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BROOKHAVEN LECTURE SERIES

The Nuclear Reactor Comes of Age

JACK CHERNICK

Number 31

November 13, 1963

BROOKHAVEN NATIONAL LABORATORY

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FOREWORD

The Brookhaven Lectures, held by and for the Brookhaven staff, are meant to provide an intellectual meeting ground for all scientists of the Laboratory. In this role they serve a double purpose: they are to acquaint the listeners with new developments and ideas not only in their own field, but also in other important fields of science, and to give them a heightened awareness of the aims and potentialities of Brookhaven National Laboratory.

Before describing some recent research or the novel design and possible uses of a machine or apparatus, the lecturers attempt to familiarize the audience with the background of the topic to be treated and to define unfamiliar terms as far as possible.

Of course we are fully conscious of the numerous hurdles and pitfalls which necessarily beset such a venture. In particular, the difference in outlook and method between physical and biological sciences presents formidable difficulties. However, if we wish to be aware of progress in other fields of science, we have to consider each obstacle as a challenge which can be met.

The lectures are found to yield some incidental rewards which heighten their spell: In order to organize his talk the lecturer has to look at his work with a new, wider perspective, which provides a satisfying contrast to the often very specialized point of view from which he usually approaches his theoretical or experimental research. Conversely, during the discussion period after his talk, he may derive valuable stimulation from searching questions or technical advice received from listeners with different scientific backgrounds. The audience, on the other hand, has an opportunity to see a colleague who may have long been a friend or acquaintance in a new and interesting light.

The lectures are being organized by a committee which consists of representatives of all departments of the Laboratory. A list of the lectures that have been given and of those which are now scheduled appears on the back of this report.

Gertrude Scharff-Goldhaber

The drawing on the cover is taken from a 5th Century B.C. relief on the Acropolis in Athens, the "Dreaming Athena," by an unknown sculptor.

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INTRODUCTION

I am pleased to introduce the thirty-first Brookhaven Lecture, which will be presented by Jack Chernick of the Nuclear Engineering Department. Mr. Chernick started out to become a biologist and entered Rutgers University for that purpose. He quickly found that his real interest in life was mathematics and went to the University of Chicago, where he received a Bachelor's degree in mathematics. He then went to Brooklyn College for his Master's degree, which he received in 1941. At that time, like so many others, he was caught up and swirled around by the war effort. He went to the Aberdeen Proving Grounds and worked on what is called the theory of interior ballistics.

He left Aberdeen in 1947 and came to Brookhaven to work with Irving Kaplan on reactor physics in the design of the Brookhaven Graphite Research Reactor, the first big reactor design effort after the war. He has stayed with us ever since, and at present he and Herbert Kouts are jointly Associate Heads of the Reactor Physics Division in the Nuclear Engineering Department. Mr. Chernick has been active, of course, in all our problems during these many years, such as the Liquid Metal Fuel Reactor and the various research reactor designs, and he was the initiator of the concept of the High Flux Beam Research Reactor, which we hope to begin operating next spring.

Among Mr. Chernick's scientific accomplishments, there are two which I personally feel are extremely important. One is the resolution of the problem of the absorption of neutrons during slowing down in a reactor lattice system, to which he brought a new viewpoint – a new formulation of the problem. As a result, many very able people both here and abroad have been able to make a great deal of progress by using this conceptual basis as a starting point. I believe that he has brought a similar viewpoint to the understanding of reactor stability by introducing the concept of the geometric representation of reactor stability. This concept will also allow many people to do fruitful research on the many problems in reactor stability.

WARREN WINSCHE

The Nuclear Reactor Comes of Age

Tonight we are going to talk about nuclear reactors, or atomic piles as they used to be called, and some of their uses. We will show you the interior of a typical reactor and describe the achievement of the first chain reaction. We will then discuss the present applications and the future importance, to all of us, of the nuclear reactor. Finally we will discuss Brookhaven's role in these developments and recall its past achievements.

I came to Brookhaven in 1947 to help Lyle Borst and Irving Kaplan in the design of the Brookhaven Graphite Research Reactor with which all of you, I am sure, are familiar. At the time, I found that the state of the existing pile literature was (to quote myself) "chaotic, incomplete, and full of rough and ready approximations." The literature at that time was mainly the literature of the Manhattan Project. On September 1, 1948, I wrote a memorandum outlining some of the theoretical problems which could be undertaken by the Pile Theory Group (now the Reactor Physics Division) at Brookhaven if it were continued beyond the Project. In this memorandum I went on to suggest that "the solution of many of the present pile problems may be expedited by the use of large computing machines. With the aid of such machines some pile problems have recently been attacked by purely statistical investigations of scattering and capture processes. These methods deserve to be explored further. The convenient mathematical fictions of one or two groups of pile neutrons must eventually give way to a more realistic appraisal of neutron energy spectra. Theoretical studies will suggest worthwhile experiments in this direction, and conversely the by-products of experimental research will suggest profitable lines of theoretical work."

Of course, all these predictions have come true. The use of high speed electronic computers at Atomic Energy Commission Laboratories has, as you know, revolutionized more than just the field of reactor physics. The Monte Carlo methods, which originated at Los Alamos, are now routine in investigations of particle transport in complex media. In addition, while reactor physicists have borrowed heavily from the fields of physics and mathematics, they have also made some contributions to these fields. However, this is another subject and can be discussed in other Brookhaven Lectures, possibly by some of our younger people who are currently very productive in these areas.

At Brookhaven we were fortunate in being able to set up an experimental reactor physics program at an early date as a by-product of a feasibility study for the Atomic Energy Commission of water moderated, slightly enriched uranium reactors. The original application that the AEC had in mind at the time does not matter and has long since been forgotten by almost everybody concerned. What does matter is that the experimental reactor physics group that was formed under the able leadership of Herbert Kouts has produced over the past dozen years a comprehensive body of new experimental techniques and of basic experimental data on fissionable assemblies, and in particular on water moderated, enriched uranium fueled assemblies.

Some of the money allotted to the Nuclear Engineering Department for this work was, I think, wisely spent in attracting a number of young theoretical physicists into the Reactor Physics Division. Finally, to complete the happy ending, the water moderated, enriched uranium reactor has turned out to be a remarkably successful and flexible nuclear power source and now occupies a central role in the United States program of peaceful uses of atomic energy.

Before I leave this theme, I would like to pay tribute also to the late Donald Hughes' contributions to reactor physics. I have tried to indicate the foolishness of prematurely conceived applications and of narrow objectives even in applied scientific research, and the wisdom of broad experimental and theoretical programs. It is these programs which are elevating the field of reactor physics to a well-verified science from the state of semi-empiricism in which it was left by the great but hurried physicists of the Manhattan Project. Parenthetically, we owe a large debt to some of these scientists, and particularly to Eugene Wigner, for their continued interest in reactor problems. However, we have not yet mentioned a most important

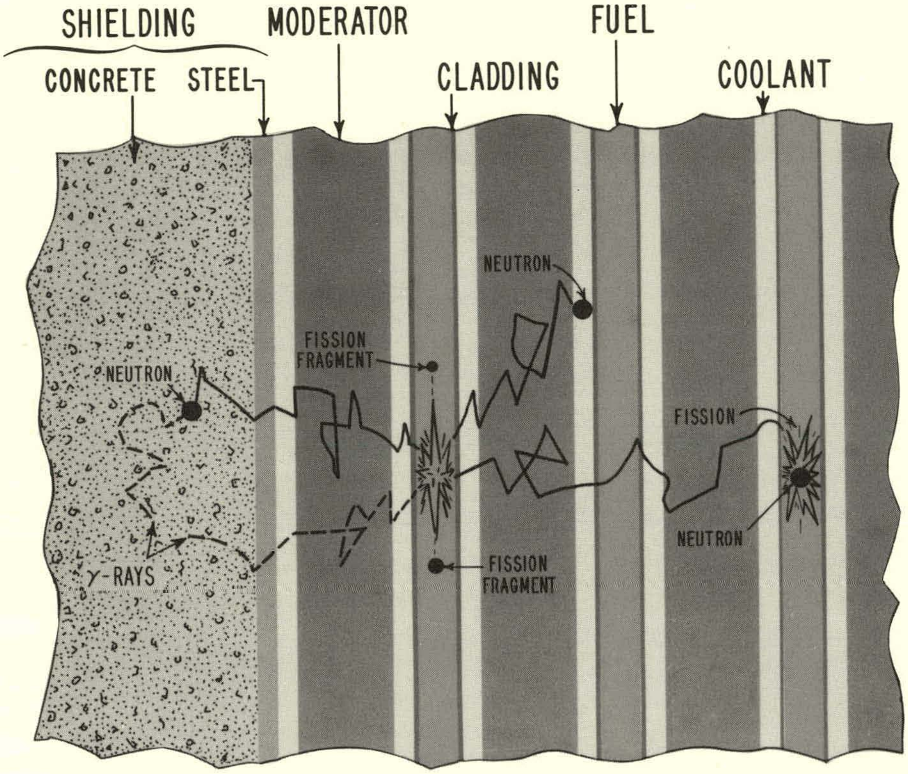

Figure 1. Components of a typical nuclear reactor.

ingredient, the cross section data without which calculations of the integral behavior of nuclear reactors would be impossible. It was Donald Hughes, with his boundless energy and enthusiasm and his genius for organization, who dramatized the importance of neutron cross sections and inspired their accurate measurement. His cross section compilations, BNL 325 and BNL 400 and their supplements, became international bibles for neutron physicists and reactor physicists alike.

