, small laboratories, and hot cells, was almost immediately too small, so that a very large addition to the building was quickly planned. This addition, which is the main Solid State Division building today, was completed in 1956, and it was already too small to house all the division members. A second addition, even larger than the existing complex, was requested and was listed as the top priority construction item at ORNL for many years. Funds were never forthcoming from Congress for the second addition, so that division members have been housed in buildings scattered throughout the Laboratory.

Most of the charter members of the Solid State Division had previously been members of other ORNL divisions, particularly the Metallurgy Division and the Physics Division. They had already been involved in research investigations of radiation effects in materials, and consolidation into one division was necessary to provide a more coordinated effort in solving the important problems of this rapidly growing area of science. A list of division members in February 1952 is given in Appendix A.

Although it was known that nuclear radiation could alter physical properties of materials, neither the macroscopic nor the microscopic effects were characterized or understood. It was believed that changes in physical properties resulted from collisions of energetic nuclear particles with atoms in a solid, which displaced the atoms from their lattice sites, causing interstitial atoms and atomic vacancies. However, the processes had not been carefully studied, and the effects of the resulting defects were not understood. Therefore, systematic studies were initiated on a wide variety of materials, which included metals, alloys, semiconductors, insulators, molten salts, polymers, and ceramics. Various types of radiation sources included gamma ray sources, the 86-inch cyclotron at Y-12, and linear accelerators, but the main effort was concentrated at the Graphite Reactor (ORGR), located across the street from the Solid State Division building.

The early programs very quickly became grouped into research investigations on radiation metallurgy under Bill Taylor; on solid state reactions under Jim Crawford, Jr.; on engineering properties under Oscar Sisman; on crystal physics under Tom Blewitt; and on fused salts under Gerry Keilholtz. There was no formal solid state theory program during this early period, but in the mid 1950s Dave Holmes, who was later joined by Hal Schweinler and Mark Robinson, provided theoretical guidance for the experimental research. In addition, Stewart Dismuke was in charge of the Solid State Division building and hot cell laboratories, and Jim Howe was responsible for engineering activities. Because so little was known about the effects of irradiation at that time, experiments were not limited to studies of the fundamental properties of materials, and many experiments of a purely engineering nature were performed. Such experiments included the effects of radiation on rectifiers, magnets, transistors, thermocouples, electronic equipment, strain gauges, teflon cable, liquid and solid fuels, Kovar, and graphite-carbon rods. Much of the early work of the Solid State Division was classified as “Secret,” but that classification was later removed.

Investigations of the effects of nuclear radiation on semiconductors had begun at ORNL in 1949, when Jim Crawford, Jr., J.C. Pigg, and John Cleland were members of the Physics Division. It was then that experiments, which were conducted by Cleland, led to the discovery of the process of neutron transmutation doping of semiconductors. This process has been widely used throughout the world to produce silicon samples that have evenly distributed and well-controlled amounts of phosphorus for the semiconductor industry. It has also been used frequently to prepare well-characterized semiconductor samples for research. Because the electrical properties of semiconductors are very sensitive to small numbers of defects, research on semiconductors became an important tool in determining the fundamental changes in solids that are produced by fast-neutron bombardment. By correlating the changes in electrical properties that occur during irradiation, it was possible to construct and test models of radiation damage and to obtain fundamental information on changes in semiconductor properties, such as the concentration and mobility of charge carriers, which are due to lattice defects. Other important investigations of radiation effects in semiconductors included very sensitive measurements of the magnetic susceptibility of electrons trapped at the lattice defects. One of the first large investments in capital equipment by the Solid State Division was the purchase from Arthur D. Little, Inc., of a large electromagnet that could be used for these measurements. The rest of the equipment, which included cryostats and an ultrasensitive microbalance, was designed and built by Don Stevens, who used the apparatus to study the magnetic susceptibility of a variety of irradiated and annealed specimens as a function of temperature. Because most of the semiconductor irradiations required exposures in a fast-neutron environment for less than 10 hours, a device was installed in the ORGR for loading and unloading samples without a reactor shutdown. Information gained from the semiconductor experiments was used to explain effects of reactor radiation on semiconductor electronic components and indicated methods to improve the radiation resistance of such devices.

There was also a significant amount of research on other nonmetallic systems, such as ionic and covalent crystals. As true of most radiation damage investigations, this research was concerned with the creation of defects by energetic radiation, interactions between these defects and other imperfections in the crystal such as dislocations and impurity atoms, and the recovery of these defects through thermal annealing. Because alkali halides are the prototype of all ionic crystals, most investigations concentrated on these compounds. The imperfections in such crystals are usually electronic defects with distinct localized electronic states, and effective means of investigation included optical absorption and luminescence, radiolysis, magnetic susceptibility, electron paramagnetic resonance, and thermal conductivity. The latter measurements were particularly sensitive to the presence of lattice defects and also provided information on whether such defects were clustered. Early members of the Solid State Division who performed research on ionic and covalent systems included Jim Crawford, Jr., Don Stevens, Dan Binder, Bill Sturm, Ed Sonder, Bob Weeks, Cecil Nelson, Ann Cohen, Mark Wittels, and Les Templeton.

Investigations of the effects of radiation on organic polymers and ceramics were undertaken primarily to obtain information that would help in the selection of the best materials to use in reactors and in the prediction of the service lifetimes of such materials in reactor use. Members of this program included Oscar Sisman, Bill Parkinson, Jr., Roy Towns, Giles Morgan, Bill Brundage, and Charles Bopp. The research on organic polymers was aimed at determining changes in molecular structure, at measuring the radiation energy required for cross-linking or scission of various polymers, and at determining the influence of variables in the radiation field. Investigations of ceramics included changes in physical properties and changes in composites, particularly with respect to loss of water. The physical properties of interest included elastic modulus, density, hardness, thermal conductivity, and specific heat.

Until 1958, the division had significant research efforts in support of the development of a nuclear-powered airplane, the so-called “ANP Project.” The ORNL portion of the project was based on a fission power reactor in which the fuel was a molten mixture of the fluorides of uranium, zirconium, sodium, and other cations, operating at a temperature near 800°C. Issues of the stability of the salts under irradiation, the effects of irradiation on the corrosion of metals by the liquid salts, and the fate of fission products were of significant concern. A group under the direction of Gerry Keilholtz began studies of these topics in 1951 using the Low Intensity Test Reactor (LITR) at ORNL and the Materials Testing Reactor (MTR) in Idaho for irradiations. After the successful operation of the Aircraft Reactor Experiment at ORNL in 1954, the emphasis on fission product behavior increased. Members of the division who worked on these problems included Carl Baumann, Bill Browning, Don Guss, Leo Hemphill, Les Jenkins, Giles Morgan, Morris Osborne, Mark Robinson, Hugh Robertson, Curt Webster, Dave Weekes, and Bill Willis. Many members of

Radiation Damage

The presence of the Graphite Reactor at ORNL in the early 1950s put the Solid State Division in a unique position to investigate neutron radiation effects in solids and to correlate microscopic structural effects with macroscopic materials properties. The technologically important cube-root fluence dependence of neutron radiation hardening in metals was discovered by Tom Blewitt and Ralph Coltman in 1951. By obtaining otherwise unavailable refrigeration equipment from the H-bomb tests at Eniwetok in the Pacific, irradiations were carried out at 3.5 K that proved to be cold enough to freeze single interstitials in metals. As a result of radiation damage work on surface reactivity initiated by Fred Young, Jr., in the 1950s, the Solid State Division retains kilogram quantities of the world's most perfect copper crystals. These studies demonstrated a one-to-one correspondence between etch pits and dislocations in metals and showed for the first time that metals could exist without dislocations. Radiation effects studies in alkali halides by Jim Crawford, Jr., during the 1950s, and later in collaboration with Bill Sibley, Ed Sonder, and Dick Wood, produced the startling result that because of an ionization mechanism, the production of vacancy-interstitial pairs was ~1000 times easier in alkali halides than in metals or other compounds.

In the early 1960s, Tom Noggle was one of the first to observe directly radiation-induced defect clusters in materials, using transmission electron microscopy. The availability of the large, high-perfection copper crystals facilitated a number of radiation damage investigations, and they led in the mid-1960s to the first application of Borrman (i.e., anomalous transmission) x-ray topography in metals and to three-dimensional stereographic studies of the initiation by single dislocations of stress-induced slip in macroscopic samples. Stan Sekula and Bob Kernohan showed that strong flux-pinning forces enabled niobium to behave as a perfect superconductor in magnetic fields up to the upper critical field. Mark Robinson developed the now widely distributed MARLOW numerical damage simulation code to simulate the damage production process, and the radiation damage program benefited significantly from an active theoretical and experimental scientific exchange with the institutes of Gunther Leibfried and Werner Schilling at the Kernforschungsanlage (KFA) in Jülich, Germany. The alkali halide radiation effects program shifted to high-temperature refractory oxides, where radiation damage was found to occur mainly by elastic collisions rather than by the highly efficient ionization process in alkali halides.

During the 1970s and on through the 1980s, experimental techniques such as x-ray and neutron diffraction, internal friction, and electrical resistivity, as well as electron microscopy, were utilized in fundamental radiation damage investigations in metals and semiconductors. Yok Chen and collaborators discovered radiation-induced diffusion of light atoms in oxides, making it possible to diffuse hydrogen, deuterium, and tritium in oxides at or below room temperature. Dave Christen, Rich Kerchner, Jim Thompson, and collaborators confirmed theories of flux pinning by defects in superconductors and made the first report of irradiation-enhanced flux pinning in high-temperature superconductors (HTSc) at the 1987 American Physical Society "Woodstock of Physics" meeting. In the early 1990s, ions from the ORNL Holifield Accelerator Facility were used to introduce amorphous defect tracks into HTSc, resulting in near-optimal flux pinning for tests of the ultimate limits of various classes of HTSc materials.

Tom Noggle, Jean Redman, Ralph Coltman, and Tom Blewitt (l to r) are shown preparing refrigeration equipment for in-pile low-temperature experiments at the Oak Ridge Graphite Reactor.

this group were transferred to the Reactor Chemistry Division when it was formed in 1958 and continued their work in support of the (civilian) Molten Salt Reactor Project.

Other ANP research was carried out in the Engineering Properties Group under the direction of Oscar Sisman. Studies of flowing molten fluorides in circuits passing through the MTR to study corrosion, fission product chemistry, and the like were made. There were also studies of loops circulating molten sodium through the LITR. This group included Frank Blacksher, Bill Brundage, Rad Carroll, Marvin Morgan, and Bill Parkinson. Work in support of the ANP Project was also performed in the Radiation Metallurgy Group, which mainly studied the mechanical properties of metals under irradiation (e.g., creep). This group under the direction of Jim Wilson included Ray Berggren, Bill Davis, Norm Hinkle, Bob Weeks, and Joe Zukas. Many members of these groups also transferred to other laboratory divisions.

Investigations of radiation damage in metals and alloys were concerned with the production of defects by irradiation; the characterization of point defects, clusters of defects, and dislocations; and the effects of these defects on physical properties. The properties of interest included electrical and thermal conductivity, critical sheer stress, anelasticity, density, creep, hardness, and sputtering from metallic surfaces. To prevent the effects of radiation-induced defects from being masked by natural defects, crystals of very high perfection were required in this research, and much attention was given to the growth, preparation, and characterization of nearly perfect metal crystals. The research on alloys was concerned with the production of lattice defects and with the effects of irradiation on diffusion-controlled solid state reactions, such as ordering and precipitation from solid solutions. Scientists involved in the early radiation metallurgy experiments included Doug Billington, Bill Taylor, Jim Wilson, Ray Berggren, Monroe Wechsler, and Mel Feldman.

Of particular importance in obtaining an understanding of radiation damage processes in metals were the in-pile low-temperature experiments of Tom Blewitt, Ralph Coltman, Tom Noggle, Don Thompson, Charlie Klabunde, and Jean Redman. Very early investigations near room temperature had shown that some radiation-induced defects might be mobile at lower temperatures. Therefore, studies of these defects could be made properly only if they were frozen into the material during bombardment and then studied under controlled low-temperature conditions. Moreover, subsequent experiments near liquid nitrogen temperatures clearly established the existence of defects mobile at even lower temperatures and showed that such defects had a significant effect on certain physical properties of materials. Maintaining a sample at 20 K and lower for a week of bombardment and measurements required a considerable amount of very reliable refrigeration, and the necessary machinery was extremely expensive. Fortuitously, at about this same time, it was learned that some helium gas refrigerators, which had been used in the first hydrogen bomb development, had become surplus. These refrigerators had operating temperatures of 15 K and heat capacities of a few hundred watts, which were extreme capabilities for that time, and were ideally suited for the required radiation damage experiments. Consequently, arrangements were quickly made for John Cleland and Ralph Coltman to visit such places as Los Alamos National Laboratory and Edwards Air Force Base to locate the surplus equipment and to discuss the possibility of transferring it to

ORNL. As it turned out, the Atomic Energy Commission (AEC) and the Air Force were extremely pleased that a government laboratory could use this equipment, because some of the original contractors wanted to buy it back for a minute fraction of the original cost. The final result allowed the division to acquire four helium refrigerators and crates of spare parts valued at $1,500,000 to $2,000,000 in 1950 dollars. With cold helium gas from one of these refrigerators at a pressure of one atmosphere, copper samples could be maintained in the ORGR at a temperature of about 15 K. A separate helium liquifier system was later inserted into the sample cryostat system allowing sample temperatures of 3 K to be obtained. Bombardments were performed at the lowest temperatures available, and effects of annealing were observed as the sample temperature was slowly raised by gamma-ray heating with the reactor operating at low power.

The in-pile experiments at low temperatures were not free from hazards, and during some of the early investigations at liquid nitrogen temperatures, there were two minor explosions of cryogenic devices inside the ORGR. Both incidents were traced to the condensation of a small amount of oxygen, which was converted to ozone by the ionizing radiations of the reactor. In the second explosion, it was concluded that the trace oxygen impurity in commercial liquid nitrogen was sufficient to produce a hazardous amount of ozone. Very strict safety precautions were then taken to prevent the formation of liquid or solid oxygen in any in-pile cryostats.

Other programs, which were initiated in the mid-to-late 1950s to provide information on radiation damage processes, included studies of the chemical properties of metal surfaces and electron microscopy. Experiments on surfaces were initiated by Fred Young, Jr., and Les Jenkins to determine the effects of irradiation on various chemical processes, such as oxidation and the dissolution of metals in aqueous solutions. Particular emphasis was placed on determining the role of imperfections on such reactions. One of the early successes of this program was the determination of an easy method to locate dislocations in copper by electrolytic etch pits. These studies quickly revealed the necessity for crystals with as few imperfections as possible in order to establish the effects that were caused by irradiation. Techniques were developed for growing copper crystals with a dislocation density much lower than that of any metal crystals grown previously. The electron microscopy experiments were started by Tom Noggle, who was soon joined by Jim Stiegler. Such experiments on structural changes caused by nuclear radiation represented a virtually unexplored area at that time. Some of the early experiments included the effect of radiation on the etching behavior of germanium, plastic deformation of copper crystals, fission fragment tracks in thin films of UO_2, and structural defects in gold films resulting from irradiation.

