

designing the bomb

The world's first man-made atomic explosion took place only 28 months after the arrival of the first scientific contingent at Los Alamos. Few greater tributes to human ingenuity have ever been written.

The theoretical basis for nuclear weapons was already understood, in its outlines, when the Laboratory was established. Many of the engineering problems were foreseen in a general way, but much remained to be done. The following summary of weapon theory (all of it known in early 1943) will serve to suggest the enormous difficulty of the task that lay ahead.

The nucleus of an atom of uranium-235 contains 92 protons and 143 neutrons. When this nucleus absorbs an additional neutron, it becomes unstable and usually divides approximately in half. The two fragments become nuclei of two lighter elements, having a total mass somewhat less than the mass of the original uranium nucleus plus the additional neutron. Most of the mass difference between the original material and the products is converted into kinetic energy—rapid flight of the fragments.

The product nuclei emit several neutrons (in 1943 nobody knew exactly how many, on the average) for every U-235 nucleus split. Other U-235 nuclei may absorb these neutrons and undergo fission in turn, producing still more neutrons. Such a chain reaction will proceed very rapidly, as long as one neutron (at least) from each fission causes another fission.

Theoretically, the energy release from one kilogram (about 2.2 pounds) of U-235 would equal the energy release from the detonation of 17,000 tons of TNT.

Given these facts, the problem was to devise a bomb deriving its explosive energy from the fission of uranium-235 (or of plutonium-239, the only other fissionable material under consideration in 1943).

Neither U-235 nor Pu-239 was available in sufficient quantity to make a bomb. It was thought that these materials would become available within two years. The task of the Los Alamos staff was to design the bomb, and to devise methods of manufacturing it, in advance of the scheduled deliveries of the needed material.

A separate and remarkable story lies behind the fact that the scheduled deliveries were made on time. The story being told here will limit itself primarily to what happened at Los Alamos.

The Los Alamos task was to discover means of making the desired explosive liberation of energy

take place *efficiently* and *at the right time*. A veritable mountain of difficulties stood in the way.

No one knew how much fissionable material had to be put together to support an explosive chain reaction, but it was known that the reaction could not *occur* if the amount *were* insufficient. The burning of conventional explosives is a chain reaction of a different kind; a tiny quantity of TNT burns as readily as a larger amount. Fission chains cannot occur in the same way, because the neutrons on which they depend must remain within the fuel until they encounter fissionable nuclei. If the surface area of the fuel mass is large compared to the volume (i.e., if the fuel mass is too small or too much flattened out), then the neutron escape area is too large compared to the neutron source volume, and too many neutrons will find their way out without causing fission.

By now it is possible to determine mathematically how much fuel is enough, but only when the shape, density, and purity of the fuel material are known. In 1943 additional unknowns stood in the way. The exact average number of neutrons emitted in fission had not yet been measured. Neither had the pertinent "cross sections."

The term "cross section" is an extremely useful one in the study of nuclear reactions. It is a measure of the likelihood that a certain reaction will occur, stated in terms of effective target area. Perhaps the following analogy will help to make this clear:

A popular carnival game is one in which the customer throws baseballs at ranks of woolly dolls. If we suppose that the solid portion of each doll presents a front surface of one square foot, and if we neglect the diameter of the baseball, then the effective area, ("cross section") of each doll, for the reaction we might call "direct hit," is one square foot. But if we investigate other possible reactions, we find the effective area of the same doll changing. Assume, for instance, that only one direct hit out of two causes the doll to fall down. For the "knockdown" reaction, then, the cross section of each doll is .5 square foot. If we throw ping pong balls, the "direct hit" cross section may remain one square foot, while the "knockdown" cross section becomes zero. Or, if the fringe on the doll is unusually stiff, so that a baseball passing through the fringe sometimes causes the doll to fall, then the doll's cross section for baseball knockdown may rise toward two square feet. And the knockdown cross section will be different for baseballs of different speeds. Cross



In Los Alamos by day great minds pondered the bomb problems, by night, talk turned to less secret discussions. From left to right across both pages: Enrico Fermi



with L. D. P. King; Eric Jette, Charles Critchfield, J. Robert Oppenheimer; Edward Teller with Norris Bradbury; E. O. Lawrence, Fermi and I. I. Rabi.

section is the effective target area for a specific reaction or event.