I would like also to recall here some of the benefits of interactions which occurred between neutron physicists and reactor physicists even during the days when our work was classified. In 1949, Eugene Wigner spent the summer at Brookhaven as an advisor to the Pile Project. At the time he was concerned, for reasons which will become clear a little later, with the fact that the neutron capture-to-fission ratio of Pu^{239} was not constant at intermediate energies but was actually found to increase with decrease in neutron energy. He suggested that the solution of this problem might lie in the statistics of the distributions of the neutron and fission widths.[1] The first quantitative attempt at fitting the statistical distributions for U^{235} was carried out by Sophie Oleksa, a Brookhaven reactor physicist. Later, two young theoretical neutron physicists, one at Brookhaven and the other at Los Alamos, arrived at a theory for the neutron width distribution which is now called after them, the Porter-Thomas distribution. Today, thousands of neutron resonances have been resolved by experimental neutron physicists and have been used not only in improvements of statistical theories of the nucleus but also in the development of accurate analytical methods of calculating the resonance absorption of neutrons in reactors.

As another example, neutron spectrometer data obtained at Columbia in 1952 indicated a sharp rise in the capture-to-fission ratio of U^{235} at thermal energies just above 25 millivolts. This result was incompatible with measurements of the temperature coefficient of the Brookhaven Graphite Research Reactor, which we had taken during its 1950 start-up. In the end it was Harry Palevsky of Brookhaven, again a neutron physicist, who devised a direct measurement of the capture-to-fission ratio of U^{235} which showed, as we had expected, that it was essentially constant in the immediate neighborhood of 0.025 ev.[2]

THE INGREDIENTS OF A NUCLEAR REACTOR

Next, for those of you who are not too familiar with reactors, I would like to explain briefly their main ingredients. Figure 1 shows the components of a typical nuclear reactor as a reactor physicist would visualize it. It is stripped down to the point that no structure is shown or control rods or the reflector, which are normal components of a reactor, but a periodic arrangement or lattice of fuel elements is shown. The coolant and the fuel are separated by a thin cladding, which separates both the fuel and its fission fragments, which have a very short range, from the coolant. The final component important to most reactors is the moderator. The purpose of the moderator, which contains light elements such as hydrogen, deuterium, or carbon, is to slow the fission neutrons down to lower energies at which they can be absorbed in the fuel and produce further fissions. The moderator, at least in Fermi's day, did one other important thing. The resonance absorption of neutrons in the fuel would have killed off the chain reaction in the graphite, natural uranium system, about the only practical system available at the time. For this reason, Fermi and his collaborators thought of the idea of lumping the fuel. This gives rise to a reactor lattice in which the fuel elements are periodically repeated and then separated by the moderator where the neutrons can slow down and stay away from the fuel during intervals of time when they are subject to resonance capture. The sketch shows a fission event in which three neutrons are produced; one is shown being absorbed nonproductively, one leaks out of the core, and only the third gives rise to further fission. It is clear that at least one neutron per fission is needed for the chain reaction to proceed even in an ideal, nonleaking, noncapturing medium. For reasons which we shall develop later, it is fortunate that nature has been bountiful and more than two neutrons are produced on the average. In addition Figure 1 also shows some gamma rays. A prompt gamma ray produced in fission is shown entering the shield. A secondary gamma ray, produced by neutron capture in the biological shield, is also shown. The properties of gamma rays are important in reactor shield design. There are other inhabitants of a reactor which are not shown here, such as beta particles, neutrinos, and alpha particles. These do not cause the reactor designer too much in the way of problems, so we have omitted them. I have called the neutrinos inhabitants, although tourists would be a better description of them.

Figure 1 shows a plate lattice, but a reactor lattice could also be a two-dimensional array, composed for example of rods, or it could even be three-dimensional as it was for the first and apparently the last time when Fermi put his reactor together by using a cubic array of uranium lumps in graphite. However, the only really essential component of a reactor is the fuel, which must contain a fissionable material such as natural uranium or some artificially produced fissionable material such as U^{235}, which becomes available by separation from ordinary uranium through a diffusion plant. One can also use plutonium or U^{233}, which are themselves produced in reactors. Divergent chain reactions in completely unmoderated, fissionable assemblies, for example in a bare metallic sphere of plutonium are, of course, possible. These are either fast reactors or atomic bombs, depending on whether they have been designed for controlled operation or for extremely rapid assembly and disruption. Perhaps the only point the average person should keep in mind here is that there is quite a difference between the atomic bomb and the worst accident that can happen even in a fast reactor, and there is really no comparison between the two. The nuclear energy release in possible fast reactor accidents is of the popgun variety in this comparison. In fact, one problem in the design of power reactors for space missions today is the present requirement of destroying them, or at least destroying the fuel, before re-entry into our atmosphere. The National Aeronautics and Space Administration program has apparently considered every conceivable alternative except that of carrying an atomic bomb aboard such a space vehicle.

It may also be remembered that the final particles shown in Figure 1 are fission fragments, of which two appear – the usual number. The fission fragments are the bugaboo of the atomic power era. Their range is quite short, but they carry off about 80% of the total energy released in fission, which is rapidly dissipated as heat in the fuel. Fission fragments are neutron heavy and undergo an average of about three beta decays, thus increasing the equilibrium curie content (i.e., the number of disintegrations per second) in the reactor. In a modern power reactor the fission products generate several billion curies, compared to the few precious curies that constituted the world's entire radium supply before the birth of the nuclear reactor. Although the totals are not quite so impressive after the reactor is shut down because of the rapid decay of the bulk of the fission products, nevertheless the reactor represents a Pandora's box which must be kept locked against the release of its fission products.

THE FIRST NUCLEAR REACTOR

I would now like to take you back to December 2nd, 1942, and the achievement of the first chain reaction. I was myself at the Ballistic Research Laboratory in Aberdeen Proving Ground, Maryland, at that time with my wife and our first-born, an infant daughter. Our daughter has herself just "come of age" and has voted in her first election. In Chicago, on December 1, 1942, the job of erecting the West Stands critical experiment on which Fermi and his co-workers were working had been completed. Two crews, one under Walter Zinn and the other one under Herbert Anderson, had been working for weeks piling up a large, dome-shaped structure of graphite blocks supported by wooden beams. Alternate layers of the graphite bricks were hollowed out to accommodate lumps of natural uranium and uranium oxide. When Zinn left that evening he was sure that when Fermi came in the next morning he would be able to make the assembly go critical by pulling out the control rods.

Figure 2 shows an artist's reconstruction of the event. You will probably be able to recognize, in addition to Fermi, both Walter Zinn and Arthur Compton. Zinn is shown holding his newspaper, Fermi is apparently trying to decide what the reactor period is with the aid of a slide rule, and to his left is Arthur Compton. Down below the balcony is George Weil moving the control rod out under Fermi's orders. There were two other control rods or safety rods, which were already out of the pile at this time. One, operated from the balcony, was an automatic rod. The other one, called ZIP, was tied by hand to the balcony somewhere with a piece of clothesline, and the idea was that

