

## CHAPTER VI

THE METALLURGICAL PROJECT AT CHICAGO IN 1942Introduction

6.1. As has been made clear in Chapters IV and V, the information accumulated by the end of 1941 as to the possibility of producing an atomic bomb was such as to warrant expansion of the work, and this expansion called for an administrative reorganization. It was generally accepted that there was a very high probability that an atomic bomb of enormous destructive power could be made, either from concentrated U-235 or from the new element plutonium. It was proposed, therefore, to institute an intensive experimental and theoretical program including work both on isotope separation and on the chain-reaction problems. It was hoped that this program would establish definitely whether or not U-235 could be separated in significant quantities from U-238, either by electromagnetic or statistical methods; whether or not a chain reaction could be established with natural uranium or its compounds and could be made to yield relatively large quantities of plutonium; and whether or not the plutonium so produced could be separated from the parent material, uranium. It was hoped also that the program would provide the theoretical and experimental data required for the design of a fast-neutron chain-reacting bomb.

6.2. As has been explained in Chapter V, the problems of isotope separation had been assigned to groups under Lawrence and Urey while the remaining problems were assigned to Compton's group, which was organized under the cryptically named "Metallurgical Laboratory" of the University of Chicago. In this chapter and the following two chapters we shall describe the work of the Metallurgical Laboratory and the associated laboratories up to June 1945. In later chapters we shall discuss isotope-separation work and the work of the bomb development group, which was separated from the Metallurgical Laboratory early in 1943.

6.3. It would be foolish to attempt an assessment of the relative importance of the contributions of the various laboratories to the overall success of the atomic-bomb project. This report makes no such attempt, and there is little correlation between the space devoted to the work of a given group and the ability or importance of that group. In deciding which subdivision of the atomic-bomb project should be discussed first and most fully, we have been governed by criteria of general interest and of military security. Some developments of great technical importance are of little general interest; others both interesting and important must still be kept secret. Such criteria, applied to the objectives and accomplishments of the various laboratories set up since large-scale work began, favor the Metallurgical Laboratory as the part of the project to be treated most completely.

## Objectives

6.4. In accordance with the general objectives just outlined, the initial objectives of the Metallurgical Laboratory were: first, to find a system using normal uranium in which a chain reaction would occur; second, to show that, if such a chain reaction did occur, it would be possible to separate plutonium chemically from the other material; and, finally, to obtain the theoretical and experimental data for effecting an explosive chain reaction with either U-235 or with plutonium. The ultimate objective of the laboratory was to prepare plans for the large-scale production of plutonium and for its use in bombs.

## Organization of the Work

6.5. The laboratory had not only to concern itself with its immediate objectives but simultaneously to bear in mind the ultimate objectives and to work toward them on the assumption that the immediate objectives would be attained. It could not wait for a chain reaction to be achieved before studying the chemistry of plutonium. It had to assume that plutonium would be separated and to go ahead with the formulation of plans for its production and use. Consequently problems were continually redefined as new information became available, and research programs were reassessed almost from week to week. In a general way the experimental nuclear physics group under E. Fermi was primarily concerned with getting a chain reaction going, the chemistry division organized by F. H. Spedding (later in turn under S. K. Allison, J. Franck, W. C. Johnson, and T. Hogness) with the chemistry of plutonium and with separation methods, and the theoretical group under E. Wigner with designing production piles. However, the problems were intertwined and the various scientific and technical aspects of the fission process were studied in whatever group seemed best equipped for the particular task. In March 1942, Thomas W. Moore was brought in to head the engineering group. Other senior men in this group were M. C. Leverett, J. A. Wheeler and C. W. Cooper, who later succeeded Moore as head of the Technical Division. In the summer of 1942 the importance of health problems became apparent and a health division was organized under Dr. R. S. Stone. The difficult task of organizing and administering a research laboratory growing in size and complexity with almost explosive violence was carried out by R. L. Doan as Laboratory Director.

6.6. We have chosen to confine this chapter to the work of 1942 because a self-sustaining chain reaction was first achieved on December 2nd of that year, at a time when the whole Chicago project was being appraised by a reviewing committee with the members particularly selected for their engineering background.\* That was a dramatic coincidence and also a

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\* This committee was composed of W. K. Lewis, C. H. Greenewalt, T. C. Gary, and Roger Williams. E. V. Murphree was also a member but due to illness was unable to participate.

convenient one for purposes of this report since either incident might be considered to mark the end of an epoch at the Metallurgical Laboratory. Furthermore, in preparation for the reviewing committee's visit a comprehensive report had been prepared. That report was generally known as the "Feasibility Report" and has been used extensively in preparing this chapter.

### Plan of this Chapter

6.7. In this chapter we shall present the material in the order of the objectives given above. In Part I we shall discuss progress towards the initial objectives, including (a) procurement of materials, (b) the experimental proof of the chain reaction, (c) the chemistry of plutonium and some of the problems of separation, (d) some of the types of auxiliary experiments that were performed, and finally (e) the "fast neutron" work. Necessarily the work described in detail is only a sampling of the large amount of theoretical and experimental work actually performed. In Part II we shall discuss the possibilities that were considered for production piles and separation methods, and the specific proposals made in November 1942.

## Part I

### Progress toward the Initial Objectives

#### Procurement of Materials

##### General

6.8. It has been made clear in earlier chapters of this report that the procurement of materials of sufficient purity was a major part of the problem. As far as uranium was concerned, it seemed likely that it would be needed in highly purified metallic form or at least as highly purified uranium oxide. The other materials which were going to be needed were either graphite, heavy water, or possibly beryllium. It was clear at this time that, however advantageous heavy water might be as a moderator, no large quantities of it would be available for months or years. Beryllium seemed less advantageous and almost as difficult to get. Therefore the procurement efforts for a moderator were centered on graphite. As has been explained in Chapter V, procurement of uranium and graphite was not primarily the responsibility of the Metallurgical Laboratory but was handled through E. V. Murphree and others on the "planning board." In fact, the obvious interest of the Metallurgical Laboratory in the problem led to continual intervention by its representatives. A great deal of the credit for the eventual success in obtaining materials is due to N. Hilberry and later R. L. Doan, always supported by A. H. Compton.

### Uranium Ore

6.9. Obviously there would be no point in undertaking this whole project if it were not going to be possible to find enough uranium for producing the bombs. Early indications were favorable, and a careful survey made in November 1942 showed that immediate delivery could be made of adequate tonnages of uranium ores.

### Uranium Oxide and Uranium Metal

6.10. At the end of 1941 the only uranium metal in existence was a few grams of good material made on an experimental basis by the Westinghouse Electric and Manufacturing Company and others and a few pounds of highly impure pyrophoric powder made by Metal Hydrides Company. The only considerable amount of raw material then available in this country was in the form of a commercial grade of black uranium oxide, which could be obtained in limited quantities from the Canadian Radium and Uranium Co. It contained 2 to 5 per cent of impurities and was the material which gave a neutron multiplication factor of only about 0.87 when used in an exponential pile.

6.11. By May 1942, deliveries averaging 15 tons a month of black oxide of higher purity and more uniform grade started coming in. Total impurities were less than 1 per cent, boron comprised a few parts per million, and the neutron multiplication factor ( $k$ ) was about 0.98. (It is to be remembered that the multiplication factor depends also on the purity of the graphite.) Deliveries of this material reached a ton a day in September 1942.

6.12. Experiments at the National Bureau of Standards by J. I. Hoffman demonstrated that, by the use of an ether extraction method, all the impurities are removed by a single extraction of uranyl nitrate. The use of this method removed the great bulk of the difficulties in securing pure oxide and pure materials for the production of metal. Early in May 1942, arrangements were completed with the Mallinckrodt Chemical Works in St. Louis to put the new grade of oxide through an ether extraction process on a production basis for a further reduction in impurity content and to deliver the final product as brown dioxide. Deliveries started in July 1942 at a rate of 30 tons a month. This oxide is now used as a starting point for all metal production, and no higher degree of purity can be expected on a commercial scale. In fact, it was a remarkable achievement to have developed and put into production on a scale of the order of one ton per day a process for transforming grossly impure commercial oxide to oxide of a degree of purity seldom achieved even on a laboratory scale.

6.13. The process which Westinghouse had been using to produce the metal was the electrolysis of  $KUF_5$  at a cost of about \$1,000 a pound. Since the  $KUF_5$  was produced photochemically under the action of sunlight this method constituted a potential bottleneck in production. It was found that uranium tetrafluoride could be used instead of  $KUF_5$ , and steps were taken to have this salt produced at the Harshaw Chemical Company in Cleveland and at the du Pont plant in Penns Grove, New Jersey. Production started in August



1942 and by October 1942 was up to 700 pounds per day at Harshaw and 300 pounds per day at du Pont, the method of manufacture in both cases being the hydrofluorination of Mallinckrodt-purified dioxide.

6.14. As the result of this supply of raw materials to Westinghouse, and as a result of plant expansion, deliveries from Westinghouse had accumulated to a total of more than 6000 pounds by November 1942 and were expected to be at the rate of 500 pounds per day by January 1943. The purity of the metal was good, and the cost had dropped to \$22 per pound.

6.15. Deliveries of acceptable metal from Metal Hydrides Co. were delayed for various reasons and were just beginning in November 1942. This company's production was supposed to reach a thousand pounds per week thereafter.

6.16. Neither the Westinghouse process nor the Metal Hydrides Process was entirely satisfactory. Intensive activity designed to accelerate metal production, and carried out independently by F. H. Spedding and his associates at Iowa State College at Ames, Iowa, and by C. J. Rodden at the National Bureau of Standards, resulted in the development of a satisfactory method. Production facilities were set up at Ames in the fall of 1942 and had already produced more than one ton by the end of November. The process was extremely simple, rapid and low cost.

6.17. Further research indicated additional changes that could be made to advantage, and by the middle of 1943 Spedding at Iowa and other producers who entered the picture were using the final production method adopted.

6.18. By the end of 1942 arrangements had been made by the Manhattan District to increase metal production by making greater use of the Mallinckrodt Chemical Works, the Union Carbide and Carbon Corporation, and the du Pont Company.

6.19. To summarize, almost no metal was available during most of 1942, a fact that seriously delayed progress as we shall see, but the production problems had been nearly solved by the end of 1942 and some 6 tons of metal were incorporated in the pile built in November 1942. The whole problem of procurement of metal was taken over by the Manhattan District at the end of the year, under the general direction of Colonel Ruhoff, formerly with the Mallinckrodt Chemical Works. From the point of view of the Metallurgical Project no further serious delays or difficulty have occurred because of metal shortages.

## Graphite Procurement

6.20. At the beginning of 1942 graphite production was still unsatisfactory but it was, of course, in quite a different condition from the metal production since the industrial production of graphite had already been very large. The problem was merely one of purity and priority. Largely through the efforts of N. Hilberry, the National Carbon Company and the Speer Carbon Company were both drawn into the picture. Following suggestions made by the experts of the National Bureau of Standards, these companies were able to produce highly purified graphite with a neutron absorption some 20 per cent less than the standard commercial materials previously used. Although efforts further to reduce the impurities have had some success, the purity problem was essentially solved by the middle of 1942 and large orders were placed with the cooperation of the War Production Board. As in the case of the metal, the graphite procurement problem was taken over by the Manhattan District.

## The Chain Reaction

### Further Intermediate Experiments

6.21. At the time that the Metallurgical Project was organized, most of the physicists familiar with the problem believed that a chain-reacting pile probably could be built if sufficiently pure graphite and pure uranium metal could be obtained. Enough work had been done on resonance absorption, on the theory of absorption and diffusion of neutrons in a pile, and on intermediate experiments to make it possible to design a lattice structure that had a very good chance of maintaining a chain reaction. Nevertheless, there were uncertainties in the experimental data and in the approximations that had to be made in the theoretical calculations. There were two alternatives: (1) to build a pile according to the best possible design; (2) to make more accurate determinations of the pertinent nuclear constants, to perform intermediate experiments, and to improve the calculations. There is little doubt that the first alternative was the one likely to lead most rapidly to the production of plutonium. There were many important questions which could have been answered more rapidly by such an operating pile than by a series of small-scale experiments. Unfortunately, the necessary amounts of materials were not available and did not become available for nearly nine months. Consequently, it was necessary to choose the second alternative, that is, to accumulate all relevant or possibly relevant information by whatever means were available.

6.22. The major line of investigation was a series of intermediate experiments. The particular set-up for each intermediate experiment could be used to test calculations based on separate auxiliary experiments. For example, the proportion of uranium oxide to graphite was varied, oxides of different purities were used, oxide was used in lumps of various sizes and shapes and degrees of compression, the lattice spacing was varied, the effect of surrounding the uranium oxide units with beryllium and with paraffin was tried, and, finally, piles of identical lattice type but of different total

size were tried to see whether the values of the multiplication factor  $k$  (for infinite size) calculated from the different sets of results were identical. In general, E. Fermi had direct charge of investigations of effects of impurities, and S. K. Allison had charge of tests involving different lattice dimensions. All these experiments strengthened the confidence of the group in the calculated value of  $k$  and in the belief that a pile could be built with  $k$  greater than unity. In July enough purified uranium oxide from Mallinckrodt was available to permit building intermediate pile No. 9. As in previous experiments, a radium-beryllium neutron source was placed at the bottom of the lattice structure and the neutron density measured along the vertical axis of the pile. By this time it was known that the neutron density decreased exponentially with increasing distance from the neutron source, (hence the name often used for experiments of this type, "exponential pile") and that, from such rates of decrease, the multiplication constant  $k$  for an infinitely large pile of the same lattice proportions could be calculated. For the first time the multiplication constant  $k$  so calculated from experimental results came out greater than one. (The actual value was 1.007.) Even before this experiment Compton predicted in his report of July 1st that a  $k$ -value somewhere between 1.04 and 1.05 could be obtained in a pile containing highly purified uranium oxide and graphite, provided that the air was removed from the pile to avoid neutron absorption by nitrogen.

#### An Auxiliary Experiment; Delayed Neutrons

6.23. We shall not mention a majority of the various auxiliary experiments done during this period. There was one, however, -- the study of delayed neutrons--that we shall discuss because it is a good example of the kind of experiment that had to be performed and because it concerned one effect, not heretofore mentioned, that is of great importance in controlling a chain-reacting pile.

6.24. From previous investigations, some of which were already published, it was known that about 1 per cent of the neutrons emitted in fission processes were not ejected immediately but were given off in decreasing quantity over a period of time, a fact reminiscent of the emission of beta rays from shortlived radioactive substances. Several half-lives had been observed, the longest being of the order of a minute.

6.25. It was realized early that this time delay gave a sort of inertia to the chain reaction that should greatly facilitate control. If the effective multiplication factor of a pile became slightly greater than one, the neutron density would not rise to harmfully large values almost instantly but would rise gradually so that there would be a chance for controls to operate. (Other time intervals involved, such as those between collisions, are too small to be useful.)

6.26. Because of the importance of this effect of delayed neutrons for control it was decided to repeat and improve the earlier measurements. (The fact that this was a repetition rather than a new measurement is also typical of much of the work in physics at this period.) A description of the

experiment is given in Appendix 3. The results indicated that 1.0 percent of the neutrons emitted in uranium fission are delayed by at least 0.01 second and that about 0.07 percent are delayed by as much as a minute. By designing a pile such that the effective value of  $k$ , the multiplication factor, is only 1.01 the number of delayed neutrons is sufficient to allow easy control.

#### The First Self-Sustaining Chain-Reacting Pile

6.27. By the fall of 1942 enough graphite, uranium oxide, and uranium metal were available at Chicago to justify an attempt to build an actual self-sustaining chain-reacting pile. But the amount of metal available was small — only about 6 tons — and other materials were none too plentiful and of varying quality. These conditions rather than optimum efficiency controlled the design.

6.28. The pile was constructed on the lattice principle with graphite as a moderator and lumps of metal or oxide as the reacting units regularly spaced through the graphite to form the lattice. Instruments situated at various points in the pile or near it indicated the neutron intensity, and movable strips of absorbing material served as controls. (For a more complete description of the pile, see Appendix 4.) Since there were bound to be some neutrons present from spontaneous fission or other sources, it was anticipated that the reaction would start as soon as the structure had reached critical size if the control strips were not set in "retard" position. Consequently, the control strips were placed in a suitable "retard" position from the start and the neutron intensity was measured frequently. This was fortunate since the approach to critical condition was found to occur at an earlier stage of assembly than had been anticipated.

6.29. The pile was first operated as a self-sustaining system on December 2, 1942. So far as we know, this was the first time that human beings ever initiated a self-maintaining nuclear chain reaction. Initially the pile was operated at a power level of 1/2 watt, but on December 12th the power level was raised to 200 watts.

#### Energy Developed by the Pile

6.30. In these experiments no direct measurements of energy released were made. The number of neutrons per second emitted by the pile was estimated in terms of the activity of standardized indium foils. Then, from a knowledge of the number of neutrons produced per fission, the resultant rate of energy release (wattage) was calculated.

#### Conclusion

6.31. Evidently this experiment, performed on December 2nd just as a reviewing committee was appraising the Chicago project, answered beyond all shadow of doubt the first question before the Metallurgical Laboratory; a self-sustaining nuclear chain reaction had been produced in a system using normal uranium. This experiment had been performed under the general direction of E. Fermi, assisted principally by the groups headed by W. H. Zinn



and H. L. Anderson. V. C. Wilson and his group had been largely responsible for developing the instruments and controls, and a great many others in the laboratory had contributed to the success of the enterprise.