Following a fire in October 1957 at the reactor in Windscale, England, considerable attention was given throughout the world to the possibility of a spontaneous release of stored energy in the graphite moderators of reactors. Mark Wittels of the Solid State Division led an investigation to study graphite from the ORGR. This investigation included calorimetric and x-ray lattice parameter measurements at ORNL and some different types of measurements at other laboratories. Division members who participated in this investigation included Frank Sherrill, Monroe Wechsler, Ralph Coltman, and Bob Kernohan. These studies established that the stored energy content of the ORGR graphite was at a reasonably safe level and that the increase in stored energy was considerably retarded because of relatively high operating temperatures. Nevertheless, as a special safety precaution, the reactor was annealed in September 1960 at modest temperatures (maximum graphite temperature of about 200°C) by using fission heat and a reverse air flow in the reactor operation. This anneal satisfactorily released the stored energy in all graphite except for peripheral regions of the fuel zone. Subsequent anneals were performed in September 1961 and in October 1962 with special efforts to achieve annealing temperatures in the graphite at the outer perimeter of the reactor core. The last anneal was very successful except for a few minor pockets, and no additional anneals were performed before the ORGR was “retired” in November 1963.

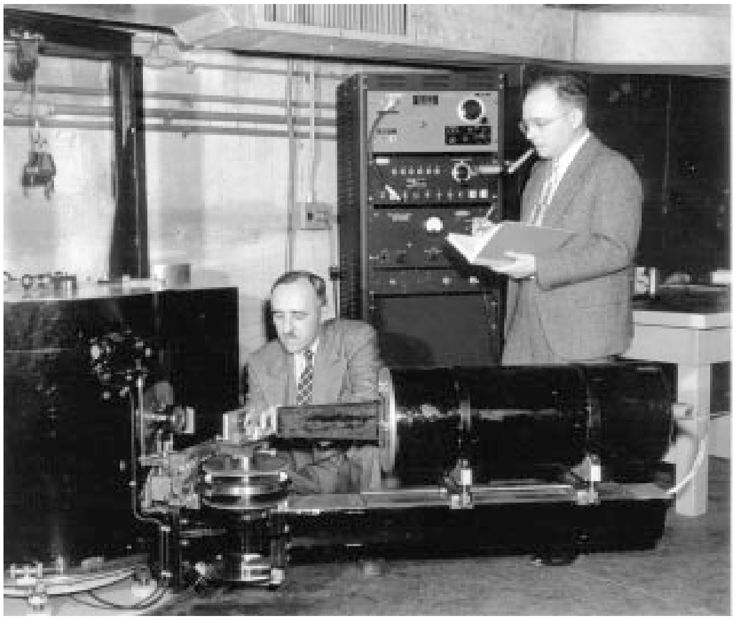
During the latter part of the first decade, a close cooperative program in the investigation of radiation effects was initiated between the Solid State Division and the Kernforschungsanlage (KFA) (today Forschungszentrum) in Jülich, West Germany. An exchange program of scientists was established so that scientists of either organization could spend short-term or long-term assignments with the other organization. Of special benefit to the Solid State Division were the assignments of Gunther Leibfried, who was on the staff at Jülich and also a Professor of Physics at the University of Aachen. Leibfried was an outstanding theoretical physicist with a special interest in the defect solid state, and he provided excellent guidance to theoretical and experimental programs of the Solid State Division.

The Second Ten Years (1962–1972): *The Emergence of Neutron Scattering*

Research during the second decade of the Solid State Division was characterized by more emphasis on investigating the fundamental properties of materials and less emphasis on engineering-oriented experiments. During the late 1950s and very early 1960s, programs such as the fused-salt research under Gerry Keilholtz and engineering materials research under Oscar Sisman were transferred to other ORNL divisions that were considered more appropriate for such research. Most of the research in the Solid State Division during this period was supported by the Materials Sciences Program of the AEC Division of Physical Research. One major exception was a program involved with fundamental studies of radiation metallurgy under Monroe Wechsler, which was supported by the AEC Division of Reactor Development and Technology. This work came under a special AEC office, which tried to bridge the gap between fundamental research under the Division of Physical Research and applied research directly involved with reactor development and technology. The funds allocated by Congress to the AEC Division of Physical Research were specified for basic research, and it was important for programs in the Solid State Division to use such funds accordingly. There were two main guidelines associated with the selection of research programs: (1) the research should involve materials properties of direct interest to the AEC, or (2) the research should utilize techniques at special facilities built by the AEC to study materials properties that could not be studied as well with other techniques.

The biggest change in research performed by the Solid State Division during the second decade was the addition of neutron scattering. This very important research on materials had its origin at the ORGR in late 1945 by members of the Physics Division. The work was pioneered by Ernie Wollan and Cliff Shull and laid the foundation for programs that developed throughout the world. Shull shared the 1994 Nobel Prize in Physics for his development of neutron scattering at ORNL from 1946 to 1955. Early in the 1960s, it became apparent that this type of research should be expanded at the Laboratory, and a decision was made by ORNL and AEC managements to expand the physics-oriented research within the Solid State Division under the AEC Materials Sciences Program. Therefore, in 1962, Mike Wilkinson and Harold Smith transferred into the division from the ORNL Physics Division to initiate research in inelastic neutron scattering at the Oak Ridge Research Reactor (ORR); they were later joined by Bob Nicklow, Herb Mook, and Nobu Wakabayashi. In 1964, the Physics Division group, which concentrated on research involving elastic neutron scattering, was also transferred into the division. This group, led by Wally Koehler, included Joe Cable, Ray Child, and Ralph Moon; Ernie Wollan was a member of the Laboratory Director's Division at that time, but he continued to participate in neutron scattering research. Jim Sellers provided technical assistance and managed to keep the instruments operating properly. Many important experiments were performed at the ORR by these two groups on a wide variety of topics that included magnetism, lattice dynamics, and superconductivity. Moreover, new equipment was planned, constructed, and installed at the High Flux

Neutron Scattering



Ernie Wollan and Cliff Shull conducted the world's first neutron scattering experiments at the Graphite Reactor. Shull shared the 1994 Nobel Prize in Physics for this early work.

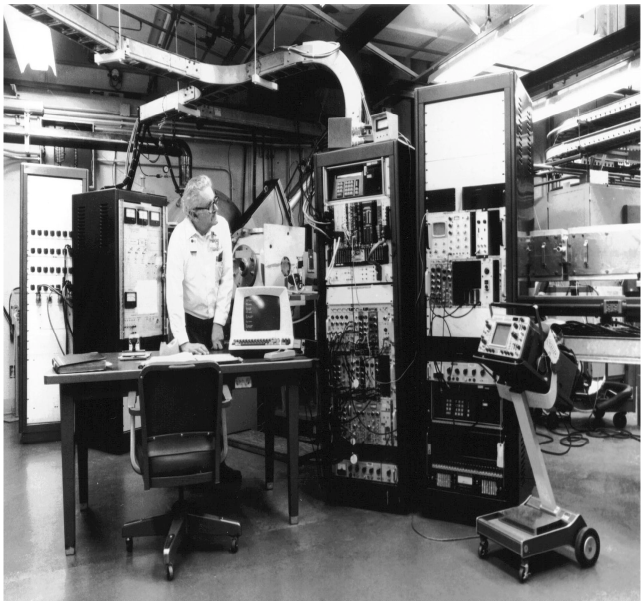
Neutron scattering is certainly one of the oldest continuous research programs at ORNL, predating the existence of the Solid State Division. Ernie Wollan of the Physics Division set up a double-crystal diffractometer at the Graphite Reactor in November 1945. The first experiments on single-crystal samples gave inconsistent results because of extinction, and it was not long before Wollan began evaluating powder diffraction (the first powder pattern, of rocksalt, was obtained in April 1946). Cliff Shull joined Wollan in August 1946, and over the next few years, they built a sound foundation for the growth of neutron scattering by developing neutron powder diffraction as a quantitative technique. Their results were used by groups all over the world who started neutron scattering programs at the first generation of research reactors. For this work Cliff Shull was awarded the 1994 Nobel Prize in Physics. Shull and Wollan were joined in the Physics Division by Wally Koehler in 1949 and Mike Wilkinson in 1950. Shull left for MIT in 1955, and shortly thereafter Joe Cable and Ray Child joined the group, followed by Ralph Moon in 1963. This group transferred to the Solid State Division in 1964 and brought with them a long list of outstanding experimental accomplishments.

- Measurement of the neutron scattering amplitudes of over 60 elements and isotopes.
- First direct evidence of antiferromagnetism.
- Confirmation of the Néel model of ferrimagnetism.
- First use of neutrons to determine the structure of hydrides.
- First observation of magnetic critical scattering.
- First measurements of $3d$ and $4f$ electronic form factors.
- First measurements of magnetic moment distributions in $3d$ alloys.
- Determination of the magnetic structures of rare-earth metals.

The Solid State Division neutron scattering program began in 1962 with the transfer of Mike Wilkinson from the Physics Division and Harold Smith from the Chemistry Division to form the nucleus of an inelastic scattering group. They were soon joined by Bob Nicklow, Herb Mook, and Nobu Wakabayashi, and with the transfer of the existing group from the Physics Division, the Solid State Division neutron program was firmly established. New instruments at the recently completed High-

Bob Nicklow is shown adjusting the incident beam aperture at the HB-3 triple-axis spectrometer at the HFIR. Nicklow was the recipient of the Sidhu Award (presented by the Pittsburgh Diffraction Society) in 1968 for his diffraction research.

Neutron Scattering (cont'd)



Wally Koehler is shown at the 30-m Small-Angle Neutron Scattering facility. Koehler was honored with both the Frank H. Spedding Award from the Rare-Earth Research Conference in 1983 and a special award from DOE in 1986 in recognition of his neutron scattering research.

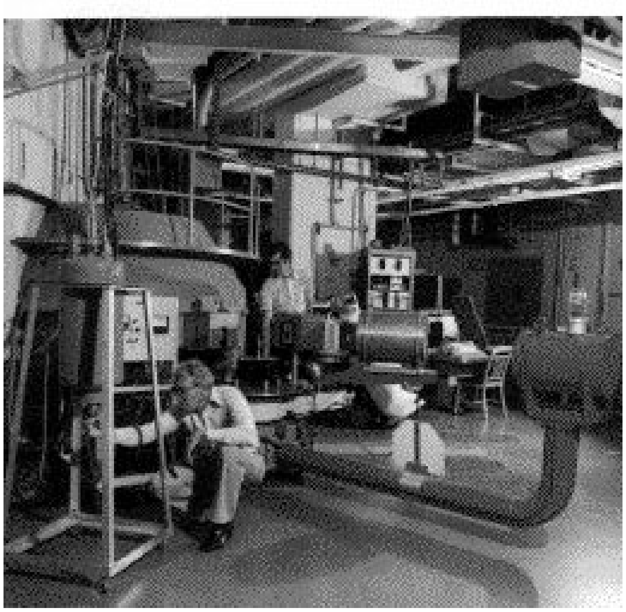
Flux Isotope Reactor (HFIR) led to a broader experimental program beginning in 1967, and important new results were produced immediately, including:

- Development of the neutron polarization analysis technique
- Phonon anomalies in superconductors
- Magnetic excitations in $3d$ and $4f$ metals
- Measurement of Bose condensate in liquid helium
- Form factors of paramagnetic metals
- Phonons and magnetic excitations in high-T_c superconductors

The most important addition to the original complement of instruments at the HFIR was the 30-m small-angle facility, installed under the leadership of Wally Koehler in 1980 with funds from the National Science Foundation. Staff additions with interest in new directions (George Wignall, polymers; John Hayter, colloids; Steve Spooner, metallurgy) have helped to make this instrument scientifically productive and very popular with outside users, including industrial scientists performing open literature and proprietary experiments. Research highlights include:

- Core-shell morphologies and film formation in polymer latexes.
- Compatibility, segregation, and interactions in polymer blends (alloys).
- Quantification of isotope effects and phase segregation in deuterium-labeled polymer mixtures.
- Order-disorder transitions in block copolymers and metal alloys.
- Structure and interactions in micelles, microemulsions, and ferrofluids.
- Flux-line lattices in high-T_C superconductors.

The neutron scattering program is an important scientific by-product of the existence at ORNL of nuclear reactors built for other purposes. Experiments have grown in complexity and sophistication as the source flux has increased from 10^{12} n cm^{-2} s^{-1} (ORGR) to 3×10^{14} n cm^{-2} s^{-1} (ORR) to 10^{15} n cm^{-2} s^{-1} (HFIR). HFIR still produces the most intense thermal neutron flux in the world, and a proposed upgrade of HFIR should continue this leadership well into the next century. ORNL is also the preferred site for the proposed National Spallation Neutron Source, the nation's most powerful pulsed neutron source.



Joe Cable (with Herb Mook in the background) is shown at the HB-1 triple-axis polarized-beam spectrometer at the HFIR. This instrument was used for pioneering work on neutron polarization analysis in 1968.

Isotope Reactor (HFIR) in the late 1960s. The HFIR provided the most intense beams of thermal neutrons that were available for research, and these high neutron intensities combined with excellent new equipment permitted types of research that could not be done at other laboratories. Sharron King wrote the operating programs for the new computer-controlled spectrometers.

Another new program initiated in 1962 was the Research Materials Program. Progress in understanding the fundamental properties of many materials had been severely limited by a lack of specimens of sufficiently high purity and crystalline perfection. The new program was initiated under the direction of John Cleland in an attempt to fill this need. Its goal was to develop the techniques necessary to produce research-quality specimens with the size, purity, and perfection required in materials research by scientists at ORNL and in other AEC organizations. In addition to the Solid State Division participation, which included Cleland, Bill Brundage, Dick Reed, Earl Bolling, Russ Westbrook, Charlie Robinson, Homer Harmon, and Chuck Butler, several other ORNL divisions were involved in this work, and there were also subcontracts with research groups outside ORNL. Prior to this time, it had been very difficult to obtain information about research materials, and the Research Materials Information Center was established as a part of this new program. The purpose of the information center, which was operated by Tom Connolly, George Battle, Anne Keesee, Emily Copenhaver, and Betty Edwards, was to collect information on the purification, characterization, and availability of research-quality materials and to provide this information to both producers and users. An accurate up-to-date listing of such materials helped to eliminate duplication in producing materials that were already available. Moreover, the simultaneous listing of research materials that were desired but not available served to focus the attention of crystal growers on new areas of investigation.

There were other programmatic changes during the second decade that were important for the Solid State Division. During the period from 1960 to 1964, Jim Crawford, Jr., was Editor of the *Journal of Applied Physics*, and the staff of that journal moved into offices at the ORGR. In fact, it was during this period that the rapid communication journal, *Applied Physics Letters*, was started. Although this journal was not a major activity of the Solid State Division, members of the division were frequently asked to serve as referees and to help in editing. A small program for NASA was performed from 1966 to 1973. As part of the Apollo program, samples from the moon were returned to earth for careful examination in several laboratories. Bob Weeks and Jim Kolopus were members of this team of investigators; they examined the specimens using magnetic resonance techniques. One of the interesting discoveries of this research was that ferric oxides are present in some lunar soils despite the extreme environmental reducing conditions. With the “retirement” of the ORGR in 1963, the low-temperature radiation damage program, which was then under the direction of Ralph Coltman, was moved to the Bulk Shielding Reactor (BSR). Although delays occurred in the program because of the necessity to design, build, and install new equipment, the BSR offered more flexibility in research and provided remarkably reproducible reactor control.

Organization changes in the division reflected both its growth and its greater emphasis on fundamental research. As the second decade began, Doug Billington remained Division Director with Jim Crawford, Jr., as Associate Division Director. The research programs were grouped into five sections, which in 1962 included the Theory Section under Dave Holmes; the Crystal Physics Section under Mike Wilkinson; the Nonmetals Section under Crawford; the Metals Section under Fred Young, Jr.; and the Radiation Metallurgy Section under Monroe Wechsler. Frank Kocur remained the division Administrative Assistant. This organization remained intact for several years, except that Mike Wilkinson became a second Associate Division Director in 1964. In 1967, when Crawford left ORNL for an academic position, Bill Sibley was appointed Section Head of the Nonmetals Section, and John Cleland became Section Head of a newly created Research Materials Section. In 1968, Young and Holmes were appointed additional Associate Division Directors.