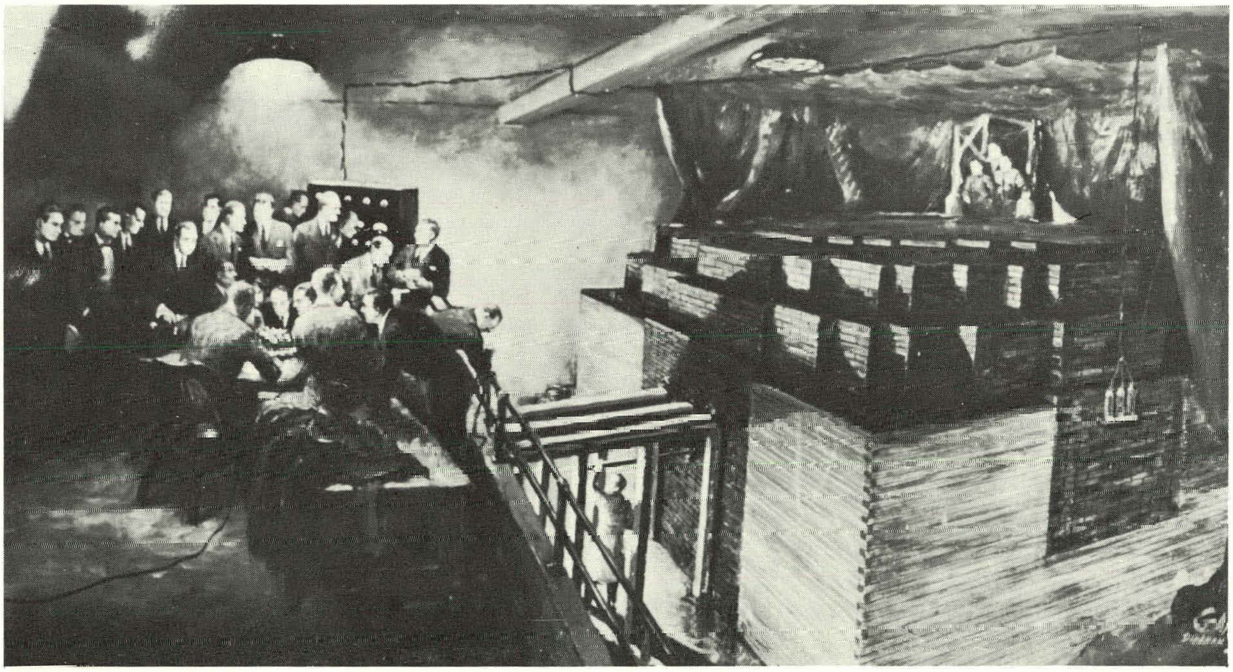

Figure 2. The first chain reaction.

if anything happened, Zinn would attack the clothesline with an ax. There were some weights, not shown in Figure 2, attached to a rope which would then have pulled the ZIP rod into the reactor. The shroud surrounding the reactor, and its attached weights, were part of a square balloon built for the Project by puzzled engineers of the Goodyear Tire and Rubber Company. If necessary to achieve criticality, the reactor could have been evacuated to remove the nitrogen, a neutron poison, from the pores of the graphite. One can see that there was quite a bit of conservatism and anxiety about this reactor even though Fermi must have known, as he slowly approached criticality, that there were a considerable number of delayed neutron emitters produced which would make control of the reactor extremely easy. The physicists here will probably remember that John Wheeler had predicted such delayed neutron emitters during his work with Niels Bohr when Bohr first arrived in this country. Thus they knew that the emitters would be there, but they may have been worried about just how many, whether there were really enough to provide a comfortable edge in controlling the reactor. One can sense this also from the fact that the three men shown standing on a platform overlooking the reactor are holding bottles of cadmium salt solution. They include Harold Lichtenberger, Warren Nyer, and Alvin Graves. A fourth member of this "last ditch" brigade, Albert Wattenberg, is not shown. While it is not clear from the sketch what the men were supposed to do with the bottles, I am informed that they carried hammers to smash them, if necessary. At any rate, any fears were groundless, and during the afternoon of December 2, 1942, Fermi watched the reactor power rising on a very slow period. He watched the neutron count rise for something of the order of a half hour on a free period before he finally ordered the reactor shut down for the day.

That was the first chain reaction. I might add a little concerning the records, which were few, of this historic event. There exists a picture of the partially loaded reactor taken during the addition of its 19th layer of graphite, and also the trace of the galvanometer which recorded the reactor's power against time.[3] Wigner had brought in a bottle of Chianti wine to celebrate the occasion appropriately, and from signatures on the label it was deduced that 42 scientists had been present. Last year the 39 surviving scientists were invited to Washington during the Winter Meeting of the American Nuclear Society to celebrate the end of the second decade of the atomic energy era and to be congratulated in person by the President of the United States.

THE NEXT TWENTY-ONE YEARS

What about the next twenty-one years? First of all, the immediate military applications of a controlled chain reaction were not overlooked. Even before Arthur Compton made his now famous announcement, "The Italian navigator has landed in the New World," the du Pont Company had been called upon to design and build the huge Hanford Engineering Works for the production of plutonium. The United States Atomic Energy Commission publishes an annual listing of nuclear reactors. As of December 31, 1962, it listed eight graphite moderated production reactors as operable at Hanford and five heavy water moderated reactors as operable at the Savannah River Plant. Only the power level of these huge reactors remains classified. However, the largest United States nuclear electric power plant being built, the 800-electrical-megawatt New Production Reactor (NPR) at Richland, Washington, over which there has been so much debate in Congress, is an offshoot of the Hanford production reactors.

The events at Alamogordo, Hiroshima, and Nagasaki shortly thereafter illustrated the prodigious power of this terrible infant when it was uncontrolled. It was little wonder that a number of scientists decided to turn their backs on their creation and to concentrate on more pleasant pursuits. For the first few years after the war, the importance of early peacetime applications of nuclear reactors was generally belittled. The usefulness of radioactive isotopes as tracers was recognized, but a single reactor could turn out the total amounts needed. And, of course, a few scientists envisioned Brookhaven National Laboratory with its research reactors and accelerators serving the great northeastern universities. However, the fate of Oak Ridge National Laboratory hung in the balance when it was decided that all the necessary research and development work on nuclear reactors could be entrusted to a single national laboratory, the Argonne National Laboratory under Walter Zinn. Only the vigor, vision, and persuasiveness of Alvin Weinberg, its postwar Director, saved his Laboratory from extinction. From Oak Ridge National Laboratory came the swimming pool reactor, the

Figure 3. The BNL Medical Research Reactor.

aqueous homogeneous breeder, and the molten salt breeder reactor concepts. We shall discuss breeders later.

The swimming pool reactor can be found by the dozens all around the world and in many research institutions in the United States in the power range between 1 and 5 megawatts. Our own Medical Research Reactor, as shown in Figure 3, is a modern version of the swimming pool reactor. This is the only reactor type of which the interior, illuminated by its own Čerenkov radiation, can be safely viewed during high power operation – through a dozen or more feet of water. I think that you can now see that our previous, simple sketch of a reactor was not too crude. Of course, there is a great deal of superstructure for control rods, and the fuel plates go into individual boxes. In fact, you can even see that the individual plates are slightly bent because this makes them more stable mechanically. The individual plates are called aluminum sandwiches: the "meat" consists of uranium-aluminum compounds in aluminum, and the cladding is aluminum. They are separated by thin slits through which the water runs. The water serves simultaneously as coolant and moderator.

Other examples of the swimming pool reactor type, but with improved heat transfer characteristics, are the high flux materials testing reactors at the National Reactor Testing Station in Idaho. This station is a huge area devoted to testing novel reactor concepts. Another reactor of this type is the so-called High Flux Isotope Reactor, which is being built for the production of transplutonium elements at Oak Ridge.

At Argonne National Laboratory, the boiling water reactor and the fast, sodium cooled breeder were developed. The present commercial use of the boiling water reactor includes several small plant prototypes and the 200-electrical-megawatt Dresden reactor near Chicago. Another large plant, the so-called SENN reactor near Naples, Italy, was scheduled for full power operation this year, but they have run into a little trouble and they may not quite make it. The first U.S. prototype fast reactor, the Enrico Fermi reactor near Detroit, has just started up.

After the war, several large industrial laboratories, supported directly or indirectly by the AEC, sprang into existence. These included the Knolls Atomic Power Laboratory, a subsidiary of General Electric; Atomics International, as it is now called, a subsidiary of North American Aviation; and, somewhat later, the Bettis Atomic Power Laboratory, a Westinghouse subsidiary.

Atomics International undertook the development of sodium cooled, graphite moderated thermal reactors as well as organic cooled and moderated reactors. Both reactor types are capable of operating at lower pressures and at higher thermal efficiencies than are the currently popular water cooled reactors. However, the development of these reactors was slow, and as a result the first power prototypes have just gone into operation. The AEC has now abandoned the organic coolant approach to nuclear power, although some foreign groups, in particular the Euratom Nations, are still committed to this reactor type. In the meantime, the main effort of Atomics International has shifted to the design and construction of a series of light weight, zirconium hydride moderated reactors called SNAP reactors. These are required for auxiliary power in space missions.

The first project of the Knolls Atomic Power Laboratory was the development of an intermediate energy, sodium cooled breeder, in competition with the fast breeder then under development at Argonne. The engineering work went ahead rapidly, but the reactor core remained a black box until the nuclear characteristics of plutonium at intermediate energies could be determined. When it finally became clear from integral experiments that the capture-to-fission ratio of plutonium was unfavorable, the project was dropped. The physics of this problem, as you may recall, was discussed in our introduction.