#### Relation between Power and Production of Plutonium

6.32. The immediate object of building a uranium-graphite pile was to prove that there were conditions under which a chain reaction would occur, but the ultimate objective of the laboratory was to produce plutonium by a chain reaction. Therefore we are interested in the relation between the power at which a pile operates and the rate at which it produces plutonium. The relation may be evaluated to a first approximation rather easily. A pile running stably must be producing as many neutrons as it is losing. For every thermal neutron absorbed in U-235 a certain number of neutrons,  $\eta$ , is emitted. One of these neutrons is required to maintain the chain. Therefore, assuming the extra neutrons all are absorbed by U-238 to form plutonium, there will be  $\eta - 1$  atoms of Pu<sup>239</sup> formed for every fission. Every fission releases roughly 200 Mev of energy. Therefore the formation of  $\eta - 1$  atoms of plutonium accompanies the release of about 200 Mev. Since  $\eta - 1$  is a small number, we can guess that to produce a kilogram a day of plutonium a chain-reacting pile must be releasing energy at the rate of 500,000 to 1,500,000 kilowatts. The first chain-reacting pile that we have just described operated at a maximum of 200 watts. Assuming that a single bomb will require the order of one to 100 kilograms of plutonium, the pile that has been described would have to be kept going at least 70,000 years to produce a single bomb. Evidently the problem of quantity production of plutonium was not yet solved.

#### The Chemistry of Plutonium

6.33. The second specific objective of the Metallurgical Laboratory was to show that, if a chain reaction did occur, it would be feasible to separate the plutonium chemically from the other material with which it is found. Progress towards this objective was necessarily slower than toward the attainment of a chain reaction. Initially little was done at the Metallurgical Laboratory on chemical problems although the extraction problem was discussed in a conference soon after the project was organized and the work of Seaborg's group at the University of California on plutonium was encouraged. On April 22-23, 1942, a general conference on chemistry was held at Chicago, attended by F. H. Spedding, E. W. Thiele, G. T. Seaborg, J. W. Kennedy, H. C. Urey, E. Wigner, N. Hilberry, G. E. Boyd, I. B. Johns, H. A. Wilhelm, I. Perlman, A. C. Wahl, and J. A. Wheeler. Spedding, in opening the meeting, pointed out that there were two main tasks for the chemists: first, to separate plutonium in the amounts and purity required for war purposes; second, to obtain a good understanding of the chemistry necessary for the construction and maintenance of the pile. The separation problem was to be studied by a new group at Chicago under the direction of Seaborg, by Johns and Wilhelm at Ames, and by Wahl and Kennedy continuing the work at California. Other closely related groups at Chicago were to be C. D. Coryell's, working on the fission products, and Boyd's on analytical

problems. The chemistry group at Chicago has grown speedily since that time. A new building had to be constructed to house it late in 1942, and this building was enlarged subsequently. Altogether, the solving of many of the chemical problems has been one of the most remarkable achievements of the Metallurgical Laboratory.

6.34. The first isotope of plutonium discovered and studied was not the 239 isotope but the 238 isotope, which is an alpha-ray emitter with a half-life of about 50 years. U-238 bombarded with deuterons gives  ${}_{93}\text{Np}^{238}$  which disintegrates to  ${}_{94}\text{Pu}^{238}$  by beta emission. The first evidence of the actual existence of these new elements, (ruling out the original erroneous interpretation of the splitting of uranium as evidence for their existence) was obtained by E. McMillan and P. H. Abelson who isolated 93-238 from uranium bombarded with deuterons in the Berkely cyclotron. This new element was identified as a beta emitter but the sample was too small for isolation of the daughter product 94-238. Later enough Pu-238 was prepared to permit Seaborg, Kennedy and Wahl to begin the study of its chemical properties in the winter of 1940-1941 by using tracer chemistry with carriers according to practice usual in radio-chemistry. By such studies many chemical properties of plutonium were determined, and several possible chemical processes were evolved by which Pu-239 might be removed from the chain-reacting pile. The success of experiments on a tracer scale led to plans to produce enough Pu-239 to be treated as an ordinary substance on the ultra-microchemical scale. Such quantities were produced by prolonged bombardment of several hundred pounds of uranyl nitrate with neutrons obtained with the aid of cyclotrons, first at Berkeley and later at Washington University in St. Louis. By the end of 1942, something over 500 micrograms had been obtained in the form of pure plutonium salts. Although this amount is less than would be needed to make the head of a pin, for the micro-chemists it was sufficient to yield considerable information; for one microgram is considered sufficient to carry out weighing experiments, titrations, solubility studies, etc.

6.35. From its position in the periodic table, plutonium might be expected to be similar to the rare earths or to uranium, thorium, or osmium. Which of these it will resemble most closely depends, of course, on the arrangement of the outermost groups of electrons and this arrangement could hardly have been predicted. On the whole, plutonium turned out to be more like uranium than like any of the other elements named and might even be regarded as the second member of a new rare-earth series beginning with uranium. It was discovered fairly early that there were at least two states of oxidation of plutonium. (It is now known that there are four, corresponding to positive valences of 3, 4, 5, and 6.) Successful micro-chemical preparation of some plutonium salts and a study of their properties led to the general conclusion that it was possible to separate plutonium chemically from the other materials in the pile. This conclusion represents the attainment of the second immediate objective of the Metallurgical Laboratory. Thus, by the end of 1942, plutonium, entirely unknown eighteen months earlier, was considered an element whose chemical behavior was as well understood as that of several of the elements of the old periodic table.

### Miscellaneous Studies

6.36. Besides the major problems we have mentioned, i.e., the chain reaction, the chemical separation, and the planning for a production plant, there were innumerable minor problems to be solved. Among the more important of these were the improvement of neutron counters, ionization chambers, and other instruments, the study of corrosion of uranium and aluminum by water and other possible coolants, the determination of the effects of temperature variation on neutron cross sections, the fabrication of uranium rods and tubes, the study of fission products, and the determination of the biological effects of radiation. As typical of this kind of work we can cite the development of methods of fabricating and coating uranium metal, under the direction of E. Creutz. Without the accomplishment of these secondary investigations the project could not have reached its goal. To give some further idea of the scope of the work, a list of twenty report titles is presented in Appendix 5, the 20 reports being selected from the 400 or so issued during 1942.

### The Fast-Neutron Reaction

6.37. The third initial objective of the Metallurgical Project was to obtain theoretical and experimental data on a "fast neutron" reaction, such as would be required in an atomic bomb. This aspect of the work was initially planned and coordinated by G. Breit of the University of Wisconsin and later continued by J. R. Oppenheimer of the University of California. Since the actual construction of the bomb was to be the final part of the program, the urgency of studying such reactions was not so great. Consequently, little attention was given to the theoretical problems until the summer of 1942, when a group was organized at Chicago under the leadership of Oppenheimer.

6.38. In the meantime experimental work initiated in most instances by G. Breit, had been in progress (under the general direction of the Metallurgical Project) at various institutions having equipment suitable for fast-neutron studies (Carnegie Institution of Washington, the National Bureau of Standards, Cornell University, Purdue University, University of Chicago, University of Minnesota, University of Wisconsin, University of California, Stanford University, University of Indiana, and Rice Institute). The problems under investigation involved scattering, absorption and fission cross section, the energy spectrum of fission neutrons, and the time delay in the emission of fission neutrons. For the most part this work represented an intermediate step in confirming and extending previous measurements but reached no new final conclusions. This type of work was subsequently concentrated at another site (see Chapter XII).

6.39. As indicated by the "Feasibility Report" (in a section written by J. H. Manley, J. R. Oppenheimer, R. Serber, and E. Teller) the picture had changed significantly in only one respect since the appearance of the National Academy Report a year earlier. Theoretical studies now showed that the effectiveness of the atomic bomb in producing damage would be

greater than had been indicated in the National Academy report. However, critical size of the bomb was still unknown. Methods of detonating the bomb had been investigated somewhat, but on the whole no certain answers had been arrived at.

## Part II Progress toward the Ultimate Objective

### Planning a Production Plant

#### Planning and Technical Work

6.40. As we have seen, the initial objectives of the Metallurgical Laboratory had been reached by the end of 1942, but the ultimate objectives, the production of large quantities of plutonium and the design and fabrication of bombs, were still far from attained. The responsibility for the design and fabrication of bombs was transferred to another group about this time; its work is reported in Chapter XII. The production of Pu-239 in quantity has remained the principal responsibility of the Metallurgical Laboratory although shared with the du Pont Company since the end of 1942.

6.41. On the basis of the evidence available it was clear that a plutonium production rate somewhere between a kilogram a month and a kilogram a day would be required. At the rate of a kilogram a day, a 500,000 to 1,500,000 kilowatt plant would be required. (The ultimate capacity of the hydroelectric power plants at the Grand Coulee Dam is expected to be 2,000,000 kw.) Evidently the creation of a plutonium production plant of the required size was to be a major enterprise even without attempting to utilize the thermal energy liberated. Nevertheless, by November 1942 most of the problems had been well defined and tentative solutions had been proposed. Although these problems will be discussed in some detail in the next chapter, we will mention them here.

6.42. Since a large amount of heat is generated in any pile producing appreciable amounts of plutonium, the first problem of design is a cooling system. Before such a system can be designed, it is necessary to find the maximum temperature at which a pile can run safely and the factors -- nuclear or structural -- which determine this temperature. Another major problem is the method for loading and unloading the uranium, a problem complicated by the shielding and the cooling system. Shielding against radiation has to be planned for both the pile itself and the chemical separation plant. The nature of the separation plant depends on the particular separation process to be used, which has to be decided. Finally, speed of procurement and construction must be primary factors in the planning of both the pile and the chemical plant.



### Possible Types of Plant

6.43. After examining the principal factors affecting plant design, i.e., cooling, efficiency, safety, and speed of construction, the "Feasibility Report" suggested a number of possible plant types in the following order of preference:

- I.
  - a. Ordinary uranium metal lattice in a graphite moderator with helium cooling.
  - b. The same, with water cooling.
  - c. The same, with molten bismuth cooling.
- II. Ordinary uranium metal lattice in a heavy-water moderator.
- III. Uranium enriched in the 235 isotope, using graphite, heavy water, or ordinary water as moderator.

Types II and III were of no immediate interest since neither enriched uranium nor heavy water was available. Development of both these types continued however, since if no other type proved feasible they might have to be used. Type I c, calling for liquid bismuth cooling, seemed very promising from the point of view of utilization of the thermal energy released, but it was felt that the technical problems involved could not be solved for a long time.

### The Pilot Plant at Clinton

6.44. During this period, the latter half of 1942, when production plants were being planned, it was recognized that a plant of intermediate size was desirable. Such a plant was needed for two reasons: first, as a pilot plant; second, as a producer of a few grams of plutonium badly needed for experimental purposes. Designed as an air-cooled plant of 1000-kw capacity, the intermediate pile constructed at Clinton, Tennessee, might have served both purposes if helium cooling had been retained for the main plant. Although the plans for the main plant were shifted so that water cooling was called for, the pilot plant was continued with air-cooling in the belief that the second objective would be reached more quickly. It thus ceased to be a pilot plant except for chemical separation. Actually the main plant was built without benefit of a true pilot plant, much as if the hydroelectric generators at Grand Coulee had been designed merely from experience gained with a generator of quite different type and of a small fraction of the power.

### Specific Proposals

6.45. As reviewed by Hilberry in the "Feasibility Report" of November 26, 1942, the prospects for a graphite pile with helium cooling looked promising as regards immediate production; the pile using heavy water for moderator and using heavy water or ordinary water as coolant looked better for eventual full-scale use. A number of specific proposals were made for construction of such plants and for the further study of the problems involved. These proposals were based on time and cost estimates which were

necessarily little better than rough guesses. As the result of further investigation the actual program of construction -- described in later chapters -- has been quite different from that proposed.

#### Summary

6.46. 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, at a power level of 1/2 watt and later at 200 watts. It was easily controllable thanks to the phenomenon of delayed neutron emission. A total of 500 micrograms of plutonium was made with the cyclotron and separated chemically from the uranium and fission products. Enough was learned of the chemistry of plutonium to indicate the possibility of separation on a relatively large scale. No great advance was made on bomb theory, but calculations were checked and experiments with fast neutrons extended. If anything, the bomb prospects looked more favorable than a year earlier.

6.47. Enough experimenting and planning were done to delineate the problems to be encountered in constructing and operating a large-scale production plant. Some progress was made in choice of type of plant, first choice at that time being a pile of metallic uranium and graphite, cooled either by helium or water. A specific program was drawn up for the construction of pilot and production plants. This program presented time and cost estimates.

Assignment of Responsibility

7.4. As soon as it had been decided to go ahead with large-scale production of plutonium, it was evident that a great expansion in organization was necessary. The Stone and Webster Engineering Corporation had been selected as the overall engineering and construction firm for the DSM Project soon after the Manhattan District was placed in charge of construction work in June 1942. By October 1942, it became evident that various component parts of the work were too far separated physically and were too complicated technically to be handled by a single company -- especially in view of the rapid pace required. Therefore it was decided that it would be advantageous if Stone and Webster were relieved of that portion of the work pertaining to the construction of plutonium production facilities. This was done, and General Groves selected the E. I. du Pont de Nemours and Company as the firm best able to carry on this phase of the work. The arrangements made with various industrial companies by the Manhattan District took various forms. The arrangement with du Pont is discussed in detail as an example.

7.5. General Groves broached the question to W. S. Carpenter, Jr., president of du Pont, and after considerable discussion with him and other officials of the firm, du Pont agreed to undertake the work. In their acceptance, they made it plain and it was understood by all concerned that du Pont was undertaking the work only because the War Department considered the work to be of the utmost importance, and because General Groves stated that this view as to importance was one held personally by the President of the United States, the Secretary of War, the Chief of Staff, and General Groves, and because of General Groves' assertion that du Pont was by far the organization best qualified for the job. At the time, it was recognized that the du Pont Company already had assumed all the war-connected activities which their existing organization could be expected to handle without undue difficulty.

7.6. The du Pont Company, in accepting the undertaking, insisted that the work be conducted without profit and without patent rights of any kind accruing to them. The du Pont Company did request, however, that in view of the unknown character of the field into which they were being asked to embark, and in view of the unpredictable hazards involved, the Government provide maximum protection against losses sustained by du Pont.

7.7. The cost-plus-a-fixed-fee contract between the Government and du Pont established a fixed fee of \$1.00. The Government agreed to pay all costs of the work by direct reimbursement or through allowances provided by the contract to cover administrative and general expenses allocated to the work in accordance with normal du Pont accounting practices as determined by audit by certified public accountants. Under the terms of the contract, any portion of these allowances not actually expended by du Pont will, at the conclusion of the work, be returned to the United States. The contract also provided that no patent rights would accrue to the company.

7.8. The specific responsibilities assumed by du Pont were to engineer, design, and construct a small-scale semi-works at the Clinton Engineer Works in Tennessee and to engineer, design, construct, and operate

a large-scale plutonium production plant of large capacity at the Hanford Engineer Works in the State of Washington. Because of its close connection with fundamental research, the Clinton semi-works was to be operated under the direction of the University of Chicago. A large number of key technical people from du Pont were to be used on a loan basis at Chicago and at Clinton, to provide the University with much needed personnel, particularly men with industrial experience, and to train certain of such personnel for future service at Hanford.

7.9. Inasmuch as du Pont was being asked to step out of its normal role in chemistry into a new field involving nuclear physics, it was agreed that it would be necessary for them to depend most heavily upon the Metallurgical Laboratory of the University of Chicago for fundamental research and development data and for advice. The du Pont Company had engineering and industrial experience, but it needed the Metallurgical Laboratory for nuclear-physics and radiochemistry experience. The Metallurgical Laboratory conducted the fundamental research on problems bearing on the design and operation of the semi-works and large-scale production plants. It proposed the essential parts of the plutonium production and recovery processes and equipment, answered the many specific questions raised by du Pont, and studied and concurred in the final du Pont decisions and designs.

7.10. The principal purpose of the Clinton semi-works was development of methods of operation for plutonium recovery. The semi-works had to include of course, a unit for plutonium production, in order to provide plutonium to be recovered experimentally. In the time and with the information available, the Clinton production unit could not be designed to be an early edition of the Hanford production units which, therefore, had to be designed, constructed and operated without major guidance from Clinton experience. In fact, even the Hanford recovery units had to be far along in design and procurement of equipment before Clinton results became available. However, the Clinton semi-works proved to be an extremely important tool in the solution of the many completely new problems encountered at Hanford. It also produced small quantities of plutonium which, along with Metallurgical Laboratory data on the properties of plutonium, enabled research in the use of the material to be advanced many months.

#### Choice of Plant Site

7.11. 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 the President (see Chapter V).

7.12. 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.



To meet these two requirements a new site was chosen and acquired on the Columbia River in the central part of the State of Washington near the Grand Coulee power line. This site was known as the Hanford Engineer Works.

7.13. 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.

#### Choice of Type of Plant

7.14. It was really too early in the development to make a carefully weighed decision as to the best type of plutonium production plant. Yet a choice had to be made so that design could be started and construction begun as soon as possible. Actually a tentative choice was made and then changed.

7.15. In November 1942, the helium-cooled plant was the first choice of the Metallurgical Laboratory. Under the direction of T. V. Moore and M. C. Leverett, preliminary plans for such a plant had been worked out. The associated design studies were used as bases for choice of site, choice of accessory equipment, etc. Although these studies had been undertaken partly because it had been felt that they could be carried through more quickly for a helium-cooled plant than for a water-cooled plant, many difficulties were recognized. Meanwhile the theoretical group under Wigner, with the cooperation of the engineering personnel, had been asked to prepare a report on a water-cooled plant of high-power output. This group had been interested in water-cooling almost from the beginning of the project and was able to incorporate the results of its studies in a report issued on January 9, 1943. This report contained many important ideas that were incorporated in the design of the production plant erected at Hanford.

