Solid-State Physics and Critical Experiments

Brookhaven's solid-state physics effort, one of whose early champions was George Dienes, is an example of a basic research program that grew out of a practical one. Dienes was born in 1918 in Budapest and finished his Gymnasium in 1936. An outspoken youth, he was openly opposed to the growing Nazi influence in Hungary, which often landed him in trouble. The rector of the local university, a family friend, told him that although he could matriculate (Dienes was not Jewish), he was likely to be severely beaten. Leave the country, the rector advised. Fortunately, the Dienes family had relatives in the U.S. who helped him enter what was then Carnegie Tech in Pittsburgh, from which Dienes received a B.A. in 1940 and a Ph.D. in 1947. Subsequently, he got a job at North American Aviation, in its atomic energy research department, studying radiation damage, that is, the effects of various types of radiation, especially neutrons, on materials. But Dienes learned that he did not care for the constant scramble for contracts in commercial work, and secured an interview at Brookhaven.

Brookhaven’s reactor engineers were looking for a specialist in radiation damage in graphite, a subject of urgent practical application to the BGRR. The reactor was almost entirely composed of stacks of graphite blocks, through which an intense flux of neutrons streamed whenever the reactor was in operation. As Eugene Wigner had first noted during the war, fast neutrons have a tendency to knock carbon atoms out of their ordered position in the graphite lattice, and push them into interstitial locations. The result, known as the Wigner effect or Wigner disease, is a distortion in the lattice, rather like introducing pebbles between the pages of a book. The distortion drastically reduces the graphite’s thermal conductivity and causes it to expand and store energy. Such expansion was potentially dangerous. Not only could it put the fuel channels out of alignment, permanently disabling the reactor, but the energy storage and drop in thermal conductivity could potentially make graphite catch fire. Hanford engineers had developed a procedure for relaxing the graphite, called annealing, which involved running the reactor for a short, controlled period at high temperatures. At high temperatures atomic mobility increases, and the dislodged atoms tend to return to their original positions, reversing the Wigner effect. But much research remained to be done on the problem both from a fundamental and practical standpoint. Moreover, Hanford’s experience
with graphite was highly classified and Brookhaven scientists knew little about it.

Shortly after his arrival in September 1951, Dienes began to study radiation damage in graphite (Dienes 1952; Kosiba, Dienes, and Gurinsky 1956), and helped draw up plans for an annealing experiment at the BGRR. Because the largest Wigner effect occurred in the center of the reactor next to the gap (where the air flow cooled the graphite most and natural annealing would be minimal), the reactor operators had to find a way to warm up those better-cooled areas more than others. Ultimately, they did this by reversing the air flow direction; they let the air flow from the surfaces into the gap and then out.35

The urgency of finding a workable annealing procedure was underscored when a sudden, unexpected release of stored energy took place inside a British reactor at Harwell late in 1952. British authorities kept the incident a tightly guarded secret. But Chadwick, now a prominent science adviser to the British government, thought it important that Haworth know and broke strict secrecy by relaying the news to Haworth; to protect the source, Brookhaven’s reactor engineers referred to it guardedly even in classified documents.36 The incident was not revealed officially to U.S. AEC personnel until January 1953. The BGRR’s annealing experiment took place later that year. Not knowing what to expect, the lab prepared elaborate safety precautions, including a plan for evacuating the region. Annealing began one morning and continued into the evening, with the temperature of the reactor monitored by thermocouples that had been installed in the graphite when the reactor was built. Dienes and the other principal members of the reactor department—and Haworth himself—stayed well past midnight until it was clear that the operation had, indeed, reversed the Wigner effect. Afterward, the reactor was annealed regularly.

In October 1957, disaster struck a British production reactor at Windscale, when the graphite caught fire during an annealing operation, spreading radioactive I131 over the surrounding countryside. (Iodine is generally the most significant poison involved in reactor accidents because of the large amount that tends to be released and its volatility—it vaporizes at a temperature above room temperature and is metabolized by the human body.) Several Brookhaven scientists were called over as consultants to help figure out what happened, including Powell in one group immediately after the accident, and Dienes and Gurinsky, who by then had become recognized experts in annealing, several weeks later. The accident scared the AEC, and the agency debated seriously and at length whether it should stop annealing the BGRR and even shut it down. While at first it appeared as though the accident had been caused by an annealing procedure similar to that used at the BGRR, contributions from Brookhaven scientists helped to show that the annealing process was safe.

The work of Coor in this program, Cori (Ronald) properties of heavy fraction methods, chairman Richard of his de good bet. Unlike X-rays the magnetic strucure to both chemists at the magnetic structure.

The first signifi cant spectrometer involved Ferrites, magnetic
the annealing procedure was not at fault, and in the end, the cause of the Windscale accident was attributed to a broken fuel cap (Schweitzer 1993).

But Diene’s greatest long-range service to Brookhaven was not in annealing but in putting the solid-state program on its feet. Andy McReynolds, an imaginative scientist who was the first head of the solid-state group, was personally and scientifically a loner, and had failed to establish the broad-based program that Haworth had envisioned for the lab. Seizing Diene’s arrival as an opportunity, Haworth and physics department chairman Sam Goudsmit instructed the collegial Diene to reinvent the solid-state physics program. A growing number of theorists and experimenters were interested in neutron diffraction, a technique (analogous to X-ray diffraction) by which the patterns created by neutrons as they pass through a specimen are used to examine its structure. The technique had been pioneered at Oak Ridge by Clifford Shull and Ernest Wollan, who adapted X-ray diffraction equipment to neutrons. The instrument used with neutron diffraction was a double-axis spectrometer. As in Sailor’s single-axis spectrometer, a monochromating crystal was mounted on an axis, around which swung an arm with a sample; unlike Sailor’s device, the sample was mounted on a second axis, around which swung a detector, permitting experimenters to determine the angular profile of the scattered neutrons. Lester Corliss and Julius Hastings of Brookhaven’s chemistry department set up a double-axis spectrometer at the BGR, incorporating for the first time Soller slits, or multiple parallel slits in the collimators (see fig. 8.9). Raymond Pepinsky, an X-ray crystallographer from the University of Pennsylvania, was the first visitor to establish a permanent neutron crystallography program there. Pepinsky’s graduate students included future neutron diffractionists and BNL staff members Chalmers Frazier and Gen Shirane. Among Brookhaven’s numerous other visitors was Shull himself, who worked at the BGR for a year and a half.