It was not the peaceful uses of atomic energy but Admiral Rickover's nuclear powered submarine that brought the Knolls and the Bettis Laboratories to life. The first nuclear submarine to be launched was the *USS Nautilus*, shown in Figure 4, with a 1954 start-up date. It should be clear to everybody that this is a submarine. You will just have to take my word or the Navy's word that it is a nuclear powered submarine. From now on you will not see any more reactors because they will be all covered up; in fact, the reactor in this particular submarine is only a little dot somewhere under water. After one experiment with a sodium cooled nuclear reactor in the *Seawolf* (1956), the Knolls Laboratory in Schenectady joined the Bettis Laboratory in Pittsburgh in designing water cooled, enriched uranium reactors for naval propulsion. There are now dozens of nuclear submarines, many of them equipped with Polaris missiles, and many more are being built. There is also a growing nuclear surface fleet including the carrier *USS Enterprise,* which is powered by eight reactors. I need not stress the success of this series of reactors because they are in the headlines almost every week. We have recently been abandoning nuclear bases, for example, in Great Britain, presumably because of our growing nuclear submarine fleet.

Today it has become clear that special purpose reactors are a huge success in areas where cost differentials with conventional power plants are not important. Figure 5 shows a pressurized water reactor plant on duty in the Antarctic. The plant was built by the Martin-Marietta Company to provide electricity and heat for the McMurdo Sound Base. Figure 6 shows the *NS Savannah*, a cross between a peace ship and a merchant vessel, first authorized by President Eisenhower, steaming under the Golden Gate bridge and being welcomed by water displays from fireboats. Finally here is KIWI-A (Figure 7), which is one in a series of experiments to produce a nuclear powered rocket. This particular experiment uses gaseous hydrogen, but the ultimate goal is a liquid hydrogen cooled reactor. This reactor is unfortunately upside down, and it will never take off in that position. The experiments on the engine, the so-called NERVA experiments, which are just starting, will test the engine in the correct position. This series is called the KIWI series after the earth-bound kiwi bird of Australia, since these reactors will not fly. However, they are prototypes of nuclear powered rockets which, it is hoped, will eventually fly.

The more prosaic but important goal of large, economically competitive, nuclear power plants has not been so easy to reach. In spite of badgering and cajolery, the utility companies were slow in making up their minds about investing in nuclear power until a small independent one, the Duquesne Light Company, agreed to put up five million dollars of its own money to operate an AEC owned pressurized water reactor at Shippingport, Pennsylvania. The 60-electrical-megawatt Shippingport reactor, started up in 1957, was followed by the 200-megawatt Dresden boiling water reactor in 1959, the 160-megawatt Yankee reactor at Rowe, Massachusetts, in 1960, and the 255-megawatt Consolidated Edison reactor at Indian Point, overlooking the Hudson River, in 1962. Figure 8 shows the Indian Point reactor under construction by the Babcock & Wilcox Company. Perhaps the most interesting thing about this picture is that it gives some idea of the type of heavy containment which, Consolidated Edison argues, makes it safe to construct the 1000-megawatt Ravenswood reactor (which also has had a great deal of publicity recently) in Long Island City.

New starts on nuclear power plants in the United States have been lagging, but in the last few months some new large reactors have been authorized, three in California and one, the Haddam Neck reactor, in Connecticut. What is the rate of progress in other countries? In the USSR the approach to nuclear power has been similar to that in the United States. Various power prototypes are being tested, and the world's first plutonium fueled fast breeder experiment has been carried successfully to over 5% fuel burnup, which I may say is a very creditable performance for a fast reactor. Some novel research and test reactors have been built in the USSR, and their nuclear icebreaker, the *Lenin* (Figure 9) is the marine counterpart of our *NS Savannah.* The Russians are very proud of this ship. Manson Benedict, Glenn Seaborg, and others recently visited the USSR and came back with impressive reports about this particular use of nuclear power. The *Lenin* with three reactors does 16 knots in open water and breaks open ice packs up to 30 feet thick. In 1960

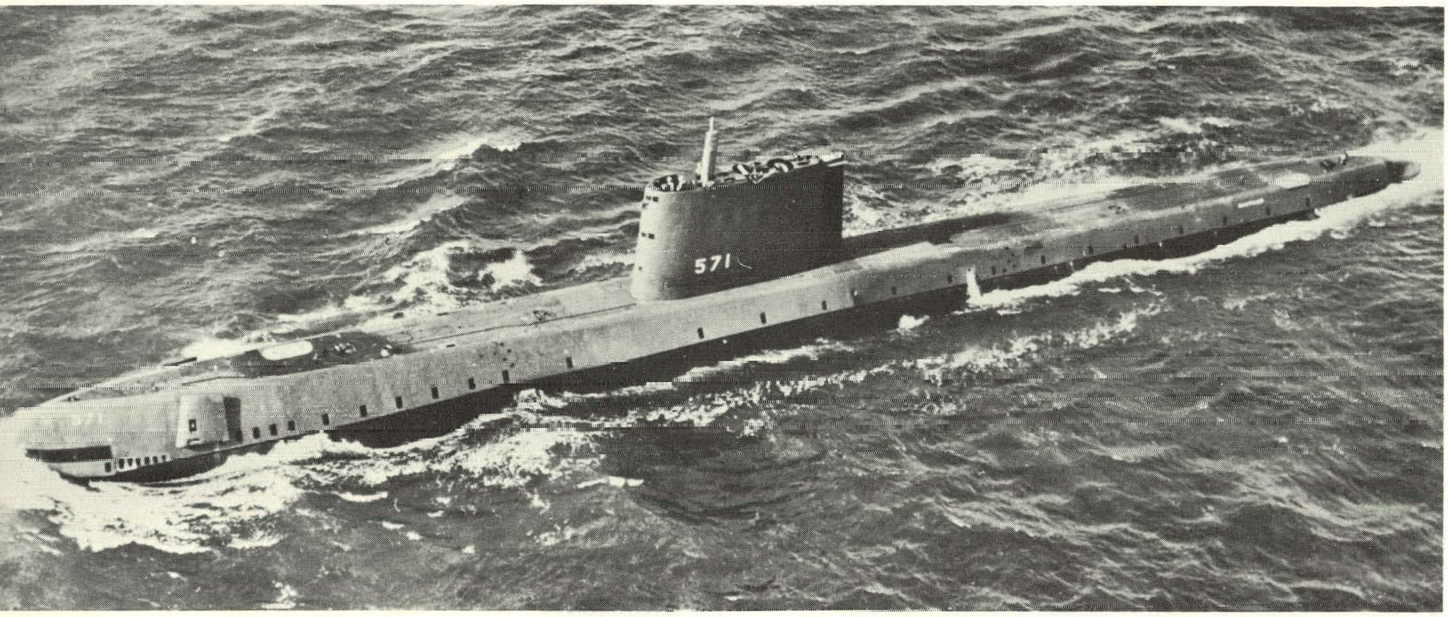

Figure 4. The *USS Nautilus*.