7.16. When du Pont came into the picture, it at first accepted the proposal of a helium-cooled plant but after further study decided in favor of water-cooling. The reasons for the change were numerous. Those most often mentioned were the hazard from leakage of a high-pressure gas coolant carrying radioactive impurities, the difficulty of getting large blowers quickly, the large amount of helium required, the difficulty of loading and unloading uranium from the pile, and the relatively low power output per kilogram of uranium metal. These considerations had to be balanced against the peculiar disadvantages of a water-cooled plant, principally the greater complexity of the pile itself and the dangers of corrosion.

7.17. Like so many decisions in this project, the choice between various types of plant had to be based on incomplete scientific information. The information is still incomplete, but there is general agreement that water-cooling was the wise choice.

## The Problems of Plant Design

### Specification of the Overall Problem

7.18. In Chapter II of this report we attempted to define the general problem of the uranium project as it appeared in the summer of 1940. 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. Needless to say, speed of construction and efficiency of operation were prime considerations.

### Nature of the Lattice

7.19. 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. It was fairly obvious that 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. There was little doubt that 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. This became a problem for both the theoretical and experimental physicists. The theoretical physicists had to compute 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

7.20. 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

7.21. If water was to be used as coolant, it would have to be conveyed to the regions where heat has generated through channels of some sort. Since graphite pipes were not practical, some other kind of pipe would have to be used. But the choice of the material for the pipe, 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. Furthermore, the pipes must be made of material which would not disintegrate under the heavy density of neutron and gamma radiation present in the pile. Finally, the pipes must meet all ordinary requirements of cooling-system pipes: they must not leak; they must not corrode; they must not warp.

7.22. 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 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.

7.23. 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.

7.24. Finally, it was not known what effect the radiation fields in the pile would have on the graphite and the uranium. It was later 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

7.25. 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

7.26. The problem of dissipating thousands of kilowatts of energy is by no means a small one. How much water was needed depended, of course, on the maximum temperature to which the water could safely be heated and 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 very 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 going 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

7.27. The control problem was very 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

7.28. As we have mentioned a number of times, the radiation given off from a pile operating at a high power level is so strong as to make it quite impossible for any of the operating personnel to go 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. But at the same time it has to be possible to load and unload the pile through these shields and to carry the water supply in and out through the shields. The shields should not only be radiation-tight but air-tight since air exposed to the radiation in the pile would become radioactive.

7.29. The radiation dangers that require shielding in the pile continue 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

7.30. The problem of maintenance is very simply stated. There could not be any maintenance inside the shield or pile once the pile had operated. The same remark applies to a somewhat lesser extent to the separation unit, where 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 the 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

7.31. Evidently 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, while 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, etc. 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

7.32. We have been speaking of the production capacity of the plant only in terms of overall 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 reduction in construction time for the first pile, the possibility of making alterations in later piles, and -- perhaps most important -- the improbability of simultaneous breakdown of all piles. The disadvantage of small piles is that they require disproportionately large amounts of uranium, moderator, etc. There is, in fact, a preferred "natural size" of pile which can be roughly determined on theoretical grounds.

#### General Nature of the Separation Plant

7.33. As we have already pointed out, 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 was suggested in the latter part of 1942, particularly in connection with plans for the Clinton separation plant. This scheme was to build a "canyon" which would consist of

a series of compartments with heavy concrete walls arranged in a line and almost completely buried in the ground. 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, everything would be operated by remote control from above ground, but the operations would be far more complicated than in the case of the pile. However, as far as the chemical operations themselves were concerned, their general nature was not so far removed from the normal fields of activity of the chemists involved.

#### Analytical Control

7.34. 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. Such testing was facilitated, however, by use of radioactive methods of analysis as well as conventional chemical analyses.

#### Waste Disposal.

7.35. The raw material (uranium) is not dangerously radioactive. The desired product (plutonium) does not give off penetrating radiation, but the combination of its alpha-ray activity and chemical properties make it one of the most dangerous substances known if it once gets into the body. However, the really troublesome materials are the fission products, i.e., the major fragments into which uranium is split by fission. The fission products are extremely active and include some thirty elements. Among them are radioactive xenon and radioactive iodine. These are released in considerable quantity when the slugs are dissolved and must be disposed of with special care. High stacks must be built which will carry off these gases along with the acid fumes from the first dissolving unit, and it must be established that the mixing of the radioactive gases with the atmosphere will not endanger the surrounding territory.

7.36. Most of the other fission products can be retained in solution but must eventually be disposed of. Of course, possible pollution of the adjacent river must be considered.

#### Recovery of Uranium

7.37. Evidently, 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 it after the plutonium is separated must be considered. Originally there was no plan for early recovery, but merely the intention of storing the uranium solution. Later, methods of large-scale recovery were developed.

### Corrosion in the Separation Plant

7.38. An unusual feature of the chemical processes involved was that these processes occur 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 these dangers.

### Effect of Radiation on Chemical Reactions

7.39. The chemical reactions proposed for an extraction process were, of course, tested in the laboratory. However, they could not be tested with appreciable amounts of plutonium nor could they be tested in the presence of radiation of anything like the expected intensity. Therefore it was realized that a process found to be successful in the laboratory might not work in the plant.

### Choice of Process

7.40. The description given above as to what was to happen in the successive chambers in the canyon was very vague. This was necessarily so, since 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.

### The Health Problem

7.41. Besides the hazards normally present during construction and operation of a large chemical plant, dangers of a new kind were expected here. Two types of radiation hazard were anticipated -- neutrons generated in the pile, and alpha-particles, beta-particles, and gamma rays emitted by products of the pile. Although the general effects of these radiations had been proved to be similar to those of X-rays, very little detailed knowledge was available. Obviously the amounts of radioactive material to be handled were many times greater than had ever been encountered before.

7.42. The health group had to plan three programs: (1) provision of instruments and clinical tests to detect any evidence of dangerous exposure of the personnel; (2) research on the effects of radiation on persons, instruments, etc.; and (3) estimates of what shielding and safety measures must be incorporated in the design and plan of operation of the plant.

### The Properties of Plutonium

7.43. Although we were embarking on a major enterprise to produce plutonium, we still had less than a milligram to study and still had only

limited familiarity with its properties. The study of plutonium, therefore, remained a major problem of the Metallurgical Laboratory.

#### The Training of Operators

7.44. Evidently the operation of a full-scale plant of the type planned would require a large and highly skilled group of operators. Although du Pont had a tremendous background of experience in the operation of various kinds of chemical plant, this was something new and it was evident that operating personnel would need special training. Such training was carried out partly in Chicago and its environs, but principally at the Clinton Laboratories.

#### The Need for Further Information

7.45. In the preceding paragraphs of this chapter we have outlined the problems confronting the group charged with designing and building a plutonium production plant. In Chapter VI the progress in this field up to the end of 1942 was reviewed. Throughout these chapters it is made clear that a great deal more information was required to assure the success of the plant. Such answers as had been obtained to most of the questions were only tentative. Consequently research had to be pushed simultaneously with planning and construction.

#### The Research Program

7.46. To meet the need for further information, research programs were laid out for the Metallurgical Laboratory and the Clinton Laboratory. The following passage is an excerpt from the 1943 program of the Metallurgical Project:

Product Production Studies - These include all aspects of the research, development and semi-works studies necessary for the design, construction, and operation of chain-reacting piles to produce plutonium or other materials.

Pile Characteristics - Theoretical studies and experiments on lattice structures to predict behavior in high-level piles, such as temperature and barometric effects, neutron characteristics, pile poisoning, etc.

Control of Reacting Units - Design and experimental tests of devices for controlling rate of reaction in piles.

Cooling of Reacting Units - Physical studies of coolant material,



engineering problems of circulation, corrosion, erosion, etc.

Instrumentation - Development of instruments and technique for monitoring pile and surveying radiation throughout plant area.

Protection - Shielding, biological effects of radiation at pile and clinical effects of operations associated with pile.

Materials - Study of physical (mechanical and nuclear) properties of construction and process materials used in pile construction and operation.

Activation Investigations - Production of experimental amounts of radioactive materials in cyclotron and in piles and study of activation of materials by neutrons, protons, electrons, gamma-rays, etc.

Pile Operation - Study of pile operation procedures such as materials handling, instrument operation, etc.

Process Design - Study of possible production processes as a whole leading to detailed work in other categories.

Product Recovery Studies - These include all aspects of the work necessary for the development of processes for the extraction of plutonium and possible by-products from the pile material and their preparation in purified form. Major effort at the Metallurgical Laboratory will be on a single process to be selected by June 1, 1943 for the production of plutonium, but alternatives will continue to be studied both at the Metallurgical Laboratory and Clinton with whatever manpower is available.

Separation - Processes for solution of uranium, extraction of plutonium and decontamination by removal of fission products.

Concentration, Purification and Product Reduction - Processes leading to production of plutonium as pure metal, and study of properties of plutonium necessary to its production.

Wastes - Disposal and possible methods of recovery of fission products and metal from wastes.

Instrumentation - Development and testing of instruments for monitoring chemical processes and surveying radiation throughout the area.

Protection - Shielding studies, determination of biological effects of radioactive dusts, liquids, solids, and other process materials, and protective measures.

Materials - Corrosion of equipment materials, and radiation stability. Necessary purity and purity analysis of process materials, etc.

Recovery of Activated Materials - Development of methods and actual recovery of activated material (tracers, etc.) from cyclotron and

pile-activated materials.

Operations Studies - Equipment performance, process control, material handling operations, etc.

Process Design - Study of product recovery processes as a whole (wet processes, physical methods) leading to detailed work in other categories.

Fundamental Research - Studies of the fundamental physical, chemical and biological phenomena occurring in chain-reacting piles, and basic properties of all materials involved. Although the primary emphasis at Clinton is on the semi-works level, much fundamental research will require Clinton conditions (high radiation intensity, large scale processes).

Nuclear Physics - Fundamental properties of nuclear fission such as cross section, neutron yield, fission species, etc. Other nuclear properties important to processes, such as cross sections, properties of moderators, neutron effect on materials, etc.

General Physics - Basic instrument (electronic, ionization, optical, etc.) research, atomic mass determinations, neutron,  $\alpha$ ,  $\beta$ ,  $\gamma$  radiation studies, X-ray investigations, etc.

Radiation Chemistry - Effects of radiation on chemical processes and chemical reactions produced by radiation.

Nuclear Chemistry - Tracing of fission products, disintegration constants, chains, investigation of nuclei of possible use of project.

Product Chemistry - Chemical properties of various products and basic studies in separation and purification of products.

General Chemistry - Chemistry of primary materials and materials associated with process, including by-products.

General Biology - Fundamental studies of effects of radiation on living matter, metabolism of important materials, etc.

Clinical Investigations - Basic investigations, such as hematology, pathology, etc.

Metallurgical Studies - Properties of U, Pu, Be, etc.

Engineering Studies - Phenomena basic to corrosion and similar studies essential to continued engineering development of processes.

7.47. An examination of this program gives an idea of the great range of investigations which were considered likely to give relevant information. Many of the topics listed are not specific research problems such as might be solved by a small team of scientists working for a few months but are whole fields of investigation that might be studied with

profit for years. It was necessary to pick the specific problems that were likely to give the most immediately useful results but at the same time it was desirable to try to uncover general principles. For example, the effect of radiation on the properties of materials ("radiation stability") was almost entirely unknown. It was necessary both to make empirical tests on particular materials that might be used in a pile and to devise general theories of the observed effects. Every effort was made to relate all work to the general objective: a successful production plant.

### Organization of the Project

7.48. There have been many changes in the organization and personnel of the project. During most of the period of construction at Clinton and Hanford, A. H. Compton was Director of the Metallurgical Project, S. K. Allison was Director of the Metallurgical Laboratory at Chicago; and H. D. Whitaker was Director of the Clinton Laboratory. The Chicago group was organized in four divisions: physics, chemistry, technology, and health. Later the physics division was split into general physics and nuclear physics. R. L. Doan was research director at Clinton but there was no corresponding position at Chicago. Among others who have been associate or assistant laboratory or project directors or have been division directors are S. T. Cantrell, C. M. Cooper, F. Daniels, A. J. Dempster, E. Fermi, J. Franck, N. Hilberry, T. R. Hogness, W. C. Johnson, H. D. Smyth, J. C. Stearns, R. S. Stone, H. C. Vernon, W. W. Watson, and E. Wigner.

7.49. It was the responsibility of these men to see that the research program described above was carried out and that significant results were reported to du Pont. It was their responsibility also to answer questions raised by du Pont and to approve or criticize plans submitted by du Pont.

### Cooperation between the Metallurgical Laboratory and du Pont

7.50. Since du Pont was the design and construction organization and the Metallurgical Laboratory was the research organization, it was obvious that close cooperation was essential. Not only did du Pont need answers to specific questions, but they could benefit by criticism and suggestions on the many points where the Metallurgical group was especially well-informed. Similarly, the Metallurgical group could profit by the knowledge of du Pont on many technical questions of design, construction, and operation. To promote this kind of cooperation du Pont stationed one of their physicists, J. B. Miles, at Chicago, and had many other du Pont men, particularly C. H. Greenwalt, spend much of their time at Chicago. Miles and Greenwalt regularly attended meetings of the Laboratory Council. There was no similar reciprocal arrangement although many members of the laboratory visited Wilmington informally. In addition, J. A. Wheeler was transferred from Chicago to Wilmington and became a member of the du Pont staff. There was, of course, constant exchange of reports and letters, and conferences

were held frequently between Compton and R. Williams of du Pont. Whitaker spent much of his time at Wilmington during the period when the Clinton plant was being designed and constructed.

#### Summary

7.51. By January 1943, the decision has been made to build a plutonium production plant with a large capacity. This meant a pile developing thousands of kilowatts and 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, 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 for the necessary fundamental and technical research and for the training of operators. Arrangements were made for liaison between du Pont and the Metallurgical Laboratory.



## CHAPTER VIII

THE PLUTONIUM PROBLEM  
JANUARY 1943 TO JUNE 1945Introduction

8.1. 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. It became essential to investigate many alternative processes. It became necessary to investigate 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 believe it is fair to say that a large percentage of the results of investigation 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 just the information required to convert failure into success. Even now it is impossible to say that future improvements may not depend on the results of researches that seem unimportant today.

8.2. It is estimated that thirty volumes will be required for 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 last chapter. In the present account it would be obviously impossible to give more than a brief abstract of all these researches. We believe this would be unsatisfactory and that it is preferable to give a general discussion of the chain-reacting units and separation plants as they now operate, with some discussion of the earlier developments.

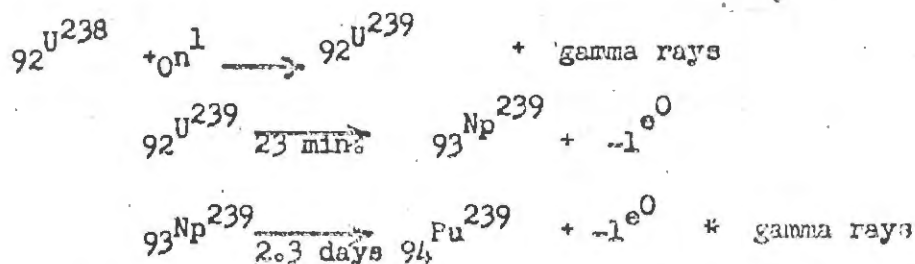
The Chain Reaction in a Pile

8.3. In Chapter I and other early chapters we have given brief accounts of the fission process, pile operation, and chemical separation. We shall now review these topics from a somewhat different point of view before describing the plutonium production plants themselves.

8.4. 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 (e.g.,  ${}_{92}\text{U}^{239}$  which produces  ${}_{94}\text{Pu}^{239}$ ).

8.5. 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:



8.6. 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.

8.7. Since the object of the chain reaction is to generate plutonium, we would like to absorb all excess neutrons in U-238, leaving just enough

neutrons to produce fission and thus to maintain the chain reaction. Actually the tendency of the neutrons to be absorbed by the dominant isotope U-238 is so great compared to their tendency to produce fission in the 140-times-rarer U-235 that the principal design effort had to be directed toward favoring the fission (as by using a moderator, a suitable lattice, materials of high purity, etc.,) in order to maintain the chain reaction.

#### Life History of One Generation of Neutrons

8.8. All the chain-reacting piles designed by the Metallurgical Laboratory or with its cooperation consist of four categories of material — the uranium metal, the moderator, the coolant, and the auxiliary materials such as water tubes, casings of uranium, control strips or rods, impurities, etc. All the piles depend on stray neutrons from spontaneous fission or cosmic rays to initiate the reaction.

8.9. Suppose that the pile were to be started by simultaneous release (in the uranium metal) of  $N$  high-energy neutrons. Most of these neutrons originally have energies above the threshold energy of fission of U-238. However, as the neutrons pass back and forth in the metal and moderator, they suffer numerous inelastic collisions with the uranium and numerous elastic collisions with the moderator, and all these collisions serve to reduce the energies below that threshold. Specifically, in a typical graphite-moderated pile a neutron that has escaped from the uranium into the graphite travels on the average about 2.5 cm between collisions and makes on the average about 200 elastic collisions before passing from the graphite back into the uranium. Since at each such collision a neutron loses on the average about one sixth of its energy, a one Mev neutron is reduced to thermal energy (usually taken to be 0.025 electron volt) considerably before completing a single transit through the graphite. There are, of course, many neutrons that depart from this average behavior, and there will be enough fissions produced by fast neutrons to enhance slightly the number of neutrons present. The enhancement may be taken into account by multiplying the original number of neutrons  $N$  by a factor  $\epsilon$  which is called the fast-fission effect or the fast-multiplication factor.

