Title
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Publication Date
1989

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Speech presented at the Imperial Hotel,
Tokyo, Japan, February 17, 1989

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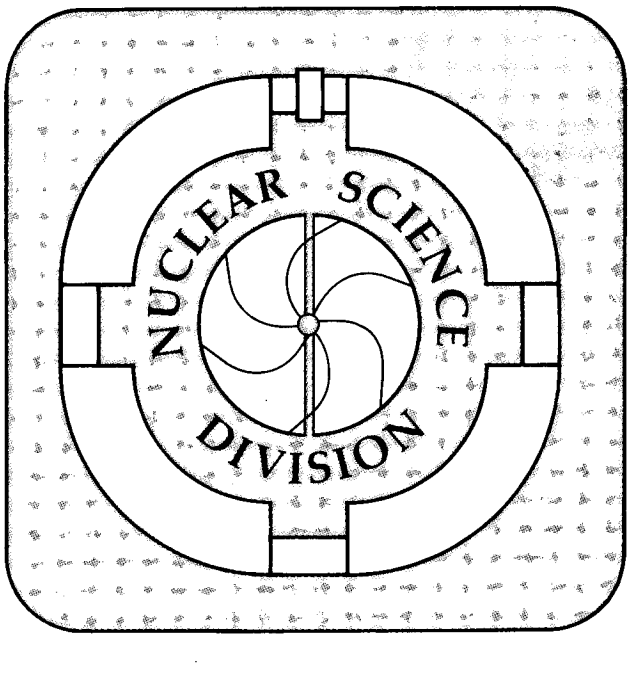
January 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-26699

ATOMIC ENERGY AS AN HUMANE ENDEAVOR-- RETROSPECTIVE ON ITS DEVELOPMENT

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Tokyo, Japan
February 17, 1989

[1] This work was supported by the Department of Energy under Contract No. DE-AC03-76SF00098.

Pre-fission and fission

As a first year graduate student at Berkeley in 1934 nearly five years before the discovery of nuclear fission, I began to read the papers coming out of Italy and Germany describing the synthesis and identification of several elements thought to be transuranium elements. In their original work in 1934, E. Fermi, E. Amaldi, O. D'Agostino, F. Rasetti and E. Segrè bombarded uranium with neutrons and obtained a series of beta-particle-emitting radioactivities. On the basis of the periodic table of that day (Figure 1) they were led to believe that the first transuranium element, with atomic number 93, should be chemically like rhenium (i.e., be eka-rhenium, Eka-Re), element 94 like osmium (Eka-Os) and so forth. Therefore they assigned a 13-minute activity to element 93. I quote from a classical paper written by Fermi [1], entitled "Possible Production of Elements of Atomic Number Higher than 92", which I remember reading at that time:

> "This negative evidence about the identity of the 13 min.-activity from a large number of heavy elements suggests the possibility that the atomic number of the element may be greater than 92. If it were an element 93, it would be chemically homologous with manganese and rhenium. This hypothesis is supported to some extent also by the observed fact that the 13 min.-activity is carried down by a precipitate of rhenium sulphide insoluble in hydrochloric acid. However, as several elements are easily precipitated in this form, this evidence cannot be considered as very strong."

I recall reading soon thereafter a paper by Ida Noddack [2], entitled "Uber das Element 93," which took issue with this interpretation, suggesting that the radioactivities observed by Fermi et al. might be due to elements of medium atomic numbers:

> "Es wäre denkbar, dass bei der Beschiessung schwerer Kerne mit Neutronen diese Kerne in mehrere grössere Bruchstücke zerfallen, die zwar Isotope bekannter Elemente, aber nicht Nachbarn der bestrahlten Elemente sind." [One could think that in the bombardment of heavy nuclei with neutrons these nuclei disintegrate into several larger fragments which, although they are isotopes of known elements, are not neighbors of the irradiated elements.]

However this paper, which intimated the possibility of the nuclear fission reaction, was not taken seriously.

Experiments in Germany during the following years by O. Hahn, L. Meitner and F. Strassmann (Figure 2) appeared to confirm the Italian interpretation and for several years the "transuranium elements" were the subject of much experimental work and discussion. In a typical paper by Hahn, Meitner and Strassmann [3], which I read, part of a series they published during 1935-1938, they reported a 16-minute $_{93}$Eka-Re^{237}, 2.2-minute $_{93}$Eka^{239}, 12-hour $_{94}$Eka-Os^{237}, 59-minute $_{94}$Eka-Os^{239}, 3-day $_{95}$Eka-Ir^{239}, 12-hour $_{96}$Eka-Pt^{239}.

In 1938 I. Curie and P. Savitch [4] found a product of 3.5 hours half-life that seemed to have the chemical properties of a rare earth, but they failed to give an interpretation of this astonishing discovery. Their paper, which I also read at the time, had the title, "Sur La Nature Du Radioélément De Période 3,5 Heures Formé Dans L'Uranium Irradié Par Les Neutrons," and included the following:

"Nous avons montré qu'il se forme dans l'uranium irradié par les neutrons un radioélément de période 3,5 heures dont les propriétés chimiques sont semblables a celles des terres rares. Nous la désignerons ci-dessous par la notation $R_{3,5h}$...

$R._{3,5h}$ se sépare nettement de Ac, allant en tête de fractionnement, alors que Ac va en queue. Il semble donc que ce corps ne puisse être qu'un élément transuranien possédant des propriétés très différentes de celles des autres éléments transuraniens connus, hypothèse qui soulève des difficultés d'interprétation."

["We have shown that in the neutron irradiation of uranium a radioactive element with a half-life of 3.5 hours is produced, with chemical properties similar to those of rare earths. In the following we will refer to it as $R_{3.5}h$.

$R_{3.5}h$ separates cleanly from Ac by going to the 'head' (beginning) of the factionation while Ac goes to the 'tail' (end). It seems, therefore, that this species cannot be but a transuranic element having properties very different from those of the other known transuranic elements, a hypothesis which raises interpretational difficulties."]

Then came the breakthrough. Early in 1939, Hahn and Strassmann [5], on the basis of experiments performed in December 1938, and with interpretive help from Meitner who had been forced to leave Germany, described experiments in which they had observed barium isotopes as the result of bombardment of uranium with neutrons. This historic paper, which I also read at the time, had the title, "Uber den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehenden Erdalkalimetalle" and contained the following conclusion:

"Als chemiker müssten wir aus den kurz dargelegten Versuchen das oben gebrachte Schema eigentlich umbenennen und statt Ra, Ac, Th die Symbole Ba, La, Ce einsetzen. Als der Physik in gewisser Weise nahestehende 'Kernchemiker' können wir uns zu diesem, allen bisherigen Erfahrungen der Kernphysik widersprechenden, Sprung noch nicht entschkliessen. Es könnten doch noch vielleicht eine Reihe seltsamer Zufälle unsere Ergebnisse vorgetäuscht haben."

["We, as chemists, based on the briefly described experiments, should rename the above-mentioned scheme and replace Ra, AC, Th with the symbols Ba, La, Ce. As nuclear chemists, being in some respects close to physics, we have not been able to take this leap which contradicts all previous experiences in nuclear physics. It could be that a series of strange coincidences could have mimicked our results."]

Subsequent work showed that the radioactivities previously ascribed to transuranium elements are actually due to uranium fission products, and hundreds of radioactive fission products of uranium have since been identified.

Thus in early 1939 there were again, as five years earlier, no known transuranium elements. During these five years I developed an increasing interest in the transuranium situation. When as a graduate student I gave my required annual talk at the College of Chemistry weekly Research Conference in 1936, I chose the transuranium elements as my topic, describing the work of Hahn, Meitner and Strassmann referred to above.

During the two years following my seminar talk in 1936 and before the discovery of fission, my interest in the neutron-induced radioactivities in uranium continued unabated and, in fact, increased. I read and reread every article published on the subject. I was puzzled by the situation, both intrigued by the concept of the transuranium interpretation of the experimental results and disturbed by the apparent inconsistencies in this interpretation. I remember discussing the problem with Joe Kennedy, a colleague in research, by the hour, often in the postmidnight hours of the morning at the old Varsity Coffee Shop on the corner of Telegraph and Bancroft Avenues near the Berkeley campus where we often went for a cup of coffee and a bite to eat after an evening spent in the laboratory.

I first learned of the correct interpretation of these experiments, that neutrons split uranium into two large pieces in the fission reaction, at the weekly Monday night seminar in nuclear physics conducted by Professor Ernest O. Lawrence in Le Conte Hall. On this exciting night in January 1939, we heard the news from Germany of Hahn and Strassmann's beautiful chemical experiments. I recall that at first the fission interpretation was greeted with some skepticism by a number of those present, but, as a chemist with a particular appreciation for Hahn and Strassmann's experiments, I felt that this interpretation just had to be accepted. I remember walking the streets of Berkeley for hours after this seminar in a combined state of exhilaration in appreciation of the beauty of the work and of disgust at my inability to arrive at this interpretation despite my years of contemplation on the subject.

Retrospective on pre-war nuclear research at Berkeley

During the years (1934- 1941) before the United States entered World War II Berkeley was a leading center of nuclear research. Lawrence, who had invented the cyclotron a few years earlier, designed and built, successively, the 27-Inch, 37-Inch, and 60-Inch cyclotrons and began construction of the 184-Inch Cyclotron. These were powerful instruments with which to conduct our research. J. Robert Oppenheimer was the leader of an extraordinary program of theoretical investigators (Figure 3). Other nuclear pioneers included Edwin M. McMillan, Luis W. Alvarez, Emilio G. Segrè, Jack Livingood, and Willard F. Libby. The research staff of Lawrence's Radiation Laboratory included many other luminaries. Some of these nuclear pioneers served as my mentors, colleagues or collaborators in research. Importantly, graduate students played an important role in the program.

During this time I conducted research, with my collaborators, on the inelastic scattering of fast neutrons (1936-1937) as a graduate student, the synthesis and identification (1937-1941) of numerous radioactive isotopes (some of which later became important agents for the diagnosis and treatment of disease [cobalt-60, iodine-131, technetium-99m]), the chemical separation of nuclear isomers (1939), the identification of the products of symmetrical fission induced at the higher energies (1940), etc.

I would now like to reflect on some of this early work. In a visit to Osaka University on March 23, 1970, I met Seishi Kikuchi, who had worked with Hiroo Aoki and Kodi Husimi at Osaka University in 1937 on the scattering of neutrons similar to the work that David C. Grahame and I were doing at the same time. (Our results at that time were contradictory so far as their interpretation was concerned; Grahame's and my interpretation, that the observed effects were due to the inelastic scattering of fast neutrons, was

later proved to be correct.) Kikuchi had come from the Institute of Science in Tokyo (he was its president) to play host to us at his old post at Osaka University. We met Professor Hiroo Kumagai (then residing in Tokyo), a member of the 1937 team which built the Cockcroft-Walton 300 kev high voltage apparatus--he was known as Aoki at that time. We also met Tetsuo Wakatsuki, then Dean of the Faculty of Science and Head of the Physics Department at Osaka University and hence Kikuchi's successor there; he was at Osaka University in 1937 and helped in the neutron experiments. In addition, we met Professor Kenzo Sugimoto of Osaka University (Figure 4). Kikuchi told me he was heading the Japanese effort on development of the gaseous diffusion process for the enrichment of uranium-235. Husimi, the other member of the 1937 team of Kikuchi, Aoki and Husimi, was then head of the nuclear fusion laboratory at Nagoya University. We first met in Wakatsuki's office where they showed me a picture of Kikuchi, Aoki, Husimi, Wakatsuki, Professor Eiichi Takeda, Okamoto, and another student of the 1937 era (Figure 5), and pictures of their high voltage and other apparatus of that era. Aoki had been able to preserve these because his house was not bombed. Kumagai (Aoki) also showed me his handwritten notes on Gibson, Grahame and Seaborg, and Grahame and Seaborg papers of 1937 and 1938; and of Livingood and Seaborg papers on induced radioactivities of that era.

The synthesis and identification of cobalt-60, iodine-131 and technetium-99m took place in 1938. In a collaboration with Jack Livingood cobalt-60 was found after bombarding cobalt with neutrons. We would never have guessed that cobalt-60 would become so useful in both internal and external radiation for the treatment of tumors. The production method was very straightforward. We bombarded a target in a known position sometimes with neutrons and sometimes with deuterons. This bombardment was followed by very careful chemical separation experiments.

Perhaps the most interesting of all my collaborations with Jack Livingood, and one which has special personal meaning to me, was the discovery of what is now the workhorse of medical tracer and therapy activity, iodine-131. One day in the spring of 1938 Joe Hamilton ran into me on the steps of LeConte Hall and mentioned the limitations on his studies of thyroid metabolism imposed by the short lifetime of the radioactive iodine that was then available to him. He was working with iodine-128 which has a half-life of only 25 minutes. When he inquired about the possibility of finding an iodine isotope with a longer half-life, I asked him what value would be best for his work. He replied, "Oh, about a week." By this time my partnership with Livingood was in full swing; Jack prepared tellurium targets which we bombarded in the 37-inch cyclotron, some with 8 Mev deuterons and some with neutrons, and I put them through chemical separation and identification procedures working in my cramped Le Conte hall quarters. (I recall that we wore gas masks and obstetrical gloves in order to avoid acquiring the dreaded "tellurium breath." We escaped this curse; however, I still don't know whether these precautions were actually necessary.)

We were soon able to identify iodine-131, and luckily enough, its half-life turned out to be eight days (Figure 6). This isotope is now used millions of times a year for the diagnosis and treatment of thyroid disease and in a large number of other applications, including the diagnosis of kidney and liver disorders and function tests of these organs, to screen for pulmonary emboli by lung scans, to locate brain tumors and melanosarcomas, and to determine blood and plasma volumes and cardiac output. I have the added satisfaction that my mother had her own life extended by many years as a result of treatment with iodine-131.

My role in the discovery of technetium-99m involved collaboration with another colleague and in this instance we had no premonition concerning its ultimate beneficial application to medicine when the the work was performed. My collaboration with Emilio Segrè began in the summer of 1938 soon after his move from Palermo, Italy to the United States. On the basis of his familiarity with my publications with Livingood describing our work on new radioactive isotopes, he sought me out as a collaborator. He had participated at Palermo with his colleague, C. Perrier, in the discovery of the first synthetic element, technetium, with the tomic number 43.

Segrè was anxious to pursue his investigations of this intriguing new element. Within a few days after our first encounter we had arranged for the bombardment of molybdenum with 8 Mev deuterons in the 37-inch cyclotron. In this case we collaborated in the chemical separations, using the techniques worked out by Segrè and his co-workers at Palermo, and we isolated a fraction designed to contain any isotopes of the element with atomic number 43. We performed our chemical separations in a rather well-equipped little chemistry laboratory in the newly occupied Crocker Laboratory. We measured the radioactive decay and the radiation absorption properties through the use of an ionization chamber connected to a vacuum tube electrometer system, a rather more sophisticated detection apparatus than the electroscope which Livingood and I had been employing. To our delight, we discovered an isotope of great scientific interest because it decayed by means of an isomeric transition with emission of a line spectrum of electrons coming from an almost completely internally converted gamma ray transition.