If we consider a free neutron, traveling through a sphere of pure U-235 metal, we need to know how likely it is to cause fission, instead of escaping from the sphere. We need to know, in other words, not how large the U-235 nucleus actually is, but how large a target it presents statistically, for the fission reaction, to a neutron of given velocity. Fission cross sections of U-235 for neutrons of a wide range of velocities (energies) needed to be known before a bomb could be designed. Also, since the uranium would not actually be pure U-235, it was necessary to know the cross sections of various impurities, especially U-238, for neutron absorption *without* fission.

Only on the basis of careful experiments and measurements could the needed cross sections be learned. Particle accelerators (atom smashers) were used in these experiments, because they could produce, indirectly, beams of neutrons with which to bombard samples of bomb material.

The mass of a sphere of fissionable material just sufficient to sustain a chain reaction is called the "critical mass." By surrounding this material with an envelope of other material, to bounce escaping neutrons back into the active volume, it was possible to improve neutron economy and thus reduce the critical mass. Such a reflecting envelope is sometimes called a tamper.

The tamper in a weapon serves a second purpose. As the fissionable mass expands during the explosion, it quickly becomes less dense, at the same time, its surface area increases. These two effects act together to "quench" the chain reaction, since they facilitate neutron escape and reduce the likeli-

hood that a given neutron will encounter a fissionable nucleus. A massive tamper slows the expansion and allows more energy to be liberated before the reaction is quenched.

Tamper materials, especially their cross sections for capturing neutrons and for scattering neutrons back into the fissionable material, needed intensive study.

It happens that the fission cross section of U-235 is greater for slow neutrons than for fast (presumably because the slow, neutron spends more time near the nucleus.) In spite of this fact, the reaction in a bomb must depend almost solely on fast neutrons. This is partly because the neutrons produced in fission are naturally fast, partly because an air-delivered bomb must be as light as possible (therefore not permitting the inclusion of moderating material to slow the neutrons), and partly because a slow-neutron reaction system would not have time to liberate a large enough fraction of the potential energy before the bomb blew itself apart.

Therefore, it was necessary to establish facts relating to the efficiency of a tamped atomic explosion produced by fast neutrons. And these facts had to be established in advance of the delivery of fissionable material for the first bomb-in advance, of course, of any atomic explosion at all.

For the sake of explosion efficiency, it was inadvisable to depend on "background" neutrons (free neutrons unavoidably present in the bomb at all times) to start the reaction. The only way to be sure the reaction would start fast, and at exactly the right moment, was to arrange an internal neutron source that would deliver millions of neutrons in a single burst at the instant of complete assembly. Devices called "initiators" had to be developed to



supply these neutrons.

As if such difficulties were not enough, a whole new supply of problems was introduced by the need to make the bomb go off at the right time and *only* at the right time.

A stick of dynamite is capable of exploding. When its cap or igniter sets it off, it explodes. A critical mass of fissionable material is not only capable of sustaining a chain reaction; it is incapable of *not* doing so. No percussion cap is necessary. Nobody lights a fuse. Once the critical conditions exist, the reaction begins. (This is because the one free neutron needed to trigger the reaction will always be supplied within a fraction of a second by neutrons from cosmic rays, spontaneous fission, or other sources.) Therefore, the detonation of a nuclear bomb occurs whenever its core is actually and fully assembled for the first time. The final assembly must occur only at the target. To say that this introduces a problem is putting it mildly.

Furthermore, the final assembly must be accomplished rapidly. As the core passes from its subcritical, or safe, configuration to its supercritical, or explosive, configuration, it must inevitably pass through configurations that are *barely* critical. Fast assembly is necessary because there must be no time for the reaction to occur and destroy the bomb before the optimum configuration is reached.

Since no assembly method would be fast enough unless it made use of high explosives, an intensive study of the potentialities of chemical explosives for this purpose had to be made.