Research in the Solid State Division during this decade fell mostly into the two general areas of radiation effects and neutron scattering. Experimental programs utilized the ORGR, BSR, LITR, ORR, and HFIR. In fact, the Solid State Division became one of the largest users of research reactors at the Laboratory, so that successes and failures of many experiments were strongly dependent on trouble-free reactor operation. A flavor of the types of research that were performed during this period can be obtained from the main topics of each research section. The Theory Section was concerned mostly with the physics of the defect solid state. Specifically, there was research on the electronic and lattice structures of defects in nonmetallic solids, exciton states in alkali halides, defect cascade theory, the theory of sputtering, the channeling of ions by a crystal lattice, defect motion (especially in metals), clustering of defects, inelastic energy losses suffered by atoms or ions moving through a solid, and anomalous x-ray transmission. Work in the Crystal Physics Section involved neutron diffraction, neutron spectrometry, x-ray diffraction, electron microscopy, magnetic resonance, superconductivity, ion channeling, low-temperature thermal conductivity, and low-temperature specific heat measurements. The Nonmetals Section was concerned with imperfections in semiconductors and with covalent and ionic crystals. Investigations included radiation effects in germanium; the production, motion, and annealing of defects in the alkali halides; the influence of impurities on defect production in alkali halides; and luminescence in alkali halides. Research in the Metals Section included low-temperature in-pile irradiation damage experiments with particular emphasis on interpreting isochronal annealing curves, determination of the number of stable Frenkel defects produced by primary knock-on ions, measurements of third-order elastic constants, chemical reactivity of metal surfaces, sputtering, and the studies of perfect crystals using Borrmann x-ray topography. The activities of the Radiation Metallurgy Section fell into two interrelated categories: (1) radiation hardening and embrittlement and (2) the effect of radiation on diffusion-controlled processes in alloys. In addition, assistance in establishing pressure-vessel surveillance for reactor programs was given, and studies of the impact properties of pressure-vessel steels following accelerated irradiation in the ORR were made.

One of the most important research accomplishments during the 1960s was the theoretical prediction in 1962 by Dean Oen and Mark Robinson that energetic ions are “channeled” by the crystal lattice as they pass through a solid. This effect had not been considered previously in the slowing down of energetic ions, because for

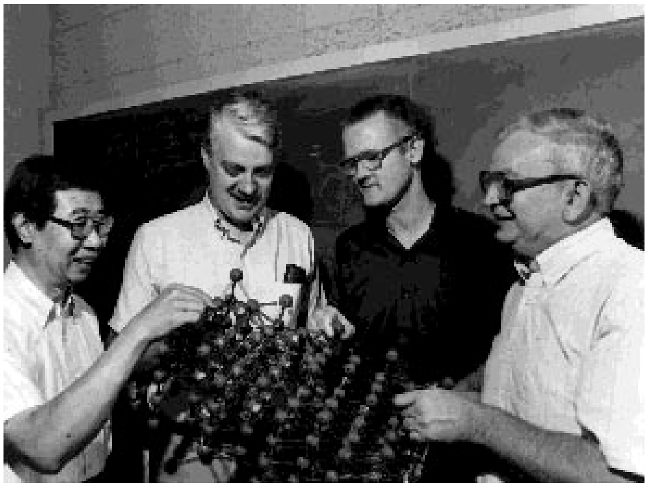
Solid State Theory

For nearly a decade following the formation of the Solid State Division in 1952, the research interests of theorists were focused on the division's primary mission at the time—the study of radiation effects in solids. The impact on the division's research programs was substantial. In the early 1960s Mark Robinson and Dean Oen discovered ion channeling and its direct connection with crystal symmetry. This discovery opened up a new field of research and played a significant role in the establishment of the division's experimental ion beam facility. The development of channeling into an important research tool was facilitated by valuable contributions from Robinson, Oen, and John Barrett. Research on radiation effects also stimulated Dick Wood's work on defects in alkali halides, which provided insight at the fundamental level on the formation and properties of these defects.

Since the early years, the theory program has grown and broadened into many areas of condensed matter physics. In addition, the program has continued to have a major impact on many of the division's experimental activities. In the early 1970s, John Cooke and Harold Davis proposed a modified itinerant-electron theory of magnetism and carried out the first realistic calculations of the spin dynamics of transition-metal ferromagnets which, together with results from the division's neutron scattering program, resolved a long-standing controversy by establishing conclusively the validity of this model for these systems. The development of fast and accurate numerical techniques for calculating the low-energy electron diffraction cross section by Harold Davis in the late 1970s provided the breakthrough necessary to establish LEED as a reliable technique for determining surface structure. Together with John Noonan, a world-class program which achieved accuracies of 0.01 Å for interlayer spacings was developed. An investigation of laser annealing of doped semiconductors by Dick Wood in the mid 1980s culminated in the evolution of theoretical and numerical techniques for describing ultra-rapid solidification, which formed the basis for correctly describing the melting and subsequent recrystallization of the surface and near-surface regions of these technologically important materials.

The discovery of copper-oxide high-temperature superconductors in the late 1980s stimulated work on the full spectrum of proposed pairing mechanisms by Jerry Mahan, Mark Rasolt, and Dick Wood. While this topic is still highly controversial, their research has helped clarify the possible role played by each. Sam Liu and Richard Klemm have investigated the implications of interlayer interactions and pairing and found, in addition to other interesting phenomena, a possible mechanism for substantially increasing the critical temperature. Collectively, this work has not only advanced the understanding of theoretical models proposed for these systems but also has been invaluable in helping to analyze and interpret experimental data.

From the early work on channeling to the present, the theory program has relied heavily on the use of state-of-the-art computers. The MARLOW code, developed by Mark Robinson in the 1970s, continues to be the world standard for simulating the collisions and transport of energetic ions in crystals. The recent acquisition by ORNL of the world's fastest computer, the Intel Paragon, together with important advances within the division of experimental tools such as the Z-contrast scanning transmission electron microscope, has afforded the program a truly unique opportunity to study the complex nature of surfaces and interfaces using numerical simulation techniques. Work in this area, which has enormous potential, is currently being performed by Ted Kaplan, Mark Mostoller, and Zhenyu Zhang. Cooperative research with industries also represents an important new direction. Theorists are currently participating in three Cooperative Research and Development Agreements with industry in the areas of varistors, photovoltaics, and thermoelectrics.



Sam Liu, Jerry Mahan, John Cooke, and Harold Davis discuss many-body theory. Mahan was elected to membership in the National Academy of Sciences in 1995.

simplicity the crystal lattice had been replaced by a random arrangement of atoms. When the full lattice symmetry was included in the calculations, it was found that penetration of the energetic ions depended strongly on the crystallographic orientation seen by the incident particles. This result was extremely important for experiments involving radiation effects, ion scattering, and ion implantation. The theoretical prediction was first confirmed experimentally at AECL, Chalk River, Canada, and many groups throughout the world quickly established research programs to study and utilize the channeling effect. At ORNL, the first channeling research was a joint project involving Tom Noggle of the Solid State Division, Sheldon Datz of the Chemistry Division, Charlie Moak of the Physics Division, and Hans Lutz, a guest scientist in the Solid State Division from Germany; they were soon joined by Bill Appleton of the Solid State Division. The research was performed on the Physics Division tandem accelerator, and a concentrated effort was devoted to energy-loss measurements, charge analysis, scattering patterns, and radiation damage studies to gain insight into the interaction of radiation with solids. This was a highly successful program in providing a good understanding of the channeling process, and much of the success was attributed to the excellent thin-film specimens prepared by Noggle and to the close theoretical interactions provided by Robinson, Oen, and John Barrett.

Another noteworthy achievement during this period was the development of techniques by Mark Wittels, Fred Young, Jr., Frank Sherrill, Bob Nicklow, and Tom Baldwin for obtaining topographs of highly perfect metal crystals using the anomalous Borrmann transmission of X rays. These techniques, which included the use of stereo pairs, were used to characterize the perfection of thick copper crystals and to analyze in detail the introduction, arrangement, and annealing of radiation-produced defects. Similar investigations were also performed on highly perfect thick crystals of niobium, silicon, and germanium.

Much progress was made during the 1960s in establishing an understanding of the defects produced in alkali halide crystals by nuclear radiation. Many investigations were performed to provide information on the defect production process, effects of impurities on radiation-produced defects, defect motion in crystals, and processes for annealing defects. A large fraction of the investigations involved various types of optical measurements, but the experiments also included radiolysis, flow stress, radiation hardening, and magnetic resonance. Because ionization damage is an important factor in defect production in these materials, extensive use of several gamma ray sources and the 2-MeV Van de Graaff accelerator of the Chemistry Division was made in this research. The ability of the Research Materials Program to supply ultrahigh purity potassium chloride (KCl) crystals was an important factor for doing experiments with the proper control of impurities. Therefore, much attention was placed on radiation-defect production and annihilation in KCl. Experimental investigators during this period included Jim Crawford, Jr., Ed Sonder, Yok Chen, Marvin Abraham, Bill Sibley, Chuck Butler, and Dick Murray, and their experiments were supported and guided by the theoretical work of Dick Wood. The results of these investigations established important background information for extending the investigations to more complex and practical materials, such as MgO.

In the late 1960s, the HFIR became operational, and state-of-the-art neutron scattering instruments were installed at this reactor. These instruments included very flexible completely automatic triple-axis spectrometers that could be used with either polarized or unpolarized neutrons and a unique magnetically pulsed time-of-flight spectrometer, which could operate in any type of autocorrelation mode. These new instruments and the very high intensity neutron beams from the HFIR allowed experiments to be performed that were previously not possible. Of particular importance were determinations of the magnetic moment distribution and spin-wave dispersion in a variety of magnetic materials, which helped to explain some very unusual magnetic properties. Lattice dynamics investigations were also important because they provided insight into the nature of interatomic and intermolecular forces in ionic, covalent, and metallic crystals. A very important new technique was developed during this period by Ralph Moon, Tormod Riste (Solid State Division guest scientist from Norway), and Wally Koehler. This technique, which is known as neutron polarization analysis, has many applications to a variety of problems that cannot be studied definitively in any other way. Unfortunately, it requires extremely high neutron intensities, and full exploitation of the technique has not been possible even at the HFIR.

The Third Ten Years (1972–1982): *An Expanded Research Agenda*

The third decade of the Solid State Division, 1972–1982, was a period of extreme significance for the division. Very important programmatic changes were made in the types of investigations that could be pursued, and these changes helped to shape the division into the very broad solid state research organization that exists today. It was also a period of some outstanding research.

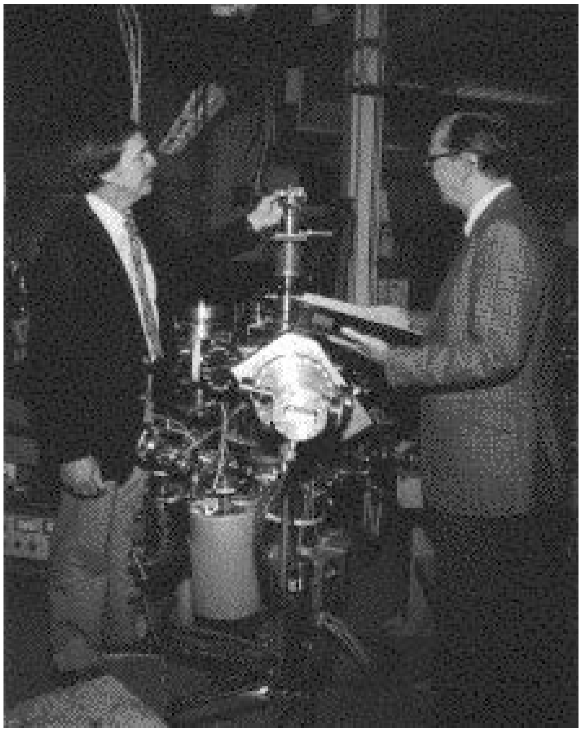
Very early in this period, in June 1972, there was a change in the division organization. Doug Billington was appointed a Senior Advisor to Alvin Weinberg, the Laboratory Director, and Mike Wilkinson became Solid State Division Director with Fred Young, Jr., as Associate Division Director. There were five sections of the division, and all of them were engaged almost entirely in fundamental research. These were the Theory Section under Dick Wood, the Radiation in Metals Section under Tom Noggle, the Crystal Physics Section under Wally Koehler, the Crystal Defects and Surfaces Section under Les Jenkins, and the Research Materials Section under John Cleland. Frank Kocur remained the division Administrative Assistant.

When this decade began, nearly all support for research in the Solid State Division came from the Materials Sciences Program of the AEC Division of Physical Research. Because of budget shortfalls within this AEC program, there were insufficient funds to support the entire division staff, and a significant staff reduction was necessary. Research programs in the division were consolidated, and other jobs were found both within and outside ORNL for the staff members who became surplus. It was then that the division began to perform a modest amount of research for organizations other than its major sponsor, and this practice continues to the present. Support from the Materials Sciences Program started to increase in 1974, the year in which the AEC was replaced by the Energy Research and Development Administration (ERDA). Whereas the AEC mission had involved the development of only fission and fusion reactors, the ERDA mission involved the development of all types of advanced energy systems. The technologies associated with these advanced systems were materials limited and required a wide variety of materials research. Research support by ERDA was much broader than that under AEC, and this broad support continued when the Department of Energy (DOE) was established to replace ERDA in 1977. The principal sponsor under DOE is the Division of Materials Sciences of the Office of Basic Energy Sciences, which comes under the Office of Energy Research.

Under ERDA and DOE, the Solid State Division was able to enter many new areas of materials research associated with the new nonnuclear energy technologies. By the late 1970s over half of the division's programs were closely related to these new technologies. A few existing programs, such as the superconductivity research of Stan Sekula and Bob Kernohan, were expanded, but the new emphasis resulted mostly in entirely new programs. There was some increase in support, but much of the new research resulted from a redirection of other programs, bringing about a decrease in the amount of research associated with radiation

Ion Implantation

Oak Ridge National Laboratory and the Solid State Division have played a prominent role in ion implantation research and development over the past four decades. Beginning with the birth of ion beam technology in the large-scale electromagnetic separation of isotopes in the 1940s, ORNL has made major advances in ion source technology and in the use of ion beams for materials processing. The Solid State Division has contributed significantly to the fundamental understanding of the interaction of ion beams with solids and to the development of advanced characterization and processing techniques using ion beams. This began in earnest in the early 1960s with the theoretical discovery of the ion channeling effect by Dean Oen and Mark Robinson. The channeling effect is widely used in ion beam analysis of materials and is a critical phenomenon in ion implantation. The importance of the crystal lattice in the transport of ions in solids and in radiation damage phenomena led to the extensive development by Robinson of the binary collision code MARLOW, which continues to be the standard for the simulation of energetic ion beams in crystalline matter.


Bill Appleton, now ORNL Associate Director for Advanced Materials, Physical, and Neutron Sciences, and Mark Robinson adjust a target manipulator at the SMAC facility.

In the early 1970s, Bill Appleton initiated an experimental effort in ion beam materials research in the Solid State Division. The program originally focused on the channeling effect and the physics of energetic ions in solids, but it was soon broadened to include ion implantation. Research on the ion beam modification of semiconductors, metals, insulators, and ceramics resulted in an enthusiastic following of collaborators from universities and industries which quickly overwhelmed Appleton’s group. As a result, the Surface Modification and Characterization (SMAC) Research Center was formed in 1980, and expansion of the ion implantation facilities was initiated. The Center now includes four accelerators with unique capabilities for high-current, high-energy implantation and low-energy ion beam deposition. The Center serves more than 100 scientists from universities, industries, and national laboratories in cooperative research projects each year. The Center also provides unique ion beam facilities for research throughout the division in areas such as superconductivity, thin-film electrolytes, quasicrystals, surface structure and chemistry, and the amorphous state.