The work of Corliss and Hastings can serve to illustrate the successes of this program. Corliss was a chemical physicist interested in the magnetic properties of heavy elements, Hastings a physical chemist skilled in diffraction methods. The two were brought together by chemistry department chairman Richard Dodson, who was seeking to boost the programmatic presence of his department at the reactor. Neutron diffraction seemed a good bet. Unlike X rays and electrons, neutrons could be used to determine the magnetic structure on an atomic level—something of special interest to both chemists and physicists, who theretofore had only been able to infer the magnetic structure of solids by measuring bulk properties.

The first significant work by Corliss and Hastings on their double-axis spectrometer involved the magnetic structures of nickel and zinc ferrites. Ferrites, magnetic materials that do not conduct electricity, were both
industrially important and scientifically interesting. The industrial importance lay in the many applications of ferrites in high-frequency devices. The scientific interest involved a theory about the structure of ferrites recently proposed by French physicist Louis-Eugène-Félix Néel (Néel 1948). Whereas ordinary magnetic materials are ferromagnetic—that is, the atoms in their lattices all have their magnetic moments aligned in the same direction—Néel had been examining antiferromagnetic materials, in which the moments point in opposite directions, in effect canceling each other out. Néel also proposed a third kind of magnetism called ferrimagnetism to account for the then-baffling behavior of the ferrites whose formula is $\text{XO}_2\text{Fe}_2\text{O}_3$, where X is a 3-d cation. The ferrites crystallize with the spinel structure, which consists of a face-centered cubic sublattice of oxygen ions, with octahedral interstitial array of iron ions and tetrahedral ones, the latter containing the various rare earth impurities.

The first real d to the Shull ar diffraction. Corliss ferrimagnetism by Néel’s theory, leading to the Neutron I (Corliss and Hasting) diffraction experiment. Thanks to staff at the Brookhaven National Laboratory, techniques, a physics department. Brookhaven concept their work looked to chemistry. Their work on the crystals of the two diatomic structures.

Throughout the 1940s, began to be employed, but began to be used in a research role. He knew the basic question: “And were never part of other reactors.”

In 1947, a converted barracks floor, the neutron sea was created. The new, higher-energy reactor seemed more promising.

Herbert Kouts: Cr

Herbert Kouts arrived at the U.S. Department of Energy’s experimental program in 1947 to join the AEC’s weapons development efforts, but soon became
CHAPTER EIGHT

Interesting. The industrial import-

soms about the structure of ferrites

Louis-Eugène-Félix Néel (Néel

crystals are ferromagnetic—that is,

magnetic moments aligned in the

antiferromagnetic materials, in

sections, in effect canceling each

of magnetism called ferrimag-

nate behavior of the ferrites whose for-

mation. The ferrites crystallize with

face-centered cubic sublattice of

oxygen ions, while the magnetic ions are found in both tetrahedral and

tetrahedral interstices within this sublattice. Néel postulated that the tetra-

hedral array of ions was antiferromagnetically arranged with respect to the

tetrahedral one. Since there are twice as many occupied octahedral sites as

tetrahedral ones, the result is a net ferromagnetic moment.

The first real demonstration of Néel's ideas about antiferromagnetism

came from Shull and Smart's groundbreaking study of MnO using neutron

diffraction. Corliss and Hastings turned their attention to Néel's theory of

tetrahedronism by studying nickel and zinc ferrites as a good test case for

Néel's theory, leading to their first important publication, in January 1953,

titled "Neutron Diffraction Studies of Zinc Ferrite and Nickel Ferrite"

(Corliss and Hastings 1953). In it, Corliss and Hastings described neutron

diffraction experiments in which they obtained results in accord with Néel's

theory. Thanks to such confirmations, at Brookhaven and elsewhere, Néel

received the Nobel Prize in physics in 1970.

Corliss and Hastings were familiar figures at the reactor, sharing equip-

ment, techniques, and information with many of their colleagues in the

physics department. Though fulfilling the interdisciplinary ambitions of the

Brookhaven concept, the two eventually ran afoul of the AEC, for which

their work looked too much like physics to warrant money earmarked for

chemistry. Their work illustrated how reactor research blurred boundaries

between these two disciplines by allowing exploration of the contributions

of atomic structure to solid-state properties.

Throughout the 1950s, Brookhaven's radiation damage research contin-

ued, but began to be overshadowed by that of the neutron diffractionists, who

were involved in a new field of unknown capabilities and promise. "We

knew the basic questions [in radiation damage research]," Dienes said,

"and were never particularly interested in practical problems involving

other reactors." In 1957, the solid-state group acquired its own building,

a converted barracks, and the radiation effects researchers took the first

floor, the neutron scatterers the second. As the years went on, especially

when a new, higher-flux reactor came on the horizon, the second floor

seemed more and more the exciting place to be.

Herbert Kouts: Critical Experiments

Herbert Kouts arrived at Brookhaven in 1950, became head of the reactor

department’s experimental division, and bore primary responsibility for the

experimental program in nuclear engineering for nearly two decades. But

his most significant work would grow out of his own free interests even

against the AEC’s wishes. Kouts had a strong background in theoretical

physics, but soon became interested in reactor design. In the 1950s, he had
almost a free hand to change his research program. “I started up many programs,” he recalled, “just because I decided to start them up, and usually the money just followed. I thought a thing would be good to do, the lab judged that I knew best, and that was good enough.” While the AEC had tapped Argonne as the central facility for reactor research, Kouts took a hole atop the BGRR that had been abandoned by the medical department, turned it into a facility where he could expose large areas to reactor neutrons, and began to explore the behavior of various arrangements of uranium rods, moderated by ordinary water.

By 1954, Kouts’s studies had progressed enough for him to ask for additional lab support in the form of a critical facility—a tiny reactor small enough that heat removal was not a problem. Over the next few years, he built two additional critical facilities, which he used in thousands of experiments testing different features of reactor design. Eventually, water-moderated reactors proved most efficient, and Kouts’s work grew into a substantial program whose results were eventually incorporated into the Westinghouse-developed light water reactor power program that the U.S. adopted.

My group and I built at Brookhaven three [critical facilities] that we did not tell [formally] the Atomic Energy Commission about until much later. We just went ahead and built them because they were a useful part of our experimental program. We didn’t run them at very high power—they were not meant to be run at very high power—we did a very thorough safety analysis of what we were doing, a very thorough engineering job, put them together, operated them, got a lot of useful experimental work out of them. We didn’t ask for a lot of money—cost a lot less to do things that way than it does when you have to go through a lot of formalism—but you got a lot more results. It’s a different world today. I’m struck by the fact that people coming into my field these days will have no perception whatsoever of how that used to be done. They think that the world really consists of making a proposal, writing it, rewriting it, presenting it and defending it, arguing, going back, maybe going through a process that takes six months to a year, and then if it’s approved, going into a relationship in which you make monthly reports, quarterly reports, and the process is reviewed thoroughly from the standpoint of, “Was it done right?” and “Was the money spent right?” That’s the world to these people and they think it never was any different. Well, it sure was."