8.10. As the average energy of the  $N\epsilon$  neutrons present continues to fall, inelastic collision in the uranium becomes unimportant, the energy being reduced essentially only in the moderator. However, the chance of non-fission absorption (resonance capture) in U-238 becomes significant as the intermediate or resonance energy region is reached. Actually quite a number of neutrons in this energy region will be absorbed regardless of choice of lattice design. The effect of such capture may be expressed by multiplying  $N\epsilon$  by a factor  $p$ , (which is always less than one) called the "resonance escape probability" which is the probability that a given neutron starting with energy above the resonance region will reach thermal energies without absorption in U-238. Thus from the original  $N$  high-energy neutrons we obtain  $N\epsilon p$  neutrons of thermal energy.

8.11. Once a neutron has reached thermal energy the chance of its losing more energy by collision is no greater than the chance of its gaining energy. Consequently the neutrons will remain at this average energy until

they are absorbed. In the thermal-energy region the chance for absorption of the neutron by the moderator, the coolant and the auxiliary materials is greater than at higher energies. At any rate it is found that we introduce little error into our calculations by assuming all such unwanted absorption takes place in this energy region. We now introduce a factor  $f$ , called the thermal utilization factor, which is defined as the probability that a given thermal neutron will be absorbed in the uranium. Thus from the original  $N$  fast neutrons we have obtained  $N\epsilon pf$  thermal neutrons which are absorbed by uranium.

8.12. Although there are several ways in which the normal mixture of uranium isotopes can absorb neutrons, the reader may recall that we defined in a previous chapter a quantity  $\eta$ , which is the number of fission neutrons produced for each thermal neutron absorbed in uranium regardless of the details of the process. If, therefore, we multiply the number of thermal neutrons absorbed in uranium,  $N\epsilon pf$ , by  $\eta$ , we have the number of new high speed neutrons generated by the original  $N$  high speed neutrons in the course of their lives. If  $N\epsilon pf\eta$  is greater than  $N$ , we have a chain reaction and the number of neutrons is continually increasing. Evidently the product  $\epsilon pf\eta = k_{\infty}$ , the multiplication factor already defined in Chapter IV.

8.13. Note that no mention has been made of neutrons escaping from the pile. Such mention has been deliberately avoided since the value of  $k_{\infty}$  as defined above applies to an infinite lattice. From the known values of  $k_{\infty}$  and the fact that these piles do operate, one finds that the percentage of neutrons escaping cannot be very great. As we saw in Chapter II, the escape of neutrons becomes relatively less important as the size of the pile increases. If it is necessary to introduce in the pile a large amount of auxiliary material such as cooling-system pipes, it is necessary to build a somewhat larger pile to counteract the increase in absorption.

8.14. To sum up, a pile operates by reducing high-energy neutrons to thermal energies by the use of a moderator-lattice arrangement, then allowing the thermal-energy neutrons to be absorbed by uranium, causing fission which regenerates further high-energy neutrons. The regeneration of neutrons is aided slightly by the fast neutron effect; it is impeded by resonance absorption during the process of energy reduction, by absorption in graphite and other materials, and by neutron escape.

#### The Effects of Reaction Products on the Multiplication Factor

8.15. Even at the high power level used in the Hanford piles, only a few grams of U-238 and of U-235 are used up per day per million grams of uranium present. Nevertheless the effects of these changes are very important. As the U-235 is becoming depleted, the concentration of plutonium is increasing. Fortunately, plutonium itself is fissionable by thermal neutrons and so tends to counterbalance the decrease of U-235 as far as maintaining the chain reaction is concerned. However, other fission products are being produced also. These consist typically of unstable and relatively unfamiliar nuclei so that it was originally impossible to predict how great an undesirable effect they would have on the multiplication constant. Such deleterious effects are called poisoning. In spite of a great deal of preliminary study



of fission products, an unforeseen poisoning effect of this kind very nearly prevents operation of the Hanford piles, as we shall see later.

#### The Reaction Products and the Separation Problem

8.16. There are two main parts of the plutonium production process at Hanford: actual production in the pile, and separation of the plutonium from the uranium slugs in which it is formed. We turn now to a discussion of the second part, the separation process.

8.17. The uranium slugs containing plutonium also contain other elements resulting from the fission of U-235. When a U-235 nucleus undergoes fission, it emits one or more neutrons and splits into two fragments of comparable size and of total mass 235 or less. Apparently fission into precisely equal masses rarely occurs, the most abundant fragments being a fragment of mass number between 134 and 144 and a fragment of mass number between 100 and 90. Thus there are two groups of fission products: a heavy group with mass numbers extending approximately from 127 to 154, and a light group from approximately 115 to 83. These fission products are in the main unstable isotopes of the thirty or so known elements in these general ranges of mass number. Typically they decay by successive beta emissions accompanied by gamma radiation finally to form known stable nuclei. The half-lives of the various intermediate nuclei range from fractions of a second to a year or more; several of the important species have half-lives of the order of a month or so. About twenty different elements are present in significant concentration. The most abundant of these comprises slightly less than 10 percent of the aggregate.

8.18. In addition to radioactive fission products, U-239 and Np-239 (intermediate products in the formation of plutonium) are present in the pile and are radioactive. The concentrations of all these products begin to build up at the moment the pile starts operating. Eventually the rate of radioactive decay equals the rate of formation so that the concentrations become constant. For example, the number of atoms of U-239 produced per second is constant for a pile operating at a fixed power level. According to the laws of radioactive disintegration, the number of U-239 atoms disappearing per second is proportional to the number of such atoms present and is thus increasing during the first few minutes or hours after the pile is put into operation. Consequently there soon will be practically as many nuclei disintegrating each second as are formed each second. Equilibrium concentrations for other nuclei will be approached in similar manner, the equilibrium concentration being proportional to the rate of formation of the nucleus and to its half-life. Products which are stable or of extremely long half-life (e.g., plutonium) will steadily increase in concentration for a considerable time. When the pile is stopped, the radioactivity of course continues, but at a continually diminishing absolute rate. Isotopes of very short half-life may "drop out of sight" in a few minutes or hours; others of longer half-life keep appreciably active for days or months. Thus at any time the concentrations of the various products in a recently stopped pile depend on what the power level was, on how long the pile ran, and on how long it has been shut down.

Of course, the longer the pile has run, the larger is the concentration of plutonium and (unfortunately) the larger is the concentration of long-lived fission products. The longer the "cooling" period, i.e., the period between removal of material from the pile and chemical treatment, the lower is the radiation intensity from the fission products. A compromise must be made between such considerations as the desire for a long running and cooling time on the one hand and the desire for early extraction of the plutonium on the other hand.

8.19. Tables can be prepared showing the chemical concentrations of plutonium and the various fission products as functions of power level, length of operation, and length of cooling period. The half life of the U-239 is so short that its concentration becomes negligible soon after the pile shuts down. The neptunium becomes converted fairly rapidly to plutonium. Of course, the total weight of fission products, stable and unstable, remains practically constant after the pile is stopped. For the Clinton and Hanford operating conditions the maximum plutonium concentration attained is so small as to add materially to the difficulty of chemical separation.

#### The Choice of a Chemical Separation Process

8.20. The problem then is to make a chemical separation at the daily rate of, say, several grams of plutonium from several thousand grams of uranium contaminated with large amounts of dangerously radioactive fission products comprising twenty different elements. The problem is especially difficult as the plutonium purity requirements are very high indeed.

8.21. Four types of method for chemical separation were examined: volatility, absorption, solvent extraction, and precipitation. The work on absorption and solvent extraction methods has been extensive and such methods may be increasingly used in the main process or in waste recovery, but the Hanford Plant was designed for a precipitation process.

8.22. \* The phenomena of co-precipitation, i.e., the precipitation of small concentrations of one element along with a "carrier" precipitate of some other element, had been commonly used in radioactive chemistry, and was adopted for plutonium separation. The early work on plutonium chemistry, confined as it was to minute amounts of the element, made great use of precipitation reactions from which solubility properties could be deduced. It was therefore natural that precipitation methods of separation were the most advanced at the time when the plant design was started. It was felt that, should the several steps in the separations process have to be developed partly by the empirical approach, there would be less risk in the scale-up of a precipitation process than, for example, of one involving solid-phase reactions. In

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\* Paragraphs 8.22 - 8.26 are quoted or paraphrased from a general report of the Metallurgical Laboratory prepared in the spring of 1945.

addition, the precipitation processes then in mind could be broken into a sequence of repeated operations (called cycles), thereby limiting the number of different equipment pieces requiring design and allowing considerable process change without equipment change. Thus, while the basic plant design was made with one method in mind, the final choice of a different method led to no embarrassments.

8.23. Most of the precipitation processes which have received serious consideration made use of an alternation between the (IV) and (VI) oxidation states of plutonium. Such processes involve a precipitation of plutonium (IV) with a certain compound as a carrier, then dissolution of the precipitate, oxidation of the plutonium to the (VI) state, and reprecipitation of the carrier compound while the plutonium (VI) remains in solution. Fission products which are not carried by these compounds remain in solution when plutonium (IV) is precipitated. The fission products which carry are removed from the plutonium when it is in the (VI) state. Successive oxidation-reduction cycles are carried out until the desired decontamination is achieved. (The process of elimination of the fission products is called decontamination and the degree of elimination is tested by measuring the change in radioactivity of the material.)

#### Combination Processes.

8.24. It is possible to combine or couple the various types of process. Some advantages may be gained in this way since one type of process may supplement another. For example, a process which gives good decontamination might be combined advantageously with one which, while inefficient for decontamination, would be very efficient for separation from uranium.

8.25. At the time when it became necessary to decide on the process to serve as the basis for the design of the Hanford plant (June 1943), the choice, for reasons given above, was limited to precipitation processes and clearly lay between two such processes. However, the process as finally chosen actually represented a combination of the two.

8.26. The success of the separation process at Hanford has exceeded all expectations. The high yields and decontamination factors and the relative ease of operation have amply demonstrated the wisdom of its choice as a process. This choice was based on a knowledge of plutonium chemistry which had been gleaned from less than a milligram of plutonium. Further developments may make the present Hanford process obsolete, but the principal goal, which was to have a workable and efficient process for use as soon as the Hanford piles were delivering plutonium, has been attained.

#### The Argonne

8.27. The Argonne Laboratory was constructed early in 1943 outside Chicago. The site originally intended for a pilot plant, was later considered to be too near the city and was used for reconstructing the so-called West

Stands pile which was originally built on the University of Chicago grounds and which was certainly innocuous. Under the direction of E. Fermi and his colleagues, H. L. Anderson, W. H. Zinn, G. Weil, and others, this pile has served as a prototype unit for studies of thermal stability, controls, instruments, and shielding, and as a neutron source for materials testing and neutron-physics studies. Furthermore, it has proved valuable as a training school for plant operators. More recently a heavy-water pile (see below) has been constructed there.

8.28. The first Argonne pile, a graphite-uranium pile, need not be described in detail. The materials and lattice structure are nearly identical to those which were used for the original West Stands pile. The pile is a cube; it is surrounded by a shield and has controls and safety devices somewhat similar to those used later at Clinton. It has no cooling system and is normally run at a power level of only a few kilowatts. It has occasionally been run at high-power levels for very brief periods. Considering that it is merely a reconstruction of the first chain-reacting unit ever built, it is amazing that it has continued in operation for more than two years without developing any major troubles.

8.29. One of the most valuable uses of the Argonne pile has been the measurement of neutron-absorption cross sections of a great variety of elements which might be used in piles as structural members, etc., or which might be present in pile materials as impurities. These measurements are made by observing the change in the controls necessary to make  $k_{eff}$  equal to 1.00 when a known amount of the substance under study is inserted at a definite position in the pile. The results obtained were usually expressed in terms of "danger coefficients."

8.30. An opening at the top of the pile lets out a very uniform beam of thermal neutrons that can be used for exponential-pile experiments, for direct measurements of absorption cross sections, for Wilson cloud chamber studies, etc.

8.31. An interesting phenomenon occurring at the top of the pile is the production of a beam or flow of "cold" neutrons. If a sufficient amount of graphite is interposed between the upper surface of the pile and an observation point a few yards above, the neutron energy distribution is found to correspond to a temperature much lower than that of the graphite. This is presumed to be the result of a preferential transmission by the (crystalline) graphite of the slowest ("coldest") neutrons, whose quantum-mechanical wavelength is great compared to the distance between successive planes in the graphite crystals.

8.32. More recently a pile using heavy water as moderator was constructed in the Argonne Laboratory. The very high intensity beam of neutrons produced by this pile has been found well-suited to the study of "neutron optics", e.g., reflection and refraction of neutron beams as by graphite.

8.33. A constant objective of the Argonne Laboratory has been a better understanding of nuclear processes in uranium, neptunium, and plutonium.



Repeated experiments have been made to improve the accuracy of constants such as thermal-fission cross sections of U-235, U-238, and Pu-239, probabilities of non-fission neutron absorption by each of these nuclei, and number of neutrons emitted per fission.

#### The Clinton Plant

8.34. In Chapter VI we mentioned plans for a "pilot" plant for production of plutonium to be built at the Clinton site in Tennessee. By January 1943, the plans for this project were well along; construction was started soon afterward. M. D. Whitaker was appointed director of the Clinton Laboratories. The pilot-plant 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.

8.35. 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 biological effects of radiations. A large laboratory was provided for chemical analysis, for research on purification methods, for fission-product studies, for development of intermediate-scale extraction and decontamination processes, etc. Later a "hot laboratory", i.e. a laboratory for remotely-controlled work on highly radioactive material, was provided. There is also an instrument shop and laboratory that has been used very actively. There are facilities for both clinical and experimental work of the health division, which has been very active. There is a small physics laboratory in which some important work was done 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

8.36. In any steadily operating pile the effective multiplication factor  $k$  must be kept at one, whatever the power level. The best  $k_{\infty}$  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.

8.37. 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, etc.

8.38. The Clinton pile was considerably larger than the first pile at Chicago (see Chapter VI). 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.

8.39. The instrumentation and controls are identical in principle to those of the first pile. Neutron intensity in the pile is measured by a  $\text{BF}_3$  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.

8.40. In spite of impressiveness of the array of instruments and safety devices, the most striking feature of the pile is the simplicity of operation. Most of the time the operators have nothing to do except record the readings of various instruments.

#### The Separation Plant

8.41. 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 feet 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.

8.42. 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

8.43. 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  $110^\circ\text{C}$ . Improvements in the air circulation and an elevation of the maximum uranium surface temperature to  $150^\circ\text{C}$  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 the distribution of uranium, the change being designed to level out the power distribution in the pile by reducing the amount of metal near the center relative to that further out and thereby to increase 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.

8.44. Thus the pile performance of June 1944, considerably exceeded expectations. In case 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.

8.45. The pile itself was simple both in principle and in practice. Not so the plutonium-separation plant. 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.

8.46. 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 1/3 ton per day. By February 1st, 1944, 190 mg of plutonium had been delivered and by March 1st, 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.

8.47. During this whole period there was a large group of chemists at Clinton working on improving the 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 process was complicated and expensive. Any improvements in yield or decontamination or in general simplification were very much to be sought.

8.48. Besides the proving of the pile and the separation plant and the production of several grams of plutonium for experimental use at Chicago, Clinton, and elsewhere, the Clinton Laboratories have been invaluable 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.

8.49. As typical of the kind of problems tackled there and at Chicago, the following problems -- listed in a single routine report for May 1944 -- are pertinent:

**Problems Closed Out during May 1944:**

- Search for New Oxidizing Agent
- Effect of Radiation on Water and Aqueous Solutions
- Solubility of Plutonium Peroxide
- Plutonium Compounds Suitable for Shipment
- Fission Product Distribution in Plant Process Solutions
- Preliminary Process Design for Adsorption Extraction
- Adsorption Semi-Works Assistance
- Completion of Adsorption Process Design

New Problems Assigned during May, 1944:

New Product Analysis Method  
 Effect of Radiation on Graphite  
 Improvement in Yield  
 New Pile explorations  
 Waste Uranium Recovery  
 Monitoring 205 Stack Gases  
 Disposal of Active Waste Solutions  
 Spray Cooling of X Pile  
 Assay Training Program  
 Standardization of Assay Methods  
 Development of Assay Methods  
 Shielded Apparatus for Process Control Assays  
 Cloud Chamber Experiment  
 Alpha Particles from U-235  
 Radial Product Distribution  
 Diffraction of Neutrons

The Hanford Plant

8.50. It is beyond the scope of this report to give any 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 at some time in the future. The 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 he had inspected it personally. It 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 of the land there were a few farms and two small villages, Hanford and Richland, on the site, which was otherwise sage-brush plains and barren hills. On the 6th of April, 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 as the operating crew is housed at Richland.

8.51. Work was begun on the first of the Hanford production piles on June 7, 1943, and operation of the first pile began in September 1944. The site was originally laid out for five piles, but the construction of only three has been undertaken. Besides the piles, there are, of course, plutonium separation plants, pumping stations and water-treatment plants. There is also 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

8.52. No one who lived through the period of design and construction of the Hanford plant is likely to forget the "canning" problem, i.e., the problem of sealing the uranium slugs in protective metal jackets. On periodic visits to Chicago the writer could roughly estimate the state of the canning problem by the atmosphere of gloom or joy to be found around the laboratory. It was definitely not a simple matter to find a sheath that would protect uranium from water corrosion, would keep fission products out of the water, would transmit heat from the uranium to the water, and would not absorb too many neutrons. Yet the failure of a single can might conceivably require shut-down of an entire operating pile.