Over the past decade, the Solid State Division has published more than 500 papers on ion beam analysis and processing of materials. New developments and advances have been made in the ion implantation of a wide range of materials for electronic, optical, and tribological applications. A new technique for deposition of thin films and isotopically pure heterostructures was developed using decelerated ion beams. An ion implantation technique for fabricating optical waveguides with sharp index changes was demonstrated. Ion implantation technology for increased wear resistance of artificial prostheses was developed and transferred to industry. This technology, which dramatically improves the corrosive wear performance of surgical alloys in prosthetic implants, is now being used on approximately 50% of the artificial hips and knees sold in the United States. The potential savings from the prevention of reworks of failed joints is $100M per year. Recently, the ion beam synthesis of complex nanocrystals in the near-surface region of materials has been demonstrated by Woody White and coworkers, and fundamental knowledge of defect physics is leading to exciting new approaches to control the morphology and properties of ion-implanted materials and layers.

effects in materials. It should be mentioned that under ERDA and DOE, there was increased emphasis on the need to perform mission-oriented research, and research programs had to be justified accordingly. Of course, this justification was obvious in such areas as superconductivity, high-temperature materials, surface science and catalysis, photovoltaic processes, superionic conductivity, and metal fracture.

Another significant change for the division occurred in 1975, when the Isotopes Research Materials Laboratory (IRML) under the direction of Ed Kobisk was transferred into the division from the ORNL Isotopes Division after it was dissolved. The primary task of IRML was to prepare special chemical and physical forms of separated, high-purity isotopes. Research samples using nearly all stable isotopes and many radioisotopes, especially of the actinide elements, were made to customer specifications in support of research programs throughout the world. Research and development activities of this organization were funded by the Division of Materials Sciences of ERDA (later DOE), and the rest of the work was supported directly from sales of materials and services. The technical functions covered a wide variety of activities, such as separations systems for tritium, inorganic chemical conversions, fixation of high-level radioactive wastes in cermet form, radioisotope source preparations, purifications, single-crystal and epitaxial growth studies, and the development of analytical techniques. Very talented scientists and technicians worked in this program, performing complex operations with sometimes limited facilities. On one evening during this period, Herman Postma, the Laboratory Director, had to go home without his shoes because of a visit to one of the IRML laboratories. Coincident with his visit was a minor leak in radioactivity from a defective dry box. Although good interactions existed between many Solid State Division programs and IRML, the latter functioned mostly as a separate organization. In 1982, IRML was transferred into the Chemical Technology Division, which was considered a more appropriate organization for the type of work that was performed. Members of IRML at this time included Kobisk, Harold Adair, Anne Caylor, Dan Ramey, Charlie Culpepper, Joe Dailey, Tom Quinby, Kermit Campbell, Bill Early, Bill Grisham, Paul Kuehn, and Joni Lovegrove.

As a result of the interest and importance of ion channeling research, a new combined accelerator and surface analysis facility was developed for the Solid State Division by Bill Appleton. This facility was originally designated the positive heavy-ion, scattering, implantation, channeling, and surface (PHISICS) facility, and it was located in part of the fan house for the ORGR. With major expansions that were made in later years, this facility became the premier Surface Modification and Characterization (SMAC) facility that exists today. The PHISICS facility permitted the integration of a wide variety of ion beams obtained from three accelerators (0.05–10-kV ion gun, 10–200-kV high-current ion implantation accelerator, and 2.5-MV Van de Graaff ion scattering analysis accelerator) into a common multipurpose ultrahigh vacuum analysis chamber. These instruments provided excellent research capabilities for many types of investigations.

This decade of the division undoubtedly will be remembered for the changes in research emphasis that occurred, but it will also be remembered for several outstanding research investigations. Whereas the division had previously gained national and international recognition for research in such areas as radiation effects in metals, defects

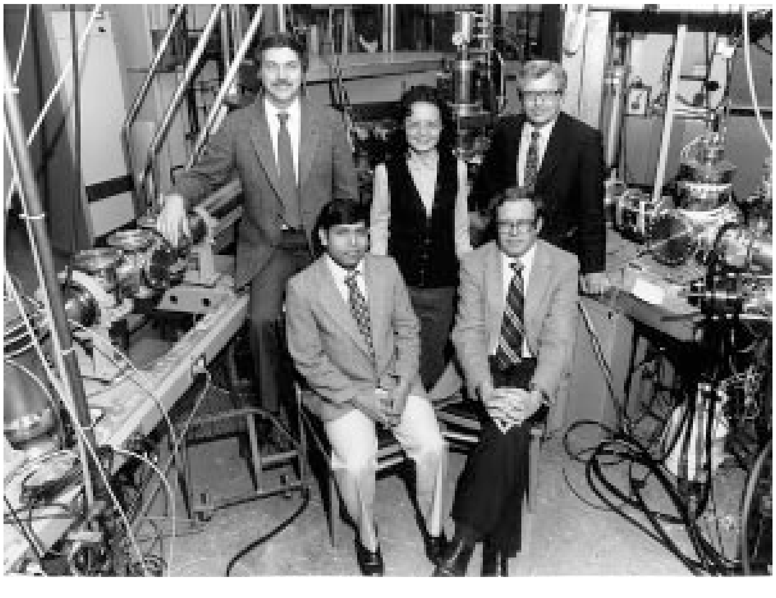
Laser Processing

The earliest uses of lasers in the Solid State Division were limited to applications that required intense well-collimated light sources (e.g., infrared and Raman scattering, ellipsometry, and alignment equipment). This changed dramatically in 1977 and 1978 when Rosa Young, following the pioneering work of Russian scientists, demonstrated that pulsed ruby lasers could be used to anneal the lattice damage and electrically activate dopant ions implanted into silicon. Young, whose work grew out of research on improved methods of making solar cells, was soon joined in the research by Woody White, Greg Clark, and Jagdish Narayan. The earliest work was followed by an intensive effort to explore the fundamental physics underlying pulsed-laser annealing (PLA). The nonequilibrium nature of the process was studied in an extensive set of experiments on dopant segregation in silicon carried out by White, Syd Wilson, Bill Appleton, and Fred Young. Their results extended earlier Russian results and showed that the equilibrium segregation coefficient could be greatly exceeded at the high recrystallization velocities (~10 m/s) obtained during PLA.

Extensive theoretical analysis by Dick Wood and collaborators at ORNL led to the thermal melting model of PLA. This model was hotly disputed by groups at IBM and elsewhere who advocated the "new state of matter" ideas proposed by the IBM group. This controversy, which raged for several years, was eventually resolved in favor of the thermal melting model by research at ORNL, Bell Laboratories, Harvard, and numerous other institutions. Notable among many contributions was the work of Doug Lowndes and Jay Jellison on time-resolved reflectivity and transmissivity during PLA and Ben Larson and collaborators on time-resolved x-ray diffraction.

Throughout this period, laser annealing was being applied to the fabrication of solar cells by Rosa Young, Wood, Jellison, and Russ Westbrook. Eventually, this work led to fabrication of cells with efficiencies of nearly 20% and demonstrated a new type of surface passivation that could only be obtained by pulsed-laser processing. The pulsed-laser annealing work in the Solid State Division eventually grew to include almost every research group in the division and many groups in other divisions at ORNL.

As the activity in laser annealing began to reach the level of a mature field, interest in a new area of laser processing of materials arose when it was found that laser ablation was an excellent way to deposit thin films of various materials, particularly the high-T_c copper oxide-based superconductors that had been discovered in 1986. Building on the experience from laser annealing, Lowndes, Dave Geohegan, Doug Mashburn, and David Norton were able to bring ORNL quickly into a leadership position in several areas of laser ablation (including the study of superconducting superlattices). Laser ablation research continues to the present, encompassing both the use of the process for thin-film semiconductor and superconductor deposition and the study of the fundamental physics underlying it.



Bill Appleton, Rosa Young, Dick Wood (standing), Jagdish Narayan, and Woody White (seated) won the 1981 DOE Division of Materials Sciences Research Competition Award for Outstanding Sustained Research for their pioneering studies in laser annealing.

in ionic crystals, and neutron scattering, it was during this period that its reputation spread to many other areas of the solid state sciences, and the division became recognized for the breadth of its research. A very important reason for the outstanding research that developed was the close interaction among research groups within the division. Many different techniques could be applied quickly to any important problem under investigation, there was close cooperation between theorists and experimentalists, and high-quality research specimens were produced through the Research Materials Program. The availability of funds from the ORNL Exploratory Studies Program for important new investigations also helped immensely in moving into new research areas.

The work on ion implantation and laser annealing of semiconductors is certainly one of the most outstanding achievements during this period, and it emphasizes the close interactions among scientists in the division. This work had its origin in research on photovoltaic conversion of solar energy through attempts to prepare better photovoltaic materials by ion implanting dopants into silicon. Serious problems occurred in such materials, because the lattice damage introduced by ion implantation could not be removed satisfactorily by furnace annealing techniques. Based on information in the Russian literature that was located through the Research Materials Information Center, Rosa Young decided that annealing with a powerful laser might overcome these difficulties. Using a large ruby laser in the Fusion Energy Division, Young, Woody White, Greg Clark (Solid State Division guest scientist from Australia), Steve Cramer (Health and Safety Research Division), Masanori Murakami (Fusion Energy Division), and Phil King (Fusion Energy Division) found that pulsed-laser annealing completely annealed the damaged layers without causing problems in the semiconductor properties. In fact, it was quickly learned that ion implantation followed by pulsed-laser annealing was a superb technique for preparing various types of new semiconductor materials that had not existed previously. In particular, materials could be prepared with dopant concentrations orders of magnitude higher than existing equilibrium solubility limits. To exploit this technique fully, an understanding of the physical processes that took place during laser annealing was required, and an extensive effort was initiated within the division. This work was led by Young, Dick Wood, White, Jagdish Narayan, and Bill Appleton, with many other division members participating in some phase of the research. Of course, many other laboratories throughout the world also became involved in this very important work.

Most of the early understanding of pulsed-laser annealing processes resulted from experimental and theoretical work performed by Solid State Division scientists and others at ORNL. An important controversy developed within the scientific community concerning the thermal melting model of Dick Wood, which proposed that the silicon surface melted and then recrystallized. This controversy led to a beautiful experiment by Ben Larson, together with Tom Noggle, Woody White, and Dennis Mills (Cornell University), in which time-resolved x-ray diffraction measurements with nanosecond resolution were performed on silicon during pulsed-laser annealing. This experiment was performed with single pulses from the Cornell High-Energy Synchrotron Source (CHESS), and these real-time measurements were the first structural measurements with nanosecond resolution that were performed with X rays. They represented three orders of magnitude better time resolution than

Surface Physics

Surface physics research in the Solid State Division is an outgrowth of a 1960’s program on radiation damage and chemical properties of metal surfaces which focused on using both optical (real space) and diffraction (reciprocal space) techniques to investigate the termination of bulk defects with surfaces. Modern-day surface science was just beginning to take root during this period, and a new program, directed by Les Jenkins, was established to determine the physical and chemical properties of surfaces at the atomic scale.

An initial focus of this program was on the determination of surface structure using the technique of low-energy electron diffraction. It was during this period that John Noonan and Harold Davis established a combined experimental and theoretical effort determining the surface structure of metals with (unprecedented) precision. Their research, starting with Cu(110), showed that surface relaxation was a natural consequence of bulk truncation and confirmed the emerging concept of multilayer relaxation at surfaces. During this same time, the first quantitative determination of excess surface density resulting from reconstruction [Au(100)] was determined using ion scattering, in conjunction with scientists from what was to become the Surface Modification and Characterization facility.

Research on the electronic structure of laser-annealed surfaces led to the utilization of unique capabilities of synchrotron radiation by David Zehner and Woody White at the Tantalus storage ring at the University of Wisconsin with Dean Eastman from IBM. During this period, Zehner also initiated a collaborative research program using synchrotron radiation with Ward Plummer at the University of Pennsylvania leading to the eventual formation of a participating research team at the National Synchrotron Light Source at Brookhaven National Laboratory. The initial research at this facility focused on determining the electronic structure of alloys, with a particular emphasis on high-temperature materials. The unique instrumetation demands of this research, a consequence of surface reactivity, led to the establishment of an additional collaboration with scientists from the University of Erlangen in Germany.

The importance of understanding high-temperature phase transitions at surfaces led to development of x-ray surface scattering techniques in the late 1980s making use of exceptional momentum resolution and direct data interpretation. Initial collaborations with scientists from BNL and MIT emphasized synchrotron x-ray investigations of surface phase transitions and the high-temperature behavior of Au and Pt surfaces. Later Art Baddorf used this technique to expand his research on the anharmonicity of Cu surfaces. Future research using this technique will be performed at the Advanced Photon Source at the Argonne National Laboratory as part of the Complex Materials Collaborative Access Team.

In 1992, the surface program expanded significantly with the appointment of Ward Plummer as an ORNL / UT Distinguished Scientist. Plummer’s group of students and postdocs effectively doubled the size of the surface effort. It was also at this time that research interest in thin-film growth and expitaxy was expanding. To enhance this effort, John Wendelken acquired a scanning tunneling microscope (STM) making it possible to obtain images of atoms in the outermost layer and, therefore, providing real space images (a manager’s delight). This instrument, coupled with Plummer’s newly acquired variable-temperature STM, resulted in a significant expansion of this new program. In addition to atomic imaging, these two instruments make it possible to perform nanofabrication (writing) and local electronic characterization. These new capabilities, in combination with a strong presence at third-generation synchrotrons, provide a unique opportunity for further advancing the understanding of surface properties at the atomic scale.

David Zehner, Joe Carpinelli, and Ward Plummer (l to r) examine the JEOL STM used to write the ORNL logo shown in the inset. At this scale (400 × 800 Å^2), 15 complete copies of the *Encyclopaedia Britannica* could be written on the head of a pin. The image was provided by Carpinelli, winner of the 1996 Nottingham Prize (Physical Electronics Conference).

previously achieved in x-ray diffraction experiments, providing the first real-time information on the pulsed-laser annealing process. The high temperatures and surface melting inferred from these measurements directly supported Wood's thermal melting model. Moreover, the depth resolution of temperature profiles provided the first opportunity for detailed evaluation of theoretical models for energy flow and crystal growth under such transient conditions.

It was during this 10-year period that a very strong program in surface science and catalysis was established in the Solid State Division by Les Jenkins and David Zehner. Other experimentalists in the program included John Noonan and John Wendelken, with Gary Ownby providing technical support. There were also strong theoretical interactions, particularly with Harold Davis. In addition to research at ORNL, a cooperative program was established with the University of Pennsylvania, utilizing a beam port at the National Synchrotron Light Source (NSLS) at BNL. Of special significance during this period was the research of Noonan and Davis, which developed low-energy electron diffraction (LEED) techniques for determining surface crystallography to an accuracy previously not possible. Their research concerned both the procedures used to collect data and the techniques used to extract the desired surface structure information by theoretical analysis of the data. Noonan and Davis were able to determine interlayer spacings in the near-surface region to a precision better than 0.01 Å. The measurements showed that surface termination can cause several atomic planes at metallic surfaces to undergo measurable relaxation away from their positions in the bulk crystals. Such knowledge of surface-atom positions is essential in studying surface-related processes, such as catalysis.