Lee Farr: BNCT

Medical department chairman Lee Farr led the largest and most daring use of atomic energy for radiotherapy in the 1950s, the Boron Neutron Capture Therapy (BNCT) program. BNCT is based on an ingenious technique (described in principle first in 1936) in which a nonradioactive isotope of an element (here, $^{10}$B) is used to capture thermalized neutron fluxes from a nuclear reactor or spallation source. The neutron is absorbed, producing an excited state that decays through a nuclear reaction releasing a large amount of energy, which is then used to kill cancer cells. BF$_3$ is used as a neutron detector. The advantage of this method is that it can selectively target cancer cells, which are more sensitive to the high-energy protons produced by the reaction. BNCT was one of the first successful applications of nuclear medicine in cancer treatment. Today, BNCT is still used in specialized centers around the world, although its use has been limited due to technical challenges and the availability of alternative treatments.
“I started up many reactors. I’d start them up, and usually the acetone would be good to do, the acetone was next to the 17th.” While the AEC provided research funds, Kouts took care of the medical department, and the University’s legal issues, to create a rapport with doctors. The arrangement of the medical research was the heart of the operation.

For him to ask for additional funding—he was a little more realistic in the next few years, he couldn’t get them to do it in thousands of examples. Eventually, water-cooled reactors became a reality, and his work grew into a medical research program. Initially, this was incorporated into the medical school, but in the mid-1950s, the program that the U.S. government could not find a medical school to train him. 

[Page 183]

element (here, $^{10}$B) is made to accumulate inside tumors, where it is bombarded by slow neutrons. These neutrons bring about a nuclear reaction in the $^{10}$B that drastically enhances the radiation damage to nearby cells—ideally, only the tumor tissues.

Three parts would go into eventually making the technique work. The first is to find a target element with a large cross-section for thermal (slow) neutrons. The second is to attach the target element to a compound that, when administered to a patient, would be taken up preferentially by the tumor rather than healthy tissue in the zone to be irradiated. The third part is to irradiate the tumor with a large dose of thermal neutrons. When these low-energy neutrons react with the nuclei of the target element, they trigger a reaction releasing millions of electron volts of ionizing radiation energy.

If all three parts of the technique are made to work, the radiation damage is confined to a short distance of about a cell diameter, meaning that only tumor cells are destroyed and healthy tissue is spared (Slatkin 1991). The $^{10}$B reaction had been discovered at the Cavendish by Maurice Goldhaber and James Chadwick in 1934. Shortly after moving to the University of Illinois in 1938, Goldhaber patented his work. The colleague, P. Gerald Kruger, took the remark seriously. Together with another researcher, Kruger irradiated boric acid—bathed mice tumor cells with neutrons in vitro and showed that these had reduced viability when transplanted to other mice. Kruger wrote up his results in an article that is the first to describe medical research involving boron neutron capture. In 1940, another group performed the first in vivo BNCT irradiation (Zahl, Cooper, and Dunning 1940). The method looked promising enough in principle to be one of the first programs that Farr and Van Slyke put on the medical department’s research agenda. The BNCT program was in many respects tailor-made for BNL, for it was reactor based and multidisciplinary, involving contributions from physics, chemistry, biology, and medicine.

Early in 1950, Farr began to study compounds with an affinity for malignant tumors to which target elements might be attached, and focused on uranium as a target element, considering boron too toxic. A young doctor named Winton Steinfeld was assigned the task of finding a way to modify bismark brown, a compound for which malignant tumors reportedly had a remarkable affinity, for neutron capture therapy. After months of struggle, Steinfeld excitedly told Farr that he had discovered a way, but that before writing up the discovery he wanted to leave for Baltimore to pick up a boat he and his wife had just purchased and sail it back to Long Island. Although Steinfeld and his wife made radio contact with the Coast Guard en route off New Jersey, the boat vanished in a storm and the couple was never heard
from again. Though Van Slyke and Farr scoured Steinfield's notes, they never managed to decipher the secret. What the youthful and ambitious Steinfield discovered and whether it would have been workable is a mystery to this day, making it possible that a major research initiative was substantially altered by a pleasure boat shipwreck.39

Meanwhile, William Sweet of MIT, who was independently studying the possibility of neutron capture therapy, fastened onto boron as a target element and was convinced that less toxic ways of administering it could be found. Sweet, a neighbor of Brookhaven trustee Baird Hastings, was naturally led to consider the BGRR as a source of thermal neutrons, and began to collaborate on the project, convincing Farr of boron's value.

Though the BGRR was nearing completion, time remained to modify the shielding on top of the reactor (it seemed too difficult to use a neutron port on one of the reactor faces) to create a BNCT irradiation facility. The facility consisted of a pit formed by removal of several shielding blocks, in which a patient could be placed next to a small, rectangular 5 × 10 cm neutron port that looked through the shield directly into the reactor core. Meanwhile, William Hale of Brookhaven's division of bacteriology and immunology developed a transplantable brain tumor in mice that made experimental feasibility tests possible. Studies of boron neutron capture effects on mice, dogs, and pigs followed. Farr later coauthored papers on these experiments, which were the first demonstration that neutron capture therapy was capable of eliminating a tumor successfully without recurrence in mice that otherwise would have been killed by the tumor in a matter of weeks (Farr and Konikowski 1967). Toward the end of 1950, the director of the AEC's division of biology and medicine, Shields Warren, gave the go-ahead for clinical trials of BNCT on patients with advanced malignant brain tumors (gliomas).

A major incentive for the BNCT program was the abysmal prognosis for the glioblastoma multiforme (the most malignant form of glioma) patients accepted for treatment. Nothing else could be done for them, and death was sure and swift. In the 1950s, when virtually all the BNCT trials took place, the average survival after diagnosis for cerebral malignant glioma patients at the Massachusetts General Hospital (where many of the BNCT patients originated) was only several months. Today, the median survival after diagnosis is about a year. Thus the Brookhaven experiments seemed a way of studying a conceptually attractive, somewhat safe, and possibly effective method of treating patients for whom death was imminent (Slatkin et al. 1986).