In principle, two general methods of assembly appeared possible. One was the so-called "gun" method, in which one subcritical mass of fissionable material would be fired as a projectile at a target consisting of another subcritical mass of fissionable material. When projectile met target, the two together would constitute a supercritical mass. (The gun, with its explosive charge and its fissionable

projectile, would have to be enclosed in the bomb casing, along with the target.) The other assembly method was "implosion," in which a slightly subcritical mass of fissionable material would be surrounded by high explosives. When these explosives were detonated, they would compress the fissionable material, thereby increasing its density (decreasing the distances between target nuclei), thus rendering it supercritical.

The gun method appeared to be the easier to develop. It involved principles already well understood by ordnance experts, while the implosion method introduced entirely new principles of guiding explosive energy. It was hoped that the gun method might work for both uranium and plutonium bombs. It was a somewhat slower detonation system than implosion was, but its development would require fewer technological innovations.

In 1944 came the verification of a piece of bad news rumored a little earlier: The gun method was unsuitable for plutonium bombs. The reason was that plutonium produced in nuclear reactors (such as those at Oak Ridge and Hanford) contained a significant percentage of an isotope identified as Pu-240. Plutonium of this mass number had a strong tendency toward spontaneous fission, releasing neutrons. This produced an unusually high neutron background in plutonium containing the 240 isotope. Therefore, assembly of a plutonium bomb would have to be lightning-fast to prevent premature initiation of the chain reaction. Assembly by the gun method would be too slow; in a plutonium bomb, it would have to be implosion or nothing.

The simplest way to proceed might have been to build a few experimental bombs in the early nineteen-forties and try them out. Not the least of the Laboratory's problems arose from the impossibility of doing this. By the time the precious shipments of fissionable material arrived at Los

Alamos, a workable bomb design had to be ready. Various components and sub-assemblies could be tested by themselves, but no integral test of the weapon would be possible until long after the time when such testing might have served its purpose best.

As soon as the Laboratory had its first skeleton staff and a minimum of equipment (a cyclotron loaned by Harvard University, two electrostatic accelerators from the University of Wisconsin, a Cockcroft-Walton accelerator from the University of Illinois, and much other borrowed equipment) the work began. In many ways it was a continuation of research already begun in a dozen laboratories, all over the country. But it had a focus for the first time. Los Alamos, and no other laboratory, would make the first bomb.

Research got under way on several fronts during the first half of 1943. Measurements of the "neutron number" (average number of neutrons emitted per fission) of plutonium-239 and uranium-235 were undertaken immediately, though the plutonium measurements had to be made on a sample scarcely visible to the naked eye.

Other research projects begun in the first months were these:

***Measurements of the fission spectrum (energy range) of neutrons from U-235.

***Measurements of fission cross sections Of U-235 and Pu-239 for neutrons of high, low, and all intermediate energies.

***Measurements of the time (a fraction Of a millionth of a second) between fission and the emission of virtually all the fission neutrons.

***Measurements of cross sections of neutron capture and neutron scattering in various possible tamper materials.

***Development of experimental techniques (including ways of producing, and counting neutrons of specific energies, measuring fission in various materials, and measuring certain non-fission reactions induced by neutrons.)

***Radiochemical studies aimed toward the development of an initiator (the neutron source mentioned earlier) for the bomb.

***Research on uranium hydride, an early possibility for bomb fuel, later abandoned.

***Research on the chemistry and metallurgy of uranium and plutonium, and of possible tamper materials (including development of purification processes and analytical methods for measuring small amounts of impurities).

***Research on projectile and target materials for the gun program.

***Planning for construction of a deuterium liquefaction plant at Los Alamos, to supply liquid deuterium for experiments useful in the development of a thermonuclear bomb.



The Water Boiler reactor under construction. This reactor was constructed for use as a research tool during the development of the bomb. The world's first enriched uranium reactor, the Water Boiler is still in operation.

***An intensive ordnance program, studying the uses of high explosives for bomb assembly.

***A tremendous theoretical effort devoted to calculations of all kinds related to the physics and thermodynamics of the bomb.

At this early stage in the work of the Laboratory, it was believed that the development of the bomb would have two more-or-less distinct phases: (a) research in physics, chemistry, and metallurgy, then

Wartime photo showing one of the practical, if primitive, ways in which radioactive materials were safely handled during the early years of the bomb development.