Very significant information on the mechanisms of fracture was obtained during this period in a program directed by Mike Ohr, which included Shigeki Kobayashi, S.-J. Chang (Engineering Technology Division), Joe Horton, and Troy Estes. This work involved direct observations in the electron microscope of crack propagation and the dislocation behavior at the crack tip during in situ tensile deformation. These experiments, which probed the fundamental aspects of fracture phenomena, showed that a dislocation-free zone exists between the crack tip and the linear pileup of dislocations in the plastic zone. Direct observations of crack-tip blunting by edge dislocations, of the formation of plastic zones ahead of crack tips, and of dislocation motion near crack tips during stress cycling were made. These experiments made major contributions to a theoretical understanding linking the microscopic theory of fracture with macroscopic fracture mechanics.

A thorough investigation under John Bates was also made during this period to determine the processes for fast-ion conduction in the β-alumina and β”-alumina systems, which have application in high-energy-density batteries. Experimental research, which included Raman scattering, infrared reflectivity, emissivity spectra, ionic conductivity, and neutron diffraction, was carried out by Bates, Nancy Dudney, Herb Engstrom, Takugi Kaneda, Bill Brundage, Roger Frech (University of Oklahoma), and George Brown (ORNL Chemistry Division), and accompanying theoretical calculations were made by Jim Wang. This research resulted in models to explain the conductivity in the two systems including the conductivity anomalies in the β-alumina system. Studies on the thermodynamics and kinetics of the reactions of these materials with water vapor and carbon dioxide provided critical information for predicting the dete-

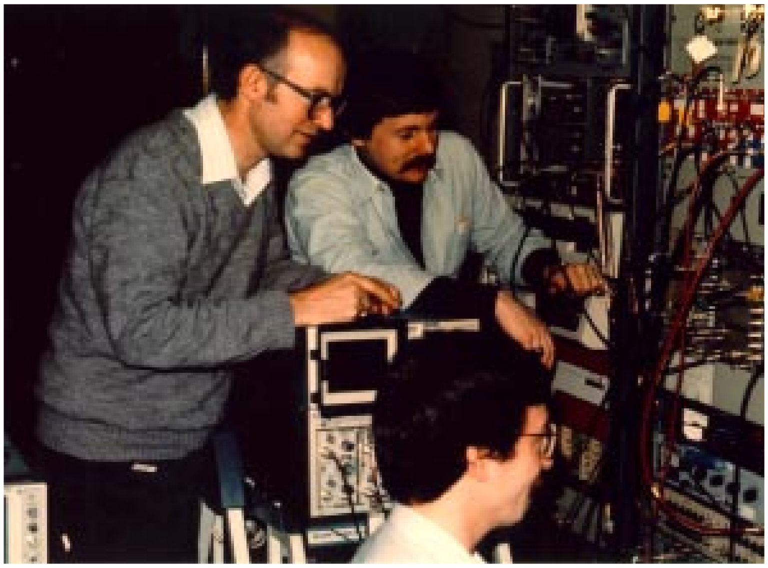
Synchrotron X-Ray Research

One of the most important developments in x-ray diffraction in recent years has been the availability of intense, highly collimated x-ray beams from synchrotron x-ray sources. The Cornell High Energy Synchrotron Source (CHESS) and the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory provide x-ray beams with 4–6 orders of magnitude higher intensity than laboratory generators, and Solid State Division scientists are collaborating with other institutions on the construction of beam lines (UNI-CAT and CM-CAT) at the third generation Advanced Photon Source (APS) synchrotron facility. When the APS becomes operational in 1996, these new (undulator) beam lines will provide ~20 times higher flux and 3–5 orders of magnitude higher brilliance than bend magnet beam lines at the NSLS.

The first Solid State Division synchrotron x-ray experiments were performed at CHESS in 1981 by Ben Larson, Woody White, and Tom Noggle. They utilized the sub-nanosecond x-ray pulses and the high intensity of CHESS to perform nanosecond resolution x-ray diffraction measurements of silicon during ~25-ns laser pulses. These initial nanosecond-resolution x-ray diffraction measurements demonstrated that silicon melted thermally during the pulses and helped resolve a controversy regarding the mechanism of pulsed-laser annealing. This work was extended to measurements of orientation-dependent undercooling at the liquid-solid interface during regrowth of the melted layer.

The first quantitative measurements of phason strain in quasicrystals were made possible by the use of synchrotron X rays at the NSLS. In 1986, John Budai, Mike Aziz, and collaborators used the high intensity of the NSLS to perform diffraction measurements on aligned quasicrystals that were formed in thin surface layers of Mn-implanted Al single crystals. Dave Zehner established a highly productive surface diffraction collaboration with Brookhaven National Laboratory and MIT in the late 1980s, and Art Baddorf and Ward Plummer extended surface investigations to collaborations with Exxon Research in the early 1990s. This work led to comprehensive temperature-dependent x-ray investigations of surface reconstructions, surface structure transformations, and surface anharmonicity in transition metals and alloys. In addition to the above-mentioned nanosecond-resolution measurements, the pulsed time-structure of synchrotron radiation has provided a mechanism for generating highly collimated Mössbauer resonant x-ray beams. As demonstrated by Jon Tischler and Ben Larson, time-slice collection of the delayed Mössbauer resonant Bragg scattering from a Mössbauer-enriched monochromator yields a high angular-resolution Mössbauer technique that is complementary to conventional Mössbauer scattering spectroscopy for the separation of elastic and inelastic x-ray scattering from nonresonant samples.

The 3–5 orders of magnitude increase in brilliance of the APS will undoubtedly have a significant impact on the direction of research in the Solid State Division. Presently, in situ, time-resolved synchrotron x-ray diffraction measurements are being integrated with pulsed-laser deposition expertise (in the group of Doug Lowndes) to initiate nonequilibrium pulsed growth research using the APS. In addition, the Solid State Division and Metals and Ceramics Division x-ray groups have begun a joint collaboration involving micron and submicron resolution x-ray measurements using the APS in combination with theoretical simulations of the dynamics of materials under physical and thermodynamic stresses. This research will utilize the unique characteristics of the APS to investigate materials on length scales of scientific and technological interest.

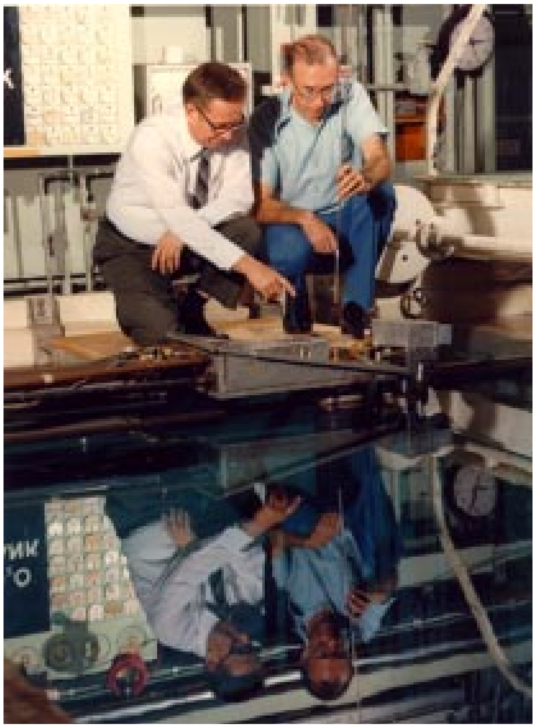


Ben Larson, Denny Mills, and Jon Tischler (bottom) adjust the timing circuitry during nanosecond-resolution time-resolved x-ray measurements of rapid melting and regrowth in semiconductors at CHESS. Larson received the 1985 Bertram Warren Diffraction Physics Award for this research.

rioration of the electrolytes during materials processing, storage, and device assembly and for establishing methods to minimize this deterioration.

An important investigation associated with the fusion energy program was performed in the early 1980s by Ralph Coltman, Jr., and Charlie Klabunde, using the Low-Temperature Irradiation Facility (LTIF) in the Bulk Shielding Reactor. The magneto-resistivity of copper was studied under conditions of irradiation that simulated conditions expected for copper as the stabilizer in superconducting magnets of the fusion Experimental Power Reactor. These experiments showed that the copper stabilizer would have a lifetime of only about ten percent of the projected reactor lifetimes and that significant changes were necessary in the design of fusion reactors. Either additional shielding was needed to protect the magnets or larger stabilizers were required to accommodate a higher neutron fluence. Other important studies for the fusion energy program during this period involved experiments by Bill Appleton, Jim Roberto, Ray Zuhr, O. E. Schow, Woody White, and Steve Withrow, with technical support by Jim Moore, to investigate the types of impurities released into the plasma in tokamaks as a result of ions, atoms, and electromagnetic radiation from the plasma striking the interior surfaces of the plasma containment structure. Such impurities drastically alter the plasma density, temperature, and stability through radiative losses. Experiments were performed with deposition-probe techniques at the ORNL ISX tokamak, and additional research was performed at the Solid State Division PHISICS facility. Of particular importance was the development of laser-induced fluorescence as a technique for determining the density and velocity distribution of impurities in the plasma edge.

Throughout this period, there were significant and exciting neutron scattering investigations on a wide variety of materials using equipment at both the ORR and HFIR. Such investigations included the magnetic properties of rare-earth metals, alloys, and compounds; the condensate state in liquid helium; fluxoid lattices in superconductors; lattice dynamical properties of materials; characterization of oil-bearing shales; water dynamics in biological systems; charge density waves in α-uranium; and mixed-valence systems. In addition to these outstanding research accomplishments, this period will be remembered for a significant change in the users and sponsors of the neutron scattering facilities. When the Ames Laboratory Research Reactor was decommissioned in 1978, three Ames Laboratory neutron scattering instruments were installed at beam ports of the ORR; this equipment and the


Ralph Coltman and Charlie Klabunde are shown at the Bulk Shielding Reactor which was used for the Low-Temperature Irradiation Facility during the 1980s.

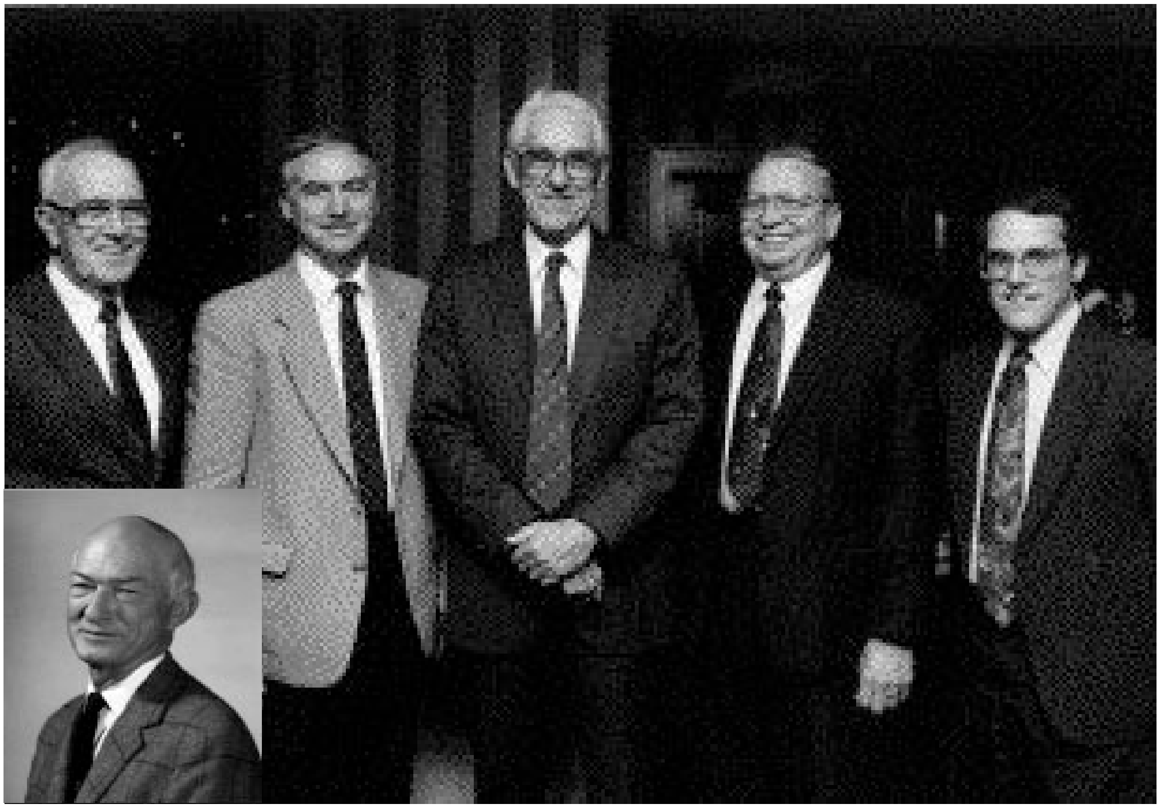
ORNL instruments at the ORR and HFIR were made available to scientists of both laboratories. In January 1978, a National Center for Small-Angle Scattering Research (NCSASR) was established at ORNL under an interagency agreement between the National Science Foundation (NSF) and DOE. This center was established and operated strictly for the benefit of users and involved the operation of small-angle x-ray and neutron facilities, which were already in existence at ORNL, and the construction and operation with NSF funds of a very sophisticated small-angle neutron scattering (SANS) facility at the HFIR. The NCSASR was administered through the Solid State Division; Wally Koehler was the first director, and George Wignall became director in 1985. In June 1980, negotiations were initiated between appropriate Japanese organizations and DOE to establish a Joint U.S.–Japan Cooperative Program in Neutron Scattering. This program was developed as part of the U.S.–Japan Agreement on Cooperation in Research and Development in Science and Technology, which had been signed by representatives of the two governments on May 1, 1980. The cooperative program started formal operation in 1982 and involved the construction of new instruments at the HFIR using Japanese funds, in return for access to HFIR neutron scattering facilities by Japanese scientists. A similar program was initiated simultaneously at the High Flux Beam Reactor (HFBR) at BNL, and the programs at both laboratories quickly became very successful.

The Modern Era (1982–1995): *New Capabilities and Partnerships*

During the past 13 years, the research of the Solid State Division has continued to flourish and to become more diverse. Investigations of the effects of radiation on materials, which had been the primary task of the division when it was formed, decreased significantly during this period and now constitute a very small part of the total research program. However, research on defects remains an important part of the division's activities, because knowledge of the defect solid state is essential in understanding many of the physical properties of materials.

Outstanding research was performed throughout this 13-year period even though there were major distractions because of organizational changes and budget difficulties. There was a change in the contractor to operate ORNL, a change in the ORNL Director, and a number of changes in Solid State Division directors during this period. In 1984 Martin Marietta Energy Systems replaced the Nuclear Division of Union Carbide Corporation as the operator of ORNL, and in 1989 Alvin Trivelpiece replaced Herman Postma as Director of ORNL, after about a year in which Alex Zucker served as Acting Laboratory Director. Moreover, after about 35 years with only two Solid State Division directors, several changes were made during this period. On April 1, 1986, Mike Wilkinson stepped down from this position to become a Senior Advisor, and Bill Appleton became the Solid State Division Director with Fred Young, Jr., as Associate Division Director. The Section Heads were John Cooke, Ralph Moon, Lynn Boatner, and Jim Roberto. Phyllis Green, who had replaced Frank Kocur as division Administrative Assistant when he retired in 1981, continued in this position. In February 1988, Appleton was appointed Acting Associate Director of ORNL for Physical Sciences, and Fred Young, Jr., was appointed Acting Solid State Division Director; both of these appointments were made permanent about a year later in March 1989. With Young as Division Director, Jim Roberto was appointed Associate Division Director; and David Zehner became a Section Head. Young retired from the Laboratory in December 1990, and Roberto became the Division Director. Ben Larson also became a Section Head at this time. In October 1992, Appleton was appointed Acting Associate Director for the Advanced Neutron Source Project, and Roberto was appointed Acting Associate Director of ORNL for Physical Sciences and Advanced Materials. Ralph Moon became Acting Solid State Division Director, and Herb Mook became Head of the Neutron Scattering Section. These appointments lasted for one year, and in October 1993, Roberto returned to his position as Director of the division and Moon was named Associate Division Director. Mook remained as Head of the Neutron Scattering Section.