This concept was so new to the experts in the Radiation Laboratory, including J. R. Oppenheimer and E. O. Lawrence, that we were asked to delay our publication until additional measurements could be made and interpretations considered. In the meantime, Segrè's former Italian colleague, Bruno Pontecorvo, then working in Paris, observed and published a description of a similar isomeric transition which he had observed in an isotope of rhodium. This was a form of radioactive decay which had never been observed before this time.

Segrè and I were able to show that this radioactive isotope of the element with the atomic number 43 (later given the name technetium by Perrier and Segrè) decayed with a half-life of 6.6 hours and that it was the daughter of a 67-hour molybdenum parent radioactivity. This chain of decay was later shown to have the mass number 99, and after the convention of designating isomeric states of measurable half-life with the symbol "m", meaning metastable, was established the 6.6-hour activity acquired the designation technetium-99m.

Its radiation quality, short half-life and pharmacological versatility make technetium-99m ideally suited for medical use. The physical characteristics allow the physician to administer high doses at a substantially lower irradiation exposure to the patient and, because of the higher count rates, greater sensitivity to sequential imaging. There are now molybdenum-99 generators of technetium-99m in hospitals all over the United States and in many other parts of the world. This radioisotope is used for more than seven million diagnostic procedures per year in bone, liver, and lung scanning and thyroid, cardiovascular, and brain imaging.

The symmetrical fission of uranium bombarded with 17 Mev neutrons, which Segrè and I investigated in 1940, was discovered earlier that year by Y. Nishina, T, Yasaki, and H. Ezoe of the Nuclear Research Laboratory, Institute of Physical and Chemical Research in Tokyo, and K. Kimura, and M. Ikawa of the Imperial University of Tokyo [6].

Perhaps the most important result of my research program was the synthesis and identification of the element with atomic number 94 (plutonium), following soon after the discovery of element 93 (neptunium) in 1940.

Neptunium and plutonium

The first transuranium element, with the atomic number 93, was synthesized and identified (i.e., discovered) at Berkeley in the spring of 1940 by McMillan (Figure 7) and Philip H. Abelson [7]. Using neutrons produced at the 60-Inch Cyclotron, they bombarded uranium to produce the 2.3-day beta-emitter that, on the basis of their chemical work they were able to assign definitely to 93-239. They showed that this element is chemically similar to uranium and not like rhenium, as suggested in the periodic table of that time (Figure 1). They suggested the name neptunium (symbol Np) after the planet Neptune because it is just beyond uranium, as the planet Neptune is beyond Uranus, for which uranium is named.

Immediately thereafter, during the summer and fall of 1940, McMillan started looking for the daughter product of the 2.3-day activity, which obviously would be the isotope of element 94 with mass number 239 (94-239). Not finding anything he could positively identify as such, he began to bombard uranium with deuterons in the 60-inch cyclotron in the hope that he might find a shorter-lived isotope--one of a higher intensity of radioactivity that would be easier to identify as an isotope of element 94. Before he could finish this project, he was called away to work on radar at M.I.T.

When I learned that McMillan had gone, I wrote to him asking whether it might not be a good idea if we carried on the work he had started, especially the deuteron bombardment of uranium. He readily assented.

Our first deuteron bombardment of uranium was conducted on December 14, 1940. What we bombarded was a form of uranium oxide, U_3O_8, which was literally plastered onto a copper backing plate. From this bombarded material we isolated a chemical fraction of element 93. The radioactivity of this fraction was measured and studied (Figure 8). We observed that it had different characteristics than the radiation from a sample of pure 93-239. The beta-particles, which in this case were due to a mixture of 93-239 and the new isotope of element 93 with mass number 238 (93-238), had a somewhat higher energy than the radiation from pure 93-239 and there was more gamma radiation. But the composite half-life was about the same, namely, 2 days. However, the sample also differed in another very important way from a sample of pure 93-239. Into this sample there grew an alpha-particle-emitting radioactivity. A proportional counter was used to count the alpha-particles to the exclusion of the beta-particles. This work led us to the conclusion that we had a daughter of the new isotope 93-238--a daughter with a half-life of about 50 years and with the atomic number 94. This is much shorter-lived than the now known half-life of 94-239, which is 24,000 years. The shorter half-life means a higher intensity of alpha-particle emission, which explains why it was so much easier to identify what proved to be the isotope of element 94 with the mass number 238 (94-238). (Later it was proved that the true half-life of what we had, i.e., 94-238, is about 90 years.)

On January 28, 1941, we sent a short note to Washington describing our initial studies on element 94; this also served for later publication in The Physical Review under the names of Seaborg, McMillan, Kennedy, and Wahl [8].

We did not consider, however, that we had sufficient proof at that time to say we had discovered a new element and felt that we had to have chemical proof to be positive. So, during the rest of January and into February, we attempted to identify this alpha-activity chemically.

Our attempts proved unsuccessful for some time. We did not find it possible to oxidize the isotope responsible for this alpha-radioactivity. Then I recall that we asked Professor Wendell Latimer, whose office was on the first floor of Gilman Hall, to suggest the strongest oxidizing agent he knew for use in aqueous solution. At his suggestion we used peroxydisulphate with argentic ion as catalyst.

On the stormy night of February 23, 1941, in an experiment that ran well into the next morning, Art Wahl performed the oxidation which gave us proof that what we had made was chemically different from all other known elements. That experiment, and hence the first chemical identification of element 94, took place in Room 307 of Gilman Hall, the room that was dedicated as a National Historic Landmark, 25 years later (Figure 9) . Thus we showed that the chemical properties of element 94 resembled those of uranium and not those of osmium.

The communication to Washington describing this oxidation experiment, which was critical to the discovery of element 94, was sent on March 7, 1941, and this served for later publication in The Physical Review under the authorship of Seaborg, Wahl, and Kennedy [9]. Later, in a paper written in March 1942 but published after the war, Wahl and I [10] suggested the name plutonium (symbol Pu) after the planet Pluto, the second and last known planet beyond Uranus.

Almost concurrent with this work was the search for, and the demonstration of the fission of, the isotope of major importance--94-239, the radioactive daughter of 93-239. Segrè played a major role in this work together with Kennedy, Wahl and me. The importance of element 94 stems from its fission properties and its capability of production in large quantities. The 0.5-microgram sample on which the fission of 94-239 with slow neutrons was first demonstrated was produced by transmutation of uranium with neutrons from the 60-inch cyclotron; it was chemically isolated in rooms in Old Chemistry Building and Crocker Laboratory and in Room 307 Gilman; and the fission counting was done using the neutrons from the 37-inch cyclotron. A fission cross section for 94-239, some 50 per cent greater than that for uranium-235, was found, agreeing remarkably with the accurate values that were determined later. This result was communicated to Washington on May 29, 1941, and this served as the basis for the later publication of an expurgated version by Kennedy, Seaborg, Segrè, and Wahl [11].

Nuclear Power as a Source of Electricity

The demonstration of the nuclear chain reaction in uranium by Enrico Fermi on December 2, 1942 led to the successful development of nuclear power for the development of electricity. The most widely used is the water cooled reactor in which about 60% of the electrical energy is produced by the nuclear fission of uranium-235 and about 40% by the nuclear fission of plutonium-239. It is fortunate that this alternate source of energy became available because electricity is so important to mankind because of the limitations on the other sources of energy that can be used for its production. There are many significant factors about the introduction and development of electricity

which affected man's total energy picture. Electricity provided a rapid means of transporting energy and power over great distances. It became possible to convert it into heat and mechanical power, and also into light, after sending it great distances. Electricity was able to supply men with power in smaller and more easily controlled quantities. But perhaps most significantly it was responsible for a revolution in human communication--a revolution that it still continuing. It is almost overwhelming to contemplate the rapid extension of knowledge and ideas since the introduction of the telegraph, the telephone, the radio, television, and the electronics of computer and data processing technology. And electricity, however provided, is essential for progress in developing countries and for the uplifting of Third World countries.

Chairman of the U.S. Atomic Energy Commission

Early in January 1961, I received a telephone call from President-Elect John F. Kennedy, inviting me to serve as Chairman of the Atomic Energy Commission in his new administration. I accepted and arrived in Washington, D.C., to witness his inauguration as president on January 20, 1961. I began my duties as chairman soon thereafter (Figure 10). After President Kennedy's death on November 22, 1963, I was asked by President Lyndon B. Johnson (Figure 11) to continue as AEC chairman and, at the start of his term of office, President Richard M. Nixon also asked me to continue.

The Atomic Energy Commission was responsible for many activities other than the development and testing of nuclear weapons and sponsorship of nuclear energy as a source of electricity, its most publicized projects. We also had major programs for the production of nuclear materials, reactor research, and development for the armed services (including the then-new nuclear navy), research in high and low energy physics and in chemistry and biology, sale of radioisotopes for use in nuclear medicine, agriculture, industry and research, licensing of nuclear materials for power plants and other peaceful purposes, and international cooperation in developing the "peaceful atom."

In March 1962 President Kennedy asked the AEC to take a "new and hard look at the role of nuclear power in our economy." The president asked that the study identify the objectives, scope and content of a nuclear power development program in light of the nation's prospective energy needs and resources and of advances in alternative means of power generation.

The year 1962 was an appropriate one for a "new and hard look." By this time 25 experimental or prototype nuclear power reactors had been funded by the U.S. government, while 12 others had been funded under cooperative programs with industry. From this work had come substantial advances in nuclear technology and considerable operating experience, sufficient to make the goal of economically competitive nuclear electric power seem attainable, at least in areas of the country with high conventional fuel costs. Not surprisingly, such progress had stimulated increased industry interest in nuclear power and in the private ownership of nuclear fuel. On the other hand, general economic conditions did not seem to warrant the construction of additional experimental facilities without more definitive program guidance. Guidance was needed particularly to help determine what reactor concepts should be emphasized in the coming period. The plants thus far built had been of several different types, each having its virtues and its champions.

Light water-cooled reactors had demonstrated their reliability, having been used extensively, for example, in nuclear submarines and in the Shippingport Atomic Power Station near Pittsburgh. They were not extremely complex either in construction or operation, and could be built and operated with available technology.

The use of nuclear superheating, to obtain higher thermal efficiencies and steam conditions more compatible with conventional turbogenerators, had been explored, for example, with the 50 Mwt Boiling Nuclear Superheat Power Station [BONUS] in Puerto Rico.

Gas-cooled systems were known to permit relatively high thermal efficiency. Potentially the coolant gas could drive a turbine directly, and this concept, known as the HTGR (High Temperature Gas-Cooled Reactor), showed promise of being able to use thorium fuel, which was in abundant supply.

Through operation of experimental reactors, it was known that liquid-metal-cooled reactors could achieve high temperatures and thermal efficiency, permitting low net power costs. In addition, the liquid-metal-cooled reactors could be breeder reactors. Their further development could therefore be considered essential to achieve the full benefit of nuclear power.

Heavy water-cooled and moderated reactors had been examined, but had limited support in the U.S., because of the availability of enriched uranium fuel material. (Heavy water reactors could use natural uranium fuel and required larger facilities because they could not produce as much energy per cubic foot of reactor as those using enriched fuel.)

At the end of my tenure as Chairman of the U.S. Atomic Energy Commission in 1971, 130 central station nuclear power plants, representing an aggregate capacity of more than 108,300 net megawatts of electricity (Mwe) were built, under construction or planned in the United States, as follows: there were 25 operable units (including two licensed for fuel loading and subcritical testing), representing a total capacity of 11,400 Mwe; 52 units (44,500 Mwe) were under construction or being reviewed for operating licenses; 39 units were under AEC review for construction permits, representing 38,400 Mwe of initial capacity; and there were 14 units for which utilities had contracted but not yet filed construction permit applications, representing 14,000 Mwe.

However, in the following years, anti-nuclear sentiment in the United States (a phenomenon shared by many other countries) led to the cancellation of many of the orders by utilities for the purchase of nuclear power plants and to a cessation by utilities of orders for new nuclear power plants.

U.S.-Japan Cooperation

When I became Chairman of the USAEC in 1961, Japan already had numerous nuclear organizations and well-equipped laboratories engaged in extensive research and development programs. Nine research reactors and two critical assemblies were in operation or under construction; two power reactors were under construction. The many activities under way included heavy water production research, thermonuclear research, an atomic ship project, long-range nuclear power planning with a view to the installation of 7 million kilowatts by 1975, and excellent training facilities, such as a radioisotopes techniques school in Tokyo, which was open to participants from other countries in the Far East and Southeast Asia.

Cooperation with the United States under our country's Atoms-for-Peace program has been a major factor in Japan's impressive advances in nuclear technology. An initial Agreement on Cooperation in Civil Uses came into effect on December 27, 1955. This was superseded by a comprehensive research and power agreement which became effective December 5, 1958. A U.S. research reactor grant of $350,000 was committed in 1957 for a reactor at Japan's Atomic Energy Research Institute at Tokai-Mura; and U.S. consultants assisted in the development of Japan's research programs. By late 1960 material transfers from the United States included four shipments of research reactor fuel, small quantities of other special nuclear materials for research, and 1,120 shipments of radioisotopes. A U.S. depository library had been established in Tokyo. Taking full advantage of training opportunities offered by the United States, Japan had sent more participants and observers than any other nation to our atomic energy installations and facilities.

Our peaceful nuclear cooperation with Japan was well-advanced, then, at the time I assumed USAEC responsibilities. This cooperation continued and expanded in the succeeding years.. In 1962 arrangements were made for technical exchanges in the field of ceramic nuclear fuels. Also, on December 12, 1962, I was paid a courtesy call by officers of the Japan Atomic Power Company--R. Sagane (Managing Director, and an old Berkeley friend), Dr. Ipponmatsu (President), Mr. Shimoyama (Legal Staff), Mr. Yoshicka (Director and Manager of Engineering), and Mr. Imai (Department Chairman, Research and Scientific Engineering)--and Mr. Haginoya, Atomic Energy Attaché of the Japanese Embassy.

The following year an amendment to our 1958 agreement was signed that gave greater flexibility to the materials provisions of that agreement. Meanwhile, Japan's research and development programs progressed rapidly. In 1963 its U.S.-built Power Demonstration Reactor (JPDR) achieved criticality--the first reactor to supply nuclear-generated electricity to the Japanese grid. That same year, during the period of the Seventh IAEA General Conference in Vienna, I attended the signing on September 23rd of the first U.S.-Japan-IAEA trilateral agreement providing for Agency administration of safeguards applicable under our bilateral agreement.

During these years I was able to meet with Japanese representatives not only at the annual IAEA assemblies, but also at Geneva in 1964, at the Third International Conference on the Peaceful Uses of Atomic Energy, and in the United States. In the course of the Geneva meeting, it was my pleasure to have Japanese AEC Commissioner Sakuji Komagata among my guests on the U.S. nuclear ship Savannah on September 3, 1964 (Figure 12). His participation on that occasion seemed particularly appropriate in view of Japan's own progress in the field of nuclear maritime propulsion; the Japanese exhibit at Geneva included a model of its first nuclear-powered ship, then in the design stage.