8.53. Attempts to meet the stringent requirements involved 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 early as the most likely solution of the problem. But the problem of getting a uniform, heat-conducting bond between the uranium and the surrounding aluminum, and the problem of 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 there was no certainty 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, there had been no can failure reported.

### Present Status of the Hanford Plants

8.54. In the course of 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, of course, some difficulties; however, none of the fears expressed as to canning failure, film formation in the water tubes, or radiation effects in the chemical processes, have turned out to be justified. As of early summer 1945 the piles are operating at designed power, producing plutonium, and heating the Columbia River. The chemical plants are separating the plutonium from the uranium and from the fission products with better efficiency than had been anticipated. The finished product is being delivered. How it can be used is the subject of Chapter XII.

### The Work on Heavy Water

8.55. In previous chapters there have been references to the advantages of heavy water as a moderator. It is more effective than graphite in slowing down neutrons and it has a smaller neutron absorption than graphite. It is therefore possible to build a chain-reacting unit with uranium and heavy water and thereby to attain a considerably higher multiplication factor,  $k$ , and a smaller size than is possible with graphite. But one must have the heavy water.

8.56. In the spring of 1943 the Metallurgical Laboratory decided to increase the emphasis on experiments and calculations aimed at a heavy water pile. To this end a committee was set up under E. Wigner, a group under A. A. Vernon was transferred from Columbia to Chicago, and H. D. Smyth, who had just become associate director of the Laboratory, was asked to take general charge. (As it turned out, this group was active for only about six months.)

8.57. The first function of this group was to consider in what way heavy water could best be used to insure the overall success of the Metallurgical project, taking account of the limited production schedule for heavy water that had been already authorized.

8.58. It became apparent that the production schedule was so low that it would take two years to produce enough heavy water to "moderate" a fair-sized pile for plutonium production. On the other hand, there might be enough heavy water to moderate a small "laboratory" pile, which could furnish information that might be valuable. In any event, during the summer of 1943 so great were the uncertainties as to the length of the war and as to the success of the other parts of the DSM project that a complete study of the possibilities of heavy-water piles seemed desirable. Either the heavy-water production schedule might be stepped up or the smaller, experimental pile might be built. An intensive study of the matter 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.

#### The Argonne Heavy-Water Pile

8.59. Perhaps the most striking aspect of the uranium and heavy-water pile at the Argonne is its small size. Even with its surrounding shield of concrete it is relatively small compared to the uranium-graphite piles.

8.60. By May 15, 1944, the Argonne uranium and heavy-water pile was ready for test. With the uranium slugs in place, it was found that the chain reaction in the pile became self-sustaining when only three fifths of the heavy water had been added. The reactivity of the pile was so far above expectations that it would have been beyond the capacity of the control rods to handle if the remainder of the heavy water had been added. To meet this unusual and pleasant situation some of the uranium was removed and extra control rods were added.

8.61. With these modifications it was possible to fill the tank to the level planned. By July 4, 1944, W. H. Zinn reported that the pile was running satisfactorily at 190 kw, and by August 8, 1944, he reported that it was operating at 300 kw.

8.62. In general the characteristics of this pile differed slightly from those of comparable graphite piles. This pile takes several hours to reach equilibrium. It shows small (less than 1 per cent) but sudden fluctuations in power level, probably caused by bubbles in the water. It cannot be shut down as completely or as rapidly as the graphite pile because of the tendency of delayed gamma rays to produce (from the heavy water) additional

neutrons. As anticipated, the neutron density at the center is high. The shields, controls, heat exchanger, etc., have operated satisfactorily.

#### The Health Division

8.63. The major objective of the health group was in a sense a negative one, to insure that no one concerned suffered serious injury from the peculiar hazards of the enterprise. Medical case histories of persons suffering serious injury or death resulting from radiation were emphatically not wanted.

8.64. To achieve its objective the health group worked along three major lines:

- 1) Adoption of pre-employment physical examinations and frequent re-examinations, particularly of those exposed to radiation.
- 2) Setting of tolerance standards for radiation doses and development of instruments measuring exposure of personnel; giving advice on shielding, etc.; continually measuring radiation intensities at various locations in the plants; measuring contamination of clothes, laboratory desks, waste water, the atmosphere, etc.
- 3) Carrying out research on the effects of direct exposure of persons and animals to various types of radiation, and on the effects of ingestion and inhalation of the various radioactive or toxic materials such as fission products, plutonium and uranium.

#### Routine Examinations

8.65. The white blood-corpuscule count was used as the principal criterion as to whether a person suffered from overexposure to radiation. A number of cases of abnormally low counts were observed and correlated with the degree of overexposure. Individuals appreciably affected were shifted to other jobs or given brief vacations; none have shown permanent ill effects.

8.66. At the same time it was recognized that the white blood-corpuscule count is not an entirely reliable criterion. Some work on animals indicated that serious damage might occur before the blood count gave any indication of danger. Accordingly, more elaborate blood tests were made on selected individuals and on experimental animals in the hope of finding a test that would give an earlier warning of impending injury.

#### Instruments for Radiation Measurements

8.67. The Health Division had principal responsibility for the development of pocket meters for indicating the extents of exposure of persons. The first of these instruments was a simple electroscope about the size and shape of a fountain pen. Such instruments were electrostatically charged at the start of each day and were read at the end of the day. The degree to

which they became discharged indicated the total amount of ionizing radiation to which they have been exposed. Unfortunately they were none too rugged and reliable, but the error of reading was nearly always in the right direction -- i.e., in the direction of overstating the exposure. At an early date the practice was established of issuing two of these pocket meters to everyone entering a dangerous area. A record was kept of the readings at the time of issuance and also when the meters were turned in. The meters themselves were continually although gradually improved. The Health Division later introduced "film badges," small pieces of film worn in the identification badge, the films being periodically developed and examined for radiation blackening.

8.68. The Health Division cooperated with the Physics Division in the development and use of various other instruments. There was "Sneezy" for measuring the concentration of radioactive dust in the air and "Pluto" for measuring  $\gamma$ -emitting contamination (usually plutonium) of laboratory desks and equipment. Counters were used to check the contamination of laboratory coats before and after the coats were laundered. At the exit gates of certain laboratories concealed counters sounded an alarm when someone passed whose clothing, skin or hair was contaminated. In addition, routine inspections of laboratory areas were made.

8.69. One of the studies made involved meteorology. It became essential to know whether the stack gasses (at Clinton and at Hanford) would be likely to spread radioactive fission products in dangerous concentrations. Since the behavior of these gasses is very dependent on the weather, studies were made at both sites over a period of many months, and satisfactory stack operation was specified.

#### Research

8.70. Since both the scale and the variety of the radiation hazards in this enterprise were unprecedented, all reasonable precautions were taken; but no sure means were at hand for determining the adequacy of the precautions. It was essential to supplement previous knowledge as completely as possible. For this purpose, an extensive program of animal experimentation was carried out along three main lines: (1) exposure to neutron, alpha, beta and gamma radiation; (2) ingestion of uranium, plutonium and fission products; (3) inhalation of uranium, plutonium and fission products. Under the general direction of Dr. Stone these experiments were carried out at Chicago, Clinton and the University of California principally by Dr. Cole and Dr. Hamilton. Extensive and valuable results were obtained.

#### Summary

8.71. Both space and security restrictions prevent a detailed report on the work of the laboratories and plants concerned with plutonium production.

8.72. 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.

8.73. 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 and further reduced by absorption of 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.

8.74. 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.

8.75. 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.

8.76. 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.

8.77. 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.

8.78. 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; (3) research on the effects of radiation.

GENERAL DISCUSSION OF THE SEPARATION OF ISOTOPESIntroductory Note

9.1. The possibility of producing an atomic bomb of U-235 was recognized before plutonium was discovered. Because it was appreciated at an early date that 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 since it was realized that the separation of deuterium was also of great importance. In the present chapter the general problems of isotope separation will be discussed; later chapters will take up the specific application of various processes.

Factors Affecting the Separation of Isotopes

9.2. By definition, the isotopes of an element differ in mass but not in chemical properties. More precisely, although the nuclear masses and structures differ, the nuclear charges are identical and therefore the external electronic structures are practically identical. For most practical purposes, therefore, the isotopes of an element are separable only by processes depending on the nuclear mass.

9.3. It is well known that the molecules of a gas or liquid are in continual motion and that their average kinetic energy depends only on the temperature, not on the chemical properties of the molecules. Thus in a gas made up of a mixture of two isotopes the average kinetic energy of the light molecules and of the heavy ones is the same. Since the kinetic energy of a molecule is  $1/2 mv^2$ , where  $m$  is the mass and  $v$  the speed of the molecule, it is apparent that on the average the speed of a lighter molecule must be greater than that of a heavier molecule. Therefore, at least in principle, any process depending on the average speed of molecules can be used to separate isotopes. Unfortunately, the average speed is inversely proportional to the square root of the mass so that the difference is very small for the gaseous compounds of the uranium isotopes. Also, although the average speeds differ, the ranges of speed show considerable overlap. In the case of the gas uranium hexafluoride, for example, over 49 percent of the light molecules have speeds as low as those of 50 percent of the heavy molecules.

9.4. Obviously there is no feasible way of applying mechanical forces directly to molecules individually; they cannot be poked with a stick or pulled with a string. But they are subject to gravitational fields and, if ionized, may be affected by electric and magnetic fields. Gravitational forces are, of course, proportional to the mass. In a very high vacuum

U-235 atoms and U-238 atoms would fall with the same acceleration, but just as a feather and a stone fall at very different rates in air where there are frictional forces resisting motion, there may be conditions under which a combination of gravitational and opposing intermolecular forces will tend to move heavy atoms differently from light ones. Electric and magnetic fields are more easily controlled than gravitational fields or "pseudo-gravitational" fields (i.e., centrifugal-force fields) and are very effective in separating ions of differing masses.

9.5. Besides gravitational or electromagnetic forces, there are, of course, interatomic and intermolecular forces. These forces govern the interaction of molecules and thus affect the rates of chemical reactions, evaporation processes, etc. In general, such forces will depend on the outer electrons of the molecules and not on the nuclear masses. However, whenever the forces between separated atoms or molecules lead to the formation of new molecules, a mass effect (usually very small) does appear. In accordance with quantum-mechanical laws, the energy levels of the molecules are slightly altered, and differently for each isotopes. Such effects do slightly alter the behavior of two isotopes in certain chemical reactions, as we shall see, although the difference in behavior is far smaller than the familiar differences of chemical behavior between one element and another.

9.6. These, then, are the principal factors that may have to be considered in devising a separation process: equality of average thermal kinetic energy of molecules at a given temperature, gravitational or centrifugal effects proportional to the molecular masses, electric or magnetic forces affecting ionized molecules, and interatomic or intermolecular forces. In some isotope-separation processes only one of these effects is involved and the overall rate of separation can be predicted. In other isotope-separation processes a number of these effects occur simultaneously so that prediction becomes difficult.

#### Criteria for Appraising a Separation Process

9.7. Before discussing particular processes suitable for isotope separation, we should know what is wanted. The major criteria to be used in judging an isotope-separation process are as follows.

##### Separation Factor

9.8. The separation factor, sometimes known as the enrichment or fractionating factor of a process, is the ratio of the relative concentration of the desired isotope after processing to its relative concentration before processing. Defined more precisely: if, before the processing, the numbers of atoms of the isotopes of mass number  $m_1$  and  $m_2$  are  $n_1$  and  $n_2$  respectively (per gram of the isotope mixture) and if, after the processing, the corresponding numbers are  $n_1'$  and  $n_2'$  then the separation factor is:

$$r = \frac{n_1^2/n_2^2}{n_1/n_2}$$

This definition may be applied to one stage of a separation plant or to an entire plant consisting of many stages. We are usually interested either in the "single stage" separation factor or in the "overall" separation factor of the whole process. If  $r$  is only slightly greater than unity, as is often the case for a single stage, the number  $r-1$  is sometimes more useful than  $r$ . The quantity  $r-1$  is called the enrichment factor. In natural uranium  $n_1 = 235$ ,  $n_2 = 238$ , and  $n_1/n_2 = 1/140$  approximately, but in 90 percent U-235,  $n_1/n_2 = 9/1$ . Consequently in a process producing 90 percent U-235 from natural uranium the overall value of  $r$  must be about 1260.

#### Yield

9.9. In nearly every process a high separation factor means a low yield, a fact that calls for continual compromise. Unless indication is given to the contrary, we shall state yields in terms of U-235. Thus a separation device with a separation factor of 2 ( $n_1/n_2 = 1/70$ ) and a yield of one gram a day is one that, starting from natural uranium, produces, in one day, material consisting of 1 gram of U-235 mixed with 70 grams of U-238.

#### Hold-up

9.10. The total amount of material tied up in a separation plant is called the "hold-up." The hold-up may be very large in a plant consisting of many stages.

#### Start-up-Time

9.11. In a separation plant having large hold-up, a long time — perhaps weeks or months — is needed for steady operating conditions to be attained. In estimating time schedules this "start-up" or "equilibrium" time must be added to the time of construction of the plant.

#### Efficiency

9.12. If a certain quantity of raw material is fed into a separation plant, some of the material will be enriched, some impoverished, some unchanged. Parts of each of these three fractions will be lost and parts recovered. The importance of highly efficient recovery of the enriched material is obvious. In certain processes the amount of unchanged material is negligible, but in others, notably in the electromagnetic method to be described below, it is the largest fraction and consequently the efficiency with which it can be recovered for recycling is very important. The importance of recovery of impoverished material varies widely, depending very much on the degree of impoverishment. Thus in



general there are many different efficiencies to be considered.

### Cost

9.13. As in all parts of the uranium project, cost in time was more important than cost in money. Consequently a number of large-scale separation plants for U-235 and deuterium were built at costs greater than would have been required if construction could have been delayed for several months or years until more ideal processes were worked out.

### Some Separation Processes

#### Gaseous Diffusion

9.14. As long ago as 1896 Lord Rayleigh showed that a mixture of two gasses of different atomic weight could be partly separated by allowing some of it to diffuse through a porous barrier into an evacuated space. Because of their higher average speed the molecules of the light gas diffuse through the barrier faster so that the gas which has passed through the barrier (i.e., the "diffusate") is enriched in the lighter constituent and the residual gas (which has not passed through the barrier) is impoverished in the lighter constituent. The gas most highly enriched in the lighter constituent is the so-called "instantaneous diffusate"; it is the part that diffuses before the impoverishment of the residue has become appreciable. If the diffusion process is continued until nearly all the gas has passed through the barrier, the average enrichment of the diffusate naturally diminishes. In the next chapter we shall consider these phenomena in some detail. Here we shall merely point out that, on the assumption that the diffusion rates are inversely proportional to the square roots of the molecular weights the separation factor for the instantaneous diffusate, called the "ideal separation factor"  $\alpha$ , is given by

$$\alpha = \sqrt{\frac{M_2}{M_1}}$$

where  $M_1$  is the molecular weight of the lighter gas and  $M_2$  that of the heavier. Applying this formula to the case of uranium will illustrate the magnitude of the separation problem. Since uranium itself is not a gas, some gaseous compound of uranium must be used. The only one obviously suitable is uranium hexafluoride,  $UF_6$ , which has a vapor pressure of one atmosphere at a temperature of  $56^\circ C$ . Since fluorine has only one isotope, the two important uranium hexafluorides are  $U^{235}F_6$  and  $U^{238}F_6$ ; their molecular weights are 349 and 352. Thus, if a small fraction of a quantity of uranium hexafluoride is allowed to diffuse through a porous barrier,

the diffusate will be enriched in  $U^{235}F_6$  by a factor

$$\alpha = \sqrt{\frac{352}{349}} = 1.0043$$

which is a long way from the 1260 required (see paragraph 9.8.).

9.15. Such calculations might make it seem hopeless to separate isotopes (except, perhaps, the isotopes of hydrogen) by diffusion processes. Actually, however, such methods may be used successfully — even for uranium. It was the gaseous diffusion method that F. W. Aston used in the first partial separation of isotopes (actually the isotopes of neon). Later G. Hertz and others, by operating multiple-stage recycling diffusion units, were able to get practically complete separation of the neon isotopes. Since the multiple-stage recycling system is necessary for nearly all separation methods, it will be described in some detail immediately following introductory remarks on the various methods to which it is pertinent.

#### Fractional Distillation

9.16. The separation of compounds of different boiling points, i.e., different vapor pressures, by distillation is a familiar industrial process. The separation of alcohol and water (between which the difference in boiling point is in the neighborhood of 20°C.) is commonly carried out in a simple still using but a single evaporator and condenser. The condensed material (condensate) may be collected and redistilled a number of times if necessary. For the separation of compounds of very nearly the same boiling point it would be too laborious to carry out the necessary number of successive evaporations and condensations as separate operations. Instead, a continuous separation is carried out in a fractionating tower. Essentially the purpose of a fractionating tower is to produce an upward-directed stream of vapor and a downward-directed stream of liquid, the two streams being in intimate contact and constantly exchanging molecules. The molecules of the fraction having the lower boiling point have a relatively greater tendency to get into the vapor stream and vice versa. Such counter-current distillation methods can be applied to the separation of light and heavy water, which differ in boiling point by 1.4°C.

#### General Application of Countercurrent Flow

9.17. The method of countercurrent flow is useful not only in two-phase (liquid-gas) distillation processes, but also in other separation processes such as those involving diffusion resulting from temperature variations (gradients) within one-phase systems or from centrifugal forces. The countercurrents may be with respect to two gases, two liquids, or one gas and one liquid.