(b) technology in engineering ordnance design. The original directive set forth a plan for putting the Laboratory on a military basis in the second phase, commissioning the scientists in military rank, and so on. As it turned out, the commissioning plan was never put into effect.

In the fall of 1943, as a result of a conference between President Roosevelt and Prime Minister Churchill, it was decided to assign about two dozen British citizens to work at Los Alamos among them were some of the world's most distinguished scientists.

Laboratory personnel were all civilians until the fall of 1943, when a detachment of WACs and several technicians and scientists drafted into the Army's Special Engineer Detachment (SED) joined the staff. By July, 1945, 50% of Laboratory personnel were military, mostly men of the SED. Total Laboratory personnel increased steadily from 250 in July, 1943, to 2,500 in July, 1945.

The most important single characteristic of Los Alamos Scientific Laboratory became apparent in the very first days. It has remained LASL'S most important single characteristic: *The Laboratory is predominantly a scientific, not an engineering, institution.* The fact that its first mission was the creation of a practical piece of hardware would seem to contradict such a statement, but the contradiction is only an apparent one. The nature of this specific piece of hardware was such that its creation called for a massive program of scientific research.

That it also called for a massive engineering program is equally true, but not central to the character of the institution as it was in 1943 or as it has been ever since. Every development program undertaken by the Laboratory has been of such an advanced kind that the technological effort was smaller, in terms of man hours, than the scientific one. It is impossible, of course, to separate the two kinds of effort in a clear-cut way, but anyone who has worked in the intellectual climate of Los Alamos knows that "Los Alamos Engineering Laboratory" or even "Los Alamos Research and Development Laboratory" would have been a misnomer. "Scientific" is right, and the word was inserted in the earlier name, "Los Alamos Laboratory" in 1947.



The ice house, a stone building long used, before the war, for storage of ice from Ashley Pond. It later assumed historic significance as the building in which nuclear components of the first atomic bomb were assembled,



Atomic bomb research was conducted in these hurriedly constructed laboratory buildings which made up the

technical area. Gamma building, below and at right above, wrapped around and obscured red Ashley Pond.



preparing the materials

Preparation of the two fissionable core materials, meanwhile was being accomplished elsewhere against almost overwhelming odds.

In the case of uranium, the difficulty arose from the fact that uranium 238 and uranium 235 are almost identical substances. Each of the two kinds of atoms has 92 nuclear protons and 92 orbital electrons. Since the chemical behavior of any atom is almost entirely governed by its orbital electrons, the two kinds of uranium could not be separated by chemical processes. Some other process—a purely physical one—was required.

U-235 has 143 neutrons in each nucleus. U-238 has 146. Somehow, those three extra neutrons had to be used to make the U-238 atoms go one way and the U-235 atoms go another. A great many methods were suggested. Half a dozen or so, including a centrifuge process like the one used to separate cream from milk, were given extensive trials. Almost every idea worked, but no idea worked very well. The difference between the two isotopes was too small.

Furthermore, all of the separation methods tried were expensive. If the isotope separation program had been an industrial enterprise, aimed at making a profit, the only sensible course would have been to close up shop.

But there was a war on. Nobody knew how much effort, if any, Germany might be devoting to nuclear weapon development (actually it was very little), but one thing was almost certain: If the Germans were first to develop a nuclear weapon, Hitler would win the war. This was no time to pinch pennies.

America's decision, based partly on extremely good work by scientists in Britain, was to continue at any cost. Investigation of many ways of separating isotopes would go on, and a really vast effort would be made on the two most promising processes. One of these was gaseous diffusion separation and the other was electromagnetic separation.

Both processes are based on the difference in weight (more properly, in mass) between the two kinds of uranium nuclei,

The molecules in a gas are in constant motion. The warmer the gas, the faster its molecules move; but some move faster than others. On the average, heavier molecules are more sluggish than light ones. They move more slowly. Therefore, when a gas diffuses through a porous barrier, the lighter molecules get through a little more often (at first)

than the heavier ones.