A few months later, in Washington, I had an opportunity for a brief talk with Japan's Prime Minister Eisaku Sato, who had formerly headed the Japanese Atomic Energy Commission and had represented Japan at the 1963 IAEA General Conference. The setting for our conversation was a reception in the Prime Mininster's honor given on January 13, 1965, by the Japanese Ambassador and Mrs. Takeuchi. Among the topics we touched on were the arrangements being made to hold the IAEA's Ninth General Conference in Tokyo the following fall. This would be the first such conference held elsewhere than in Vienna. I was, of course, eager to attend; but, as I indicated in my response to a question

by the Prime Minister, I could not be sure this would be possible. Fortunately, plans did work out as hoped, and my first visit to Japan took place in September 1965.

In the meantime I had another opportunity for contact with Japanese nuclear officials when I hosted a luncheon, on April 30, 1965, for Commissioner Kinichi Aoki of the Japanese Atomic Energy Commission, including Otajimi of Tokyo Electric Power Company, at the International Club in Washington. Others present were Ambassador Ryuji Takeuchi, the USAEC Commissioners and staff.

The IAEA Conference in September 1965, like other such gatherings, permitted useful personal discussions with delegates from other countries. Naturally, however, I was especially eager on occasion to take advantage of the location to meet with Japanese officials concerned with nuclear matters, visit some of their facilities, and see something of their country. Also, I had agreed to address Japan's Atomic Industrial Forum, whose annual meeting was scheduled to take place during the period of the IAEA Conference. During this visit I met Professor Takashi Mukaibo of the University of Tokyo; I recall that he accompanied Kiuchi Aichi, a friend of Prime Minister Eisaku Sato (whom I had met in Washington), for a stimulating discussion of U.S.-Japanese cooperation in the peaceful uses of atomic energy.

During my 1965 visit to Japan I had the opportunity to visit Japan's principal nuclear research center, the Japan Atomic Energy Research Center at Tokai-Mura. Here I had the pleasure of seeing my friend Ryokichi Sagane, whom I had known during his stay at the Radiation Laboratory in Berkeley in the late 1930's, and Keiji Naito, who worked with us at the Radiation Laboratory in 1958 (Figure 13).

During July 1968, representatives from the Japanese Atomic Energy Commission met with us in Washington to sign a new U.S.-Japan Agreement for Cooperation (Figure 14). The group that came from Japan to attend the meeting, held July 15th and 16th, at our H Street Headquarters in Washington, D.C., was headed by Dr. Naotsugu Nabeshima, who in November 1967 had succeeded Nikaido as Minister of State in charge of the Science and Technology Agency and Chairman of the JAEC. He was accompanied by Hironori Itoh (Counselor from the Japanese Embassy), JAEC Commissioner Tasaburo Yamada, Japan Atomic Energy Bureau Director Tsuneo Fujinami, Takashi Ishikawa (Minister Nabeshima's secretary), and three officials of the government-owned Power Reactor and Nuclear Fuel Corporation (PNC)--Director General Goro Inouye, Director Hiroshi Murata, and Secretary Kunihiko Uematsu. Representatives of the USAEC attending some or all of the sessions were Commissioners James T. Ramey, Gerald F. Tape, Wilfrid E. Johnson, and I; Deputy General Manager Edward J. Bloch; Assistant General Manager for International Affairs Myron B. Kratzer, and certain Division Directors and staff members as appropriate to the various subjects taken up.

A second USAEC-JAEC meeting, which I attended, was held in Tokyo on March 24-25, 1970. As on the occasion of our first joint meeting, a number of matters made the opportunity for personal high-level discussions particularly welcome at this time. First, Japan had by now greatly expanded its nuclear power plant program. When our 1968 Agreement for Cooperation was signed, 13 plants using enriched uranium fuel were scheduled for construction starts by 1972. Based on this program, our bilateral agreement contemplated the transfer from the United States of a maximum of 161 tons of enriched U-235

(whether or not Japanese-owned natural uranium was supplied for toll enrichment), of which 154 tons would be for power reactors. In the spring of 1970, the expanded Japanese program called for start of construction of a total of 17 units by December 1972 and another 28 units of which construction was scheduled to start over the years 1973-1979. The estimated total U-235 required to fuel these plants amounted to over 681 tons! The Japanese were understandably anxious to obtain assurances regarding the availability of this material. Committing ourselves to meeting the total long-range requirements indicated was not feasible in the light of our existing enrichment capability. We did not feel able to consider supply commitments with respect to reactors that would start construction beyond 1973.

During this visit we inspected a number of Japanese nuclear power stations, including the Tsuraga Power Station (Figure 15) and Osaka University, as mentioned earlier, to meet my Japanese colleagues, who had conducted research in 1936-1937 on the inelastic scattering of neutrons along the same lines as I had done during my graduate student days at Berkeley.

The Status of Nuclear Power

Introduction

Fission power is in a state of transition. The general loss of public and political support as a result of both TMI-2 and the Chernobyl accidents is being replaced by the realization that nuclear power must be a vital part of the future energy mix if the current concerns about global warming are borne out.

Nuclear power remains the ultimate component of an electrified "non-smoking" energy system. As a non-smoking system, it is exempt from the political and potential economic troubles of acid rain from coal combustion or the longer range concern over the greenhouse effect which mark all combustion systems. The need for nuclear power will intensify before the other promising non-smoking energy sources, fusion and solar, will become both economically attractive and widely deployed. Fusion power has many major hurdles to jump before it can meet the promise of being a practical, economic power producer. Break even power production is yet to be demonstrated, and the very difficult problems of first wall lifetime of the plasma confinement structure and energy conversion to electricity remain to be solved in a practical and economic manner. In solar power, great strides are being made. Amorphous cell technology for direct photovoltaic electricity production holds the promise of substantial increase in conversion efficiency at lower cost, although further work remains before we will see the widespread industrial development of these systems. The problem is quite difficult because the diffuse nature of sunlight mandates a very low energy density system. Moreover, even as the photovoltaic systems are perfected they will remain regional and seasonal in utilization. Because of these problems with the other non-smoking technologies, the need for a viable nuclear power program remains strong.

Present Status of Nuclear Power

A nuclear electric power generating capability has been deployed throughout the world at an unprecedented rate, one on the order of five times faster than any other previous new source of energy. 417 nuclear power plants are operating around the world today, generating 300,000 megawatts of electricity in twenty-six countries [13]. Most of these countries depend

vitally on the electricity generated by nuclear power. In 1987, France generated 70% of its electricity from nuclear power plants, Belgium 67%, South Korea 53%, Taiwan 48%, Sweden 45%, Finland 38%, and Japan 32% [14]. What may not be familiar is that in the Soviet bloc Bulgaria generates 30% of its electricity from nuclear power, Hungary 26%, and Czechkoslovakia 21% [14]. Furthermore, although the United States is not a leader in percentage, it has the largest total electric output for nuclear power: 100,000 MWe from 110 plants, generating 18% of the United States electric power in 1987 [14].

And what about costs? IAEA statistics [13] show the following ratio of costs from coal as compared to nuclear power: France - 1.8, West Germany - 1.68, Belgium - 1.62, Japan - 1.37, Finland - 1.33, Spain - 1.2. Unfortunately, and an exception to the general rule, the United States did not produce its nuclear electricity more cheaply on the average than coal in 1986, even though many of its plants were doing so. For example, 16 of the 20 most economic thermal power plants in the United States operated during the period 1981 to 1985 were nuclear plants. The nuclear plants recently brought on the line have been so expensive in capital cost that they have slipped the average cost above that of coal. Nevertheless, the electricity produced by nuclear power in the U.S. since 1973 has resulted in a cumulative reduction in electricity costs of $65 billion [15]. And we must not forget that if we set aside amortization costs on the investment which has already been paid, the average variable costs [16] of nuclear electricity in 1986 was less than that of fossil electricity: $19/MWhr for nuclear compared to $21.60/MWhr from coal and $34/MWhr from oil.

But what about plant availability? In 1977, the average availability of the 137 units operating around the world was 64.7%, quite comparable if not superior to the existing track record of fossil plants. In 1982, 200 nuclear units operated at an average plant availability of 65%. But then the lessons learned began to pay off. In 1986, 288 operating units achieved an average availability of 70.4%, and 55% of these achieved a plant availability of 75% or better. Since 1984, 40% of the units around the world operated at greater than an 80% plant availability factor [14]. Everything indicates that these impressive improvement trends will continue.

And what about safety? Chernobyl marks the most serious industrial accident involving nuclear power. The immediate death toll was 32 involving plant operators and firemen. However, no member of the general public was immediately killed. Some members of the public will have their lives shortened from cancer induced by the accident, although the percentage increase will be so low that the experts judge the increase will not be quantitatively verified. The most probable estimate is several hundred. However unfortunate this loss of human life is, we do need to look at these figures in perspective, and they are very low when compared to the immediate loss of life in the Soviet Union each year, due to transportation accidents or the lives shortened by smoking.

The United States' most publicized nuclear accident, Three Mile Island, caused no immediate deaths. In addition, the potential loss of life from latent cancer is estimated to be between 0 and 1.

The total industrial safety record of nuclear power is substantially superior to that achieved through alternate methods of generating electricity and of many other activities which make up our daily lives: the normal annual risk of mortality among the U.S. general population is 330,000 from smoking

cigarettes, 120,000 from all accidents, 57,000 from automobile riding, 7,000 from fires, 6,200 from drowning, 1,100 from accidental electrocutions, 88 from lightning, 10-20 per GWe of electricity from coal plants or 2,500, and 0.4 per GWe from nuclear plants or 35 [17]. The statistics for coal and nuclear plants consider the entire fuel cycle from mining, transportation, energy conversion and waste disposal.

And what about the environment? The normal operations of these nuclear plants have been environmentally benign. IAEA data [14] show that there has been a reduction of sulphur dioxide emissions of 66% in Belgium even though a major amount of additional power has been generated. Similarly, a reduction of 50% in France and 40% in Finland has been achieved. Nuclear power plants reduced emissions of carbon dioxide by 378 million tons, or 7.3% of the world's total. Regrettably, the Chernobyl accident has caused significant land contamination, the consequences of which are still not fully understood nor the extend of recovery from the environmental insult. But it is clear that the net benefit to the environment from nuclear power has been substantial.

Nuclear power plants have had another beneficial effect. We in the United States have been blessed by low oil and gas prices over the past five years or so which have strongly contributed to the reduction in inflation and have helped the world recover from the serious economic recession created by the formation of the OPEC monopoly and the tremendous increases in oil and gas prices which drove us to double digit inflation in the '70s. Nuclear power has clearly contributed to this improvement. OPEC's monopoly grasp was loosened in part by the reduction in oil usage caused by the conversion to nuclear power, which is estimated to have reduced the market for oil by as much as 50 billion dollars annually.

As we look to the future, it is clear we must develop the breeder reactor for assurance of fuel supply. Japan is in the forefront of this development with the only active breeder reactor construction program in the Western world. The Japanese breeder reactor, Monju, is a 280 MWe unit which is scheduled to be completed in 1994. Along with Monju, the Japanese are developing the Fast Breeder Reactor Pilot Reprocessing Plant at Tokai to separate plutonium from spent breeder fuel.

With this pilot plant and the commercial LWR reprocessing plant to be built at Rokkasho-mura, Japan will be taking a largest step in closing the fuel cycle. This is something that the United States has not been able to do, due to the policies of Presidents Ford and Carter related to non-proliferation of nuclear weapons. Without, however, an active reprocessing industry, it will be difficult for the U.S. to maintain credibility in international forums treating non-proliferation issues.

Public Perception of Nuclear Power

In the past the electronic and print media have tended to paint a bleak picture of the public reaction to nuclear power. However, this is changing. Recent articles in such public opinion forming journals as The New York Times [18], Wall Street Journal [19] and Fortune Magazine [20] have been very supportive of nuclear power and in particular the new generation of "passive safety" plants. Several recent surveys show an increasing realization that nuclear power is a safe neighbor and a necessity for a secure energy future. A recent Cambridge report survey of scientists and engineers who subscribed to

Scientific American [21] found the following responses to this question "If you had to live within 5 miles of a major industrial facility, which would you prefer: a nuclear power plant, a chemical plant, a coal-fired plant, an airport, or an oil refinery?" Respondents substantially favored the nuclear power plant: 45% preferred the nuclear plant, 26% the airport, 17% the coal plant, 6% the chemical plant and 4% the oil refinery.

Another poll of the general public taken in late 1987 [21] revealed:

- 75 percent of those polled said the need for nuclear energy will increase in the years ahead
- 59 percent preferred the use of more nuclear energy over increased dependence on foreign oil
- 39 percent favored using less nuclear power even if that course increases U.S.dependence on imported oil
- 67 percent called nuclear energy a good or realistic choice as an energy source for large-scale use.

Utility Perspective on The Future of Nuclear Power

Despite the somewhat positive recent public polls concerning nuclear power in the United States, its future as a source of new generating capacity still remains clouded from the utility standpoint. The unpredictability of the cost and scheduling of new plants must be resolved before utility executives will have enough confidence in the technology to make major future commitments to it. Cost and time schedules of nuclear power plants completed in the United States in the last five years range from a short schedule of 6 years for the Saint Lucy-2 (Florida) plant to a long of 18 years for the Diablo Canyon-2 (California) plant, and complete construction costs range from $1050 per KWe for the LaSalle (Illinois) plant to $4475 per KWe for the Clinton (Illinois) plant. Such a wide range of variation of construction times and costs makes future planning difficult, if not impossible. Once a plant is completed, however, the utility's economic exposure is not over. Almost every major nuclear plant completed in the United States in the last several years has been faced with the spectre of "prudency hearings." In prudency hearings detailed audits are made of power needs, construction practices, financing, and a myriad of other details surrounding the acquisition and construction of a new power facility. In many cases major disallowances have been made, and the utility has not been able to recover full cost of its investment. Currently the total impact of nuclear plant cost disallowance is about $3 billion and is expected to reach $5-6 billion when plants currently under construction are completed. $1.4 billion has been disallowed from the cost of Shoreham (New York), $121 million from Wolf Creek (Kansas), and $628 million from Perry (Illinois), just to name a few.

The regulatory uncertainty of current government processes in the United States remain a major stumbling block to the addition of new nuclear power capacity in this country. Both the Seabrook and the Shoreham nuclear power plants were built in accordance with all existing nuclear power regulations. Yet despite their successful construction programs which were in compliance with quality control construction practices, they have been unable to start up because the Nuclear Regulatory Commission has been unwilling or unable to issue their operating licenses because of the failure of local governments to cooperate in emergency evacuation planning. This impasse has been broken by President Reagan who has issued an executive order authorizing the federal government to take over in the cases where local governments are unwilling to

participate in emergency evacuation planning. It is hoped that both plants will be started up within this year.

