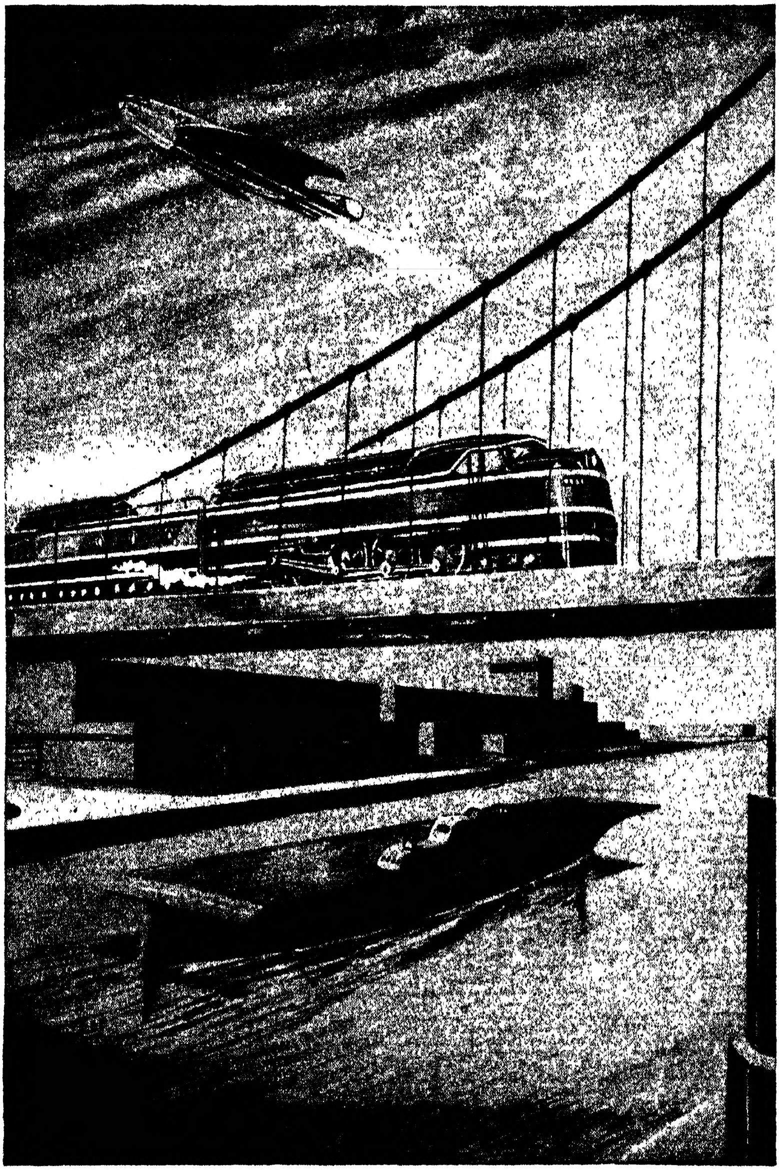
Applied
ATOMIC POWER



Atomic Power — The Servant of Man

Applied
ATOMIC POWER

by

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Foreword

ON THE walls of the Engineering Societies building in New York were the following words:

"Engineering — the art of organizing and directing men, and controlling forces and materials of nature for the benefit of the human race."

Probably more has been written in the public press and technical journals within the past several months on the subject of atomic energy than on any other new scientific development within the same length of time. And yet probably less has been understood by the public at large.

This book, written by outstanding men in the fields of science and engineering, covers what can now be told of the history of the development, the present-day scientific status, and the possibilities as we know them today of the applications of atomic power to industrial progress. It is written in language that can be understood by the careful reader. It will serve as a guide to the thinking of all who wish to see the benefits of atomic power applied to constructive endeavors.

Let us all acquaint ourselves with the knowledge that is now available and insist that this "instrument of nature" be used only for the "benefit of the human race."

J. B. ENNIS

Senior Vice President
American Locomotive Company
President
Steam Locomotive Research Institute
Fellow, A. S. M. E.

Acknowledgments

THE following statement was made in Professor H. D. Smyth's governmental report: "We find ourselves with an explosive which is far from completely perfected. Its development raises many questions that must be answered in the near future. The people of the country must be informed if they are to discharge their responsibilities wisely." The object of this book is to help inform the people, to explain in a relatively simple language what atomic power is. For this reason we are indebted, not only to Professor H. D. Smyth for writing his press release, but also to Major General L. R. Groves, U. S. Army, and other government officials who are actively interested in the release of information on the development of atomic energy.

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Part I

Natural Radioactivity

By Professor Edward S. C. Smith

Chapter I

Radioactivity

Discovery of Uranium

It all began in 1789, more than a century and a half ago, when Martin Heinrich Klaproth, a German scientist, isolated from the mineral pitchblende a heavy, insoluble yellow powder which he could not identify. Apparently it was a metallic oxide heretofore unknown. Assuming the yellow powder to be the oxide of a new metal, Klaproth attempted its reduction and obtained a powder, black uranium oxide, which he incorrectly assumed to be the new metal. At any rate, he called the black powder "uranium," after the planet Uranus, then but newly discovered (1781) by Sir William Herschel. Klaproth did not succeed in obtaining metallic uranium from its oxides, but the metal was produced about 1842 by Eugene M. Peligot, a French agricultural chemist. Metallic uranium was found to be silvery white, tarnishing easily in air to a blackish color. It has a high melting point, probably somewhat below the usually quoted figure of 1850° C, and is of high density, being 18.7 times as heavy as water. Only tungsten, platinum, gold, and a few rarer elements, such as osmium, iridium, and rhenium, are heavier than uranium.

For a long time uranium remained merely a chemical curiosity, its radioactivity being discovered incidental to investigations of another sort. It will be recalled that the Roentgen rays, or X rays, were discovered in 1895 by Wilhelm Roentgen. Roentgen made this discovery by allowing electrical discharges — that is, high-speed cathode rays — to strike some sort of metallic "target." When these streams of electrons, for that is what they were, hit the metallic target, they caused radiations of very short wave length, which passed easily through wood, human flesh, and other substances of low density, but were stopped by very dense materials, such as lead or similar elements. The same powerful radiations caused some substances to fluoresce — that is, to give off long-wave-length radiations visible to the human eye. Sometimes the substances acted upon by the X rays fluoresced, or gave off visible light that continued only during the period of excitation; other substances phosphoresced, or continued to give off visible radiations after X-ray excitation had ceased. Roentgen observed also that the X rays would affect the silver salts on photographic plates. In this connection it is interesting to note that had photography not been as far developed as it was in 1895, the discovery of radioactivity might have been delayed.

Discovery of Radioactivity

The discovery of radioactivity was made in 1896 by Antoine Henri Becquerel, professor in the École Polytechnique in Paris (Figure 1). He was interested in the phenomenon of fluorescence as induced by Roentgen's X rays and set about examining all sorts of substances for possible fluorescent and phosphorescent effects. One of the compounds tested was the double sulphate of uranium and potassium, which not only would discharge an electroscope and phosphoresce but also would continuously emit invisible rays that penetrated the black paper in which his photographic plates were wrapped. This property of matter, then made known for the first time by Becquerel, is now called *radioactivity.* Because uranium, as well as its compounds, displayed radioactivity and because this spontaneous radiation of energy appeared to be entirely independent of chemical combination or of physical condition, Professor Becquerel, with characteristic zeal, at once showed that the property of radiation must be in some way directly associated with

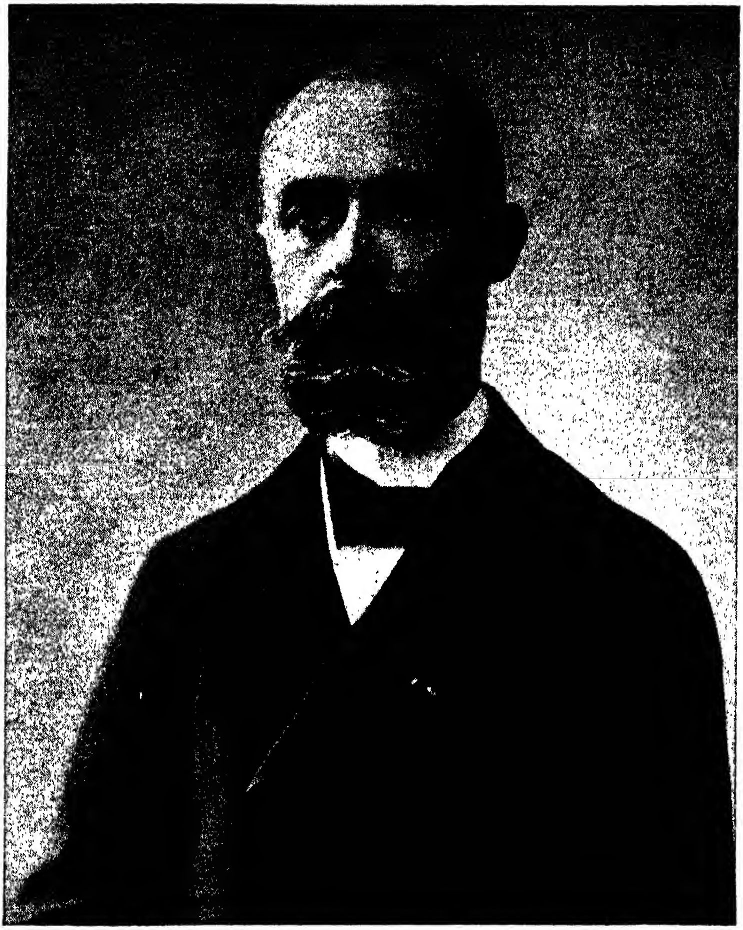

Figure 1. Antoine Henri Becquerel.

the uranium atom itself. A new chemistry was beginning to dawn.

Becquerel's discovery aroused the curiosity of Professor Pierre Curie and his wife, Marie Slodowska Curie, two young scientists in Paris, the latter, above all others, soon to become so intimately associated with the phenomena of radioactivity. Mme. Curie began the examination of all available chemical materials to obtain further evidence of the existence of the extraordinary radioactive property of matter. By 1898 her studies had shown that compounds of the rare element thorium were radioactive. By a strange coincidence the radioactive properties of thorium were discovered independently in the same year by G. C. Schmidt. Turning from the purified chemical substances of the laboratory, and following what today we might refer to as a scientific "hunch," Mme. Curie next examined a series of minerals, nature's own chemical compounds, as they had been taken directly from the earth's crust.

Figure 2. Marie Slodowska Curie and Pierre Curie.

From this bit of research, prosaic as it doubtless seemed at the time, emerged a striking discovery. Those minerals showing radioactivity, and they were many, displayed it to a far greater degree than could have been predicted from the activity of the supposedly pure compounds in laboratory bottles. In other words, minerals that contained natural compounds of uranium and thorium were much more strongly radioactive than the known compounds of these metals produced in the laboratory or in industry. Not unnaturally, Marie Curie believed that she had made an experimental error. Again and again she repeated her tests, but obtained the same astonishing results. Thus she concluded that not only was there something present in the uranium and thorium minerals which was a far more powerfully radioactive substance than either uranium or thorium, but that this substance must be present in very small amounts. Mme. Curie might well have been awed, for the only logical answer to this perplexing question was that the uranium and thorium minerals carried in them a new and hitherto unknown element, or perhaps more than one, which was highly radioactive.

Discovery of Polonium

In April 1898, the French Academy of Sciences published a communication from Mme. Curie on the probable existence of a new and powerfully radioactive element, as yet unknown to science. Thereupon commenced that remarkable collaboration between Pierre and Marie Curie in a search for the suspected new element. In July 1898, only a few months later, the Curies were able to announce that they had discovered a metallic element much like bismuth, except that the new element was radioactive. This new element was named "polonium," in honor of Poland, Mme. Curie's native land. Polonium was originally precipitated chemically with bismuth, which is not radioactive; therefore the amount of polonium present could be determined by the radioactivity of the bismuth. Metallic polonium has since been obtained by chemical deposition upon silver and by electrolytic deposition upon gold or platinum. Polonium is associated with all of the uranium minerals thus far made known, but it occurs in infinitesimally small quantities, the ratio of uranium to polonium being about ten thousand to one.

Discovery of Radium

While they had been working to isolate polonium, the Curies found evidence of the existence of another radioactive element in pitchblende, the uranium ore. In collaboration with M. G. Bemont, the Curies were able to announce in

December 1898 the discovery of a second radioactive element which they named "radium." This element was closely related to barium and chemically precipitated with it. In order to separate enough reasonably pure radium salts for determining atomic weight accurately, which the Curies had to do to prove that the new elements did actually exist, they needed a larger quantity of pitchblende, much more than they possessed at the time. Where were they, with their meager resources, to obtain the great quantities of pitchblende needed to extract even the most minute amounts of radioactive substances? The difficulty seemed insurmountable.

At that time, pitchblende was obtainable in quantities only in the Joachimsthal, in Bohemia, now Czechoslovakia. The pitchblende mines were operated as a government monopoly in the production of uranium salts, which were used in the making of opalescent glass, and in the ceramic industries to impart a yellow glaze to porcelain. The Curies reasoned that the new radioactive substances would remain in the residues from the manufacturing processes at the Joachimsthal, and that large amounts ought therefore to be obtained at low cost. The Curies had reasoned correctly; in fact, the Austrian government made them a gift of a ton of the residues. Four years of tireless work under most difficult experimental conditions were followed by success, and 0.2 of a milligram of radium chloride was obtained. The atomic weight of radium was determined as 226.

The atomic weight of an element was originally defined as the weight of a substance compared with the lightest known element, hydrogen. The form of this definition is somewhat analogous to the form of the definition of specific gravity, which is the weight of a given substance compared with an equal volume of water at 4° C. The definition of atomic weight, as used today, is in relation to the atomic weight of oxygen, which is taken as 16. The figure "16" was derived from an early belief that oxygen was exactly sixteen times heavier than hydrogen. However, we now know that the true atomic weight of hydrogen is 1.008132 if the atomic weight of oxygen is taken as 16. With the discovery of isotopes, shortly to be discussed, atomic weights today assume far less importance from the standpoint of nuclear studies than do the *masses* of the isotopes of a given element. Atomic weights are still of importance, of course, to the analytical chemist.

Figure 3. Mme. Curie in Her Laboratory.

Pure metallic radium was isolated by Mme. Curie and André Debierne in 1911 by an ingenious method. The radium was deposited electrolytically on mercury, and the mercury distilled off in a current of hydrogen. The radium thus prepared was a silvery-white metal melting (and volatilizing) at 700° C.

Other Radioactive Elements

Great interest had been aroused by the announcement of the discovery of radium and other new radioactive elements (Debierne had discovered actinium in 1899), especially as these radioactive elements were found to fit into Mendeleeff's Periodic Table. About thirty years previously, Dimitri Mendeleeff, a Russian chemist, had arranged all known elements in order of increasing atomic weights. Hydrogen, the lightest element, was placed first and the others followed in order. Elements with similar chemical characteristics fell naturally into groups, or "periods," as Mendeleeff called them, in which certain of their properties were observed to recur. The blank spaces in his table Mendeleeff suggested might be occupied by hitherto undiscovered elements. Mme. Curie's investigations of radium showed that it was very closely related to barium and strontium, and when the atomic weight of radium had been determined as 226, it was found to fall into a place heretofore empty in Mendeleeff's table. Since that time, other elements have been found whose properties were predicted in advance of their actual discovery.

Chiefly because of work done by Sir Ernest Rutherford, the British physicist and Nobel Prize winner, and his coworkers (Figure 4), we know today that uranium, thorium, and actinium atoms are spontaneously disintegrating into a whole series of radioactive substances, each of which is of lower atomic weight than its parent element. Some of these changes are very rapid, requiring only a few minutes or a few hours for one half of the material to be changed to a substance of lower atomic weight. Some changes, however, require thousands or even millions of years. The length of time during which one half of a given radioactive element is converted into that element of next lower atomic weight is called its *half-life period.*

In one sense, we might call these radioactive atoms "natural atomic bombs" because, as these atoms break down, they emit three types of energy-carrying rays, which are collectively called *Becquerel rays.*

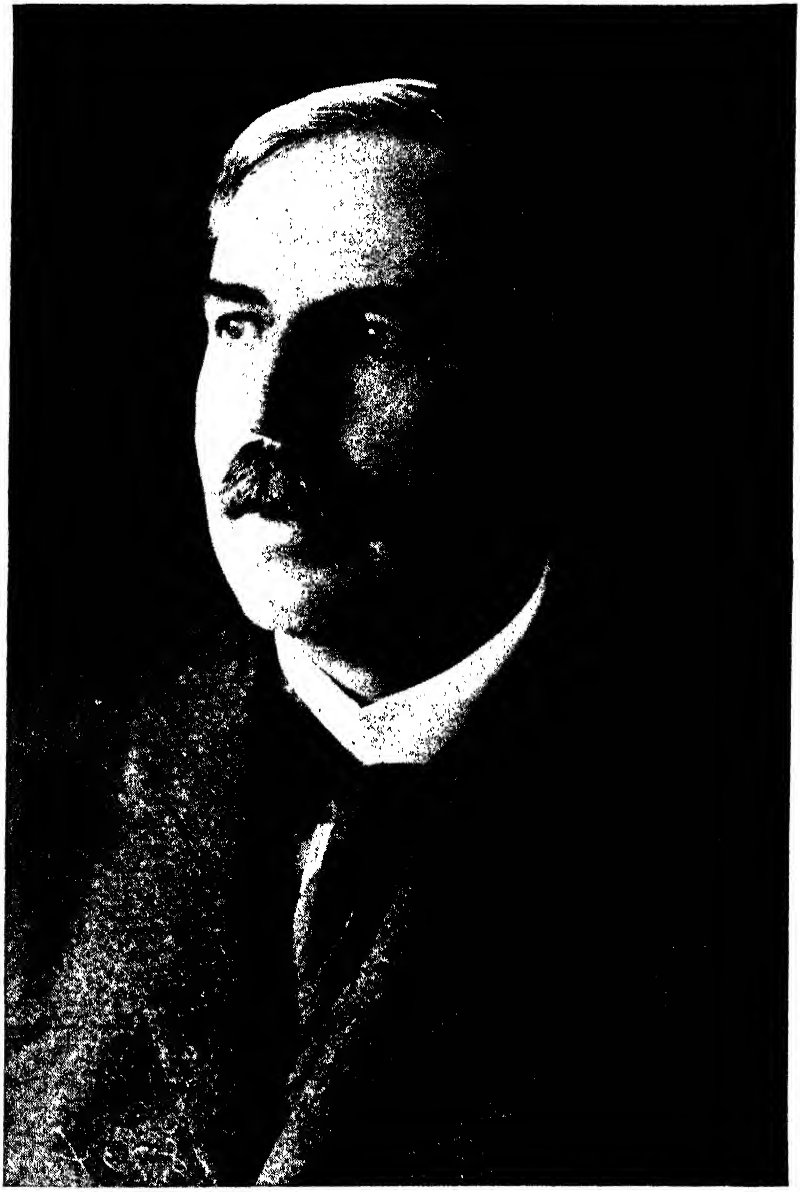

Figure 4. Sir Ernest Rutherford.

Alpha, Beta, and Gamma Rays

Rutherford and others showed that the Becquerel rays were of three kinds, which they called *alpha*, *beta*, and *gamma* rays. Alpha rays were shown to be, in effect, nuclei of helium atoms which traveled at velocities of 9000 to 12,000 miles per second. The fastest of these alpha rays are completely absorbed by 0.006 cm of aluminum foil, and their range in air is about 3.39 cm. Beta rays have been shown to be streams of electrons carrying negative charges which travel at a speed which may approach that of light (186,000 miles per second). A 2-mm thickness of lead may be required to stop the beta rays. Gamma rays are not discreet particles of high velocity but consist of radiation resembling X rays. The penetrating power of these rays is very great, a thickness of 14 mm of lead being sufficient to absorb only half of a given emission of hard gamma rays. Their velocity is that of light.

Secret of Atomic Disintegration

Today, half a century since Becquerel noticed the mysterious rays which affected his photographic plates, the secret of atomic disintegration has become no secret at all. Tables I, II, and III illustrate what is known concerning the disintegration of uranium, actinium, and thorium. In the first column, the element itself is named; in the second column, its atomic weight is given; in the third column is found the atomic number of the element, which represents the number of positively charged protons inside the atomic nucleus. The fourth column indicates the types of radiation which, when emitted by the parent substance, give rise to the element of next lower atomic weight. In the last column is indicated the time in which one half of the parent element is converted into the member of the series of next lower atomic weight. It will be noted that the uranium, actinium, and thorium disintegration series of elements terminate with products whose atomic weights are close to that of lead.

TABLE I

URANIUM SERIES

Element	Atomic Weight	Atomic Number	Radiation Emitted	Time to Decay to Half Value
Uranium I	238.2	92	Alpha	4.6×10^9 yr
Uranium X_1	234	90	Beta	24.6 da
Uranium X_2	234	91	Beta and gamma	1.15 min
Uranium II	234	92	Alpha	1.7×10^5 yr
Ionium	230	90	Alpha	6.9×10^4 yr
Radium	226	88	Alpha	1,690 yr
Radon (emanation)	222	86	Alpha	3.833 da
Radium A	218	84	Alpha	3.0 min
Radium B	214	82	Beta and gamma	26.8 min
Radium C	214	83	Alpha, beta, and gamma	19.5 min
Radium C′	214	84	Alpha	1.5×10^{-4} sec
Radium C″	210	81	Beta	1.4 min
Radium D	210	82	Beta (soft)	16.5 yr
Radium E	210	83	Beta (soft)	5.0 da
Radium F (polonium)	210	84	Alpha	136 da
Lead	206	82	None	Stable

TABLE II

ACTINIUM SERIES

Element	Atomic Weight	Atomic Number	Radiation Emitted	Time to Decay to Half Value
Actino-uranium	235	92	Alpha	7×10^8 yr
Uranium Y	231	90	Beta	24.6 hr
Protoactinium	231	91	Alpha	32×10^3 yr
Actinium	227	89	Beta	13.4 yr
Radioactinium	227	90	Alpha	19.5 da
Actinium X	223	88	Alpha	11.4 da
Actinon (emanation)	219	86	Alpha	2.9 sec
Actinium A	215	84	Alpha	.002 sec
Actinium B	211	82	Beta	36.1 min
Actinium C	211	83	Beta	2.15 min
Actinium C′	211	84	Alpha	5×10^{-3} sec
Actinium C″	207	81	Beta	4.71 min
Lead	207	82	None	Stable

TABLE III

THORIUM SERIES

Element	Atomic Weight	Atomic Number	Radiation Emitted	Time to Decay to Half Value
Thorium	232	90	Alpha	1.8 × 10^{10} yr
Mesothorium I	228	88	Beta	6.7 yr
Mesothorium II	228	89	Beta	6.1 hr
Radiothorium	228	90	Alpha	1.90 yr
Thorium X	224	88	Alpha	3.64 da
Thoron (emanation)	220	86	Alpha	54.5 sec
Thorium A	216	84	Alpha	0.14 sec
Thorium B	212	82	Beta	10.6 hr
Thorium C	212	83	Alpha, beta	60.5 min
Thorium C′	212	84	Alpha	3 × 10^{-7} sec
Thorium C″	208	84	Beta	3.1 min
Lead	208	82	None	Stable

The final product of the uranium disintegration series is a substance whose atomic weight is 206; the final product of the actinium series is a substance whose atomic weight is 207; and the final product of the thorium series is a substance whose atomic weight is 208. It had been noticed that lead minerals were usually found associated with uranium minerals; hence the conclusion ought to be that lead — plain lead, heavy and inert as we know it to be — is the ultimate product of these series of disintegrations. However, the accepted atomic weight of lead had always been about 207.2; what, then, were these substances whose atomic weights were 206, 207, and 208? When the atomic weights of samples of lead from uranium and thorium deposits were determined, the results were amazing. Lead associated with uranium had an atomic weight of 206, lead associated with thorium was found to have an atomic weight of 207, and lead associated with actinium was found to have an atomic weight of 208. These several kinds of lead differ in no way from each other save in their atomic weights; that is, their masses are different when compared to the mass of hydrogen. Chemically, the different leads are indistinguishable from one another, and the difference in atomic weight, consequently, is believed to be due to difference in the atomic nuclei themselves.

Isotopes and Atomic Weight

Elements having the same properties but differing slightly in atomic weights are termed *isotopes* and are well recognized by modern chemistry. The word *isotope* is derived from the Greek words ἰσος, meaning "equal," and τοπος, meaning "place." We now know that atomic weights fail to be whole numbers because of the association of unequal amounts of the different isotopes of a given element. Uranium itself has, as far as is known, at least three isotopes, with atomic weights of 234, 235, and 238, respectively. Isotope 234 is rare, its ratio to 238 being 1 to 17,000; isotope 235 is much more common, having a ratio to 238 of 1 to 140. Uranium isotope 238 is the parent element of the radioactive series shown in Table I, and the possibility exists that uranium isotope 235 (Table II) is the parent element of the actinium series.

As has been previously suggested, the atomic weight of an element has become of far less importance than formerly in theoretical chemistry and theoretical physics. Today, atomic numbers and atomic mass numbers are all important. The atomic number represents the number of positive electric charges, or protons, inside of the nucleus of the atom. These protons are exactly balanced by an equal number of negative charges, or *orbital electrons*. Hydrogen has 1 as its atomic number; helium is number 2, which means that the helium atom has two outside negative charges which are balanced by a nucleus containing two positive charges, or protons, but at the same time having four times the mass of the hydrogen nucleus. Lithium has three outer negative electrical charges balanced by three positive charges in the nucleus, whose mass, however, is six times that of the hydrogen atom; the atomic number of lithium is therefore 3. We might continue until we reach uranium, which has an atomic number of 92, meaning that it has 92 positive charges in a nucleus containing a mass 238 times that of hydrogen. Experimental work has shown that the nuclei of atoms are very small indeed, in spite of their apparently considerable masses, in comparison with the outer negatively charged masses which surround the nuclei. The number of neutrons, or uncharged particles, present in the nucleus is equal to the mass number minus the atomic number. For example, uranium isotope 238 has 92 positive charges, or protons, in the nucleus; the number of neutrons present, therefore, would be 238 minus 92, or 146.

Because of the existence of isotopes it is possible for elements with different mass numbers to have the same atomic number, and the present method used to distinguish between isotopes is to place the atomic number as a subscript before the chemical symbol of the element and to write the atomic mass as an exponent; thus uranium of atomic number 92 and mass number 238 would be written ${}_{92}U^{238}$; lead from the radioactive disintegration of uranium would be written ${}_{82}Pb^{206}$; and lead from the radioactive disintegration of thorium would be written ${}_{82}Pb^{207}$. This terminology is used throughout the chapter of this book dealing with nuclear phenomena.

Chapter II

Radioactive Minerals

SINCE the discovery that the mineral pitchblende contains radioactive substances, many other naturally occurring compounds of uranium, thorium, and actinium have been found, so that today we possess a formidable list of radioactive minerals. With few exceptions, the radioactive minerals are present in almost infinitesimal amounts throughout the rocks of the earth's crust, but they are widely distributed and often highly complex substances. Some are undoubtedly primary; that is, they were formed simultaneously with the rocks which enclose them. Others are unquestionably secondary compounds, having been formed by the action of water or chemical solutions upon the primary radioactive minerals.

Out of the nearly one hundred known radioactive minerals, thirty-two species have been selected for description in the list which follows. Omitted are doubtful species, very rare types, or those about which insufficient data exist. The reader may obtain additional information from the larger works on mineralogy.

Allanite

This mineral is a hydrous aluminum silicate of the cerium metals (cerium, lanthanum, and so on), iron, and calcium with very small and variable amounts of uranium and thorium. Allanite occurs in long, slender, monoclinic crystals which are brownish in color, and have a somewhat resinous luster. Its specific gravity is 3.5 to 4; its hardness, 5½ to 6. Allanite is sometimes called "orthite," a word derived from the Greek word ορθος, meaning "straight." It is a primary mineral commonly found in granites, syenites, and gneisses, and particularly in the pegmatites. Foreign localities are in part the Ural Mountains, Saxony, Norway, Sweden, Greenland, where it was first discovered, Madagascar, and Canada. In the United States, it has been found in New York, New Jersey, Maine, Pennsylvania, Virginia, and Texas. Allanite was named for Thomas Allan, a Scottish mineralogist.

Ampangabeite

This mineral is a hydrated niobate and titanate of uranium, thorium, iron, and other minor constituents and is believed to be orthorhombic. It is brownish red, with a greasy luster, and has a specific gravity of about 4 and a hardness of 4. It was named because of its occurrence at Ampangabe, Madagascar, where it was found associated with columbite in pegmatite. A mineral similar in composition to ampangabeite, but with a somewhat higher titanium content, has been reported from Brazil, and it carries about 6 per cent uranium oxides.

Autunite

This mineral is a hydrous phosphate of calcium and uranium, and crystallizes in the orthorhombic system, usually in tabular or flaky crystals of lemon-yellow color. It has a pearly luster, a specific gravity of 3.1, and a hardness of 2 to 2½. It has a yellow streak, its permeability to light ranges from transparent to translucent, and it is strongly fluorescent. Autunite derives its name from the original locality at Autun in France. It is a secondary mineral, derived, in part at least, from uraninite with which it is commonly associated. Foreign localities, in addition to France, are Portugal, England, Czechoslovakia, and South Australia. In the United States, it occurs in small quantities in the pegmatites of Maine, Connecticut, New Hampshire, New York, Pennsylvania, North Carolina, and South Dakota. It contains from 55 to 62 per cent uranium oxides.

Becquerelite

This mineral is a hydrous uranium oxide, crystallizing in the orthorhombic system in small, brown-yellow crystals with a resinous luster. It is found associated with other uranium-bearing minerals at Kasolo in the Belgian Congo. It carries about 86.5 per cent of uranium oxides. It was named for Henri Becquerel.

Betafite

This mineral is a hydrous titano-niobate of uranium, thorium, calcium, iron, and other minor constituents. It crystallizes in the isometric system, both octahedrons and dodecahedrons being known. Its specific gravity is 4; its hardness, 5; its color, greenish-black. Betafite is opaque with a greasy luster, and has been found in the pegmatites near Betafo, Madagascar, whence its name. It has not yet been reported outside of Madagascar. Betafite is the most abundant radioactive mineral so far found in Madagascar, its content of UO_3 running slightly above 25 per cent.

Bloomstrandine

This mineral, sometimes called *priorite*, consists of niobates and titanates of yttrium, erbium, cerium, and uranium. It occurs in orthorhombic, tabular crystals of brownish-black color whose specific gravity is 4.8. It has been found in Norway, Sweden, and South Africa. It was named in honor of the Norwegian chemist, C. W. Bloomstrand.

Bloomstrandite

This mineral is a hydrous titano-tantalo-niobate of uranium, calcium, and iron. It is apparently related to betafite, but richer in titanium and tantalum. It occurs both as octahedral crystals and massive. Its color is black; its specific gravity, 4.17–4.25; and its hardness, 5½. Bloomstrandite has been found in Sweden, in the Ural Mountains, and in Madagascar. It should not be confused with bloomstrandine, both minerals being named for C. W. Bloomstrand of Lund, Sweden. It contains 20 per cent of uranium oxides.

Brannerite

This mineral is made up essentially of uranium and titanium oxides, and occurs as water-worn pebbles in alluvial gravels containing gold in the Stanley Basin, Idaho.

Bröggerite

This mineral is a variety of uraninite carrying thorium. It crystallizes in the isometric system in octahedral crystals. It occurs in Anneröd, Norway, and was named in honor of the Swedish geologist W. C. Brögger. It contains about 75 per cent of uranium oxides.

Carnotite

This is a hydrous mineral composed of the oxides of vanadium, uranium, and potassium. The actual water content is still uncertain. It crystallizes in the orthorhombic system, occasionally in tabular or flaky crystals. It usually occurs as a crystalline powder filling rock cavities, or as botryoidal crusts of canary or lemon-yellow color. It is present in sandstones in Colorado and Utah, where it is mined for vanadium, uranium, and radium. These deposits average 2 to 3 per cent of the uranium oxide U_3O_8. Carnotite is found also in gneisses at Radium Hill, near Olary, South Australia, and in shale at Mauch Chunk, Pennsylvania. While carnotite is obviously a secondary mineral, its origin still remains a matter of doubt. It was named for Adolphe Carnot, the well-known French engineer and analytical chemist. It contains 43 per cent uranium oxides.

Chalcolite

This is a term occasionally encountered in the older literature. It is synonymous with *torbernite.*

Clarkeite

This mineral is a sodium, lead, uranium oxide, also carrying water. It is massive with a conchoidal fracture. Its hardness varies from 4 to 4½, its specific gravity is 6.4, its color is dark brown, and its luster is waxy. Evidently, it is derived from uraninite by hydrothermal alteration. It occurs in Mitchell County, North Carolina. Samples from this locality indicate 80 per cent uranium oxides.

Cleveite

This mineral is a variety of uraninite, but carries a larger amount of UO_3 than the latter mineral, about 10 per cent of rare earths of the yttrium group, and considerable helium. It occurs at Arendal, Norway, and was named for the Swedish chemist P. T. Cleve. It contains 76 per cent uranium oxides.

Curite

This mineral is a rare hydrous lead uranate crystallizing in minute orthorhombic needle-like crystals. Its specific gravity is 7.19, its hardness is 4 to 5, and its color is reddish-brown. It is found in the uranium deposits of the Belgian Congo and was named in honor of Mme. Marie Curie. It contains 73 per cent uranium oxides.

Ellsworthite

This mineral is essentially hydrated calcium, niobium and uranium oxides. Ellsworthite is isometric; its specific gravity is 3.6 to 3.7; and its hardness, 4. Its color may be dark yellow to dark brown. It occurs in Hastings and Haliburton Counties, Ontario, Canada, and was named for H. V. Ellsworth of the Canadian Geological Survey. It contains 22 per cent uranium oxides.

Euxenite

This mineral is a niobate and titanite of yttrium, cerium, erbium, and uranium often with iron, calcium, and so on.

The rare element germanium also has been found in euxenite. Euxenite is usually massive but is found sometimes in orthorhombic crystals. Its specific gravity is 4.7 to 5; its hardness, 6½; and its color is brownish-black. It derives its name from the Greek word ευχεινος, meaning "friendly" or "hospitable" because of the number of rare elements found in it. Euxenite is of relatively wide occurrence, being found in Norway, Sweden, Finland, Brazil, Greenland, Australia, and Canada. In the United States, it has been found in North Carolina. It may contain as much as 10 per cent or more uranium oxides.

Fergusonite

This mineral is a niobate and tantalate of yttrium, cerium, and erbium with small amounts of uranium, iron, and calcium. It is found in tetragonal crystals, pyramidal or prismatic. Its specific gravity is 5.8; its hardness, 5 to 5½; and its color brownish-black. Fergusonite, originally found in Greenland, is now known from localities in Norway, Sweden, Ceylon, Madagascar, Japan, and Russia. In the United States, it has been found in Massachusetts, Virginia, North Carolina, South Carolina, and Texas. It may contain up to about 8 per cent uranium oxides. It was named for Robert Ferguson.

Gummite

This mineral is a hydrous alteration product of uraninite and pitchblende. Its exact chemical composition is still in doubt. Its color may be yellow, orange, or reddish-brown, and its rounded masses, which resemble resin or gum, suggested the name it now bears. It is amorphous, with a specific gravity of 3.9 to 4.2, and a hardness of 2½ to 3. It is found in many localities associated with uraninite and pitchblende, among which may be mentioned the Joachimsthal in Czechoslovakia, Saxony, and the Belgian Congo. In the United States, there are two well-known localities for this mineral — Mitchell County, North Carolina, and Grafton

County, New Hampshire. It may contain as much as 75 per cent uranium oxides.

Hatchettolite

This mineral is essentially a hydrous titano tantalate of uranium, calcium, iron, and other minor constituents. Hatchettolite is isometric occurring in octahedrons. Its specific gravity is 4.77 to 4.90; its hardness, 5; its luster, resinous; and its color, yellow brown to dark brown. It occurs in the pegmatites of Mitchell County, North Carolina, at Mesa Grande, California, and at Hybla, Ontario. Foreign localities are India and Madagascar. It was named in honor of the English chemist Charles Hatchett. It may contain as much as 15 per cent uranium oxides.

Mackintoshite

This mineral is a hydrous silicate of uranium, thorium, cerium, and other minor constituents. It crystallizes in the tetragonal system, but may be massive. Its specific gravity is 5.42; its hardness, 5½; and its color, black. Mackintoshite has been found in Western Australia and in Llano County, Texas. It was named in honor of the American chemist J. B. Mackintosh. It contains about 22 per cent UO_2 and 45 per cent ThO_2.

Monazite

This mineral is a phosphate of cerium, lanthanum, yttrium, thorium, and other minor constituents, the uranium content often being negligible. Monazite crystallizes in the monoclinic system, although good crystals are rare because monazite generally occurs in irregular masses or grains. Its specific gravity is 4.9 to 5.3; its hardness, 5 to 5½; its color, yellowish to brown; and its luster is vitreous to resinous. It occurs in many parts of the world in granites and gneisses, and has been used as a commercial source of thorium where the grains of monazite have been concentrated in places. Foreign occurrences are many, including Russia, France, Norway, India, Madagascar, South Africa, Brazil, and Canada. In the United States, it has been found in Connecticut, Virginia, North Carolina, and Idaho. The name *monazite* is derived from the Greek word *μοναζειν*, meaning "to be solitary."

Orthite

See ALLANITE.

Pitchblende

This mineral name is the term applied to the amorphous, massive, or cryptocrystalline forms of uraninite. It differs from uraninite also in the fact that essentially no thorium or rare earths are carried by it. Some forms of pitchblende seem to be hydrous, and the specific gravity is frequently considerably lower than uraninite, owing perhaps to various mixed impurities. Pitchblende is found chiefly in the metalliferous veins. Localities for pitchblende include the Joachimsthal, where it is found associated with pyrite, chalcopyrite, and silver-bearing galena; Saxony, where it is associated with cobalt-silver veins; and Cornwall, England, where it is associated with copper, cobalt, arsenic, and nickel minerals. In the Belgian Congo, pitchblende is found in the Katanga area associated with gummite and other secondary minerals. Pitchblende has been found in the United States in Gilpin County, Colorado, associated with pyrite, chalcopyrite, spalerite, and

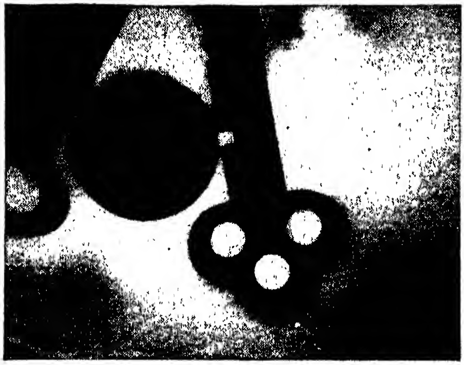

Photo by E. S. C. Smith

Figure 5. Radiograph of Keys Taken by Radioactive Rays Emitted by a Specimen of Pitchblende. The pitchblende was collected at the famous Joachimsthal, Czechoslovakia, locality, whence came the residues of uranium ore used by the Curies in isolating radium.

galena. Rich veins of pitchblende associated with native silver occur at LaBine Point, Great Bear Lake, Northwestern Territories, Canada. Pitchblende derives its name from the pitchy luster some varieties have when they are fresh and unweathered, and from the German verb "to dazzle" (see Figures 5 and 6).

Photo by E. S. C. Smith

Figure 6. Radiograph of Specimen of Pitchblende Taken by Its Own Radioactive Rays. This specimen was collected at the Ruggles Mine near Grafton, New Hampshire.

Polycrase

This mineral is a niobate and titanate of yttrium, cerium, erbium, and uranium; in fact, polycrase is much like euxenite. It crystallizes in the orthorhombic system; its specific gravity is 4.9 to 5.0; its hardness is 5 to 6; and its color is black. It has been found in Norway, Sweden, and Brazil. In the United States, polycrase is found in North Carolina and South Carolina. Its name is derived from the Greek *πολύ*, "many" and *κραοις*, "mixture." It may contain as much as 20 per cent uranium oxides.

Priorite

See BLOOMSTRANDINE.

Samarskite

This mineral is a tantalo niobate of yttrium, cerium, calcium, iron, uranium, and other minor constituents. It crystallizes in the orthorhombic system, and, although sometimes found in prismatic crystals, samarskite is commonly massive. Its specific gravity is 5.6 to 5.8; its hardness, 5½; its luster, submetallic; and its color, black. It has been found in Russia, Norway, Madagascar, India, and Brazil. In the United States, it is fairly abundant in Mitchell County, North Carolina, and has been found in Colorado and elsewhere in granite pegmatites. It was named in honor of the Russian engineer Oberst von Samarski. The uranium content may be as much as 15 per cent uranium oxides.

Thorianite

This mineral seems to be an isomorphous mixture of thorium and uranium oxides in varying proportions. It is isometric, crystallizing in cubes; its specific gravity is 9.5; its hardness, about 6; and its color, black. Thorianite has been obtained from the river gravels of Ceylon, being derived from nearby pegmatites; it has also been found in Madagascar and Siberia. It was so named because of its thorium content. It may contain from 15 to 30 per cent uranium oxides.