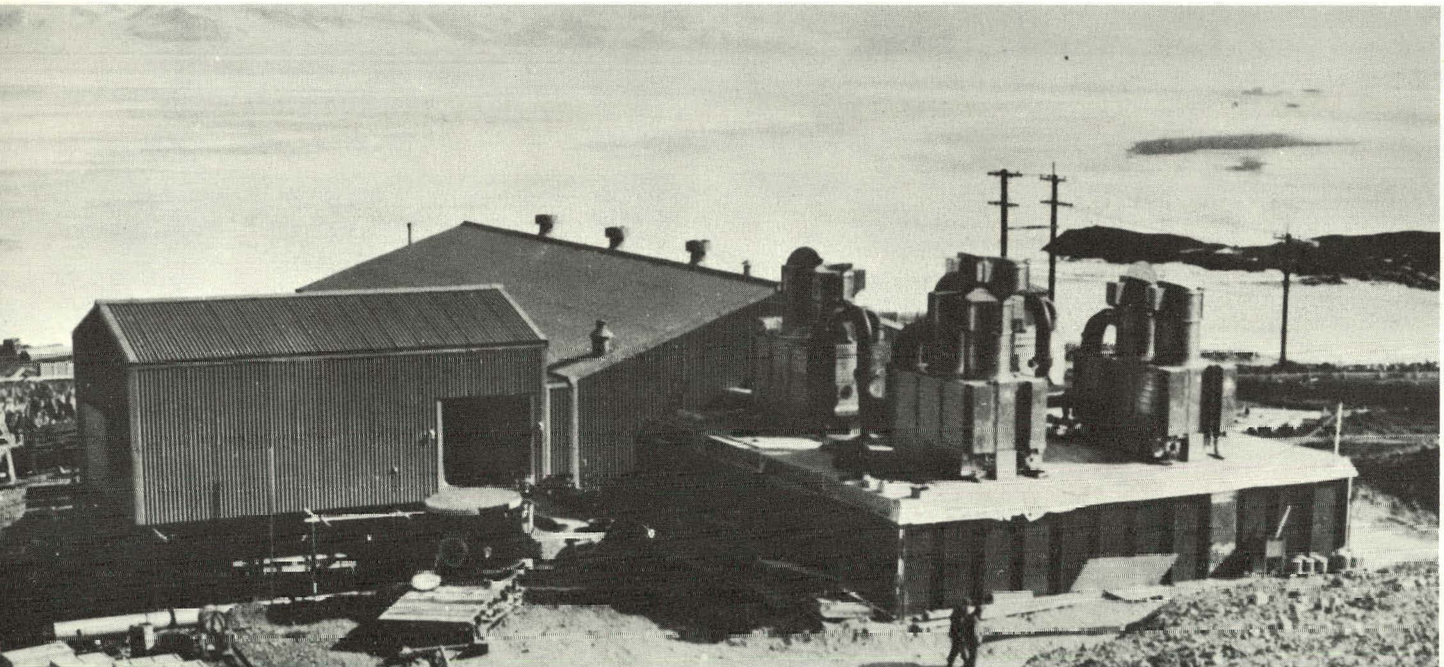

Figure 5. The nuclear power plant at the McMurdo Sound Base.

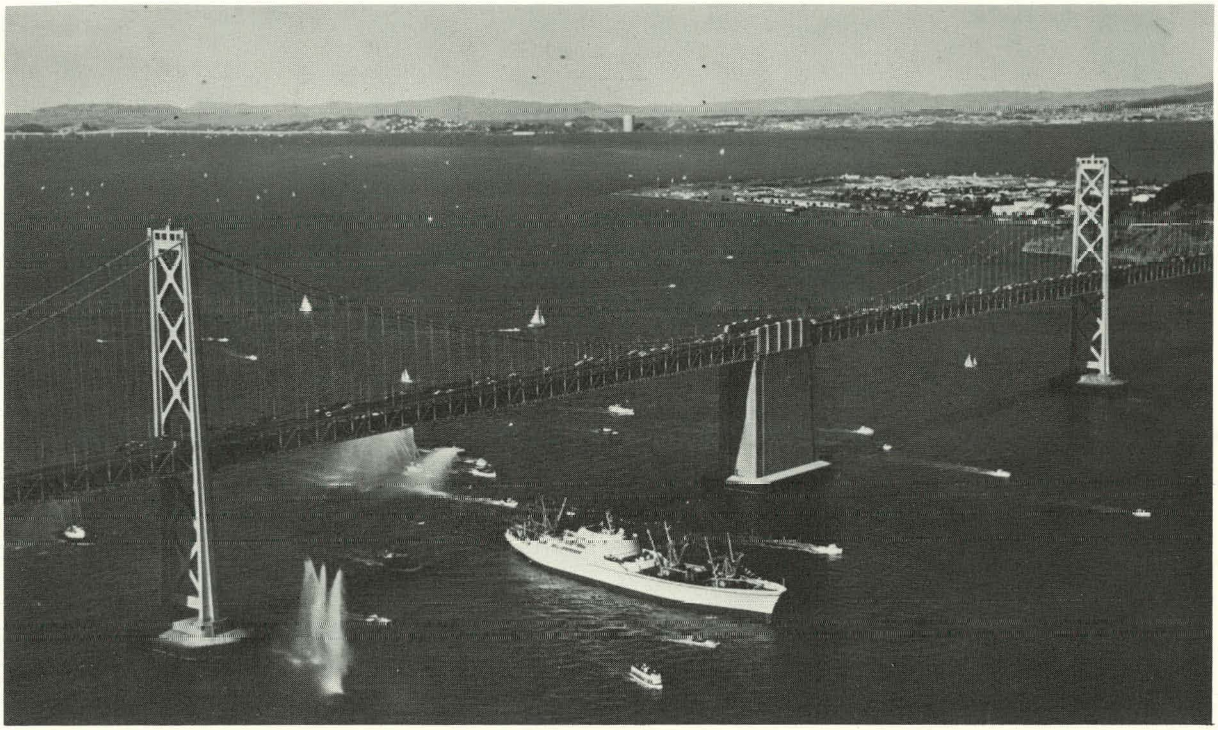

Figure 6. The *NS Savannah*.

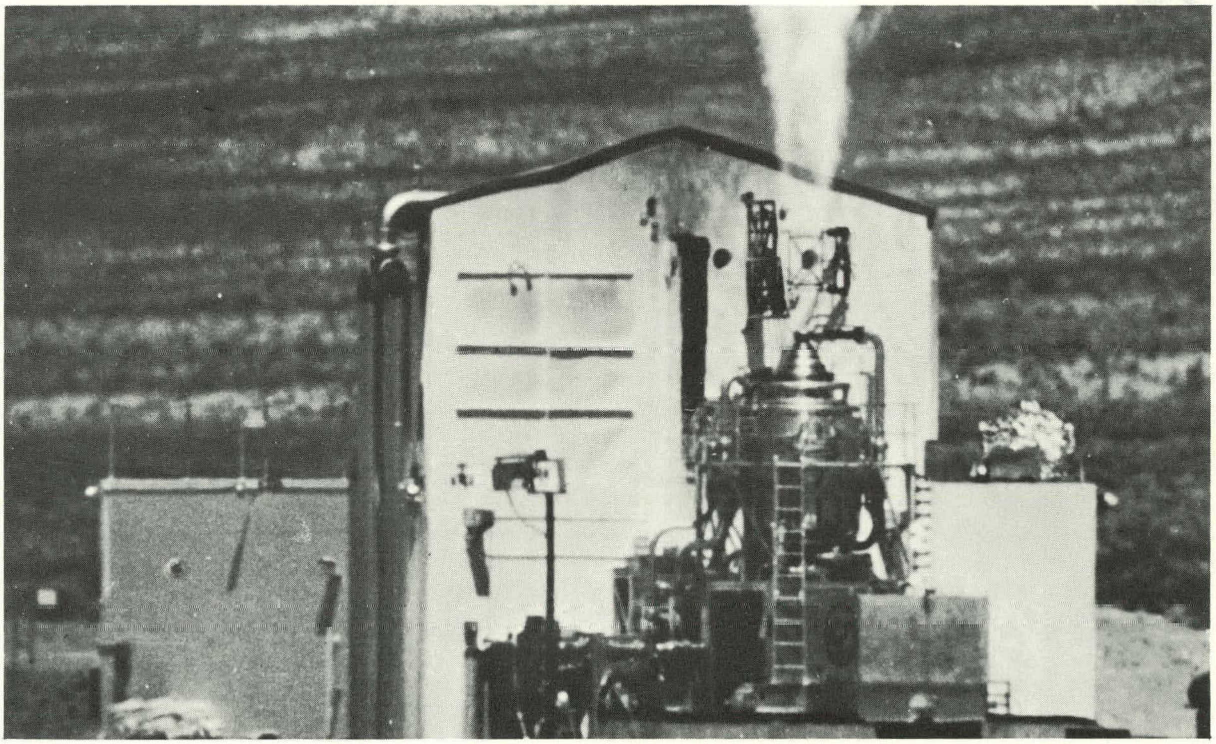

Figure 7. KIWI-A.

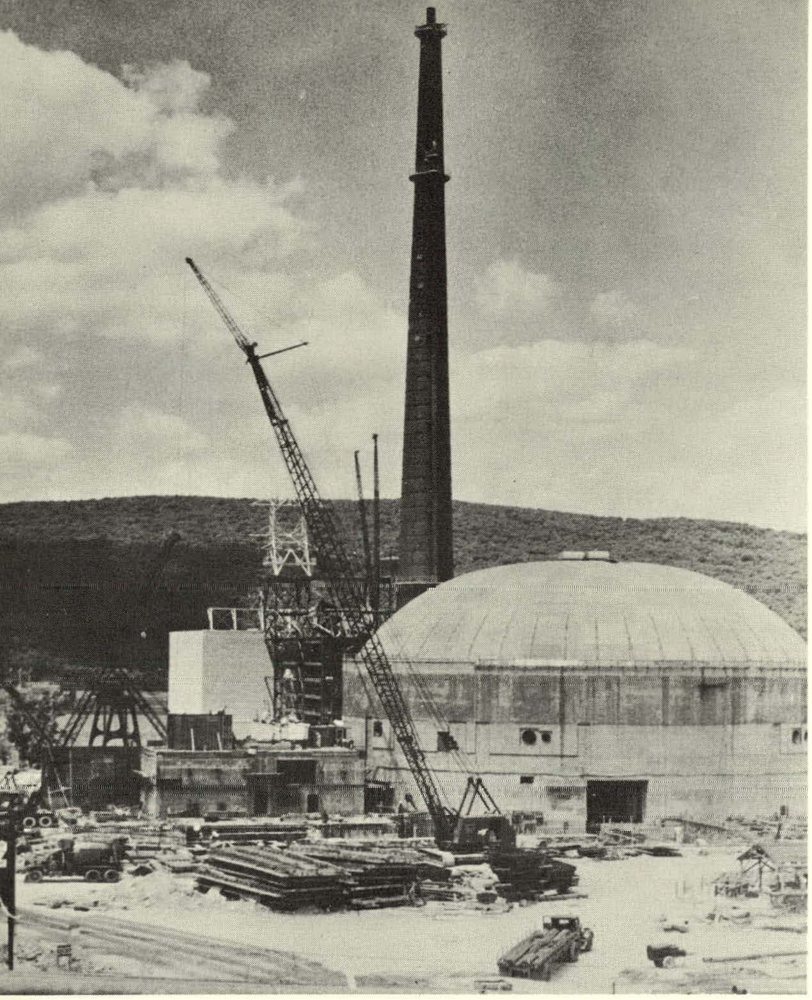

Figure 8. Indian Point Reactor.