As nuclear power has matured in the United States, plant sizes have risen to the 1300 MWe level. In the past it has been customary for several smaller utilities to share the output of a larger nuclear power plant to take advantage of the perceived economy of scale. Because numerous difficulties have been encountered by some of these enterprises, it is questionable whether this type of sharing arrangement will be utilized in the future. Problems encountered with several public utility commissions ruling differently on charges for the same plants are an example of these problems. The Palo Verde plant for Arizona Public Services has come under the jurisdiction of four separate public utility commissions. Complex and difficult rate setting precedents have being undertaken by four separate public utility commissions in Arizona, New Mexico, Texas and California, which may hamper the ability of Arizona Public Services and its partners to fully recover their investment in these units.

In current sharing arrangements in the United States, one utility takes on the responsibility for plant construction while the other utility partners in the enterprise provide money but are not directly involved in the construction process itself. Because of the failure of some large nuclear power projects and large cost overruns on others, the utility which has accepted responsibility as the construction manager finds itself in the position of being potentially legally liable if the enterprise runs into construction or licensing difficulties which delay the plant startup date or increase costs. The potential legal liabilities to the construction management utility are much larger than any savings due to economy of scale which would be present if a smaller, wholly owned, project were chosen. Furthermore, load growth in the United States has been low over the past several years, averaging about 2%. This means that there are very few utilities that would be able to absorb a plant of 1300 MWe on their grid without the creation of excess generating capacity and opening themselves up to possible prudency action.

Recent Legislative Action

There is recognition on the part of the Congress of the United States that legislative action is necessary to remove some of the barriers to future deployment of nuclear power if it is to remain as a viable energy source for the future. Senator Bennett Johnston (Democrat-Louisiana) and Chairman of the Senate Energy Committee in a recent policy speech stated "We must preserve the nuclear option. Nuclear power is too vital a component of our energy mix to be forsaken." Johnston also announced his intention to "introduce, report and pass legislation in this Congress to begin development of an improved nuclear reactor technology." This technology, he said would cost less, would "satisfy public concerns about safety and environment" and "would do more for energy independence than any other issue" [22]. Since his speech, Senator Johnston has introduced a bill calling for $500 million of funding for development of passively safe reactors. In addition to the proposed Johnston legislation, several other initiatives which are positive to the future of nuclear power are presently being considered on Capitol Hill. An NRC reorganization act to replace the Nuclear Regulatory Commission with a New Nuclear Safety Administration has been introduced. New legislation concerning the uranium enrichment industry has also been introduced which would clarify the existing industry costs and stimulate the domestic uranium mining industry. Finally, several drafts of a Nuclear Standardization and Reform Act are being

considered for introduction. The major feature of this legislation is the establishment of a policy for standardization of nuclear power plant design and the provision for a one-step licensing procedure in which a construction permit and operating license can be obtained prior to the undertaking of a nuclear power project. A check would be made at the end of construction to ensure that it was done in accordance with the mandates of the license.

Current Nuclear Industry Initiatives to Ensure a Nuclear Future

There is much discussion concerning what type of nuclear power system - Advanced Passive Light Water Reactor (APLWR), Liquid Metal Reactor (LMR), Modular High Temperature Gas Cooled Reactor (MHTGR)- best meets the needs of the future. The Advanced Reactor Corporation (ARC) serves as the utility oversight organization for advanced reactor development in the U.S. In a recent review of US DOE's advanced reactor program, ARC concluded "It is the present judgment of the majority of the nuclear power industry that the Light Water Reactor (LWR) will remain the dominant nuclear power technology over the next several decades. Over 25 years of favorable operating experience world-wide, along with extensive development testing programs, support the LWR and provide a sound basis of confidence in this concept. Thus, an improved version of the LWR is expected to be the preferred choice for the next increment of nuclear capacity order in the U.S." [23]

Presently, in the United States, there is an aggressive program to develop reactors with passive safety features. Passive safety features can be thought of as characteristics of a reactor which without intervention of a human operator will tend to shut a reactor down, keep it in a safe configuration, or prevent released radiation to the public. These features fall into two broad categories -- features which are designed to prevent accidents from taking place and those which mitigate the effects of potential accidents if they do happen. Although there are significant differences in how passive safety is achieved between the three types of passive reactors, we do not see significant differences in overall safety between systems. However, there are significant differences between reactor designs in: time to commercially introduce, cost to commercially introduce, commercial acceptance by utilities, technical maturity, ease of licensing and public perception. These differences are summarized in Tables 1, 2, 3 and 4.

Let's take a look in more detail at each of the proposed reactors. The most developed of the three is the advanced passive light water reactor (APLWR), of which two designs are being developed under a joint program of the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE). Their design lead comes, in part, from the fact that there are currently about 110 light water reactors operating in the U.S. and 310 operating worldwide. This depth of operating experience gives the reactor designer great confidence in the characteristics of the machine he is designing. The two current designs being carried by the EPRI/DOE program [24] are the AP600 (Advanced Passive 600 MWe), a pressurized water reactor being designed by Westinghouse, Burns and Roe and Avondale Shipyards, and the SBWR (Simplified Boiling Water Reactor), a boiling water reactor being designed by General Electric, Bechtel, and the Massachusetts Institute of Technology.

These two reactors are similar in that they are both 600 MWe in size, run at lower temperatures and with larger water inventories than current light water reactors, and have passive emergency core cooling systems which utilize gravity, thus eliminating the necessity for the large electrically driven

emergency pumps common to the current generation light water reactors. They both use passive natural circulation for the removal of decay heat from the core and rejection of it to containment, and passive containment cooling systems to cool the containment which would otherwise be heated as a result of the rejected decay heat in a post-accident situation. Both reactors are designed to withstand a full loss of coolant accident without requiring operator action for a minimum period of three days. Additional features of the AP600 include a greatly simplified reactor coolant loop to reduce hydraulic losses, utilizing canned rotor pumps to eliminate the need for an active source of pump seal lubrication, and a design which accommodates modularization, so that the reactors may be factory built to ensure consistent and high quality under factory-controlled conditions.

The SBWR features a totally natural circulation loop with no recirculation pumps and a passive steam injector which utilizes steam generated by decay heat, as a motive force for feedwater in times of station blackout, when all electricity is lost. Because of these passive safety features, both plants are able to cope with station blackout (full loss of all on-site AC power) and, as a result, the necessity for safety grade diesel generators is eliminated. (It is anticipated that for ease of operation and investment protection, non-safety grade diesels will be included.) The elimination of the active emergency core cooling systems, with associated pumps valves and piping, along with other passive design features allows a significant simplification in design when compared to conventional units.

Table 5 shows the comparison of bulk commodities and components of an AP600 as compared to the conventional 600 MWe Westinghouse designed nuclear power plant. Conceptual diagrams of the SBWR and AP600 are given in Figures 16 and 17.

The liquid metal reactor (LMR) passive design is the PRISM [25,26,27,28] (Power Reactor Inherently Safe Module) concept which is being developed by the U.S. Department of Energy by a team headed by General Electric. Other team members include Babcock & Wilcox, Bechtel, Borg Warner, Burns and Roe, Foster Wheeler, Stearns Rogers and Westinghouse. The PRISM concept utilizes nine identical reactor modules arranged in three 465 MWe power blocks for an overall net electric rating of 1395 MWe. Each of the three modules in a power block has its own steam generator, and all three jointly supply saturated steam to a single turbine generator. Smaller plant sizes of 465 MWe and 930 MWe can be provided by using one or two of the standard blocks. The reactor itself is a pool-type sodium-cooled reactor with an intermediate heat transport system to isolate the steam generators from the reactor in the event of a steam generator leak and subsequent metal/water reaction. The reactor and its safety-related systems are all protected from ground motion during an earthquake through the utilization of seismic isolators. The seismic isolator concept has been used in many non-nuclear installations and in two foreign nuclear plants. Further testing of the particular isolator design is necessary for qualification for nuclear service. Under accident conditions, decay heat is removed from the core using a passive reactor vessel auxiliary cooling system. Unlike the light water reactor, the reactor vessel auxiliary cooling system dumps its heat directly to the atmosphere. No containment cooling is necessary because the designers believe that overall reactor safety goals may be met without the necessity for containment. One of the major features in the PRISM accident prevention scheme is the utilization of a uranium/plutonium/zirconium metallic fuel now under development by Argonne National Laboratory. This fuel has been selected as a reference for PRISM

because of its excellent negative reactivity feedback under loss of coolant flow and transient overpower events. The present core design makes PRISM a breeder reactor (it produces more fissile material than it consumes) with a breeding ratio of 1.14.

As previously mentioned, one of the major safety features of the PRISM reactor is provided by the large negative reactivity feedback of its metallic fuel. This negative feedback characteristic of metallic fuel was first demonstrated by two landmark tests in EBR-II (Experimental Breeder Reactor-II) in Idaho on April 3, 1986. The first test was a loss of flow without scram and the other was a loss of heat sink without scram. These tests demonstrated that the high heat conductivity of the metallic fuel and the thermal inertia of a large sodium pool can shut down a reactor during these potentially severe accident situations without depending on human intervention or operation of active engineered components. The design schematic of the PRISM reactor is given in Figure 18.

The third of the family of passive reactors under development is the modular high temperature gas-cooled reactor (MHTGR). [29,30,31,32] This reactor is being developed by a team lead by General Atomics assisted by Bechtel, Combustion Engineering and Stone & Webster. The MHTGR is a helium-cooled graphite moderated reactor system. This concept has four reactors feeding two turbines to make up a 540 MWe power block. In the MHTGR, the plant is separated into two major areas-- the nuclear island containing the reactor modules and the energy conversion area. All of the safety-related structures systems and components are contained within the nuclear island, permitting procurement and construction of equipment in the energy conversion area to be done to conventional (non-nuclear safety) standards. Under accident conditions when the steam generators are not available for heat removal, decay heat is removed by a natural circulation cavity core cooling system which rejects heat to outside air. Like PRISM, this reactor does not have a conventional containment; thus no containment cooling systems are required.

The heart of the safety of the MHTGR is its unique fuel design. The reference fuel cycle employs enriched uranium. Fissile fuel is a two-phase mixture of 19.8% enriched UO_2 and UC_2 referred to as uranium oxycarbide (UCO). The fertile fuel is thorium oxide, ThO_2. Both fissile and fertile particles are subjected to a process wherein the particles are coated with three layers of ceramic materials to form the primary fission product barrier. The coated fissile and fertile particles are blended and bonded together with a carbonaceous binder in the form of cylindrical compacts which are sealed into holes in the graphite moderator blocks. Because of the high temperature characteristics of the ceramic coating around the fissile and fertile fuel particles, the particles maintain their integrity to very high temperatures. Fuel tests done in the AVR (Arbeitsgeminschaft Versuchs-Reaktor) reactor at Julich, Federal Republic of Germany, showed that the fuel reached a temperature between 2100° and 2200°C before the onset of fuel failure was detected. The fuel itself has a very strong negative temperature coefficient. A series of tests were run at the Julich reactor which demonstrates the passive nature of this type of fuel. Although the AVR reactor is a pebble-bed design, meaning that the reactor is fueled with a series of soft ball-sized spheres composed of fuel and moderator, as opposed to the prismatic core used in the MHTGR design, which consists of monolithic blocks of graphite with carbonaceous bonded fuel inserts, the results obtained at Julich should be valid for the MHTGR design.

Another AVR test at Julich demonstrated the response of the reactor and fuel to the loss of flow condition starting at full power. Both helium circulators were intentionally stopped and the flapper valves at blower outlets were closed to prohibit circulation through the primary system. All rods were locked out of the core. The strong negative temperature coefficient of reactivity automatically shut the reactor down without operator intervention. Some internal high convection heating exchange between the core and the steam generator did remove some of the afterheat, and a small flow of feedwater was maintained in the steam generators to prevent the lower section of tubes from overheating. Heat was also removed by radiation from the outer vessel walls. After twenty-three and one-half hours, due to decreasing temperatures and xenon decay, the reactor went critical again with a peak power of 1.8 megawatts, stabilized at less than 1% of full power after several hours. The latest test to be run at AVR is a simulated loss of coolant accident with no emergency cooling. For this test, the reactor was shut down and depressurized to atmospheric pressure. The reactor was then brought back to criticality and operating temperature, circulators stopped, and the reactor kept critical but the power was run down to match decay heat fall off from full power. The test was kept up for five days. The temperature went up for the first 14 hours and then turned down. It is calculated that the fuel did not exceed 1150°C during this test. There were a number of graphite pebbles containing 20 quartz pellets with 650° to 1350°C wire fuses placed in the center of the core to measure peak fuel temperatures. They will be discharged next spring and X-rayed to determine the exact maximum fuel temperatures. Figure 19 shows the layout of the MHTGR primary system.

We will review now the status of development and future plans for the three passively safe reactor designs.

The advanced light water reactor is in the final year of its conceptual design phase. During this phase, co-sponsored by DOE and EPRI along with a consortium of overseas utilities including ENEL in Italy and KEMA in The Netherlands, approximately $25 million have been applied to the completion of a detailed conceptual design. This work includes not only engineering feasibility and design studies but also includes hardware tests of some major components. Negotiations are currently underway to bring EDF of France and CRIEPI and JAPC of Japan in as additional sponsors of this work. In addition, JAPC has been sponsoring separate but coordinated studies.

The next phase of the program will begin in federal fiscal year 1990 and will continue through the end of 1994, at which time it is anticipated that two passive light water reactors will be certified by the NRC, with sufficient design and testing detail to allow orders to be made with confidence by respective utilities. The approximate cost for this five-year effort is $200 million, $125 million of which has been identified as DOE and EPRI funding. The remaining funds will be sought from vendor cost-sharing and overseas utilities.

There are presently no plans to build a prototype for power demonstration of either of the LWR passive light water reactor designs. Current licensing plans discussed with the Nuclear Regulatory Commission (NRC) do not rely on a prototype demonstration for licensing. This differs from the approach used by both the PRISM and the MHTGR programs which are relying on prototype demonstration as part of their licensing process. One of the reasons for this difference lies in the lack of a conventional containment (i.e. a low leakage

boundary surrounding the reactor system boundary) in either the PRISM or the MHTGR designs The absence of a conventional containment is based upon the predicted retention of the radioactive material by the fuel during even extremely improbable severe accident scenarios. Regulatory acceptance of this novel approach will be a challenge and is considered to require a prototypic demonstration of the benign reactor response.

Current PRISM design funding is running at approximately $10 million per year, planned to last through 1991, while a determination is made in parallel regarding private sector and international interest in supporting the necessary prototype demonstration. The design effort is supported by a $170 million per year program of fuel, fuel cycle and plant hardware development and experimental reactor operation.

Current MHTGR funding is also running at approximately $10 million per year with another approximately $10 million per year of supportive technology research and development. In parallel, interest in private sector support of the necessary prototype is being investigated.