Perhaps unfortunately, uranium is not a gas. For the gaseous diffusion process, the uranium has to be combined with fluorine to produce an easily-vaporized compound called uranium hexafluoride. Uranium hexafluoride gas is extremely corrosive, tending to attack pumps, piping, barriers, and almost anything else it happens to touch.

But the gaseous diffusion method works. Passage through each barrier in a multi-stage separation plant increases (very slightly) the concentration of U-235 in some of the gas. By using thousands of stages, thousands of miles of piping, and hundreds of acres of barriers, it is possible to produce very highly enriched uranium hexafluoride. Uranium metal made from the enriched gas has a very low concentration of U-238.

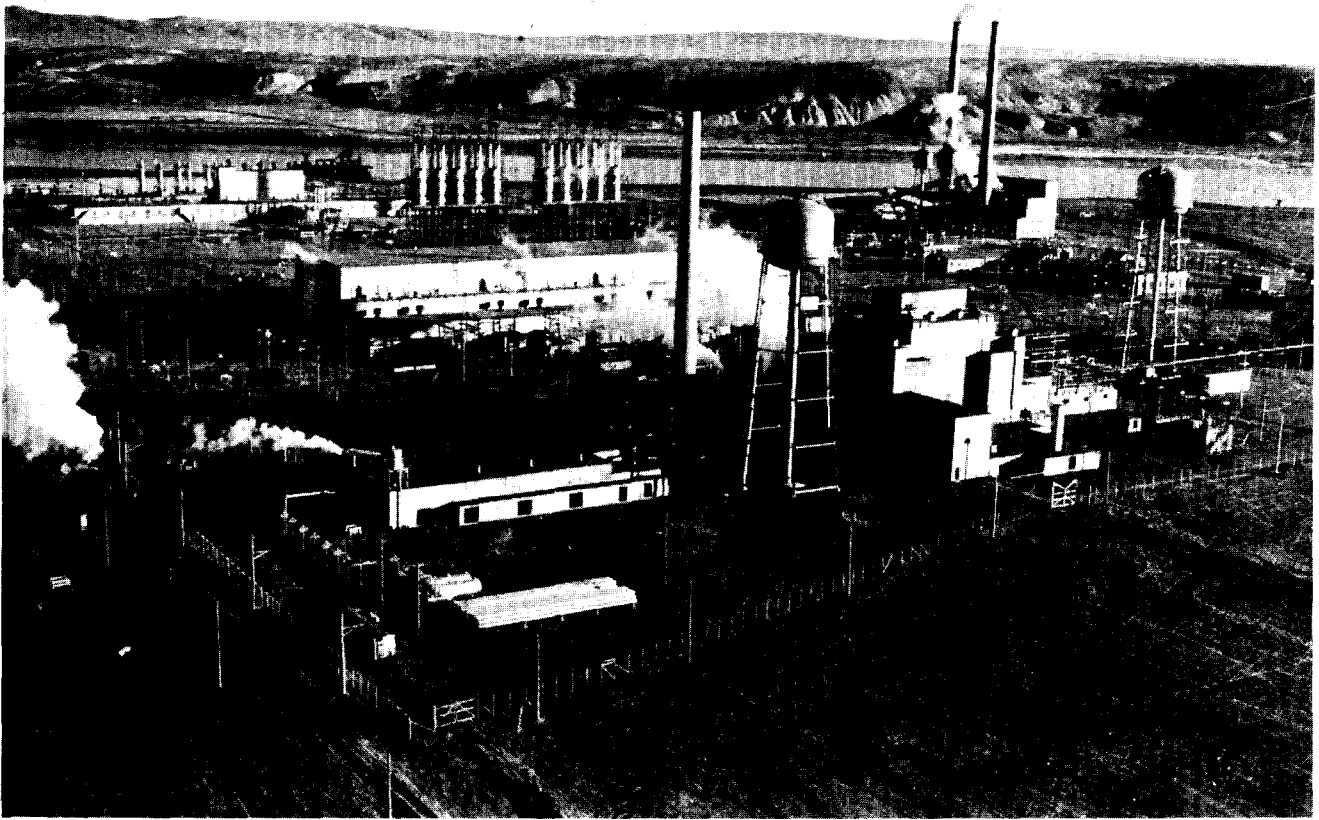
A large part of the wartime project consisted of planning and building a separation plant to employ the principle just described. The plant was built in Oak Ridge, Tennessee, in the years from 1943 to 1945.