On 15 February 1951, half a year after the commissioning of the graphite reactor, the first BNCT patient was treated (fig. 8.10). It was the first BNCT attempt on human beings, and the start of a trial involving ten patients over two yr. had failed to arrest the matic events. First ing blocks tempo facility. The patience to the reactor built a half dozen men like pit. Farr and borate (borax) into position over As the control roc the pit and sprint reactor to come up ominous, stentor's power is now criti until then had litt gone wrong, but a took to achieve cr. sorbing the boron tumor would have make irradiation till the reactor hissed through its shield pit, exposed to the case of the first pr actor was then sht the ambulance by

The first BNCT another lesson in pr known science wr head Lloyd Berkna ing anecdote of ho of their craft were 243.) Lear came to refused to speak w and persuaded the article until after it sidered unprofess raising false hopes Brookhaven scient the accuracy of the show restraint in pi
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mysterious and ambitious
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work on boron as a target
to administer it to patients?

Baird Hastings, was
administering thermal neutrons, and
the potential of boron’s value.

chemistry remained to modify
the technique to make it easier to use a neutron
source in the Brookhaven
radiation facility. The
scientists suggested the use of shielding blocks, in
the form of rectangular $5 \times 10 \text{ cm}$ blocks, placed into the reactor core.

In this study, a group of bacteriology and
radiobiology researchers in mice that made
experiments with neutron capture ef
tiveness. These results, published in a
journal, showed that neutron capture
therapy could achieve a significant
reduction in tumor size and a
considerable increase in survival
of patients with brain tumors.

In 1950, the director
of the Brookhaven National Laboratories, Warren, gave
the green light to proceed with advanced malignant
tumor research.

The overall prognosis for advanced malignant tumors (such as glioma) patients
was poor, with none of them surviving more than a year. Several clinical trials took place,
and some promising results were reported. The BNCT patients
showed increased survival after
treatment. These encouraging results seemed a way to treat
advanced and possibly lethal malignancies.

In conclusion, BNCT was found to be safe and effective
in the treatment of certain types of brain tumors.

It is the first

tients over two years. In each case, neurosurgery had been attempted but
had failed to arrest tumor growth. These early treatments were rather
dramatic events. First, the reactor was shut off completely and radiation
shielding blocks temporarily removed from the neutron port in the floor of the
building. The patient was then taken to the nearest hospital to
the reactor building, and then by stretcher to the top of the reactor, where
a half dozen men would lower the barely conscious patient into the
coffin-like pit. After the patient had been brought into the pit, his
head was placed in position over the port. He would then signal for
restart of the reactor. As the control rods were removed, the reactor
was decaying, and the patient was able to breathe.

The reactor power was now critical! Upon hearing the word “critical,”
Sweet’s assistants would open the lid of the pit and
in the event of a radio logic failure, they
would decouple the patient from the reactor.

The patient would then be moved to another
hospital, where he would receive further treatment.

The first BNCT treatment was performed
on a fifty-one-year-old woman, who
gave another lesson in public relations. An associate editor of
Collier’s and well-known science writer, John Lear, learned of the
BNCT project from AUI head Lloyd Berkner, who happened to be a personal friend. (For an
amusing anecdote of how Lear and other science journalists with an
exalted view of their craft were generally regarded by scientists, see Van Allen
1997, 243.) Lear came to Brookhaven, and Van Slyke,
Farr, and Sweet initially refused to speak with him. But Lear was persistent, seemed trustworthy,
and persuaded the scientists to speak, on condition that he would hold
the article until after the results were presented in a scientific forum; it is
considered unprofessional to do otherwise, given the well-known dangers
of raising false hopes about improved treatments for terminal illnesses. The
Brookhaven scientists also pointedly insisted that Lear promise to check
the accuracy of the article with them beforehand, and that Collier’s
would show restraint in publicizing the article.
Lear broke all three conditions. "ATOMIC MIRACLE" was the superheated and misleading headline splashed across the cover of *Collier's* 21 April 1951 issue; "Science Explodes an Atom in a Woman's Brain" (Lear 1951). Lear described BNL's reactor building as a "modernistic cathedral of science" that "blazed emerald sheen." And in contrast to the six atomic explosions that the U.S. set off in the first seven weeks of 1951 in its weapons testing program, Lear described the "nuclear explosions" taking place inside the woman's head as being "as quiet as the voice of conscience," and as loosing "a gleam of hope for peaceful men of good will everywhere." Lear's article is a reminder that, once upon a time, rhetorical imagery could be used to champion the achievements of reactors. In the media, it was not a given that reactors were essentially threats to humanity, yet.

*Collier's* had accompanied Lear's article with an imaginative rendition of the reactor by noted illustrator Chesley Bonestell, photographs of it being restricted prior to Atoms for Peace. The illustration gave an outraged Farr the idea of charging *Collier's* with security violations, but AEC law-

yers told him the illust case.  

The fate of the patient而 several days after quickly deteriorated and although most of the temporary alleviation of the

All in all, three groups of patients from 1951 through 1955, and a nitroglycerin group received their borated; though the bone effects, and the patient's neutron radiation. This obtained with stronger neutron exposure was in a compound, sodium pentaborate injected into the neutron port so the patient received treatment, and the treatment, however, the exposure series of treatments, another injected could be less pentaborate was injected into the patient's body significantly, some patients' all results continued to 97 days for the first group.

Farr continued to have patients and their physicians later ethical questions and he gave a paragraph from a patient's letter:

It must be clearly explained for a disease, any time no satisfactory treatment is available in the patient would not be suitable for definitive treatment and there may be some prol
yers told him the illustration was too sketchy to provide the basis for a case.\(^40\)

The fate of the patient, in fact, showed how premature the treatment was. While several days after the treatment she could speak and walk about, she quickly deteriorated and died the week the *Collier’s* article was published. Although most of the nine patients who followed her experienced a temporary alleviation of their symptoms, few ultimately fared much better.

All in all, three groups of patients were treated at the BGRR: a ten-patient group from 1951 through 1953, a nine-patient group from 1954 through 1955, and a nine-patient group from 1956 through 1958. The first group received their boron dose in the form of borax, intravenously administered; though the borax made many nauseous, it had no long-term side effects, and the patients suffered only slight skin burns from the thermal neutron radiation. This raised hopes that more effective results could be obtained with stronger doses, and in the second series of patients a higher neutron exposure was used together with a new, less toxic boron-containing compound, sodium pentaborate. Also, a twenty-ton shutter was installed at the neutron port so the reactor did not have to be shut down before and after each treatment, and the port itself enlarged to 10 \(\times\) 10 centimeters. This time, however, the exposure proved to be too high: patients in the second group suffered severe skin damage due to the high neutron dosage. In the third series, another injection method was tried so that the time of radiation exposure could be lessened while maintaining the total radiation dose; the pentaborate was injected directly into the artery that fed the brain hemisphere containing the tumor. Though this enabled the dose to be lowered significantly, some patients still suffered skin damage. Moreover, the overall results continued to disappoint. The median postoperative survival was 97 days for the first group, 147 days for the second, and 96 days for the third.