It was during this period that the division assumed a leadership role in the development of the Materials Research Society (MRS) and the Division of Materials Physics (DMP) of the American Physical Society. Woody White served as MRS President in 1984 followed by Jim Roberto in 1991. Fred Young played a pivotal role in the establishment of DMP, and this division was later led by Bill Appleton and Roberto.



The Solid State Division has had six directors since its inception in 1950. Shown (l to r) are Fred Young (1988–1990), Bill Appleton (1986–1988), Ralph Moon (1992–1993), Mike Wilkinson (1972–1986), and Jim Roberto (1990–1992 and 1993 to present). Doug Billington, the first director of the division (1950–1972), is shown in the inset.

Division members also held elective office in the APS Division of Condensed Matter Physics, the American Vacuum Society, and the American Ceramic Society.

Throughout the latter part of this decade, the Solid State Division experienced budget difficulties, which caused a reduction of approximately 15 percent in staff. Efforts by Appleton, Young, Roberto, Moon, and others helped to place division members on other assignments, both permanent and temporary, and to find additional support for programs, both within and outside ORNL, avoiding the need for involuntary terminations. These budget problems were caused by requirements for DOE laboratories to put more emphasis on environmental safety and health issues, including environmental restoration and waste management, even though appropriate budget increases could not be obtained for such projects. Because the Director of the Office of Energy Research serves as the “landlord” for ORNL, Laboratory programs under this office were the ones hardest hit by the new emphasis; of course, most of the Solid State Division programs were included in that group.

In addition to causing budget difficulties, the new emphasis on environmental safety and health also required a considerable amount of time and effort by research staff. There were many different audits, including an audit of ORNL by a DOE “Tiger Team” in the fall of 1990; these audits required many hours of preparation, of report writing, and of correcting deficiencies that were discovered. It should be mentioned that the attention to safety was not new for the Solid State Division. There has always been a significant safety program in the division, which was administered by excellent safety officers and radiation control officers, such as Jim Howe, Ralph Coltman, Stan Sekula, Steve Withrow, John Wendelken, Mike Galloway, Steve Spooner, Ray Child, and Jaime Fernandez-Baca. Division members have been very safety conscious, as evidenced by the fact that in over 45 years, in which the Physics of Solids Institute and the Solid State Division have existed, there has never been a lost-time accident by a member of this organization. This is an outstanding record, especially for an organization engaged in state-of-the-art research, and division members are very proud of it. The biggest difference in the safety program of the division today and that of earlier years is not in safety awareness, but in formalization, requiring much more extensive documentation.

During the past few years major program modifications were undertaken by division members in efforts to establish closer interactions with industrial organizations and to promote better technology transfer. National initiatives in the areas of high-temperature superconductivity and advanced semiconductor processing were established, and the Solid State Division became involved in both of them. ORNL was asked by DOE to be a lead laboratory in a cooperative program on high-transition-temperature superconducting materials, involving ORNL, LBL, and LANL, and the ORNL work was coordinated through the division. DOE also formed Superconductivity Pilot Centers (now known as the Superconductivity Technology Program), including one at ORNL, to promote collaborations in high-temperature superconductivity between national laboratories and industrial organizations. The division has become highly involved in research for the ORNL Superconductivity Technology Program, which has included cooperative projects with more than 20 high-technology industries. Dave Christen has served as Scientific Coordinator of the Superconductivity Technology Program since 1988. Major national concern also arose during this period concerning the waning international competitiveness of the U.S. semiconductor industry. This concern resulted in the formation of SEMATECH, a national multimillion dollar semiconductor industry cooperative venture, and the division established a program in advanced processing techniques for SEMATECH led by Lee Berry (Fusion Energy Division), Steve Gorbatkin, and Jim Roberto. Considerable work has also been initiated recently in the division through Cooperative Research and Development Agreements (CRADAs) with industry. The first CRADA involved the development of microbatteries and was started in 1992 with Eveready Battery Company. This research, directed by John Bates, used new techniques in rf magnetron sputtering, plasma polymerization, and evaporation to fabricate rechargeable thin-film batteries consisting of a lithium metal anode, amorphous inorganic electrolytes, and cathodes of a lithium intercalation compound. These batteries, which have record energy densities and can be fabricated to conformal shapes, hold significant promise for applications in electronics and medicine. Since 1992, 14 other CRADAs have been approved for division members.

The past decade was also characterized by additional emphasis in the division on the development and expansion of formalized users' programs, whereby scientists outside ORNL utilize unique equipment located at the Laboratory. Informal programs for collaborative research have always existed, but these formalized programs help to ensure that the facilities

Technology Transfer—From Basic Research to the Marketplace

The Solid State Division has a long history of the successful transfer of technology to the private sector. Much of this has been achieved informally through sustained research relationships throughout the scientific community. These relationships have included personnel exchanges, cooperative research, and shared use of unique division research facilities. These interactions bring more than 300 guest scientists who perform research in the division each year, with approximately 20% from industry. More recently, an increased fraction of the division research effort has involved cost-shared research with industry through Cooperative Research and Development Agreements (CRADAs), a formal mechanism for industry-laboratory cooperation established by Congress in 1989.

John Bates examines a thin-film lithium battery in the light of the glow discharge of a vacuum deposition chamber. Bates and his coworkers won an R&D 100 Award in 1996 for their research on thin-film batteries.

Although the creation of basic knowledge has been the primary objective of the Solid State Division, there are numerous products in the marketplace which owe their origin to division research programs. Two outstanding examples are neutron transmutation doped silicon and ion-implanted artificial prostheses. Neutron transmutation doping was developed in the division by John Cleland in the 1950s. This process allows large crystals of silicon to be uniformly doped with electrically active phosphorus by transmutation of some of the silicon atoms in a neutron flux. The resulting material has electrical properties particularly suitable for large power rectifiers. Neutron transmutation doping continues to be commercially important today, with more than 100 tons ($100M) of neutron transmutation doped silicon produced worldwide each year.

Ion implantation of surgical alloys to improve the wear resistance of artificial prostheses for hip and knee replacements was developed in the 1980s by Bill Appleton and Jim Williams in collaboration with the biomedical school at the University of Alabama at Birmingham. This process significantly extends the lifetime of certain artificial prostheses in human service. The technology is currently used on approximately one-half of the artificial hips and knees sold in the United States, representing $200M in annual sales. Many other Solid State Division research developments are finding their way into commercial products including phosphate glasses for glass-to-metal seals, multilayer coatings for neutron waveguides, and high-performance electron microscopes for Z-contrast scanning transmission electron microscopy. Since 1975, the division has won 12 R&D-100 awards, given by R&D Magazine for the 100 most technologically significant products developed each year. A list of these awards is given in Appendix B.

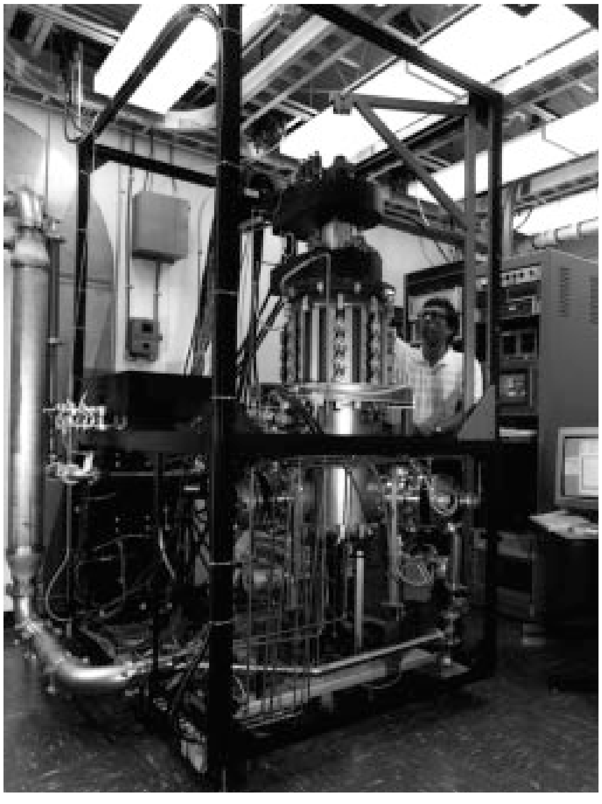
The implementation of CRADAs has substantially improved the technology transfer process by allowing the national laboratories to engage in cost-shared research with industry. The Solid State Division currently has 15 CRADAs with U.S. industry in thin-film battery technology, photovoltaic materials, optical materials, thermoelectric materials, varistor materials, crystal growth, plasma processing, semiconductor processing, and ion implantation. Although basic materials research remains the primary mission of the division, cooperative research with industry to develop and transfer related technology has become an additional focus of division activity.

are used for the best possible research. Of 11 officially designated user programs at ORNL in 1986, the Solid State Division was responsible for four—NCSASR, the Neutron Users' Program at HFIR, the SMAC Collaborative Research Center, and the Low-Temperature Neutron Irradiation Facility (LTNIF) at the BSR.

In addition to the formalized users' programs, members of the division have been involved in a number of other cooperative research arrangements. As stated in activities of the third decade, highly successful cooperative programs in neutron scattering were established with scientists from Ames Laboratory and Japan. Moreover, members of the division became involved in two participating research teams (PRT) at the NSLS at BNL. One PRT, with the University of Pennsylvania, operated a facility on the VUV ring to investigate the properties of surfaces, and the other PRT, which included scientists from ORNL and several universities, operated a very flexible diffractometer on the x-ray ring. The most recent collaboration of this type is the involvement of division members in collaborative access teams (CATs) at the Advanced Photon Source which is nearing completion at Argonne National Laboratory. Three types of instruments are being developed or planned in partnership with other ORNL divisions, several universities, industrial laboratories, and other government agencies.

Close research collaborations also have been established with The University of Tennessee as part of the ORNL/UT Distinguished Scientist Program. A strong collaboration in solid state theory research was initiated in 1985 with Jerry Mahan, who was the first professor appointed to this program. A similar close collaboration was formed in 1993 in surface physics research with Ward Plummer, also appointed an ORNL/UT Distinguished Scientist. Both professors and their associates spend about one-half time at ORNL, participating in the overall division research effort. The various collaborations not only provide stimulating interactions with many scientists outside ORNL, but they have contributed to a large increase in the number of graduate students, postdoctoral fellows, and guest scientists performing research in the division. Such appointments now are approximately equal to the number of staff members.

A devastating perturbation on various division research programs and on three of the four users' programs occurred with the shutdown of the ORNL research reactors in late 1986 and early 1987. The HFIR was shut down by ORNL management in November 1986 because of possible embrittlement



Steve Gorbatkin adjusts an electron cyclotron resonance plasma processing system jointly developed with SEMATECH for research on advanced etching of submicron semiconductor devices.

Materials Synthesis and Characterization

The long-standing commitment of the Solid State Division to research in the growth of high-quality single-crystal research specimens and the synthesis of novel materials is founded in the realization that world-class research in solid state science requires access to specialized and unique research specimens. For example, the development of techniques for the growth of dislocation-free copper single crystals and highly perfect crystals of other metals by Fred Young, Jr., was critical to many of the pioneering investigations of radiation-induced defects in metals which were carried out in the early days of the division. Other capabilities for the growth and purification of metal and alloy single crystals such as electron-beam float-zone methods were subsequently developed by Dick Reed with the assistance of Homer Harmon and Earl Bolling. The high-purity metal single crystals emerging from this effort were used extensively by SSD researchers in studies of the effects of neutron irradiation on the intrinsic properties of metals, and the reputation for purity and quality of these materials led to their being eagerly sought by scientists throughout the world. The Research Materials Information Center was established as a part of the division in 1963 under the direction of Tom Connolly. The center functioned for over 15 years providing information worldwide on the properties, preparation, and availability of ultrapure inorganic materials and single crystals. In more recent times, materials synthesis and characterization areas have expanded to studies of the structural properties of glasses and the amorphous state in conjunction with research leading to the development of new phosphate glasses for applications such as glass-to-metal seals, optical fibers, and lenses.

Examples of the division's research highlights in the field of crystal growth and materials synthesis include the development of neutron-transmutation doping of silicon; study of Marangoni convection effects in microgravity—Apollo-Soyuz Mission; growth of large MgO, CaO, and SrO crystals (R&D-100, 1975); development of ceramic-wire neutron-dosimetry materials (R&D-100, 1976); growth and characterization of beta-alumina solid electrolyte single crystals; use of stainless steel crystals to study welding (Jacquet-Lucas Award, 1988); development of "monazite" nuclear-waste-disposal ceramics (R&D-100, 1982); discovery of a new scintillator material for x-ray imaging; development of new types of highly stable phosphate glasses (R&D-100, 1985); development of new substrate materials for high-temperature superconductors (R&D-100, 1996); and development of stable electrolytes for thin-film microbatteries (R&D-100, 1996). The electrolyte research, led by John Bates, resulted in the development of thin-film rechargeable batteries of unprecedented performance.

Significant scientific benefits of access to nuclear research reactors have extended beyond radiation damage into other areas of solid state science such as crystal growth and materials characterization. In particular, with the advent of the ORNL High-Flux Isotope Reactor and the Transuranic Processing Facility, a wide variety of radioactive actinide isotopes became available in the late 1960s. These were timely developments for Marvin Abraham of SSD who had previously carried out the first magnetic resonance study of the actinide element curium at the Lawrence Berkeley Laboratory. Working with Cabell Finch and Wayne Clark, two crystal growers in the Metals and Ceramics Division, Abraham was able to establish a unique crystal-growth facility in ORNL's new Transuranic Research Laboratory (TRL). This group published the first research article to emanate from the TRL, a magnetic-resonance study of the actinide element curium doped as an impurity into single crystals of ThO_2 and CeO_2. As larger amounts of different actinide isotopes became available, Abraham and Finch were joined by Lynn Boatner and Bob Reynolds in carrying out magnetic-resonance studies of the nuclear spins of the actinide isotopes. Eventually, the magnetic-resonance studies were extended to encompass actinide elements ranging from uranium to einsteinium.

Marvin Abraham (left) and Lynn Boatner (center) discuss the submerged arc-fusion growth of MgO single crystals with Commercial Crystal Laboratories (CCL) President Michael Urbanik (right). CCL was a partner in a CRADA with ORNL to improve the size and quality of MgO single crystals.

problems in the pressure vessel, and this shutdown was extended by DOE because of reactor management problems that were discovered. The BSR, ORR, and Health Physics Research Reactor were shut down in March 1987 as a result of similar management problems. Because of the new emphasis on environment, safety, and health, numerous committees were formed to examine the reactor problems and to assure safe reactor operation; the procedure for restart turned out to be very lengthy and complicated. Although the HFIR was operated at low power for a short period in 1989, it did not resume long-term operation until early in 1990, with the shutdown lasting more than three years. Because of budget problems, none of the other reactors were operated again for research, even though the procedures to start operation were successfully completed. The BSR shutdown caused a termination of the user program on the LTNIF, which had been developed and operated by Ralph Coltman, Rich Kerchner, and Charlie Klabunde. This facility had been planned as the principal facility within the U.S. to study radiation effects at low temperatures; with the shutdown of the BSR, there are no adequate facilities in this country to perform such research. The ORR shutdown required that the Ames Laboratory neutron scattering program be accommodated at the HFIR. Moreover, during the HFIR shutdown, NSF withdrew its support from NCSASR, and DOE has been able to give only limited additional support for it. Fortunately, the HFIR is currently operating very successfully at a slightly reduced power (85 MW). During the long period that HFIR was not operating, members of the division's Neutron Scattering Program remained active in research using instrument time allocated to them at a number of neutron scattering centers throughout the world.