The electromagnetic separation process is quite different, but it also exploits the very slight mass differences created by the presence of those three extra neutrons in each U-238 nucleus.

Everything possessing mass has inertia. The more mass, the more inertia. It is perhaps usual to think of inertia as a reluctance to move, but inertia is a broader phenomenon than that. It is less a resistance to movement than a kind of resistance to change. If an object is stationary, inertia makes it reluctant to move; if it is moving, inertia makes it reluctant to stop or to change direction.

Since inertia is proportional to mass, the U-238 nucleus has a little more inertia than the U-235 nucleus. If both are traveling at the same speed, the heavier nucleus will have a slightly stronger resistance to any change in direction. Therefore, a given force tending to change the direction of motion will have a slightly greater effect on the lighter nuclei than on the heavier.

This principle is exploited in the electromagnetic separation of isotopes in the following way: First, the uranium atoms are "ionized," usually by being deprived of one orbital electron each. This leaves the atoms positively charged, so that they can be accelerated electrically and acted on magnetically. When they have been accelerated—many millions of them at a time—they are formed into a beam, all traveling in the same direction. The beam of ura-



One of eight plutonium-producing reactor facilities at Hanford works. This one operated for the first time with full loading on December 17, 1944.

mium ions is then passed through a magnetic field which has been arranged in such a way as to bend their trajectories. Under the influence of the magnetic field, the U-235 ions change direction more than the U-238 ions. The beam becomes two beams, each of which can be caught in a separate receptacle.

Though the development of the electromagnetic separation process encountered many difficulties, the method ultimately succeeded in producing important quantities of U-235. Electromagnetic separating machines called "calutrons," developed by the University of California, were installed at Oak Ridge. They were used mainly to increase the enrichment of already-enriched products of the immense gaseous diffusion plant and of a smaller thermal diffusion plant, which used uranium hexafluoride in liquid form.

By late 1944, highly enriched uranium compounds were being produced at Oak Ridge in kilogram quantities.

Meanwhile, the program to produce the previously unknown element of atomic number 94 had made great strides.

Berkeley scientists produced minute quantities of plutonium in the winter of 1940-41, by bombardment of uranium with particles from an accelerator. The new element proved to be readily fissionable, as had been predicted.

However, production in quantities of military significance could not be carried out with particle

accelerators. What was needed was a really plentiful source of free neutrons. The only sufficient source would be a nuclear fission reactor.

Fission reactors are devices in which a chain reaction is maintained under controlled conditions. No such device had been built when the Berkeley scientists produced their first plutonium. It would take two more years to achieve the first man-made fission chain reaction.

The leader in that achievement was the same Enrico Fermi who had first split the uranium nucleus. He had come to the United States and was working at the University of Chicago.

Fermi and his associates sought to demonstrate the possibility of a fission chain reaction in natural uranium—uranium containing less than one per cent U-235. Though a natural-uranium reaction would release energy at a rate unsuitable for an efficient nuclear explosion, the demonstration that such a reaction could be maintained would have great significance. Among other things, it could lead to the construction of reactors capable of producing large quantities of plutonium.

In Fermi's experiment, lumps of natural uranium metal and of natural uranium oxide were placed in a "lattice" (a system of regular spacing) within a pile of graphite blocks.

The graphite was necessary to enable the pile to sustain a chain reaction. Here is why:

When a uranium nucleus undergoes fission, neu-

trons come out at high velocity. In a natural uranium system, these high-speed neutrons collide with uranium nuclei of both kinds. Some of the collisions cause fission, but many others do not. Most of the neutrons become involved in a series of "elastic" (glancing or bouncing) collisions with nuclei. Such collisions do not cause fission, and each such collision robs a neutron of some of its speed.