### The Centrifuge

9.18. We have pointed out that gravitational separation of two isotopes might occur since the gravitational forces tending to move the molecules downward are proportional to the molecular weights, and the intermolecular forces tending to resist the downward motion depend on the electronic configuration, not on the molecular weights. Since the centrifuge is essentially a method of applying pseudogravitational forces of large magnitude, it was early considered as a method for separating isotopes. However, the first experiments with centrifuges failed. Later development of the high speed centrifuge by J. W. Deams and others led to success. H. C. Urey suggested the use of tall cylindrical centrifuges with countercurrent flow; such centrifuges have been developed successfully.

9.19. In such a countercurrent centrifuge there is a downward flow of vapor in the outer part of the rotating cylinder and an upward flow of vapor in the central or axial region. Across the interface region between the two currents there is a constant diffusion of both types of molecules from one current to the other, but the radial force field of the centrifuge acts more strongly on the heavy molecules than on the light ones so that the concentration of heavy ones increases in the peripheral region and decreases in the axial region, and vice versa for the lighter molecules.

9.20. The great appeal of the centrifuge in the separation of heavy isotopes like uranium is that the separation factor depends on the difference between the masses of the two isotopes, not on the square root of the ratio of the masses as in diffusion methods.

### Thermal Diffusion Method

9.21. The kinetic theory of gases predicts the extent of the differences in the rates of diffusion of gases of different molecular weights. The possibility of accomplishing practical separation of isotopes by thermal diffusion was first suggested by theoretical studies of the details of molecular collisions and of the forces between molecules. Such studies made by Enskog and by Chapman before 1920 suggested that if there were a temperature gradient in a mixed gas there would be a tendency for one type of molecule to concentrate in the cold region and the other in the hot region. This tendency depends not only on the molecular weights but also on the forces between the molecules. If the gas is a mixture of two isotopes, the heavier isotope may accumulate at the hot region or the cold region or not at all, depending on the nature of the intermolecular forces. In fact, the direction of separation may reverse as the temperature or relative concentration is changed.

9.22. Such thermal diffusion effects were first used to separate isotopes by H. Clusius and G. Dickel in Germany in 1938. They built a vertical tube containing a heated wire stretched along the axis of the tube and producing a temperature difference of about 600°C. between the axis and

the periphery. The effect was twofold. In the first place, the heavy isotopes (in the substances they studied) became concentrated near the cool outer wall, and in the second place, the cool gas on the outside tended to sink while the hot gas at the axis tended to rise. Thus thermal convection set up a countercurrent flow, and thermal diffusion caused the preferential flow of the heavy molecules outward across the interface between the two currents.

9.23. The theory of thermal diffusion in gases is intricate enough; that of thermal diffusion in liquids is particularly complicated. A separation effect does exist, however, and has been used successfully to separate the light and heavy uranium hexafluorides.

#### Chemical Exchange Method

9.24. In the introduction to this chapter we pointed out that there was some reason to hope that isotope separation might be accomplished by ordinary chemical reactions. It has in fact been found that in simple exchange reactions between compounds of two different isotopes the so-called equilibrium constant is not exactly one, and thus that in reactions of this type separation can occur. For example, in the catalytic exchange of hydrogen atoms between hydrogen gas and water, the water contains between three and four times as great a concentration of deuterium as the hydrogen gas in equilibrium with it. With hydrogen and water vapor the effect is of the same general type but equilibrium is more rapidly established. It is possible to adapt this method to a continuous countercurrent flow arrangement like that used in distillation, and such arrangements are actually in use for production of heavy water. The general method is well understood, and the separation effects are known to decrease in general with increasing molecular weight, so that there is but a small chance of applying it successfully to heavy isotopes like uranium.

#### Electrolysis Method

9.25. The electrolysis method of separating isotopes resulted from the discovery that the water contained in electrolytic cells used in the regular commercial production of hydrogen and oxygen has an increased concentration of heavy water molecules. A full explanation of the effect has not yet been worked out. Before the war practically the entire production of heavy hydrogen was by the electrolysis method. By far the greatest production was in Norway, but enough for many experimental purposes had been made in the United States.

#### Statistical Methods in General

9.26. The six methods of isotope separation we have described so far (diffusion, distillation, centrifugation, thermal diffusion, exchange reactions, and electrolysis) have all been tried with some degree of success on either uranium or hydrogen or both. Each of these methods depends on



small differences in the average behavior of the molecules of different isotopes. Because an average is by definition a statistical matter, all such methods depending basically on average behavior are called statistical methods.

9.27. The criteria set up for judging separation processes are rather similar for the six statistical methods. In every case the separation factor is small so that many successive stages of separation are required. In most cases relatively large quantities of material can be handled in plants of moderate size. The hold-up and starting-time values vary considerably but are usually high. The similarity of the six methods renders it inadvisable to make final choice of method without first studying in detail the particular isotope, production rate, etc., wanted. Exchange reaction and electrolysis methods are probably unsuitable in the case of uranium, and no distillation scheme for uranium has survived. All of the other three methods have been developed with varying degrees of success for uranium, but are not used for hydrogen.

#### The Electromagnetic Method and its Limitations

9.28. The existence of non-radioactive isotopes was first demonstrated during the study of the behavior of ionized gas molecules moving through electric and magnetic fields. It is just such fields that form the basis of the so-called mass-spectrographic or electro-magnetic method of separating isotopes. This method is the best available for many types of isotope relative abundance determinations. The method is used constantly in checking the results of the uranium isotope separation methods we have already described. The reason the method is so valuable is that it can readily effect almost complete separation of the isotopes very rapidly and with small hold-up and short start-up time. If this is so, it may well be asked why any other method of separation is considered. The answer is that an ordinary mass spectrograph can handle only very minute quantities of material, usually of the order of fractions of a microgram per hour.

9.29. To understand the reasons for this quantitative (yield) limitation, we shall outline the principle of operation of a simple type of mass spectrograph first used by A. J. Dempster in 1918. Such an instrument is illustrated schematically in the following figure. The gaseous compound to be separated is introduced in the ion source, where some of its molecules are ionized in an electric discharge. Some of these ions go through the slit  $s_1$ . Between  $s_1$  and  $s_2$  they are accelerated by an electric field which gives them all practically the same kinetic energy, thousands of times greater than their average thermal energy. Since they now all have practically the same kinetic energy, the lighter ions must have less momenta than the heavy ones. Entering the magnetic field at the slit  $s_2$  all the ions will move (perpendicular to the magnetic field) in semi-circular paths of

given by Major General L. R. Groves after personal inspection of the 70-square-mile site. In September 1942, the first steps were taken to acquire the tract, which is on the Clinch River about thirty miles from Knoxville, Tennessee, and eventually considerably exceeded 70 square miles. The plutonium pilot plant is located in one valley, the electromagnetic separation plant in an adjoining one, and the diffusion separation plant in a third.

10.35. Although the plant and site development at Hanford is very impressive, it is all under one company dealing with but one general operation so that it is in some respects less interesting than Clinton, which has a great multiplicity of activity. To describe the Clinton site, with its great array of new plants, its new residential districts, new theatres, new school system, seas of mud, clouds of dust, and general turmoil is outside the scope of this report.

#### Dates of Start of Construction

10.36. Construction of the steam power plant for the diffusion plant began on June 1, 1943. It is one of the largest such power plants ever built. Construction of other major buildings and plants started between August 29, 1943 and September 10, 1943.

#### Operation

10.37. Unlike Hanford, the diffusion plant consists of so many more or less independent units that it was put into operation section by section, as permitted by progress in constructing and testing. Thus there was no dramatic start-up date nor any untoward incident to mark it. The plant was in successful operation before the summer of 1945.

10.38. For the men working on gaseous diffusion it was a long pull from 1940 to 1945, not lightened by such exciting half-way marks as the first chain-reacting pile at Chicago. Perhaps more than any other group in the project, those who have worked on gaseous diffusion deserve credit for courage and persistence as well as scientific and technical ability. For security reasons, we have not been able to tell how they solved their problems -- even in many cases found several solutions, as insurance against failure in the plant. It has been a notable achievement. In these five years there have been periods of discouragement and pessimism. They are largely forgotten now that the plant is not only operating but operating consistently, reliably, and with a performance better than had been anticipated.

#### Summary

10.39. 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.

10.40. 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, and on a previously-unheard-of scale. Many problems of instrumentation and control were solved; extensive use was made of various forms of mass spectrograph.

10.41. The research was carried out principally at Columbia under Dunning and Urey. In 1942, the W. Kellogg Company was chosen to design the plant and set up the Kellogg 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.

10.42. A very 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.

## CHAPTER XI

ELECTROMAGNETIC SEPARATION OF URANIUM ISOTOPESIntroduction

11.1. In Chapter IV we said that 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. In Chapter IX we described the principles of one method of electromagnetic separation and listed the three limitations of that method: difficulty of producing ions, limited fraction of ions actually used, and space charge effects.

11.2. 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 officially placed in charge of the preparation of further samples and the making of 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 production 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 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. Most of this chapter will be devoted to the calutron since that is the method that has resulted in large-scale production of U-235. A brief description will also be given of the thermal diffusion plant built to provide enriched feed material for the electromagnetic plant.

11.3. Security requirements make it impossible here -- as for other parts of the project -- to present many of the most interesting technical details. The importance of the development is considerably greater than is indicated by the amount of space which is given it here.



Electromagnetic Mass Separators

Preliminary Work

11.4. A. O. Nier's mass spectrograph was set up primarily to measure relative abundance 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 micro-ampere. (A mass spectrograph in which one micro-ampere 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 for nuclear study was recognized early by Lawrence, who decided to see what could be done with the help of the 37-inch (cyclotron) magnet at Berkeley. The initial stages of this work were assisted by a grant from the Research Corporation of New York, which was later repaid. Beginning January 1, 1942 the entire support came from the OSRD through the S-1 Committee. Later, as in other parts of the uranium project, the contracts were taken over by the Manhattan District.

11.5. At Berkeley, after some weeks of planning, the 37-inch cyclotron was dismantled on November 24, 1941 and its magnet was 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 corresponding to the ion source shown in the drawing in Chapter IX. Ions were then accelerated to the slit  $s_2$  through which they passed 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 that 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 much improved separation factor. 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.

Initiation of a Large Program

11.6. By this time it was clear that the calutron was potentially able to effect much larger scale separations than had ever before been approached. It was evidently desirable to explore the whole field of electromagnetic separation. With this end in view, Lawrence mobilized his group at the Radiation Laboratory of the University of California at Berkeley and began to call in others to help. Among those initially at Berkeley were D. Cooksey, P. G. Abersold, W. M. Brobeck, F. A. Jenkins, K. R. MacKenzie, W. B. Reynolds, D. H. Sloan, F. Oppenheimer, J. G. Backus, B. Peters, A. C. Helmholtz, T. Finkelstein, and W. E. Parkins, Jr. Lawrence called back some of his former students, including R. L. Thornton, J. R. Richardson, and others. Among those working at Berkeley for various periods were L. P. Smith from Cornell, E. U. Condon and J. J. Slepian from Westinghouse, and I. Langmuir and K. H. Kingdon from General Electric. During this early period J. R. Oppenheimer was still at Berkeley and contributed some important ideas. In the fall of 1943 the group was further strengthened by the arrival of a number of English physicists under the leadership of M. L. Olyphant of the University of Birmingham.

11.7. Initially a large number of different methods were considered and many exploratory experiments were performed. The main effort, however, soon became directed towards the development of the calutron, the objective being a high separation factor and a large current in the positive ion beam.

Immediate Objectives

11.8. Of the three apparent limitations listed in the first paragraph -- difficulty of producing ions, limited fraction of ions actually used, and space charge effects -- only the last had yielded to the preliminary attack. Apparently space charge in the neighborhood of the positive ion beam could be nullified to a very great extent. There remained as the immediate objectives a more productive ion source and more complete utilization of the ions.

11.9. The factors that control the effectiveness of an ion source are many. Both the design of the source proper and the method of drawing ions from it are involved. The problems to be solved cannot be formulated simply and must be attacked by methods that are largely empirical. Even if security restrictions permitted an exposition of the innumerable forms of ion source and accelerating system that were tried, such exposition would be too technical to present here.

11.10. 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. Fortunately, however, since all the ions of the isotopes 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. It is, of course, at this position of re-convergence that the collector is placed. Naturally, the ions of another isotope (for example, ions of mass 233 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 readily enough 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. Indeed it can be accomplished only by use of carefully proportioned space-variations in the magnetic field strength. Fortunately, such variations were worked out successfully.

11.11. Another problem, not so immediate but nevertheless recognized as important to any production plant, was that of more efficient use of the magnetic field. Since large electromagnets are expensive both to build and to operate, it was natural to consider using the same magnetic field for several ion beams. The experimental realization of such an economical scheme became a major task of the laboratory.

#### The Giant Magnet

11.12. Although the scale of separation 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-inch cyclotron magnet that had been used was still capable of furnishing 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 inches and a pole gap of 72 inches, 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, etc., were almost ideal for the development of the calutron. Needless to say, work was resumed on the giant magnet and by the end of May 1942, it was ready for use.

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\*The construction of the giant cyclotron had been undertaken with private funds largely supplied by the Rockefeller Foundation. In order to push the construction as fast as possible overtime work was required at additional expense. To cover these costs the Rockefeller Foundation made an extra appropriation.

Development up to September 1942

11.13. The first experiments using the 37-inch magnet have been described in a previous paragraph. Later developments proceeded principally along these two lines: construction and installation of a properly engineered separation unit for the 37-inch magnet, and design and construction of experimental separation units to go into the big magnet.

11.14. 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, using 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.

11.15. It was evident that many separator units would be needed to get an amount of production of military significance. Therefore, consideration was given to various systems of combining groups of units in economical arrangements. A scheme was worked out which was later used in the production plants and which has proved satisfactory.

Advantages of the Electromagnetic System

11.16. In September 1942, both the gaseous diffusion and the centrifugal methods of uranium isotope separation had been under intensive study -- and for a longer period than in the case of the electromagnetic method. Both of these methods -- gaseous diffusion and centrifuge -- looked feasible for large-scale production of U-235, but both would require hundreds of stages to achieve large scale separation. Neither had actually produced any appreciable amounts of separated U-235. No large-scale plant for plutonium production was under way, and the self-sustaining chain reaction which was to produce plutonium had not yet been proved attainable. But in the case of the electromagnetic method, after the successful separation of milligram amounts, there was no question as to the scientific feasibility. If one unit could separate 10 mg a day, 100,000,000 units could separate one ton a day; The questions were of cost and time. Each unit was to be a complicated electromagnetic device requiring high vacuum, high voltages, and intense magnetic fields; and a great deal of research and development work would be required before complete, large-scale, units could be constructed. Many skilled operators would probably be needed. Altogether, at that time it looked very expensive, but it also looked certain and relatively quick. Moreover, the smallness of the units had the advantage that development could continue, modifications could be made in the course of construction or, within limits, after construction, and capacity could always be expanded by building new units.



### Policy Question

11.17. On the basis of rather incomplete scientific and engineering information on all the methods and on the basis of equally dubious cost estimates, decisions had to be made on the three issues: (1) whether to build an electromagnetic plant; (2) how big such a plant should be; (3) at what point of development the design should be frozen.

### Approval of Plant Construction

11.18. On the strength of the results reported on experiments at Berkeley in the summer of 1942, the S-1 Executive Committee, at a meeting at Berkeley on September 13-14, 1942, recommended that commitments be made by the Army for an electromagnetic separation plant to be built at the Tennessee Valley site (Clinton Engineer Works). It was recommended that it should be agreed that commitments for this plant might be cancelled on the basis of later information. It was recommended that a pilot plant should be erected at the Tennessee Valley site as soon as possible. (However, this recommendation was subsequently withdrawn and such a pilot plant was never built.) The construction of a production plant was authorized by General Groves on November 5, 1942, with the understanding that the design for the first units was to be frozen immediately.

### Organization for Planning and Construction

11.19. In describing the production of plutonium, we discussed the division of responsibility between the Metallurgical Project and the du Pont Company. The electromagnetic separation plant was planned and built under a somewhat different scheme of organization. The responsibility was divided between six major groups. The Radiation Laboratory at the University of California was responsible for research and development; the Westinghouse Electric and Manufacturing Company for making the mechanical parts, i.e., sources, receivers, pumps, tanks, etc.; the General Electric Company for the electrical equipment and controls; the Allis-Chalmers Company for the magnets; the Stone and Webster Engineering Company for the construction and assembly; and the Tennessee Eastman Company for operation. All five industrial concerns kept groups of their engineers at Berkeley so that a system of frequent informal conference and cross-checking was achieved. Thus the major part of the planning was done cooperatively in a single group, even though the details might be left to the home offices of the various companies.

### The Basis of the Technical Decisions

11.20. Strangely enough, although the theory of the self-sustaining chain-reacting pile is already well worked out, the theory of gaseous discharge, after fifty years of intensive study, is still inadequate for the prediction of the exact behavior of the ions in a calutron. The amount of U-235 collected per day, and the purity of the material collected, are affected by many factors, including: (1) the width, spacing, and shape of the collector, (2) the pressure in the magnet space, (3) the strength and uniformity of the magnetic field, (4) the shape and spacing of the defining slits and accelerating system, (5) the accelerating voltage, (6) the size

and shape of the slit in the arc source from which the ions came, (7) the current in the arc, (8) the position of the arc within the arc chamber, (9) the pressure of vapor in the arc chamber, (10) the chemical nature of the vapor. Evidently there was not time for a systematic study of all possible combinations of variables. The development had to be largely intuitive. A variety of conditions had to be studied and a number of partial interpretations had to be made. Then the accumulated experience of the group, the "feel" of the problem, had to be translated into specific plans and recommendations.