Farr continued to be enthusiastic. Still, he conveyed the risks to potential patients and their physicians, who had to sign consent forms. In light of later ethical questions about research on human subjects, it is worth quoting a paragraph from a typical letter from Farr to a physician of a prospective patient:

It must be clearly explained to the patient’s family that this is an experimental procedure for a disease, namely glioblastoma multiforme, for which at the present time no satisfactory therapy exists, that since it is an experimental procedure there are certain risks inherent in it which we believe are satisfactorily met or the patient would not be subjected to the treatment. However, as you well appreciate, absolute assurance in this regard cannot be extended. Results would suggest that there may be some prolongation of life in patients so treated. In most instances
there has been a temporary alleviation of many aspects of the symptomatology and evidence of a temporary cessation of tumor growth. Ultimately this growth has been resumed and the patient has died. Since it is an experimental procedure it is necessary also that the family be advised that an autopsy examination of the brain is expected and that the brain is to be removed for comprehensive studies to determine the degree of success of the treatment and the reason for its failure. Detailed studies done thus far on the central nervous system as yet revealed no evidence of damage to normal structures by this procedure. The decision to send a patient here must be made by the referring physician and concurred in by the family. We accept patients only from a referring physician and not directly. 41

However, the physician, while informing the family of the patient’s condition, might well follow the paternalistic doctor-patient relation of the day and not inform the patient that he or she had a malignant brain tumor. For example, the doctor might refer only to “cells suspicious of malignancy in his brain which required further attention.” 42

Meanwhile, Brookhaven scientists began to think that the neutron beam available at the BGRR was too weak for effective BNCT. One problem was that the BGRR’s thermal neutrons were rapidly attenuated; each 1.8 cm into the brain, the neutron flux was cut in half. Sweet, who had collaborated on the first two series of patients at Brookhaven, began developing a BNCT center at MIT and curtailed his collaboration with Brookhaven’s program. In 1955, the medical department had begun planning a Brookhaven Medical Center, to include a reactor, which would be designed principally with BNCT in mind and the center with the primary aim of supporting BNCT patients. In December 1955, AEC chairman Lewis L. Strauss officially announced that a new medical research center and medical reactor would be built at Brookhaven. Construction began the following year, the facility was completed at the end of 1958, and the Brookhaven Medical Research Reactor went critical the following March. Just as the BGRR was the first reactor designed in peacetime to be built specifically for research, the BMRR was the first designed explicitly for medical research.

When the reactor went operational, the BNCT program was transferred to the BMRR. With a substantially higher flux, the duration of exposure could be markedly reduced, and instead of seventeen to forty minutes it was twenty-three to three hundred seconds. A total of seventeen patients were ultimately treated by a standardized protocol at the new medical reactor between 1959 and 1961; several other patients were treated by individualized protocols.

But these results were even more disappointing than the earlier ones at the BGRR. Only one case looked satisfactory, a man with grave neurological symptoms who received a high BNCT radiation dose; these were completely reversed after the treatment. He lived 151 days after irradiation, and died primarily of metastasis to the brain. He, it turns out, was his own clinical benefit from BNCT treatment was not sustained for patients who were much less well treated within two weeks. The large doses had produced permanent brain damage in some cases.

The ten-year optimistic clinical research program was equally disappointing in three decades, the great applications of atomic energy being less dramatic (thus the title of the episode was a textbook). Possibly dangerous treatment was successful, the results were mixed, and sharp criticisms of the medical center’s failure. Later, Brookhaven would be branded as guilty of allowing radiation sickness in patients, but the reactor was being revived.

The BMRR was an extreme of experimental performance. The reactor served many purposes: it was a research center in art and archaeology, a reactor in New York City, and a center for studies of their authentic reactors.

The reactor department was Columbia and Pennsylvania University’s electric laboratory to put together a telephone laboratory of semiconductors Corporation (which had Laboratory Corporation, Aviation Development Center (General Electric), Phillips Petro
died primarily of metastasis of pancreatic cancer into the liver and abdominal lymph nodes; in his brain, at autopsy, there were no residual signs of tumor growth. He, it turns out, was the first patient ever to receive substantial clinical benefit from BNCT. But of all seventeen patients, the median posttreatment survival was only eighty-seven days. Most ominously, the four patients who were much later found to have had the largest doses died within two weeks. Autopsies revealed acute swelling of their brains. The large doses had probably contributed to their deaths by causing the swelling (Slatkin 1991).

The ten-year optimism finally crashed, and in 1961 Brookhaven's BNCT clinical research program was terminated. At MIT, Sweet's program proved equally disappointing and that work also ceased in 1961. Thus ended, for three decades, the great hopes of those who looked for quick, therapeutic applications of atomic energy to medicine. The applications existed, but in far less dramatic (thus less newsworthy) areas than immediate cancer cures. The episode was a textbook case in the perils of exploring unproved and possibly dangerous treatments for terminal illnesses. When such treatments are successful, the researchers are generally hailed as compassionate and courageous saviors of humankind; when unsuccessful, the participants can be branded as guilty of unethical, life-threatening conduct. Three decades later, Brookhaven would be sued for its early role in the BNCT effort, even as it was reviving BNCT in a much more promising form.

The BGRR was an extremely versatile facility able to stage a wide variety of experimental performances. In addition to the groups described above, the reactor served many others, and most of Brookhaven's departments besides physics were assigned holes. Chemist Ed Sayre, to cite one example of the reactor's broad research program, used the reactor for pioneering work in art and archaeology; at one time, the Metropolitan Museum of Art in New York City sent its Rembrandts to Brookhaven for noninvasive studies of their authenticity.

The reactor department also assigned holes to off-site universities including Columbia and Pennsylvania State, and many industrial concerns, including General Electric (whose research laboratory was the first industrial laboratory to put together a full-time research program at the BGRR), Bell Telephone Laboratories (which had a spectrometer and carried out irradiations of semiconductors in a special shielding tank), Westinghouse Electric Corporation (which had a low-temperature facility), the Naval Research Laboratory (conducting a magnetic core material test irradiation), Republic Aviation Corporation (a carbon adsorption experiment), and Wright Air Development Center (capture gamma studies).
### B.11 Space assignments at the BGR, 1957.

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One service provided me with a new lease on life. I went to the University of Wisconsin and then to the University of California, Berkeley, for training. During the war, I worked with Dr. William H. Triumph at the University of California, Berkeley, on the development of the atomic bomb. This was an exciting time, and it was a privilege to be part of such a great team. The work we did laid the foundation for many of the technologies we use today. It was a formative period in my career, and I am grateful for the opportunity to have been a part of such a significant event in history.
DuPont, and Bendix also used the BGRR (see fig. 8.11). All were charged at a rate set by the AEC, which sought for the lab to "recover the equivalent of the general and administrative costs which are normally associated with one of our own scientists after taking due regard of the fact that the visitor is paying directly for shared services."