During the past decade, members of the Solid State Division became actively involved in the promotion and development of a new advanced neutron source at ORNL. In late 1983, a project was officially started at ORNL under the direction of Ralph Moon, who successfully obtained support from the ORNL Director's R&D fund. Moon represented this project, which was then designated the Center for Neutron Research, before important national committees that were appointed to make recommendations on the need for major national facilities; these committees gave strong recommendations for such a reactor. Mike Wilkinson also became highly involved in this project, and John Hayter was appointed its Scientific Director. Direct support for the project was first obtained from DOE in 1987, and the name was changed to the Advanced Neutron Source (ANS). A detailed design for the ANS was completed in 1994, but construction plans were abandoned due primarily to the $2.9 billion project cost. Instead, DOE has proposed construction of a more modest (but still world-class) spallation neutron source at ORNL. Members of the Solid State Division played a crucial role in developing plans for instrumentation for the ANS and enlisting support for the project from the scientific community, and this role will continue with the proposed spallation source.

It was also during this period that the original PHISICS facility was extensively expanded into the excellent SMAC facility that exists today. The expansion included three separate projects over five years. Simultaneously, capital equipment funds were provided by the DOE Division of Materials Sciences to purchase a new 1.7-MV tandem accelerator, a new 500-kV LINAC implantation accelerator, new sample chambers and beam lines, and a new data processing system. This facility provides excel-

Electron Microscopy

The electron microscopy program initiated by Tom Noggle in the 1960s played an important role in early investigations of radiation damage defect clusters in metals and in the exploration of ion channeling and ion implantation, including fundamental ion beam radiation damage simulations. In the 1970s and 1980s, Mike Ohr broadened the microscopy program to the study of fracture and performed a series of pioneering in situ electron microscopy studies of the behavior of crack tip dislocation motion under brittle and ductile conditions. These investigations led to a quantitative understanding of the relationship between microscopic fracture effects, such as the dislocation free zone in front of crack tips, and macroscopic fracture mechanisms. J. Narayan performed a wide range of electron microscope studies on the mechanisms and materials-related properties changes associated with ion beam radiation damage simulation, pulsed-laser annealing, and nonequilibrium growth and processing in metals, semiconductors, and ceramics.

Steve Pennycook joined the Electron Microscopy Group in 1982, bringing new scanning transmission microscopy imaging techniques from the Cavendish Laboratory and applying them to the study of highly doped semiconductor crystals. Although the electron microscope at the time could only produce a 50-Å scanning probe, it was clear that by detecting the (largely incoherent) high-angle scattering, a chemically sensitive image could be obtained that was complementary to the conventional structural images obtained by diffraction or phase contrast. This suggested that at higher resolution, it should be possible to image the atomic structure of materials in this way. The Z-contrast method, developed by Crewe at Chicago for isolated atoms and clusters, could then be applied to materials of all types.

Steve Pennycook at the controls of the world's highest resolution scanning transmission electron microscope. Pennycook received the 1992 Materials Research Society Medal for the development and application of atomic resolution Z-contrast scanning transmission electron microscopy.

Following delivery of a customized 100-kV high-resolution scanning microscope in 1988, incoherent imaging at atomic resolution was demonstrated in semiconductors and superconductors, overturning conventional wisdom that such imaging was impossible in thick crystals. In fact, the theoretical resolution limit for incoherent Z-contrast imaging actually exceeds that of the coherent imaging methods that were the standard method for imaging crystal lattices. Theoretical work by Dave Jesson showed that column-by-column imaging is possible in thick crystals because of a strong columnar channeling effect. The Z-contrast images retained the chemical sensitivity of their low-resolution predecessors, bringing about for the first time a technique for structure determination that did not rely on preconceived structure models. The technique was rapidly applied to the study of interface structures in semiconductors, superconductors, metals, and ceramic materials and was utilized to infer atomistic processes associated with nonequilibrium materials synthesis and processing.

In 1993, Nigel Browning and Pennycook completed a parallel detection system modification of the Z-contrast microscope to collect electron energy loss spectra from individual atomic columns. This produced the first atomic-resolution chemical analysis and, together with atomic-resolution Z-contrast structural information, represented a unique and extremely powerful materials characterization capability at the atomic level. In the same year, the Solid State Division took delivery of the world's first 300-kV Z-contrast scanning microscope, providing an unprecedented resolution of 1.3 Å, thereby making all materials accessible to direct imaging along several crystallographic projections.

lent instruments for research utilizing ion beam scattering, ion beam mixing, ion beam implantation, and ion beam deposition; it also accommodates a large number of users in collaborative research. Of particular importance has been the utilization of ion beam techniques for the development of materials that are required in various energy technologies. Members of the program have included Bill Appleton, Woody White, O. E. Schow III, Tom Noggle, Wayne Holland, Dave Poker, Steve Withrow, Ray Zuhr, Jim Williams, and Terry Sjoreen, with technical support by Jim Moore, Dale Hensley, and Darrell Thomas. The techniques have been used to achieve new materials properties; to alter electrical, mechanical, and optical properties of metallic, semiconducting, and insulating materials; and to modify other materials, such as high-temperature ceramics, laser mirror surfaces, and surgical alloys. The latter materials were studied by Jim Williams, Bill Appleton, and Ray Buchanan (formerly from the University of Alabama at Birmingham, now at The University of Tennessee), who determined that implantation of nitrogen into the surgical Ti-6Al-4V alloy used for artificial joints results in a very large improvement in the corrosive wear performance of such joints. This process is now being used in 50% of hip and knee replacements in the U.S.

Investigations of ion implantation and laser annealing, which were discussed in activities of the third decade, led to dramatic improvements in the ability to produce high-efficiency silicon solar cells. Prompted by this success, the photovoltaic group, which included Dick Wood, Rosa Young, Jay Jellison, Russ Westbrook, and Gerard van der Leeden, developed a technology for fabricating very high efficiency solar cells by low-cost particle and energy beam processing. Using low-cost glow discharge implantation of dopants into single-crystal silicon substrates, followed by pulsed-laser annealing with an XeCl laser, solar cells were fabricated with the highest efficiency that had been measured at that time at the Solar Energy Research Institute. The solar cells were of a particularly simple structure and were large area devices compared with the highest efficiency solar cells produced previously by conventional methods. The excellent results obtained by this procedure, together with the high degree of reproducibility, make it a potential technique for use in future assembly-line production of solar cells.

In a research investigation that was directed toward the problem of long-term storage of high-level nuclear wastes, Brian Sales, Lynn Boatner, and Joanne Ramey discovered and developed a new class of highly stable phosphate glasses. High-performance liquid chromatography was used to obtain information on the structure of phosphate glasses on a level of unprecedented detail, and this structural information was correlated with physical and chemical properties of these glasses. Of particular importance in this investigation was the development of lead-iron phosphate glass for possible use in the immobilization and permanent disposal of both commercial and U.S. defense high-level nuclear wastes. The lead-iron phosphate glass can be processed using a technology similar to that developed in the nuclear waste program for borosilicate glass, and it offers several distinct advantages. Other stable phosphate glasses were developed for a variety of uses, including optical components, glass-to-metal seals, and as a new laser host.

The discovery in 1986 of superconductivity at relatively high temperatures in certain copper oxide materials by scientists at

IBM was one of the most exciting events in the solid state sciences in many years. Many division members, both theorists and experimentalists, have contributed research on these materials, and the excellent facilities of the division for synthesizing and characterizing materials have played an important role. Investigations of dimensionality in epitaxial copper-oxide superlattices and of the effects of tailored defects on flux pinning have had particular significance. Experiments by Doug Lowndes, David Norton, and John Budai have shown that a single CuO_2 bilayer in $YBa_2Cu_3O_7$ is superconducting and that the resistive behavior of such layers is highly two-dimensional. Because the superconducting transition temperature for a bilayer is significantly lower than that of the compound, three-dimensional coupling apparently is necessary to obtain high transition temperatures. Experiments by Jim Thompson, Dave Christen, Ron Feenstra, Charlie Klabunde, and Rich Kerchner, in which $YBa_2Cu_3O_7$ was irradiated by heavy and light ions, have shown that the critical current density in magnetic fields can be increased significantly by the introduction of defects. These experiments showed that tailored flux-pinning defect geometries can be created in these superconductors, which will permit their use in various applications that require high magnetic fields. The theoretical research on high-temperature superconductors by Mark Rasolt, Sam Liu, and Dick Wood also played a significant role in obtaining a better understanding of these materials.

It was particularly unfortunate that the HFIR shutdown occurred just about one month before news broke about the new high-temperature superconductors. Neutron scattering experiments have provided much of the understanding of these materials, and for several years this work could not be done at ORNL. However, since the restart of HFIR, many neutron scattering experiments have been performed on these materials; a good example is the flux-line lattice work of Mohana Yethiraj and Herb Mook. Other important investigations by the Solid State Division neutron scattering staff included the first observation of antiferromagnetic nuclear spin ordering as part of the U.S.-Japan Program; investigations of magnetic spin glasses; SANS experiments on block copolymers that proved existing theories incorrect; and observations of the simultaneous existence of ferromagnetism and superconductivity, which had been considered impossible. Of particular importance were the investigations of Herb Mook with Bob Nicklow, Jeff Lynn (University of Maryland), and Donald McK. Paul (University of Warwick) on the ferromagnetic metals, iron and nickel, which were closely associated with the theoretical calculations of John Cooke and John Blackman (University of Reading). This combination of theory and experiment showed that a proper account of the itinerant nature of the electrons in iron-group-metal ferromagnets is essential in understanding the neutron scattering results. The recent development of excellent transmission neutron polarizers and neutron guides by Herb Mook, John Hayter, and Chuck Majkrzak (National Institute for Standards and Technology) also is extremely important. These devices will have a revolutionary impact on the method by which many future neutron scattering experiments are performed. Moreover, significant new capabilities in neutron scattering are being developed at the HFIR. Of particular importance is the new neutron residual stress facility to study stress relief in welds and to improve manufacturing processes for composite materials and complex parts. This facility, which is operated by Steve Spooner of the Solid State Division and Cam Hubbard of the Metals and Ceramics Division, is of great interest to many industrial organizations for collaborative research. Other important additions to the experimental capability at HFIR are the construction of a neutron reflectometer by Bill Hamilton and John Hayter and a new multidetector powder diffractometer, operated by Jaime Fernandez-Baca and Bryan Chakoumakos. The growing number of outside users of the neutron scattering equipment has required an expansion of the technical support staff. Important technical support contributions were made throughout this period by James Weir III, Terry Collins, Charlie Malone, Brent Taylor, and Ron Maples.

The development of an entirely new technique in electron microscopy by Steve Pennycook, with assistance from Dave Jesson and Matt Chisholm and technical support from Julia Luck and Troy Estes, provided another very exciting and significant research activity for the division in recent years. This new technique represents a major breakthrough in the field of electron microscopy and is likely to be a turning point in the application of electron microscopy to materials research. All transmission electron microscopy for the past forty years has been based on coherent electron diffraction. The new technique, which is called Z-contrast scanning transmission electron microscopy, is based on incoherent imaging in a scanning transmission electron microscope (STEM). This new technique provides an intuitively interpretable image showing extremely high resolution and strong chemical sensitivity. Moreover, the image can be used to position the electron probe for simulataneous electron energy loss spectroscopy with atomic precision, so that the electronic structure of the material can be determined on the same scale as the atomic structure. It is an ideal tool for research on interfaces, defects, multilayers, and new materials of all kinds. A new microscope, the world's highest resolution STEM (1.3 Å), was obtained for this research in 1993.

Many other significant research investigations were performed by members of the Solid State Division during the modern era,

Doug Lowndes, Al Trivelpiece, ORNL Director, and B. R. Appleton examine laser MBE equipment in the new Solid State Research Facility (Building 3150) during Open House on September 16, 1995.

including impressive results from programs initiated during the previous decade. Improvements continued in the high resolution achieved in LEED investigations of surfaces by Harold Davis and John Noonan, reaching an accuracy of 0.01 Å in the determination of interlayer spacings. These investigations showed that many near-surface atomic layers are involved in the relaxation processes of monatomic surfaces and that lateral displacement of the atoms within layers also takes place. Investigations of fast-ion conductivity included both experimental and theoretical studies of the very large enhancement of ionic conductivity by incorporating submicron particles of an insoluble second phase. Investigations were also made of transport across interfaces; different models, including fractal models of the interface, were developed by John Bates, Nancy Dudney, Jim Wang, and Sam Liu to account for the experimental results. This work led to studies of thin-film ceramics and composite electrolytes and to the development of a new class of thin-film microbatteries. Nanosecond resolution time-resolved x-ray investigations of silicon during pulsed-laser annealing, which were continued at CHESS by Ben Larson, Jon Tischler, and Dennis Mills (Cornell University), were the first determinations of interfacial overheating and undercooling in materials under highly nonequilibrium conditions; they provided new information on the kinetics of melting and crystallization. In situ electron microscope investigations of fracture by Mike Ohr, Chan Park, and Robb Thomson (National Institute for Standards and Technology), with technical support by Troy Estes, gave a description of the stress field at the crack tip in terms of a stress intensity factor and proposed a criterion for ductile vs brittle fracture of materials that was based on the magnitude of the stress intensity factor. New work was initiated during this period on metallic alloys possessing icosahedral orientational order with five-fold symmetry. John Budai and Mike Aziz (Harvard University) prepared long-range-oriented Al-Mn quasicrystals by a new ion implantation technique and investigated them with synchrotron X rays at the NSLS at BNL. Their investigation was the first quantitative study of the quasicrystal packing and phason strain in icosahedral materials. It showed that phason defects, which have no analogue in ordinary crystals, play a very important role in the structure of quasicrystals.

Other new techniques and facilities are making significant contributions to the research program of the division. New capabilities in scanning tunneling microscopy include the first high-temperature instrument in the United States and an ambient-temperature instrument with attachments for molecular beam epitaxy (MBE). These instruments permit new capabilities in monitoring thin-film growth and in manipulating materials on an atomic scale for device fabrication. Multitarget pulsed-laser ablation has been applied recently to the growth of epitaxial films and strained-layer superlattices. The resulting products are comparable in quality with those grown by other methods such as MBE and have the potential for a wide variety of applications. Access to the ORNL Intel Paragon massively parallel supercomputer provides new opportunities in numerical simulations for problems in solid state theory. The division is also significantly involved at the Advanced Photon Source at Argonne National Laboratory and in the proposed HFIR Upgrade and National Spallation Neutron Source at ORNL, each of which offers unparalleled solid state research opportunities for the future.

Epilogue

For more than four decades, the Solid State Division has provided research leadership in the synthesis, processing, characterization, and fundamental understanding of materials. Pioneering advances have been made in many areas, including neutron and x-ray scattering, radiation damage, materials synthesis, ion implantation, condensed matter theory, laser processing, surface physics, thin films, electron microscopy, photovoltaics, and superconductivity. In almost all cases, this research has been strengthened by an integration of theory, experiment, and advanced research facilities which is often unique to the division. The continued support of the DOE Division of Materials Sciences, Office of Basic Energy Sciences, has been essential to this progress.

During this period, the DOE mission has broadened from a nuclear energy focus to incorporate all energy technologies and, more recently, R&D partnerships with industry and universities. The evolution of the Solid State Division has reflected these changes. In the 1970s, new research programs supporting nonnuclear energy technologies were initiated. Outreach to the materials research community was increased in the 1980s through the development of cooperative research facilities based on unique division capabilities in neutron scattering and ion implantation. The 1990s have seen increased emphasis on R&D partnerships with industry and universities to leverage research resources and increase technology transfer. The division has emerged from these changes with broader scientific capabilities, a more diverse staff including students and postdoctoral associates, strengthened research relationships with The University of Tennessee and other universities, and significant involvement with industry.