#### Technical Decisions Required

11.21. (a) The Number of Stages. As in all methods, a compromise must be made between yield and separation factor. In the electromagnetic system, the separation factor is much higher than in other systems so that the number of stages required is small. There was a possibility that a single stage might be sufficient. Early studies indicated that attempts to push the separation factor so high as to make single-stage operation feasible cut the yield to an impractically small figure.

11.22. (b) Specifications. The information and experience that had been acquired on the variables such as those mentioned above had to be translated into decisions on the following principal points before design could actually begin: (1) the size of a unit as determined by the radius of curvature of the ion path, the length of the source slit, and the arrangement of sources and receivers; (2) the maximum intensity of magnetic field required; (3) whether or not to use large divergence of ion beams; (4) the number of ion sources and receivers per unit; (5) whether the source should be at high potential or at ground potential; (6) the number of accelerating electrodes and the maximum potentials to be applied to them; (7) the power requirements for arcs, accelerating voltages, pumps, etc.; (8) pumping requirements; (9) number of units per pole gap; (10) number of units per building.

#### Experimental Units at Berkeley

11.23. Most of the design features for the first plant had to be frozen in the fall of 1942 on the basis of results obtained with runs made using the giant magnet at Berkeley. The plant design, however, called for units of a somewhat different type. While there was no reason to suppose that these changes would introduce any difference in performance, it was obviously desirable to build a prototype unit at Berkeley. The construction of this unit was approved at about the same time that the first plant units were ordered so that experience with it had no influence on fundamental design, but it was finished and operating by April 1943, that is, six months before the first plant unit. Consequently, it was invaluable for testing and training purposes. Later, a third magnet was built in the big magnet building at Berkeley. All told, there have been six separator units available simultaneously for experimental or pilot plant purposes at Berkeley. Much auxiliary work has also been done outside the complete units.

The Isotron Separator

11.24. As we have already said, H. D. Smyth of Princeton became interested in electromagnetic methods of separation in the late summer and fall of 1941. He was particularly interested in devising some method of using an extended ion source and beam instead of one limited essentially to one dimension by a slit system as in the calutron mass-separator. A method of actually achieving separation using an extended ion source was suggested by R. R. Wilson of Princeton. The device which resulted from Wilson's ideas was given the deliberately meaningless name "isotron."

11.25. The isotron is an electromagnetic mass separator using an extended source of ions, in contrast to the slit sources used in ordinary mass spectrographs. The ions from the extended source are first accelerated by a constant, high-intensity, electric field and are then further accelerated by a low-intensity electric field varying at radio frequency and in "saw tooth" manner. The effect of the constant electric field is to project a strong beam of ions down a tube with uniform kinetic energy and therefore with velocities inversely proportional to the square root of the masses of ions. The varying electric field, on the other hand, introduces small, periodic variations in ion velocity, and has the effect of causing the ions to "bunch" at a certain distance down the tube. (This same principle is used in the klystron high-frequency oscillator, where the electrons are "bunched" or "velocity-modulated.") The bunches of ions of different mass travel with different velocities and therefore become separated. At the position (actually on a plane perpendicular to the beam) where this occurs, an analyzer applies a transverse focussing electric field with a radio frequency component synchronized with the arrival of the bunches. The synchronization is such that the varying component of the transverse field strength is zero when the U-235 ion bunches come through and a maximum when the U-238 ion bunches come through. Thus the U-235 beams are focussed on a collector, but the U-238 bunches are deflected. Thus the separation is accomplished.

11.26. This scheme was described at the December 18, 1941 meeting of the Uranium Committee and immediately thereafter was discussed more fully with Lawrence, who paid a visit to Princeton. The promise of the method seemed sufficient to justify experimental work, which was begun immediately under an OSRD contract and continued until February 1943. Since the idea involved was a novel one, there were two outstanding issues: (1) whether the method would work at all; (2) whether it could be developed for large-scale production promptly enough to compete with the more orthodox methods already under development.

11.27. An experimental isotron was constructed and put into operation by the end of January 1942. Preliminary experiments at that time indicated that the isotopes of lithium could be separated by the method. The first successful collection of partially separated uranium isotopes was made in the spring of 1942.

11.28. Unfortunately, progress during the summer and fall of 1942 was not as rapid as had been hoped. Consequently, it was decided to close down the Princeton project in order to permit sending the personnel

to the site where the atomic-bomb laboratory was about to get under way. Before the group left Princeton a small experimental isotron collected several samples of partly separated uranium. Thus, the method worked; but its large-scale applicability was not fully investigated.

The Magnetron and the Ionic Centrifuge

11.29. In December 1941, when the whole subject of isotope separation was under discussion at Berkeley, the magnetron was suggested as a possible mass separator. In the meantime, Smyth of Princeton had been in contact with L. P. Smith of Cornell and had discovered that Smith and his students had done a considerable amount of work -- and with evidence of success -- on the separation of the isotopes of lithium by just such a method. This was reported to Lawrence in Washington at one of the December, 1941, meetings of the Uranium Committee. Lawrence immediately got in touch with Smith, with the result that Smith worked on the method at Berkeley from February 1942 to June 1942. J. Slepian of the Westinghouse Research Laboratory in East Pittsburgh came to Berkeley in the winter of 1942-43 at Lawrence's invitation and became interested in a modification of the magnetron which he called an ionic centrifuge. Slepian stayed at Berkeley most of the time until the fall of 1942, after which he returned to East Pittsburgh where he continued the work.

11.30. No separation of uranium was actually attempted in the magnetron. Experiments with lithium with low ion currents showed some separation, but no consistent results were obtained with high ion currents. In the case of the ionic centrifuge, uranium samples have been collected showing appreciable separation, but the results have not been clear-cut or consistent.

The Situation as of Early 1943

11.31. With the virtual elimination of the isotron and the ionic centrifuge from the development program, the calutron separator became the only electromagnetic method worked on intensively. Construction of initial units of a plant had been authorized and designs had been frozen for such units, but the whole electromagnetic program had been in existence for only a little more than a year and it was obvious that available designs were based on shrewd guesses rather than on adequate research. A similar situation might have occurred with the chain-reacting pile if unlimited amounts of uranium and graphite had been available before the theory had been worked out or before the nuclear constants had been well determined. Fortunately the nature of the two projects was very different, making it a less speculative venture to build an electromagnetic plant unit hastily than would have been the case for the pile. Further research and development could proceed advantageously even while initial units of the plant were being built and operated.



Construction and Operation; March 1943 to June 1943

Comparison with Diffusion and Plutonium Plants

11.32. The preceding chapters show that the end of 1942 was a time of decision throughout the uranium project. For it was at that time that a self-sustaining chain reaction was first produced, that construction was authorized for the Hanford plutonium plant, the diffusion plant at Clinton, and the electromagnetic plant at Clinton. The diffusion plant was more flexible than the plutonium plant, since the diffusion plant could be broken down into the sections and stages, built in whole or in part, to produce varying amounts of U-235 of varying degrees of enrichment. The electromagnetic plant was even more flexible, since each separator unit was practically independent of the other units. The separation process consisted of loading a charge into a unit, running the unit for a while, then stopping it and removing the product. To be sure, the units were built in groups, but most of the controls were separate for each unit. This feature made it possible to build the plant in steps and to start operating the first part even before the second part was begun. It was also possible to change the design of subsequent units as construction proceeded; within limits it was possible even to replace obsolescent units in the early groups with new improved units.

Nature and Organization of Development Work

11.33. 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. In fact, 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.

11.34. Such developments as these required constant interchange of information between laboratory, engineering, construction, and operating groups. Fortunately the liaison was excellent. The companies stationed representatives at Berkeley, and members of the research group at Berkeley paid frequent and prolonged visits to the plant at Clinton. In fact, some of the research men were transferred to the payroll of the Tennessee Eastman Company operating the plant at Clinton, and a group of over one hundred physicists and research engineers still kept on the Berkeley payroll were assigned to Clinton. Particularly in the early stages of operation the Berkeley men stationed at Clinton were invaluable as "trouble shooters" and in instructing operators. A section of the plant continued to be maintained as a pilot unit for testing modified equipment and revised operating procedures, and was run jointly by the Berkeley group and by Tennessee Eastman. In addition to the British group under Oliphant already mentioned, there was a British group of chemists at Clinton under J. W. Baxter.

### Chemical Problems

11.35. Originally, the uranium salts used as sources of vapor for the ion-producing arcs had not been investigated with any very great thoroughness at Berkeley, but as the process developed, a good deal of work was done on these salts, and a search was made for a uranium compound that would be better than that originally used. Some valuable studies were also made on methods of producing the compound chosen.

11.36. By far the most important chemical problem was the recovery of the processed uranium compounds from the separation units. This recovery problem had two phases. In units of the first stage it was essential to recover the separated uranium from the receivers with maximum efficiency; whereas recovery of the scattered unseparated uranium from other parts of the unit was less important. But if higher stage units are used even the starting material contains a high concentration of U-235, and it is essential to recover all the material in the unit at the end of each run, i. e., material remaining in the ion source and material deposited on the accelerating electrodes, on the walls of the magnet chamber, and on the receiver walls.

### The Thermal Diffusion Plant

11.37. For nearly a year the electromagnetic plant was the only one in operation. Therefore the urge to increase its production rate was tremendous. It was realized that any method of enriching -- even slightly enriching -- the material to be fed into the plant would increase the production rate appreciably. For example, an electromagnetic unit that could produce a gram a day of 40 percent pure U-235 from natural uranium could produce two grams a day of 80 percent U-235 if the concentration of U-235 in the feed material was twice the natural concentration (1.4 percent instead of 0.7 percent).

11.38. We have already referred to the work done by P. H. Abelson of the Naval Research Laboratory on the separation of the uranium isotopes by thermal diffusion in liquid compound of uranium. By the spring of 1943 Abelson had set up a pilot plant that accomplished appreciable separation of a considerable quantity of uranium compound. It was therefore proposed that a large-scale thermal diffusion plant should be constructed. Such a plant would be cheaper than any of the other large-scale plants, and it could be built more quickly. Its principal drawback was its enormous consumption of steam, which made it appear impracticable for the whole job of separation.

11.39. Not only was a pilot plant already in operation at the Naval Research Laboratory, but a second, somewhat larger plant was under construction at the Philadelphia Navy Yard. Through the cooperation of the Navy both the services of Abelson and the plans for the large-scale plant were made available to the Manhattan District. It was decided to erect the large-scale thermal diffusion plant at Clinton (using steam from the power plant constructed for the gaseous diffusion plant) and to use the thermal-diffusion-plant product as feed material for the electromagnetic plant.

11.40. This new thermal diffusion plant was erected in amazingly short time during the late summer of 1944. In spite of some disappointments, operation of this plant has succeeded in its purpose of considerably increasing the production rate of the electromagnetic plant. It has also stimulated work on the uranium recovery problem. The future of this plant is uncertain. Operation of the gaseous-diffusion plant makes it difficult to get enough steam to operate the thermal diffusion plant, but also furnishes another user for its product.

Miscellaneous Problems

11.41. Although the scientific and technical problems which confronted the Berkeley groups were probably not as varied or numerous as the problems encountered at Chicago and Columbia, they were nevertheless numerous. Thus many problems arose in the designing of the electric power and control circuits, magnetic fields, insulators, vacuum pumps, tanks, collectors, and sources. Many equipment items had to be designed from scratch and then mass-produced under high priority.

Present Status

11.42. The electromagnetic separation plant was in large-scale operation during the winter of 1944-1945, and produced U-235 of sufficient purity for use in atomic bombs. Its operating efficiency is being continually improved. Research work is continuing although on a reduced scale.

Summary

11.43. In the early days of the uranium project, electromagnetic methods of isotope separation were rejected primarily because of the expected effects of space-charge. In the fall of 1941 the question was reopened; experiments at Berkeley showed that space-charge effects could be largely overcome. Consequently a large-scale program for the development of electromagnetic methods was undertaken.

11.44. Of the various types of electromagnetic methods proposed, the calutron (developed at Berkeley) received principal attention. Two other novel methods were studied, one at Berkeley and one at Princeton. The calutron mass separator consists of an ion source from which a beam of uranium ions is drawn by an electric field, and accelerating system in which the ions are accelerated to high velocities, a magnetic field in which the ions travel in semicircles of radius depending on ion mass, and a receiving system. The principal problems of this method involved the ion source, accelerating system, divergence of the ion beam, space charge, and utilization of the magnetic field. The chief advantages of the calutron were large separation factor, small hold-up, short start-up time, and flexibility of operation. By the fall of 1943 sufficient progress had been made to

justify authorization of plant construction, and a year later the first plant units were ready for trial at the Clinton Engineer Works in Tennessee.

11.45. Research and development work on the calutron were carried out principally at the Radiation Laboratory of the University of California, under the direction of Lawrence. Westinghouse, General Electric, and Allis Chalmers constructed a majority of the parts; Stone and Webster built the plant, and Tennessee Eastman operated it.

11.46. Since the calutron separation method was one of batch operations in a large number of largely independent units, it was possible to introduce important improvements even after plant operation had begun.

11.47. In the summer of 1944 a thermal-diffusion separation plant was built at the Clinton Engineer Works to furnish enriched feed material for the electromagnetic plant and thereby increase the production rate of this latter plant. The design of the thermal-diffusion plant was based on the results of research carried out at the Naval Research Laboratory and on the pilot plant built by the Navy Department at the Philadelphia Navy Yard.

11.48. 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.



## CHAPTER XII

THE WORK ON THE ATOMIC BOMBThe Objectives

12.1. The entire purpose of the work described in the preceding chapters was to explore the possibility of creating atomic bombs and to produce the concentrated fissionable materials which would be required in such bombs. In the present chapter, the last stage of the work will be described-- the development at Los Alamos of the atomic bomb itself. As in other parts of the project, there are two phases to be considered: the organization, and the scientific and technical work itself. The organization will be described briefly; the remainder of the chapter will be devoted to the scientific and technical problems. Naturally, security considerations prevent a discussion of many of the most important phases of this work.

History and Organization

12.2. The project reorganization that occurred at the beginning of 1942, and the subsequent gradual transfer of the work from OSRD auspices to the Manhattan District have been described in Chapter V. It will be recalled that 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 got various laboratories (see Chapter VI, paragraph 6.33) started on the experimental study of problems that had to be solved before progress could be made on bomb design. As has been mentioned in Chapter VI, J. R. Oppenheimer of the University of California gathered a group together in the summer of 1942 for further theoretical investigation and also undertook to coordinate this experimental work. This work was officially under the Metallurgical Laboratory but the theoretical group did most of its work 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.

12.3. In the choice of a site for this 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.

12.4. By November 1942 a site had been chosen -- at Los Alamos, New Mexico. It was located on a mesa about 20 miles from Santa Fe. One asset of this site was the availability of considerable area for proving grounds, but initially the only structures on the site consisted of a handful of buildings which once constituted a small boarding school. There was no laboratory, no library, no shop, no adequate power plant. The sole means of

approach 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.

12.5. J. R. Oppenheimer has been 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.

12.6. Naturally, the task of assembling the necessary apparatus, machines, and equipment was an enormous one. 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, 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.

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

### State of Knowledge in April 1943

#### General Discussion of the Problem

12.8. In Chapter II we stated 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 taken for granted that the chain-reacting system must not blow up. Now we want to consider how to make it blow up.

12.9. 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 expanded before a substantial fraction of the available nuclear energy has been released. (For expansion leads to increased escape of the 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 (a) the speed with which neutrons generated by the first fissions get into other nuclei and produce further fission, and (b) 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.

12.10. In earlier chapters 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 micro-seconds) 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.

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

#### Critical Size

12.12. The calculation of the critical size of a chain-reacting unit is a problem that has already been discussed in connection with 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 all 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 using various methods of calculation and using the best available nuclear constants, but the limits of error remained large.

#### The Reflector or Tamper

12.13. 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

12.14. 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.

12.15. 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

12.16. As stated in Chapter II, it is impossible to prevent a chain reaction from occurring when the size exceeds the critical size. For there are always enough neutrons (from cosmic rays, from 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 one 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 two-fold: (1) to reduce the time of assembly to a minimum; and (2) to reduce the number of stray (pre-detonation) neutrons to a minimum.

12.17. 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

12.18. In Chapters II and IV it was pointed out that the amount of energy released was not the sole criterion of the value of a bomb. There was no assurance that one uranium bomb releasing energy equal to the energy 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



holds the total amount of energy released per kilogram of fissionable material (i.e., 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 the matter further is the advantage of 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

12.19. Since estimates had been made of the speed that would bring together subcritical masses of U-235 rapidly enough to avoid predetonation, a good deal of 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.

12.20. 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

12.21. 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 using only minute quantities until larger quantities became available.

12.22. Besides these problems in theoretical and experimental physics, there was a host of chemical, metallurgical, and technical problems that had hardly been touched. Examples were the purification and fabrication of U-235 and plutonium, and the fabrication of the tamper. Finally, there were problems of instantaneous assembly of the bomb that were staggering in their complexity.

### The Work of the Laboratory

#### Introduction

12.23. For administrative purposes the scientific staff at Los

Alamos was arranged in seven divisions, which have been 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 the divisions reported to J. R. Oppenheimer, Director of the Los Alamos Laboratory who has been assisted in coordinating the research by S. K. Allison since December 1944. 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

12.24. 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 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.

12.25. 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 naive analogy had to be forsaken. In the early theoretical work the assumptions were made that the neutrons all had the same velocity and 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 secondly 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.

12.26. 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.