The MHTGR has been chosen as one of the nation's two weapons materials production reactors. As such it is possible that this weapons materials production reactor may fulfill the prototype requirements of the MHTGR; however, there are substantial differences at this stage between the civilian and the military concepts, the most notable of these being that the military version of the MHTGR includes a conventional containment.

The largest hurdle for all three of these systems appears to lie in their ability to meet the as of yet unspecified NRC requirements for severe accident. Meeting these requirements for either the MHTGR or the PRISM will require a new regulatory approach to licensing because of their use of a confinement as opposed to a conventional containment system.

Conclusion

The United States who led the world in early nuclear power development was also the first country to be affected by its decline. Over the past decade the U.S. nuclear power industry has seen no new domestic orders due to a combination of low load growth, environmentalist pressure, regulatory uncertainty and increased costs. Many of these same pressures are now affecting nuclear power worldwide. However, in the U.S. which has lead the world in the birth and then the decline of the nuclear power industry, there are signs that its rebirth may be imminent.

This work was supported by the Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. E. Fermi, Nature 133 (1934) 898.

2. Ida Noddack, Angew, Chem. 47 (1934) 653.

3. O. Hahn, L. Meitner and F. Strassmann, Ber. 69 (1936) 905.

4. I. Curie and P. Savitch, C.R. 206 (1938) 1643.

5. O. Hahn and F. Strassmann, Naturw. 27 (1939) 11.

6. Y. Nishina, T. Yasaki, H. Ezoe, K. Kimura, and M. Ikawa, Nature 146 (1940) 24.

7. E. M. McMillan and P. H. Abelson, Phys. Rev. 57 (1940) 1185.

8. G. T. Seaborg, E. M. McMillan, J. W. Kennedy and A. C. Wahl, Phys. Rev.69 (1946) 366.

9. G. T. Seaborg, A. C. Wahl and J. W. Kennedy, Phys. Rev. 69 (1946) 367.

10. G. T. Seaborg and A. C. Wahl, J. Am. Chem. Soc. 70 (1948) 1128.

11. J. W. Kennedy, G. T. Seaborg, E. Segrè, and A. C. Wahl, Phys. Rev. 70(1946) 555.

12. DELETED

13. Nuclear Power Status & Trends, 1988, International Atomic Energy Agency, Vienna Austria, Septemer 1988.

14. Hans Blix, In Proceedings of Conference on Nuclear Power Performance & Safety, International Atomic Energy Agency, Vienna, Austria, September 28, 1987.

15. INFOWIRE 87-72, U.S. Committee for Energy Awareness, Washington, DC November 6, 1987.

16. The Energy Daily, November 12, 1987.

17. R. L. Gotchy, "Health Risks from the Nuclear Fuel Cycle", Health Risks of Energy Technologies, C. Travis and E. Etnier, Editors, AAAS Selected Symposium Series, Westview Press, 1983.

18. William J. Broad, "Experts Call Reactor Design 'Immune" to Disaster", New York Times, November 15, 1988.

19. Ron Winslow, "New Breeder Reactor May Operate More Safely, Produce Less Waste", The Wall Street Journal, December 1, 1988.

20. Edmund Flatermayer, "Taking the Fear Out of Nuclear Power", Fortune, August 1, 1988.

21. INFO #225, U.S. Committee for Energy Awareness, Washington, DC, November 1987.

22. Senator Bennett Johnston, Address to Americans for Independent Energy, Washington, DC, March 1988.

23. "The Advanced Reactor Corporation Ad Hoc Committee Review of DOE's Advanced Reactor Plan", Advanced Reactor Corporation, Chicago, IL, November 1987.

24. J. J. Taylor, K. E. Stahlkopf, D. M. Nobel, G. J. Dau, "LWR Development in the U.S.A.". Proceedings of the First International Seminar on Small and Medium Sized Reactors, Lausanne, Switzerland, August 1987.

25. R. C. Berglund, F. E. Tippets, and L. N. Salerno, "PRISM, A Safe, Economic, and Testable Liquid Metal Fast Breeder Reactor Plant", Proceedings of the ANS International Topical Meeting on the Safety of Next Generation Nuclear Reactors, Seattle, WA, May 1988.

26. E. L. Gluekler, F. J. Tajirian, and J. E. Kelley, "Seismic Isolation for Modular Liquid Metal Reactor Concept (PRISM)", Proceedings of the ANS International Topical Meeting on the Safety of Next Generation Nuclear Reactors, Seattle, WA, May 1988.

27. A. Hunsbedt and P. M. Maggee, "Design and Performance of the PRISM Natural Convection Decay Heat Removal System", Proceedings of the ANS International Meeting on the Safety of Next Generation Nuclear Reactors, Seattle, WA, May 1988.

28. P. M. Magee, A. E. Dubberley, S. K. Rhow, and T. Wu, "Transient Safety Performance of the PRISM Innovative Liquid Metal Reactor", Proceedings of the ANS International Topical Meeting on the Safety of Next Generation Nuclear Reactors, Seattle, WA, May 1988.

29. A. Neyland, A. Ng and D. Dilling, "Designing a Reactor for the Next Generation", Proceedings of Intersociety Energy Conversion Engineering Conference, Denver, CO, August 1988.

30. "Gas-Cooled Reactor Safety and Accident Analysis", Proceedings of Specialists' Meeting on Safety and Accident Analysis for Gas-Cooled Reactors, International Atomic Energy Agency, Vienna, Austria, May 1985.

31. Peter M. Williams, Thomas L. King and Jerry N. Wilson, "Results of a Preliminary Safety Review of the MHTGR", Proceedings of International Conference on the HTGR, Gas-Cooled Reactor Associates, San Diego, CA, September 1988.

32. Kenneth C. Rogers, "Key Questions Facing the NRC on the MHTGR", Proceedings of International Conference on the HTGR, Gas-Cooled Reactor Associates, San Diego, CA, September 1988.

FIGURES

Figure 1: Periodic Table before World War II. Parentheses indicate elements undiscovered at that time. XBL 769-10601

Figure 2: F. Strassman, L. Meitner, and O. Hahn, Mainz, 1956 XBB 791-641

Figure 3: E. O. Lawrence, Seaborg, and J. R. Oppenheimer, Berkeley, 1946. Morgue 1946-12 (P-1)

Figure 4: Outside Van de Graff Accelerator Building, Osaka University, March 23, 1970. Hiroo Kumagai (Aoki), Seishi Kikuchi, Seaborg, Tetsuo Wakatsuki, Kenzo Sugimoto. XBB 761-7030

Figure 5: Picture of Kikuchi group taken in 1938 or 1939. (L to R back): Tetsuo Wakatsuki, Eiichi Takeda, Seishi Kikuchi, Hiroo Kumagai (Aoki); (L to R front): K. Husimi, Okamoto, unidentified. XBB 761-7031

Figure 6: Seaborg and Jack Livingood, 1938, at Sather Gate on the Berkeley campus on their way to mail their iodine-131 paper to Physical Review. XBB 754-2571

Figure 7: Edwin M. McMillan, Berkeley, June 8, 1940. XBB 761-7256

Figure 8: Seaborg with geiger counter equipment, Berkeley, 1941. XBB 761-7413

Figure 9: Arthur C. Wahl and Seaborg, Room 307, Gilman Hall, February 21, 1966. XBB 769-8637

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Figure 13: Visit to the Japan Atomic Energy Institute, Tokai-Mura, September 23, 1965. (L to R): Seiri Kawabata, Ryokichi Sagane, Seaborg and Keiji Naito. XBB 761-7027

Figure 14: USAEC Commissioners meeting with Japanese AEC officials, Washington, D.C. headquarters, July 15, 1968. (L to R): Hironori Itoh, Tsuneo Fujinami, Tasaburo Yamada, Naotsugu Nabeshima, Seaborg, Goro Inouye, Hiroshi Murata, J. T. Ramey, W. E. Johnson, and G. F. Tape. XBB 761-7028

Figure 15: Visit to Mihama Nuclear Power Station, Tsuraga, Japan, March 22, 1970. (L to R): Masashi Odashima, Eiichi Takeda, Yoshio Tanaka, unidentified in back, Toshio Ito, Hiromi Kato, Seaborg, M. B. Kratzer, C. E. Larson, unidentified, Mamoru Sueda, W. B. McCool. XBB 761-7029

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Figure 17: AP600 (Advanced Passive 600 MWe) nuclear island. EPRI

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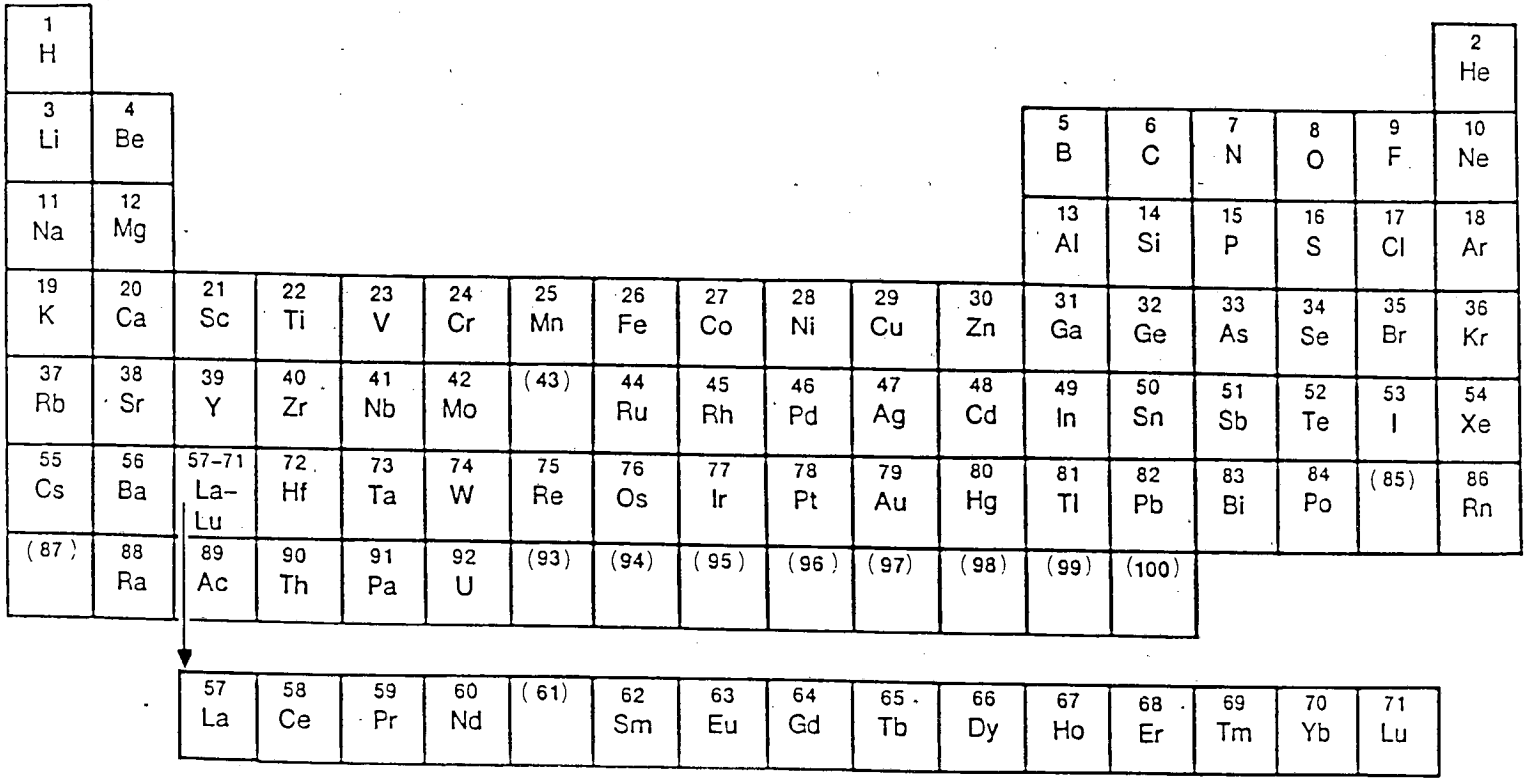
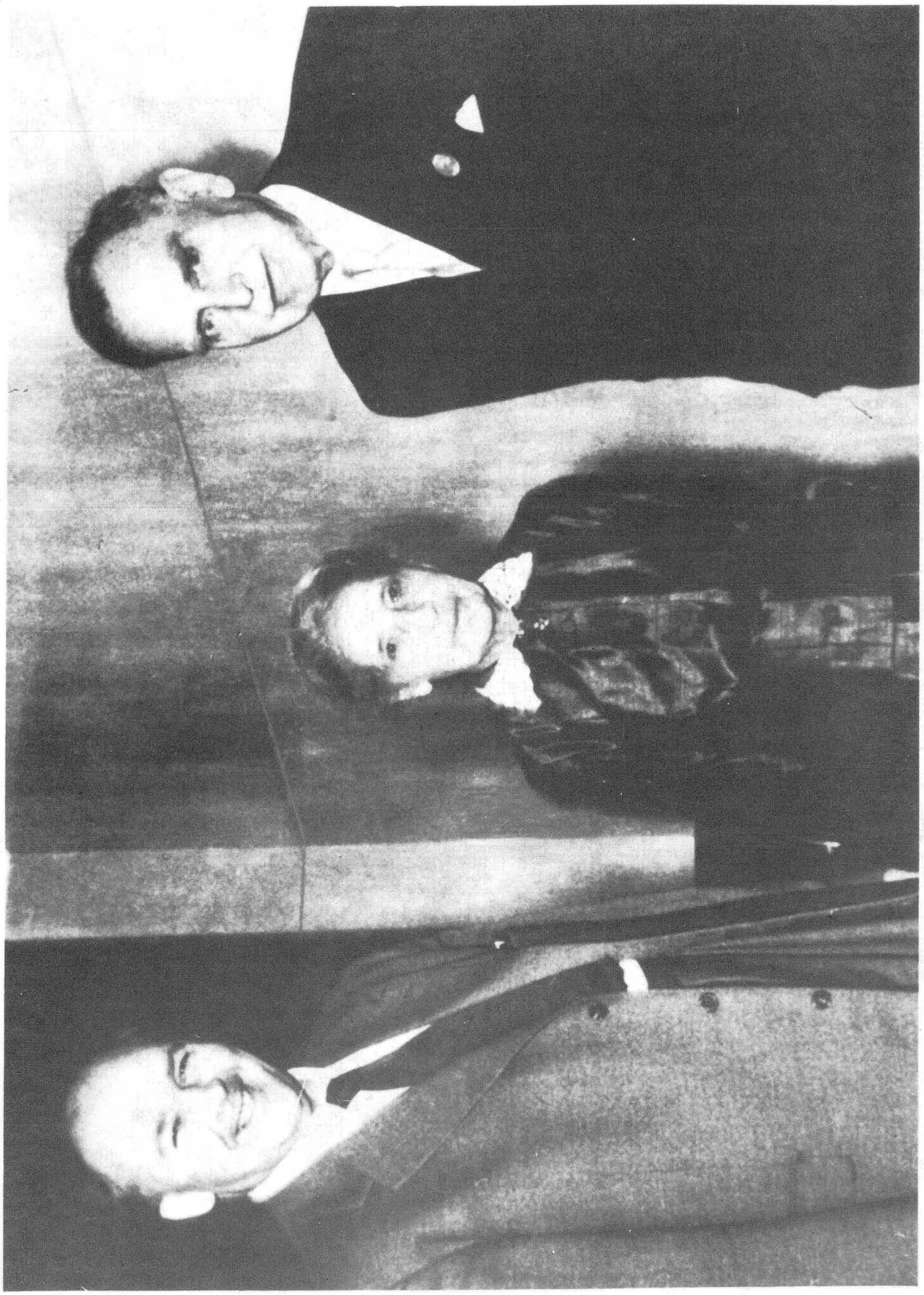
PERIODIC TABLE - BEFORE WORLD WAR II