Thorite

This mineral is a hydrous silicate of thorium together with rare earth elements, uranium, and so on. It crystallizes in the tetragonal system, but is usually found in rounded, irregular fragments. Its specific gravity is 4.4 to 4.8; its hardness, 4 to 5½; its luster, resinous; and its color, yellow to brown. True thorite contains only small amounts of uranium. It was so named because of its thorium content.

Torbernite

This is a hydrous phosphate of uranium and copper, with arsenic sometimes replacing part of the phosphorus. It crystallizes in the orthorhombic system, with crystals varying from thin, sometimes tabular squares, to forms resembling cubes at first glance. The color ranges from emerald to a grass or lighter green. Its specific gravity is 3.2; its hardness, 2 to 2½; its permeability to light varies from transparent to translucent. Like autunite, with which it is frequently associated, torbernite is a secondary mineral. It occurs in the Joachimsthal mines in Czechoslovakia; in Saxony; in Cornwall, England, where especially fine crystals have been obtained; and in South Australia. Torbernite was named for the Swedish chemist and naturalist Torbernus Bergmann. It contains 50 to 60 per cent uranium oxides.

Uraninite

This mineral is composed of the crystalline uranium oxides corresponding chiefly to UO_2, U_3O_8, and UO_3 plus variable amounts of thorium and lead, metals of the rare-earth groups, and the rare gases helium and argon. Uraninite is isometric, but, although crystals are relatively rare, they have sometimes been found of large size. Ordinarily the mineral is massive or botryoidal. Uraninite has a specific gravity of 9.0 to 9.7 and a hardness of 5½. Its color on fresh surfaces is a velvet black, but it is usually grayish, greenish, or brownish. The luster varies from submetallic to greasy or pitchlike. Uraninite is widely distributed, occurring both as a primary mineral in the pegmatites and as a secondary mineral with the sulphides of silver, lead, iron, zinc, and copper. However, only three deposits in the world may be

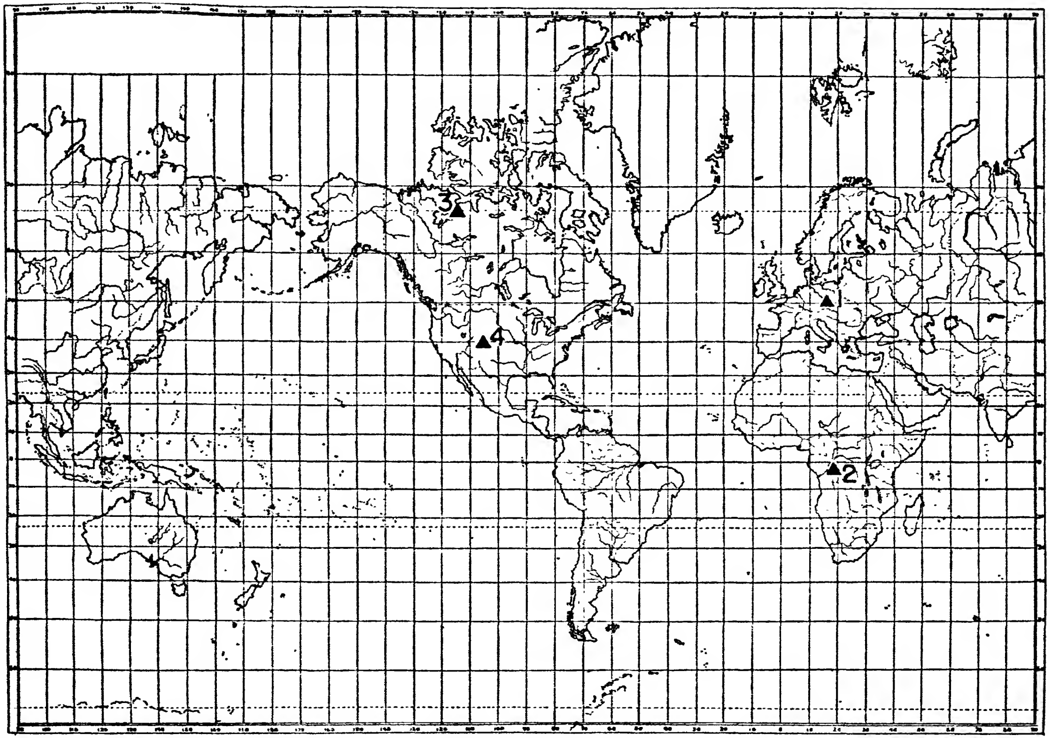

Figure 7. Present Known Commercial Sources of Uranium. (1) Joachimsthal, Czechoslovakia; (2) Belgian Congo, Africa; (3) Great Bear Lake, Northwest Territory, Canada; (4) Colorado, U.S.A.

considered as large scale and commercial. The classic locality is, of course, the Joachimsthal in Czechoslovakia, from whose deposits came the material from which radium was first obtained. Another area is in the Belgian Congo, where exist relatively rich uraninite deposits whose full extent is by no means yet accurately known. The third area is what may yet prove to be both the richest and most extensive deposits of uraninite in the world. It is the Great Bear Lake region in the Northwestern Territories of Canada, discovered in 1930 (Figure 7).

Uranothorite

This name is applied to a uranium-rich thorite which has been found in Norway and in Ontario, Canada. Its physical characteristics are very similar to thorite but may contain up to 17 per cent uranium oxides.

Zippeite

This mineral is a hydrous uranium sulphate. It has been found at the Joachimsthal mines, Czechoslovakia; in association with carnotite in Colorado; in the asphaltic sandstones of Wayne County, Utah; and at Great Bear Lake, Northwestern Territories, Canada.

Part II

Physical Background of Atomic Energy Production

By Dr. A. H. Fox

Chapter I

Natural Sources of Power

BEFORE we can appreciate fully the enormous storehouse of energy to be found inside the atom, let us first make comparative estimates of other known power sources. Energy production may be measured in different ways, and different units are used, each appropriate to the kind of energy considered.

Energy Units

Mechanical energy is usually measured in *foot-pounds,* a unit measuring the amount of work done, or energy used up, when a body is moved by a constant force of one pound through a distance of one foot along the line of action of the force (Figure 1A). A quantity of water weighing 1000 lb falling over a dam and down a height of 20 ft releases 20,000 ft-lb

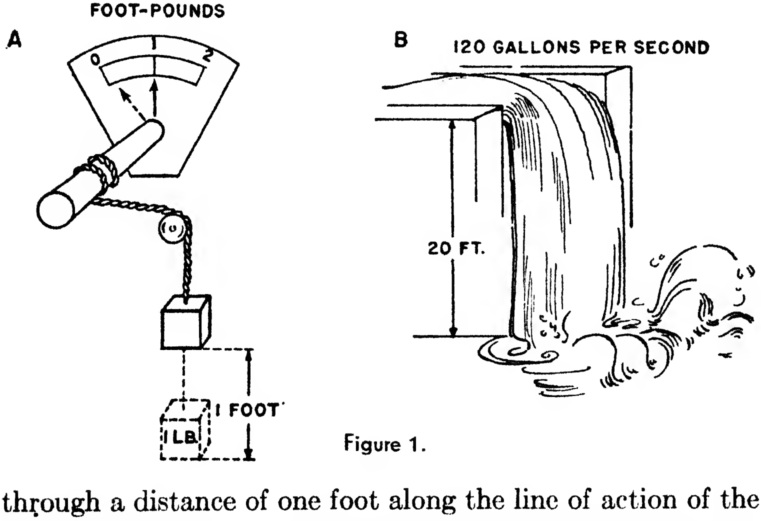

Figure 1.

of energy on entering the pool at the bottom (Figure 1B). This energy goes into energy of motion, called *kinetic energy,* into heat energy, and into sound energy. The time rate at which this energy is released measures the *power* of the waterfall. The mechanical unit of power is the *horsepower* (hp). One hp is equivalent to 550 ft-lb expended per second. In the case of the waterfall, if the 1000 lb of water flows over the dam every second (a rate of flow of about 120 gal per second), then 20,000 ft-lb per second, or 36.5 hp, are developed.

The units of power commonly used in electrical measurements are the *watt* (w) and its larger relative the *kilowatt* (kw); one kw equals 1000 w. The watt is related to the *erg,* which is the unit of energy in the metric system. An erg is the work done in moving a body a distance of one centimeter using a constant force of one dyne. The erg is so small, about equal to the work done in lifting a postage stamp an inch, that another and larger unit called a *joule* is also used. One joule equals 10,000,000 ergs. One watt is the power produced when one joule is given up per second. One hp equals 756 w. In electrical measurements, the usual energy unit is the *kilowatt-hour* (kw-hr), defined as the energy expended when the power of 1000 w is used for an hour; several cents per kilowatt-hour is the usual cost of electrical energy. One kw-hr is equal to 360,000 joule-seconds, or 3.6×10^{13} ergs.[*] A 100-w light bulb uses up about a billion ergs while burning for only one second; from this, it can be seen that the erg is relatively a small unit of work.

In atomic measurements, however, a still smaller unit of energy is used. When a negatively charged particle is placed in an electric field, as between the plates of a charged condenser, the particle tends to move toward the point of high-

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[*] Any number can be written as the product of a number between 1 and 10, and some power of 10. The exponent of the power indicates how many places the decimal point should be moved, positive to the right, negative to the left. Thus $2.5 \times 10^{4} = 25{,}000$, and $2.5 \times 10^{-3} = .0025$.

est potential. If the field strength is uniformly one volt per centimeter, and the particle is an electron, then the work done by the field in moving the electron one centimeter (Figure 2) is one *electron-volt* (ev). This unit is about as much smaller than an erg as the erg is smaller than a kilowatt-hour.

$$\text{One ev} = 1.6 \times 10^{-12} \text{ erg} = 4.4 \times 10^{-26} \text{ kw-hr.}$$

Small as the ev is, enormous amounts of atomic energy are computed by multiplying this unit by the large numbers of atoms found in the usual experiment, something like 10^{20} atoms per gram.

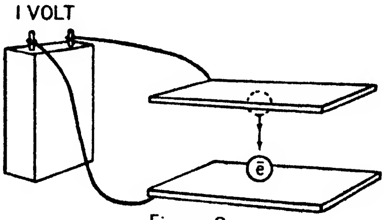

Figure 2.

Still other units of energy are used when heat is the principal consideration. Chemists use a unit called a *calorie* or *gram-calorie,* defined as the heat required to raise the temperature of a gram of water one degree centigrade. This is equivalent to 4.18×10^7 ergs. The corresponding unit in the English system is the Btu (British thermal unit), which is the heat required to raise the temperature of one pound of water one degree Fahrenheit. This unit is used in measurements of fuel combustion and is equivalent to a little more than 10^{10} ergs.

For the energy production in a nuclear reaction of one atom with another, the unit consisting of one million electron volts (Mev) is about the correct magnitude to obtain small, easily handled numbers of units such as 1 to 200. But the reader should not be misled by the word *million;* the energy per particle is still extremely minute. When grams of elements are considered in the reactions, a unit as large as a kilowatt-hour becomes more convenient.

Power Sources

It has been noted above that the power of a waterfall discharging 120 gal per second with a drop of 20 ft is 36.5 hp, or 27.5 kw. By increasing the flow of water or the height of the fall, the power can be increased many times. The equipment necessary to convert this energy into useful work is, of course, usually large and expensive.

Another source of power is the burning of coal or other fuels. One gram of coal, pure carbon, when completely burned to CO_2, liberates about 7920 calories, or 3.3×10^{11} ergs, not quite one hundredth of a kilowatt-hour. All of this energy cannot be used without enormous loss. In the atoms of ashes left after ordinary coal is burned there is a hundred thousand times as much atomic energy as was liberated as heat energy in the burning. Fuel oil releases about 19,500 Btu per pound, or 4.5×10^{11} ergs per gram. Heating losses must be considered before useful work is done.

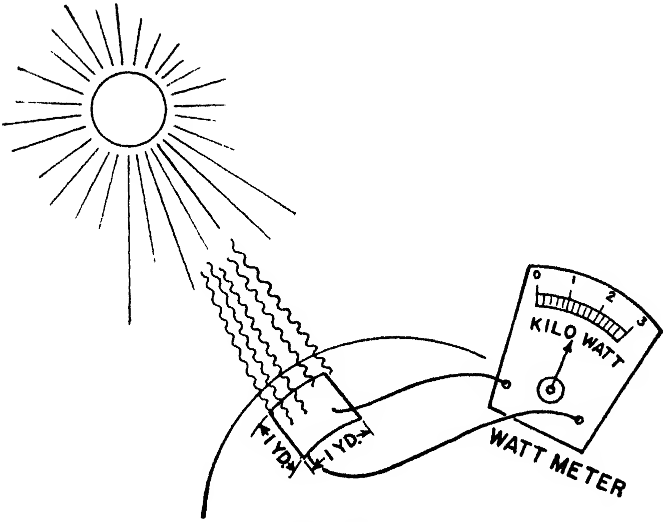

Figure 3.

The energy in coal and fuel oil, and even in water power, comes originally from the energy of the sun. Sunlight was used by plants to form large areas of vegetation many years ago, and these areas, by the action of heat and pressure, have been turned into coal and oil. If we go directly to sunlight as a source of power, we find that, on a cloudless day, on the average about 1.35×10^6 ergs fall per second on a square centimeter of the earth's surface (Figure 3). This means that an area of 7400 square centimeters, or a little less than a square yard, will gather energy at the rate of one kilowatt. Elaborate systems of mirrors and storage tanks are used to collect solar energy and convert it into heat energy for some purposes. So far, this process has not been developed commercially to any great extent.

Natural radioactive elements liberate relatively large amounts of energy in each emission of a particle; but these processes go on too slowly to provide much power, unless larger amounts of radioactive substances be used than are now available. An alpha particle from radium carries an energy of 4.9 Mev (Figure 4). This is only 7.6×10^{-6} erg, or 2.15×10^{-19} kw-hr. But when we take account of the fact that there are about 2.8×10^{19} atoms of radium in a gram, we find that a total energy of 2.1×10^{14} ergs, or 6.2 kw-hr, would be released if all the atoms in one gram were to disintegrate. Radium has a half-life of 1690 yr and hence, in order to have one gram decay per second, a mass of 7.3×10^{10} g, or about 80,000 tons, of radium would have to be present. Much larger amounts of uranium, with its longer half-life of 4.6 billion years, would be required to give any appreciable power production.

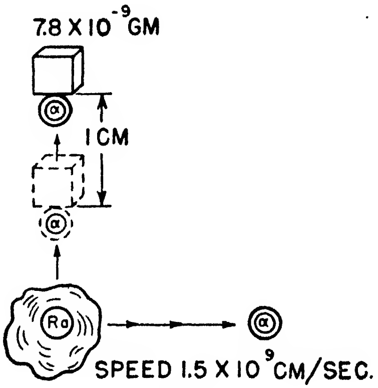

Figure 4.

Natural sources of power known at the present time require large and elaborate turbine generator installations, or similar plants, in order to convert their power into a form, usually electrical, which can be transmitted and used conveniently. Natural radioactive elements cannot be used to produce large power sources, but they are very convenient when a small amount of energy is required at an almost inaccessible point. Radioactive treatment of cancer, in which the sources may be placed right inside the diseased tissue, employs the energy continuously liberated by these atoms. The use of radioactive materials on watch dials is another example; here, only a small amount of energy is required to produce enough light to make the numbers visible. The source, however, is continuous, and once the paint containing the radioactive atoms is in place, it continues to produce light as long as the watch lasts, and longer.

We see, therefore, that atomic energy sources seem much simpler and more convenient to handle than other natural sources of power. But they are either too weak or depend on materials which are too scarce to make practical, at present, the continuous production of large amounts of power.

Chapter II

Nuclear Reactions

AS EARLY as 1919, when Rutherford was conducting an experiment on the range of α-particles in air, he discovered that the air into which the α-particles were shot contained atoms of hydrogen. He repeated the experiment with pure nitrogen in place of air, which is about 80 per cent nitrogen, and obtained the same result. This was the first definite artificially produced transmutation of one element into another.

Nitrogen Transmutation

The α-particle, on striking a nitrogen atom head-on, penetrates the nucleus of the atom and forms another nucleus with a charge of 9 units, normally found only on a fluorine nucleus (Figure 5). The newly formed nucleus, however, contains 9 protons and 9 neutrons and therefore has a mass of about 18 units, while the stable fluorine found in nature

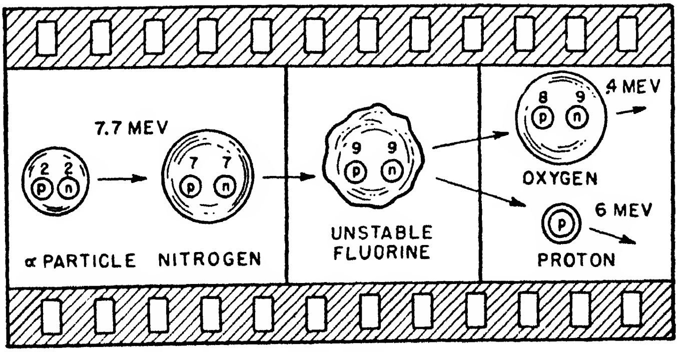

Figure 5.

has 19 mass units. Hence, the newly formed fluorine nucleus is unstable; in fact, it breaks down in a small fraction of a second into a nucleus of an oxygen atom — with charge 8 and mass 17 — and a proton, a nucleus of hydrogen that has one unit of charge and one of mass. The newly formed fluorine nucleus is disrupted so quickly that its existence cannot be proved; it is merely inferred from the general theory of nuclear reactions.

The existence of the hydrogen atoms, which were produced artificially, was inferred from the range of their rapid motion in the gas and by other more direct photographic methods.

The energy of the α-particles used was 7.7 Mev and the observed energies of the proton and oxygen nucleus were 6 Mev and .7 Mev, respectively. Thus a net energy loss of 1 Mev is involved in each individual transmutation. This is an example of the conversion of energy into mass. The masses of the nuclei of the original materials ${}_7N^{14}$ and ${}_2He^4$ are known from careful experiments to be 14.0036 and 4.0028 mass units, in the system in which the mass of an atom of ${}_8O^{16}$ is exactly 16. The nuclear masses of ${}_8O^{17}$ and ${}_1H^1$ are 17.0001 and 1.0076. By computation, we find that the products are heavier than the original materials by .0013 mass unit.

Mass and Energy

In 1905 Einstein, in formulating the special theory of relativity, showed that there should be a relation between mass and energy. This involves the equation $mc^2 = E$, where the mass m is in grams, the number c is the velocity of light in centimeters per second, and the energy E is measured in ergs. A mass of one gram is related by this equation to c^2 ergs. Since $c = 3 \times 10^{10}$, this amounts to an energy of 9×10^{20} ergs, or 25 million kw-hr, released merely by the transformation of one gram of mass into energy. The mass of an atom of ${}_8O^{16}$, by careful measurement, is only 1.013×10^{-23} g; therefore one mass unit, a sixteenth part of this, is 1.660×10^{-24} gram. Consequently, the energy produced in the annihilation of one mass unit is 1.48×10^{-3} erg or 931 Mev.

In the nitrogen transmutation, there is a deficiency of .0013 mass unit which is converted from energy of the α-particle into mass of the product nuclei, and, on multiplying by 931, we find that this is equal to 1.26 Mev. Since the energy of the incident α-particle is 7.7 Mev and the sum of the energies of the products is just 6.4 Mev, the energy balance is just right. This kind of mass-energy balance in nuclear reactions is always possible, and is the most striking confirmation of relativity theory.

In the reaction discussed above, the conversion of energy into mass is, of course, going in the wrong direction insofar as our search for sources of atomic power is concerned; the reaction is described here because it was the first nuclear reaction analyzed, and the technique is the same as that applicable to the power-producing reactions described below.

Neutron Production

Many other such experiments with other elements gave similar transmutations and formed a most active field of physics for the decade before 1940. In fact, the discovery of the neutron by Chadwick in 1932 was the result of such an experiment. Several investigators had exposed beryllium to α-particle bombardment and found that the resulting high-energy particle had a range and penetrating power far above those produced in other reactions. They showed that a proton of these properties would have to possess thousands of Mev which were certainly not accounted for in the mass energy balance. Chadwick showed that the only particle with the available energy which could have the measured range and penetrating power must have a mass equal to that of the proton, but must not have any charge at all. The existence of such a particle, called a neutron, had been predicted from theoretical considerations by Rutherford in 1920, but no experiment had exhibited this particle prior to Chadwick's work. On passing through atoms of air or other elements, such a particle would not be retarded by electrical interaction with the electrons around the nuclei. Only direct action of the nuclei could have any stopping effect; hence the long range and high penetrating power of the particle. In fact, ordinary methods of detection, which usually depend on electrical properties of the particles, were of no use here, and an indirect method of detection had to be devised.

The reaction studied by Chadwick is illustrated in Figure 6. The carbon atom of mass 13 exists for only a microsecond (10^{-6} sec) and cannot be detected. The energy of the incident α-particle from polonium is 5.3 Mev, and the energy of the neutron may be as much as 10 Mev. Here the total mass of the products is less than that of the original elements. The neutrons flying out of the unstable carbon atoms in the beryllium target are allowed to hit a block of paraffin (Figure 7), a substance rich in hydrogen atoms. When a neutron strikes a hydrogen nucleus, the transfer of energy from the neutron to the hydrogen nucleus is considerable because their masses are nearly equal; in fact, a proton of about the same energy as that of the neutron is likely to be knocked out of the paraffin, and a proton can be readily detected by ordinary methods. This transfer of energy is similar to that which occurs when a fast-moving marble hits another of the same mass. If the hit is head-on, the first

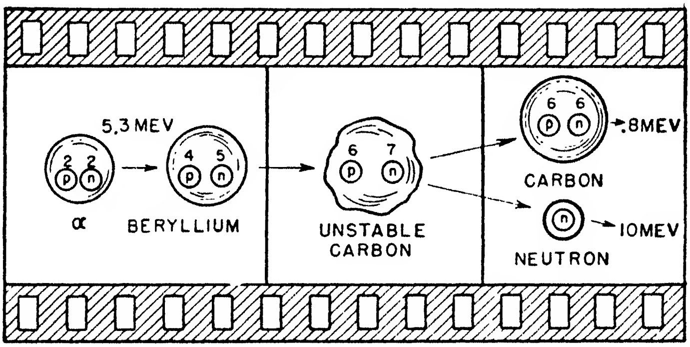

Figure 6.

marble stops and the second goes on with almost the speed of the first. If the second marble is much heavier than the first, it is more likely to cause the first merely to bounce off without much loss of energy. This effect of equal-sized particles is important in the methods discussed later for slowing down fast neutrons.

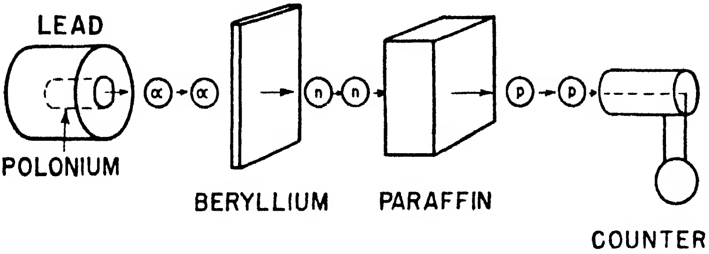

Figure 7.

As a source of power, this reaction depends on naturally radioactive sources for α-particles, and hence the rate of production of even 10 Mev neutrons is too slow to be used as a primary source of power, although it tends in the right direction.

Chapter III

Artificial Radioactivity

ARTIFICIALLY produced radioactive substances were first recognized in 1933, when Curie and Joliot were performing an experiment in which aluminum targets were bombarded by α-particles. The primary result was the production of neutrons as in Chadwick's experiment. But the experimenters found that even after the α-particle bombardment had been stopped, the target continued to give off high-velocity particles, which were found to have the same mass as an electron but a positive charge like that of the proton (Figure 8). These positive electrons had been observed in cosmic-ray experiments a year earlier. The emission of positive electrons from the phosphorus had all the random decay characteristics of a natural radioactive substance, with a half-life of 2.5 min. This artificial radioactivity, which continues after the direct activating source has been turned off, fulfills one of the requirements that a power-producing reaction must satisfy. Here, however, the

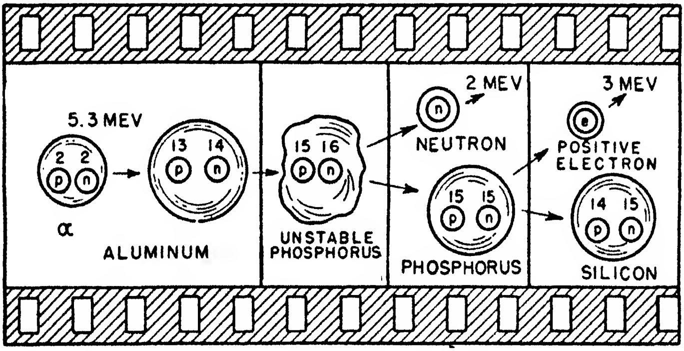

Figure 8.

energy of the 3 Mev positive electron is soon given up when the particle is neutralized by a negative electron, a process in which radiant energy of approximately one Mev is released. Since the α-particle causing the reaction had more than 5.3 Mev, we still have an energy loss.

Radio-Sodium

Various types of machines were devised for increasing the speed, and hence the kinetic energy, of different ionized particles, in order to use them to induce nuclear reactions.

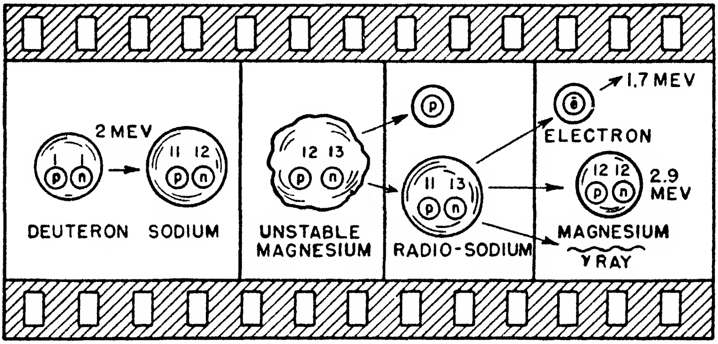

Figure 9.

One of the most successful of these is the cyclotron, a device invented by Lawrence. He used deuterons accelerated by a cyclotron to 2 Mev as projectiles, and sodium as a target, and was able to produce a radioactive sodium whose half-life of 14.8 hr makes it a very convenient substance to handle. The reaction, illustrated in Figure 9, shows that the magnesium nucleus gives off a proton and produces radioactive sodium. Then this sodium gives off both a β-ray (electron) and a γ-ray (radiation) just as some radioactive atoms do. A salt, sodium chloride, is made with this radio-sodium and then this salt is fed to an animal in a biological experiment. The final location of the radio-sodium and the rate at which it is absorbed may be measured merely by using a device for detecting the intensity of the emitted electrons. The half-life of nearly 15 hr allows all but a negligible part of the radiation to be lost in a week or so, and hence no lasting effect is produced. But the energy output is only about one Mev greater than that of the incident deuterons, and the cyclotron is a very inefficient user of energy at best.

By using different targets and projectiles, hundreds of other radioactive isotopes have been formed artificially with half-lives that range from less than a second to several thousand years.

Neutron Reactions

When neutrons are used as projectiles, radioactive atoms are formed by either high-energy or low-energy neutrons.

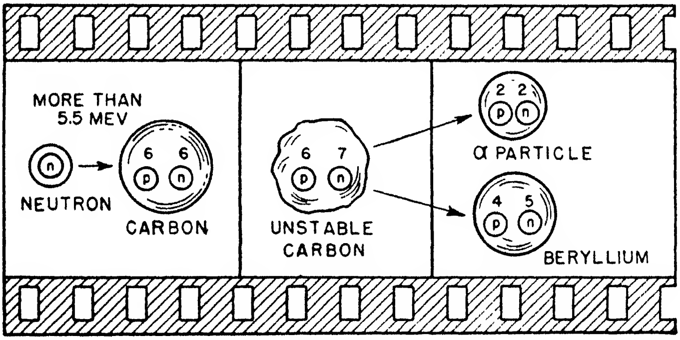

Figure 10.

The fast-neutron reactions often cause considerable disruption of the nucleus, as in the case of a reaction using a carbon target, shown in Figure 10. Since the masses of the carbon and neutron are 12.0007 and 1.0089, respectively, and those of beryllium and helium are 9.0128 and 4.0028, we find an energy defect of .0060 mass unit, or 5.6 Mev. This means that the energy of the neutron must be above 5.6 Mev before this reaction can take place. Any excess energy will increase the energies of the α-particle and beryllium nucleus at the end. This reaction is just the reverse of that in which Chadwick discovered the neutron (Figure 6), and neutrons are observed with energies up to 10 Mev. Very few reactions in which α-particles are emitted have been found.

Much of the work involving neutron bombardment was done by Fermi and his associates, who found that in some cases the activity was greatly increased by decreasing the energy of the neutrons. For instance, in the case of a silver target (as in Figure 11) radioactive silver was formed which gave off electrons of nearly 3 Mev when the energy of the incident neutron was only a few electron-volts. The fast neutrons from the usual sources may be slowed down by making them pass through some "moderator" in which they strike atoms light enough to cause the neutrons to give up most of their energy by elastic collision, as was explained at the end of the last chapter. The best substance for this purpose is hydrogen, since protons and neutrons are almost identical in mass, but other light atoms might serve; carbon nuclei, for instance, absorb on the average about ⅙ the energy of the neutron at each collision, and in very few collisions can reduce a million electron-volt neutron to one whose energy is on the same level as the heat energy of the other atoms in the neighborhood, say, of a few hundredths of an electron-volt. Hence any energy given off in a reaction caused by such a slow neutron is all released from the mass of the atoms involved. In fact, this kind of slow-neutron reaction, when uranium is used as a target, forms one of the best-known sources of atomic power.

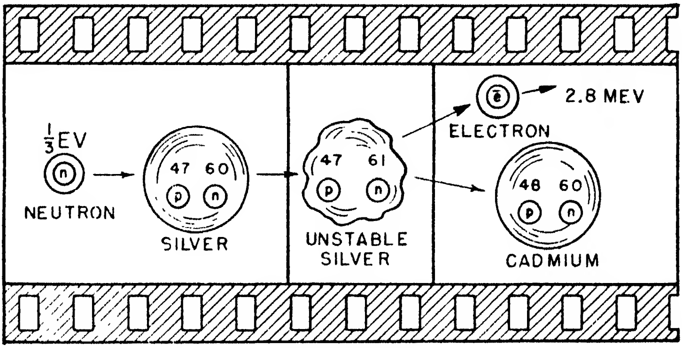

Figure 11.

Chapter IV

Nuclear Fission

IN 1937 Enrico Fermi and his collaborators bombarded uranium by neutrons and reported that radioactive atoms had been produced whose half-lives were different from those of any known elements in the neighborhood of uranium in the periodic table. They believed them to be new elements of charge 93 and 94, so-called transuranic elements, and much work was done to establish their chemical identity. It was not until 1939 that another explanation based on an entirely new idea was given. Hahn and Strassmann reported that one of the radioactive products of the reaction which had a half-life of 86 min was identical with a known radioactive isotope of barium. Meitner and Frisch suggested that the uranium atom might have been split into pieces of large masses, and that barium was only one possible particle. They called this process "nuclear fission" because it resembled fission in biological processes. Since the mass of uranium is 235 or 238 and that of barium about 139, the mass of the other "fission fragment" must be near 98. Almost immediately the identification of strontium and ytterbium in the products confirmed this conjecture, and many substances were identified with other observed half-lives of the reaction products.

Fission Example

A typical reaction is shown in Figure 12. The neutron is absorbed by the uranium atom, here the U–235 isotope, and this U^{236} nucleus then splits into several pieces, which in this example are a xenon nucleus, a strontium nucleus, and in addition, two fast neutrons. The masses involved in the initial and final states of the system differ by more than .2 mass unit, so there is produced a total of over 200 Mev of energy, which is divided among the products.

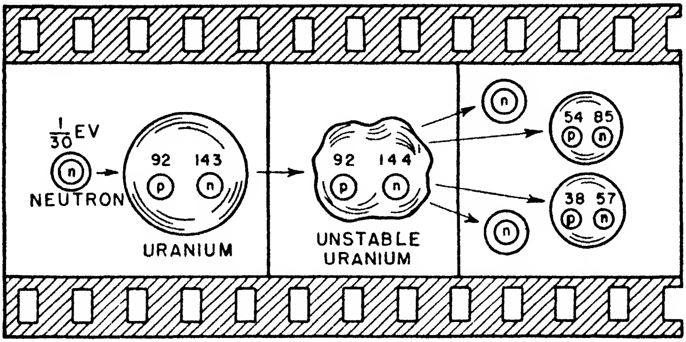

Figure 12.

Nuclear Theory

The forces that keep the particles in a heavy nucleus together were studied theoretically by Bohr and Wheeler, and by Frenkel, who showed that only a few elements at the very top of the periodic table possess just the right characteristics to permit fission. Their theory involves the use of a model of a heavy nucleus in the form of a large drop, like a drop of water, with the protons and neutrons filling the inside. Protons and neutrons are assumed to be held together by forces that act like those producing surface tension in the drop of water. The neutrons and protons, however, have individual kinetic energies, and mutual forces of repulsion exist between the protons; these effects tend to disrupt the nucleus.

For lighter atoms, the balance of energy is greatly in favor of the surface forces, and the nuclei are difficult to break apart. If a particle penetrates the nucleus, the energy balance is disturbed and another particle may be released to restore the balance. But the emitted particle is always small, and the remaining nucleus is about the same as that of the original target atoms. For the heavier atoms, this balance of internal energies becomes more delicate.

Theory of Fission

When the numbers of neutrons and protons get as large as those found, for instance, in the nucleus of $_{92}U^{235}$, which contains 92 protons and 143 neutrons, the situation may be different. Here the balance of energy for disruption is just about equal to the energy holding the nucleus together. It is as if the drop of water were held together by a very weak surface tension. When a neutron approaches, slowly enough to add its energy to that of the nucleus, the balance is upset and the drop splits into fragments.

Each fragment, since it contains fewer neutrons and protons than the unstable nucleus, is drawn together by the tension forces among the smaller number of particles. Some few extra neutrons may get left out in the recombination, but the protons all go into either one fragment or the other. The fragments may each contain various proportions of the 92 protons available, and hence many different elements may be formed. Actually only about 30 different fission products of uranium have been identified in two groups, one having masses between 90 and 115, and the other having masses between 125 and 145. This means that about two fifths of the protons are likely to be in one fragment and three fifths in the other. A division into equal halves is unlikely. Along with the protons go various numbers of the neutrons; but in general, there are too many of them to bring about a stable isotope in the first-formed fragments. An unstable nucleus thus formed emits an electron, and this emission is continued until a stable form of some other element is reached.

Radioactive Fragments

An illustration is given in Figure 12. Here the main fragments contain 54 and 38 protons, and 85 and 57 neutrons, respectively. Two neutrons are left over, are emitted at high speed, and may start reactions in other nuclei. The $_{54}Xe^{139}$ nucleus is an unstable isotope of xenon, has a half-life of a few seconds, and gives off an electron to become

$_{55}Cs^{139}$ (Figure 13). This secondary product is also radioactive, with a half-life of 7 min, and gives off an electron to become $_{56}Ba^{139}$. Though this barium isotope is radioactive too, it has a half-life of 86 min, and so a chemical analysis of the fission products is likely to show the presence of barium, as Hahn and Strassmann found in their key experiment. The barium also gives off an electron and finally a stable isotope of lanthanum — namely, $_{57}La^{139}$ — is left. The nucleus now has 57 protons and 82 neutrons, which provide just the correct energy balance. Incidentally, this $_{57}La^{139}$ is the only known stable isotope of lanthanum.

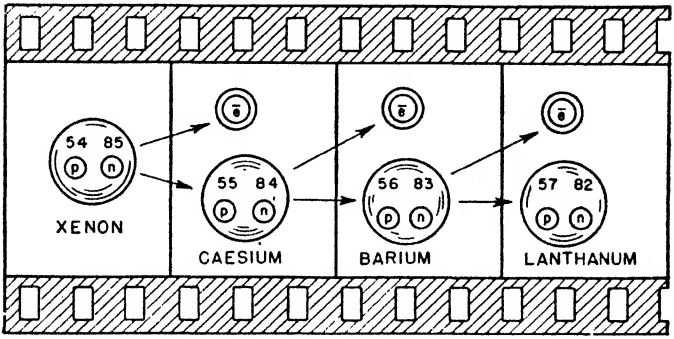

Figure 13.

The other original fragment goes through a similar series of changes (Figure 14). $_{38}Sr^{95}$ has ten more neutrons than

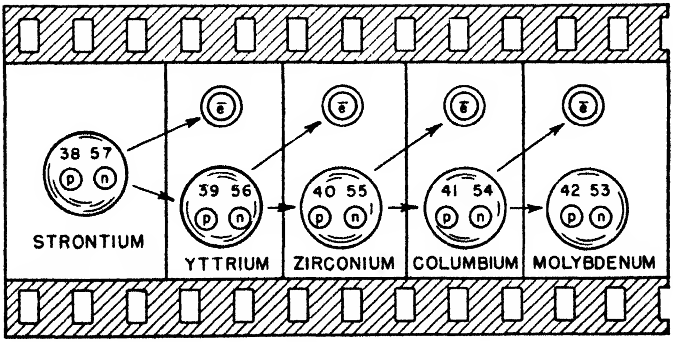

Figure 14.

the heaviest stable isotope of strontium. The series of radioactive nuclei formed by successive electron emission is ${}_{38}\mathrm{Sr}^{95} \longrightarrow {}_{39}\mathrm{Y}^{95} \longrightarrow {}_{40}\mathrm{Zr}^{95} \longrightarrow {}_{41}\mathrm{Cb}^{95} \longrightarrow {}_{42}\mathrm{Mo}^{95}$. After emission of four electrons, a stable isotope of molybdenum is reached. This isotope is only one of seven known stable forms of molybdenum.

Energy Produced

Thus the fission of one ${}_{92}\mathrm{U}^{235}$ nucleus produces, in all, a nucleus of ${}_{57}\mathrm{La}^{139}$ and a nucleus of ${}_{42}\mathrm{Mo}^{95}$, along with 2 neutrons and 7 electrons. The masses of the original ${}_{92}\mathrm{U}^{235}$ and of the neutron are 235.075 and 1.0089, respectively. The masses of the fission products are 138.920 and 94.925, plus twice 1.0089 for the neutrons, and seven times .0054 for the electrons. The excess mass converted into energy amounts to .217 unit, or 202 Mev, divided among all the particles and the γ-radiation that may occur. This energy yield is 10 times greater than the energy produced in any known nuclear reaction, and the fission of a whole gram of ${}_{92}\mathrm{U}^{235}$ would produce 25,000 kw-hr. Other pairs of fission products give approximately this same amount of energy, if not more.

Fission in U-238

A more detailed investigation shows that while fission may be caused in thorium and protactinium by fast neutrons, thermal neutrons of energies of a few hundredths of an electron-volt are sufficient to produce fission in ${}_{92}\mathrm{U}^{235}$. Fast neutrons are needed for the more plentiful ${}_{92}\mathrm{U}^{238}$ isotope.

Plutonium

One effect of the slower neutrons on ${}_{92}\mathrm{U}^{238}$ has been the capture of the neutron and the formation of an unstable isotope of uranium, ${}_{92}\mathrm{U}^{239}$, of half-life 23 min (Figure 15). This isotope of uranium gives off an electron and becomes a nucleus with 93 charges, more than on any atom found in nature. This nucleus is also unstable, having a half-life of 2.3 da, and it gives off another electron to form a nucleus of charge 94. These two nuclei are the transuranic elements which Fermi thought he had discovered several years before the fission of uranium actually was explained. The names "neptunium" for the $_{93}$Np element and "plutonium" for $_{94}$Pu were selected, referring to the planets Neptune and Pluto, which are beyond Uranus in the solar system. $_{94}Pu^{239}$ is radioactive with a moderately long half-life; it gives off an α-particle and becomes $_{92}U^{235}$. The most important property of $_{94}Pu^{239}$, however, is that it undergoes fission even more readily than $_{92}U^{235}$.

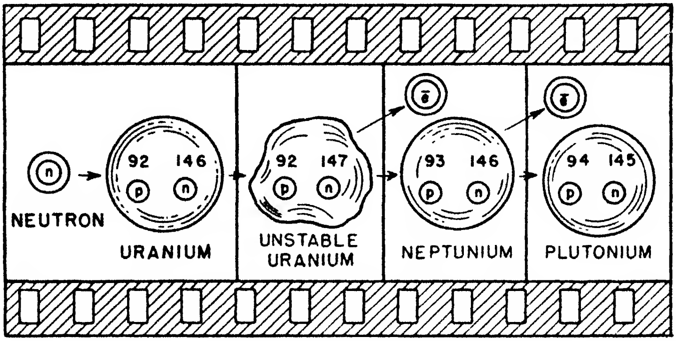

Figure 15.