The BGRR also created isotopes for hospitals and research facilities throughout the northeast. Brookhaven supplied a sodium isotope, for instance, to Harvard Medical School; samples were irradiated in the early morning, removed from the reactor at 6 A.M., taken to LaGuardia, flown to Boston by private plane, and put in use before noon. The nuclear engineering department also had an isotope development program headed by Walter Tucker. One of its aims was to develop "generators" for isotopes—devices containing long-lived radioactive materials that users outside Brookhaven could "milk" for isotopes with shorter half-lives, removing the need for constant express shipments of short-lived isotopes. In August 1954, Brookhaven sent its first generator (of iodine 132, generated by tellurium 132) to the Mayo Clinic in Minnesota. After Tucker's group had some difficulty purifying the $^{132}$I, they discovered it was contaminated by an isomer of technetium known as $^{99m}$Tc. Further research showed that $^{99m}$Tc was an ideal material for a diagnostic tracer, and soon Tucker and his group began to develop a generator for it, reporting on their work at an American Nuclear Society meeting in Los Angeles in June 1958. They sought to patent the device, but the AEC balked. "The product will probably be used mostly for experimental purposes in the laboratory," it wrote in turning down the application. "On this basis, no further patent action is believed warranted." The agency misjudged. Three years later, in 1961, the Argonne Cancer Research Hospital ordered a $^{99m}$Tc generator, the first of a torrent of requests as the advantages of $^{99m}$Tc for research and clinical use became apparent. A Technetium Club was formed to facilitate dissemination of the generators. By 1965, several companies asked Brookhaven to cease distributing the generator so that they could take over the business, and the lab complied. $^{99m}$Tc gave a huge push to nuclear medicine, and in one form or another "is the predominantly used radionuclide in the several-million nuclear-medicine procedures performed worldwide annually" (Richards et al. 1982, 793).

Service irradiations were done on everything from piston rings to seeds. One service irradiation at the BGRR must surely be the only reactor activity that may have been initiated by a maharajah. According to a story that made the rounds in the early 1950s, an Indian maharajah commissioned Harry Winston, the leading diamond merchant in New York City, to create a necklace entirely fashioned out of green diamonds. Whatever the truth of the story, a consultant to Winston named Fred Pough, former head
of the mineralogy department at the American Museum of Natural History in New York, actually did contact Brookhaven about using the BGRR to irradiate diamonds. (Green diamonds are generally due to natural radiation rather than trace impurities. After an initial short-lived, fifteen-hour half-life activity decays away, irradiated diamonds are safe and cannot be distinguished from naturally occurring green diamonds.) Fox reluctantly complied when the AEC's isopes division gave the merchants permission to “study colorations induced by irradiation in precious stones” and “observe changes in irradiated gems.” But after more diamond merchants asked to use the reactor he protested to the AEC that it was unwise to use a government facility in this way (“nature ought to hold the patents,” he grumbled). The AEC deliberated, but decided it could find no reason for placing gems in a different category from other service irradiations.48 Merchants were charged on the basis of the standard schedule—pneumatic tube irradiations in a single day shift for a single client were $10 for a short irradiation, $50 for an entire day plus $25 handling charge.49

The Pile: 1957–1961

It was difficult to prevent the BGRR fuel elements, and those of any reactor fueled by natural uranium, from occasionally leaking. Each of the eleven hundred elements was eleven feet long and weighed about a hundred pounds. Once every ten-day cycle, when the reactor was shut down and then restarted, the element would heat up and expand, then cool and contract. If cooled suddenly, the heavy weight of uranium kept it from fully contracting, causing stress on the container. Even a tiny crack in the aluminum container could oxidize the uranium metal, widening the split, and cause volatile fission products contained in the irradiated uranium fuel to discharge into the cooling air. An innovative leak detection system, developed by Borst, bathed the uranium inside each element with helium, usually caught leaking elements quickly. Another check was radiation monitors in the exhaust air filters. The first sign of a leaking element would be a draw on the helium system, and no oxidation could take place because the continued helium pressure prevented exposure of the metal to air, giving reactor operators time to remove the element. If the leak was tiny, this could safely be postponed until the next scheduled shutdown.

Every now and then one of the “leakers,” as they were known, was more urgent. The first such episode took place on 2 January 1952. Twenty minutes after a regularly scheduled startup, a drop in helium pressure signaled a leaking element. Partly due to pleas from “many research people anxious to use the reactor decided to wait a bit longer for prompt repair, during the clear weather, a rate that view, the BGRR both the extent a elements were expe rimental in the next few months, little to the natur e. The fissile material used in the reactor to be stored was the same as the old ALR-1 reactor, in the vicinity, in sediments of around 1 meter in depth, contaminated with radioactive waste from the reactor. The area was declared a no-take zone, and the contaminated sediments were removed. The reactor was then dismantled and transported to a remote location for further decontamination.
to use the reactor for the remainder of the day shift,” the reactor operators decided to wait until 5:00 before shutting down the reactor to discharge the element. That proved a mistake. At 3:40, alarms in the exit filters signaled the presence of fission products in the exhaust, and the reactor was shut down. After removal, the leaking element was found to have two small cracks, each a few inches long, in which black uranium oxide was clearly visible. The removal procedure was a “dirty” operation itself, and resulted in gross contamination of tools and clothes that were inadvertently tracked to other parts of the building. The exhaust filters had caught virtually all fission products, and no sign of additional contribution to the normal background radiation appeared in the radiation monitors scattered around the site.50