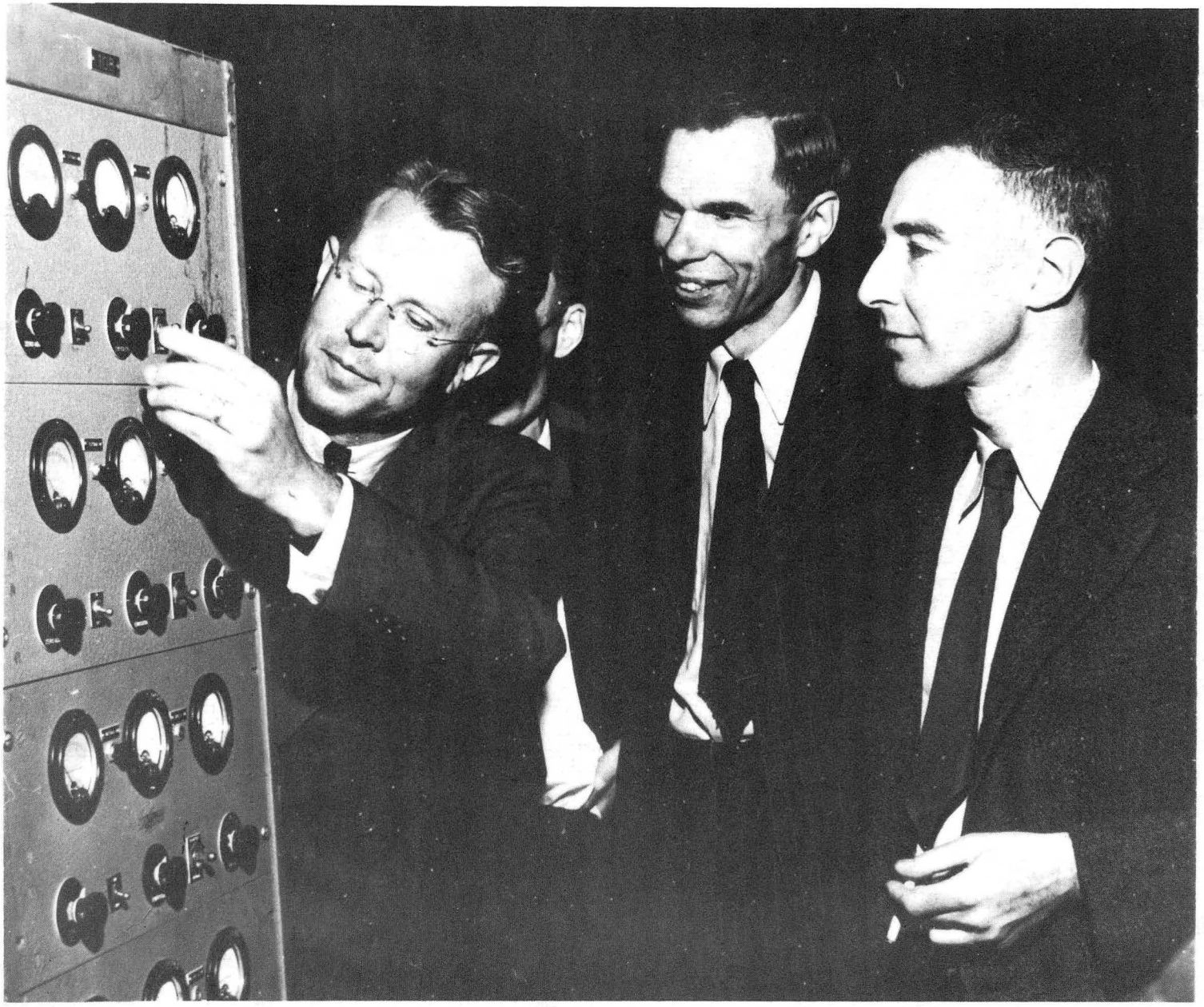
XBL 769-10601

Figure 1.



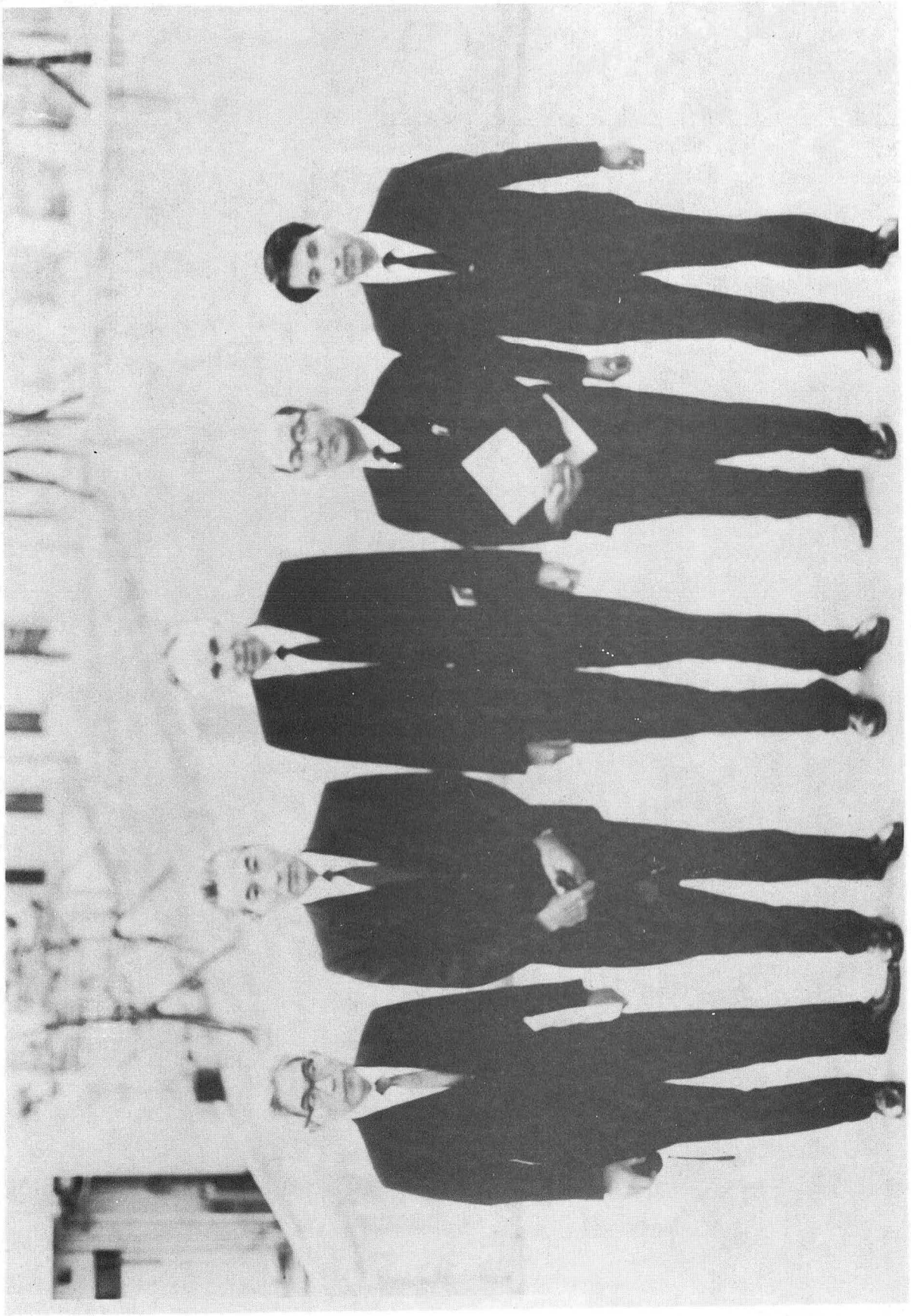
XBB 791-641

Figure 2



MORGUE 1946-12(P-1)