Figure 9. The *Lenin*.

the ship travelled some 20,000 miles, and its original fuel charge has enabled it to operate for three full summers. After this time the fuel reached a burnup of 25,000 megawatt-days per ton and was removed. The Russians are using this fuel – a ceramic fuel, similar to our more successful fuel types, consisting of enriched uranium oxide clad with a zirconium-aluminum alloy – in their first pressurized water reactor. The Russians still do not have a large power reactor in operation, although their first pressurized water reactor will soon be completed at Novovoronezh on the Don River below Moscow, and a nuclear superheat power reactor prototype is under construction at Beloyarsk. Construction of large nuclear power plants in the USSR has also tended to lag even though their coal transportation problems are greater than ours.

Outside of Europe, Japan and India are large investors in nuclear power reactors. In western Europe, France and Italy in particular and the Common Market nations in general have strong research programs and heavy financial commitments in nuclear power plants. However, the British involvement in nuclear power far outstrips the others and in sheer numbers of megawatts makes even the U.S. program look small by comparison. The British are apparently determined they are not going to be caught short again as they were during the Suez crisis. Already a considerable fraction of the electricity used in England comes from nuclear power, and 20% of the new power stations under construction are nuclear plants. Figure 10 shows a nearly completed station in north Wales called Trawsfynydd. Figure 11 also gives some idea of the size of the British reactors, which are natural uranium fueled, graphite moderated, and gas cooled. It shows the 560-megawatt Oldburg Nuclear Power Station in Gloucestershire at an early stage of construction. This reactor represents a break from the steel pressure vessels that have been used in the past. The cylinder in the distance is not a pressure vessel, it is only the liner for a prestressed, steel cable reinforced, concrete pressure vessel of the type to be used on all the reactors which have recently been authorized. The long building on the left will contain the turbines. British reactors are generally twins; the base of the first one is seen in the foreground with the second one immediately behind it. The British claim that with prestressed concrete vessels it will be possible to go to 1000 electrical megawatts in single reactor units, and that the

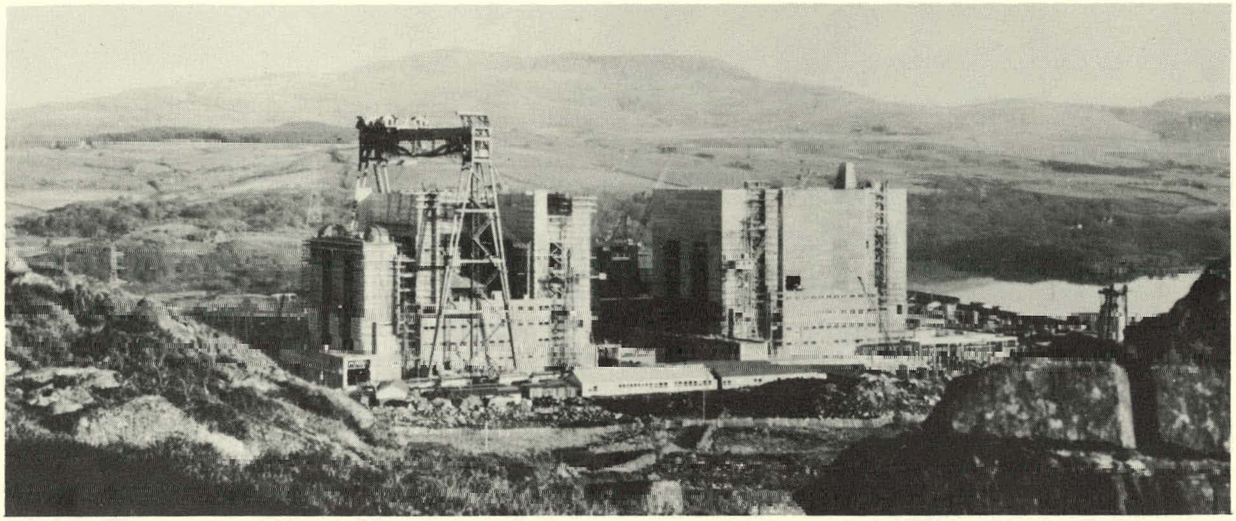

Figure 10. The Trawsfynydd Station.

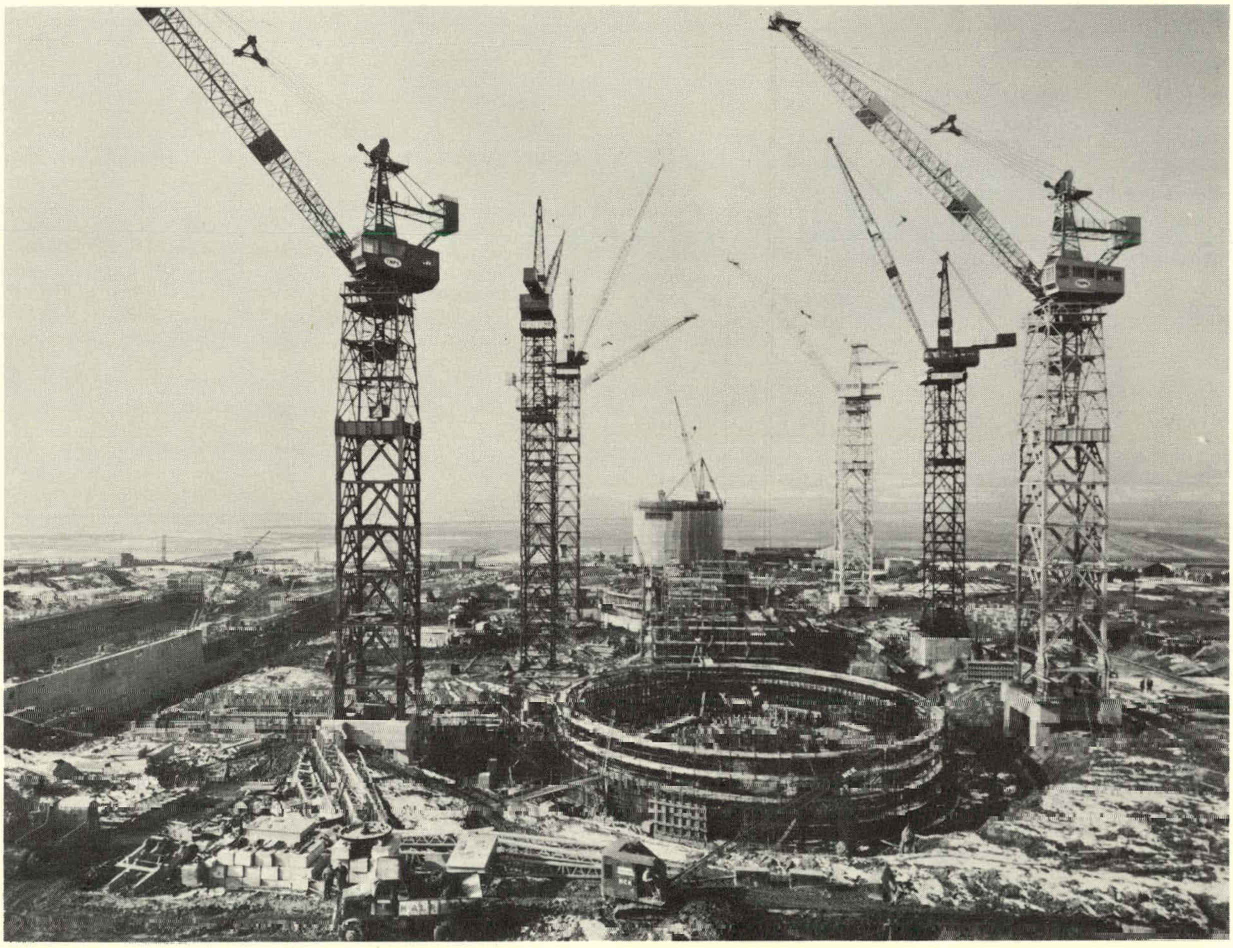

Figure 11. The Oldburg Nuclear Power Station.

concrete itself may double as the containment. It is ironic that the French, who originated the prestressed concrete vessels for reactors, were going to give them up and follow the British example. However, the British have now decided that it is impossible to guarantee against failure of steel pressure vessels over long periods of time and this is their main reason for changing to concrete vessels.