The 1990s are a time of significant challenge and opportunity for the Solid State Division. Driven by the end of the Cold War, the emerging global economy, and increased competition for federal resources, the research establishment is undergoing unprecedented change. After 50 years, the social contract between science and the rest of society, as set forth in Vannevar Bush's *Science, the Endless Frontier*, is coming into question. A new and sustainable paradigm on how science and technology will contribute to the national welfare in the future has yet to be defined. Materials, a key enabler in all advanced technologies, will be prominent in this new paradigm. And the Solid State Division, with a strong fundamental materials research program, key alliances with universities and industry, and access to world-class research facilities, will help create this future.

Appendices

A. Solid State Division Charter Members

B. Solid State Division R&D 100 Awards

C. Organization Charts

Appendix A

Solid State Division Charter Members

February 1952

- I. M. Barker
- C. D. Baumann
- R. G. Berggren
- D. S. Billington
- F. M. Blacksher
- T. H. Blewitt
- C. D. Bopp
- W. E. Brundage
- W. E. Busby
- R. M. Carroll
- J. W. Cleland
- A. F. Cohen
- R. R. Coltman, Jr.
- J. H. Crawford, Jr.
- W. W. Davis
- S. T. Dismuke
- C. Ellis
- M. J. Feldman
- J. T. Howe
- D. T. James
- R. E. Jamison
- G. W. Keilholtz
- R. H. Kernohan
- B. Kinyon
- W. K. Kirkland
- G. H. Klein
- P. R. Klein
- H. W. Mate
- R. P. Metcalf
- J. G. Morgan
- M. T. Morgan
- G. T. Murray
- A. S. Olson
- W. W. Parkinson
- J. C. Pigg
- J. K. Redman
- H. E. Robertson
- M. T. Robinson
- F. A. Sherrill
- O. Sisman
- R. L. Sproull
- D. K. Stevens
- M. R. Stewart
- W. J. Sturm
- W. E. Taylor
- A. W. Tell
- L. C. Templeton
- R. L. Towns
- J. B. Trice
- C. C. Webster
- R. A. Weeks
- J. T. West
- J. C. Wilson
- M. C. Wittels
- J. C. Zukas

Appendix B

Solid State Division R&D 100 Awards

1975	Large, Totally Transparent Crystals of the Alkaline-Earth Oxides MgO, CaO, SrO—M. M. Abraham and Y. Chen
1976	Ceramic-Wire Neutron Dosimetry Materials—E. H. Kobisk and T. C. Quinby
1979	Low-Cost Diffused Solar Cells—J. Narayan, R. F. Wood, and R. T. Young
1982	Monazite Process for Stabilization of High-Level Radioactive Waste—L. A. Boatner and M. M. Abraham
1982	Dispersed-Metal Toughened Ceramics—C. S. Morgan, A. J. Moorhead, J. Narayan, and Y. Chen
1983	Supersaturated Semiconductor Alloys—C. W. White, J. Narayan, B. R. Appleton, and O. W. Holland
1984	Ultrasonically Pulsed Neutron Time-of-Flight Spectrometer—H. A. Mook and G. K. Schulze
1985	Lead-Iron Phosphate Glass Process for High-Level Radioactive Waste Disposal—B. C. Sales and L.A. Boatner
1989	Transmission Polarizer for Neutron Beams—H. A. Mook and J. B. Hayter,
1990	Scanning Transmission Electron Microscope (ORNL; VG Microscopes Ltd.)—S. J. Pennycook
1996	Thin-Film Rechargeable Lithium Batteries—J. B. Bates, N. J. Dudney, and C. F. Luck
1996	Potassium Tantalate (Niobate) Substrate—L. A. Boatner and R. Feenstra

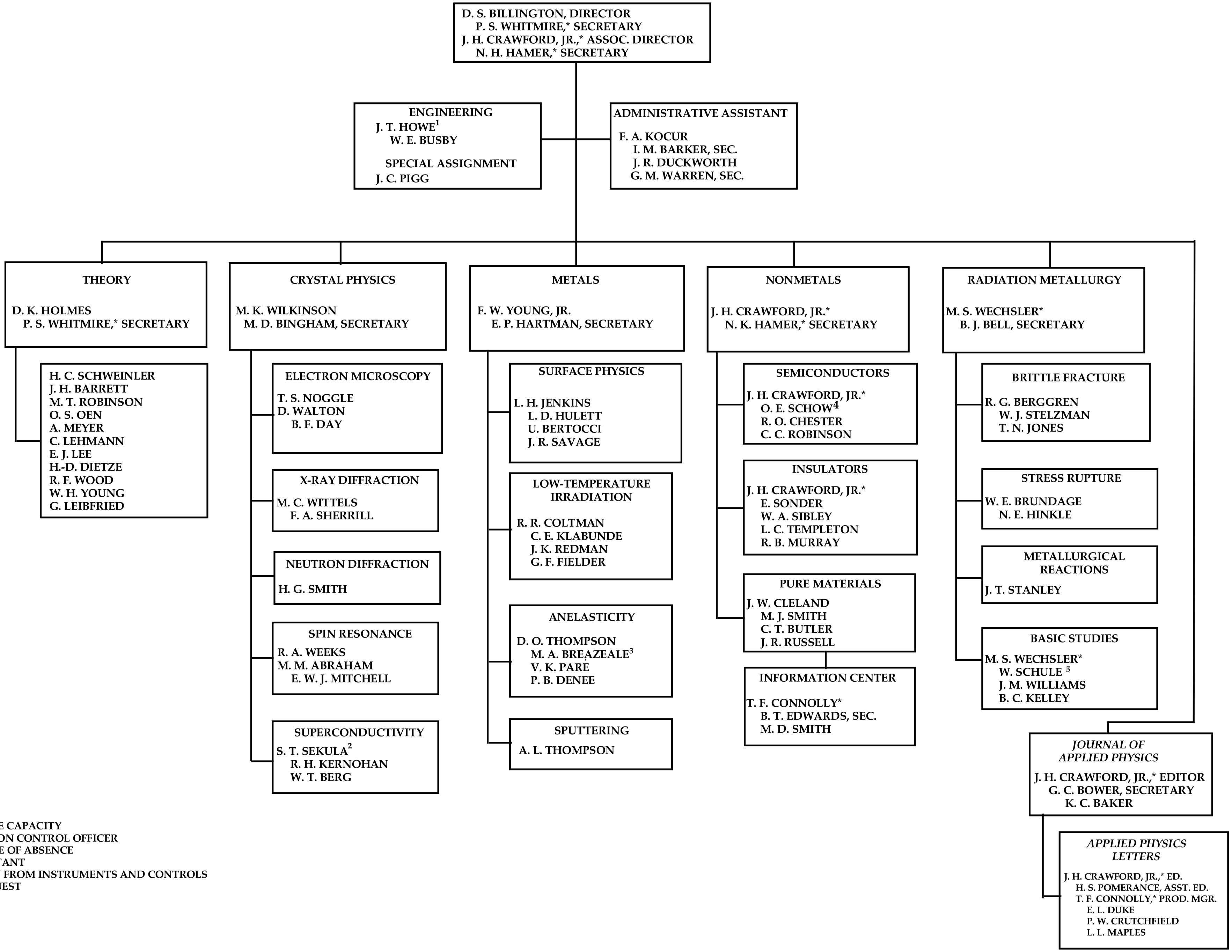
Appendix C

Organization Charts

1. September 1, 1963
2. May 1, 1976
3. October 1, 1986
4. November 1, 1995

SOLID STATE DIVISION

Effective September 1, 1963



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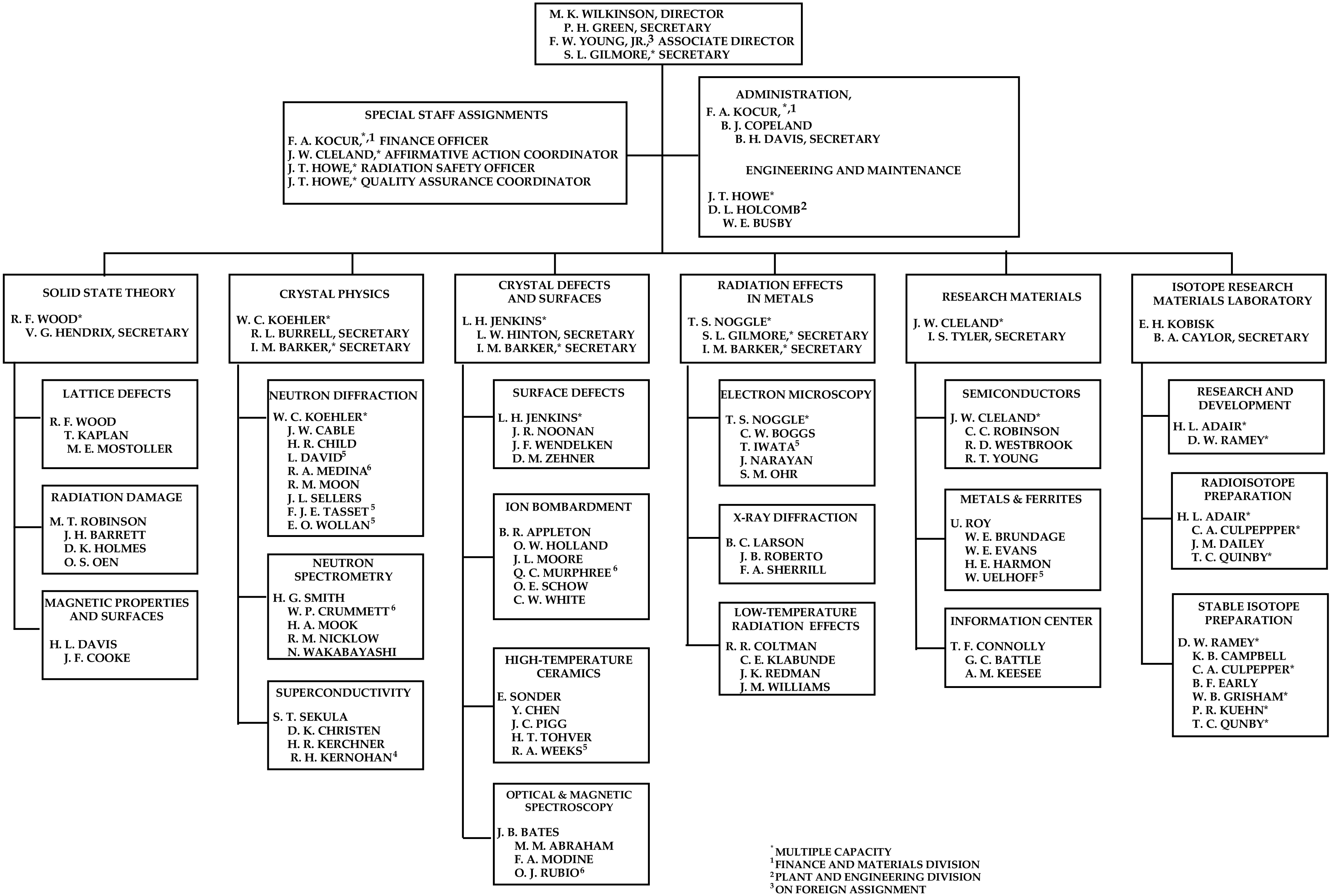
SOLID STATE DIVISION

May 1, 1976



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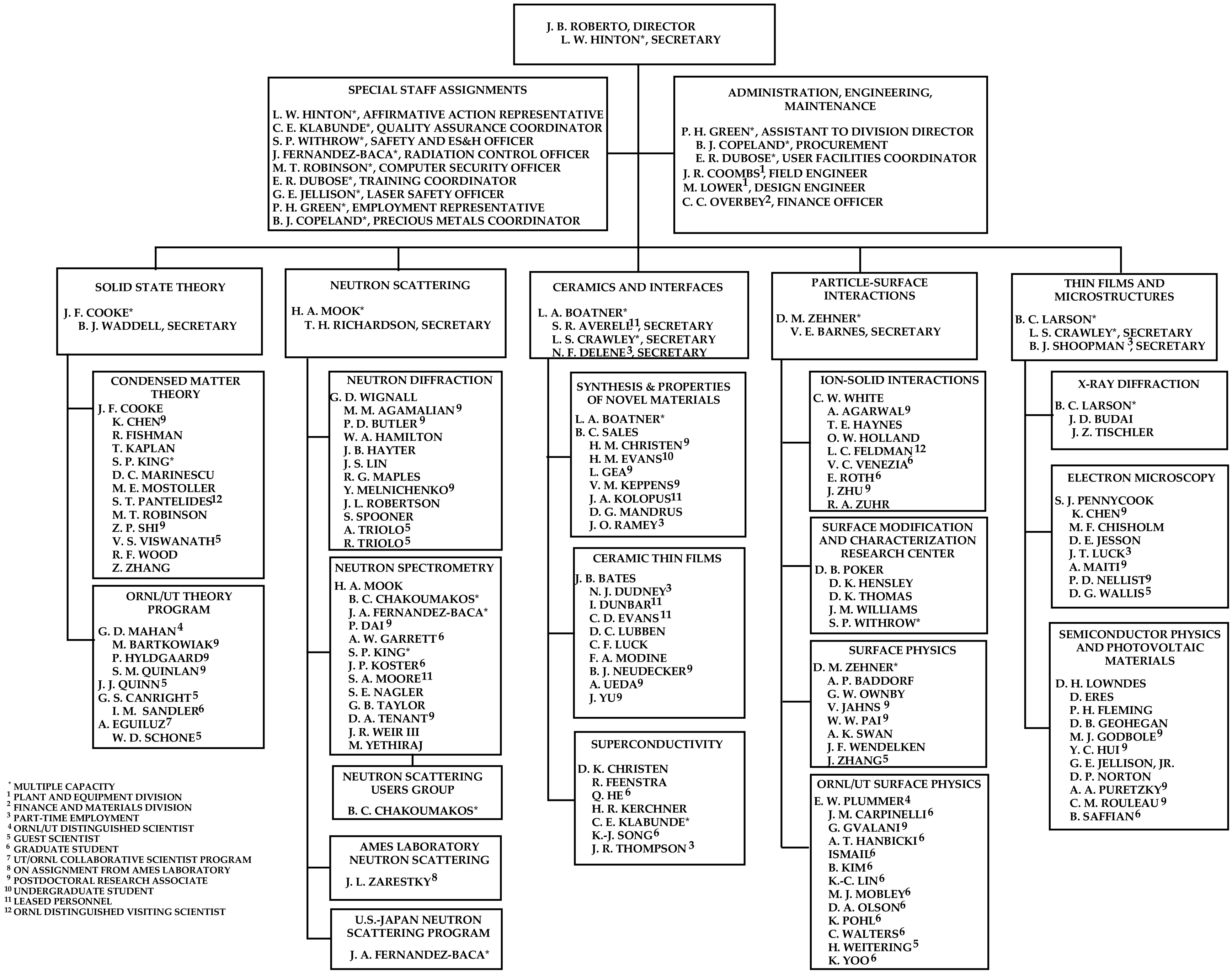

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What made us great—*our people*—through the decades: (top to bottom) Information Meeting social (1957); Information Meeting socials (1964 and 1968); retirement party for Les Templeton (1975); 25-year anniversary for Stan Sekula (1984), and retirement party for Harold Davis, Ralph Moon, Marvin Abraham, Bob Nicklow, Velma Hendrix, and Joe Cable (1994).

Back Cover: Clockwise from top left: neutron scattering pattern of the flux lattice in a superconductor, laser ablation of yttrium into argon background gas, Z-contrast image of individual atoms in Si, and ion-implanted hip joint.