Figure 3



XBB 761-7030

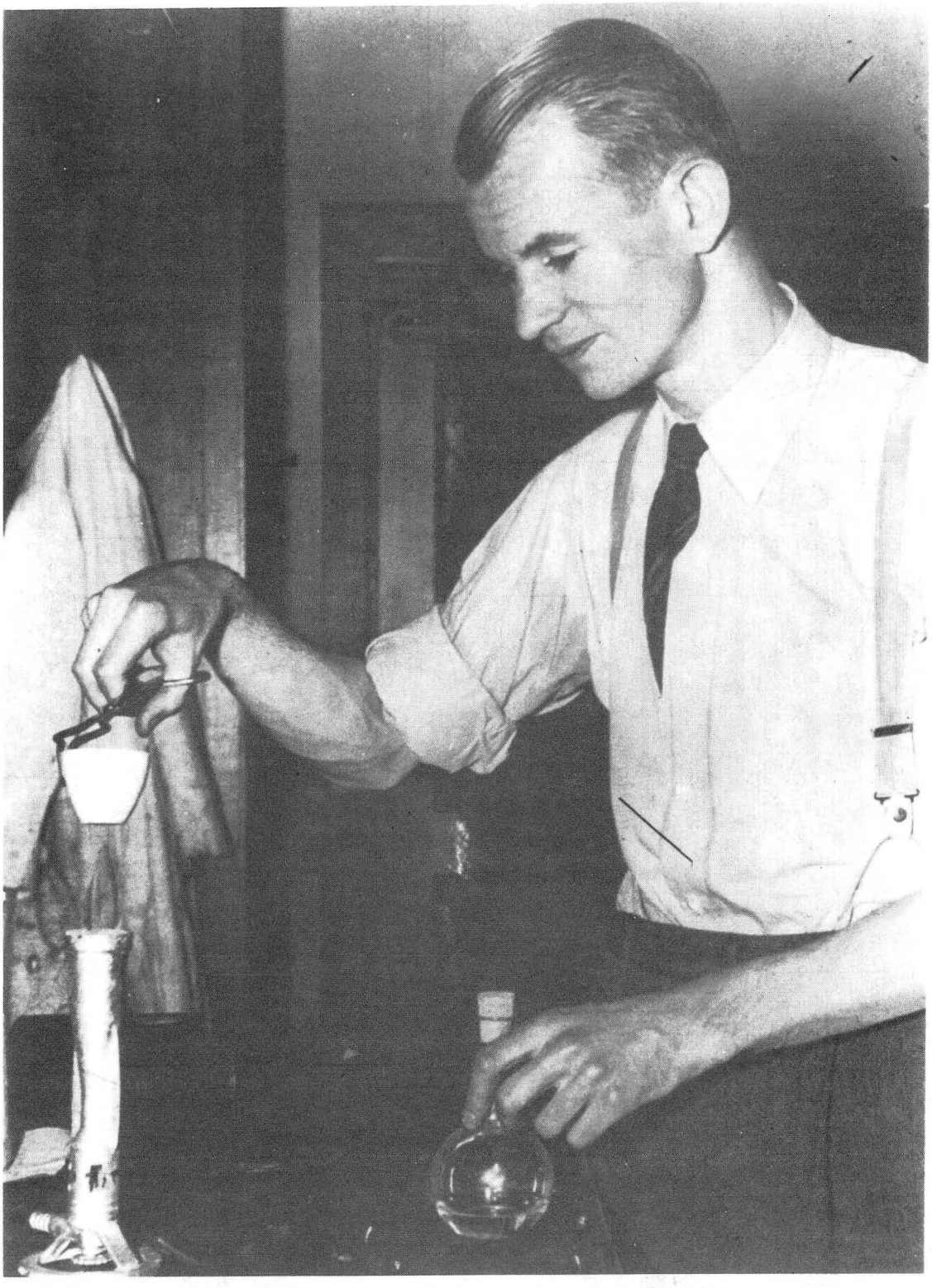
Figure 4

XBB 761-7031

Figure 5

XBB 754-2571

Figure 6



XBB 761-7256

Figure 7

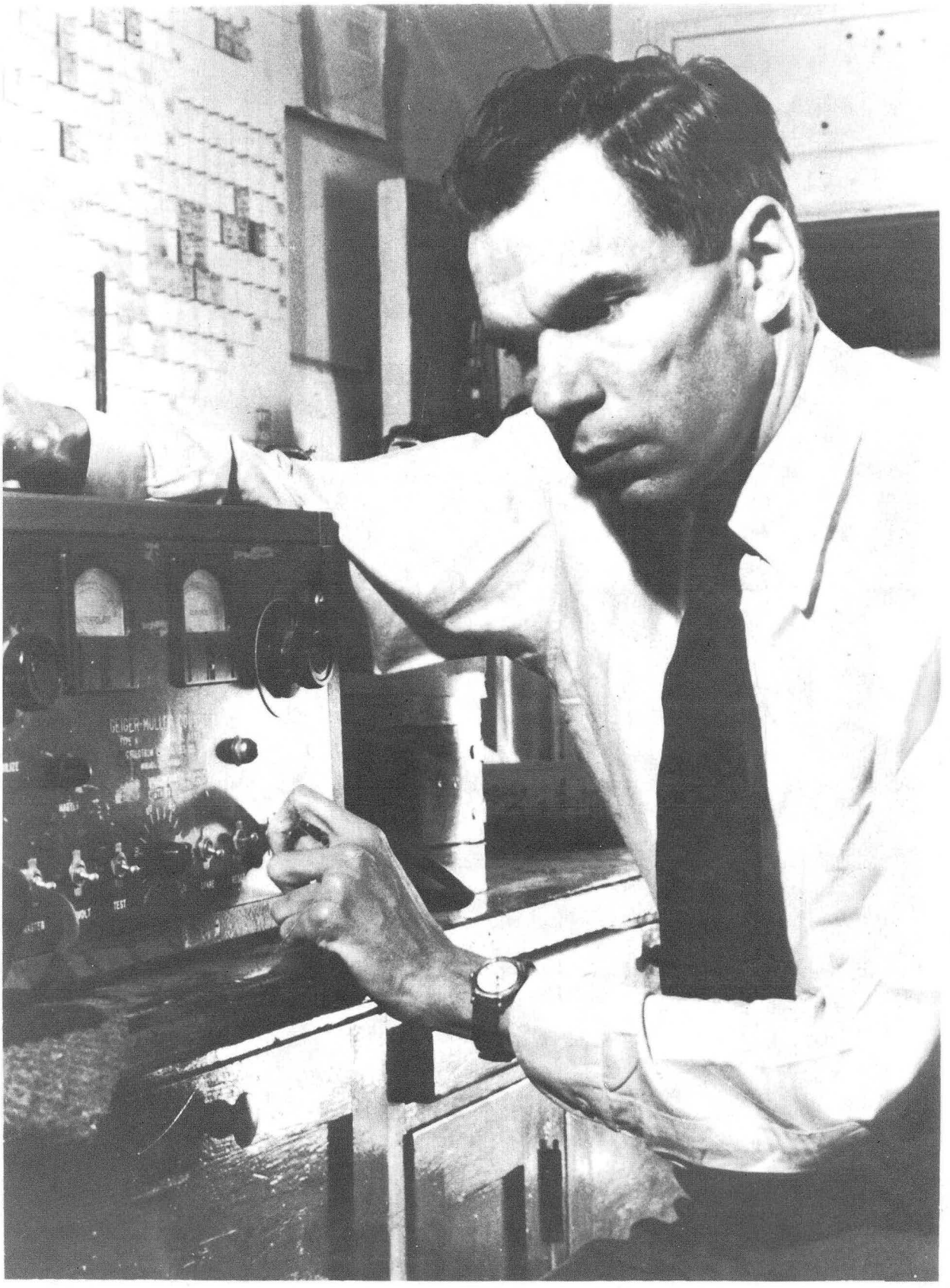


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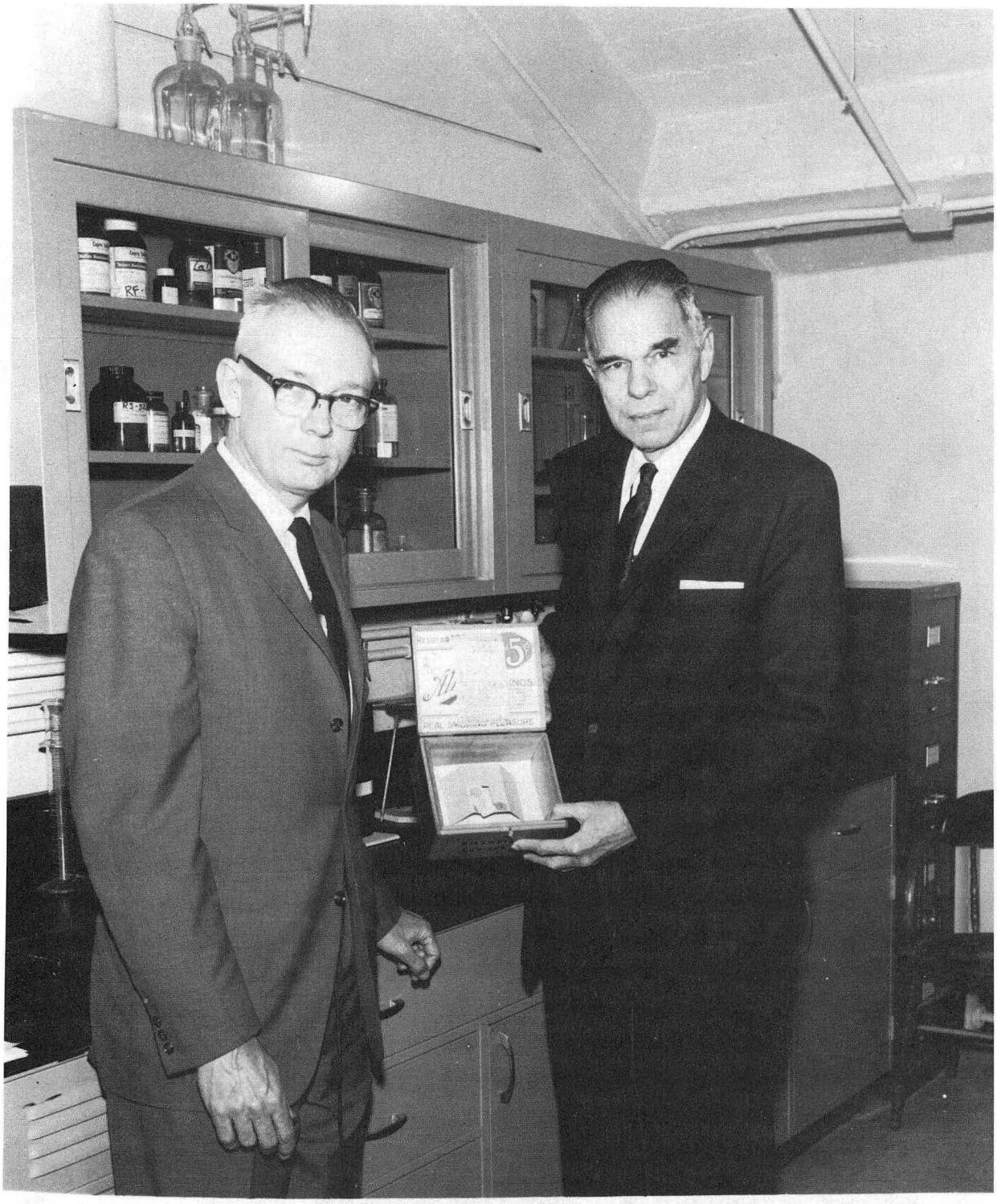
Figure 8



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FEBRUARY 21, 1966

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Figure 9

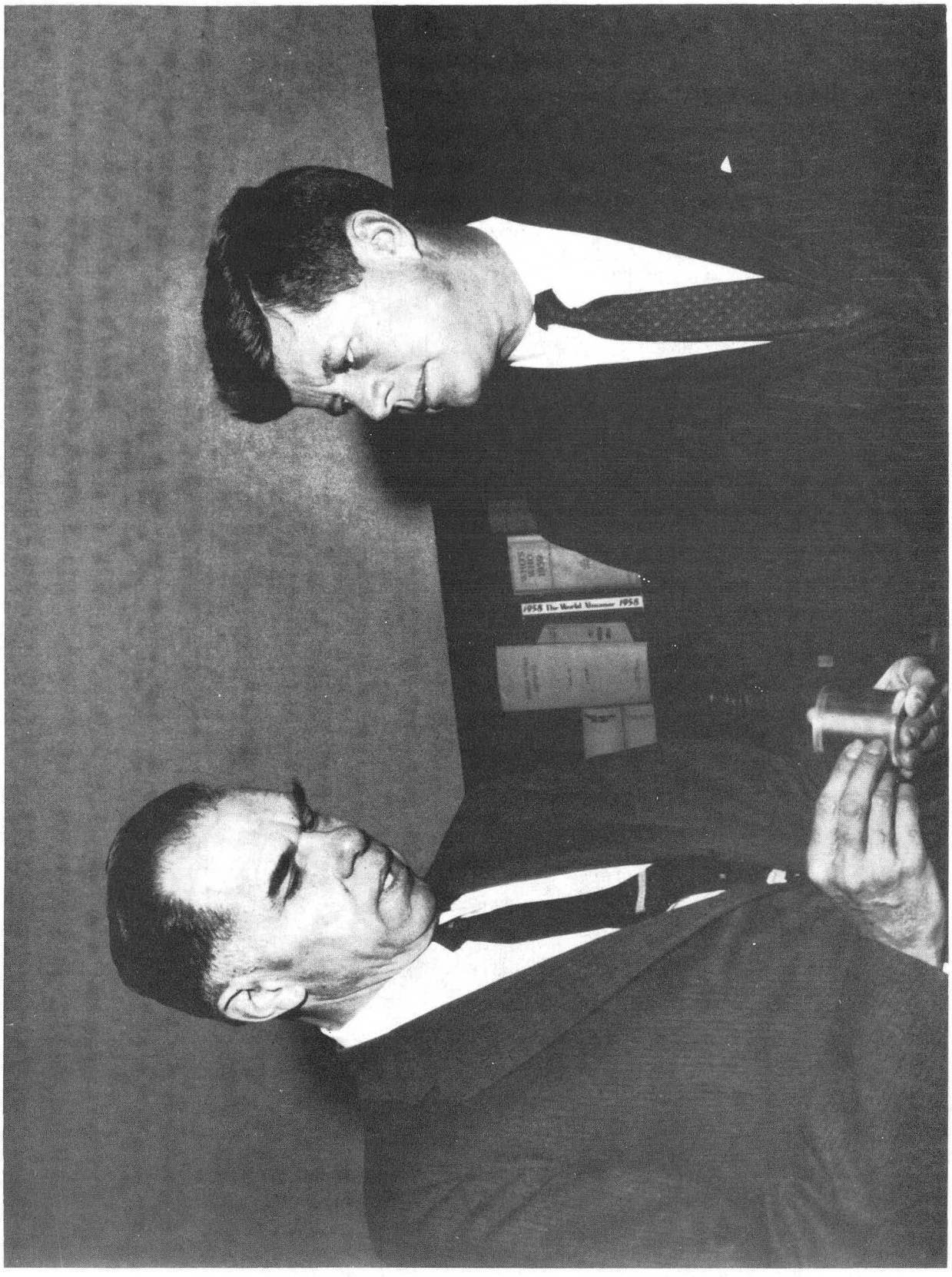

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Figure 10

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Figure 11

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Figure 12

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Figure 13

XBB 761-7028

Figure 14

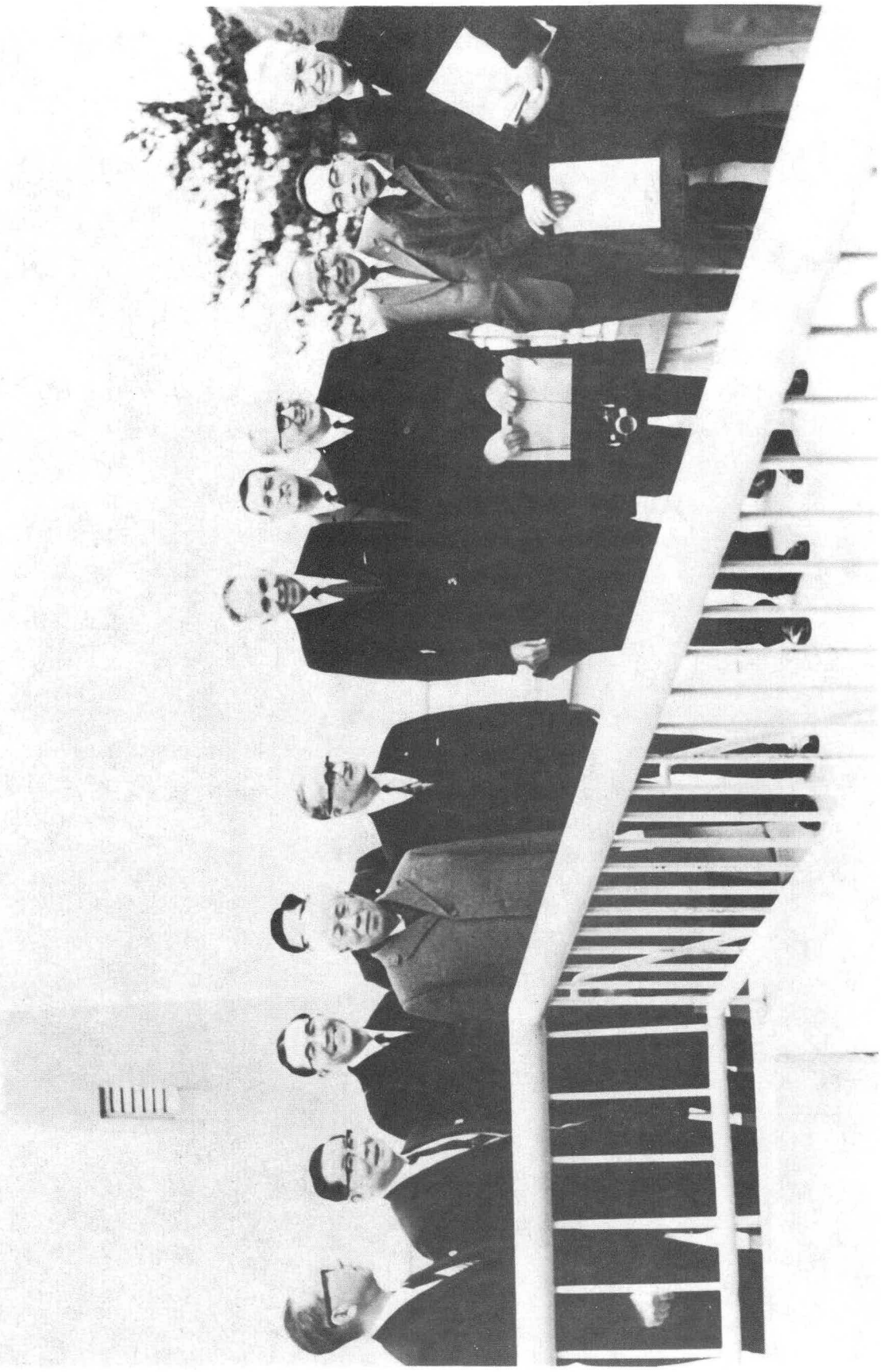

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Figure 15

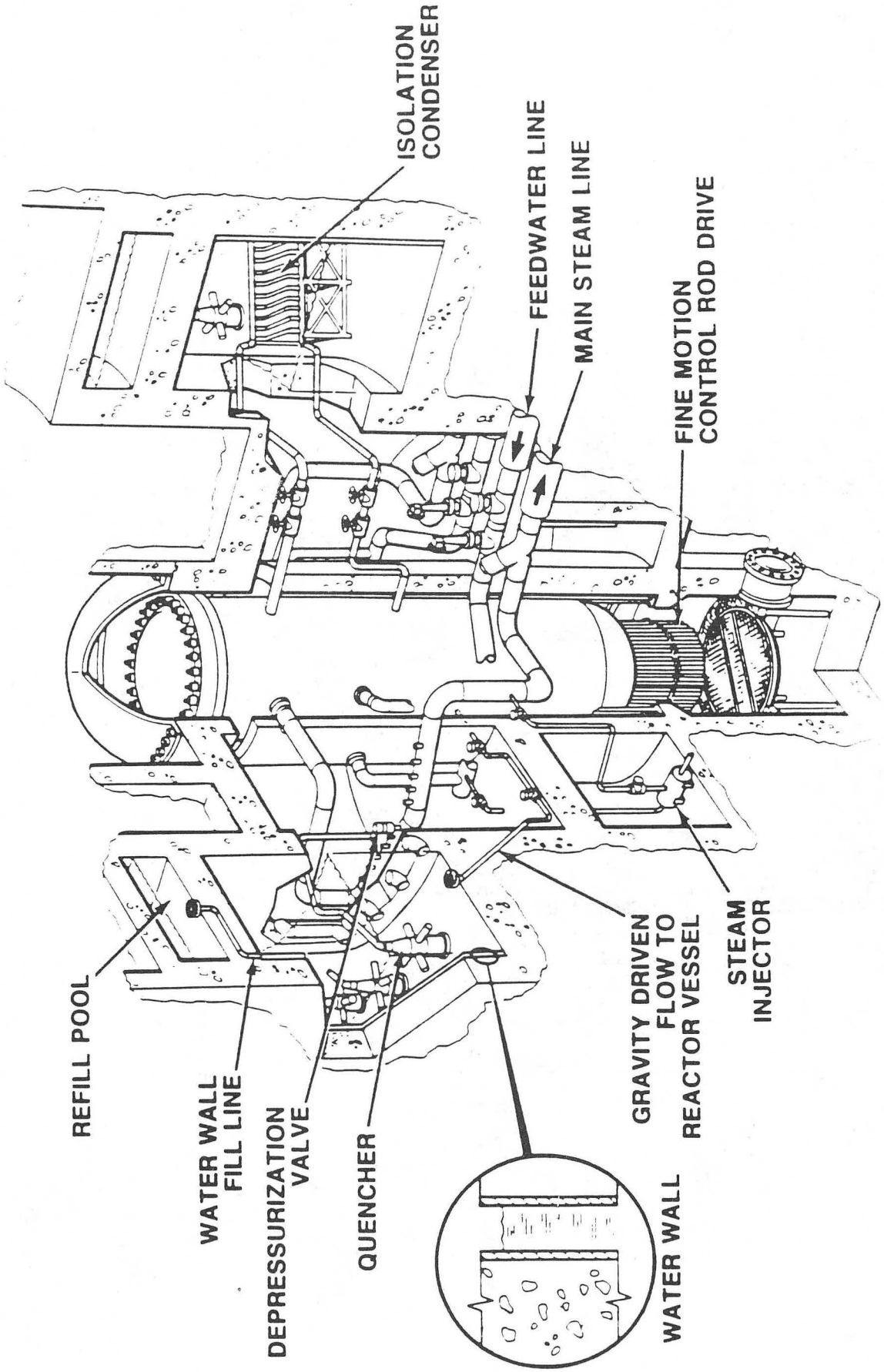

Figure 16. SBWR features.