Probability of Fission

Targets of ordinary U_3O_8 are composed of one part of $_{92}U^{235}$ to 139 parts of $_{92}U^{238}$. Hence a slow neutron aimed at such a target has much less chance of producing fission than of being absorbed by a nucleus of $_{92}U^{238}$. And there is a still greater chance that a slow neutron will pass through the target without causing any reaction at all. The latter chance can be decreased by increasing the size of the target, but calculations indicate that very large amounts of uranium, a cubic meter or so, would be required to eliminate this chance of escape.

Power

As for power production, fission experiments are still dependent on sources of neutrons and large amounts of rare materials such as ${}_{92}U^{235}$ and ${}_{94}Pu^{239}$. One feature of the fission process which we have not yet explained is, however, the deciding factor in this search for atomic power. We saw that when a nucleus undergoes fission, fast neutrons are given off in addition to the major fission products. If these fast neutrons could produce more fissions, and if the neutrons released in these new fissions could cause still more fissions, then a "chain reaction" might be set up. Such a chain reaction would produce fission at a rate high enough to provide a practical source of power.

Chapter V

Chain Reactions

MOST of the nuclear reactions we have considered so far produce relatively large amounts of energy per particle. However, the reactions require a steady stream of incident particles to insure the production of any reasonable number of reactions per unit time. If the reaction itself were able to produce these particles, which might then act upon other nuclei of the target to keep the reaction going, considerable power might be produced. Such self-sustaining processes are called "chain reactions." The burning of a match is an example of a chain reaction: only the end is kindled by chemical reaction in the match head, and the burning wood maintains its own combustion from point to point in the match.

Fission Chain Reaction

As soon as nuclear fission reactions were understood (especially the fact that in addition to the large fragments more than one neutron might be produced in a single fission) it was suggested that a chain reaction could be maintained in this way — that is, by causing the reaction to produce a continuous stream of neutrons. Because of the different things that may happen to a fission neutron, a chain reaction will take place only when enough neutrons actually produce other fissions so that their number does not decrease.

Condition for Fission

Let us assume that a number of neutrons produced by fissions are flying around in a U_3O_8 target (Figure 16). Some neutrons will escape from the target and be lost to the reaction; others will be captured by ${}_{92}U^{238}$ atoms, producing a γ-ray; and some will be absorbed by oxygen atoms or fission products. In the case of slower neutrons, an electron emission will be produced in ${}_{92}U^{238}$. Neither the γ-ray nor the electron emission is useful in maintaining the chain reaction.

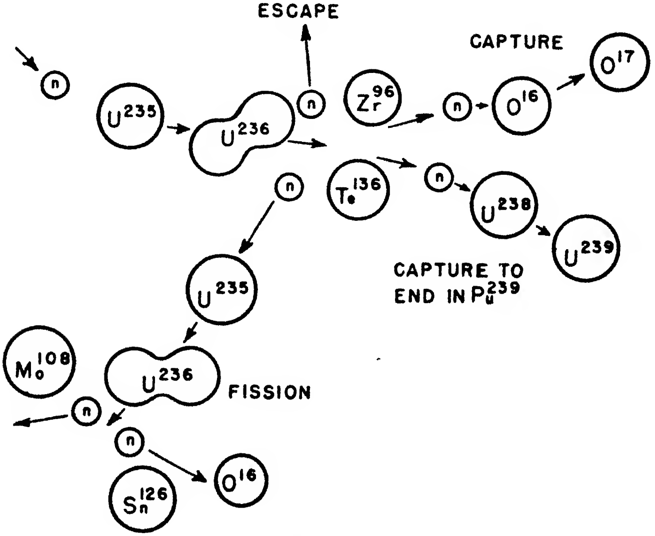

Figure 16.

Only a few of these neutrons will cause more fissions and more fission neutrons. Now, if the number of these additional fissions is actually larger than, or equal to, the original number of neutrons, then a chain reaction will keep on going. We may express this condition by a factor *K*, which is the ratio of the number of fission-producing neutrons arising from one cycle to the number of fission-producing neutrons available at the beginning of the cycle. Whenever this factor *K* is greater than or equal to 1, a chain reaction is possible; otherwise it is impossible.

The whole problem of maintaining a chain reaction with continuous liberation of power involves methods of keeping this constant *K* above the limiting value 1. This means that methods must be devised to decrease the number of neutrons lost by escape and by absorption in other atoms, and to increase the number of fissions by slowing down the fast neutrons.

Critical Size

The escape of neutrons can be decreased by increasing the size of the target. In fact, most calculations are made on the basis of a target of infinite volume, and then reduced to practical dimensions by changing other factors. This means that the effect of escape is first neglected in computing one *K*, and then for a limited volume a slightly higher value of *K* will be required. The minimum volume of the material which will maintain the chain reaction is called the "critical size" of the target; this is a very important factor in the design of the atomic bomb, which involves just this kind of chain reaction.

Absorption

The absorption of neutrons in other atoms is minimized by making the target as pure as possible. Atoms of various elements differ considerably in their ability to absorb neutrons. Some elements, like cadmium and some of the rare earths, are a hundred to a thousand times more effective than others. Only a small fraction, a few parts per million, of these high absorption elements may reduce the factor *K* well below the effective value. And no matter how pure the target is originally, after fission takes place the fragments introduce impurities which may have high absorption properties. This "poisoning" of the target is a limitation which tends to stop the chain reaction after it once is started.

Moderator

When a stream of neutrons strikes a uranium target, the fast neutrons cause a small number of fissions in ${}_{92}U^{238}$, but slower neutrons cause the more frequent fissions of ${}_{92}U^{235}$. Since the neutrons given off during fission of ${}_{92}U^{235}$ are fast neutrons, they must be slowed down before they can be expected to produce other fissions in ${}_{92}U^{235}$ nuclei. In order to cut down the speed of these fast neutrons, a "moderator" is used. A moderator consists of atoms whose masses are so small, nearly like those of the neutrons, that in a collision with one of them, a neutron will give up a considerable part of its momentum. Roughly speaking, the fraction of momentum given up on the average per collision is inversely proportional to the mass of the moderator atom. The best moderator, from the mass point of view, is hydrogen, since the proton mass 1.0076 is almost equal to that of the neutron, 1.0089. Hydrogen nuclei, however, stop many neutrons completely. Other more suitable moderators are deuterium, beryllium, and carbon. A choice among these for a given experiment depends on the amount needed and on the physical and chemical properties of the moderators.

Heavy water made from deuterium instead of hydrogen, and oxygen, is a convenient moderator. Since, in slowing down neutrons, deuterium is about three times as effective as carbon, much smaller amounts of deuterium are needed to produce the same results. However, deuterium is relatively rare, and only a limited amount of heavy water is available.

Beryllium is a relatively scarce material, but may be used in small-scale experiments.

Carbon is used as a moderator in the chain reaction involved in producing plutonium. Carbon is available in great quantity, and can be made as pure as necessary. It can also be used as a building material and as a support for containers of uranium, various instruments, and cooling tubes.

Slow-Neutron Fission

The answer to why some nuclei favor slow neutrons and others require fast neutrons depends on the quantum theory of interaction between nuclear particles. The answer does not depend on penetration energy entirely, for, if this were the case, fast neutrons would always produce more fissions than slow ones. The reason why some nuclei favor slow neutrons and others require fast neutrons must be explained in terms of "phase" and "wave-length" effects like those of radio reception. The incident neutron has to be tuned, in a quantum mechanical sense, to a particular wave length which is characteristic of the fission process in the nucleus. This is an analogy, rather than a strict explanation of the process.

Plutonium-Producing Pile

To follow all these various factors in the production of a chain reaction, let us consider as an example the process used to manufacture plutonium. A structure, called a pile, made of purified carbon has correctly spaced cylindrical holes passing through it (Figure 17). Slugs of purified uranium are pushed into these holes. Rods of boron steel are inserted into other holes to act as controls. Water is allowed to flow through the pile to control the temperature. When the boron rods are in place, their high absorption effect decreases the value of K in the pile to less than 1, and so any reactions will die out from lack of neutrons. When the

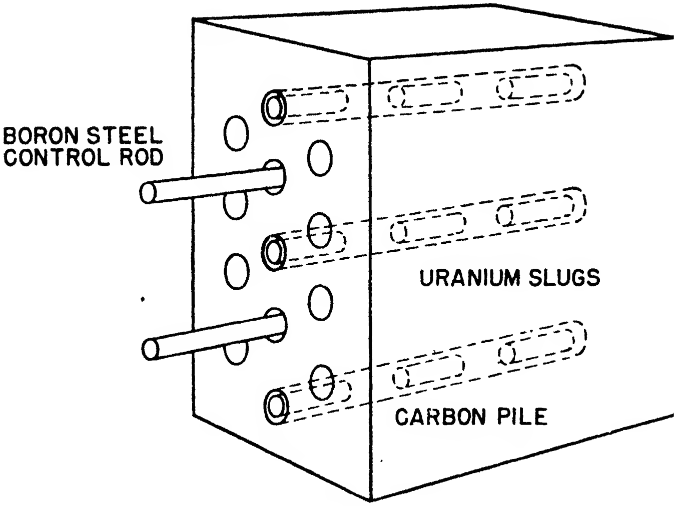

Figure 17.

rods are pulled out to a certain point, the absorption effect is decreased, and K may be made greater than 1. Then any fissions produced by stray radioactive products or by cosmic rays will produce fast neutrons which may strike $_{92}U^{238}$ atoms to produce fission and a few more neutrons (Figure 18).

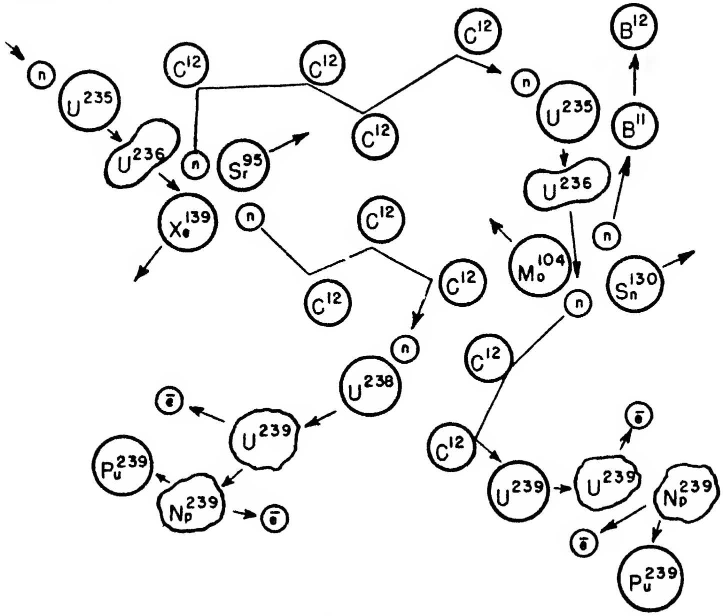

Figure 18.

This fission of $_{92}U^{238}$ tends to increase the over-all value of K, but the probability is low that it will happen with any one neutron. During the reaction, other neutrons will be slowed down, by passing through layers of carbon, to energies of a few electron-volts and will be absorbed by $_{92}U^{238}$;* and the resulting $_{92}U^{239}$ nucleus will decay to form $_{93}Np^{239}$ and then $_{94}Pu^{239}$. The boron rods absorb other neutrons. The absorption of some neutrons by other impurities and fission products gives various reactions, and this loss becomes

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* Energies of a few electron-volts are most favorable for absorption by $_{92}U^{238}$.

more important as time goes on. Still other neutrons are slowed down by the carbon to thermal energies of about .03 ev and cause fission in $_{92}U^{235}$, with the resultant production of more fast neutrons.

Power Production

Energy production can be controlled by varying the position of the boron rods and the over-all design of the pile. The heat produced in various reactions may be absorbed by the water, since an increase in temperature decreases *K* by increasing the thermal energy of the neutrons. This temperature is of the order of 400–600° Fahrenheit, so that the pile is not a very good source of power. This pile, however, is designed mainly to produce as much $_{94}Pu^{239}$ as possible; piles of other designs have been made to work at higher temperatures.

Finally, the slugs of uranium in the pile can then be pushed out of the holes and carried to a chemical separation plant, in which the uranium and other elements are removed and the small amount of $_{94}Pu^{239}$ is collected. The uranium is recovered and returned to the pile. The radioactive fission products are usually allowed to pass off in solution or as gases, and proper precautions must be taken to avoid effects damaging to life.

Atomic Bomb

Another example of a chain reaction of a different kind is that used in the atomic bomb. Here the geometric design of the constituents made the factor *K* so large that even the reduced number of fissions due to fast neutrons was sufficient to cause a chain reaction. By using nearly pure $_{92}U^{235}$ or $_{94}Pu^{239}$ in an amount above the critical size, and by covering it with a substance which decreased the number of escape neutrons by acting as a sort of reflecting container, the chain reaction was made to take place at such a rapid rate that an extremely large amount of energy was liberated almost instantaneously (Figure 19). If an amount of, say, 5 kg was present, and 500 g of it underwent fission before the bomb had time to spread far apart, say, in a few millionths of a second, the power released would be 13 million kw. All this power is developed at very high temperatures, with a sudden increase in pressure, and a sharp shock wave, so that the reaction is not a useful source of power for peaceful purposes. Since this type of chain reaction cannot be maintained without the presence of a critical amount of the element, the chain reaction is controlled by keeping several pieces of smaller size separated, and then suddenly shooting them together to explode the bomb. In this way the reaction takes place before the bomb can explode and leave too much undissociated material behind. The design of this control mechanism is, perhaps, the key to the safe handling and effective functioning of the bomb.

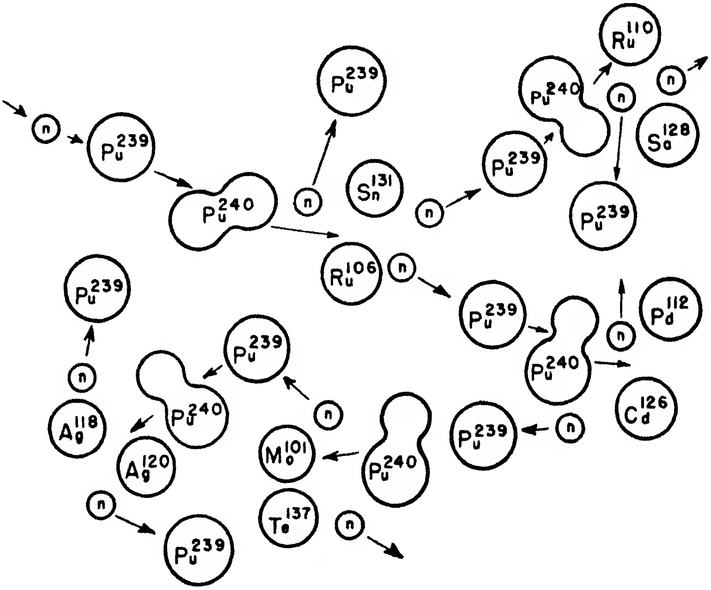

Figure 19.

Power Source from Fission

A practical source of atomic power must produce a continuous supply of energy at a rate which can be absorbed by heating a gas or liquid to a high, but not too high, temperature. Such a source probably will be made up of a high concentration of pure ${}_{92}U^{235}$, or perhaps of ${}_{94}Pu^{239}$, with a suitable moderator. There must be provision for absorbing, or making harmless, the radioactive fission products, and sufficient shielding to absorb all escaping neutrons. This source of power may be no larger than an ordinary home heating unit provided that the shielding is not taken into account, but will be capable of producing many kilowatts of power. As to comparative cost of this and other power sources, no estimate can be made until commercial sources of pure uranium isotopes are established. At present, the engineering problems involved in such a device are numerous, but the physical model has been established in the plutonium-producing pile.

Part III

Summary of the Development of Atomic Energy Leading to the Atomic Bomb

Abstracted by Dr. A. H. Fox from the Report Written
by Professor H. D. Smyth at the Request of Major
General L. R. Groves, United States Army

Figure 1 Major General Leslie R Groves, Left, Officer in Charge of the Government's Atomic Bomb Project at Oak Ridge, Near Knoxville, Tennessee, Checking Data in His Office with Brigadier General Thomas F. Farrell, His Assistant.

Chapter I

History of the Development

MAJOR GENERAL L. R. Groves stated in the Foreword to Professor Smyth's account of the Atomic Bomb Project, "There is no reason why the administrative history of the Atomic Bomb Project and the basic scientific knowledge on which the several developments were based should not be available now to the general public.

Figure 2. Two U. S. Army Officers Who Played Important Roles in the Development and Manufacture of the Atomic Bomb. At Left, Colonel Franklin T. Matthias, Commanding Officer of the Hanford Engineering Works, Near Pasco, Washington; and at Right, Colonel Kenneth D. Nichols, District Engineer of the Manhattan Project at Oak Ridge, Tennessee.

"The success of the development is due to the many thousands of scientists, engineers, workmen, and administrators — both civilian and military — whose prolonged labor, silent perseverance, and whole-hearted cooperation have made possible the unprecedented technical accomplishments."

General State of Nuclear Physics in 1940

By 1940 nuclear reactions had been intensively studied for over ten years. Several books and review articles on the subject had been published. New techniques had been developed for producing and controlling nuclear projectiles, for studying artificial radioactivity, and for separating submicroscopic quantities of chemical elements produced by nuclear reactions. Isotope masses had been measured accurately. Neutron capture cross sections had been measured. Methods of slowing down neutrons had been developed. Physiological effects of neutrons had been observed: They had even been tried in the treatment of cancer. All such information was generally available, but was incomplete because of many gaps and inaccuracies. Techniques of nuclear reactions were difficult, and the quantities of materials available were often sub-microscopic. Although the fundamental principles of the reactions were clear, the theory contained unverified assumptions, and calculations were hard to make. Predictions made in 1940 by different physicists of equally high ability were often at variance. The subject was, in all too many respects, an art rather than a science.

In retrospect, we see that all prerequisites to a serious attack on the problem of producing atomic bombs and controlling atomic power were at hand in the year 1940. The equivalence of mass and energy had been demonstrated. It had been proved that the neutrons initiating fission of uranium reproduced themselves in the process, and therefore that a multiplying chain reaction might occur with explosive force. To be sure, no one knew whether the required conditions could be achieved, but many scientists had clear ideas about the problems involved and the directions in which solutions might be sought.

Statement of the Problem

From the first discovery of the large amounts of energy released in nuclear reactions to the discovery of uranium fission, the idea of atomic power or even atomic bombs was discussed periodically in scientific circles. With the discovery of atomic fission, this talk appeared much less speculative than before, but the possibility of producing atomic power still seemed in the distant future, and there was a belief among many scientists that the possibility might not, in fact, ever be realized. During 1939 and 1940, many public statements, some by responsible scientists, called attention to the enormous energy available in uranium for explosives and for controlled power, so that "U–235" became a familiar by-word, indicating great things to come. The possible military importance of uranium fission was called to the attention of the government, and in a conference with representatives of the Navy Department in March 1939, Fermi suggested the possibility of achieving a controllable reaction using slow neutrons or a reaction of an explosive character using fast neutrons. He pointed out, however, that the data then available might be insufficient for accurate predictions.

By the summer of 1940, it was possible to formulate the problem of controllable nuclear reactions fairly clearly, although scientists were yet unable to answer the various questions involved or even to decide whether a chain reaction ever could be obtained. In this chapter, we shall state the problem in its entirety. For purposes of clarification, we may cite facts and conclusions out of chronological order, but these facts and conclusions will be in context with the ideas being discussed.

It had been established (1) that uranium fission did occur with release of great amounts of energy and (2) that in the process of fission, extra neutrons which might start a chain reaction were set free. That such a reaction should take place and that it should have very important military application as a bomb was not contrary to any known principle. However, the idea was revolutionary and therefore suspect; certain it was that many technical operations of great difficulty would have to be worked out before such a bomb could be produced. Probably the only materials satisfactory for a bomb were either U–235, which would have to be separated from the 140-times more abundant isotope U–238, or Pu–239, an isotope of the hitherto unknown element plutonium, which would have to be generated by a controlled chain-reacting process itself hitherto unknown. To achieve such a controlled chain reaction, uranium metal and heavy water or beryllium or carbon might have to be produced in great quantity with high purity. Once bomb material had been produced, a process would have to be developed for using the material safely and effectively.

By the summer of 1940, the National Defense Research Committee had been formed and was asking many scientists to work on urgent military problems. Scientific personnel was limited (although this was not fully realized at the time). Consequently, to decide at what rate work should be carried forward on an atomic bomb was difficult. The decision had to be reviewed by the Research Committee at frequent intervals during the subsequent four years.

Interest in Military Possibilities

The announcement of the hypothesis of fission and its experimental confirmation took place in January of 1939. Immediate interest was aroused in the possible military use of the large amounts of energy released in fission. At that time, American-born nuclear physicists were so unaccustomed to using their science for military purposes that they hardly realized what needed to be done. Consequently, early efforts both at restricting publication and at getting government support were stimulated largely by a small group of foreign-born physicists centering on L. Szilard and including E. Wigner, E. Teller, V. F. Weisskopf, and Enrico Fermi.

Figure 3. Professor Enrico Fermi, Who Won the 1938 Nobel Prize for His Radioactive Substances.

The National Academy Reviewing Committee Report

In the spring of 1941 F. B. Jewett, president of the National Academy of Sciences, appointed the National Academy Reviewing Committee to evaluate the military importance of the uranium problem. This committee consisted of A. H. Compton, chairman, W. D. Coolidge, E. O. Lawrence, J. C. Slater, and J. H. Van Vleck.

The committee's first report, in May 1941, mentioned (a) radioactive poisons, (b) atomic power, and (c) atomic bombs, but the emphasis was on power. The second report stressed the importance of the new results obtained from experimentation on plutonium, but was not specific about the military uses to which the fission process might be put. Both these reports urged that the project be pushed more vigorously.

The third report (November 6, 1941) was specifically concerned with the "possibilities of an explosive fission reaction with U–235." Although neither of the first two National Academy reports indicated that uranium would be likely to be of decisive importance in World War II, this possibility was emphasized in the third report. We can do no better than quote portions of this report.

> Since our last report, the progress toward separation of the isotopes of uranium has been such as to make urgent a consideration of (1) the probability of success in the attempt to produce a fission bomb, (2) the destructive effect to be expected from such a bomb, (3) the anticipated time before its development can be completed and production be underway, and (4) a preliminary estimate of the costs involved.
>
> ### 1. Condition for a Fission Bomb
>
> *A fission bomb of superlatively destructive power will result from bringing quickly together a sufficient mass of element U–235.* This seems to be as sure as any untried prediction based upon theory and experiment can be.
>
> Our calculations indicate further that the required masses can be brought together quickly enough for the reaction to become efficient. . . .

2. Destructive Effect of Fission Bombs

a. Mass of the Bomb

The mass of U–235 required to produce explosive fission under appropriate conditions can hardly be less than 2 kg (4.4 lb) nor greater than 100 kg (220 lb). These wide limits reflect chiefly the experimental uncertainty in the capture cross section of U–235 for fast neutrons. . . .

b. Energy Released by Explosive Fission

Calculations for the case of masses properly located at the initial instant indicate that between 1 and 5 per cent of the fission energy of the uranium should be released at a fission explosion. This means from 2 to 10 × 10^8 kilocalories per kilogram of uranium 235. *The available explosive energy per kilogram of uranium is thus equivalent to several hundred tons of TNT.*

3. Time Required for Development and Production of the Necessary U–235

a. Amount of Uranium Needed

Since the destructiveness of present bombs is already an important factor in warfare, it is evident that, if the destructiveness of the bombs is thus increased 10,000-fold, they should become of decisive importance.

The amount of uranium required will, nevertheless, be large. If the estimate is correct that 500,000 tons of TNT bombs would be required to devastate Germany's military and industrial objectives, *from 1 to 10 tons of U–235 will be required to do the same job.*

b. Separation of U–235

The separation of the isotopes of uranium can be done in the necessary amounts. Several methods are under development, at least two of which seem definitely adequate, and are approaching the stage of practical test. These are the methods of the centrifuge and of diffusion through porous barriers. Other methods are being investigated, or need study, which may ultimately prove superior, but which are now farther from the engineering stage.

c. Time Required for Production of Fission Bombs

An estimate of time required for development, engineering, and production of fission bombs can be made only very roughly at this time.

If all possible effort is spent on the program, one might, however, expect fission bombs to be available in significant quantity within three or four years.

4. Rough Estimate of Costs

(The figures given in the Academy report under this heading were recognized as only rough estimates, since the scientific and engineering data for greater precision were not available. The figures showed only that the undertaking would be enormously expensive, but in line with other war expenditures.)

The report then goes on to consider what requirements were needed immediately and what reorganization in the undertaking was desirable.

Summary of Progress up to December 1941

We wish to review the next eighteen months' progress. Tangible progress was not great. No chain reaction had been achieved; no appreciable amount of U-235 had been separated from U-238; only minute amounts of Pu-239 had been produced; and production of large quantities of uranium metal, heavy water, beryllium, and pure graphite was still largely in the discussion stage. But there had been progress. Mathematical constants were better known; calculations had been checked and extended; and guesses about the existence and nuclear properties of Pu-239 had been verified. Some study had been made of engineering problems, process effectiveness, costs, and time schedules. Most important of all, the critical size of the bomb had been shown to be almost certainly within practical limits. Altogether the likelihood that the problems might be solved seemed greater in every case than it had in 1940. Perhaps more important than the actual change was the psychological change. Possibly Wigner, Szilard, and Fermi were no more thoroughly convinced that atomic bombs were possible than they had been in 1940, but many other people had become familiar with the idea and its possible consequences.

Apparently, the British and the Germans, both grimly at war, thought the problem worth undertaking. Furthermore, the whole national psychology of the American people had changed. Although the attack on Pearl Harbor was yet to come, the impending threat of war was much more keenly felt than before, and expenditures of effort and money that would have seemed enormous in 1940 were considered obviously necessary precautions in December 1941. Thus, it was not surprising that Dr. Vannevar Bush, Director of the Office of Scientific Research and Development, and his many associates felt it was time to push the uranium project vigorously. For this purpose, there was created an entirely new administrative organization.

Summary of Administrative History, 1942–1945

By the end of 1941, as a result of an extensive review of the whole uranium situation, Bush and his advisers decided to increase the effort on, and change the organization of, the uranium project — a decision which was approved by President Roosevelt. From January 1942 until early summer of 1942, the uranium work was directed by Bush and Conant, who worked with the Program Chiefs and a Planning Board. In the summer of 1942 the Army, through its Corps of Engineers, was assigned an active part in the procurement and engineering phases, and organized the Manhattan District for the purpose. In September 1942, Dr. Bush, Dr. Conant, General Styer, and Admiral Purnell were appointed as a Military Policy Committee to determine the general policies of the whole project. Also in September, General Groves was appointed to take charge of all Army activities on the project. The period of joint OSRD * and Army control continued through April 1943, with the Army playing an increasingly important role as the industrial effort got fully under way. In May 1943 the research contracts were transferred to the Corps of Engineers; the period of joint OSRD-Army control ended, and the period of complete Army control began.

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* Office of Scientific Research and Development.

Since the earliest days of the project, President Roosevelt had followed it with interest and continued, until his death, to study and approve the broad programs of the Military Policy Committee. President Truman, who as a United States Senator had been aware of the magnitude of the project, was given, immediately after his inauguration, the complete up-to-date picture by the Secretary of War and General Groves at a White House conference. Thereafter the President gave the program his complete support and kept in constant touch with progress made.

Summary of the Metallurgical Project at Chicago in 1942

The procurement problem, which had been delaying progress, was essentially solved by the end of 1942. A small self-sustaining graphite-uranium pile was constructed in November 1942, and was put into operation for the first time on December 2, 1942, originally at a power level of ½ w, and later at a level of 200 w. The graphite-uranium pile was easily controllable owing to the phenomenon of delayed neutron emission. A total of 500 micrograms of plutonium, made with the cyclotron, was separated by chemical means from the uranium and fission products. Enough was learned of the chemistry of plutonium to indicate the possibility of separating plutonium on a relatively large scale. No great advance was made in the theory of the atomic bomb, but calculations were checked and experiments with fast neutrons were extended. If anything, the prospects for producing atomic bombs looked more favorable than they did a year earlier.

Enough experimenting and planning were done to delineate the problems involved in constructing and operating a large-scale production plant. The type of plant receiving first choice was one having a pile of metallic uranium and graphite, cooled either by helium or by water. A complete and detailed program, including time and cost estimates, was drawn up for the construction of pilot and production plants.

Summary of the Plutonium-Production Problem as of February 1943

By the first of January 1943, the Metallurgical Laboratory had achieved its first objective: the production of a chain-reacting pile, and was well on the way to its second objective: a process for extracting the plutonium produced in such a pile. Clearly it was time to formulate more definite plans for building a production plant. The policy decisions were made by the Policy Committee on the recommendations from the Laboratory Director (A. H. Compton), from the S–1 Executive Committee of the Office of Scientific Research and Development, and from the National Academy Reviewing Committee, which had visited Chicago in December 1942. The only decisions already made had been that the first chain-reacting pile be dismantled and then reconstructed a short distance from Chicago, and that a 1000-kw plutonium plant be built at Clinton, Tennessee.

Now, a large figure was set as the goal of plutonium production, a figure which, for reasons of security, may not be disclosed to the public.

The production of one gram of plutonium per day corresponds to a generation of energy at the rate of 500 to 1500 kw. Therefore a plant for large-scale production of plutonium will release a very large amount of energy. Hence, the problem was to design a plant of this capacity on the basis of experience with a pile that could operate at a power level of only .2 kw. As regards the plutonium separation work, which was equally important, it was necessary to draw plans for an extraction and purification plant which would separate a certain number of grams a day of plutonium from a certain number of tons of uranium, and such planning had to be based on information obtained by microchemical studies involving only half a milligram of plutonium. To be sure, information for designing the large-scale pile and separation plant was available from auxiliary experiments and from large-scale studies of separation processes of uranium instead of plutonium, but even so, the proposed extrapolations, both as to chain-reacting piles and as to separation processes, were staggering. In peacetime no engineer or scientist in his right mind would consider making such a leap from small- to large-scale production in a single step, and even in wartime only the imperative need for achieving tremendously important results could justify it.

By January 1943, the decision had been made to build a large-capacity plutonium-production plant. This meant producing a pile developing thousands of kilowatts and constructing a chemical-separation plant to extract the product. The du Pont Company was to design, construct, and operate the plant; the Metallurgical Laboratory was to do the necessary research. A site was chosen on the Columbia River at Hanford, Washington. A tentative decision to build a helium-cooled plant was reversed in favor of water-cooling. The principal problems were those involving lattice design (the arrangement of uranium and its moderator), loading and unloading, choice of materials particularly with reference to corrosion and radiation, water supply, controls and instrumentation, health hazards, chemical-separation process, and design of the separation plant. Plans were made to conduct the necessary fundamental and technical research and for the training of operators. Arrangements were made for liaison between du Pont and the Metallurgical Laboratory.

Summary of the Plutonium Problem January 1943 to June 1945

Two types of neutron absorption are fundamental to the operation of the plant: one, neutron absorption in U–235, resulting in fission, maintains the chain reaction as a source of neutrons; the other, neutron absorption in U–238, leads to the formation of plutonium, the desired product.

The course of a nuclear chain reaction in a graphite-moderated heterogeneous pile can be described by following a single generation of neutrons. The original fast neutrons are slightly increased in number by fast fission, reduced by resonance absorption in U–238, further reduced by absorption at thermal energies in graphite and other materials, and by escape; the remaining neutrons, which have been slowed in the graphite, cause fission in U–235, producing a new generation of fast neutrons similar to the previous generation.

The product, plutonium, must be separated by chemical processes from a comparable quantity of fission products and a much larger quantity of uranium. Of several possible separation processes, the one chosen consists of a series of reactions including precipitating with carriers, dissolving, oxidizing, and reducing.

The chain reaction was studied at low power at the Argonne Laboratory beginning early in 1943. Both chain-reaction and chemical-separation processes were investigated at the Clinton Laboratories beginning in November 1943, and an appreciable amount of plutonium was produced there.

Construction of the main production plant at Hanford, Washington, was begun in 1943, and the first large pile went into operation in September 1944. The entire plant was in operation by the summer of 1945, with all chain-reacting piles and chemical-separation plants performing better than had been anticipated.

Extensive studies were made on the use of heavy water as a moderator, and an experimental pile containing heavy water was built at the Argonne Laboratory. Plans for a production plant using heavy water were given up.

The Health Division was active along three main lines: (1) medical examination of personnel, (2) advice on radiation hazards and constant check on working conditions, and (3) research on the effects of radiation.

Summary of the General Discussion of the Separation of Isotopes

The possibility of producing an atomic bomb of U–235 was recognized before plutonium was discovered. Because the separation of the uranium isotopes would be a direct and major step toward making such a bomb, methods of separating uranium isotopes have been under scrutiny for at least six years. Nor was attention confined to uranium: the separation of deuterium was also of great importance.

The principal methods of isotope separation were known in principle and had been reduced to practice before the separation of uranium isotopes became of paramount importance. The methods had been applied neither to uranium, except for the separation of a few micrograms, nor to any substance on a scale comparable to that now required. But the fundamental questions were costs, efficiency, and time, not of principle; in other words, the problem was fundamentally technical, not scientific. The plutonium-production problem did not reach a similar stage until after the first self-sustaining chain-reacting pile had operated and the first microgram amounts of plutonium had been separated. Even after this stage, many experiments done on the plutonium project were of vital interest for the military use either of U-235 or plutonium, and for the future development of nuclear power. As a consequence, the plutonium project has continued to have a more general interest than the isotope separation projects. Many special problems arose in the separation projects which were extremely interesting and which required a high order of scientific ability for their solution, but which must still be kept secret. It is for such reasons that the present non-technical report has given first emphasis to the plutonium project and will give less space to the separation projects. This is not to say that the separation problem was any easier to solve or that its solution was any less important.

Except in electromagnetic separators, isotope separation depends on small differences in the average behavior of molecules. Such effects are used in six "statistical" separation methods: (1) gaseous diffusion, (2) distillation, (3) centrifugation, (4) thermal diffusion, (5) exchange reactions, and (6) electrolysis. Probably only methods (1), (3), and (4) are suitable for uranium. Methods (2), (5), and (6) are preferred for the separation of deuterium from hydrogen. In all these "statistical" methods, the separation factor is small so that many stages are required, but in the case of each method, large amounts of material may be handled. All these methods had been tried with some success before 1940; however, none had been used on a large scale and none had been used for uranium. The scale of production by electromagnetic methods was even smaller, but the separation factor was larger. The electromagnetic method had apparent limitations of scale. There were presumed to be advantages in combining two or more methods because of the differences in performance at different stages of separation. The problem of developing any or all of these separation methods was not one of scientific principle, but a technical one of scale and cost. Developments in separation methods can therefore be reported more briefly than those of the plutonium project, although they are no less important. A pilot plant using centrifuges was built and operated successfully. No large-scale plant was built. Plants were built for the production of heavy water by two different methods.

Summary of the Separation of the Uranium Isotopes by Gaseous Diffusion

Work at Columbia University on the separation of isotopes by gaseous diffusion began in 1940, and by the end of 1942, the problems of large-scale separation of uranium by this method had been well defined. Since the amount of separation that could be effected by a single stage was very small, several thousand successive stages were required. It was found that the best method of connecting the many stages required extensive recycling, so that thousands of times as much material would pass through the barriers of the lower stages as would ultimately appear as product from the highest stage.

The principal problems were the development of satisfactory barriers and pumps. Acres of barrier and thousands of pumps were required. The obvious process-gas was uranium hexafluoride, for which the production and handling difficulties were so great that a search for an alternative was undertaken. Since much of the separation was to be carried out at low pressure, problems of vacuum technique arose on a previously unheard-of scale. Many problems of instrumentation and control were solved; extensive use was made of various forms of mass spectrograph.

The research was carried out principally at Columbia under Dunning and Urey. In 1942, the M. W. Kellogg Company,* which was chosen to design the plant, set up the Kellex Corporation for the purpose. The plant was built by the J. A. Jones Construction Company. The Carbide and Carbon Chemicals Corporation was selected as operating company.

A satisfactory barrier was developed, although the final choice of barrier type was not made until the construction of the plant was well under way at Clinton Engineer Works in Tennessee. Two types of centrifugal blower were developed to the point where they could take care of the pumping requirements. The plant was put into successful operation before the summer of 1945.

Summary of Electromagnetic Separation of Uranium Isotopes

The possibility of large-scale separation of the uranium isotopes by electromagnetic means was suggested in the fall of 1941 by E. O. Lawrence of the University of California and H. D. Smyth of Princeton University.

By the end of December 1941, when the reorganization of the whole uranium project was effected, Lawrence had already obtained some samples of separated isotopes of uranium, and in the reorganization he was placed in charge of the preparation of further samples and of making various associated physical measurements. However, just as the Metallurgical Laboratory very soon shifted its objective from the physics of the chain reaction to the large-scale pro-

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* See Part V for report.

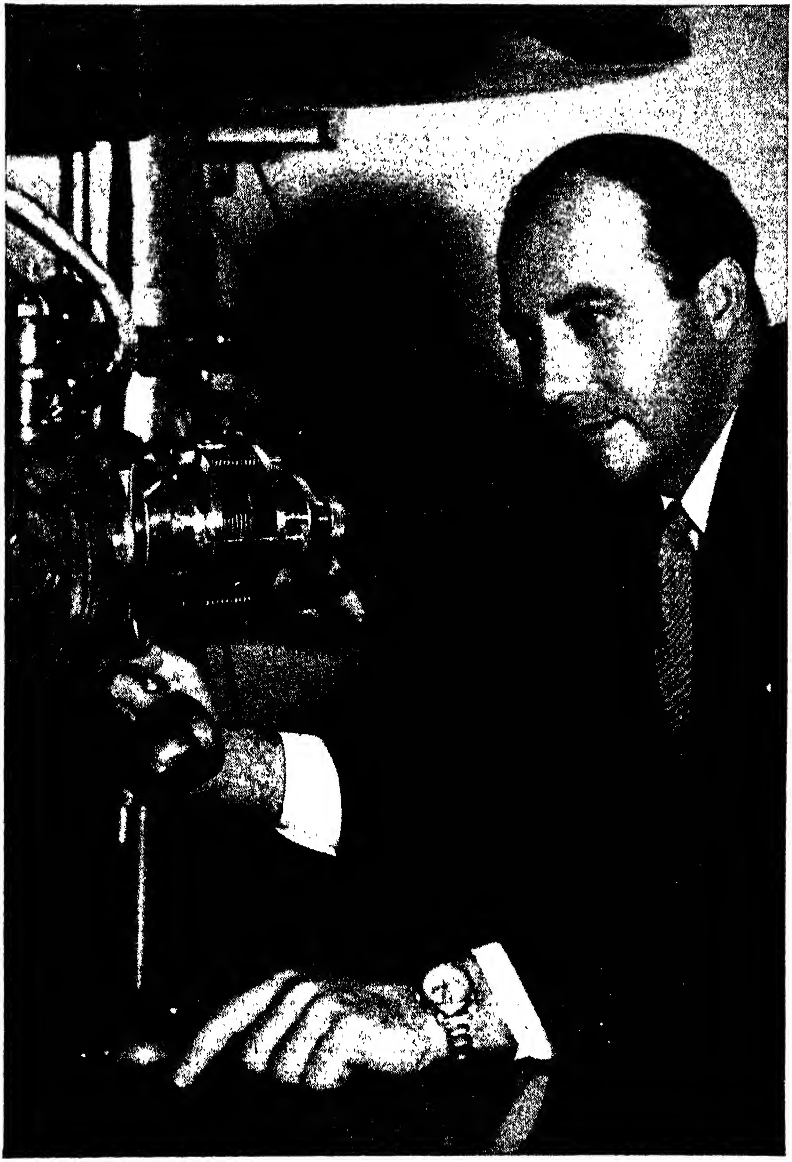


Figure 4. Professor John R. Dunning with Cyclotron of Columbia University.

duction of plutonium, the objective of Lawrence's division immediately shifted to the effecting of large-scale separation of uranium isotopes by electromagnetic methods. This change was prompted by the success of the initial experiments at California, and by the development, at California and at Princeton, of ideas on other possible methods. Of the many electromagnetic schemes suggested, three soon were recognized as being the most promising: the "calutron" mass separator, the magnetron-type separator later developed into the "ionic centrifuge," and the "isotron" method of "bunching" a beam of ions. The first two of these approaches were followed at California, and the third was followed at Princeton. After the first few months, by far the greatest effort was put on the calutron, but some work on the ionic centrifuge was continued at California during the summer of 1942 and was further continued by J. Slepian (at the Westinghouse laboratories in Pittsburgh) on a small scale through the winter of 1944–1945. Work on the isotron was continued at Princeton until February 1943, when most of the group was transferred to other work.