It happens that the velocity of a neutron has a large effect on what the neutron can do to a uranium nucleus. As the velocity goes down, the neutron loses its ability to cause fission in U-238, while acquiring *even greater* ability to cause fission in U-235. At what is called "thermal" velocity (when the neutron has lost all of the initial impulse it received from the fissioning nucleus) its ability to cause fission in U-235 is very high.

Unfortunately, there is a certain intermediate velocity at which a neutron is most likely to be captured by a U-238 nucleus, without causing fission. In a chain-reacting pile using natural uranium, it is therefore desirable to prevent collisions between medium-speed neutrons and U-238 nuclei. Otherwise, so many neutrons will be captured that the chain reaction will die out. (It is exactly such captures that result in the formation of plutonium, but Fermi was not yet trying for that; his pile would require a maximum number of free neutrons, just to keep the chain reaction alive.)

By using lumps of uranium separated by blocks of graphite, it is possible to avoid many of the neutron captures that would occur in a structure of pure uranium. Neutrons produced by fissions in one

lump of fuel fly out of that lump and into the graphite before they have lost enough speed to be captured readily by U-238 nuclei. In the graphite, they lose much of their velocity, because of elastic collisions with carbon nuclei. By the time the neutrons reach the next lump of fuel, they are "thermal" (slow), and are not so likely to be captured by the U-238.

Fermi's pile produced its first sustained chain reaction in December, 1942, exactly one week after the Under Secretary of War had directed that a site at Los Alamos, New Mexico, be acquired for a nuclear weapon laboratory. Fermi's success demonstrated the possibility of the sustained chain reaction and gave great encouragement to those who planned to use larger piles as neutron sources for the production of plutonium.

Construction of one such pile began in Tennessee in 1943. By November of the same year, it was in operation. Within a few months after that, it had produced several grams of plutonium.

However, much larger plutonium production reactors would be necessary for the production of enough plutonium to be used in bomb cores. In June, 1943, construction of such reactors began at Hanford, Washington, where water from the Columbia River could be used as a reactor coolant. By September, 1944, the first Hanford pile was in operation. Plutonium nitrate from Hanford would soon join the flow of fissionable material that was already moving from the uranium and plutonium production facilities in Tennessee toward the Los Alamos Laboratory.



A sketch of Fermi's chain-reacting pile at the University of Chicago.

By September, 1944, the first kilogram of highly enriched uranium (63% U-235) had been received from the separation plant at Oak Ridge. By July, 1945, 50 kilograms had been received, and the enrichment had increased to 89%.

The first small quantities of plutonium (as nitrate, not as metal) arrived at the Laboratory in October, 1943. Gram amounts were delivered early in 1944, and soon after that still larger amounts began coming in, first from Oak Ridge and later from Hanford.

Both the uranium and the plutonium needed purification (an unprecedented job) before becoming suitable for weapons use. Means of purifying these elements were developed at Los Alamos and have been constantly improved.

The problem of preparing plutonium metal of high purity was started in the Laboratory in August, 1943 at a time when no plutonium was available for research. It gradually became available in amounts varying from micrograms to grams, but in the meantime, extensive preliminary investigations of possible methods of preparation had been made using other elements as stand-ins.

By the spring of 1944, the world's first piece of plutonium metal prepared in any scale larger than a few micrograms was produced by the graphite centrifuge method which used centrifugal force to throw down molten metal into the tip of a cone during reduction. This was accomplished by placing the reaction mixture in a cone-shaped refractory liner sealed inside a steel "bomb." The bomb was then placed in a graphite centrifuge which was heated rapidly to a high temperature while rotating. As the reduction took place the metal was thrown together in the tip of the liner, producing a good yield of coherent metal.

Meantime, however, research on the stationary bomb method indicated that gravitational force alone was adequate to separate the metal from plutonium fluoride, using calcium and iodine with appropriate heating conditions. The stationary bomb method, more suited to large scale production and much less complicated than the centrifuge method, was then adopted and is still used for routine production of pure plutonium metal. The centrifuge method, however, served its purpose at a time when it was most desperately needed.

A section of the electromagnetic process equipment, used for enriching uranium at Oak Ridge, Tennessee.

Units of the electromagnetic system are used today to produce stable isotopes for peaceful purposes.