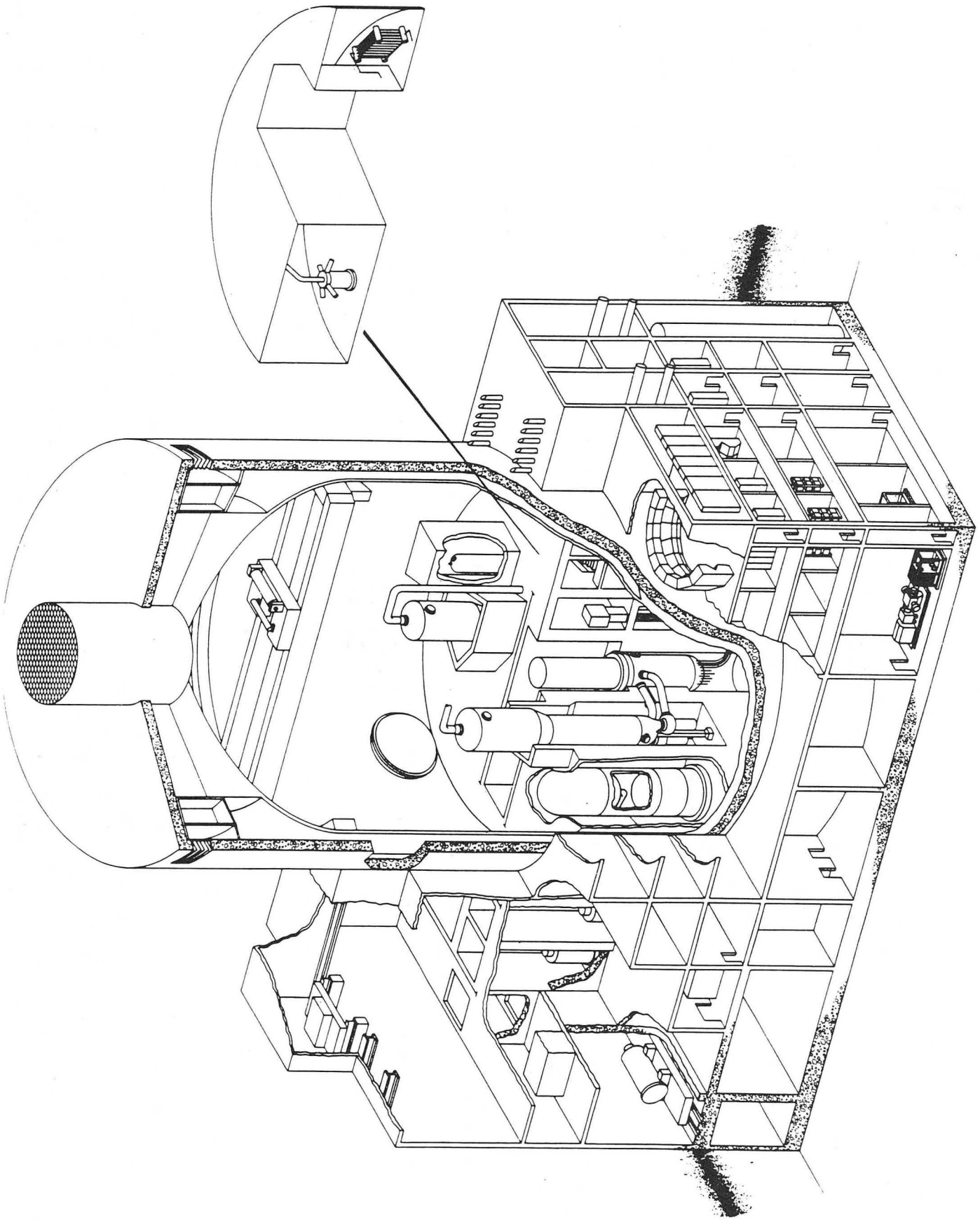

Figure 17. AP600 nuclear island.

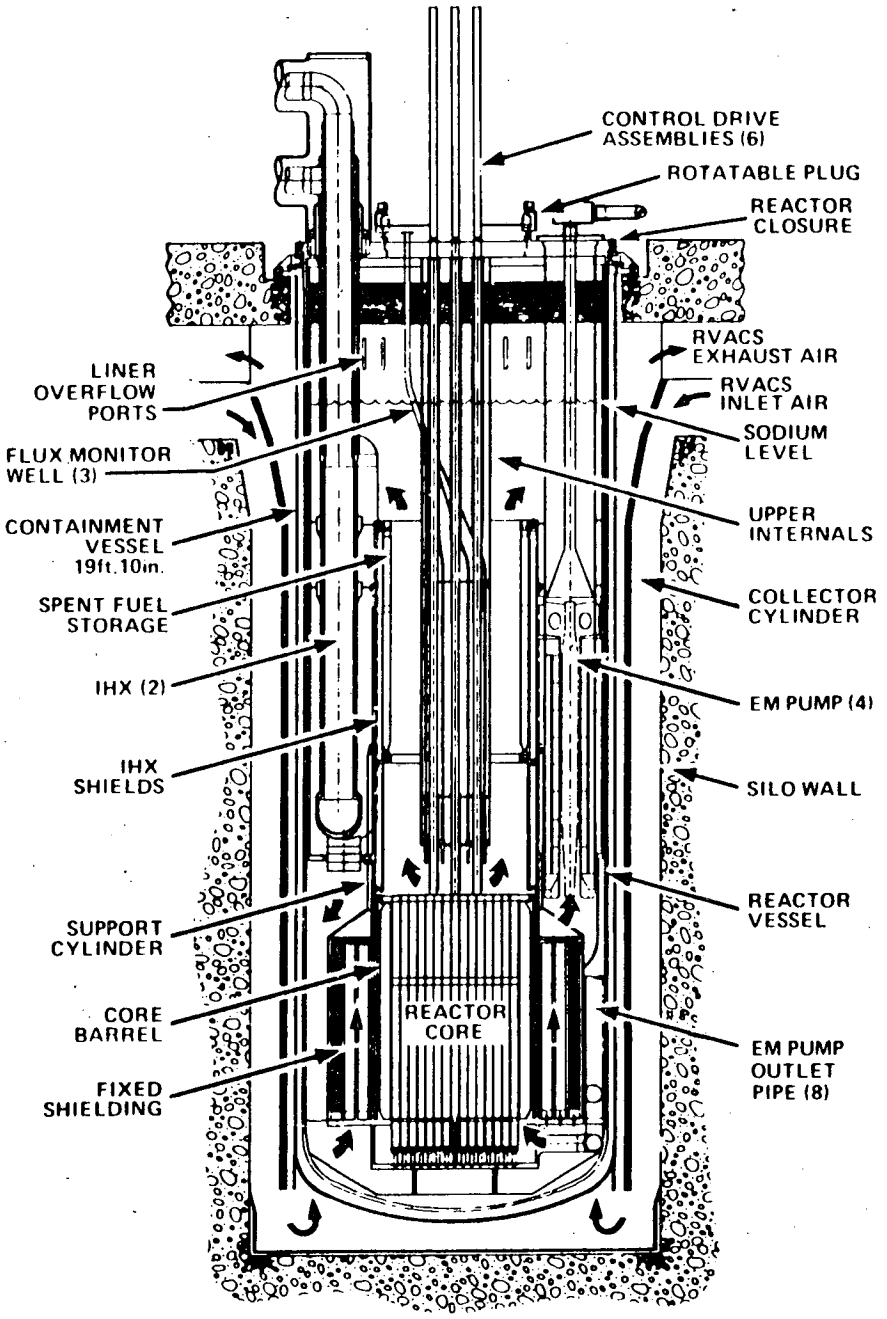

Figure 18. PRISM reactor module.

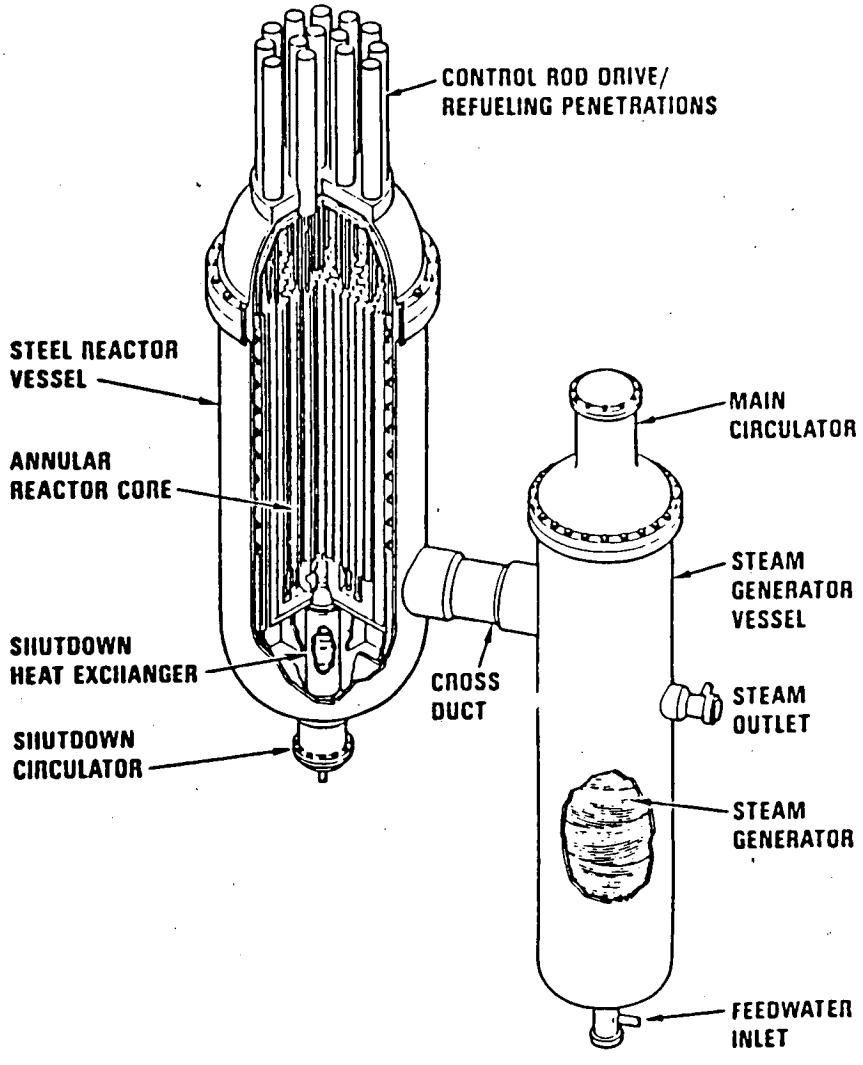

Figure 19. MHTGR

Table 1

Comparison of Features APLWR, PRISM, and MHTGR

Feature / Reactor	No. of Reactors of Generic Type Operating Worldwide	Operating Temperature Hot Leg (°F)	Conventional Containment	Passive Containment Cooling	Passive Decay Heat Removal	Passive Emergency Core Cooling
APLWR	310	600	Yes	Yes	Yes	Yes
PRISM	7	905	No	NA	Yes	Yes
MHTGR	3	1268	No	NA	Yes	Yes

NA -Not applicable

Table 2

Comparison of Features APLWR, PRISM, and MHTGR

Feature / Reactor	Modular Design	Negative Temperature Coefficient	Negative Void Coefficient	Negative Rod Worth for Total Travel Length	Prototype Required for Licensing	Other Features
APLWR	Yes	Yes	Yes	Yes	No	
PRISM	Yes	Yes	No	Yes	Yes	Breeds more fuel than it uses
MHTGR	Yes	Yes	N.A.	Yes	Yes	Could be used for high temperature process heat

NA - Not applicable

Table 3

Comparison of Features APLWR, PRISM, and MHTGR

Reactor \ Feature	Date of Commercial Introduction (License complete)	Cost per reactor to Commercially Introduce (Complete design and license)	Commercial Acceptance by Utilities (Relative ranking)
APLWR	1995 (Vendor assessment) 1996 (Authors' assessment)	$100 Million (Vendor assessment) $125 million (Authors' assessment)	1
PRISM	2003 (Vendor assessment) 2005 (Authors' assessment)	$750 million (Vendor assessment) $1,000 million (Authors' assessment	3
MHTGR	1995 (Vendor assessment) 2000 (Authors' assessment)	$1,000 million (Vendor assessment) $1,250 million (Authors' assessment)	2

Table 4

Comparison of Features APLWR, PRISM, and MHTGR

Feature / Reactor	Technical Maturity (relative ranking)	Ease of licensing (relative ranking)	Public perception (relative ranking)
APLWR	1	1	3
PRISM	2 (Tie)	2 (Tie)	2
MHTGR	2 (Tie)	2 (Tie)	1

Table 5

Bulk Quantity Comparison of AP600 and Standard Two-Loop PWR

Bulk Commodity	% Reduction
Valves	60
Large Pumps	50
Piping	60
Heat exchangers	50
Heating, ventilation & cooling ducting	35
Seismic building volume	60
Control cable	80

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