A. O. Nier's electromagnetic mass spectrograph was set up primarily to measure relative abundances of isotopes, not to separate large samples. Using vapor from uranium bromide, Nier had prepared several small samples of separated isotopes of uranium, but his rate of production was very low, indeed, since his ion current amounted to less than one microampere. (A mass spectrograph, in which one microampere of normal uranium ions passes through the separating fields to the collectors, will collect about one microgram of U–235 per 16-hr day.) The great need of samples of enriched U–235 to carry on nuclear study was recognized early by Lawrence, who decided to see what could be done with the help of the 37-in. (cyclotron) magnet at Berkeley. The initial stages of this work were assisted by a grant, later repaid, from the Research Corporation of New York. Beginning January 1, 1942, the entire support came from the OSRD through the S–1 Committee. Later, as in other departments of the uranium project, the contracts were taken over by the Manhattan District.

At Berkeley, after some weeks of planning, the 37-in. cyclotron was dismantled on November 24, 1941, and its magnet used to produce the magnetic field required in what came to be called a "calutron" (a name representing a contraction of "California University cyclotron"). An ion source consisting of an electron beam traversing the vapor of a uranium salt was set up (Figure 5). The movement of ions was then accelerated through a slit into the separating region, where the magnetic field bent their paths into semicircles terminating at the collector slit. By December 1, 1941, molecular ion beams from the residual gas were obtained, and shortly thereafter the beam consisting of singly charged uranium ions (U+) was brought up to an appreciable strength. It was found that a considerable proportion of the ions leaving the source were U+ ions. For the purpose of testing the collection of separated samples, a collector with two pockets was installed, the two pockets being separated by a distance appropriate to the mass numbers 235 and 238. Two small collection runs, using U+ beams of low strength, were made in December, but subsequent analyses of the samples showed only a small separation factor. (Note that even in this initial experiment the separation factor was much larger than in the best gaseous diffusion method.) By the middle of January 1942, a run had been made with a reasonable beam strength, and an aggregate flow, or through-put, of appreciable amount which showed a

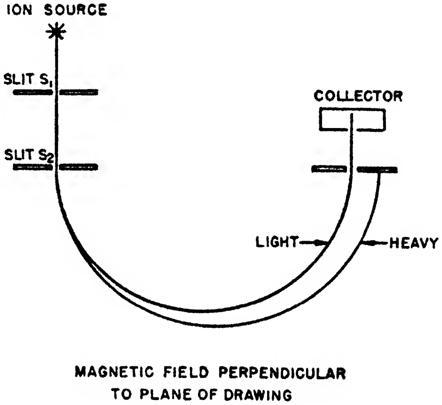


Figure 5. Electromagnetic Separation of Isotopes.

much improved separation factor was obtained. By early February 1942, beams of much greater strength were obtained, and Lawrence reported that good separation factors were obtainable with such beams. By early March 1942, the ion current had been raised still further. These results tended to bear out Lawrence's hopes that space charge could be neutralized by ionization of the residual gas in the magnet chamber.

Initially a large number of different methods were considered and many exploratory experiments performed. The main effort, however, soon became directed toward the development of the calutron, the objective being a high separation factor and a large current in the positive ion beam. *By this time it was clear that the calutron was potentially able to effect separation on a much larger scale than had ever before been approached.*

Turning to the problem of effecting more complete utilization of the ions, we must consider in some detail the principle of operation of the calutron. The calutron depends on the fact that singly charged ions, moving in a uniform magnetic field perpendicular to their direction of motion, are bent into circular paths of radius proportional to their momenta. Considering now just a single isotope, it is apparent that the ions passing through the two slits (and thus passing into the large evacuated region in which the magnetic field is present) do not initially follow a single direction, but have many initial directions lying within a small angle, whose size depends on the width of the slits. However, since all the ions of the isotope in question follow curved paths of the *same* diameter, ions starting out in slightly different directions tend to meet again — or almost meet again — after completing a semicircle. At this position of re-convergence the collector is placed. The ions of another isotope (for example, ions of mass 238 instead of 235) behave similarly, except that they follow circles of slightly different diameter. Samples of the two isotopes are caught in collectors at the two different positions of re-convergence. Now the utilization of a greater fraction of the ions originally produced may be accomplished by widening the two slits referred to. But to widen the slits to any great extent without sacrificing sharpness of focus at the re-convergence positions is not easy. Correct widening of slits can be accomplished only by use of carefully proportioned space-variations in the magnetic field strength. Such variations were worked out successfully.

Although the scale of separation of uranium isotopes reached by March 1942 was much greater than anything that had previously been done with an electromagnetic mass separator, it was still very far from that required to produce amounts of material that would be of military significance. The problems that have been outlined not only had to be solved, but they had to be solved on a grand scale. The 37-in. cyclotron magnet that had been used was still capable of providing useful information, but larger equipment was desirable. Fortunately a very much larger magnet, intended for a giant cyclotron, had been under construction at Berkeley. This magnet, with a pole diameter of 184 in. and a pole gap of 72 in., was to be the largest in existence. Work on it had been interrupted because of the war, but it was already sufficiently advanced so that it could be finished within a few months if adequate priorities were granted. Aside from the magnet itself, the associated building, laboratories, shops, and so on were almost ideal for the development of the calutron. Work was resumed on the giant magnet, and by the end of May 1942, it was ready for use.

Besides the gradual increase in ion beam strength and separation factor that resulted from a series of developments in the ion source and in the accelerating system, the hoped-for improvement in utilization of ions was achieved during the summer of 1942 with the use of the giant magnet. Further, it was possible to maintain more than one ion beam in the same magnetic separating region. Experiments on this latter problem did run into some difficulties, however, and it appeared that there might be limitations on the number of sources and receivers that could be put in a single unit, as well as on the current that could be used in each beam without spoiling the separation.

Construction of the first series of electromagnetic units at Clinton began in March of 1943, and this part of the plant was ready for operation in November 1943. The group at Berkeley continued to improve the ion sources, the receivers, and the auxiliary equipment, aiming always at greater ion currents. Berkeley reports describe no less than seventy-one different types of source and one hundred and fifteen different types of receiver, all of which reached the design stage and most of which were constructed and tested. As soon as the value of a given design change was proved, every effort was made to incorporate it in the designs of new units.

Although research work on the calutron was started later than on the centrifuge and diffusion systems, the calutron plant was the first to produce large amounts of the separated isotopes of uranium.

Summary of the Work on the Atomic Bomb

In the spring of 1943, a new laboratory was established at Los Alamos, New Mexico, under J. R. Oppenheimer, to investigate the design and to construct the atomic bomb. The work was to begin with the first stage, the receipt of U–235 or plutonium, and was to proceed to the stage of actual use of the bomb. The new laboratory improved the theoretical treatment of design and performance problems of the atomic bomb, refined and extended the measurements of the nuclear constants involved, developed methods of purifying the materials to be used, and, finally, designed and constructed operable atomic bombs.

Over-All Status as of June 1945

As the result of the labors of the Manhattan District organization in Washington and in Tennessee; of the scientific groups at Berkeley, Chicago, Columbia, Los Alamos, and elsewhere; of the industrial groups at Clinton, Hanford, and many other places, the end of June 1945 found us expecting from day to day to hear of the explosion of the first atomic bomb ever devised by man. All the problems were believed to have been solved, at least well enough to make the bomb practicable. A sustained neutron chain reaction resulting from nuclear fission had been demonstrated; the conditions necessary to cause such a reaction to occur explosively had been established and could be achieved; and production plants of several different types were in operation, building up a stock pile of the explosive material. Even if the first use of the atomic bomb had been relatively ineffective, there is little doubt that later efforts would have been highly destructive, since the devastation caused by a single bomb is comparable to that of a major air raid by usual methods.

A weapon has been developed that is potentially destructive beyond the wildest flights of imagination — a weapon so ideally suited to sudden unannounced attack that a country's major cities might be destroyed overnight by an ostensibly friendly power. The atomic bomb has been created, not by the devilish inspiration of some warped genius, but by arduous labor of thousands of normal men and women working to secure the safety of their country and the defeat of the enemy. Many of the principles embodied in the atomic bomb were well known to the international scientific world in 1940. To develop the necessary industrial processes which would embody these principles in an atomic bomb has been costly in time, effort, and money, but the laboratory and manufacturing processes upon which we selected to concentrate have worked, and several processes that we have not chosen could probably be made to work. We have an initial advantage in time over other countries because, so far as we know, other countries have not been able to carry out parallel developments during the war period. We also have a general advantage in scientific and particularly in industrial strength, but such an advantage can easily be thrown away.

Prognostication

As to the future, one may guess that technical developments will take place along two lines. From the military point of view, it is reasonably certain that there will be improvements both in the processes of producing fissionable material and in its use. It is conceivable that totally different methods may be discovered for converting matter into energy, since it is to be remembered that the energy released in uranium fission corresponds to the utilization of only about one tenth of one per cent of its mass. Should a scheme be devised for converting to energy even as much as a few per cent of the matter of some common material, civilization would have the means to commit suicide at will.

The possible uses of nuclear energy are not all destructive, and the second direction in which technical development can be expected is along the paths of peace. In the fall of 1944 General Groves appointed a committee to look into these possibilities as well as those of military significance. This committee (Dr. R. C. Tolman, chairman; Rear Admiral E. W. Mills [USN] with Captain T. A. Solberg [USN] as deputy; Dr. W. K. Lewis; and Dr. H. D. Smyth) received a multitude of suggestions from men on the various projects, principally along the lines of the use of nuclear energy for power and the use of radioactive by-products for scientific, medical, and industrial purposes. While there was general agreement that a great industry might eventually arise, comparable, perhaps, with the electronics industry, there was disagreement as to how rapidly such an industry would grow; the consensus was that the growth would be slow over a period of many years. At least there is no immediate prospect of running cars with nuclear power or lighting houses with radioactive lamps, although there is a good probability that nuclear power for special purposes could be developed within ten years and that plentiful supplies of radioactive materials can have a profound effect on scientific research and perhaps on the treatment of certain diseases in a similar period.

Planning for the Future

During the war the effort was to achieve the maximum military results. It was apparent for some time that some sort of government control and support in the field of nuclear energy should continue after the war. Many men associated with the project recognized this fact and came forward with various proposals, some of which were considered by the Tolman Committee, although it was only a temporary advisory committee reporting to General Groves. An interim committee at a high level was created later and was soon engaged in formulating plans for a continuing organization. This committee also discussed matters of general policy about which many of the more thoughtful men on the project had been deeply concerned since the work was begun and especially since success became more and more probable.

The Question Before the People

We find ourselves with an explosive which is far from being completely perfected. Yet the future possibilities of such explosives are appalling, and their effects on future wars and international affairs are of fundamental importance. Here is a new tool for mankind, a tool of unimaginable destructive power. Its development raises many questions that must be answered in the near future.

Such questions have been seriously considered by all concerned and vigorously debated among the scientists, and the conclusions reached have been passed along to the highest authorities. These questions are not technical questions; they are political and social questions, and the answers given to them may affect all mankind for generations. In thinking about them the men on the project have been thinking as citizens of the United States vitally interested in the welfare of the human race. It has been their duty and that of the responsible high government officials who were informed to look beyond the limits of the present war and its weapons to the ultimate implications of these discoveries. This was a heavy responsibility. In a free country like ours, such questions should be debated by the people and decisions must be made by the people through their representatives.

Chapter II

Plutonium Production

Problems as of February 1943

Choice of Plant Site

Once the scale of production had been agreed upon and the responsibilities assigned, the nature of the plant and its whereabouts had to be decided. The site in the Tennessee Valley, known officially as the Clinton Engineer Works, had been acquired by the Army for the whole program as recommended in the report to President Roosevelt.

Reconsideration at the end of 1942 led General Groves to the conclusion that this site was not sufficiently isolated for a large-scale plutonium production plant. At that time, it was conceivable that conditions might arise under which a large pile might spread radioactive material over a large enough area to endanger neighboring centers of population. In addition to the requirement of isolation, there remained the requirement of a large power supply, which had originally determined the choice of the Tennessee site.

Since the Columbia River is the finest supply of pure cold river water in this country, the Hanford site was well suited to either the helium-cooled plant originally planned or to the water-cooled plant actually erected. The great distances separating the home office of du Pont in Wilmington, Delaware; the pilot plant at Clinton, Tennessee; the Metallurgical Laboratory at Chicago; and the Hanford site were extremely inconvenient, but this separation could not be avoided. Difficulties also were inherent in bringing workmen to the site and in providing living accommodations for them.

Specification of the Over-All Problem

We now wish to give precise definition to the problem of the design of a large-scale plant for the production of plutonium. The objective had already been delimited by decisions as to scale of production, type of plant, and site. As it then stood, the specific problem was to design a water-cooled graphite-moderated pile (or several such piles) with associated chemical-separation plant to produce a specified, relatively large amount of plutonium each day, the plant to be built at the Hanford site beside the Columbia River. Speed of construction and efficiency of operation were prime considerations.

Nature of the Lattice

The lattices we have been describing heretofore consisted of lumps of uranium imbedded in the graphite moderator. There are two objections to such a type of lattice for production purposes: first, it is difficult to remove the uranium without disassembling the pile; second, it is difficult to concentrate the coolant at the uranium lumps, which are the points of maximum production of heat. Both these difficulties could be avoided if a rod lattice rather than a point lattice could be used — that is, if the uranium could be concentrated along lines passing through the moderator instead of being situated merely at points. The rod arrangement would be excellent structurally and mechanically, but there was real doubt as to whether it was possible to build such a lattice which would still have a multiplication factor K greater than unity. Both the theoretical and the experimental physicists tackled this problem. The theoretical physicists had to determine by computation what was the optimum spacing and diameter of uranium rods; the experimental physicists had to perform exponential experiments on lattices of this type in order to check the findings of the theoretical group.

Loading and Unloading

Once the idea of a lattice with cylindrical symmetry was accepted, it became evident that the pile could be unloaded and re-loaded without disassembly, since the uranium could be pushed out of the cylindrical channels in the graphite moderator, and new uranium inserted. The decision had to be made as to whether the uranium should be in the form of long rods, which had advantages from the nuclear-physics point of view, or of relatively short cylindrical pieces, which had advantages from the point of view of handling. In either case, the materials would be so very highly radioactive that unloading would have to be carried out by remote control, and the unloaded uranium would have to be handled by remote control from behind shielding.

Possible Materials; Corrosion

If water was to be used as coolant, it would have to be conveyed to the regions where heat was generated through channels of some sort. Since graphite pipes were not practical, the choice of material, like the choice of all the materials to be used in the pile, was limited by nuclear-physics considerations. The pipes must be made of some material whose absorption cross section for neutrons was not large enough to bring the value of *K* below unity; which would not disintegrate under the heavy density of neutron and gamma radiation present in the pile; and which would meet all ordinary requirements of cooling-system pipes: the pipes must not leak, must not corrode, and must not warp.

From the nuclear-physics point of view, there were seven possible materials (Pb, Bi, Be, Al, Mg, Zn, Sn), none of which had high neutron-absorption cross sections. No beryllium tubing was available, and of all the other metals, only aluminum was thought to be possible from a corrosion-resisting point of view. But it was by no means certain that aluminum would be satisfactory, and doubts about the corrosion of the aluminum pipe were not settled until the plant had actually operated for some time.

While the choice of material for the piping was very difficult, similar choices — involving both nuclear-physics criteria and radiation-resistance criteria — had to be made for all other materials that were to be used in the pile. For example, the electric insulating materials to be used in any instruments buried in the pile must not disintegrate under the radiation. In certain instances, where control or experimental probes had to be inserted and removed from the pile, the likelihood had to be borne in mind that the probes would become intensely radioactive as a result of their exposure in the pile and that the degree to which this would occur would depend on the material used.

Finally, it was not known what effect the radiation fields in the pile would have on the graphite and the uranium. Later it was found that the electric resistance, the elasticity, and the heat conductivity of the graphite all change with exposure to intense neutron radiation.

Protection of the Uranium from Corrosion

The most efficient cooling procedure would have been to have the water flowing in direct contact with the uranium in which the heat was being produced. Indications were that this was probably out of the question because the uranium would react chemically with the water, at least to a sufficient extent to put a dangerous amount of radioactive material into solution and probably to the point of disintegrating the uranium slugs. Therefore it was necessary to find some method of protecting the uranium from direct contact with the water. Two possibilities were considered: one was some sort of coating, either by electroplating or dipping; the other was sealing the uranium slug in a protective jacket or "can." Strangely enough, this "canning problem" has turned out to be one of the most difficult problems encountered in such piles.

Water Supply

The problem of dissipating thousands of kilowatts of energy is by no means a small one. How much water was needed depended on the maximum temperature to which the water could safely be heated and on the maximum temperature to be expected in the intake from the Columbia River; certainly the water supply requirement was comparable to that of a fair-sized city. Pumping stations, filtration, and treatment plants all had to be provided. Furthermore, the system had to be a reliable one; it was necessary to provide fast-operating controls to shut down the chain-reacting unit in a hurry in case of failure of the water supply. If it was decided to use "once-through" cooling instead of recirculation, a retention basin would be required so that the radioactivity induced in the water might die down before the water was returned to the river. The volume of water discharged was expected to be so great that such problems of radioactivity were important, and therefore the minimum time that the water must be held for absolute safety had to be determined.

Controls and Instrumentation

The control problem was similar to that discussed in connection with the first chain-reacting pile, except that everything was on a larger scale and was, therefore, potentially more dangerous. It was necessary to provide operating controls which would automatically keep the pile operating at a determined power level. Such controls had to be connected with instruments in the pile which would measure neutron density or some other property which indicated the power level. There would also have to be emergency controls which would operate almost instantaneously if the power level showed signs of rapid increase or if there was any interruption of the water supply. It was highly desirable that there be some means of detecting incipient difficulties such as the plugging of a single water tube or a break in the coating of one of the uranium slugs. All these controls and instruments had to be operated from behind the thick shielding walls described below.

Shielding

The radiation given off from a pile operating at a high power level is so strong as to preclude positioning operating personnel near the pile. Furthermore, this radiation, particularly the neutrons, has a pronounced capacity for leaking out through holes or cracks in barriers. The whole of a power pile therefore has to be enclosed in very thick walls of concrete, steel, or other absorbing material and at the same time permit loading and unloading of the pile through these shields and the carrying of the water supply in and out of them. The shields should be air-tight as well as radiation-tight, since air exposed to the radiation in the pile would become radioactive.

Radiation dangers that require shielding in the pile exist through a large part of the separation plant. Since the fission products associated with the production of the plutonium are highly radioactive, the uranium, after ejection from the pile, must be handled by remote control from behind shielding and must be shielded during transportation to the separation plant. All the stages of the separation plant, including analyses, must be handled by remote control from behind shields up to the point where the plutonium is relatively free of radioactive fission products.

Maintenance

There could be no maintenance inside the shield or pile once the pile had operated. As to the separation unit, it was probable that a shut-down for servicing could be effected, provided, of course, that adequate remotely controlled decontamination processes were carried out in order to reduce the radiation intensity below the level dangerous to personnel. The maintenance problem for auxiliary parts of the plant was normal except for the extreme importance of having stand-by pumping and power equipment to prevent a sudden accidental breakdown of the cooling system.

Schedule of Loading and Unloading

The amount of plutonium in an undisturbed operating pile increases with time of operation. Since Pu–239 itself undergoes fission, its formation tends to maintain the chain reaction. On the other hand, the gradual disappearance of the U–235 and the appearance of fission products with large neutron-absorption cross sections tend to stop the reaction. The determination of when a producing pile should be shut down and the plutonium extracted involves a nice balancing of these factors against time schedules, material costs, separation-process efficiency, and so on. Strictly speaking, this problem is one of operation rather than of design of the plant, but some thought had to be given to it in order to plan the flow of uranium slugs to the pile and from the pile to the separation plant.

Size of Units

Production capacity of the plant has been spoken of only in terms of over-all production rate. Naturally, a given rate of production might be achieved in a single large pile or in a number of smaller ones. The principal advantage of the smaller piles would be the relatively shorter time required to construct the first pile, the possibility of making alterations in later piles, and, what is perhaps most important, the improbability of a simultaneous breakdown of all piles. The disadvantage of small piles is that they require disproportionately large amounts of uranium, moderator, and so on. There is, in fact, a preferred "natural size" of pile which can be roughly determined on theoretical grounds

General Nature of the Separation Plant

The slugs coming from the pile are highly radioactive and therefore must be processed by remote control in shielded compartments. The general scheme to be followed in processing was suggested in the latter part of 1942, particularly in connection with plans for the Clinton separation plant. A "canyon," to consist of a series of compartments with heavy concrete walls arranged in a line and almost completely buried in the ground was to be built. Each compartment would contain the necessary dissolving or precipitating tanks or centrifuges. The slugs would come into the compartment at one end of the canyon; they would then be dissolved and go through the various stages of solution: precipitation, oxidation, or reduction, being pumped from one compartment to the next until a solution of plutonium free from uranium and fission products came out in the last compartment. As in the case of the pile, all operations would proceed by remote control from above ground, but these operations would be far more complicated than in the case of the pile. However, the general nature of the chemical operations themselves was not far removed from the normal fields of activity of the chemists involved.

Analytical Control

In the first stages of the separation process, even the routine analysis of samples, which was necessary in checking the operation of the various chemical processes, had to be done by remote control. Testing was facilitated, however, by use of radioactive as well as by conventional chemical methods of analyses.

Waste Disposal

The raw material (uranium) is not dangerously radioactive. The desired product (plutonium) does not give off penetrating radiation, but when plutonium penetrates the body, its alpha-ray activity and chemical properties endanger health and life. However, really troublesome to dispose of are the fission products — that is, the major fragments into which uranium is split by fission. Fission products include some thirty elements and are extremely active. Among these products are radioactive xenon and radioactive iodine, which are released in considerable quantity when the slugs are dissolved and must be disposed of with special care. High stacks which will carry off these gases along with the acid fumes from the first dissolving unit must be built, and it must be established that the mixing of the radioactive gases with the atmosphere will not endanger the surrounding territory.

Most of the other fission products can be retained in solution but must eventually be disposed of. Possible pollution of the adjacent river must be considered.

Recovery of Uranium

Even if the uranium were left in the pile until all the U–235 had undergone fission, there would still be a large amount of U–238 which had not been converted to plutonium. Actually the process is stopped long before this stage is reached. Uranium is an expensive material and the total available supply is seriously limited. Therefore the possibility of recovering uranium after the plutonium is separated must be considered. Originally the plan was merely to store the solution, not to recover the uranium at an early date. Later, methods of large-scale recovery were developed.

Corrosion in the Separation Plant

The chemical processes involved possess the unusual feature of occurring in the presence of a high density of radiation. Therefore the containers used may corrode more rapidly than they would under normal circumstances. Furthermore, any such corrosion will be serious because of the difficulty of access. For a long time, information was sadly lacking on how to meet these dangers.

Effect of Radiation on Chemical Reactions

Chemical reactions proposed for use in an extraction process were first tested in the laboratory. However, since such reactions could not be tested with appreciable amounts of plutonium or in the presence of radiation of anything like the expected intensity, it was realized that an extraction process which worked to be successful in the laboratory might not work in the plant.

Choice of Process

The description of what was to happen in the successive chambers in the "canyon" of the separation plant was necessarily vague because even by January 1943 no decision had been made as to what process would be used for the extraction and purification of plutonium. The major problem before the Chemistry Division of the Metallurgical Laboratory was the selection of the best process for the plant.

Problems from January 1943 to June 1945

Introduction

The necessity for pushing the design and construction of the full-scale plutonium plant simultaneously with research and development inevitably led to a certain amount of confusion and inefficiency. The investigation of many alternative processes became imperative, as was the need to probe for all possible causes of failure even when the probability of their becoming serious was very small. Now that the Hanford plant is producing plutonium successfully, we can say that a large percentage of the results of investigations made between the end of 1942 and the end of 1944 will never be used — at least not for the originally intended purposes. Nevertheless, had the Hanford plant run into difficulties, any one of the now-superfluous investigations might have furnished precisely the information required to convert failure into success. Even now we are unable to forecast what future improvements may not depend on the results of researches that seem unimportant today.

It is estimated that thirty volumes will be required to contain a complete report of the significant scientific results of researches conducted under the auspices of the Metallurgical Project. Work was done on every item mentioned on the research program presented in the preceding chapter. Rather than present a brief account of these vast researches, which would be highly unsatisfactory, we shall instead present a general discussion of the chain-reacting units and separation plants as they now operate, with some discussion of the earlier developments.

The Chain Reaction in a Pile

The operation of a pile depends on the passage of neutrons through matter, and on the nature of the collisions of neutrons with the nuclei encountered. The collisions of principal importance are the following:

I. Collisions in which neutrons are scattered and lose appreciable amounts of energy.
   (a) Inelastic collisions of fast neutrons with uranium nuclei.
   (b) Elastic collisions of fast or moderately fast neutrons with the light nuclei of the moderator material; these collisions serve to reduce the neutron energy to very low (so-called thermal) energies.

II. Collisions in which the neutrons are absorbed.
   (a) Collisions which result in fission of nuclei and give fission products and additional neutrons.
   (b) Collisions which result in the formation of new nuclei which subsequently disintegrate radioactively (for example, ${}_{92}U^{239}$, which produces ${}_{94}Pu^{239}$).

Only the second class of collision requires further discussion. As regards collisions of type II (a), the most important in a pile are the collisions between neutrons and U–235, but the high-energy fission of U–238 and the thermal fission of Pu–239 also take place. Collisions of type II (b) are chiefly those between neutrons and U–238. Such collisions occur for neutrons of all energies, but they are most likely to occur for neutrons whose energies lie in the "resonance" region located somewhat above thermal energies. The sequence of results of the type II (b) collision is represented as follows:

$$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \text{gamma rays}$$

$$_{92}U^{239} \xrightarrow[\text{23 min}]{} {}_{93}Np^{239} + {}_{-1}e^{0}$$

$$_{93}Np^{239} \xrightarrow[\text{2.3 da}]{} {}_{94}Pu^{239} + {}_{-1}e^{0} + \text{gamma rays}$$

Any other non-fission absorption processes are important chiefly because they waste neutrons; they occur in the moderator, in U–235, in the coolant, in the impurities originally present, in the fission products, and even in plutonium itself.

Since our purpose for starting the chain reaction is to generate plutonium, we should like to absorb all excess neutrons into U–238, leaving just enough neutrons to produce fission and thus to maintain the chain reaction. Actually, instead of producing fission in the 140-times rarer U–235, neutrons tend to be absorbed by the dominant isotope U–238. Hence, the principal designing problem was to maintain the chain reaction by favoring the fission (as by using a moderator, a suitable lattice, materials of high purity, and so on).

The Clinton Plant

By January 1943, the plans for a "pilot" plant for producing plutonium were well along; construction was started on the Clinton site in Tennessee soon afterward. The plans were made cooperatively by du Pont and the Metallurgical Laboratory; construction was carried out by du Pont; plant operation was maintained by the University of Chicago as part of the Metallurgical Project. M. D. Whitaker was appointed director of the Clinton Laboratories.

The main purposes of the Clinton plant were to produce some plutonium and to serve as a pilot plant for chemical separation. As regards research, the emphasis at Clinton was on chemistry and the biological effects of radiation. A large laboratory was provided for chemical analysis, research on purification methods, fission-product studies, development

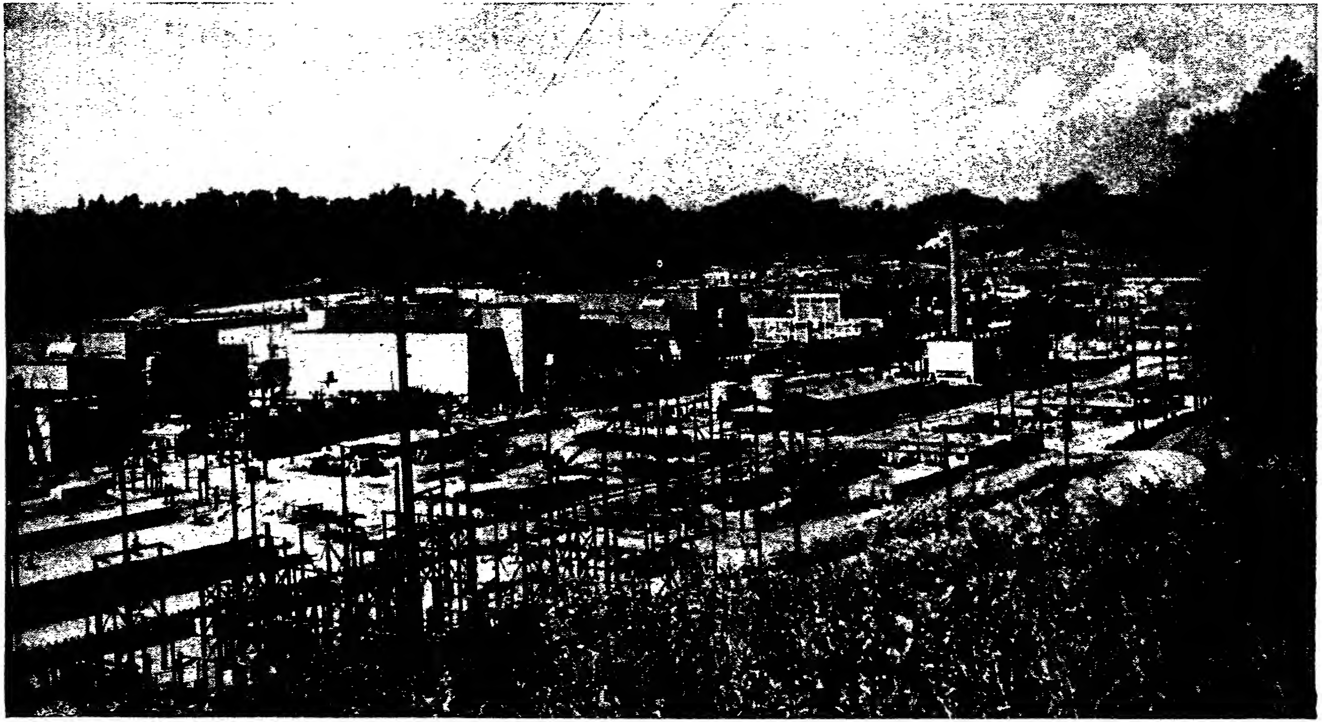


Figure 6. Part of the Production Area at the Clinton Engineer Works at Oak Ridge, Tennessee.

Figure 7. One of the Giant Production Plants at the Clinton Engineer Works at Oak Ridge, Tennessee.

of intermediate-scale extraction, decontamination processes, and so on. Later a "hot laboratory" — that is, a laboratory for remotely controlled work on highly radioactive material, was provided. The plant also has an instrument shop and laboratory that has been used very actively; facilities for both clinical and experimental work of the health division, which has been very active; and a small physics laboratory in which some important work was done by using higher neutron intensities than were available at the Argonne Laboratory. The principal installations constructed at the Clinton Laboratory site were the pile and the separation plant; these are briefly described below.

The Clinton Pile

In any steadily operating pile, the effective multiplication factor K must be kept at unity, whatever the power level. The best K that had been observed in a uranium-graphite lattice could not be achieved in a practical pile because of neutron leakage, cooling system, cylindrical channels for the uranium, protective coating on the uranium, and other minor factors. Granted air-cooling and a maximum safe temperature for the surface of the uranium, a size of pile had to be chosen that could produce 1000 kw. The effective K would go down with rising temperature, but not sufficiently to be a determining factor. Though a sphere was the ideal shape, practical considerations recommended a rectangular block.

The Clinton pile consists of a cube of graphite containing horizontal channels filled with uranium. The uranium is in the form of metal cylinders protected by gas-tight casings of aluminum. The uranium cylinders or slugs may be slid into the channels in the graphite; space is left to permit cooling air to flow past, and to permit pushing the slugs out at the back of the pile when they are ready for processing. Besides the channels for slugs there are various other holes through the pile for control rods, instruments, and so on.

The Clinton pile was considerably larger than the first pile at Chicago. More important than the increased size of the Clinton pile were its cooling system, heavier shields, and means for changing the slugs. The production goal of the Clinton plant was set at a figure which meant that the pile should operate at a power level of 1000 kw.

The instrumentation and controls are identical in principle to those of the first pile. Neutron intensity in the pile is measured by a BF_3 ionization chamber and is controlled by boron steel rods that can be moved in and out of the pile, thereby varying the fraction of neutrons available to produce fission.

In spite of the impressive array of instruments and safety devices, the most striking feature of the pile is simplicity of operation. Most of the time, operators do nothing but record readings of instruments.

The Separation Plant

Here, as at Hanford, the plutonium processes have to be carried out by remote control and behind thick shields. The separation equipment is housed in a series of adjacent cells having heavy concrete walls. These cells form a continuous structure (canyon) which is about 100 ft long and is two thirds buried in the ground. Adjacent to this canyon are the control rooms, analytical laboratories, and a laboratory for further purification of the plutonium after it has been decontaminated to the point of comparative safety.

Uranium slugs that have been exposed in the pile are transferred under water to the first of these cells and are then dissolved. Subsequent operations are performed by pumping solutions or slurries from one tank or centrifuge to another.

Performance of Clinton Pile

The Clinton pile started operating on November 4, 1943, and within a few days was brought up to a power level of 500 kw at a maximum slug surface temperature of 110° C. Improvements in the air circulation and an elevation of the maximum uranium surface temperature to 150° C brought the power level up to about 800 kw, where it was maintained until the spring of 1944. Starting at that time, a change was made in order to level out the power distribution in the pile. This was accomplished by reducing the amount of metal near the center relative to that farther out, and thereby increasing the average power level without anywhere attaining too high a temperature. At the same time, improvements were realized in the sealing of the slug jackets, making it possible to operate the pile at higher temperature. As a result, a power level of 1800 kw was attained in May 1944; this was further increased after the installation of better fans in June 1944.

Thus, the pile performance of June 1944 considerably exceeded expectations. In ease of control, steadiness of operation, and absence of dangerous radiation, the pile has been most satisfactory. There have been very few failures attributable to mistakes in design or construction.

The plutonium-separation plant posed greater problems than the pile. The step from the first chain-reacting pile to the Clinton pile was reasonably predictable, but a much greater and more uncertain step was required in the case of the separation process, for the Clinton separation plant was designed on the basis of experiments using only microgram amounts of plutonium.

Nevertheless, the separation process worked! The first batch of slugs from the pile entered the separation plant on December 20, 1943. By the end of January 1944, metal from the pile was going to the separation plant at the rate of ⅓ ton per day. By February 1, 1944, 190 mg of plutonium had been delivered, and by March 1, 1944, several grams had been delivered. Furthermore, the efficiency of recovery at the very start was about 50 per cent, and by June 1944, it was between 80 and 90 per cent.

During the whole period there was a large group of chemists at Clinton working on improving the separation process and developing it for Hanford. The Hanford problem differed from that at Clinton in that much higher concentrations of plutonium were expected. Furthermore, though the chemists were to be congratulated on the success of the Clinton plant, the separation process was complicated and expensive. Any improvements in yield or decontamination or in general simplification were much to be sought after.

In addition to proving the pile and the separation plant and producing several grams of plutonium for experimental use at Chicago, Clinton, and elsewhere, the Clinton Laboratories have served as a training and testing center for Hanford, for medical experiments, pile studies, purification studies, and physical and chemical studies of plutonium and fission products.

The Hanford Plant

It is beyond the scope of this report to give an account of the construction of the Hanford Engineer Works, but it is to be hoped that the full story of this extraordinary enterprise and the companion one, the Clinton Engineer Works, will be published in the future. Hanford site was examined by representatives of General Groves and of du Pont at the end of 1942, and use of the site was approved by General Groves after a personal inspection. The site was on the west side of the Columbia River, in central Washington, north of Pasco. In the early months of 1943, a two hundred square mile tract in this region was acquired by the government (by lease or purchase) through the Real Estate Division of the Office of the Chief of Engineers. Eventually, an area of nearly a thousand square miles was brought under government control. At the time of acquisition, a few farms and two small villages, Hanford and Richland, were within the chosen area, which otherwise contained sage-brush plains and barren hills. On April 6, 1943, ground was broken for the Hanford construction camp. At the peak of activity in 1944, this camp was a city of 60,000 inhabitants, the fourth largest city in the state. Now, however, the camp is practically deserted, since the operating crew is housed at Richland.

Work was begun on the first of the Hanford production piles on June 7, 1943, and operation of the first pile began

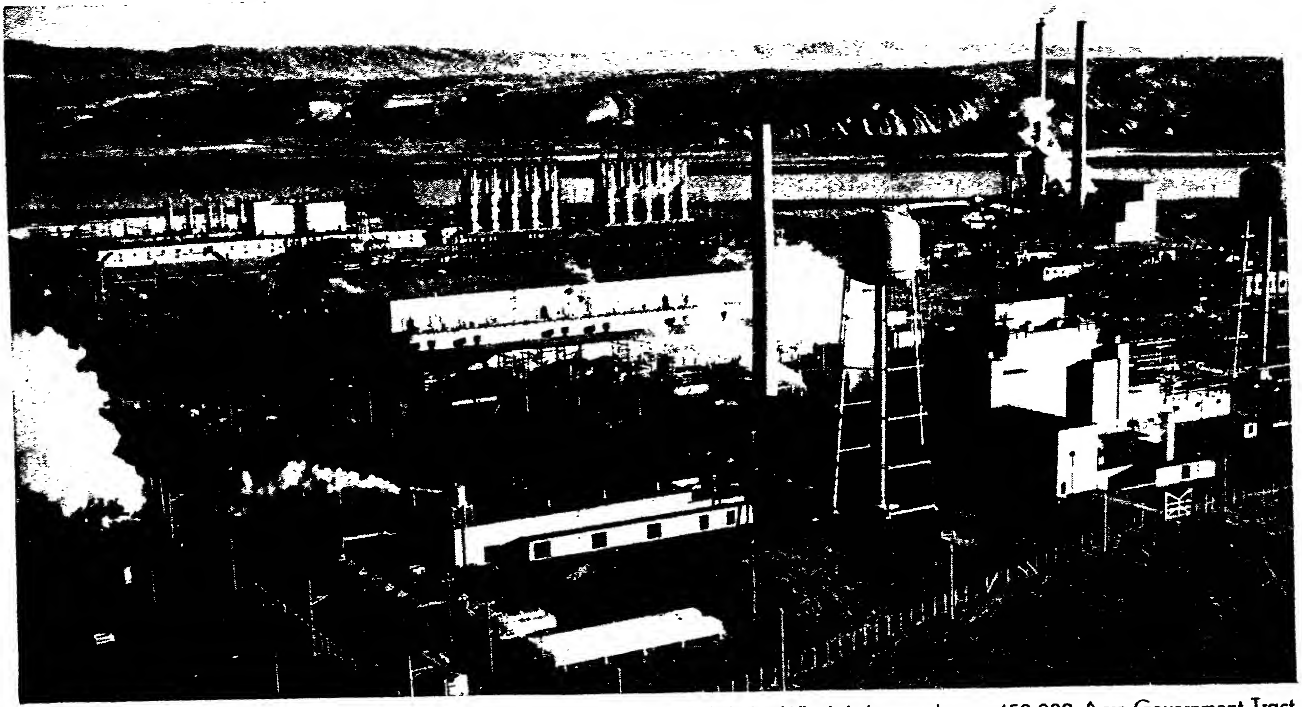


Figure 8. View of One of the Production Areas of the Hanford Engineer Works, Which Is Located on a 450,000-Acre Government Tract 15 Miles Northwest of Pasco, Washington, and Now Is the City of Richland

in September 1944. The site was originally laid out for five piles, but the construction of only three has been undertaken. In addition to the piles, there are plutonium-separation plants, pumping stations, water-treatment plants, and a low-power chain-reacting pile for material testing. Not only are the piles themselves widely spaced for safety — several miles apart — but the separation plants are well away from the piles and from each other. All three piles were in operation by the summer of 1945.

Canning and Corrosion

No one who lived through the period when the design and construction of the Hanford plant was carried through is likely to forget the "canning" problem — that is, the problem of sealing the uranium slugs in protective metal jackets. On periodic visits to Chicago, the writer was able roughly to deduce the success achieved in the solution of the canning problem by the atmosphere of gloom or joy to be found in and about the laboratory. Extremely difficult was the search after a sheath that would protect uranium from water corrosion, keep fission products out of the water, transmit heat from the uranium to the water, and that would not absorb too many neutrons. Yet the failure of a single can might conceivably require shut-down of an entire operating pile.

Attempts to meet the stringent requirements demanded experimental work on electroplating processes, hot-dipping processes, cementation-coating processes, corrosion-resistant alloys of uranium, and mechanical jacketing or canning processes. Mechanical jackets or cans of thin aluminum were feasible from the nuclear point of view and were chosen at an early date as the most likely solution of the problem. However, getting a uniform, heat-conducting bond between the uranium and the surrounding aluminum, and effecting a gas-tight closure for the can both proved very troublesome. Development of alternative methods had to be carried along up to the last minute, and even up to a few weeks before it was time to load the uranium slugs into the pile, no one was certain that any of the processes under development would be satisfactory. A final minor, but apparently important, modification in the preferred canning process was adopted in October 1944, after the first pile had begun experimental operation. By the summer of 1945, no can failure had been reported.