Nonetheless, the episode prompted operators to revise their procedures for prompt removal of leaking elements and for reducing contamination during the cleanup. But two more leaks showed up in the next two months, a rate that Powell described as “somewhat ominous.” After a review, the BGR’s engineers revised its operating procedures to minimize both the extent and frequency of the temperature changes to which the elements were exposed.31 Still, a half-dozen or so serious leaks developed in the next few years. Although the released fission products contributed little to the natural background radiation, the fuel element discharge process often resulted in contamination of the entire building, which required the reactor to be shut down for several days. When discharged to the fuel storage canal, the leaks also contaminated the canal with fission products, including long-lived strontium 90 (half-life twenty-eight years) and cesium 137 (thirty-three years), some of which eventually showed up in the liquid waste discharge of the laboratory, and plumes from storage tanks, years after the old elements were replaced. Years later, too, small amounts of contamination also showed up in soil and groundwater in and around the reactor, in the vicinity of waste decontamination and concentration facilities, in sediments from the sand filter beds, and certain old landfills. The airborne amounts of strontium 90 and cesium 137 released by the lab and deposited on land were small compared to the levels due to the atmospheric weapons tests then taking place in Nevada and in other parts of the world. And the liquid radioactivity discharged into the Peconic River was a fraction (generally 2 to 15 percent) of the permissible federal limit. The principal source of radiation, above natural background levels, in the Long Island area was almost certainly atmospheric tests of nuclear weapons. Other occasional sources of accidental release into the environment included an occasional broken pneumatic tube or sample container and defective tubes in the evaporation plant.52
The problem of leakers was addressed indirectly, in the course of the BGRR’s only important upgrade. At a visiting committee meeting of the department of nuclear engineering in January 1954, Alvin Weinberg mentioned the possibility of using enriched uranium as fuel. Enriched uranium would substantially increase the flux while allowing the reactor to be run at a lower power. Adapting the reactor would initially cost about $1 million but the savings in operating costs would be about $400,000 a year. (Argonne's CP-3 had switched to enriched fuel in 1950; Holl 1997, 113.)

Haworth leap at the opportunity, and put the department of nuclear engineering to work trying to exploit it. Modifying the fuel plate design of the Materials Testing Reactor in Idaho, which in turn was a version of the design of Oak Ridge's Low Intensity Testing Reactor, Powell devised an enriched fuel element. They were made up of thin plates of 5 percent alloy of $^{235}$U and aluminum, and the plates served as their own cooling “fins,” so to speak. The MTR and LITR were water cooled, and because air cooling is less efficient the BGRR plates had to be spaced further apart, and curved into an S shape to fit into the BGRR's smaller fuel channels. Fox drafted a proposal, and in July Haworth was able to ask the AEC to convert the reactor to enriched fuel elements. To avoid a long shutdown, conversion took place in several stages between December 1956 and March 1958, when loading the new elements was complete and the BGRR became the first large research reactor to use enriched uranium. The maximum central neutron flux increased fourfold, but the area in which the fuel elements were located decreased, removing the availability of a number of experimental ports. While eliminating the problem of leakers—though defective elements still caused problems—the upgrade did increase the concentration of $^{40}$Ar in the cooling air discharge, from about 7,000 to 20,000 curies a day. But these levels were still well within AEC limits.

Over time, the acceptable emissions levels at nuclear facilities, and the standard practices for handling radioactive materials and wastes, have changed dramatically. One result of this “cultural shift,” as it is often described, is that practices acceptable in the past are now considered unacceptable. Many of these practices—such as the so-called drag jobs, when highly radioactive material was put on the back of trailers in containers and driven, with escorts, to the waste management areas—would not be done today in the same manner. Another result of the changed culture is the existence, at Brookhaven and at numerous other sites with nuclear facilities, of areas of soil and groundwater containing amounts of contamination that are unacceptably high by today’s standards. Brookhaven has attempted to identify, study, and remediate them where practical, though the necessity to do so sometimes has had painful consequences. In the fall of 1997, for instance, scientists discovered that rainwater infiltrating the old ducts of the

**The HFBR**

In 1954, with BGRR, Hugh several reacto (Chalk River, BGRR). In ac (the one at Ca taking that of a reactor stud, reactor,” to county. Hastings, Guri told the comm submitted in th year 1959.”
In the course of the 1950s, the committee meeting of the Technical Advisory Panel, Enriched uranium programs, and the reactor to be run cost about $1 million and $400,000 a year.53 (Holl 1997, 113.)

The development of nuclear engineering of the fuel plate design of the reactor was a version of the original, Powell devised an alternative, using 3 percent of 5 percent alloying by cooling "fins," so that the reactor was not because air cooling remained separate, and curved channels, Fox drafted a plan for the AEC to convert the reactor to a shutdown, conversion December 19, 1956, and March 1958, when the BGR was in the maximum central 1,500 to the 3,000 number of experiments, reactors—though defects were rare—increased the concentration and $5,000 per 1,000 N/C limits.54

The reactor facilities, and the processes of instruments and wastes, have been called drag jobs, when the reactors are in containers and the reactors would not be done in the traditional culture is the primary field of public relations with nuclear facilities; the reactor was contaminated by the BGR. Brookhaven has attempted to optimize the reactor for the fall of 1997, for the need to close the old ducts of the reactor.

BGR was producing pools of radioactive water, adding to large amounts there; before the ducts were finally sealed, an inch of rainfall at the lab created 500 gallons of contaminated liquid that had to be disposed of at a cost of $15–17 a gallon. Because no budgetary provision had been set aside for this cleanup, funds for it were taken partly out of the overhead that normally would have gone into research, causing the programs of some individuals to suffer. For these scientists, thanks to the unfortunate legacy of past practices, it was literally raining on their research.

In 1989, Brookhaven became a Superfund site—less because of the total amount of contamination (other sites on the Superfund list had vastly higher levels of contamination) than because of the risk involved in the lab's location above a sole source aquifer. The furious controversy about the lab's emissions that would develop toward the end of the following decade would concern the hazard, if any, posed by the residual amounts of plutonium, strontium 90, and cesium 137 that the BGRR., and possible long-term effects of the 14Ar and emissions from the reactors.

These health concerns raised questions about the adequacy of the contemporary regulations and standard practices, particularly in the possible relation of any or all these to an alleged increase of breast cancer on Long Island. But judging these requirements and standard practices by today's standards would require analyzing them in the context of present-day interests, agendas, and knowledge, and hence must be deferred.

The HFBR

In 1954, with an eye to the future only shortly after completion of the BGR, Hughes began to pressure Haworth for another reactor. Already, several reactors had equalized or bettered the BGR for cross-section work (Chalk River, in Ontario, had a reactor with a flux several times that of the BGR). In addition, the resolution of accelerator-based neutron sources, the one at Columbia's Nevis laboratory, for instance, was rapidly overtaking that of reactor-based sources. In August 1956, Haworth appointed a reactor study group to examine "the question of a high-flux research reactor," to cost $10 million, chaired by Hughes and including Dienes, Hastings, Gurinsky, Powell, and reactor theorist Jack Chernick. Haworth told the committee to come up with a "definitive budget proposal to be submitted in the spring of 1957 calling for construction funds in the fiscal year 1959." The committee met weekly to discuss issues such as fuel loading and unloading, experimental arrangements, and so forth. The group decided early on to optimize the new reactor for intense external beams of neutrons, which were especially useful for neutron diffraction. Optimizing reactors for specific functions was a new approach. Existing
research reactors were multipurpose, like the BGRR, and incorporated a number of design compromises to satisfy different groups of users. Oak Ridge, which completed a new reactor in 1957 (the Oak Ridge Research Reactor, known as the ORR), was also planning a new one to be optimized for the isotope production of transactinides, the High Flux Isotope Reactor (HFIR). Argonne’s scientists, meanwhile, began planning a high-flux Argonne Advanced Research Reactor, or A^{3}R^{2}. In November 1958, members of those three labs, and scientists from the University of California, met with AEC officials for a general discussion of future high-flux research facilities (Holl 1997, 236).