THE FUTURE OF THE NUCLEAR REACTOR

Our outline of the growth and development of the nuclear reactor has necessarily been brief and incomplete. We have not mentioned a number of reactor types under development in the United States and abroad. Additional uses are being suggested for nuclear reactors: the production of chemicals such as hydrazine or ozone, process heat in chemical or steel industries, space heating of buildings, mobile or stationary emergency energy depots, water desalinization, and so on. Water desalinization alone, if carried out on the scale envisioned by its proponents, would make the desert bloom, or would supply both electricity and drinking water economically for large cities, but preferably in huge plants with investments of the order of billions of dollars per plant. Men like Alvin Weinberg foresee a real large-scale future need for nuclear reactors for such purposes – monster reactors of up to 25,000 thermal megawatts. At these sizes it is clear that capital costs and fuel costs in mils per kilowatt-hour come down quite rapidly. But initial capital investments would become an appreciable fraction of our national budget.

In terms of the future requirements of the nation, however, the need is for reactors that not only produce power but simultaneously produce more fissionable material than they destroy and are therefore called breeders. The bootstrap operation of breeding is rendered possible by the fact that nature, as mentioned earlier, has generously provided more than two neutrons per fission, or one more than is necessary to achieve a chain reaction. If this extra neutron is captured by U^{238}, then U^{239} is formed, which soon goes through two beta decays to Pu^{239}. Similarly, if the neutron is captured by thorium, U^{233} is the end product. The uranium-plutonium and the thorium-U^{233} cycles are the only practical breeding cycles. Whereas the thorium-U^{233} cycle appears to be feasible in either thermal or fast reactors, it is generally conceded that breeding will become possible on the uranium-plutonium cycle only with the development of fast breeders.

Although the need for breeders has long been understood at the national laboratories, it was not until the November 20th, 1962, *AEC Report to the President* by our Commissioners that a concrete program of breeder development and prototype breeder reactor construction was spelled out by an AEC Commission, of which scientists Leland Haworth and Glenn Seaborg were members.

To illustrate the main point, let us consider Figure 12, taken from the *AEC Report to the President*. It shows three different extrapolations of energy consumption against fossil fuel resources for the United States. Curves A and B are extrapolations from energy use over the last 60 years and the last 10 years, respectively. The *Q* unit is 10^{18} Btu. It is an enormous unit, since at present we use only a little more than 1/20 *Q* per year. The known fossil fuel reserves are indicated on the right, and comparison with the curves shows that we are fairly certain to run out of our known reserves in the next 50 or 60 years. The 124 *Q* listed are marginal or undiscovered resources of which about 30 *Q* has been taken as a reasonable estimate of fuel with a relatively low cost, i.e., not much more than what we pay today for coal. Obviously the exact decade in which our low cost fossil fuel peters out depends on which curve we use. Note that curve C is a

Table 1

Energy Content of U.S. Nuclear Fuel Resources

Uranium resources price range, \$/lb U_3O_8	Fission energy content in *Q*: Reasonably assured resources	Total resources
5- 10	22	50
10- 30	24	40
30- 50	300	500
50-100	360	900
100-500	30,000	120,000
Thorium resources price range, \$/lb ThO_2		
5- 10	6	25
10- 30	6	13
30- 50	200	650
50-100	500	1,600
100-500	63,000	190,000

compromise estimate, and also includes saturation effects such as saturation of population and per capita consumption. Of course, these curves have not factored in possible enormous expansions of atomic power for such uses as water desalinization and so on. What is the position of someone who is concerned about the nation, then? What curve should he use? It is clear that he should not be optimistic and use curve A, at any rate. Whether our cheap coal resources will last only several decades or as much as 150 years is mere quibbling.

As may be seen from Table 1, the *nuclear* fuel resources of the United States are unlimited. Table 1 shows the energy content of U.S. nuclear fuel resources, both uranium and thorium. We know less about thorium because we have not really tried to find it in this country. If we denote fuel prices of under 30 dollars per pound as relatively cheap, then it is clear that the Q values available in this price range are only of the order of magnitude of what we already have in the way of fossil fuels, and this only if we use all or most of the energy content and not the 1% or less which is usual in present day power reactors. On the other hand, the higher priced fuels could also be considered relatively cheap if we used all the energy and not a small fraction of it. Total U.S. nuclear resources are measured in hundreds of thousands of Q, and obviously this is infinite from the practical viewpoint. This is the basis of the argument that, for the best interests of the nation, breeder reactors must be developed with reasonable speed. No true power breeders are yet being built, although the AEC Commissioners have spelled out a program of encouraging industry to propose several breeder prototypes to be built over the next decade or so.

BROOKHAVEN'S REACTORS

What has Brookhaven's role been in these developments? Like other BNL Departments, the Nuclear Engineering Department stresses research rather than large-scale projects. Nevertheless, we have retained the ability to carry major projects through when it is in the interests of the Laboratory or the nation. For this reason, our major projects have been limited to the design of Brookhaven's research reactors, to reactor studies under-

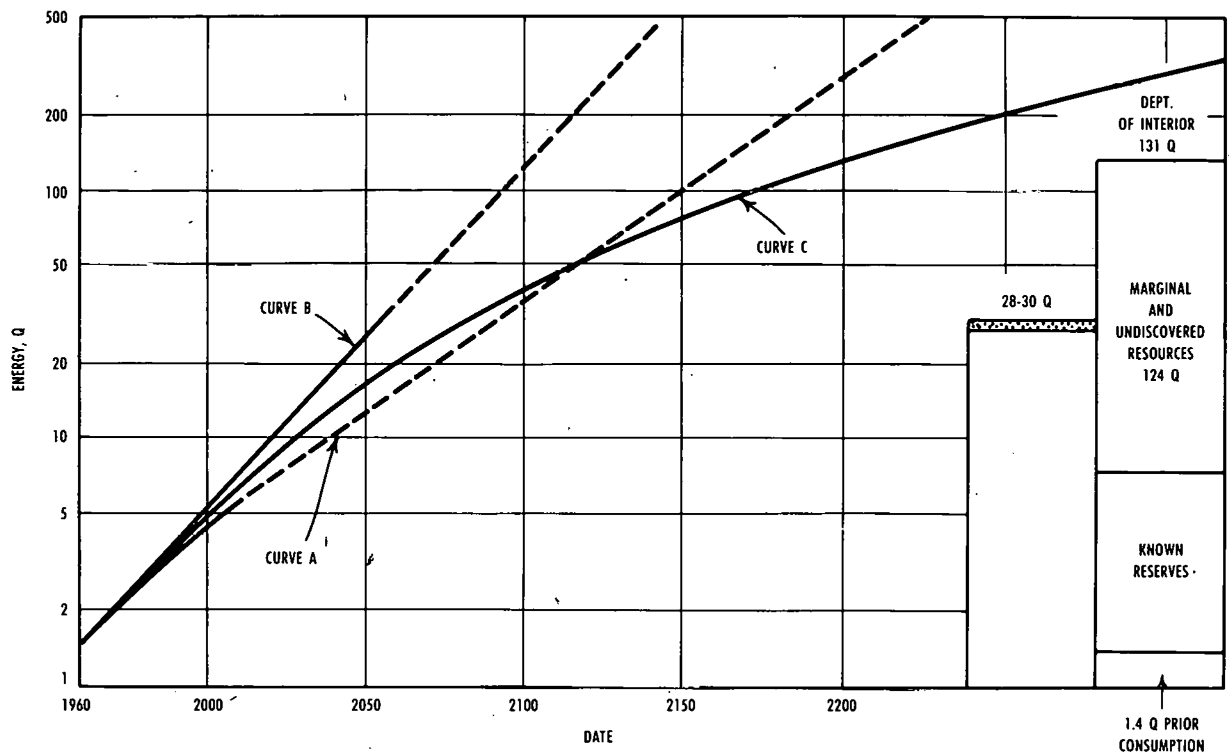

Figure 12. Cumulative energy consumption and fossil fuel resources for the United States.

taken at the request of the AEC, and to the conceptual design of advanced breeder reactors.