Status as of June 1945

In the fall of 1944 and the early months of 1945, the second and third Hanford piles were finished and put into operation, as were the additional chemical separation plants. There were difficulties, but failures of canning, film formation in the water tubes, or radiation effects in the chemical processes did not occur in the final designs. As of early summer 1945, the piles were operating at designed power, producing plutonium and heating the Columbia River. The chemical plants were separating the plutonium from the uranium and from the fission products with better efficiency than had been anticipated. The finished product was being delivered.

The Work on Heavy Water

Heavy water is more effective than graphite in slowing down neutrons and it has a smaller neutron absorption than graphite. A chain-reacting unit with uranium and heavy water therefore can be built; a considerably higher multiplication factor, K, can be attained; and a smaller size unit than is possible with graphite can be achieved. But one must have heavy water.

The production schedule of heavy water was so low that it would take two years to produce enough to "moderate" a fair-sized pile for plutonium production. An intensive study of the problem was made during the summer of 1943, but in November it was decided to curtail the program and construction was limited to a 250-kw pile located at the Argonne site.

Part IV

Possible Methods of Converting Atomic Energy into Mechanical Power

By R. Tom Sawyer

Chapter I

Power from the Uranium Pile

WE HAVE seen how plutonium is manufactured in a "pile" of uranium and carbon. The atomic energy in the pile produces heat, and the heat can be converted into mechanical power. In this chapter, we shall illustrate some of the ways in which this heat may be utilized in existing machines, and the possibilities of bringing nearer the day of plentiful power for peaceful purposes.

The uranium pile consists of appropriately spaced rods of uranium imbedded in graphite carbon. Neutrons from the uranium in one rod bombard the uranium of another rod, while the graphite maintains the speed of bombardment at an effective value. The bombarded uranium rod is then removed from the pile and chemically treated to separate the plutonium which has been formed.

Neutron bombardment produces heat in the pile, and normally the heat is removed by water cooling. This heat is our chief concern in the making of power and will be the chief topic of our discussion. Owing to radioactive by-products, ordinary ferrous materials cannot be used as pipes to convey water in the water-cooling process. Aluminum pipes were, however, found suitable in the normal pile.

The pile at Hanford contained normal uranium ore, consisting mostly of U–238. For every 140 lb of normal uranium 238, there is only 1 lb of uranium 235. At Hanford, a large quantity of cold water taken from the Columbia River was used to keep the pile cool. The heat rejected to the water was not used, because the prime objective was to produce plutonium quickly, regardless of economy, for military purposes. Today, when we are no longer at war, we must critically review the cooling process from an economical standpoint. To what useful purpose can we put the heat absorbed by the cooling water?

Power Produced from Normal Pile

Figure 1 shows cold water entering the pile and hot water coming out. The hot water may be used in several ways: as hot-water heat in radiators; for industrial drying processes, as well as other industrial or chemical processing; as feed water to a boiler; or the hot water may be put to all three uses. Possibly, the water can actually be boiled under pressure, and the resulting steam used directly in a steam turbine to produce power or for other uses normally requiring steam.

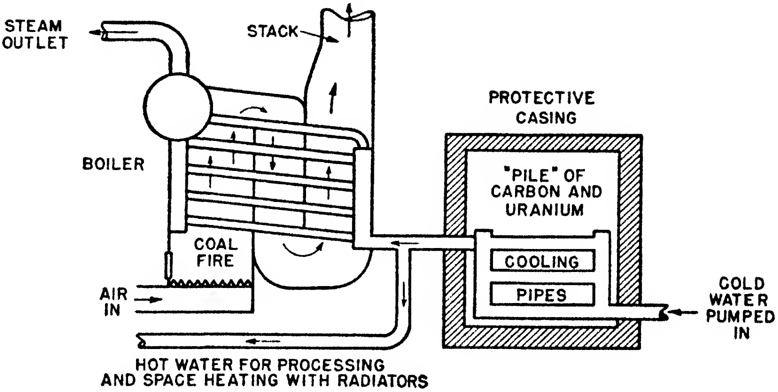


Figure 1. Hot Water Produced by Uranium Pile Piped into Coal-Fired Boiler.

Figure 2 shows another way of heating the boiler illustrated in Figure 1. In this case, a suitable gas turbine generator plant is employed, the waste heat from the gas turbine exhaust then being used in the boiler. A high-temperature gas turbine must be used with an initial temperature of at least 1500° F, so that the exhaust at about 1000° F can generate steam, which forms at about 400 to 500° F at moderate pressures.

In a normal gas turbine plant, the air enters the compressor, where it is compressed to 50 to 100 lb per square inch. This air then enters the firebox, which in this case has an oil burner in it. The theoretical combustion temperature is between 3000 and 4000° F, but this high temperature does not exist at the turbine inlet because sufficient excess air is used to hold the temperature down to the desired value, say 1500° F. After the air has done work in the tur-

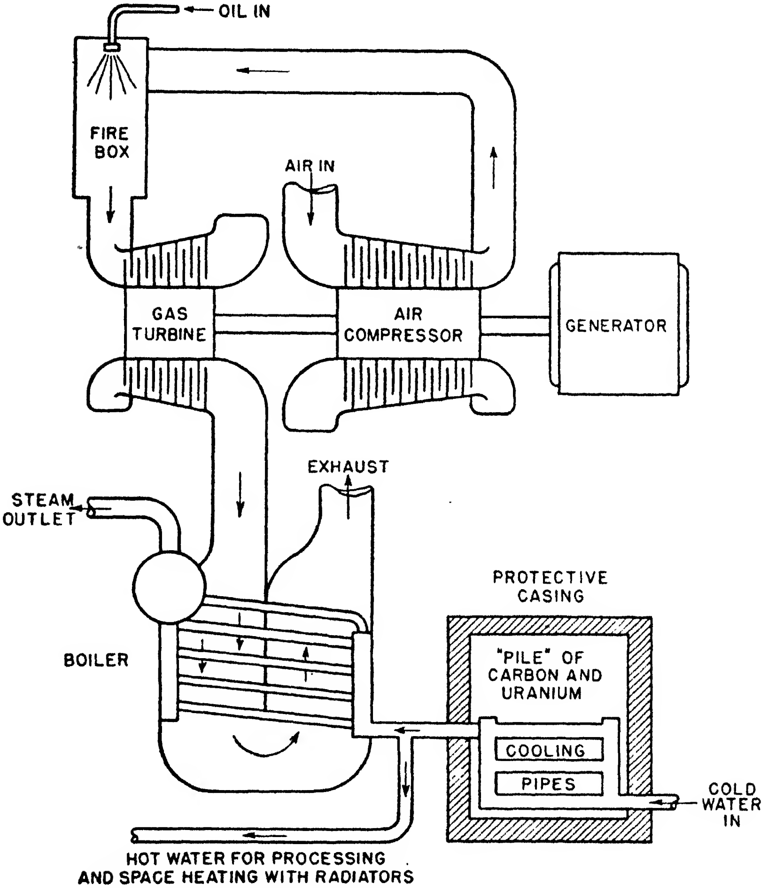


Figure 2. Hot Water Produced by Uranium Pile Piped into Boiler Heated by Gas Turbine Exhaust Gases.

bine, it has been expanded to only a few pounds above atmospheric pressure — enough to force it through the boiler. Its temperature has been reduced in passing through the turbine to about 1000° F. The turbine drives the compressor, and excess power is converted to electrical energy by the generator.

The uranium pile can be cooled by air as well as by water. For a diagram showing the air cooling of a normal pile (.7 per cent of U-235), let us look at Figure 3. Aluminum tubes are used to carry the air, and their arrangement is probably similar to the water-cooling pipes. In this case the gas turbine would be an ideal machine for driving the air compressor. A motor is required for starting the unit, after which the motor becomes a generator and absorbs excess energy.

In Figure 3, the cycle of operation is to bring cool air into the compressor and raise it to a pressure of about 50 lb. The air then goes through the cooling tubes and is heated several hundred degrees. This preheated air is then raised to its final temperature in the firebox by the use of an oil or gas burner. The heated air drives the turbine, producing all of the compressor power, and finally is exhausted to the atmosphere.

Thus a normal uranium atomic-energy pile can produce heat which can be utilized in an already existing type of power plant.

Power Produced from Concentrated Uranium Pile

The results obtained from a uranium pile containing ten times the concentration of U–235 (7 per cent of U–235) that is found in the normal pile look even more promising for power production. In this case there are two purposes for having a highly concentrated pile: to produce plutonium and to produce heat for power purposes. As in the normal pile, the uranium rods must be removed periodically for the treatment involved in the separation of the plutonium. Normally, it is not possible to obtain ore with a high concentra-

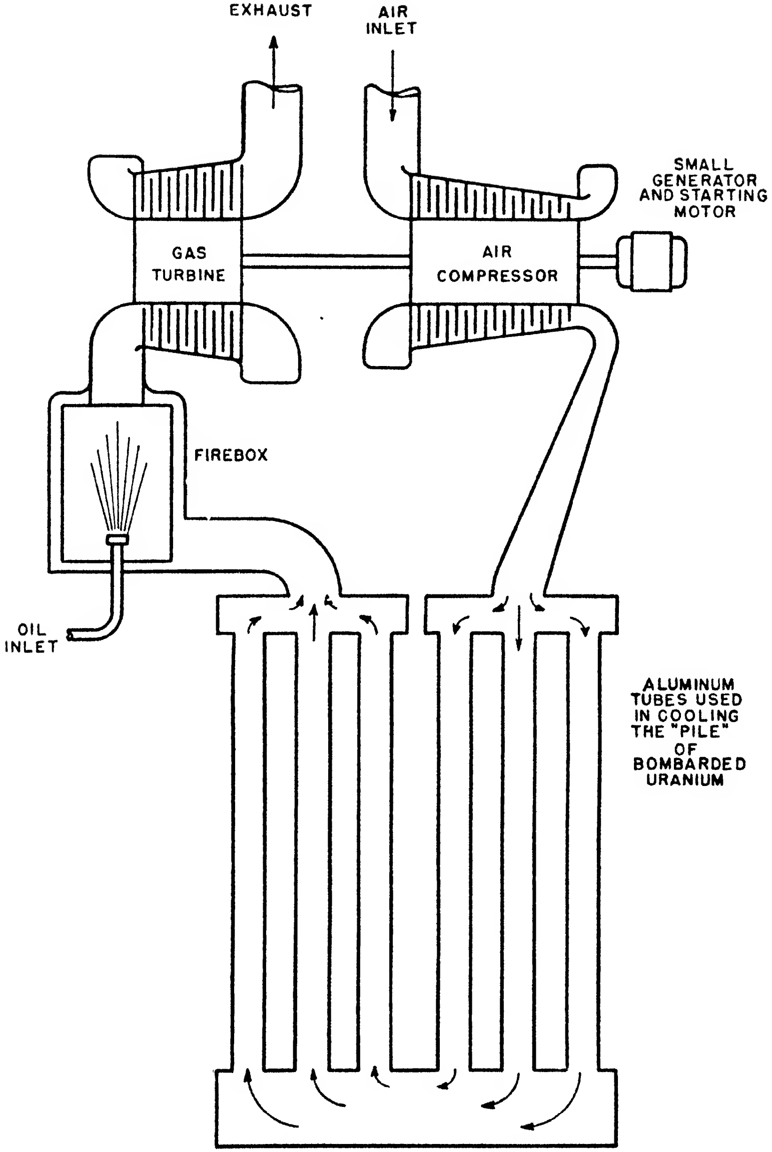


Figure 3. Gas Turbine Used to Cool the Uranium Pile and Obtain Heat for Turbine.

tion of U–235, and for this reason it would be necessary to manufacture U–235 by one of the four methods described in Chapter I of Part III: (1) gaseous diffusion by use of barriers, (2) electromagnetic, (3) thermal diffusion, and (4) centrifugal method with gasified U–235 and U–238. Part V states that the first method will be favored because it is the most economical.

Having manufactured a sufficient quantity of U–235 and having added it to the normal uranium ore, we should obtain the effect of a highly concentrated ore. Water used in the cooling pipes in such a pile is not only heated but actually forms steam.

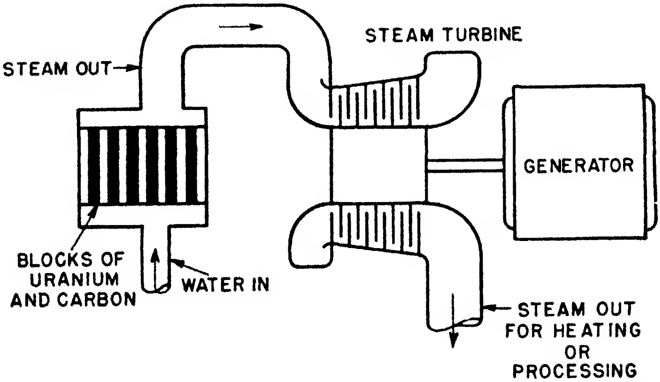


Figure 4. Steam Turbine Generating Plant, Using Steam from Uranium Pile.

Figure 4 shows a steam turbine generating plant. The cold water is pumped into the uranium pile and steam is produced at a sufficient temperature and pressure to drive the turbine generator. If a non-condensing turbine is employed, the exhaust steam may be used for process or steam heating. We may, on the other hand, use a closed cycle condensing unit, the condensate being pumped back into the pile. Turbine plants operate more efficiently with a condenser, while the pile operates more efficiently with cold water, so that desire for economy will dictate the exact design in a given case.

Instead of water, it is likely that other liquids may be used as coolant and working fluid. In Figure 5, a mercury cycle is shown. In this arrangement, liquid mercury is heated by being pumped into the pile, and leaves the pile as a vapor. After the vapor passes through a special mercury vapor turbine, the exhaust vapor is condensed in a condenser-boiler, which acts as both a mercury condenser and steam boiler. The mercury, in liquid form, is returned to the pile. The steam made in the condenser-boiler enters and drives a steam turbine, and then exhausts to its own condenser. The condensate is returned to the mercury condenser-boiler. The latter acts as a steam generator because the temperature of the mercury vapor exhaust is hotter than the boiling water. A pile to operate in this manner may have a large percentage of U–235, and therefore the *higher the temperature of the carbon or other medium, the less effective the U–235 becomes.* This phenomenon is of vital importance, because it causes the uranium pile to be inherently stable, thermally, and also causes an equilibrium temperature to be reached.

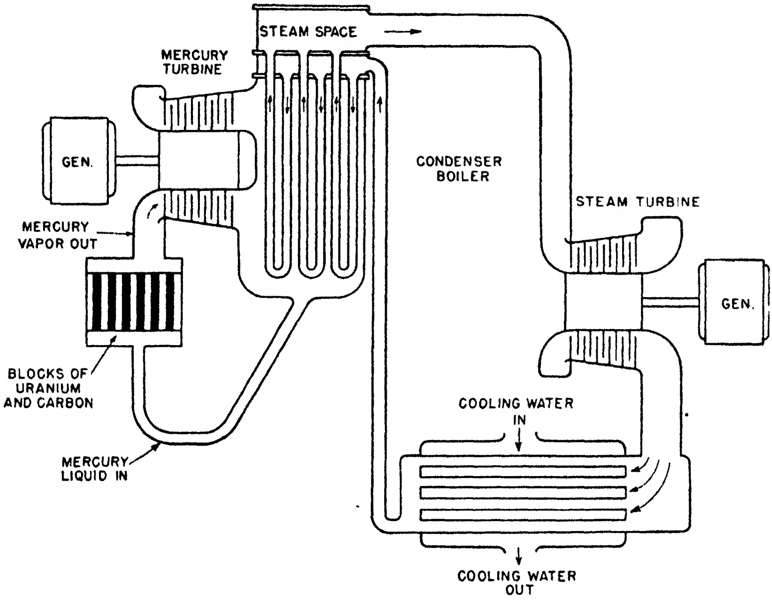


Figure 5. Combination Steam Turbine and Mercury Turbine Generating Plant.

Instead of using water or liquid cooling, we may air-cool the highly concentrated pile, as was done to the normal pile. Thus, in Figure 3, the oil burner in the firebox may only be

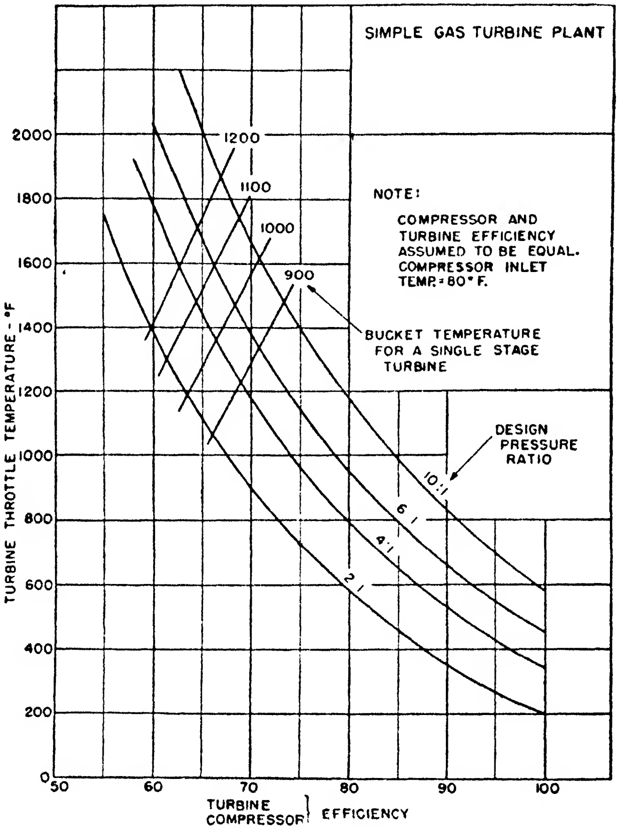


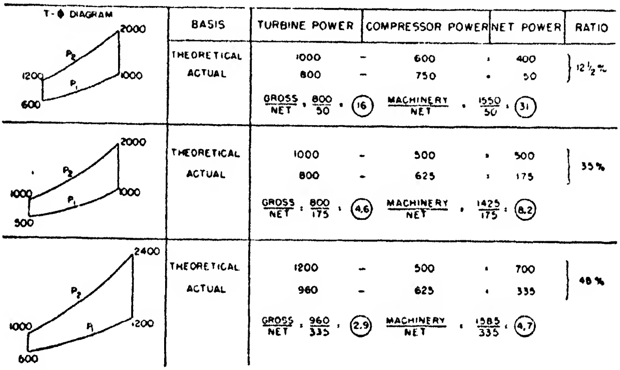
Figure 6. Turbine Throttle Temperature Required for Zero Net Output.

used in starting the unit, after which the air from the cooling pipes in the highly concentrated pile may be sufficiently hot to operate the turbine. If the air coming out of the pipes were not hot enough, the temperature could be raised by adding a small quantity of fuel.

Figures 6 and 7 are taken from Mr. J. Kenneth Salisbury's paper presented before the Oil and Gas Power Division of the American Society of Mechanical Engineers at Tulsa, May 8, 1944. The curves are explained in Mr. Salisbury's paper as follows:

> Figure 6 illustrates the minimum turbine-inlet temperature at which useful output can be obtained, plotted against machine efficiency. Modern turbine and compressor efficiencies are in the 80 to 85 per cent range; hence useful output can be obtained with temperatures as low as about 600° F.

FOR CONSTANT FLOW POWER IS PROPORTIONAL TO TEMPERATURE CHANGE
(THEORETICAL BASIS IS 100% TURBINE AND COMPRESSOR EFFICIENCY
'ACTUAL' BASIS IS 80% TURBINE AND COMPRESSOR EFFICIENCY)



BASIS	TURBINE POWER	COMPRESSOR POWER	NET POWER	RATIO
THEORETICAL	1000	600	400	12½%
ACTUAL	800	750	50	
	$\frac{GROSS}{NET} = \frac{800}{50} =$ ⑯	$\frac{MACHINERY}{NET} = \frac{1550}{50} =$ ㉛		
THEORETICAL	1000	500	500	35%
ACTUAL	800	625	175	
	$\frac{GROSS}{NET} = \frac{800}{175} =$ (4.6)	$\frac{MACHINERY}{NET} = \frac{1425}{175} =$ (8.2)		
THEORETICAL	1200	500	700	48%
ACTUAL	960	625	335	
	$\frac{GROSS}{NET} = \frac{960}{335} =$ (2.9)	$\frac{MACHINERY}{NET} = \frac{1585}{335} =$ (4.7)		

Figure 7. Comparative Outputs for Gas Turbine Power Plants.

> Fortunately the output of the gas-turbine power plant increases very rapidly as the turbine initial temperature is increased, or as the compressor inlet temperature is decreased. This fact is illustrated in Figure 7, in which are shown progressively the effects of (1) decreasing the compressor-inlet temperature, and (2) increasing the turbine-inlet temperature.
>
> Figure 7 assumes, for convenience, that the flow and specific heat of the fluid have such values that the temperature change represents numerically the output in horsepower (the flow would be 10,600 lb per hour when using air). The temperatures chosen are arbitrary. The pressure ratio used is such that the adiabatic temperature ratio is exactly 2 : 1 — a pressure ratio of about 11 : 1 when using air as the fluid. The outputs are shown on both a theoretical and an "actual" basis, the theoretical and actual bases being 100 per cent and 80 per cent machine efficiency, respectively. The circled figures indicate clearly the rapid decrease in the ratio of the gross to the net turbine power, as well as in the machinery power to net power ratio. It is to be noted also that the ratio of

actual to theoretical net power increases very rapidly as the turbine-inlet temperature is increased and the compressor-inlet temperature is decreased.

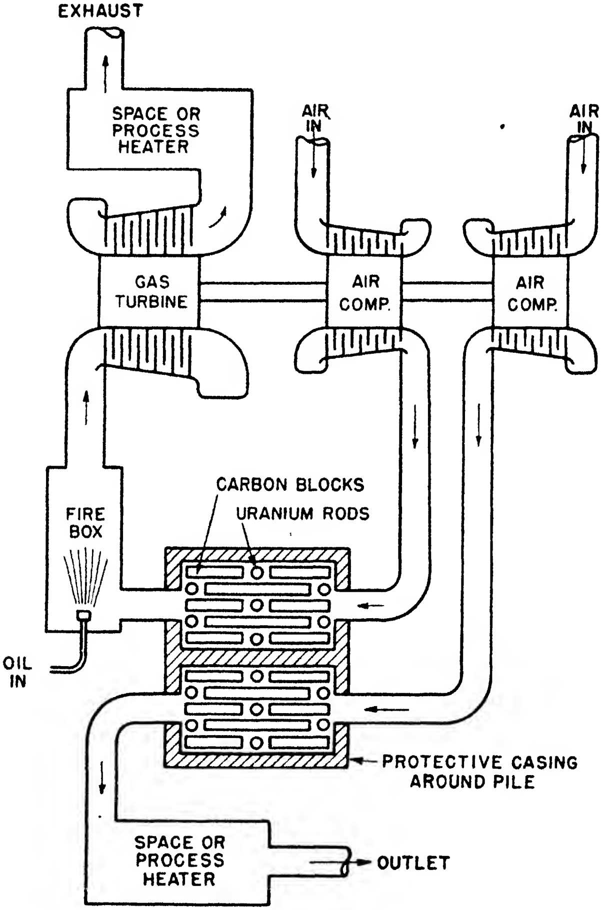


Figure 8. Combination Gas Turbine Unit and Uranium Heating Pile.

The arrangement shown in Figure 8 is similar to that in Figure 3. An additional compressor is used for the purpose of blowing air into the pile in order to cool it, the air later being utilized for heating purposes within a factory, either as space heating or process heating, and drying. Figure 8 does not show cooling pipes, but instead it shows simply the pile of uranium and carbon. The uranium and carbon may be so arranged that pipes are not necessary. Possibly, the uranium may be "canned" — that is, placed in air-tight aluminum containers. These containers of uranium, of course, could have integral fins to assist in cooling, thereby permitting the blowing of air across them, without the need for complex auxiliary cooling channels.

In Figure 8 the firebox is shown because here, as well as in Figure 3, the air temperature may not be sufficiently high, and additional heat may be required before the air enters the turbine. In addition, the firebox can take care of variable loads, allowing the pile to run at the temperature which best suits its characteristics.

Summary

In summation, there are two types of piles: one with normal ore, and one with concentrated ore — that is, normal ore with U–235 added. The eight illustrations in this chapter show various methods of producing power from the heat produced in the manufacture of plutonium. How the radioactive by-products are to be taken care of is not described in this chapter. We know that the pile is well protected, as is the equipment for handling the uranium and carbon within the pile. The radioactive by-products found in the cooling water or cooling air will have to be eliminated in certain cases. However, these radioactive by-products may or may not be sufficient to warrant the use of much additional equipment. Many obstacles have already been overcome, and elimination or reduction of radioactive by-products should not be as difficult as some which have already been hurdled.

Power plants, as illustrated in this chapter, would not necessarily be used by an industry which decided to produce its own power instead of buying from a public utility. Such an industry would have to be capable not only of operating the pile, but also of properly refining the plutonium. Large chemical industries of certain types would be in a favored position to operate the piles economically.

The Manhattan Project has in operation several huge plants built for the primary purpose of producing plutonium and uranium 235. The work done in portions of these plants can be combined with peacetime chemical industries for the purpose of producing economically from one plant a variety of chemicals, plutonium, uranium 235, and electric power. This same plant may also produce, by the use of atomic energy, various rare elements of value in industry or elsewhere.

Chapter II

Power Direct from Uranium or Plutonium

ATOMIC energy, U-235, and plutonium are known to most people only through the highly destructive bomb used against Japan, but even explosive atomic energy might possibly be used to drive a reciprocating engine. Gunpowder is an explosive; yet it was used to start gasoline engines years before the electric starter was developed. A shotgun shell, with the shot removed, was placed in the head of the engine; and the explosion pushed the piston to start the engine.

Generation of Steam

According to *Atomic Power Magazine* of August 7, 1945, published by McGraw-Hill, uranium 235 is self-governing when used to produce power. It was suggested that a block of uranium of a given size be placed in a container, the uranium being perforated so as to allow water to flow into it. The hydrogen atoms in the water have the effect of slowing up the neutrons thrown off from the uranium, enabling the neutrons to hit and explode a uranium nucleus. The released energy causes a temperature rise in the water even to the boiling point. The temperature of the cooling medium, whether it be water, air, or some other fluid, depends on the activity of the uranium.

If the liquid used for slowing down the neutrons is also used for cooling, the liquid may be converted into vapor or steam to operate a turbine. We would then have an ideal arrangement, but not necessarily the most economical, because such an arrangement would only be possible with a material rich in uranium 235 or its equivalent. For example, we obtain heat by burning coal because it is cheap. If coal were more expensive, many by-products would be taken out of it before it was burned. Since concentrated uranium is expensive, it may be broken down into many valuable substances rather than being used exclusively for power. In the process of breaking uranium down, energy will be released which may produce steam or hot gases for use in either a steam or gas turbine.

In Figure 4, instead of having a pile of concentrated uranium ore, let us assume we have a perforated block of pure uranium 235. The action of uranium on the water would produce steam in sufficient quantity to operate a turbine or for other purposes.

Liquids other than water may be used to better advantage, as in Figure 5, where mercury is the liquid. Mercury can be a cooling medium, but what mercury would do if forced through perforations in one or more properly spaced blocks of uranium 235 is problematical.

The Gas Turbine

The first gas turbine patent was taken out by John Barber of England in 1791, only two years after the discovery of uranium by Martin H. Klaproth. Apparently Hero, the Greek, in the years before Christ, was aware of the principle implied in gas and steam turbines. Today the gas turbine is becoming commercially feasible and uranium has emerged from the laboratory; both have unusual potentialities for development, providing hitherto unplowed fertile fields for exploitation by the engineer.

Figure 9 shows an elementary turbine wheel, either steam or gas. The cylinder may act as the combustion chamber or energy release element, if we are using some form of atomic energy. In either case, the energy appears as a high-velocity jet of steam or gas, spouting from the nozzle and impinging on the blading system to drive the wheel.

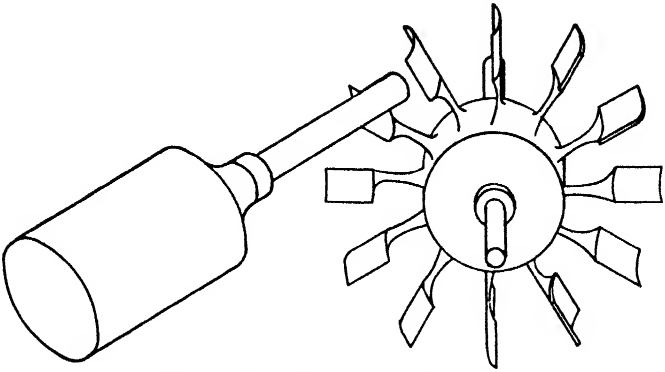


Figure 9. Elementary Gas Turbine Wheel.

Figure 10 illustrates a normal open-cycle gas turbine power plant. A normal gas turbine plant designed for good fuel economy would have a heat exchanger. In the case of an atomic-powered unit, the heat exchanger is more necessary than ever, owing to the high price of atomic fuel as we

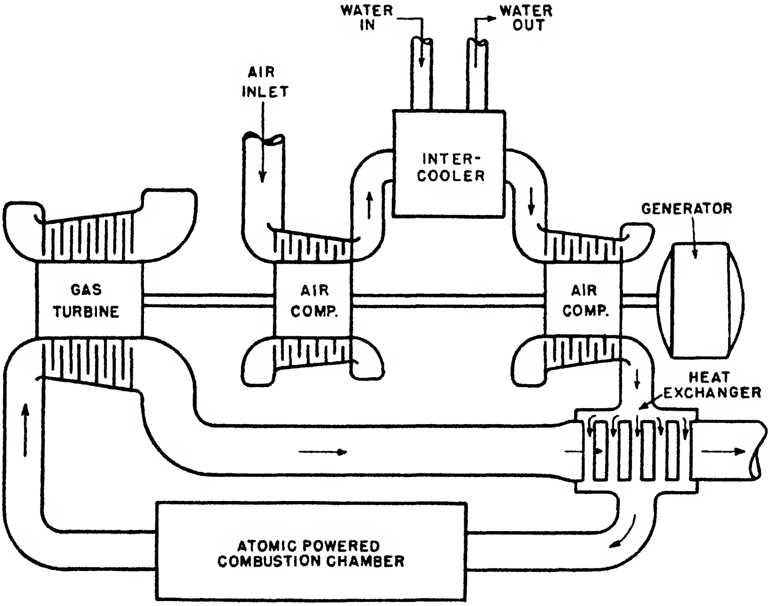


Figure 10. Schematic Arrangement of Open-Cycle Gas Turbine Plant Showing Location of Atomic-Powered Combustion Chamber If Used.

know it today. A large quantity of air (several hundred tons per hour) in the combustion chamber is obtained from the blowers which are driven by the turbine. Two blowers are used, with a water-cooled intercooler between them, an arrangement which appreciably decreases the power required to drive them. Consequently, the turbine net power is augmented, and the efficiency of the cycle is improved.

A unit of this type could be used in marine, central station, or industrial service, but would not be applicable to locomotive service unless the intercooler were omitted, because there are no facilities available for carrying large quantities of cooling water on board.

We have heretofore referred only to gas turbines of the open-cycle type. Figure 11 is given to show how the closed-cycle type of gas turbine functions when using atomic energy in the combustion chamber.

The turbines in Figures 10 and 11 are similar. Pure air or preferably a non-radioactive gas like helium is used over and over again in Figure 11; hence the name, *closed cycle.* In a closed cycle a precooler is needed to cool the compressor or gas. Thus a considerable amount of cold water is required, which makes the closed system unsuitable for all types of vehicles. However, the turbine shown in Figure 11 is ideal for developing high power in central station use. This is described in detail in the next chapter.

The fuel in the combustion chambers of the turbines illustrated in Figures 10 and 11 may be uranium 235 or plutonium, in either solid or liquid state. Here there are many problems yet to be solved. Even today, because of the ash residue which may literally eat away the blades, we cannot satisfactorily burn ordinary coal in a gas turbine plant. Research is in progress with a view to perfecting the burning of coal in gas turbines, and a solution may be found within the next year. One such development program is being sponsored by the Locomotive Development Committee of the Bituminous Coal Research Institute under the direction of Dr. J. I. Yellott.

It is possible that when atomic energy is used in the combustion chamber of Figure 10, the blades may be literally eaten away due to radioactive by-products, a defect which would be not likely to occur in the arrangement shown in Figure 11. Enormous obstacles to the safe handling of radioactive by-products have been overcome, and these same precautions may be required wherever radioactive by-products are encountered by the production of atomic energy.

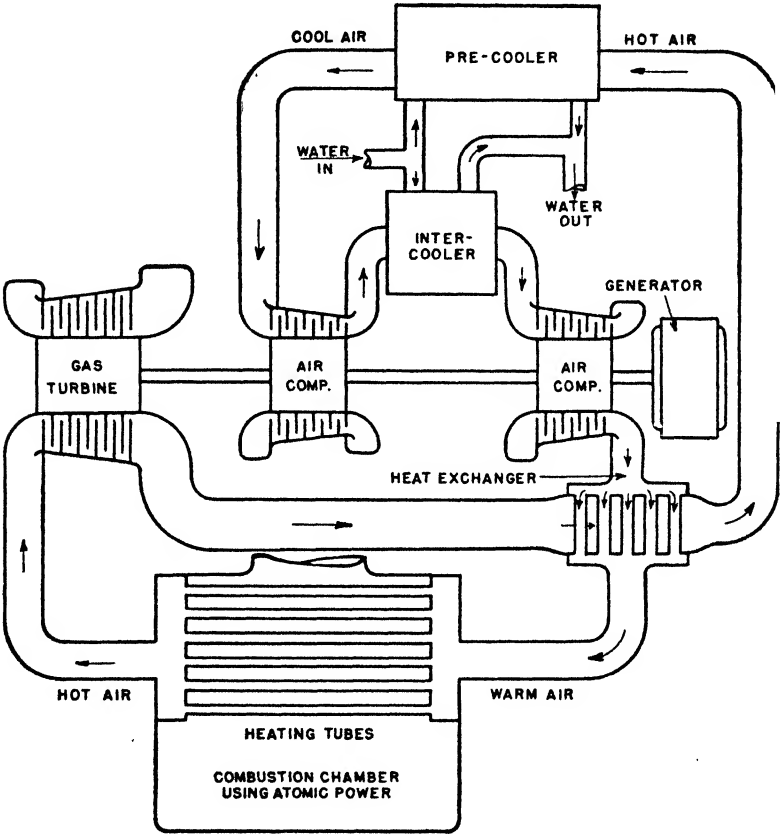


Figure 11. Schematic Arrangement of the Closed-Cycle Gas Turbine Plant Showing Location of Atomic-Powered Combustion Chamber If Used.

It will be many years before a gas turbine will be used to drive the family automobile whether the fuel be oil or atomic energy even if the passengers are protected from radioactivity by light-weight shielding. The normal rating for gas turbines is above 2000 hp when burning present fuels, but may some day exceed 200,000 hp in a single unit with atomic energy. The highest capacity of a single steam turbine unit today is 208,000 kw. In any case, it looks as though the horsepower range of the open-cycle gas turbine will be 2000 to 20,000 hp; and outputs above 30,000 hp will be obtained with the closed cycle.

A Possible Simplified Atomic-Powered Turbine

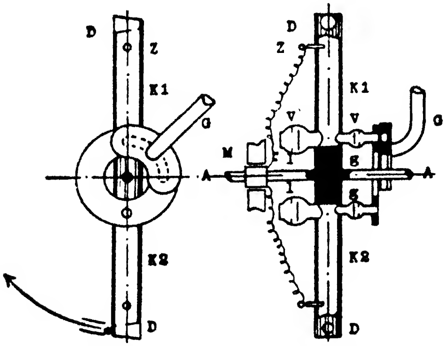
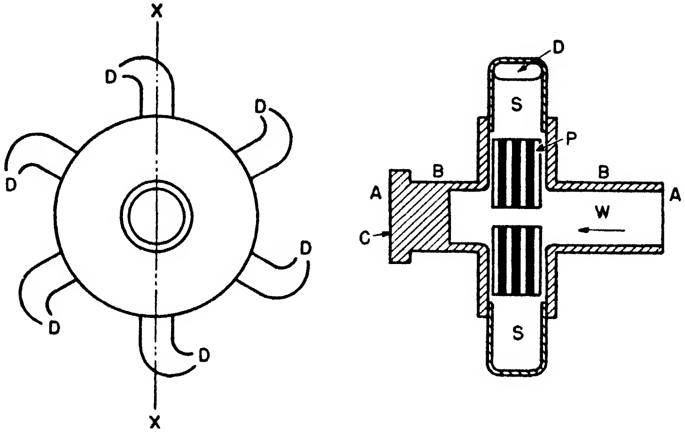


Figure 12. Gas-Burning Gas Turbine of an Early Design.

Figure 12 has been taken from a book published in 1908 by C. J. E. Volckmann in Rostock, Germany, and written by Dr. Wegner-Dallwitz. It illustrates what probably is the simplest type of gas turbine ever devised for the purpose of turning a shaft. *G* is the fuel inlet, which admits manufactured gas through a rotary valve into a small check valve shown as *g*, and then into the combustion chambers K_1 or K_2. Here the gas mixes with air which comes in through a large check valve, shown as 1. The spark plug *Z* is used for igniting this mixture. Force from the explosion goes out through the jet *D*, making the turbine turn in the direction of the arrow. The turbine shaft power can be used in a generator or otherwise. As the propulsion of this unit arises from the jet, it must rotate at a very high speed in order to be even moderately efficient, which makes necessary a reduction gear between the shaft and the driven element.

It has been suggested that this type of turbine could be used with atomic power, making an extremely simple unit as shown in Figure 13. This unit has multiple combustion chambers, each combustion chamber containing atomic fuel. The shaft is hollow to admit a supply of air or fluid. After this air or fluid is forced through the atomic fuel by centrifugal force, it is ejected at the nozzles *D*, thus rotating the turbine. This turbine is simple compared to that of Figure 12, and, since it has few parts, its maintenance cost should be unusually low. The fuel within the turbine should last for a long period of time, possibly a year or more.



SIDE VIEW

CROSS SECTION "X-X"

W = WATER OR FLUID
A = SHAFT
P = PILE OF URANIUM AND CARBON
S = STEAM CHAMBER
D = NOZZLES
B = BEARINGS
C = COUPLING

Figure 13. Modification of Design Shown in Figure 12 Making the Turbine Suitable for Using Atomic Energy.

The Atomic-Powered Rocket

Another method of obtaining useful mechanical work from atomic energy is found in rocket propulsion. Figures 14 and 15 show the relationship between a bomb and a rocket. The bomb (Figure 14) is sealed, and the internal gaseous pressure developed imposes equal forces on all areas. The bomb, therefore, has no tendency to move, but blows apart in all directions, if the pressure is great enough. The rocket (Figure 15) is similar to the bomb, except that an orifice at the tail permits the high-velocity gases to escape gradually. The rocket walls are designed to withstand the internal pressure. While the internal pressures against the sides are balanced, the force exerted against the head of the rocket is greater than that exerted against the rear because of the opening. The rocket is therefore propelled forward, as shown by the head of the arrow in the illustration. The tail feathers of the arrow correspond to the issuing jet of gases.

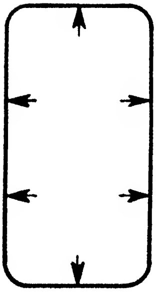


Figure 14. Bomb.

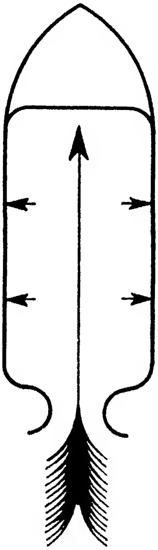


Figure 15. Rocket.

Other things being equal, the propulsive force acting on a rocket depends upon the nature of the explosive used. TNT, for instance, is more powerful than the gunpowder used in rockets for fireworks. In rocket warfare, still more powerful explosives, liquid as well as solid, are used. The solid explosives are primarily suitable for short-range work. The most common liquid explosive is a combination of liquid oxygen and gasoline or alcohol, employed in a long-range German V–2 rocket.

The acceleration of the V–2 rocket was, at the start, equal to about 1 g (32 ft per second per second), and increased to 5 g by the time the fuel was consumed. At this point the speed was approximately 1 mi per second, the maximum altitude was over 20 mi, and the time of flight was about 1 min.

A rocket using atomic energy may be able to exceed a speed of 7 times the V–2, or 7 mi per second, which means that this rocket is capable of being shot up away from the earth never to return.

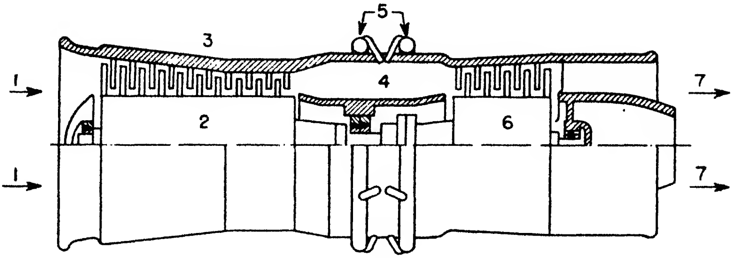
For passenger use, acceleration should be limited to about 4 *g*, or 129 ft per second per second, which is the acceleration attained by a high-speed elevator. The human body can withstand only a certain maximum acceleration, so that a passenger rocket would have to act like an elevator; it would not, however, stop at the 100th floor but would continue to accelerate at a uniform rate until the desired speed was reached.