Chernick was a key figure in Brookhaven’s reactor study group, for he was able to translate theoretical specifications into practical design concepts. In late 1956 and early 1957, the committee reviewed two major types of reactors under consideration: a Chernick-designed, 10-megawatt D_{2}O-moderated reactor with small core, and a sodium-cooled, 100-megawatt reactor of slightly larger volume. It soon became clear that the first was superior for the lab’s purposes, with the second costing significantly more than $10 million and involving many engineering difficulties.

Chernick’s work, completed in 1957, was a breakthrough in reactor design. Apart from so-called fast reactors, reactors depend on thermalizing (slowing down) neutrons in a moderator to the energy where they can cause uranium atoms to fission. In conventional reactors such as the BGRR, the moderator is placed between the uranium fuel elements, which are spaced widely enough apart so that the neutrons emitted from one element have time to thermalize during the trip to the next element. Chernick’s idea was to put all the fuel elements closely together and surround them by a large vat of heavy water. When first produced, most neutrons would be too energetic to cause fission and would leave the core area into the heavy water moderator. But it would take them longer to slow down in heavy water than in regular water, precisely because it’s heavier: when one billiard ball collides with another of about the same mass, the two tend to split the energy between them, on the average—but when striking a much heavier object, it tends to rebound elastically, keeping its energy. A further advantage of heavy water is that the deuterium in it has a lower absorption cross-section than hydrogen, because one neutron is already tacked on to its proton. Thus the neutron flux would peak outside the core (the core is “undermoderated”), slowing down gradually in the heavy water, though enough thermalized neutrons would return to sustain the chain reaction, resulting in a remarkable flux distribution that is illustrated in figure 8.12 (Auerbach et al. 1958).

By contrast, Oak Ridge’s HFIR was a “flux-trap” reactor, which traps the maximum flux in the dead center of the reactor for isotope production. It was originally thought that the HFIR might interfere with other user facilities, but it proved to be an excellent reactor for isotope production. Fast neutrons were used for transmutation reactions, but the neutron flux was too low for most other applications. The neutron flux was distributed in a bell-shaped manner, with the peak flux occurring near the core region. The neutron flux profile is shown in figure 8.12 (Auerbach et al. 1958).
It was originally designed without beam tubes, which engineers feared might interfere with its central flux intensity, but Weinberg insisted that the reactor have beam tubes for neutron scattering, and some were installed.

Kouts and company did mock-ups of Chernick’s designs, while Hastings kept looking for ways to maximize slow neutrons and minimize fast ones. Fast neutrons were a liability for neutron scatterers; not only did they contribute unwanted background, they also forced experimenters to install much extra shielding. Here Hastings came up with a design innovation: mount the beam tubes tangentially, thus reducing the high-energy neutron background. “Thermal neutrons are going in all directions,” Hastings said. “So whichever way the beam tubes point, you get the same number. But if you point the tube tangentially, so they don’t look at the core, you won’t get the fast neutrons.”

The five designers—Chernick, Hastings, Joseph Hendrie, Kenneth

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8.12 HFBR neutron profile. The calculated (and for the thermal neutrons, measured) neutron flux density in neutrons per square centimeter per second at different distances from the core, for five groups of neutrons. Group I are the most energetic neutrons, which have just come from fissioning nuclei. Groups II, III, and IV contain neutrons that have slowed down through collisions with heavy water nuclei in the moderator. Group V, the thermal neutrons, have lost all of their fission energy and are in equilibrium with the motion of the surrounding atoms. The significant feature of the HFBR was that its thermal neutron flux peaks outside rather than inside the core, so that they can be most efficiently used by experimenters.
Downes, and Kouts — applied for and received a patent on the new system. They submitted their first proposal to the AEC in July 1957. The AEC had been on an austerity budget for two years, and the response was not encouraging. But on 4 October 1957, a tiny Soviet satellite named Sputnik altered the situation. Worried about declining American superiority in science, the U.S. Congress voted to include extra money for research in the AEC’s budget. In March 1958, the AEC asked Brookhaven to resubmit its reactor proposal (another beneficiary was Oak Ridge’s HFIR). The lab then contracted with General Nuclear Engineering Company for a conceptual design study of the heat transfer system, on the basis of which the lab could ask the AEC for money. General Nuclear was run by Wally Zinn, one of the principal members of the Chicago part of the Manhattan Project, father of the CP-5 at Argonne, who had gone into industry. Heat transfer was the crucial factor in determining the ultimate performance of the reactor; how fast one could get the heat out of the core determined the upper limit of the flux. The General Nuclear study concluded that the power level would have to be twenty megawatts and that the reactor could be built for
$10 million. Kouts's group conducted critical experiments on the design between July 1958 and April 1959, allowing finalization of features like core size and shape, fuel elements, and flux. Haworth struggled with the AEC for the lab to hold the prime contract, but in mid-1960 the AEC announced that it would hold the prime contract. Ground was broken in September 1961 (fig. 8.13). 59

Donald Hughes never lived to see the groundbreaking. He was a diabetic but a hard drinker, and in the late 1950s circulatory problems began to take a toll on his health. In 1960, he died a week after suffering a heart attack. After his death, Palevsky took over the neutron physics group, and the Sigma Center was moved from the physics to the nuclear engineering department.

Although some groups continued to mount major efforts at the BGRR during the 1960s, the HFBR's impending completion caused many to spend their time preparing experiments there. After the HFBR came on line, in 1965, there was little reason to keep the old reactor running. Experiments could normally be done faster and more efficiently on the new reactor. The BGRR was put to certain specialized uses, such as testing out chemical engineering loop concepts, but there were not enough of these to justify its continued operation. It was shut down in June 1968, periodically reactivated over the next few months, and then shut down for good in 1969. Over its eighteen-year lifetime, it supported an experimental community that was exceptionally diverse in its people, auxiliary instruments, and scientific fields. Its closing heralded the end of an era for reactors; henceforth, they would be much more specialized tools.

While the graphite pile and support structures were preserved as part of a display in an exhibit center, all fuel elements were removed with the last batch shipped to the Savannah River reprocessing plant in 1972. In 1986, the BGRR was designated a nuclear historic landmark by the American Nuclear Society, and a bronze commemorative plaque can be seen on the reactor's south face.