Our first project was, of course, the design of Brookhaven's Graphite Research Reactor. Under the dynamic leadership of Lyle Borst, the Pile Project which came into existence in 1947 made some radical advances in then existing reactor technology. A power level of 30 thermal megawatts was the target, orders of magnitude above its only prototypes, Fermi's West Stands or CP-1 reactor, which we have described and which was torn down and rebuilt at the Argonne Laboratory as CP-2, and the so-called X-10 reactor at Oak Ridge. It has just been announced that this reactor is being honorably retired after 20 years of service. The BNL graphite pile was divided into halves so that the cooling air could enter at the middle and divide, thus greatly reducing the pumping power costs. One half of the reactor, some 350 tons, was movable so that it could be further opened, if desirable after attaining criticality, as a hedge against radiation induced graphite growth. In order to detect leaks which might lead to rapid oxidation and rupture of the metallic uranium fuel slugs which were used, a forest of helium tubes was snaked through the reactor and joined to individual fuel containers. The reactor shield, consisting of concrete mixed with steel plugs cut from scrap naval vessel plates, was tested out against more expensive shields in the X-10 reactor, as was the extent of radioactivity of the helium system due to the stoppage and diffusion of fission products.

The success of the Project can be judged by the amount of research work done with the reactor since its start-up in 1950. Brookhaven was fortunate when key members of the Project decided to join the newly formed Nuclear Engineering Department in 1949.

With a team that had learned to work together on such difficult reactor problems it was small wonder that the research in Metallurgy under David Gurinsky, in Chemical Engineering under Warren Winsche, and in Reactor Physics under Irving Kaplan should soon indicate some useful common goals such as the Liquid Metal Fueled Breeder Reactor (LMFR). Under the Chairmanship of Clarke Williams, our present Deputy Director, this reactor concept grew in promise and size of effort until 1959, when the AEC decided to choose only one of three rival fluid fuel breeders for further development and picked the Oak Ridge molten salt reactor over the LMFR and the aqueous homogeneous reactors.

In 1954 another opportunity arose for members of the Nuclear Engineering Department to work as a team. As a member of our Scientific Visiting Committee, Alvin Weinberg had asked if we had considered the replacement of natural uranium fuel elements in the Brookhaven Graphite Research Reactor with enriched fuel, which was then becoming available from the AEC in large quantities. Our preliminary studies, based on aluminum sandwich type elements, showed that we could obtain a factor of four increase in flux in this way together with a substantial reduction in pumping power costs. The scheme appealed particularly to Marvin Fox, then Chairman of Reactor Operations, as an opportunity to get rid of the cumbersome helium leak detection system, since rapid oxidation of aluminum fuel elements could not occur under a cladding failure. The conversion of the reactor to enriched fuel sounds easy but it was actually a delicate and difficult job carried out over a period of years by senior members of the Nuclear Engineering Department and the Reactor Operations Division without benefit of a Project and without inconvenience to any of the experimenters using the reactor. The enriched fuel elements were designed, procured and tested by David Gurinsky and his Metallurgy Division. Sample elements were vibrated, irradiated, mutilated, and melted to determine their behavior under normal and abnormal conditions. When we suggested that optimum neutron flux conditions for the experiments would be obtained if the fuel elements could be moved periodically from both ends toward the middle of the reactor, Robert Powell of Reactor Operations worked out a practical scheme for just such fuel shuffling in a reactor which had hardly been designed for flexible operation. The loading of the enriched fuel had to proceed in stages. As the thermal neutron flux rose, temperatures in the surrounding natural uranium fuel elements became limiting. The solution was the provision of a buffer region of graphite moderator between the two types of fuel elements.

I have already mentioned the Medical Research Reactor and the High Flux Beam Research Reactor, a concept which originally arose from some theoretical studies of externally moderated LMFR's which were carried out in 1955. This reactor has been fully described in a previous Brookhaven Lecture (No. 5), but at this time I would like to credit

Don Hughes and Lee Haworth for their enthusiastic support of a novel reactor concept, Herbert Kouts for guiding the experimental work which helped shape the design of the reactor, and Joseph Hendrie, an experimental physicist turned project engineer, for turning a primitive design concept into a practical but uncompromising reality.

I am almost at the end of my story. With the abandonment of the LMFR in 1959, the various Divisions of the Nuclear Engineering Department have returned to their individual pursuits. However, a few of our engineers have continued to study new reactor concepts. Out of small-scale studies and experiments has emerged a fast breeder concept called the Settled Bed Reactor which appears to present major challenges to our metallurgists, our chemical and mechanical engineers, and our reactor physicists. The reactor core would consist of a settled bed of fuel lumps, possibly uranium-plutonium monocarbide lumps about ⅛ inch in diameter. The reactor would be cooled by downward flow of liquid metal coolant. At reactor shutdown, the flow could be reversed to fluidize and remove the fuel for processing. The concept gives promise of lowering fuel fabrication and processing costs, which are at present the chief barriers to the development of the fast breeder reactor. It is still too early to foretell what will happen to this largely untested fuel concept.

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19. The Renewal of Cells and Molecules – The Fountain of Youth
Walter L. Hughes, Medical Department — September 19, 1962

20. A Neutron's Eye View of Magnetic Materials
Julius M. Hastings, Chemistry Department — October 17, 1962

21. Landscaping the Groves of Academe
R.C. Anderson, Director's Office — November 14, 1962

22. Chemical Communication Systems in the Cell
Henry Quastler, Biology Department — December 12, 1962

23. Neutrino Physics, BNL 787
Leon M. Lederman, Physics Department — January 9, 1963

24. The Use and Misuse of the Atmosphere, BNL 784
Maynard E. Smith, Instrumentation and Health Physics Department — February 13, 1963

25. The Nucleus Today
Denys Wilkinson, Physics Department — March 6, 1963

26. Trace Metals: Essential or Detrimental to Life, BNL 828
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Jacob Bigeleisen, Chemistry Department — October 16, 1963

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32. Radio Galaxies
David Heeschen, National Radio Astronomy Observatory — January 15, 1964

33. The Impact of Isotopic Tracers on Physiological Concepts, BNL 857
James S. Robertson, Medical Department — February 12, 1964

34. The Biology of Aging, BNL 854
Howard J. Curtis, Biology Department — March 18, 1964

35. The Problem of Development
Ernst W. Caspari, University of Rochester — April 15, 1964

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1. Radioastronomy and Communication Through Space, BNL 658
Edward M. Purcell, Physics Department — November 16, 1960

2. Current Ideas on the Endocrine Regulation of Cellular Processes, BNL 685
Irving Schwartz, Medical Department — December 14, 1960

3. Inside the Protein Molecule, BNL 649
Werner Hirs, Biology Department — January 11, 1961

4. Nuclear Chemistry Research With the Cosmotron
Gerhart Friedlander, Chemistry Department — February 15, 1961

5. Neutron Physics Of and With the High Flux Beam Research Reactor, BNL 664
Herbert Kouts, Nuclear Engineering Department — March 15, 1961

6. High Energy Accelerators, BNL 747
Ernest Courant, Physics Department — April 12, 1961

7. Dislocations in Crystal Lattices
George H. Vineyard, Physics Department — May 17, 1961

8. The History of Cosmic Rays and Meteorites, BNL 779
Oliver A. Schaeffer, Chemistry Department — June 14, 1961

9. The Physics of Semiconductor Radiation Detectors, BNL 699
G.L. Miller, Instrumentation and Health Physics Department — September 27, 1961

10. Theory of the Gene, BNL 739
Milislav Demerec, Biology Department — October 18, 1961

11. Fundamental Particles of Physics
Maurice Goldhaber, Director, Brookhaven National Laboratory — November 15, 1961

12. Excessive Salt Intake and Hypertension: A Dietary and Genetic Interplay, BNL 733
Lewis K. Dahl, Medical Department — December 13, 1961

13. Galaxies, BNL 710
Otto Struve, National Radio Astronomy Observatory — January 17, 1962

14. A Computer Learns To See, BNL 725
Paul Hough, Physics Department — February 14, 1962

15. Wet Electrons – The Radiation Chemistry of Water
A.O. Allen, Chemistry Department — March 14, 1962

16. Fundamental Studies of Radiation Damage in Graphite, BNL 745
Donald G. Schweitzer, Nuclear Engineering Department — April 17, 1962

17. The Role of the Cell Nucleus in Determining Radiosensitivity, BNL 766
Arnold H. Sparrow, Biology Department — May 16, 1962

18. Accelerators of the Future, BNL 741
John P. Blewett, Accelerator Department — June 13, 1962

(Continued inside back cover)