Building such a rocket is one way of converting atomic energy into mechanical power. When such a rocket is built to carry passengers, it will be possible to "shoot the moon"; some will even say, "*Why* stop at the moon; we can now shoot the universe!"

A description of the many uses to which such a rocket can be put is beyond the scope of this book. Atomic power is the only power now known which will make it possible for people to leave the gravitational field of the earth.

Possible Construction of Atomic-Powered Jet-Propulsion Units for Rockets or Planes

Figures 16 and 17 illustrate two types of gas turbine jet-propulsion units. Figure 16 is the ideal type of atomic-powered unit, similar in design to that now normally used in airplanes, and burning a high grade of fuel oil. The design includes two pipes leading into the combustion chamber, on the assumption that, when the material carried by these two pipes comes together in the combustion chamber, atomic energy is released. The air comes into the left side of the unit, is compressed in the compressor, and then enters the combustion chamber, from which it goes to the turbine and exhausts as a jet. The purpose of the turbine is to drive the compressor, which provides the air for the jet. So that the excessive heat will not injure the turbine blades, a large amount of excess air is used to reduce the temperature in the combustion chamber.



1- AIR INTAKE
2-AIR COMPRESSOR ROTOR
3-CASING
4-COMBUSTION CHAMBER
5-PIPES FOR ADMITTING LIQUID TO 4
6-GAS TURBINE
7-EXHAUST OR JET

Figure 16. Possible Construction of Atomic-Powered Jet Turbine Unit.

Figure 17 illustrates a combination rocket and gas turbine jet-propulsion unit. In this case the actual jet, instead of passing through the turbine, goes directly to atmosphere. The gas turbine is used only to drive the compressor, which forces air around the combustion chamber to assist in cooling it. The cooling air is heated and then used to drive the turbine. The compressor also furnishes additional air, which is directed into the combustion chamber. When this air mixes with the fuel material, atomic energy release takes place, causing continuous explosive combustion. The air used in the combustion chamber is also used to reduce the temperature. We are unable, at this time, to predict what material can be used in the construction of the rocket combustion chamber. The air surrounding the chamber does have a cooling effect, but actually some supplementary method of cooling may also be required. The present method of cooling a high-powered rocket is by circulating the liquid fuel itself around the jet opening. This method of cooling may possibly be used with the atomic-powered rocket.

In Figure 16, no protection is given the turbine blades from radioactive by-products, while in Figure 17 the turbine

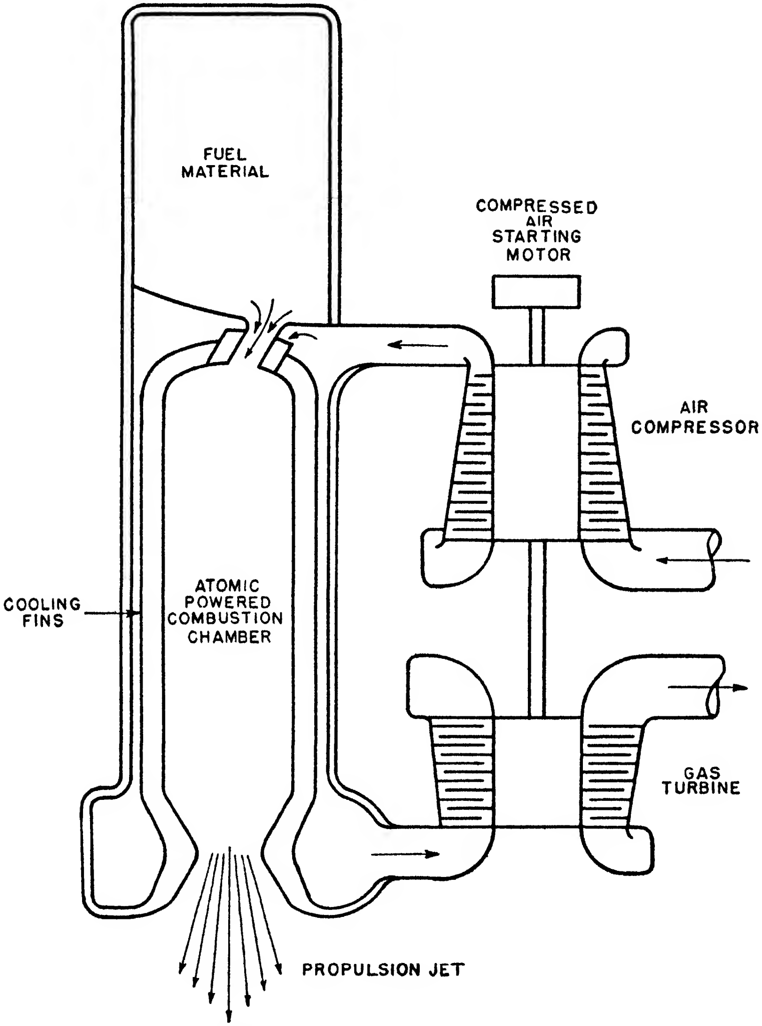


Figure 17. Possible Construction of Atomic-Powered Rocket, Using Gas Turbine for Cooling.

air obtains heat only by indirect transfer, not from the air coming directly from the outlet of the combustion chamber. The outlet shown in Figure 17 forms the jet, which causes a tremendous pressure against the head of the unit, thus driving it forward.

The Diesel engine and the type of furnace placed under a boiler still contain many combustion problems. The chief problem of the turbines shown in Figures 16 and 17, or in Figures 10 and 11, is the proper control of atomic power so that its energy will be released smoothly and regulated as desired. In Figure 16, two different materials are brought together on the assumption that their meeting will cause fission. The combustion problem in Figure 17 is approached from an entirely different viewpoint. In this case, only one material is used, say plutonium, which is placed in the fuel bin only after having been packaged or canned in bits about the size of marbles. Some type of injecting device would be necessary to regulate the flow of these plutonium "marbles" and at the same time strip the casing from around each "marble." All such thoughts on the subject of control of atomic energy, and there are many, can be grouped as "combustion problems."

Thus there are many ways of employing uranium 235 or plutonium usefully to produce power when we once learn the secret of how to control properly these two powerful atom-smashing elements. It may be years before we are in a position to control completely either these or other similar elements, but when the time comes, engineers will design new types of prime movers or adapt existing types to handle atomic power.

Chapter III

Construction of an Atomic-Powered 35,000-Horsepower Gas Turbine Plant

Abstracted from material submitted by Dr. Curt Keller, Director of Research and Development, Escher Wyss Engineering Works, Zurich, Switzerland

THE CLOSED-CYCLE gas turbine power plant using helium or helium mixtures appears to be one of the best systems for generating power by the use of the uranium pile. For this reason Dr. C. Keller, a world authority on closed-cycle systems, was asked to contribute the information embodied in this chapter. Helium is not affected by the radioactive rays produced by a uranium pile, and for that reason helium or a helium mixture with carbon dioxide is ideal for use in a gas turbine plant requiring a uranium heater. Helium does not absorb the neutrons, but slows them down, like graphite.

If air is used, not only will the nitrogen in it pick up some of the radioactive rays and particles, but the oxygen in air will tend to burn up graphite parts when the turbine operates with a uranium heater in the closed cycle at high temperatures and pressures.

Dr. Curt Keller read an excellent paper before the annual meeting of the American Society of Mechanical Engineers in November 1945. This paper was sponsored by the Gas Turbine Coordinating Committee of the Oil and Gas Power Division of the Society. The paper described in detail the AK closed cycle and its equipment, but did not indicate wherein the closed cycle could be used with a uranium heater. This chapter goes far beyond the scope of Dr. Keller's paper in order to include the uranium heater, which requires a helium mixture in the system to operate with the best results.

It is assumed that the 35,000-hp plant which Dr. Keller describes in his paper could be built within the next few years, when all necessary data have been collected.

General Construction of Plant

Unlike combustion gas turbines, little has so far been reported about the gas turbine process employing a closed cycle. The first plant of this kind, an experimental installation of 2000 kw useful output, was completed in Switzerland during the summer of 1939 just before the outbreak of World War II. The enforced seclusion of Switzerland during the following 6 years, and more especially the interruption of communications with America, prevented scientists here and elsewhere from examining and discussing the new AK plant developed by the Escher Wyss Engineering Works in Zurich according to proposals made by Ackeret * and Keller. However, in spite of the many difficulties arising from the war, the experimental plant was tried out until normal industrial operation was reached, and all its components were fully investigated. In December 1944 Professor H. Quiby (the successor of Professor Stodola at the Swiss Federal Institute of Technology in Zurich) carried out exhaustive official performance trials on the new plant. A report on these trials was published in June 1945 in the *Revue Polytechnique Suisse* † and in Dr. Keller's paper of November 1945, previously referred to.

These official trials represent the termination of the first phase of internal scientific development, and the results obtained have justified in every respect both theoretical and practical expectations. Projects for power generation or ship propulsion embodying such closed-circuit plants, with

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* Professor of Aerodynamics and Flow Mechanics, Swiss Federal Institute of Technology, Zurich.

† English translation in *The Oil Engine,* London, November 1945.

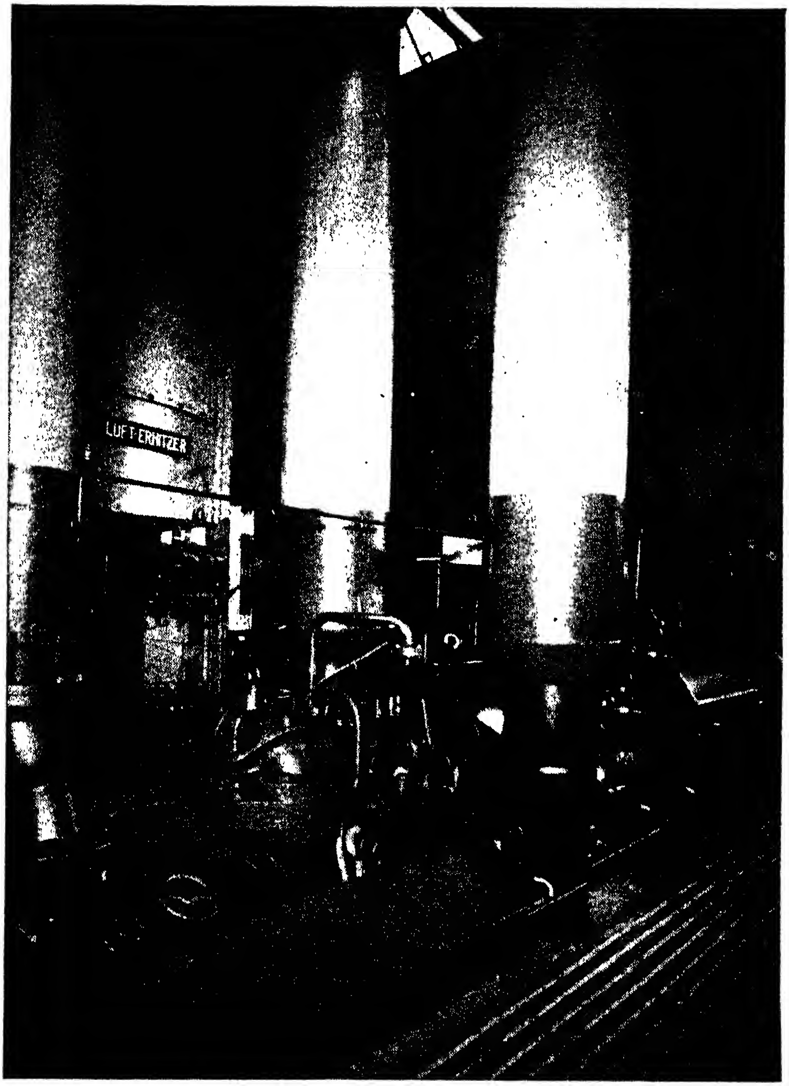


Figure 18. AK Closed-Cycle Test Plant of 2000 kw. The compressor is in the foreground with high-pressure turbine driving it. The low-pressure turbine is in the background driving the generator in the rear. The other two compressors located to the left are not shown. Part of the air heater is shown in the background.

air as the working medium, can now be realized without technical risks, on the basis of preliminary studies extending over a number of years.

Since 1939 a number of original articles have been published regarding the theoretical and the physical basis of the AK process. These are now accessible to American engineers (several articles have already been printed in English). It suffices, therefore, to give a brief summary of the chief characteristics of the new process as an introduction. Some information, but not all data, has been provided in the preliminary Escher Wyss report which was read by R. T. Sawyer and discussed by S. A. Tucker during the June 1945 meeting of the American Society of Mechanical Engineers.

In 1945 the Escher Wyss Works had been favored by a number of visits from American engineers, where information concerning the development work in connection with these AK plants was given them and the trial installation itself was explained. As a consequence, work in this field has become known among a wider circle of specialists.

After about 10 years of intensive development and research, Escher Wyss believe they have realized a simple and highly efficient machine for stationary power plants. These results have not been brought about by inventors' tricks but are the outcome of consistent and consequent application to turbo-machines of new knowledge from the fields of flow mechanics, aerodynamics, and metallurgy.

The first trial plant (Figure 18) uses oil for fuel. It is primarily an experimental installation, all components being arranged wide apart so as to facilitate the use of diverse measuring equipment. The maximum pressure is about 350 psi abs (output 2000 kw) direct expansion with a pressure ratio of 4. Wartime conditions, with the consequent impossibility of replacing damaged parts, made it imperative to exercise great care in carrying out the trials, and fortunately no particular difficulties were encountered. In the years intervening between the completion of the plant and December 1944, when the official performance tests were carried

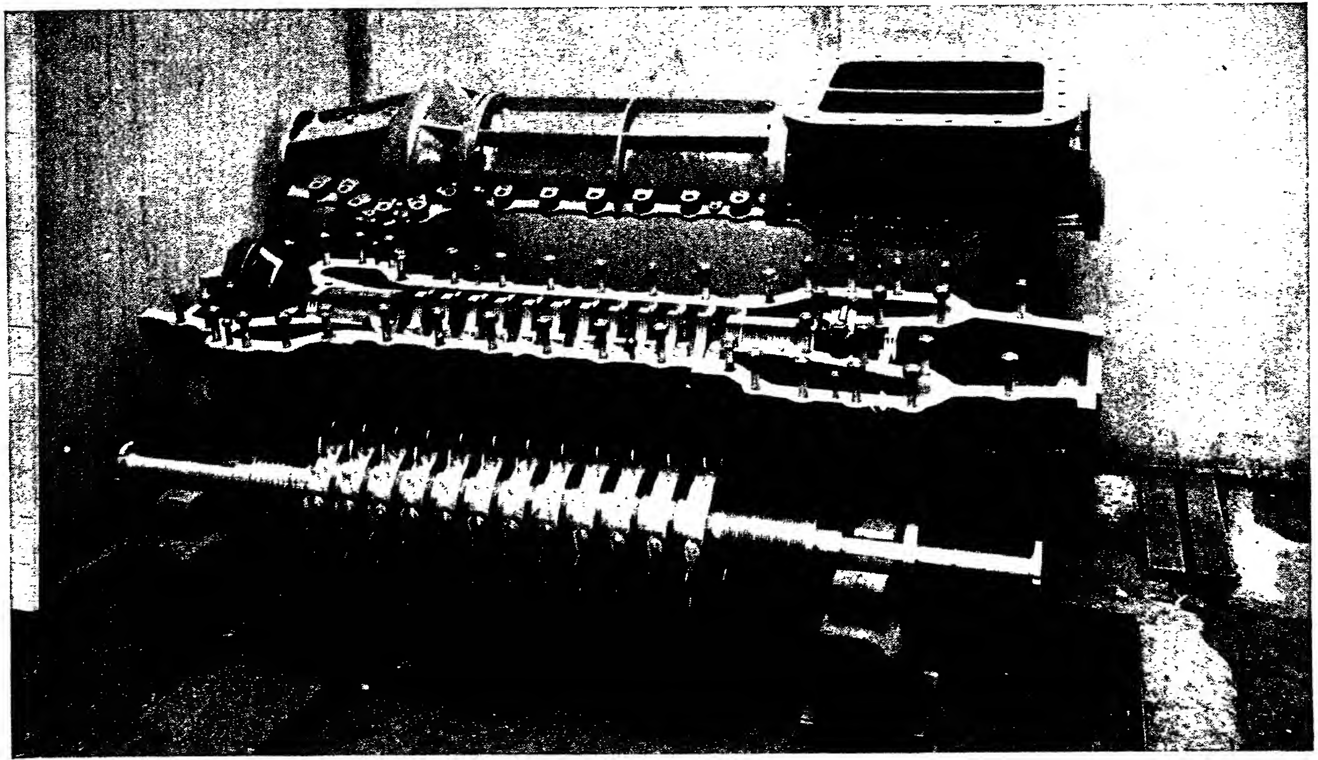


Figure 19. Compressor with Top Half Removed Showing Rotor Removed.

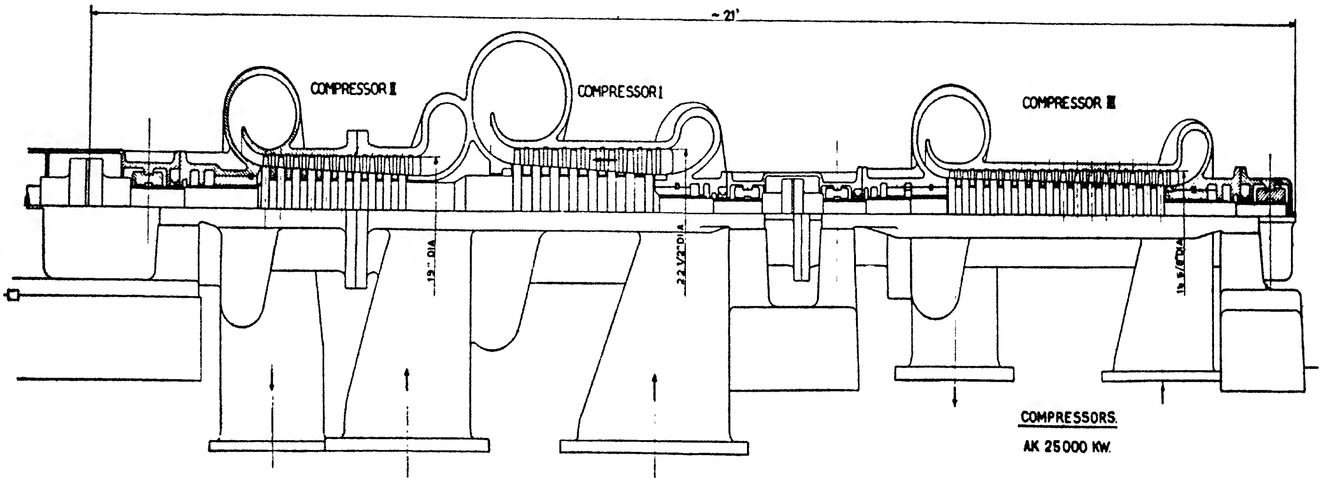


Figure 21. High-Pressure Axial-Flow Compressors for the Plant Shown in Figure 20.

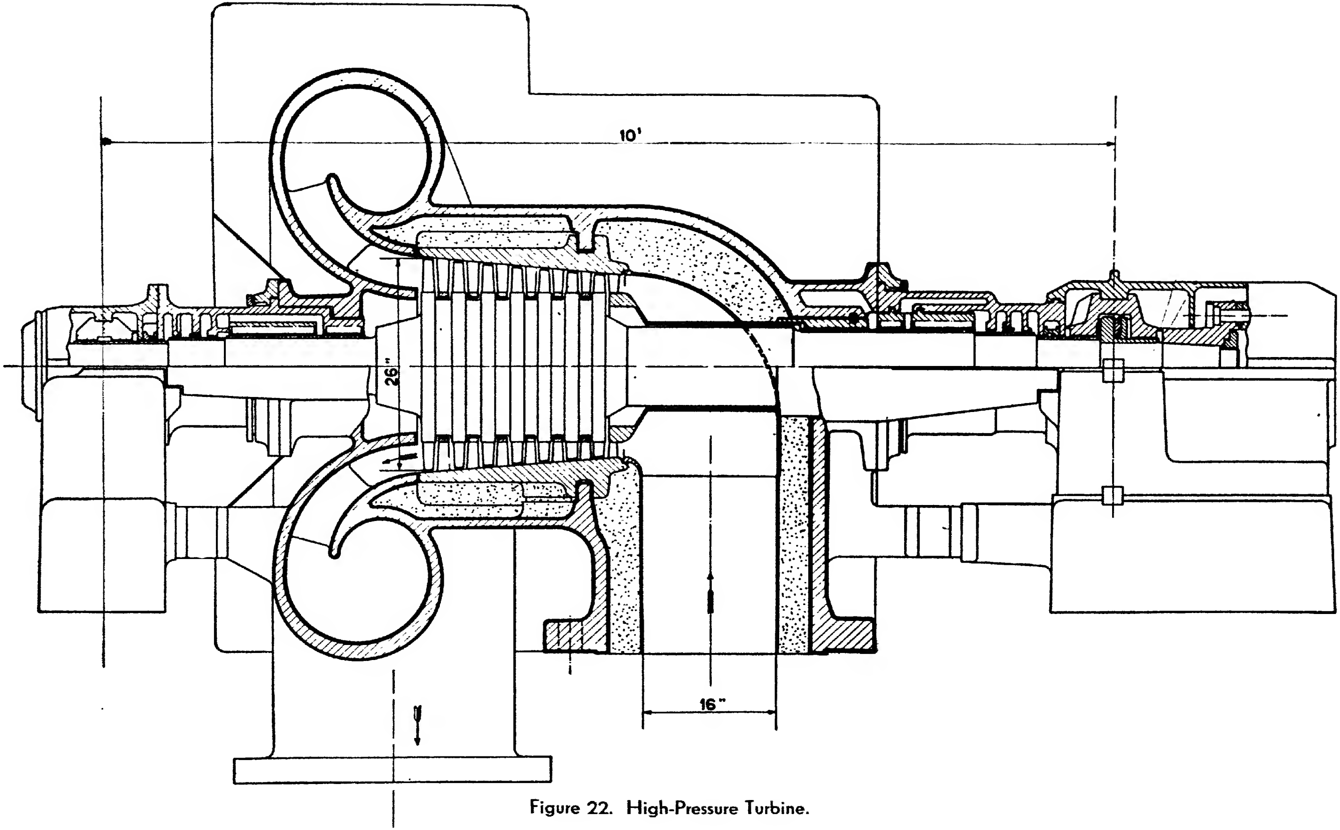


Figure 22. High-Pressure Turbine.

and compressors, while no temperatures exceeding 785° F need be adopted for the heat exchanger, thus permitting the use of ordinary steel tubing.

In all gas turbine processes, a good heat exchanger is necessary for attaining good over-all efficiencies. With the closed cycle, the conditions are particularly favorable. The high density and purity of the air or other gas, on the high-pressure and low-pressure side, permit the use of ordinary steel tubes of small diameter. Compared to open-cycle combustion turbines, the heat transmission coefficients are increased manifold (for example, 30 to 50 Btu per square foot *h*° F) and a heat exchanger efficiency of about 90 per cent is attained.

Figure 21 shows the cross section of the three compressors driven by the high-pressure turbine. Note that compressor I is the low pressure of the three; compressor II, the intermediate; and compressor III, the final high-pressure unit. Compressors I and II are on the same shaft; this shaft is coupled to compressor III at one end and the high-pressure turbine unit at the other end. The compressor is of the Escher Wyss axial-flow type.

Figure 22 is the cross section of the high-pressure turbine which drives the compressors shown in Figure 21. The cross section shows the 7 rows of rotating turbine blades between the stationary blades. In Figure 23 the low-pressure turbine has 10 rows of rotating blades between the stationary blades. Particularly note that the hot gases go out of this turbine directly into the heat exchanger located on the right, without the use of piping. Figure 20 shows the outside view of both the low-pressure turbine and heat exchanger; the precooler is on the other end of the heat exchanger.

The following data, which are based on the present state of progress in the use of air, concern installations such as have been described for oil, coal, and gas firing:

Efficiency, 34–37 per cent at full load, and 30–33 per cent at ⅕ load, all auxiliaries included.

Pressure, 850/85 psi.

Temperature into turbine, 1200° F.

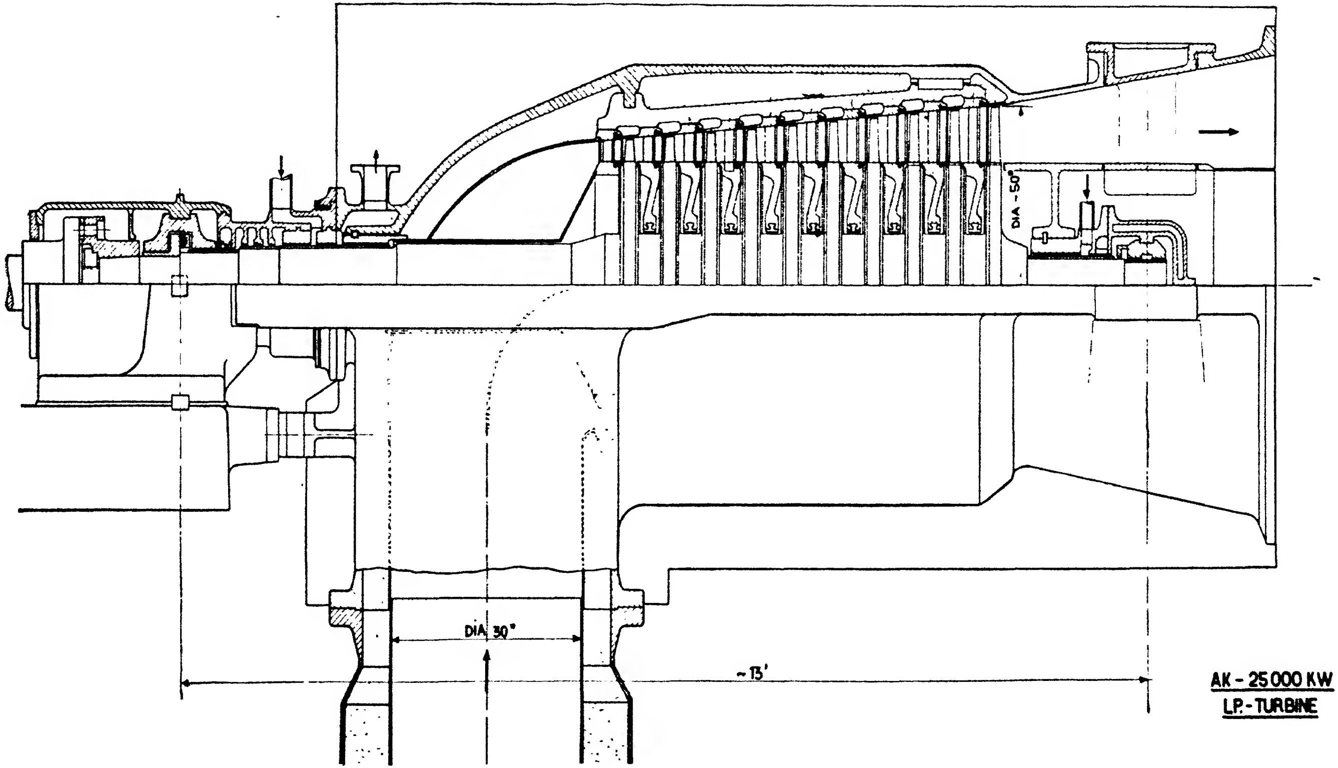


Figure 23. Low-Pressure Turbine.

Weight, about 40–50 lb per kilowatt, of which only 16 per cent is alloyed steel.

Cooling water, 80 gal per second with 60° F inlet, 160° F exit temperature.

Heat-exchanger surface, 1.5–3 sq ft per kilowatt.

Turbine diameter: high pressure, 26 in.; low pressure, 50 in.

Compressor diameter, 16–33 in.

These data are in accordance with the information indicated on Figure 24, which illustrates the complete cycle. This system uses air within the closed cycle and all figures are on this basis. If a helium mixture were used, these figures would be modified.

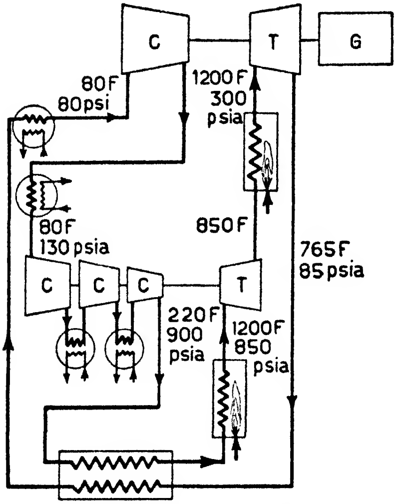


Figure 24. Diagram of Air Flow in Power Plant of Figure 23. T, turbine; C, compressor; G, generator.

To trace the flow of air through the system, let us start at the air going into the low-pressure compressor *C*. It then comes out of this compressor and is cooled back to 80° F before entering the series of three high-pressure compressors. Inter-cooling between compressors is necessary and is shown. Coming out of the compressors, the air goes to the heat exchanger and then to the first heater. If helium or a helium mixture is used in the system, the heaters would be similar to those shown in Figure 27, which illustrates the uranium pile. After the air or helium mixture goes through this first heater, it passes through the first, or high-pressure, turbine to the second heater, which gives about the same amount of heat to the working medium as the first. From the second, or low-pressure, turbine the air or helium mixture goes to the heat exchanger and from there to the cooler, before entering the low-pressure compressor again.

Helium

If a helium mixture is used in this system, unusual efficiencies may be expected, as shown in Figure 25, without having metals of unusual constructional material. This shows that a thermal efficiency of over 50 per cent (based on calculations by Professor Ackeret) may be expected, which is unusually high in any type of prime mover. The attainment of this degree of thermal efficiency will be possible only when good data for machines and apparatuses are available.

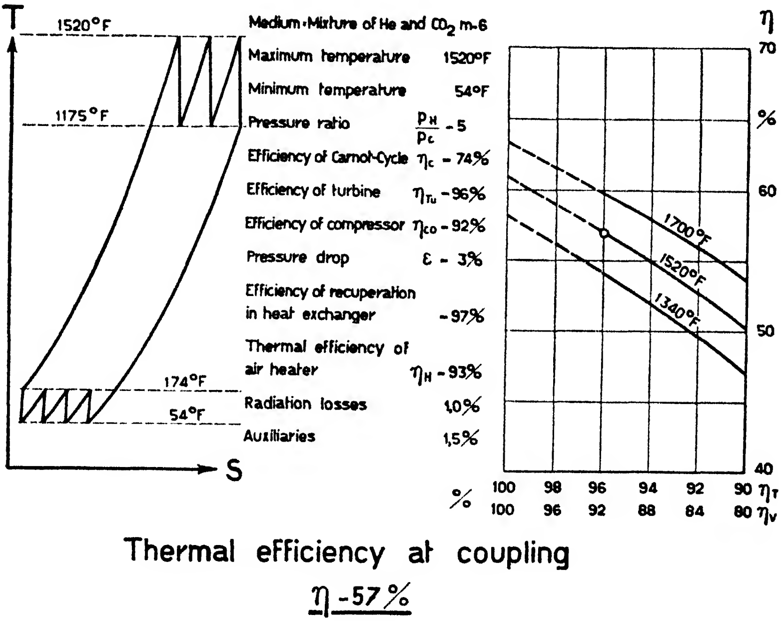


Figure 25. Ideal Efficiency Values Using Helium Mixture in AK Power Plant.

Working media other than air can only be adopted in the case of a closed circuit having an external supply of heat. The employment of suitable light gases, such as helium, opens the possibility of substantially increasing the output of the plant for the same dimensions, or of further raising its efficiency, as a consequence of the adaptability for special purposes of the particular physical characteristics of such gases.

TABLE I

A COMPARISON OF VARIOUS GASES FOR THE AK PROCESS

(Machines assumed to have equal output and maximum pressure, temperature, and triangles of velocity. T = constant; p = constant.)

	Air	He + CO_2	He + CO_2	He	H_2
Mean molecular weight	29	8	6	4	2
Specific heat (Btu per pound °F)	0.26	0.755	0.90	1.25	3.5
Ratio of viscosity (T = constant)	1	1	1	1	0.5
Ratio of sound velocity	1	2.1	2.4	3.0	3.9
Adiabatic pressure ratio for temperature ratio	4.0	2.92	2.71	2.52	3.65
CO_2 (per cent by volume)	1.45	10	5		
Number of stages (constant circumferential velocity — ratio)	1	2.8	3.5	4.8	13.5
Circumferential velocity (constant number of stages)	1	1.75	1.9	2.2	3.7
Diameter (constant number of stages -- ratio)	1	0.76	0.73	0.68	0.52
Revolutions per minute (constant number of stages)	1	2.30	2.6	3.3	7.1
Heat exchanger:					
Coefficient of heat transmission (ratio)	1	1.86	2.12	2.56	4.35
Number of tubes (ratio)	1	0.66	0.62	0.56	0.27
Length of tubes (ratio)	1	0.82	0.76	0.70	0.85
Surface area of tubes (weight)	1	0.54	0.47	0.30	0.23
Heater:					
Coefficient of heat transmission (on one side)	1	1.6	1.7	2.0	4.0
Number of tubes (ratio)	1	0.78	0.75	0.68	0.30
Length of tubes (ratio)	1	0.82	0.79	0.74	0.85
Surface area of tubes (weight)	1	0.64	0.59	0.50	0.25

A careful study of Table I, the data of which have been established after studies by Ackeret for the American Society of Mechanical Engineers meeting, shows the relative merits of helium or helium mixture compared with air. It is of value to know that these gases have better characteristics than air, because in the uranium pile air will pick up some radioactive rays, while helium at high pressures is the ideal gas to use for cooling the uranium pile. It should be kept in mind that Table I applies to units of 30,000 to 70,000 net horsepower.

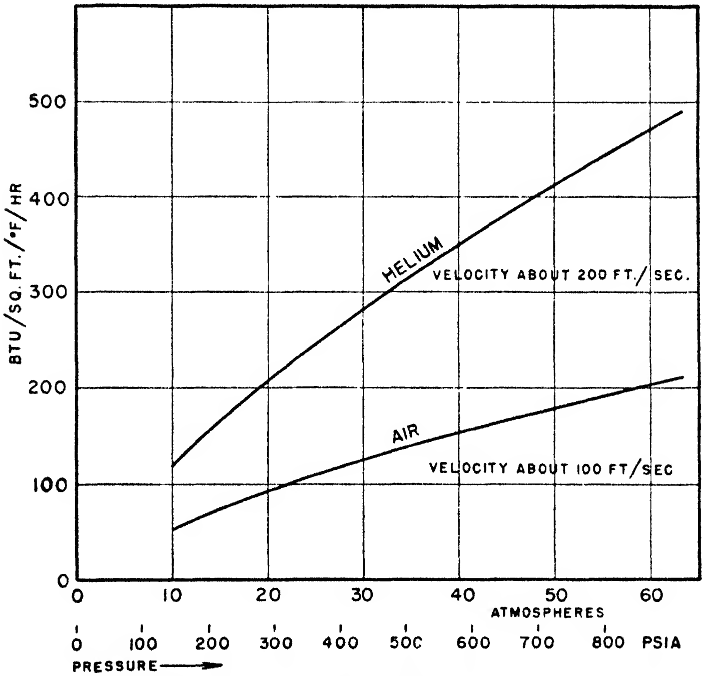


Figure 26. Comparison of Heat Transfer for Air and Helium in Tubes of 1.2-in. Diameter. Equal relative pressure drop, $E = \Delta p/p$, for helium and air.

Figure 26 clearly shows an advantage of helium as compared to air. The heat-transfer characteristics apply to the heat exchanger as well as to the heater. By the use of helium as the working medium, the heat-transmission coefficients in the heater tubes can become as large as with water without involving high-pressure losses. This fact is important as an indication that a gas turbine plant should be more efficient than a steam plant using water because the composition of water will vary, even depositing "boiler" scale. Helium or helium mixture, like air, would be a clean gas, giving the same blade efficiency after a long period of service as the gas did at the start. Even though helium does have the advantages of very high heat transmission coefficients, small relative pressure losses, and three times higher sound velocity than air, it has one serious disadvantage — it does cost money while air does not. For that reason helium can be used only in special cases, and an excellent special purpose is the use of atomic energy for creating heat.

Uranium Heater

In principle, the helium heater could be built much more simply than the usual air heater. In the latter, the compressed air is heated in tubes, like steam in a steam boiler. If helium is used in the cycle, it *could* be heated in the same manner, but it need not be. As helium is neutral (indifferent) to radioactive parts and pile material, it can be let directly into a pressure casing that is in contact with the hot pile. Suitable canals can be provided to get enough heating surface, because the heat transfer with helium is very high at the elevated pressures (500 to 1400 psi). In this way, no special heater tubes are necessary, and the uranium bars are cooled directly by the helium.

Let us regard the air-flow diagram of Figure 24 as a helium-mixture flow diagram. The pressures and temperatures would be slightly modified, but the arrangement of equipment would not change. (The choice of suitable pressures and temperatures for the helium cycle depends mainly on the constructional problems.) The helium-mixture heaters, which come just before the turbines in the air-flow diagram, would be of the uranium type shown in Figure 27, which illustrates the simple structure of such a "boiler."

The uranium heater under discussion has a core 15 ft square and 30 ft high. These figures are approximate because the size of the pile depends not only on the heat which can be given out to the helium, but also on the still yet unknown physical conditions (temperatures) at which the pile can operate in stationary service. That the dimensions can be kept even smaller may be possible in the future. Four of these units should be sufficient to take care of the 35,000-hp plant of Figure 20. Two of these uranium heaters will be used to heat the helium before it enters the first (high-pressure) turbine; and two will be required to heat the helium before it enters the second turbine, the low-pressure unit. It is suggested that a spare unit be provided. A large overhead crane can be used to replace the discharged unit with the spare, which means the power generating plant can be located in one place. The uranium heaters can be removed as necessary and transported to another building which is capable of handling the uranium and graphite separately.

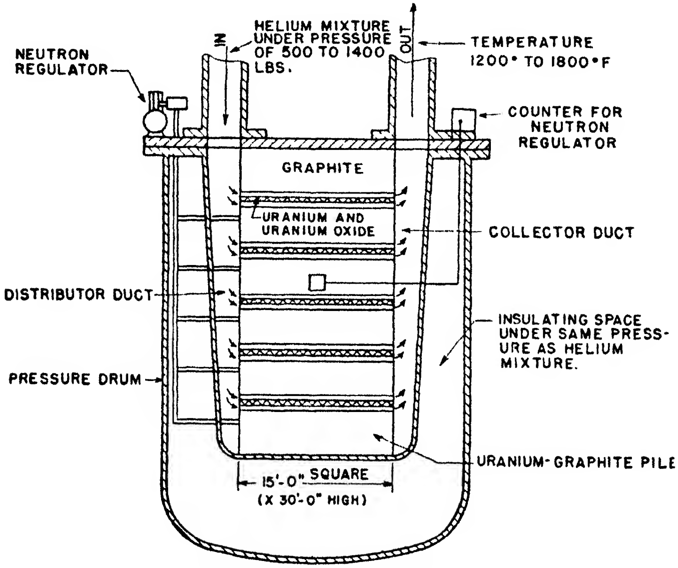


Figure 27. Construction of Uranium Heater.

The total powerhouse capacity may be 200,000 hp or more. A capacity of 200,000 hp requires six generating plants of

35,000 hp each and 24 uranium heaters. For such large capacities (50,000 or 200,000 hp) single generating units could be built. By using closed-cycle machines, this will be possible. All uranium heaters would be taken by the same overhead crane into the chemical building, where the contents could be properly handled.

The uranium heater is so designed that the top is easily removed and the graphite and uranium readily taken out and replaced. The uranium pile is placed in a square container, which admits and distributes the helium mixture. Before removing the top, the helium-mixture "supply" and "return" must be shut off, and the pressure relieved in the outer insulating space inside the circular pressure drum. This helium can be pumped into a storage reservoir for use in the next heater unit.

A counter, located in a suitable place, indicates uranium activity and is used to operate the neutron regulator. The neutron regulator moves in or out the cadmium or other metal which is used to regulate the activity of the uranium.

Summary

The closed-cycle gas turbine process, which was proposed some years ago by Ackeret and Keller, provides a new, promising means for getting high efficiencies from thermal power plants, without the need for complicated operating cycles. Compressed hot air of about 600 to 900 psi expands in turbines to a back pressure of 60 to 100 psi, and is recompressed and reheated. This supercharged cycle permits the use of very small rotating machines, in comparison with the normal open-cycle gas turbine, and is especially desirable for units with outputs of 20,000 to 50,000, and even 200,000 hp.

The closed cycle offers the unique possibility of using any suitable gas instead of air. Helium or helium-carbon dioxide mixtures give high efficiencies and small dimensions for special purposes. The properties of helium at high pressures, properties such as heat transfer, pressure drop, sound velocity, neutralness toward radioactive material and graphite make it possible to build tubular gas heaters of small dimensions, and enables us to place uranium piles directly in contact with the helium flow for the purpose of transferring heat to this flow. The size and efficiency of such an "atomic heater" and of a whole plant using a supercharged helium cycle are estimated to be more favorable than those of steam plants of the same output.

Chapter IV

Construction of Atomic-Powered Locomotives

SEVERAL types of atomic-powered locomotives eventually may be used on the railroads. The steam locomotive will benefit most by the use of atomic power because the uranium fuel U–235 will occupy a small space compared to coal, which requires a large tender. A steam locomotive tender, built for long through runs, may contain as much as 50 tons of coal; therefore the use of atomic power would eliminate the coal and the tender. The gas turbine locomotive should benefit by the use of atomic power. Today the gas turbine locomotive burns oil; shortly it will be built to burn coal. By using atomic power, no oil tanks or coal equipment would be required. At this time, it is hard to visualize how the Diesel locomotive can use atomic power within its combustion chambers (its cylinders). Doubtless, the Diesel locomotive will be used even after atomic-powered locomotives come into service, as each type of locomotive will have its place on the railroads.

The electric locomotive will not necessarily benefit by the use of atomic power, as it will obtain power from the overhead wire or a third rail regardless of how power is developed — unless, of course, fission of atoms will cause the generation of power directly in sufficient quantity and be capable of being controlled on a locomotive frame. If this should ever become the case, electric traction motors will be mounted on the driving wheels in the same way as they are now. The atomic-powered electric generating plant would be located on the top of the locomotive underframe. This, of course, would make an ideal locomotive, as the electrical generating equipment would in all probability have no moving parts, except possibly for cooling purposes.

Let us now analyze the future possibilities of the steam locomotive and the gas turbine locomotive which will no doubt be the two outstanding self-contained types of motive power in the atomic era.

The Steam Locomotive

The steam locomotive can be built in many different ways even though atomic power is used. The atomic-powered unit may be built like the conventional steam locomotive of today, using large driving wheels on a rigid wheel base, cylinders, pistons, and side rods. The boiler, however, would be very small compared to the present-day boiler, and, instead of carrying a large quantity of water on the tender, the water may be carried where the boiler is now located. Coal and the water tender would be eliminated except in desert regions, where large quantities of water may be required on unusually long runs, in which case a water tender may be necessary. Today, on the New York Central, the Pennsylvania, and similar railroads, a water scoop is used to pick up water from long troughs which lie in the center of the tracks along the right of way. Quantity of water is, therefore, no longer an important item on these railroads. The steam locomotive on the Twentieth Century, powered by atomic energy, would not have to stop anywhere from Chicago to Harmon.

An atomic-powered steam locomotive could be similar to the latest Pennsylvania Railroad experimental unit, which has a steam turbine geared to the four center driving wheels. Side rods couple all driving axles, an arrangement which permits them all to be driven together from the one steam turbine. One large turbine is used for operating the locomotive in the forward direction, and a small steam turbine, which is engaged through a series of gears, is used for propelling the locomotive in the reverse direction at reduced speeds, similar to the reverse gear in an automobile.

The Pennsylvania Railroad proposes to build a powerful steam-turbine locomotive of approximately 9000 hp with a possible wheel arrangement of 4–8–8–4. Such a wheel arrangement would be well suited to an atomic-powered locomotive if it is operated in special heavy-duty service such as is being planned for the proposed coal-fired turbine locomotive. This turbine locomotive has two sets of main turbines, one of which is geared to each set of drivers. An unusual feature is the location of a portion of the water in a hood ahead of the engineer.

What would the appearance of a steam locomotive be were it powered with atomic energy as we know that energy today? Based upon Dr. J. A. Wheeler's talk before the American Society of Mechanical Engineers on January 30, 1946, several feet of shielding thickness is required, so that it "might just be possible [for the locomotive] to carry such a shield through existing railway tunnels." This means that the "boiler" would be about 10 ft in diameter, having a shell about 3 ft thick. This leaves a space 4 ft in diameter within the "boiler." A space about 9 ft long within the "boiler" should be sufficient, which makes the "boiler" 15 ft long over all. This boiler would weigh in the neighborhood of 250 tons, or 500,000 lb. Such a weight could not be carried on the locomotive frame, but it can be carried on a specially constructed car. This car would have four 8-wheel trucks under it. If an axle load of 55,000 lb is used, the total weight of the car including the boiler would be 880,000 lb.

Figure 28 shows this boiler car and locomotive. The locomotive is similar to the conventional 4–8–4 type, using outside cylinders and side rods. This design is unusual and interesting, as a short hood can be located in front of the engineer's cab to hold train control and other equipment. The hood behind the engineer's cab would contain the water supply and can be shaped to suit locomotive balance and outside appearance. Allowing 40,000 lb axle load on the leading truck, 50,000 lb for each axle on the trailing truck, and

60,000 lb for each driving axle, the locomotive would weigh 420,000 lb. The locomotive together with the atomic boiler car would weigh 1,300,000 lb, or 650 tons.

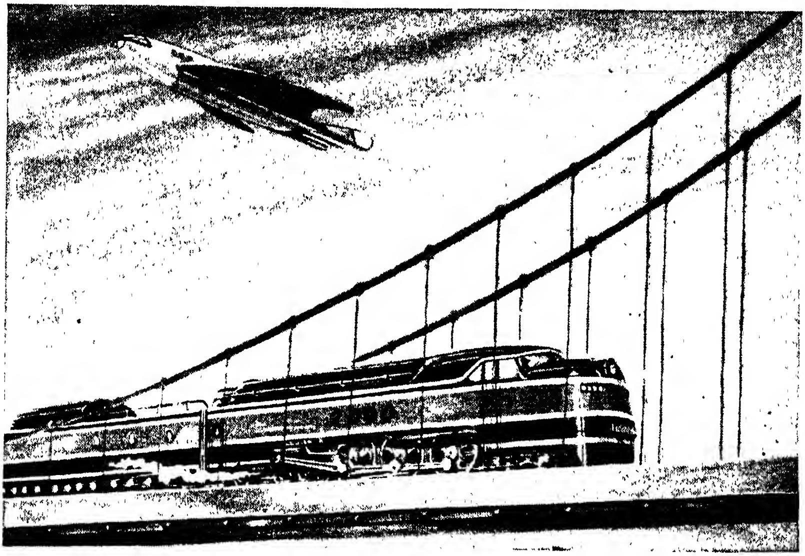


Figure 28. Proposed Atomic-Powered Steam Locomotive.

A locomotive of this weight would not be suitable in fast passenger service, but this additional weight would mean little when handling a 5000-ton freight train, especially on long through runs. This atomic-powered locomotive would therefore be well suited to heavy freight service on the long through runs between New York, Chicago, and the West Coast. We must realize that in time this construction may be altered materially with the advance in the knowledge of how to handle atomic energy.

Figure 29 shows an unusual design of atomic-powered locomotive which may be possible when boiler thickness can be reduced from 3 ft to 1 ft or less. This unit would have a wheel arrangement of 6–8–6. Its outside appearance above the wheels is similar to that of the GG1, the large electric locomotive operating on the Pennsylvania Railroad. The leading truck at each end is 6-wheeled, similar in design to the 6-4-4-6 locomotive built by the Pennsylvania Railroad and exhibited at the World's Fair in New York in 1940. The driving wheels have the same wheel distribution as the New York Central No. 6000, which has a rating of 6000 hp. A rigid wheel base is used, since only 8 driving wheels are required. The driving wheels are 60 in. in diameter, and to each wheel is geared a small, 3-cylinder steam engine.

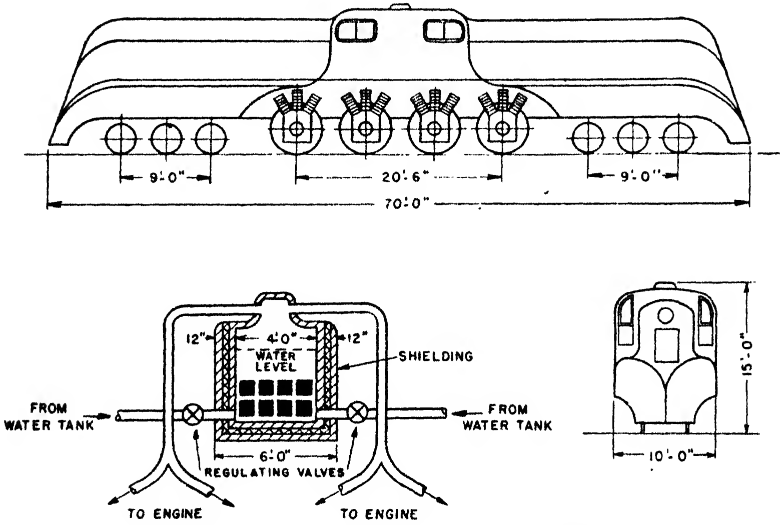


Figure 29. Proposed 6000-Horsepower Atomic-Powered Steam Locomotive.

The steam engine considered for this locomotive design is now being used on an experimental locomotive in France. The French locomotive has a boiler pressure of approximately 800 lb, and the cylinders are approximately 6 in. in diameter. This gives a very small cylinder, especially when we consider that one of these engines consisting of 3 cylinders will produce 750 hp. This size of engine has many advantages, one being that all repair work on the engine would be done in the locomotive shop away from the locomotive, because the engine is sufficiently light to be easily pulled off and another engine mounted in its place. With two of these engines mounted on each axle, a total power of 1500 hp is produced for each pair of driving wheels. This makes a total of 6000 hp for the locomotive.

The engineer's cab would be located in the center of the locomotive, similar to the arrangement on the GG1. The cab would be long, possibly 15 ft, to give ample space in the center of the cab for the locomotive boiler. A long hood would extend out from the engineer's cab to the front of the locomotive. This hood would be filled with water. A similar hood would be located on the other end of the locomotive, giving ample water capacity. The two hoods would be so shaped as to give excellent visibility in both forward and reverse directions. The locomotive would operate with full power equally well in either direction. With this wheel arrangement, the riding quality should be equal to the finest Pullman car. With cylinders individually mounted on each axle, there would be no jerking owing to dead center encountered in the usual type of steam locomotive. The acceleration would be even, smooth, and fast. Locomotive performance, in other words, should be excellent.

The design of the boiler is the heart of the atomic-powered locomotive because it makes possible the construction of a powerful, yet relatively light-weight, locomotive. The total weight of this ideal locomotive would be approximately 560,000 lb, assuming 65,000 lb per driving axle, which amounts to 93 lb per horsepower and is considerably lighter than Diesel road locomotives built today. One reason for so much weight in an atomic-powered locomotive is that it must carry a large quantity of water, which is necessary on any type of steam locomotive. However, an atomic-powered locomotive must have sufficient weight to keep it on the track while it is producing its high rating of 6000 hp. Without sufficient weight, the driving wheels would spin around like a skidding automobile on ice.

The boiler on this ideal atomic-powered locomotive is estimated to have a diameter of 6 ft over all and an inside diameter of 4 ft, which allows a 1-ft thickness for the boiler shell in order to protect the engineer, fireman, and crew members from radioactive rays. It is assumed that the boiler would be made of stainless-steel welded plates of possibly 2-inch thickness, sufficient to hold a steam pressure of 800 to 1000 pounds. In time, we will find what is the best shielding material to put around this boiler. In our present state of knowledge, we would no doubt use a series of laminated shielding materials at least three times as thick as what can be expected in the future. It is very possible that a combination of several materials will be required to give the best results. The bottom of the boiler will of course have to be protected the same as the sides, but it appears there will be no need for protecting the top to any extent, as men will not be allowed to climb up over the boiler when it is in operation any more than they are allowed to climb on top of a running electric locomotive.

In spite of the excellent progress to date, we have a great deal to learn about how to protect workmen from the radioactive rays produced by fission of atoms. Can we find an analogy in the progress made in the insulation of homes? Nineteenth-century (and earlier) home insulation was provided by walls 3 to 4 ft thick; today, home-insulator thickness has been reduced to inches. Today, shielding from radioactive rays is a matter of feet, but in the years to come we may find that a thin wall consisting of certain special laminated material will be sufficient. We already know that the four electrically charged particles (alpha particles, deuterons, protons, and electrons) can be easily stopped. Mr. E. V. Murphree, Executive Vice President of the Standard Oil Development Company, states in the June 1946 issue of *The Lamp:*

> In general, a mere sheet of paper can shield against alpha particles; six sheets, against deuterons; ten sheets, against protons; 500 sheets, against electrons. . . . Roughly, it takes two inches of lead to shield against gamma rays and the equivalent of six feet of water to shield against neutrons.

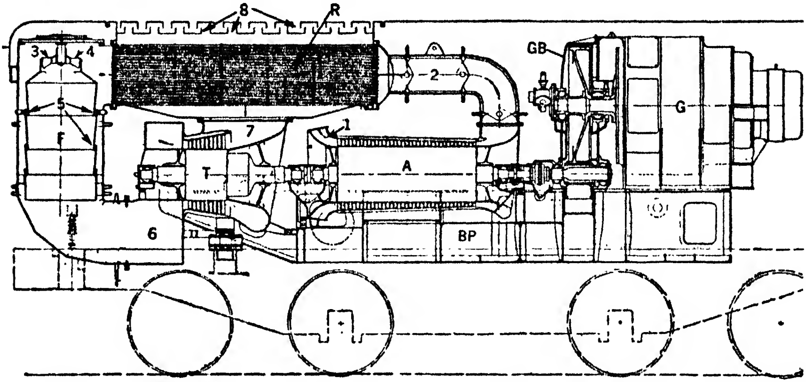
Obviously the neutrons have to be stopped; when they are, the other five particles are also stopped. On a locomotive we cannot use six feet of water as a shield, but we should be able to use its equivalent. In the future that equivalent may be reduced to a thickness of one foot, or even less.

In the center of the boiler will be located blocks of uranium 235 as well as the necessary controlling plates to control the activity of the U-235. The water will come in to the bottom as shown in Figure 29, and as the U-235 is of the refined type, it will be extremely active and immediately turn the water into high-pressure, high-temperature steam. The steam may be controlled by regulating the amount of water coming into the boiler. The steam will go out the dome at the top of the boiler, branching off to the various locomotive cylinders. The controls for such a locomotive should not be too difficult to design. It is felt that by using a boiler of the size shown in Figure 29, we will not be very far from the correct boiler to be used after sufficient experimentation is made to determine just what is required.

Gas Turbine Locomotive Possibilities

Figure 30 shows the cross section of the gas turbine locomotive now operating in Switzerland and built by Brown, Boveri & Company. When we have learned to use atomic energy in the combustion chamber of this locomotive, we will find that the design of turbine and compressor will have materially advanced, producing more horsepower in less space. The wheel arrangement of this locomotive may be a duplicate of Figure 29, and, instead of using steam in the cylinders, we may use very hot gases under high pressure. The engineer's cab would be located in the center, as in Figure 29, but, in place of water tanks under the front and rear hood, a gas turbine unit of approximately 3000 net horsepower would be located under each hood. Instead of cylinders to produce the power, as shown in Figure 29, it is possible that a generator, connected to each turbine shaft, would produce the power to drive the traction motors on the same 8 driving wheels. This much would not be difficult to arrange.

The difficult feature in this locomotive is the creating of atomic energy within the size of combustion chamber shown as *F* in Figure 30. It may be many years before this can be done. The combustion chamber shown in Figure 30 is only about 3 ft in diameter, but, if blocks of uranium were placed in this combustion chamber and if the uranium were cooled by forcing air under high pressures over it, we might find that considerably more space would be required. The cooling of the uranium 235 with high-pressure air would cause a rise in the temperature of the air possibly to 1500° F or more. We can feel safe in saying that the turbine will be capable of standing extremely high gas temperatures by the time we learn how to use atomic energy within the firebox or combustion chamber of a gas turbine locomotive.



Courtesy of Brown, Boveri & Company

F — Firebox.
T — Gas Turbine.
A — Compressor.
R — Regenerator, Air Heater.
GB — Gear.
G — Generator.
BP — Bedplate of Unit.
1 — Air Inlet to A.
2 — Air Inlet to Inside of Tubes in R.
3 — Fuel Nozzle.
4 — Air Inlet to F at 3.
5 — Air Inlet at Sides of F.
6 — Gas Inlet to T from F.
7 — Gas Outlet from T to Go Around Tubes of R.
8 — Outlet from R.

Figure 30. Section of Gas Turbine Generator Set Shown Mounted on the Locomotive Frame.

Here again considerable shielding will be required to protect the locomotive crew from the fireboxes or combustion chambers. It was suggested that two of these turbine units be used on one locomotive, and in that case the atomic-powered firebox of each unit would be located at the far end from the engineer's cab.

Conclusion

In this chapter, we have pointed out that revolutionary designs will be made when atomic power can be utilized in locomotives. However, the steam locomotive and the newest type of gas turbine locomotive will have a place on the railroads in the atomic era. The steam locomotive still appears to have a very excellent future, and the gas turbine locomotive will unquestionably be improved by the use of atomic energy. We can feel confident that locomotives powered by atomic energy will not replace the Diesel locomotive burning oil, except in certain classes of service. The locomotive using atomic energy must be used in heavy-duty continuous service. This leaves the Diesel locomotive still the ideal locomotive for switching service, and for the considerable amount of light- and heavy-duty service on intermittent runs. The electric locomotive of course will continue to be used in tunnel service and on unusually heavy traffic service in connection with tunnel and terminal conditions.

No matter how bright a picture may be painted to show the advantages of the atomic-powered locomotive, whether it be steam, gas turbine, or some other type, we can be safe in saying it will not be here for at least 20 years. The atomic era has just started, so that, if atomic-powered locomotives do not appear for another 20, 30, or 40 years, they will still be early in the atomic era, which is destined to endure for many centuries.

Chapter V

Marine Possibilities

THE construction of an atomic-powered ship appears to be the next step after building an atomic power plant. The plants now constructed are built primarily for the purpose of producing plutonium to be used in the manufacturing of bombs. The first plant destined for the primary purpose of producing power, with plutonium as a by-product, will no doubt be built by our government, owing to both high experimental cost and secrecy reasons at this time. The first ship will in all probability also be built by the government; the Navy could afford the necessary high experimental costs. There are other reasons why the Navy should build the first ship; for example, the heavy shielding required can also be used for armor plate.

Let us assume the first ship to be an aircraft carrier, as shown in Figure 31, which would be of a special design, not only because of the power plant but because some planes would be used to carry atom bombs. It may seem fantastic to think of the ship's power plant as being capable of producing material for atom bombs, and yet this may be within the realm of possibilities.

In a talk before the American Society of Mechanical Engineers on January 30, 1946, Dr. J. A. Wheeler pointed out the two possible ways of accomplishing the regeneration process. The first is the generally assumed method wherein new fissionable material as well as raw material is added from time to time to keep the process going. The other possible way is far more economical. In this case, the raw material is added as necessary, while no new fissionable material is added; in fact, the process may produce a surplus of fissionable material which may be removed and used in atom bombs. The practicability of producing this fissionable material at sea and placing it into bomb cases has not yet been determined, but we can visualize it as practical — and what we are able to visualize today may be accomplished in the future.

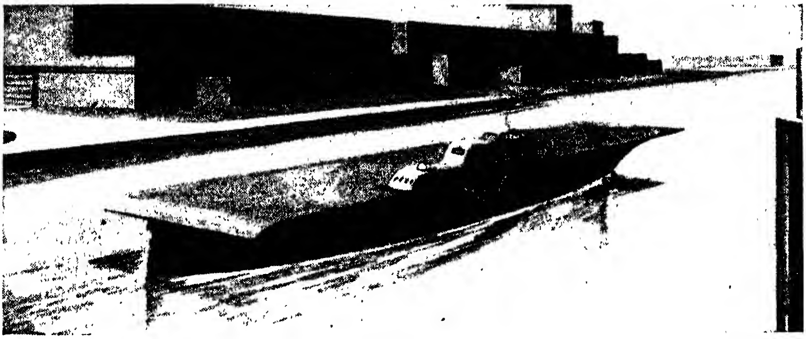


Figure 31. Proposed Atomic-Powered Aircraft Carrier.

Whether this ship produces excess fissionable material or not is a secondary factor today. Another reason the Navy rather than a commercial line would be more interested in building an atomic-powered ship is that the "pay load" is of secondary importance as compared to range of operation without taking on fuel. With an atomic power plant, the ship may stay in enemy waters for months without coming into port or even contacting a friendly vessel. This is a very important advantage to a ship at war.

Another decided advantage is the complete absence of smoke, with the consequent elimination of smokestacks or funnels. The only reason for having an opening of any kind is to provide ventilation for the crew, and this can be accomplished through the side of the ship. There will be no need of any structure above the flight deck except the bridge, chart room, and so on. This structure could be in its normal position at the side of the ship except when the ship is in action, and then it could be swung clear of the plane deck and located out over the water, the entire bridge structure being mounted on a steel framework as shown in Figure 31. This framework would be changed from normal to fighting position by air-operated power cylinders. This structure is of course a minor item, but it is just one of the possible changes that may be made to advantage when an atomic power plant is used.

The type of power plant may be similar to that of the steam locomotive, but on shipboard this would have the disadvantage of carrying water for steam or the chemicals for changing sea water into fresh water. It is therefore suggested that the power plant be of the gas turbine type similar to the one shown in Figure 20, which has the advantage of not requiring air from the outside for use within the plant or for cooling. Figure 24 shows the closed cycle of this arrangement whereby all cooling is done by water. Since there is naturally an ample supply of sea water under a ship, this seems to be the ideal arrangement. In Chapter III of Part IV of this book, this type of power plant is explained in detail. The uranium-graphite pile shown in Figure 27 would be used. This is especially desirable on shipboard, since a helium mixture, used for cooling, is circulated over and over again. A supply of the helium mixture must be carried on board only to replace any leakage that may occur. These piles, as shown in Figure 27, will be heavy and will require considerable space, but the piles, together with the power-plant equipment, may be located in the hold of the ship in an arrangement which will serve the best purpose.

There are great possibilities in ship design where both an oil-fired and atomic-powered plant may be jointly operated. The atomic-powered plant would be used for normal cruising speed while the oil-fired plant may be used for peak speeds. In this case, it is very possible for the two plants to be of about the same capacity.

In time, certain types of commercial ships may be powered by atomic energy, but this seems to lie in the distant future.

Chapter VI

Conclusions

ATOMIC energy is a suitable substitute for fuel; it is another means of creating heat. This heat can be converted into mechanical energy by using present-day types of prime movers, such as the steam engine and steam turbine, the gas turbine (both open and closed cycle), and possibly even the internal combustion engine. The steam turbine, in large sizes, has proved more efficient than the steam engine. The gas turbine has already proved that it is more efficient than the gasoline engine, and indications are now that for sizes well above 2000 hp its efficiency approaches that of the Diesel engine.

In Chapter III we found that the AK closed-cycle gas turbine that uses helium is the ideal method for generating power from the uranium pile. It can be used efficiently in sizes above 30,000 hp. In time, the open-cycle gas turbine unit should be applied to locomotive use, as described in Chapter IV, but before this happens we can expect a Navy ship to be operating on the closed cycle, as described in Chapter V. The steam locomotive with uranium fuel will no doubt be the first type of rail motive power to be built for using atomic power. Unquestionably, each type of prime mover will have its place in the power field.

The same reasoning applies to fuels. For example, in the nineteenth century, electric light was beginning to replace the gas light, and the statement was made that the gas industries would soon be out of business; they actually were soon out of the lighting business, and yet today the total business of the gas industry is greater than ever. Atomic energy will not *replace* any of the fuels; it will *supplement* them.

We find that atomic energy will not be produced cheaply in large quantities even if it were capable of replacing coal or oil. For example, the cost of coal is not even one fifth the cost of producing electric power in the public utility industries. Therefore, if the cost of fuel were eliminated entirely, the cost of electric power to the consumer could not be reduced by more than one fifth. The fuel used depends entirely upon the supply and demand in each particular territory. Only experience will determine how atomic power can be utilized to the most economical advantage.

Various tables have been published showing relative competitive costs between uranium and coal, taking into account their relative heating values. Comparison in cost is difficult, however, because of the many variable factors in the production of atomic energy, or even in the production of uranium 235 itself. We can safely state that, if coal costs ten dollars a ton, we can afford to pay at least ten thousand dollars for one pound of uranium 235, which means two million times as much for one pound of uranium 235 as for one pound of coal. In the case of fuel oil or gasoline, we can afford to pay two hundred thousand times as much for a pound of uranium 235 as for a gallon of fuel oil or gasoline. Thus, even though uranium 235 is expensive to produce in concentrated form, its heating value is enormous.

In summing up the uses of atomic energy for power purposes, we find that hot water and steam can be produced for processing, space heating, generation of power, and for various other industrial applications. Furthermore, we also find that cold air, helium, and various mixtures can be heated to produce power in gas turbines, as well as for industrial uses, such as drying, processing, and general heating applications.

Of the many applications of atomic energy, one is outstanding: rocket propulsion. The day may come when rockets will take us to the moon, or even to the planets.

While many people feel that this is impossible, we need only to look back less than five hundred years, when Columbus' proposal to reach the Orient by sailing westward was derided because of a general lack of knowledge and absence of vision. Today, we have traveled all over the world: under water, on the surface of the oceans, and in the sky. We have mapped nearly every portion of the world. We have won another World War. It may soon become possible for war-loving men to fight on Mars, and adventuresome, peace-loving people may choose to live on another planet.

It is difficult for us to realize that atomic energy has now actually been produced, and to conceive the magnitude of the devastation wrought by the bombs dropped on Japan. By the same token it is difficult to realize that this same force can take us away from the earth, to new worlds and new places. The possibility of traveling by rocket brings into prominent relief the epoch-making significance of atomic energy. For the propulsion of steam and gas turbines and many other types of power machinery, including those of the present day, as well as those of the future, atomic power is of equal significance. Atomic power is now here!

Let us attempt to look into the distant future before bringing our discussion to an end. In Part IV, we have shown how power can be produced by the *heat* of atomic energy. However, electric power can be produced *directly* from the splitting of the atom. This depends upon the type of atoms split, the arrangement of the atoms when split, and a satisfactory means of carrying off the electric energy in wires or suitable conductors. In the uranium pile, neutrons from one block of uranium are continually bombarding uranium in another block to produce plutonium. At the same time, electrons are being thrown off, and it is not a difficult matter to collect these electrons. The difficulty lies in utilizing the electrons, since they do not become free with any degree of regularity. Scientists will in time be able to regulate commercially the flow of electrical energy from a uranium pile or similar self-sustaining method of atom-splitting.

Articles on atomic energy have appeared in many publications. The contents of the better articles have been summed up in the Australian *Commonwealth Engineer* of September 1945, as follows:

> A new stage has been reached in the development of motive power. Whereas yesterday the internal combustion engine and the steam turbine were the prime movers, tomorrow the gas turbine and possibly the atomic engine will also power our factories, supply our light, and propel us along the roads and through the air at enormous speeds. It remains for us to adapt our way of life to the new scientific order, that we may gain the ultimate benefit from our rapidly increasing control of natural forces.

Part V

Industrial Benefits from U-235 Research

By H. R. Austin

Chapter I

War's Gift to Peace

A LARGE amount of space in our daily papers and periodicals has been devoted to glowing accounts of the painstaking, involved research by world-famous nuclear physicists culminating in the splitting of the uranium atom. Interesting speculations on the possibilities and availability of atomic power have been indulged in, but all too little has been said about the benefits which industry, as it is today, might expect, not from the use of atomic bomb ~~power~~, but from engineering principles, new equipment, and new methods that have been developed as a necessary prerequisite of the atomic b~~omb~~. energy.

It is therefore the purpose of this section to make available to the public some tangible assets accruing to American industry *right now* from knowledge gained in the successful solution of the problems faced in separating U–235 from natural uranium by gaseous-diffusion methods. Incidentally, the success of that process was underlined in 1945 by two developments: (1) The Kellex Corporation shared with others serving at Oak Ridge the honor — so well deserved by all of them — of the Army-Navy "E" Award, which tribute was announced by the government; and (2) even more important, from an engineering viewpoint, the technical soundness of the diffusion plant's processes and equipment were strikingly demonstrated in the announcement that, of the three methods in use at Oak Ridge, this was the only plant to be continued on normal operation. This decision, it was stated, was the result of a new postwar policy in which emphasis was shifted from all-out war production at any cost to concentration on a single process which would yield maximum peacetime production consistent with efficiency and economy of operation. Wartime performance of the diffusion plant was such that the authorities selected this process alone for the separation of U–235 in postwar use.

The development work for this method had to be transformed from a highly theoretical concept without even a laboratory process upon which to base design and performance data into an efficient, multi-stage, commercial gas-recycling process. And it all had to be done in a hurry. So vast was the undertaking and so enormous the cost that it is quite safe to state that no single corporation or group of corporations would even consider industrial research on this subject with such little prospect of success. The saying "necessity is the mother of invention" was never so true as in the new developments, both in apparatus and process, conceived, developed, and applied under the emergency of war to bring the project to a successful conclusion.

It is doubtful if such concentrated research was ever before brought to bear on any one problem. That it was solved quickly is a tribute to the ingenuity and resourcefulness of American science and engineering and bodes well for future developments in this field. The total cost of just separating the U–235 isotope by the diffusion process in important volume reached a substantial portion of the overall figure of $2,000,000,000. Mistakes were made, of course, because decisions had to be made quickly, but progress is not achieved without mistakes. The important point is that these mistakes were capitalized on, and, now that it is all over, the vast sum of money spent can be considered not only as a necessary war expenditure or as a preliminary to developing superpower resources in the future, but also as our government's contribution toward the betterment of industry as a whole.

For there is no doubt about it, industry does not have to wait for atomic power to utilize the experience of the project.

Many lessons have been learned which can and will be applied to more efficient processing immediately. It cannot all be revealed in print at present, but it is in the minds of engineers and firms participating in the project and will be inextricably bound up with their future thinking, engineering design, construction, and processing. Some items in these fields can be mentioned and are considered below. It is hoped that they will afford to the serious thinker some idea of the enormity of the problem and the scope of its application toward the betterment of our industries.

Following are some of the industries with indications of how they will benefit from knowledge gained in the U-235 problem:

1. *Petroleum refining:*
    - (a) improved pumping.
    - (b) new-type, more efficient heat exchangers.
    - (c) mass spectroscope (continuous analytical control).
    - (d) possible new methods of separating gasoline fractions.
    - (e) improved automatic control.
2. *General chemical and processing industries:*
    same as in petroleum refining.
3. *Manufacture of pressure and vacuum vessels:*
    - (a) checking welds.
    - (b) pre-testing vessels for leaks before operation.
    - (c) improved vacuum techniques.
4. *High-vacuum industries:*
    - (a) improved vacuum methods for vitamin distillation.
    - (b) new methods of detecting high vacua in electronic tube manufacture.
    - (c) low-pressure, low-temperature dehydration of foodstuffs.

5. *Gas-processing industries:*
    - (a) diffusional separation of helium from natural gas.
    - (b) efficient separation of hydrogen from process gases.
    - (c) diffusional separation of oxygen and rare gases from air.
    - (d) new techniques in gas recycling.
6. *Electrical industry:*
    - (a) new electronic techniques in high vacua.
    - (b) improved micro-sensitive instrumentation.
7. *Medical profession:*
    - (a) low cost, abundant source of radioactivity.
    - (b) improved protective methods for combating toxicity in industry.
    - (c) extension of cancer therapy.
8. *Refrigeration industry:*
    - (a) increased safety in equipment.
    - (b) improved handling of fluorides for refrigerants.
9. *Industries employing corrosive chemicals:*
    - (a) new pump and valve lubricants and packing methods.
    - (b) new treatment of metal surfaces to prevent corrosion.
    - (c) improved safety practices.
    - (d) completely enclosed pumps operated from exterior by induction.
10. *Optical industry:*
    - (a) exceedingly accurate (billionths of an inch) methods of measurement using radioactive rays, applicable, for example, to lens grinding.

Corrosion Factors

Right from the start of the project staggering obstacles loomed. Uranium, being a solid, had first to be transformed into a gas for utility in the selected gas-diffusion process.

This meant selecting a compound of uranium with some other element which would be gaseous at nominal temperatures and from which elemental uranium could be readily regained after diffusion. After much experimentation, which included uranium hexafluoride, UF_6, and other gases, a suitable process gas was selected. One of the big advantages of UF_6, which brought it into special consideration, was that fluorine, having only one isotope, would not complicate the separation by adding new combinations which would diffuse at varying speeds. Uranium hexafluoride is a solid at room temperature but fortunately turns into a gas at 56° C. Unfortunately, however, like most fluorine compounds, it was highly reactive, physiologically poisonous, and introduced problems of corrosion which pointed toward difficulties in production and handling. As one spokesman for the Kellex Corporation has stated, "Uranium hexafluoride is one of the hardest things to handle in the history of mankind."

It was found that practically all the techniques and developments gained in the successful study of the problem could be carried over into a number of industries plagued by corrosion factors through improvement in equipment and processing. The results indicated a saving of millions of dollars annually in the conservation of critical equipment and materials, minimum breakdown of moving parts, and increased safety for workers.

In the process it was imperative that no material in contact with the process gas react with it, since such corrosion would lead not only to plugging of the microscopic pores of the diffusion barrier and various mechanical failures but also to absorption (that is, virtual disappearance) of enriched U-235 isotope. Obviously, therefore, standard-type valves and piping could not be used; instead, new methods of pretreating metal surfaces against corrosion were worked out, and new-type coolants, piping, heat exchangers, lubricants, pumps, and packing were developed to satisfy the stringent requirements.

Application of New Corrosion Knowledge to Industry

Hydrogen fluoride is an important isomerization and alkylation catalyst in petroleum refining as well as an important raw material in the production of aluminum and refrigerants. It is, however, so highly active and dangerous that industry has not yet capitalized on many of its potentialities. Its handling may now be made safer and simpler without excessive maintenance costs, and as a result its increased use in industry may be realized.

Other important starting materials for a host of industrial products such as sulfur dioxide, hydrogen chloride, and the mineral acids (sulfuric, nitric, and phosphoric) have all presented severe problems of transfer and corrosion, with particular emphasis on valve lubricants and pump packings. These difficulties can be greatly simplified by application of the knowledge gained through the extensive experimentation with UF_6 and the other related gases.

Chapter II

Improvements in Industrial Equipment

Pumps

The story on pumps, the heart of the process and one of its most difficult problems, is particularly interesting and applicable to modern industry. Thousands of pumps operating under reduced pressure at Oak Ridge created problems in vacuum technique on an unheard-of scale. Other thousands operated at nominal pressures. But regardless of the type or service, none could leak or corrode and all had to have as small a volume as possible. Many different types of centrifugal blower pumps and sylphon-sealed reciprocating pumps were tried out and new types developed. For example, in one of the pumps for the larger stages the impeller was driven through a coupling containing a very novel and ingenious new seal. Another type of pump was completely enclosed, its centrifugal impeller and rotor being run from the outside by induction. One of the outstanding achievements was a single-stage valve-in-head reciprocating pump with gas lubrication between piston and cylinder and a sylphon bellows between piston rod and cylinder. Other types of pumps were given such descriptive titles as the "shaker pump," the "snake pump," and the "paddle pump."

Top-flight pump designers from leading manufacturers in this country collaborated in research at the central Kellex laboratories in Jersey City and succeeded to a remarkable degree in increasing industry's knowledge of this all-important phase of processing. For security reasons the practical applications of the new types of pumps developed cannot yet be revealed publicly. However, the engineers who participated in this phase of the project have brought to their parent companies a vastly increased lore of new techniques which cannot help but be reflected in increased service to their customers.

Perhaps the most significant advance in pump design which has been most successfully accomplished is the utilization of supersonic velocities of a very high order (Mach numbers of over 1.0). Because of this high rotor velocity, small centrifugal pumps now can be made with capacities equaling much larger pumps. Centrifugals can now develop higher compression ratios than ever before and may even be used for compression purposes, whereas in the past they have been employed mainly for transfer and blowing purposes.

Barrier Requirements

Literally acres of porous barriers were required for the gas-diffusion plant with billions of holes smaller than 0.01 micron (about two millionths of an inch). Despite the high degree of porosity required, such barriers had to be able to withstand a pressure head of one atmosphere. The pores had to be of uniform size and spacing and must not become enlarged or plugged up as the result of direct corrosion or dust coming from corrosion elsewhere in the system, and the barriers had to be amenable to manufacture in large quantities and with uniform quality.

One of the major reasons for the lack of diffusion techniques in industry today has been the barrier problem. Few, if any, corporations cared to expend the prohibitive time and money in the necessary research on this problem, until it was made necessary by the exigency of the situation. Almost at the last minute an excellent barrier was developed, and today these operate successfully throughout the more than several thousand stages.

Application of Diffusion Principles to Industry

Now that a large part of the basic research on diffusion barriers and their application to full-scale industrial separations has been completed, particularly with reference to gas recycling and instrumentation, it seems almost certain that helium will be separated from natural gas by diffusion techniques rather than by the present refrigeration method. Helium is so light in comparison to other components of natural gas that its diffusion velocity through a porous barrier is over twice as great as the next lightest compound present in the same source.

It may be even easier to isolate hydrogen by these new methods from a number of process gases now used merely as fuel because the diffusion velocity of hydrogen, the lightest of our elements, is over four times that of any compound associated with it.

The isolation of ethylene from cracked-gas oil by incorporating diffusion barriers as an integral part of cracking units could conceivably supply an abundant source of this versatile chemical, which is used for the manufacture of synthetic rubber, plastics, antifreeze, alcohol, and many other products.

The preparation of oxygen and rare gases from air without resorting to refrigeration and fractional distillation is another possible application, when economic methods are developed.

The direct isolation of natural gasoline fractions from crude petroleum without resorting to distillation, and new types of fractionating columns for the petroleum refining industry, also appear feasible. But the barrier material may be used in a number of non-diffusive applications. For example, it can be used for filtering in a manner analogous to the fritted glass plate — only better, since it can be made in much finer porosity. The coarser types of barrier might be used in filtering normal dusts and would have the advantage of not plugging up. Barriers might also be used to replace the costly and dangerous high-voltage "Precipitrons" for disposal of fly ash, soot, and so on, in industrial plants and even in private homes (for instance, in such cities as Pittsburgh or St. Louis).

Welding

Automatic welding of vacuum-tight joints was refined and developed to a high degree. As a result, future welded plant construction will be cheaper and will be accomplished with less manpower and with uniform high-quality workmanship. The skills developed in automatic welding techniques are even now available and greatly extend man's mastery of vacuum and pressure-vessel fabrication.

Instrumentation

If pumping is the heart of processing, then instrumentation is the brain. No continuous process could function efficiently without adequate automatic control. In the gaseous-diffusion plant the problems of instrumentation were far greater than in any other industry because the theory involved the assumption that diffusion took place through an infinite number of stages, whereas practicability dictated that such stages be limited in number.

Even so, several thousand stages were required, necessitating an intricate system of gas recycling involving abnormally large volumes of gases in relation to the finished product and continuous high-precision analytical control. About half of the gas processed in each stage diffused through the porous barrier as enriched U-235 product, and after repressuring was sent on to the next higher stage for further concentration; the impoverished half was also repressured and recycled through the next lower stage. The recycling involved was enormous, over 100,000 times the volume of the final enriched gas.

There were developed to meet these needs the most precise, continuous, automatic, analytical control instruments ever produced by man. This refinement is one of the outstanding features of the gas-diffusion plant and constitutes one of its most important applications to industry today. Instruments which before had existed only in research laboratories were improved upon and adapted to commercial use; completely new prototypes were conceived, developed, *and put into mass production.* The result is that now as never before there is available to industry a more nearly perfect system of continuous automatic control than has ever existed.

Applications of New Instrumentation to Industry

Mass Spectroscope. One of the developments employed is a new type of mass spectroscope, which every petroleum refiner will welcome for control of cracking operations and transfer line analysis. The mass spectroscope has been employed for several years in research laboratories and even within the last two years in certain phases of the refining industry but never on the perfected scale developed at Oak Ridge. The foremost instrument engineers and physicists in this country and England devoted their full time not only toward gearing this instrument to continuous control but also to expanding this country's capacity for its quantity output. In no other country has electronic research been applied on so grand a scale. Security considerations are not violated in revealing that the mass spectroscope is an electronic device for analyzing gases both qualitatively and quantitatively from a mass standpoint by separating a beam of dissimilar gas molecules into separate beams according to their formula weight. Determinations are very fast, require only a thimbleful of gas, and make obsolete the formerly used Orsat and chemical analyses particularly for the purposes of continuous control where instantaneous changes must be effected the moment a process swings "off the line."

Its potential uses in industry include the accurate analysis of natural gas or any process gas, the continuous automatic control of any gaseous process such as alkylation, dehydrogenation, vapor phase cracking, and so forth, the checking of inert gases such as nitrogen used to provide a protective atmosphere in furnaces, the checking of the completeness of any evacuation process, as in the manufacture of radio tubes, the detection of impurities, and many others. Industry will not have to wait for benefits from this versatile tool because production facilities have been enormously increased since the new type was created.

Leak Detector. A second development, aptly and simply called "the leak detector," is more sensitive than any other existing device previously utilized for the same purpose. It played an important part in ensuring that all parts of the gaseous-diffusion plant were vacuum tight. Any leaks out of or into the system would be damaging both from the standpoint of loss and contamination of an exceedingly valuable material. The leak detector is well adapted for locating annoying leaks in industrial high-vacuum processing industries such as vitamin manufacture, where even microscopic leaks undetectable by the familiar ammonia-hydrogen chloride method or Tesla coil method are still potent enough to prevent drawing the necessary high vacuum on the equipment. Other potential uses include the pre-testing of pressure and vacuum apparatus before putting it in service, checking the "tightness" of condensers and heat exchangers, checking equipment in operation to ensure no wasteful loss or contamination, the testing of welds for minute pores which would otherwise escape detection, and ensuring the physiological safety of refrigeration equipment employing toxic coolants. Indeed the significance of this device to industry is so broad that the full range of its applications will not be apparent for some years. For example, in the manufacture of electronic equipment, transmitting or rectifying tubes may be constructed with metal envelopes (with good vacuum testing available) at a great saving in cost and with greater durability than the present-day glass types. The incandescent or luminescent electric light and rectifiers of the mercury-vapor type are also manufactured articles which can benefit from the application of the leak detector.

Heat Exchangers. Of great interest to the petroleum refining industry is the development of a new type heat exchanger. Since an unavoidable concomitant to pumping gas is heating it, and since enormous volumes of gas were processed, individual cooling units for each stage had to be developed. A brand-new type of heat exchanger was conceived for this purpose and developed up to the production stage. A manufacturer was then selected and was shown how to make it even to the extent of redesigning his equipment so that thousands of units could be turned out quickly. They were installed and functioned very well. Not one failure occurred. The result is that smaller heat exchangers, very tight, can be used in industry to achieve the same effect which formerly required much larger ones. Reduced investment cost, conservation of metal, and greater operating efficiency for a myriad of functions is indicated.

Possible Medical and Physiological Benefits

Thanks to the variety and multiplicity of radioactive products which can be produced by means of U–235, we face the prospect of soon having available for therapeutic medicine radioactive materials possessing a wide variety of properties. It is logical to expect, therefore, that these new materials will be suitable for products offering a greater range of usefulness, and at lower cost than radium.

The possibility exists of incorporating a micro quantity of a radioactive isotope in food to observe its metabolism in the body of experimental animals. Such "tagged" material could be readily traced in its passage through the organs of the body. Thus new light might be thrown on the action of drugs, hormones, and vitamins on the body; the methods by which sugars and fats are burned; and the perplexing problems of heredity in plants and animals. Increased knowledge concerning how and why cancer spreads throughout the body might lead to better preventive treatments.

The use of such radioactive elements as mercury and gold might make the use of "gold rays" instead of X rays applicable to extremely accurate measurement, as, for instance, in the grinding of optical lenses. The comparatively cheap radioactive materials might also be used in industry to supplement X rays in the inspection of castings, welds, and forgings.

Money Not Wasted

It should be borne in mind that the benefits mentioned above accruing to American industries as a result of knowledge gained in the development of the gas-diffusion plant represent only a small part of what is permitted to be revealed at this time. The total cost of the project, $2,000,000,000, actually only represented 8 days of war cost to the United States.

If it be estimated that the war would have lasted another 6 months the actual saving could be estimated at $45,000,000,000.

Appendixes

Appendix I

The Work on the Atomic Bomb

The Objective

The development at Los Alamos of the atomic bomb will be described in Appendix I. Two phases of the project to be considered are the organization, and the scientific and technical work itself. The organization will be described briefly; the remainder of the Appendix will be devoted to a discussion of the scientific and technical problems. Security considerations prevent a discussion of many of the most important phases of this work.

History and Organization

Reorganization of the project occurred at the beginning of 1942, and a gradual transfer of the work from the Office of Scientific Research and Development auspices was made to the Manhattan District. The responsibilities of the Metallurgical Laboratory at Chicago originally included a preliminary study of the physics of the atomic bomb. Some preliminary studies were made in 1941, and early in 1942, G. Breit set into operation various laboratories for experimental study of problems that had to be solved before progress could be made on bomb design. J. R. Oppenheimer, of the University of California, gathered together a group of scientists, in the summer of 1942, for further theoretical investigation, and undertook to coordinate their activities. This work was officially under the Metallurgical Laboratory, but the group devoted to theoretical studies operated largely at the University of California. By the end of the summer of 1942, when General L. R. Groves took charge of the entire project, it was decided to expand the work considerably, and, at the earliest possible time, to set up a separate laboratory.

In the choice of a site for the atomic-bomb laboratory, the all-important considerations were secrecy and safety. It was therefore decided to establish the laboratory in an isolated location and to sever unnecessary connection with the outside world.

By November 1942 a site had been chosen at Los Alamos, New Mexico, on a mesa about 20 miles from Santa Fe. One advantage possessed by this site was a large area that could be used as proving grounds, but initially the only structures on the site consisted of a handful of buildings which were once a small boarding school. There was no laboratory, no library, no shop, no adequate power plant. The sole means of approach to the site was a winding mountain road. That the handicaps of the site were overcome to a considerable degree is a tribute to the unstinting efforts of the scientific and military personnel.

J. R. Oppenheimer was director of the laboratory from the start. He arrived at the site in March 1943, and was soon joined by groups and individuals from Princeton University, University of Chicago, University of California, University of Wisconsin, University of Minnesota, and elsewhere. With the vigorous support of General L. R. Groves, J. B. Conant, and others, Oppenheimer continued to gather around him scientists of recognized ability, so that the end of 1944 found an extraordinary galaxy of scientific stars gathered on this New Mexican mesa. The recruiting of junior scientific personnel and technicians was more difficult, since for such persons the disadvantages of the site were not always counterbalanced by an appreciation of the magnitude of the goal; the use of Special Engineer Detachment personnel improved the situation considerably.

Naturally, the task of assembling the necessary apparatus, machines, and equipment was enormous. Three carloads of apparatus from the Princeton project filled some of the most urgent requirements. A cyclotron from Harvard, two Van de Graaff generators from Wisconsin, and a Cockcroft-Walton high-voltage device from Illinois soon arrived. As an illustration of the speed with which the laboratory was set up, we may record that the bottom pole-piece of the cyclotron magnet was not laid until April 14, 1943, and yet the first experiment was performed in early July. Other apparatus was acquired in quantity; subsidiary laboratories were built. Today this is probably the best-equipped physics research laboratory in the world.

The laboratory was financed under a contract between the Manhattan District and the University of California.

State of Knowledge in April 1943

We stated in Parts II and III the general conditions required to produce a self-sustaining chain reaction. It was pointed out that there are four processes competing for neutrons: (1) the capture of neutrons by uranium which results in fission, (2) non-fission capture by uranium, (3) non-fission capture by impurities, and (4) escape of neutrons from the system. Therefore the condition for obtaining such a chain reaction is that process (1) shall produce as many new neutrons as are consumed or lost in all four of the processes. It was pointed out that (2) may be reduced by removal of U–238 or by the use of a lattice and moderator, that (3) may be reduced by achieving a high degree of chemical purity, and that (4) may be reduced (relatively) by increasing the size of the system.

In our earlier discussions of chain reactions, it was always assumed that the chain-reacting system must not blow up. Below, we shall examine methods for making it blow up.

By definition, an explosion is a sudden and violent release (in a small region) of a large amount of energy. To produce an efficient explosion in an atomic bomb, the parts of the bomb must not become appreciably separated before a substantial fraction of the available nuclear energy has been released (because expansion leads to increased escape of neutrons from the system and thus to premature termination of the chain reaction). Stated differently, the efficiency of the atomic bomb will depend on the ratio of (1) the speed with which neutrons generated by the first fissions get into other nuclei and produce further fission and (2) the speed with which the bomb flies apart. Using known principles of energy generation, temperature and pressure rise, and expansion of solids and vapors, it was possible to estimate the order of magnitude of the time interval between the beginning and end of the nuclear chain reaction. *Almost all the technical difficulties of the project come from the extraordinary brevity of this time interval.*

In Part III we stated that no self-sustaining chain reaction could be produced in a block of pure uranium metal, no matter how large, because of parasitic capture of the neutrons by U–238. This conclusion has been borne out by various theoretical calculations and also by direct experiment. For purposes of producing a non-explosive pile, the trick of using a lattice and a moderator suffices — by reducing parasitic capture sufficiently. For purposes of producing an explosive unit, however, it turns out that this process is unsatisfactory on two counts. First, the thermal neutrons take so long (so many microseconds) to act that only a feeble explosion would result. Second, a pile is ordinarily far too big to be transported. It is therefore necessary to cut down parasitic capture by removing the greater part of the U–238 — or to use plutonium.

Naturally, these and other general principles had been well established before the Los Alamos project was set up.

Critical Size. The calculation of the critical size of a chain-reacting unit is a problem that has already been discussed in connection with our consideration of piles. Although the calculation is simpler for a homogeneous metal unit than for a lattice, inaccuracies remained in the course of the early work, both because of lack of accurate knowledge of constants and because of mathematical difficulties. For example, the scattering, fission, and absorption cross sections of the nuclei involved vary with neutron velocity. The details of such variation were not known experimentally and were difficult to take into account in making calculations. By the spring of 1943, several estimates of critical size had been made by using various methods of calculation and the best available nuclear constants, but the limits of error remained large.

The Reflector, or Tamper. In a uranium-graphite chain-reacting pile, the critical size may be considerably reduced by surrounding the pile with a layer of graphite, since such an envelope "reflects" many neutrons back into the pile. A similar envelope can be used to reduce the critical size of the bomb, but here the envelope has an additional role: its very inertia delays the expansion of the reacting material. For this reason such an envelope is often called a *tamper.* Use of a tamper clearly makes for a longer lasting, more energetic, and more efficient explosion. The most effective tamper is the one having the highest density; high tensile strength turns out to be unimportant. It is a fortunate coincidence that materials of high density are also excellent as reflectors of neutrons.

Efficiency. As has already been remarked, the bomb tends to fly to bits as the reaction proceeds, and this tends to stop the reaction. To calculate how much the bomb has to expand before the reaction stops is relatively simple. The calculation of how long this expansion takes and how far the reaction goes in that time is much more difficult.

While the effect of a tamper is to increase the efficiency both by reflecting neutrons and by delaying the expansion of the bomb, the effect on the efficiency is not as great as on the critical mass. The reason for this is that the process of reflection is relatively time-consuming and may not occur extensively before the chain reaction is terminated.

Detonation and Assembly. As stated in Part III, it is impossible to prevent a chain reaction from occurring when the size exceeds the critical size because there are always enough neutrons (from cosmic rays, spontaneous fission reactions, or from alpha-particle-induced reactions in impurities) to initiate the chain. Thus, until detonation is desired, the bomb must consist of a number of separate pieces, each of which is below the critical size (either by reason of small size or unfavorable shape). To produce detonation, the parts of the bomb must be brought together rapidly. In the course of this assembly process, the chain reaction is likely to start — because of the presence of stray neutrons — *before* the bomb has reached its most compact (most reactive) form. Thereupon the explosion tends to prevent the bomb from reaching that most compact form. Thus, it may turn out that the explosion is so inefficient as to be relatively useless. The problem, therefore, is twofold: (1) to reduce the time of assembly to a minimum; and (2) to reduce the number of stray (predetonation) neutrons to a minimum.

Some consideration was given to the danger of producing a "dud" or a detonation so inefficient that even the bomb itself would not be completely destroyed. This would, of course, be an undesirable outcome since it would present the enemy with a supply of highly valuable material.

Effectiveness. The amount of energy released was not the sole criterion of the value of a bomb. There was no assurance that one uranium bomb that released energy equal to that released by 20,000 tons of TNT would be as effective in producing military destruction as, say, 10,000 two-ton bombs. In fact, there were good reasons to believe that the destructive effect per calorie released decreases as the total amount of energy released increases. On the other hand, in atomic bombs, the total energy released per kilogram of fissionable material (that is, the efficiency of energy release) *increases* with the size of the bomb. Thus, the optimum size of the atomic bomb was not easily determined. A tactical aspect that complicates matters further is the advantage of causing the simultaneous destruction of a large area of enemy territory. In a complete appraisal of the effectiveness of an atomic bomb, attention must also be given to effects on morale.

Method of Assembly. Since estimates had been made of the speed that would bring together subcritical masses of U–235 rapidly enough to avoid predetonation, thought had been given to practical methods of doing this. The obvious method of very rapidly assembling an atomic bomb was to shoot one part as a projectile in a gun against a second part as a target. The projectile mass, projectile speed, and gun caliber required were not far from the range of standard ordnance practice, but novel problems were introduced by the importance of achieving sudden and perfect contact between projectile and target, by the use of tampers, and by the requirement of portability. None of these technical problems had been studied to any appreciable extent prior to the establishment of the Los Alamos laboratory.

It had also been realized that schemes probably might be devised whereby neutron absorbers could be incorporated in the bomb in such a way that they would be rendered less effective by the initial stages of the chain reactions. Thus the tendency for the bomb to detonate prematurely and inefficiently would be minimized. Such devices for increasing the efficiency of the bomb are called "auto-catalytic."

Summary of Knowledge as of April 1943

In April 1943 the available information of interest in connection with the design of atomic bombs was preliminary and inaccurate. Further and extensive theoretical work on critical size, efficiency, effect of tamper, method of detonation, and effectiveness was urgently needed. Measurements of the nuclear constants of U–235, plutonium, and tamper material had to be extended and improved. In the cases of U–235 and plutonium, tentative measurements had to be made while using only minute quantities until larger quantities became available.

In addition to these problems in theoretical and experimental physics, there was a host of chemical, metallurgical, and technical difficulties which had hardly been touched. Examples were the purification and fabrication of U–235 and plutonium; the fabrication of the tamper; and problems of instantaneous assembly of the bomb, which were staggering in complexity.

The Work of the Laboratory

Introduction. For administrative purposes, the scientific staff at Los Alamos was arranged in seven divisions, subsequently rearranged at various times. During the spring of 1945 the divisions were: Theoretical Physics Division under H. Bethe; Experimental Nuclear Physics Division under R. R. Wilson; Chemistry and Metallurgy Division under J. W. Kennedy and C. S. Smith; Ordnance Division under Capt. W. S. Parsons (USN); Explosives Division under G. B. Kistiakowsky; Bomb Physics Division under R. F. Bacher; and an Advanced Development Division under E. Fermi. All divisions reported to J. R. Oppenheimer, Director of the Los Alamos Laboratory, who, since December 1944, has been assisted in coordinating research by S. K. Allison. J. Chadwick of England and N. Bohr of Denmark spent a great deal of time at Los Alamos and gave invaluable advice. Chadwick was the head of a British delegation which contributed materially to the success of the laboratory. For security reasons, most of the work of the laboratory can be described only in part.

Theoretical Physics Division. There were two considerations that gave unusual importance to the work of the theoretical physics division under H. Bethe. The first of these was the necessity for effecting simultaneous development of everything from the fundamental materials to the method of putting them to use — all this despite the virtual unavailability of the principal materials (U–235 and plutonium) and the complete novelty of the processes. The second consideration was the impossibility of producing (as for experimental purposes) a "small-scale" atomic explosion by making use of only a small amount of fissionable material. (No explosion occurs at all unless the mass of the fissionable material exceeds the critical mass.) Thus it was necessary to proceed from data obtained in experiments on infinitesimal quantities of materials and to combine it with the available theories as accurately as possible in order to make estimates as to what would happen in the bomb. Only in this way was it possible to make sensible plans for the other parts of the project, and to make decisions on design and construction without waiting for elaborate experiments on large quantities of material. To take a few examples, theoretical work was required in making rough determinations of the dimensions of the gun, in guiding the metallurgists in the choice of tamper materials, and in determining the influence of the purity of the fissionable material on the efficiency of the bomb.

The determination of the critical size of the bomb was one of the main problems of the theoretical physics division. In the course of time, several improvements were made in the theoretical approach whereby it was possible to take account of practically all the complex phenomena involved. It was at first considered that the diffusion of neutrons was similar to the diffusion of heat, but this naïve analogy had to be forsaken. In the early theoretical work, assumptions were made that all neutrons had the same velocity and that all were scattered isotropically. A method was thus developed which permitted calculation of the critical size for various shapes of the fissionable material provided that the mean free path of the neutrons was the same in the tamper material as in the fissionable material. This method was later improved, first, by taking account of the angular dependence of the scattering, and, second, by allowing for difference in mean free path in core and tamper materials. Still later, means were found of taking into account the effects of the distribution in velocity of the neutrons, the variations of cross sections with velocity, and inelastic scattering in the core and tamper materials. Thus it became possible to compute critical sizes assuming almost any kind of tamper material.

The rate at which the neutron density decreases in bomb models which are smaller than the critical size can be calculated, and all the variables mentioned above can be taken into account. The rate of approach to the critical condition as the projectile part of the bomb moves toward the target part of the bomb has been studied by theoretical methods. Furthermore, the best distribution of fissionable material in projectile and target was determined by theoretical studies.

Techniques were developed for dealing with set-ups in which the number cf neutrons is so small that a careful statistical analysis must be made of the effects of the neutrons. The most important problem in this connection was the determination of the mathematical probability that, when a bomb is larger than critical size, a stray neutron will start a continuing chain reaction. A related problem was the determination of the magnitude of the fluctuations in neutron density in a bomb whose size is close to the critical size. By the summer of 1945, many such calculations had been checked by experiments.

A great deal of theoretical work was done on the equation of state of matter at high temperatures and the pressures to be expected in the exploding atomic bombs. The expansion of the various constituent parts of the bomb during and after the moment of chain reaction has been calculated. The effects of radiation have been investigated in considerable detail.

Having calculated the energy that is released in the explosion of an atomic bomb, one naturally wants to estimate the military damage that will be produced. This involves analysis of the shock waves in air and in earth, the determination of the effectiveness of a detonation beneath the surface of the ocean, and so on.

In addition to all the work mentioned above, a considerable amount was done in evaluating preliminary experiments. Thus, an analysis was made of the back-scattering of neutrons by the various tamper materials proposed. An analysis was also made of the results of experiments on the multiplication of neutrons in sub-critical amounts of fissionable material.

Experimental Nuclear Physics Division. The experiments performed by the Experimental Nuclear Physics group at Los Alamos were of two kinds: "differential" experiments, as for determining the cross section for fission of a specific isotope by neutrons of a specific velocity, and "integral" experiments, as for determining the average scattering of fission neutrons from an actual tamper.

Many nuclear constants had already been determined at the University of Chicago Metallurgical Laboratory and elsewhere, but a number of important constants were still undetermined, especially those involving high neutron velocities. Some of the outstanding questions were:

1. What are the fission cross sections of U–234, U–235, U–238, Pu–239, and so on? How do they vary with neutron velocity?
2. What are the elastic scattering cross sections for the same nuclei (also for nuclei of tamper materials)? How do they vary with neutron velocity?
3. What are the inelastic cross sections for the nuclei referred to above?
4. What are the absorption cross sections for processes other than fission?
5. How many neutrons are emitted per fission in the case of each of the nuclei referred to above?
6. What is the full explanation of the fact that the number of neutrons emitted per fission is not a whole number?
7. What is the initial energy of the neutrons produced by fission?
8. Does the number or energy of such neutrons vary with the speed of the incident neutrons?
9. Are fission neutrons emitted immediately?
10. What is the probability of spontaneous fission of the various fissionable nuclei?

In addition to attempting to find the answers to these questions, the Los Alamos Experimental Nuclear Physics Division investigated many problems of great scientific interest which were expected to play a role in the atomic bomb. Whether or not this turned out to be the case, the store of knowledge thus accumulated by the Division forms an integral and invaluable part of all thinking on nuclear problems.

To obtain answers to the ten questions posed above, we should like to be able to:

(1) determine the number of neutrons of any given energy.
(2) produce neutrons of any desired energy.
(3) determine the angles of deflection of scattered neutrons.
(4) determine the number of fissions occurring.
(5) detect other consequences of neutron absorption — for example, artificial radioactivity.

We shall indicate briefly how such observations are made.

Detection of Neutrons. There are three ways in which neutrons can be detected: by the ionization produced by light atomic nuclei driven forward at high speeds by elastic collisions with neutrons, by the radioactive disintegration of unstable nuclei formed by the absorption of neutrons, and by fission resulting from neutron absorption. All three processes lead to the production of ions, and the resulting ionization may be detected by means of electroscopes, ionization chambers, Geiger-Müller counters, Wilson cloud chambers, tracks in photographic emulsion, and so on.

While the mere detection of neutrons is not difficult, the measurement of the neutron velocities is decidedly more so. The Wilson cloud-chamber method and the photographic emulsion method give the most direct results, but are tedious to apply. More often, various combinations of selective absorbers are used. Thus, for example, if a foil known to absorb neutrons of only one particular range of energies is inserted in the path of the neutrons and is then removed, the resultant degree of radioactivity of the foil is presumably proportional to the number of neutrons in the particular energy range concerned. Another scheme is to study the induced radioactivity known to be produced only by neutrons whose energy lies above a certain threshold energy.

One scheme for studying the effects of neutrons of a single, arbitrarily selected velocity is the "time-of-flight" method. In this method, a neutron source is modulated; that is, the source is made to emit neutrons in short "bursts" or "pulses." (In each pulse there are a great many neutrons — of a very wide range of velocities.) The target material and the detector are situated several feet or yards from the source. The detector is "modulated" also, and with the same periodicity. The timing or phasing is made such that the detector is responsive only for a short interval, beginning a certain time after the pulse of neutrons leaves the source. Thus, any effects recorded by the detector (for example, fissions in a layer of uranium deposited on an inner surface of an ionization chamber) are the result only of neutrons that arrive just at the moment of responsivity and therefore have traveled from the source in a certain time interval. In other words, the measured effects are due only to the neutrons having the appropriate velocity.

Production of Neutrons. All neutrons are produced as the result of nuclear reactions, and their initial speed depends on the energy balance of the particular reaction. If the reaction is endothermic — that is, if the total mass of the resultant particles is greater than that of the initial particles — the reaction does not occur unless the bombarding particle has more than the "threshold" kinetic energy. At higher bombarding energies, the kinetic energy of the resulting particles, specifically of the neutrons, goes up with the increase of kinetic energy of the bombarding particle above the threshold value. Thus the $Li^7(p,n)Be^7$ reaction * absorbs 1.6 Mev energy since the product particles are heavier than the initial particles. Any further energy of the incident protons

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* In 1930 W. Bothe and H. Becker in Germany found that if the very energetic natural alpha particles from polonium fell on certain of the light elements, specifically beryllium, boron or lithium, an unusually penetrating radiation was produced. In 1932 J. Chadwick in England performed a series of experiments showing that this new radiation consisted of unchanged particles of approximately the mass of the proton, which particles are now called *neutrons*.

goes into kinetic energy of the products, so that the maximum speed of the neutrons produced goes up with the speed of the incident protons. However, to get neutrons of a narrow range of speed, a thin target must be used, the neutrons must all come off at the same angle, and the protons must all strike the target with the same speed.

Although the same energy and momentum conservation laws apply to exothermic nuclear reactions, the energy release is usually large compared to the kinetic energy of the bombarding particles, and therefore essentially determines the neutron speed. Often there are several ranges of speed from the same reaction. There are some reactions that produce very high energy neutrons (nearly 15 Mev).

Since there is a limited number of nuclear reactions usable for neutron sources, there are only certain ranges of neutron speeds that can be produced originally. There is no difficulty about slowing down neutrons, but it is impossible to slow them down uniformly — that is, without spreading out the velocity distribution. The most effective slowing-down scheme is the use of a moderator, as in the graphite pile; in fact, the pile itself is an excellent source of thermal (that is, very low speed) or nearly thermal neutrons.

Determination of Angles of Deflection. The difficulties in measuring the angles of deflection of neutrons are largely of intensity and interpretation. The number of neutrons scattered in a particular direction may be relatively small, and the "scattered" neutrons nearly always include many strays not coming from the intended target.

Determination of Number of Fissions. The determination of the number of fissions which are produced by neutrons or occur spontaneously is relatively simple. Ionization chambers, counter tubes, and many other types of detectors can be used.

Detection of Products of Capture of Neutrons. Often it is desirable to find in detail what has happened to neutrons that are absorbed but have not produced fission — for example, resonance or "radiative" capture of neutrons by

U–238 to form U–239, which leads to the production of plutonium. Such studies usually involve a combination of microchemical separations and radioactivity analyses.

Some Experiments on Nuclear Constants. By the time that the Los Alamos laboratory had been established, a large amount of work had been done on the effects of slow neutrons on the materials then available. For example, the thermal-neutron fission cross section of natural uranium had been evaluated, and similarly for the separated isotopes of uranium and for plutonium. Some data on high-speed-neutron fission cross sections had been published, and additional information was available in project laboratories. To extend and improve such data, Los Alamos perfected the use of the Van de Graaff generator for the $Li^7(p,n)Be^7$ reaction, so as to produce neutrons of any desired energy lying in the range from 3000 to 2,000,000 ev. Success was also achieved in modulating the cyclotron beam and developing the neutron time-of-flight method to produce (when desired) effects of many speed intervals at once. Special methods were devised for filling in the gaps in neutron energy range. Particularly important was the refinement of measurement made possible as greater quantities of U–235, U–238, and plutonium were received. On the whole, the values of cross section for fission as a function of neutron energy from practically 0 to 3,000,000 ev is now fairly well known for these materials.

Some Integral Experiments. Two "integral experiments" (experiments on assembled or integrated systems comprising fissionable material, reflector, and perhaps moderator also) may be described. In the first of these integral experiments, a chain-reacting system was constructed which included a relatively large amount of U–235 in liquid solution. It was designed to operate at a very low power level, and it had no cooling system. Its purpose was to provide verification of the effects that had been predicted for reacting systems containing enriched U–235. The results were very nearly as expected.

The second integral experiment was carried out on a pile containing a mixture of uranium and a hydrogenous moderator. In this first form, the pile was thus a slow-neutron chain-reacting pile. The pile was then rebuilt with less hydrogen. In this version of the pile, fast-neutron fission became important. The pile was rebuilt several more times, less hydrogen being used each time. By such a series of reconstructions, the reaction character was successively altered, so that thermal-neutron fission became less and less important, while fast-neutron fission became more and more important — approaching the conditions to be found in the bomb.

Summary of Results on Nuclear Physics. The nuclear constants of U–235, U–238, and plutonium have been measured with a reasonable degree of accuracy over the range of neutron energies from thermal to 3,000,000 ev. In other words, questions 1, 2, 3, 4, and 5 of the 10 questions posed at the beginning of this section have been answered. The fission spectrum (question 7) for U–235 and Pu–239 is reasonably well known. Spontaneous fission (question 10) has been studied for several types of nuclei. Preliminary results on questions 6, 8, and 9, involving details of the fission process, have been obtained.

Chemistry and Metallurgy Division. The Chemistry and Metallurgy Division of the Los Alamos Laboratory was under the joint direction of J. W. Kennedy and C. S. Smith. It was responsible for final purification of the enriched fissionable materials, for fabrication of the bomb core, tamper, and so on, and for various other matters. In all this division's work on enriched fissionable materials, especial care had to be taken not to lose any appreciable amounts of the materials (which are worth much more than gold). Thus the procedures, already well established at Chicago and elsewhere for purifying and fabricating natural uranium, were often *not* satisfactory for handling highly enriched samples of U–235.

Ordnance, Explosives, and Bomb Physics Divisions. The above account of the work of the Theoretical Physics, Experimental Nuclear Physics, and Chemistry and Metallurgy Divisions is incomplete because important aspects of this work cannot be discussed for reasons of security. For the same reasons, none of the work of the Ordnance, Explosives, and Bomb Physics Divisions can be discussed at all.

Summary. In the spring of 1943, an entirely new laboratory was established at Los Alamos, New Mexico, under J. R. Oppenheimer for the purpose of investigating the design and construction of the atomic bomb, from the stage of receipt of U–235 or plutonium to the stage of use of the bomb. The new laboratory improved the theoretical treatment of design and performance problems, refined and extended the measurements of the nuclear constants involved, developed methods of purifying the materials to be used, and, finally, designed and constructed operable atomic bombs.

Appendix II

Conversion Table for Energy Units

Multiply	*By*	*To Obtain*
mev	1.07×10^{-3}	mass units
	1.60×10^{-6}	ergs
	3.83×10^{-14}	g-cal
	4.45×10^{-20}	kw-hr
mass units	9.31×10^{2}	mev
	1.49×10^{-3}	ergs
	3.56×10^{-11}	g-cal
	4.15×10^{-17}	kw-hr
ergs	6.71×10^{2}	mass units
	6.24×10^{5}	mev
	2.39×10^{-8}	g-cal
	2.78×10^{-14}	kw-hr
g-cal	2.81×10^{10}	mass units
	2.62×10^{13}	mev
	4.18×10^{7}	ergs
	1.16×10^{-6}	kw-hr
kw-hr	2.41×10^{16}	mass units
	2.25×10^{19}	mev
	3.60×10^{13}	ergs
	8.60×10^{5}	g-cal

Appendix III

Nuclear and Atomic Masses of Isotopes

(1) True rest mass of O^{16} atom	1.0128×10^{-23} g
(2) True atomic mass unit	1.6603×10^{-24} g
(3) True rest mass of electron	9.035×10^{-28} g
(4) Relative rest mass of electron	5.442×10^{-4} mass unit

Element	Nuclear Mass	+ Electrons	= Atomic Mass
$_0N^1$	1.0089		
$_1H^1$	1.0075	.0005	1.0080
$_1H^2$	2.0142	.0005	2.0147
$_1H^3$	3.0165	.0005	3.0170
$_2He^3$	3.0159	.0011	3.0170
$_2He^4$	4.0027	.0011	4.0038
$_2He^5$	5.0126	.0011	5.0137
$_2He^6$	6.0196	.0011	6.0207
$_3Li^5$	5.0120	.0016	5.0136
$_3Li^6$	6.0152	.0016	6.0168
$_3Li^7$	7.0165	.0016	7.0181
$_3Li^8$	8.0233	.0016	8.0249
$_4Be^6$	6.0197	.0022	6.0219
$_4Be^7$	7.0170	.0022	7.0192
$_4Be^8$	8.0054	.0022	8.0076
$_4Be^9$	9.0126	.0022	9.0148
$_4Be^{10}$	10.0138	.0022	10.0160
$_4Be^{11}$	11.0255	.0022	11.0277
$_5B^9$	9.0137	.0027	9.0164
$_5B^{10}$	10.0133	.0027	10.0160
$_5B^{11}$	11.0101	.0027	11.0128
$_5B^{12}$	12.0166	.0027	12.0193
$_5B^{13}$	13.0180	.0027	13.0207
$_6C^{10}$	10.0167	.0033	10.0200
$_6C^{11}$	11.0117	.0033	11.0150
$_6C^{12}$	12.0005	.0033	12.0038
$_6C^{13}$	13.0043	.0033	13.0076
$_6C^{14}$	14.0043	.0033	14.0076
$_6C^{15}$	15.0132	.0033	15.0165

Element	Nuclear Mass	+ Electrons	= Atomic Mass
${}_{7}\mathrm{N}^{12}$	12.0195	.0038	12.0233
${}_{7}\mathrm{N}^{13}$	13.0062	.0038	13.0100
${}_{7}\mathrm{N}^{14}$	14.0037	.0038	14.0075
${}_{7}\mathrm{N}^{15}$	15.0010	.0038	15.0048
${}_{7}\mathrm{N}^{16}$	16.0072	.0038	16.011
${}_{7}\mathrm{N}^{17}$	17.0098	.0038	17.0136
${}_{8}\mathrm{O}^{14}$	14.0088	.0043	14.0131
${}_{8}\mathrm{O}^{15}$	15.0035	.0043	15.0078
${}_{8}\mathrm{O}^{16}$	15.9957	.0043	16.0000
${}_{8}\mathrm{O}^{17}$	17.0002	.0043	17.0045
${}_{8}\mathrm{O}^{18}$	18.0007	.0043	18.0050
${}_{8}\mathrm{O}^{19}$	19.0096	.0043	19.0139
${}_{9}\mathrm{F}^{16}$	16.0126	.0049	16.0175
${}_{9}\mathrm{F}^{17}$	18.0027	.0049	17.0076
${}_{9}\mathrm{F}^{18}$	18.0017	.0049	18.0066
${}_{9}\mathrm{F}^{19}$	18.9996	.0049	19.0045
${}_{9}\mathrm{F}^{20}$	20.0014	.0049	20.0063
${}_{9}\mathrm{F}^{21}$	21.0010	.0049	21.0059
${}_{9}\mathrm{F}^{22}$	22.0108	.0049	22.0157
${}_{10}\mathrm{Ne}^{18}$	18.0060	.0054	18.0114
${}_{10}\mathrm{Ne}^{19}$	19.0024	.0054	19.0078
${}_{10}\mathrm{Ne}^{20}$	19.9935	.0054	19.9989
${}_{10}\mathrm{Ne}^{21}$	20.9942	.0054	20.9996
${}_{10}\mathrm{Ne}^{22}$	21.9932	.0054	21.9986
${}_{10}\mathrm{Ne}^{23}$	22.9959	.0054	23.0013
${}_{11}\mathrm{Na}^{20}$	20.0100	.0060	20.0160
${}_{11}\mathrm{Na}^{21}$	20.9975	.0060	21.0035
${}_{11}\mathrm{Na}^{22}$	21.9957	.0060	22.0017
${}_{11}\mathrm{Na}^{23}$	22.9901	.0060	22.9961
${}_{11}\mathrm{Na}^{24}$	23.9916	.0060	23.9976
${}_{11}\mathrm{Na}^{25}$	24.9907	.0060	24.9967
${}_{11}\mathrm{Na}^{26}$	25.9984	.0060	26.0044
${}_{12}\mathrm{Mg}^{22}$	21.9997	.0065	22.0062
${}_{12}\mathrm{Mg}^{23}$	22.9937	.0065	23.0002
${}_{12}\mathrm{Mg}^{24}$	23.9848	.0065	23.9913
${}_{12}\mathrm{Mg}^{25}$	24.9873	.0065	24.9938
${}_{12}\mathrm{Mg}^{26}$	25.9833	.0065	25.9898
${}_{12}\mathrm{Mg}^{27}$	26.9863	.0065	26.9928
${}_{13}\mathrm{Al}^{24}$	23.9988	.0071	24.0059
${}_{13}\mathrm{Al}^{25}$	24.9910	.0071	24.9981
${}_{13}\mathrm{Al}^{26}$	25.9858	.0071	25.9929
${}_{13}\mathrm{Al}^{27}$	26.9827	.0071	26.9899
${}_{13}\mathrm{Al}^{28}$	27.9832	.0071	27.9903
${}_{13}\mathrm{Al}^{29}$	28.9822	.0071	28.9893
${}_{13}\mathrm{Al}^{30}$	28.9883	.0071	29.9954

Element	Nuclear Mass	+ Electrons	= Atomic Mass
${}_{14}\mathrm{Si}^{26}$	25.9917	.0076	25.9993
${}_{14}\mathrm{Si}^{27}$	26.9878	.0076	26.9954
${}_{14}\mathrm{Si}^{28}$	27.9790	.0076	27.9866
${}_{14}\mathrm{Si}^{29}$	28.9790	.0076	28.9866
${}_{14}\mathrm{Si}^{30}$	29.9756	.0076	29.9832
${}_{14}\mathrm{Si}^{31}$	30.9786	.0076	30.9862
${}_{14}\mathrm{Si}^{32}$	31.9773	.0076	31.9849
${}_{14}\mathrm{Si}^{33}$	32.9294	.0076	32.9370
${}_{15}\mathrm{P}^{28}$	27.9919	.0082	28.0001
${}_{15}\mathrm{P}^{29}$	28.9837	.0082	28.9919
${}_{15}\mathrm{P}^{30}$	29.9800	.0082	29.9882
${}_{15}\mathrm{P}^{31}$	30.9761	.0082	30.9843
${}_{15}\mathrm{P}^{32}$	31.9759	.0082	31.9841
${}_{15}\mathrm{P}^{33}$	32.9744	.0082	32.9826
${}_{15}\mathrm{P}^{34}$	33.9792	.0082	33.9874
${}_{15}\mathrm{P}^{35}$	34.9751	.0082	34.9833
${}_{15}\mathrm{P}^{36}$	35.9788	.0082	35.9870
${}_{16}\mathrm{S}^{30}$	29.9857	.0087	29.9944
${}_{16}\mathrm{S}^{31}$	30.9805	.0087	30.9892
${}_{16}\mathrm{S}^{32}$	31.9721	.0087	31.9808
${}_{16}\mathrm{S}^{33}$	32.9731	.0087	32.9818
${}_{16}\mathrm{S}^{34}$	33.9711	.0087	33.9798
${}_{16}\mathrm{S}^{35}$	34.9717	.0087	34.9804
${}_{16}\mathrm{S}^{36}$	35.969	.0087	35.9777
${}_{16}\mathrm{S}^{37}$	36.9725	.0087	36.9812
${}_{17}\mathrm{Cl}^{32}$	31.9858	.0092	31.9950
${}_{17}\mathrm{Cl}^{33}$	32.9780	.0092	32.9872
${}_{17}\mathrm{Cl}^{34}$	33.972	.0092	33.981
${}_{17}\mathrm{Cl}^{35}$	34.9711	.0092	34.9803
${}_{17}\mathrm{Cl}^{36}$	35.9688	.0092	35.9780
${}_{17}\mathrm{Cl}^{37}$	36.9687	.0092	36.9779
${}_{17}\mathrm{Cl}^{38}$	37.9707	.0092	37.9799
${}_{17}\mathrm{Cl}^{39}$	38.9702	.0092	38.9794
${}_{17}\mathrm{Cl}^{40}$	39.9727	.0092	39.9819
${}_{18}\mathrm{A}^{34}$	33.9800	.0098	33.9898
${}_{18}\mathrm{A}^{35}$	34.9753	.0098	34.9851
${}_{18}\mathrm{A}^{36}$	35.9674	.0098	35.9772
${}_{18}\mathrm{A}^{37}$	36.9671	.0098	36.9769
${}_{18}\mathrm{A}^{38}$	37.9648	.0098	37.9746
${}_{18}\mathrm{A}^{39}$	38.9649	.0098	38.9747
${}_{18}\mathrm{A}^{40}$	39.9658	.0098	39.9756
${}_{18}\mathrm{A}^{41}$	40.9672	.0098	40.9770

Element	Nuclear Mass	+ Electrons	= Atomic Mass
$_{19}K^{36}$	35.9805	.0102	35.9907
$_{19}K^{37}$	36.9728	.0102	36.9830
$_{19}K^{38}$	37.9693	.0102	37.9795
$_{19}K^{39}$	38.9645	.0102	38.9747
$_{19}K^{40}$	39.9658	.0102	39.976
$_{19}K^{41}$	40.9638	.0102	40.9740
$_{20}Ca^{40}$	39.9641	.0109	39.975
$_{20}Ca^{41}$	40.9627	.0109	40.9736
$_{20}Ca^{42}$	41.9602	.0109	41.9711
$_{20}Ca^{43}$	42.9614	.0109	42.9723
$_{20}Ca^{45}$	44.9584	.0109	44.9693
$_{21}Sc^{45}$	44.9576	.0114	44.969
$_{21}Sc^{46}$	45.9576	.0114	45.9690
$_{22}Ti^{46}$	45.9558	.0120	45.9678
$_{22}Ti^{47}$	46.9527	.0120	46.9647
$_{22}Ti^{48}$	47.9513	.0120	47.9633
$_{22}Ti^{49}$	48.9544	.0120	48.9664
$_{22}Ti^{50}$	49.9512	.0120	49.9632
$_{22}Ti^{51}$	50.9490	.0120	50.9610
$_{23}V^{51}$	50.9578	.0125	50.9603
$_{23}V^{52}$	51.9460	.0125	51.9585
$_{24}Cr^{51}$	50.9469	.0131	50.960
$_{24}Cr^{52}$	51.9444	.0131	51.9575
$_{24}Cr^{53}$	52.9441	.0131	52.9572
$_{25}Mn^{55}$	54.9517	.0136	54.9653
$_{26}Fe^{54}$	53.9460	.0141	53.9601
$_{26}Fe^{56}$	55.9467	.0141	55.9608
$_{26}Fe^{57}$	56.9468	.0141	56.9609
$_{29}Cu^{63}$	62.9799	.0158	62.9957
$_{29}Cu^{65}$	64.9797	.0158	64.9955
$_{30}Zn^{64}$	63.9395	.0163	63.9558
$_{30}Zn^{66}$	65.9348	.0163	65.9511
$_{47}Ag^{107}$	106.9217	.0253	106.9470
$_{47}Ag^{109}$	108.9207	.0253	108.9460
$_{78}Pt^{195}$	194.9971	.0424	195.0395
$_{79}Au^{197}$	196.9964	.0430	197.0394

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