12.27. Techniques were developed for dealing with set-ups in which the number of 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 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.

12.28. A great deal of theoretical work was done on the equation of state of matter at the high temperatures and 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.

12.29. 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, etc.

12.30. In addition to all the work mentioned above, a considerable amount of work 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 subcritical amounts of fissionable material.

#### Experimental Nuclear Physics Division

12.31. 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.

12.32. 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 the following:

1. What are the fission cross sections of U-234, U-235, U-238, Pu-239, etc.? 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?

12.33. 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 their final device. 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.

12.34. Experimental Methods. The earlier chapters contain little or no discussion of experimental techniques except those for the observing of fast (charged) particles (See Appendix I.). 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, e.g., artificial radioactivity.

We shall indicate briefly how such observations are made.



12.35. 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 using electroscopes, ionization chambers, Geiger-Müller counters, Wilson cloud chambers, tracks in photographic emulsion, etc.

12.36. 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, its degree of radioactivity 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.

12.37. One elegant 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, i.e., 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 a considerable distance from the source (several feet or yards from it). 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 (e.g., 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 travelled from the source in a certain time interval. In other words, the measured effects are due only to the neutrons having the appropriate velocity.

12.38. 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  $\text{Li}^7(p,n)\text{Be}^8$  reaction absorbs 1.6 Mev energy since the product particles are heavier than the initial particles. Any further energy of the incident protons 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.

12.39. 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).

12.40. 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 (i.e., very low speed) or nearly thermal neutrons.

12.41. 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.

12.42. 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.

12.43. 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, e.g., 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.

12.44. 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  $\text{Li}^7(p,n)\text{Be}^7$  reaction, so as to produce neutrons of any desired energy lying in the range from 3000 electron volts to two million electron volts. 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 began to be received. On the whole, the values of cross section for fission as a function of neutron energy from practically zero electron volts to three million electron volts is now fairly

well known for these materials.

12.45. 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. The purpose was to provide verification of the effects predicted for reacting systems containing enriched U-235. The results were very nearly as expected.

12.46. 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 using 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.

12.47. 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 three million electron volts. In other words, questions 1,2,3,4, and 5 of the ten 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

12.48. 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, etc., and for various other matters. In all this division's work on enriched fissionable materials special 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

12.49. The above account of the work of the Theoretical Physics, Experimental Nuclear Physics, and Chemistry and Metallurgy Divisions is somewhat 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

19.50. 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.



## CHAPTER XIII

GENERAL SUMMARYPresent Overall Status

13.1. 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 finds us expecting from day to day to hear of the explosion of the first atomic bomb devised by man. All the problems are believed to have been solved at least well enough to make a bomb practicable. A sustained neutron chain reaction resulting from nuclear fission has been demonstrated; the conditions necessary to cause such a reaction to occur explosively have been established and can be achieved; production plants of several different types are in operation, building up a stock pile of the explosive material. Although we do not know when the first explosion will occur nor how effective it will be, announcement of its occurrence will precede the publication of this report. Even if the first attempt is relatively ineffective, there is little doubt that later efforts will be highly effective; the devastation from a single bomb is expected to be comparable to that of a major air raid by usual methods.

13.2. A weapon has been developed that is potentially destructive beyond the wildest nightmares of the 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. This weapon has been created not by the devilish inspiration of some warped genius but by the arduous labor of thousands of normal men and women working for the safety of their country. Many of the principles that have been used were well known to the international scientific world in 1940. To develop the necessary industrial processes from these principles has been costly in time, effort, and money, but the processes which we selected for serious effort have worked and several that we have not chosen could probably be made to work. We have an initial advantage in time 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.

13.3. Before the surrender of Germany there was always a chance that German scientists and engineers might be developing atomic bombs which would be sufficiently effective to alter the course of the war. There was therefore no choice but to work on them in this country. Initially many scientists could and did hope that some principle would emerge which would prove that atomic bombs were inherently impossible. This hope was faded gradually; fortunately in the same period the magnitude of the necessary industrial effort has been demonstrated so that the fear of German success weakened even before the end came. By the same token, most of us are certain that the Japanese cannot develop and use this weapon effectively.

Prognostication

13.4. 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.

13.5. 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

13.6. During the war the effort has been to achieve the maximum military results. It has been apparent for some time that some sort of government control and support in the field of nuclear energy must continue after the war. Many of the men associated with the project have recognized this fact and have come 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 is now engaged in formulating plans for a continuing organization. This committee is also discussing matters of general policy about which many of the more thoughtful men on the project have been deeply concerned since the work was begun and especially since success became more and more probable.

The Questions before the People

13.7. We find ourselves with an explosive which is far from 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.

13.8. Because of the restrictions of military security there has been no chance for the Congress or the people to debate such questions. They 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. This is one reason for the release of this report. It is a semi-technical report which it is hoped men of science in this country can use to help their fellow citizens in reaching wise decisions. The people of the country must be informed if they are to discharge their responsibilities wisely.

## APPENDIX 1

METHODS OF OBSERVING FAST PARTICLES FROM NUCLEAR REACTIONS

In Chapter I we pointed out the importance of ionization in the study of radioactivity and mentioned the electroscope. In this appendix we shall mention one method of historical importance comparable with the electroscope but no longer used, and then we shall review the various methods now in use for observing alpha particles, beta particles (or positrons), gamma rays, and neutrons, or their effects.

Scintillations

The closest approach that can be made to "seeing" an atom is to see the bright flash of light that an alpha particle or high-speed proton makes when it strikes a fluorescent screen. All that is required is a piece of glass covered with zinc sulphide, a low-power microscope, a dark room, a well-rested eye, and of course a source of alpha particles. Most of Rutherford's famous experiments, including that mentioned in paragraph 1.17, involved "counting" scintillations but the method is tedious and, as far as the author knows, has been entirely superseded by electrical methods.

The Process of Ionization

When a high-speed charged particle like an alpha particle or a high-speed electron passes through matter, it disrupts the molecules that it strikes by reason of the electrical forces between the charged particle and the electrons in the molecule. If the material is gaseous, the resultant fragments or ions may move apart and, if there is an electric field present, the electrons knocked out of the molecules move in one direction and the residual positive ions in another direction. An initial beta particle with a million electron volts energy will produce some 18,000 ionized atoms before it is stopped completely since on the average it uses up about 60 volts energy in each ionizing collision. Since each ionization process gives both a positive and a negative ion, there is a total of 36,000 charges set free by one high-speed electron, but since each charge is only  $1.6 \times 10^{-19}$  coulomb, the total is only about  $6 \times 10^{-15}$  coulomb and is still very minute. The best galvanometer can be made to measure a charge of about  $10^{-10}$  coulomb. It is possible to push the sensitivity of an electrometer to about  $10^{-16}$  coulomb, but the electrometer is a very inconvenient instrument to use.

An alpha particle produces amounts of ionization comparable with the beta particle. It is stopped more rapidly, but it produces more ions per unit of path. A gamma ray is much less efficient as an ionizer since the process is quite different. It does occasionally set free an electron from



a molecule by Compton scattering or the photoelectric effect, and this secondary electron has enough energy to produce ionization. A neutron, as we have already mentioned in the text, produces ionization only indirectly by giving high velocity to a nucleus by elastic collision, or by disrupting a nucleus with resultant ionization by the fragments.

If we are to detect the ionizing effects of these particles, we must evidently use the resultant effect of a great many particles or have very sensitive means of measuring electric currents.

### The Electroscope

Essentially the electroscope determines to what degree the air immediately around it has become conducting as the result of the ions produced in it.

The simplest form of electroscope is a strip of gold leaf a few centimeters long, suspended by a hinge from a vertical insulated rod. If the rod is charged, the gold leaf also takes up the same charge and stands out at an angle as a result of the repulsion of like charges. As the charge leaks away, the leaf gradually swings down against the rod, and the rate at which it moves is a measure of the conductivity of the air surrounding it.

A more rugged form of electroscope was devised by C. C. Lauritsen, who substituted a quartz fiber for the gold leaf and used the elasticity of the fiber as the restoring force instead of gravity. The fiber is made conducting by a thin coating of metal. Again the instrument is charged, and the fiber, after initial deflection, gradually comes back to its uncharged position. The position of the fiber is read in a low-power microscope. These instruments can be made portable and rugged and fairly sensitive. They are the standard field instrument for testing the level of gamma radiation, particularly as a safeguard against dangerous exposure.

### Ionization Chambers

An ionization chamber measures the total number of ions produced directly in it. It usually consists of two plane electrodes between which there is a strong enough electric field to draw all the ions to the electrodes before they recombine but not strong enough to produce secondary ions as in the instruments we shall describe presently.

By careful design and the use of sensitive amplifiers an ionization chamber can measure a number of ions as low as that produced by a single alpha particle, or it can be used much like an electroscope to measure the total amount of ionizing radiation present instantaneously, or it can be arranged to give the total amount of ionization that has occurred over a

period of time.

### Proportional Counters

While ionization chambers can be made which will respond to single alpha particles, it is far more convenient to use a self-amplifying device, that is, to make the ions originally produced make other ions in the same region so that the amplifier circuits need not be so sensitive.

In a proportional counter one of the electrodes is a fine wire along the axis of the second electrode, which is a hollow cylinder. The effect of the wire is to give a strong electric field strengths close to it even for relatively small potential differences between it and the other electrode. This strong field quickly accelerates the primary ions formed by the alpha or beta particle or photon, and these accelerated primary ions (particularly the electrons) in turn form secondary ions in the gas with which the counter is filled so that the total pulse of current is much increased.

It is possible to design and operate such counters in such a way that the total number of ions formed is proportional to the number of primary ions formed. Thus after amplification a current pulse can be seen on an oscilloscope, the height of which will indicate how effective an ionizer the initial particle was. It is quite easy to distinguish in this way between alpha particles and beta particles and photons, and the circuits can be arranged to count only the pulses of greater than a chosen magnitude. Thus a proportional counter can count alpha particles against a background of betas or can even count only the alpha particles having more than a certain energy.

### Geiger-Mueller Counters

If the voltage on a proportional counter is raised, there comes a point when the primary ions from a single alpha particle, beta particle, or photon will set off a discharge through the whole counter, not merely multiply the number of primary ions in the region where they are produced. This is a trigger action and the current is independent of the number of ions produced; furthermore, the current would continue indefinitely if no steps were taken to quench it. Quenching can be achieved entirely by arranging the external circuits so that the voltage drops as soon as current passes or by using a mixture of gases in the counter which "poison" the electrode surface as soon as the discharge passes and temporarily prevent the further emission of electrons, or by combining both methods.

The Geiger-Mueller counter was developed before the proportional counter and remains the most sensitive instrument for detecting ionizing radiation, but all it does is "count" any ionizing radiation that passes

through it whether it be an alpha particle, proton, electron, or photon.

### The Art of Counter Measurements

It is one thing to describe the various principles of ionization chambers, counters, and the like; quite another to construct and operate them successfully.

First of all, the walls of the counter chamber must allow the particles to enter the counter. For gamma rays this is a minor problem, but for relatively low-speed electrons or positrons or for alpha particles the walls of the counter must be very thin or there must be thin windows.

Then there are great variations in the details of the counter itself, spacing and size of electrodes, nature of the gas filling the chamber, its pressure, and so on.

Finally, the interpretation of the resultant data is a tricky business. The absorption of the counter walls and of any external absorbers must be taken into account; the geometry of the counter with relation to the source must be estimated to translate observed counts into actual number of nuclear events; last but not always least, statistical fluctuations must be considered since all nuclear reactions are governed by probability laws.

### The Wilson Cloud Chamber

There is one method of observing nuclear particles that depends directly on ionization but is not an electrical method. It uses the fact that supersaturated vapor will condense more readily on ions than on neutral molecules. If air saturated with water vapor is cooled by expansion just after an alpha particle has passed through it, tiny drops of water condense on the ions formed by the alpha particle and will reflect a bright light strongly enough to be seen or photographed so that the actual path of the alpha particle is recorded.

This method developed by C. T. R. Wilson in Cambridge, England, about 1912 has been enormously useful in studying the behavior of individual particles, alphas, protons, electrons, positrons, mesotrons, photons, and the fast atoms caused by collisions with alphas, protons, or neutrons. Unlike the scintillation method, its companion tool for many years, it has not been superseded and is still used extensively, particularly to study details of collisions between nuclear particles and atoms.

### The Photographic Method

The tracks of individual particles passing through matter can also be observed in photographic emulsions, but the lengths of path are so small that they must be observed under a microscope, where they appear as a series of developed grains marking the passage of the particle. This method of observation requires practically no equipment but is tedious and of limited usefulness. It is possible, however, to use the general blackening of a photographic film as a measure of total exposure to radiation, a procedure that has been used to supplement or to replace electroscopes for safety control in many parts of the project.

### The Observation and Measurement of Neutrons

None of the methods we have described are directly applicable to neutrons, but all of them are indirectly applicable since neutrons produce ions indirectly. This happens in two ways -- by elastic collision and by nuclear reaction. As we have already described, a fast neutron in passing through matter occasionally approaches an atomic nucleus so closely as to impart to it a large amount of momentum and energy according to the laws of elastic collision. The nucleus thereby becomes a high-speed charged particle which will produce ionization in an ionization chamber, counter, or cloud chamber. But if the neutron has low speed, e.g., thermal, the struck nucleus will not get enough energy to cause ionization. If, on the other hand, the neutron is absorbed and the resultant nucleus breaks up with the release of energy, ionization will be produced. Thus, for the detection of high-speed neutrons one has a choice between elastic collisions and nuclear reaction, but for thermal speeds only nuclear reaction will serve.

The reaction most commonly used is the  ${}^5\text{B}^{10}(n,\alpha){}^3\text{Li}^7$  reaction which releases about 2.5 Mev energy shared between the resultant alpha particle and  ${}^3\text{Li}^7$  nucleus. This is ample to produce ionization. This reaction is used by filling an ionization chamber or proportional counter with boron trifluoride gas so that the reaction occurs in the region where ionization is wanted; as an alternative the interior of the chamber or counter is lined with boron. The ionization chamber then serves as an instrument to measure overall neutron flux while the proportional counter records numbers of individual neutrons.

One of the most valuable methods of measuring neutron densities by nuclear reactions depends on the production of artificial radioactive nuclei. A foil known to be made radioactive by neutron bombardment is inserted at a point where the neutron intensity is wanted. After a given time it is removed and its activity measured by an electroscope or counter. The degree of activity that has been built up is then a measure of the number of neutrons that have been absorbed. This method has the obvious disadvantage that it does not give an instantaneous response as do the ionization chamber and counter.



One of the most interesting methods developed on the project is to use the fission of uranium as the nuclear reaction for neutron detection. Furthermore, by separating the isotopes, fast and slow neutrons can be differentiated.

Since the probability of a neutron reaction occurring is different for every reaction and for every neutron speed, difficulties of translating counts or current measurements into numbers and speeds of neutrons present are even greater than for other nuclear particles. No one need be surprised if two able investigators give different numbers for supposedly the same nuclear constant. It is only by an intricate series of interlocking experiments carefully compared and interpreted that the fundamental facts can be untangled from experimental and instrumental variables.

## APPENDIX 2

THE UNITS OF MASS, CHARGE AND ENERGYMass

Since the proton and the neutron are the fundamental particles out of which all nuclei are built, it would seem natural to use the mass of one or the other of them as a unit of mass. The choice would probably be the proton, which is the nucleus of a hydrogen atom. There are good reasons, historical and otherwise, why neither the proton nor the neutron was chosen. Instead, the mass unit used in atomic and nuclear physics is one sixteenth of the mass of the predominant oxygen isotope,  $O^{16}$ , and is equal to  $1.6603 \times 10^{-24}$  gram. Expressed in terms of this unit, the mass of the proton is 1.00758 and the mass of the neutron is 1.00893. (Chemists usually use a very slightly different unit of mass.)

Charge

The unit of electric charge used in nuclear science is the positive charge of the proton. It is equal in magnitude but opposite in sign to the charge on the electron and is therefore often called the electronic charge. One electronic charge is  $1.60 \times 10^{-19}$  coulomb. It may be recalled that a current of one ampere flowing for one second conveys a charge of one coulomb; i.e., one electronic charge equals  $1.60 \times 10^{-19}$  ampere second.

Energy

The energy unit used in nuclear physics is the electron volt, which is defined as equal to the kinetic energy which a particle carrying one electronic charge acquires in falling freely through a potential drop of one volt. It is often convenient to use the million-times greater unit: million electron volt (Mev).

The relationships among the electron volt and other common units of energy are in the following table:

Conversion Table for Energy Units

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
Mev	$1.07 \times 10^{-3}$	mass units
	$1.60 \times 10^{-6}$	ergs
	$3.83 \times 10^{-14}$	g. cal.
	$4.45 \times 10^{-20}$	kw. hrs.
mass units	$9.31 \times 10^2$	Mev
	$1.49 \times 10^{-3}$	ergs
	$3.56 \times 10^{-11}$	g. cal.
	$4.15 \times 10^{-17}$	kw. hrs.
ergs	$6.71 \times 10^2$	mass units
	$6.24 \times 10^5$	Mev
	$2.39 \times 10^{-8}$	g. cal.
	$2.78 \times 10^{-14}$	kw. hrs.
g. cal.	$2.81 \times 10^{10}$	mass units
	$2.62 \times 10^{13}$	Mev
	$4.18 \times 10^7$	ergs
	$1.16 \times 10^{-6}$	kw. hrs.
kw. hrs.	$2.41 \times 10^{16}$	mass units
	$2.25 \times 10^{19}$	Mev
	$3.60 \times 10^{13}$	ergs
	$8.60 \times 10^5$	g. cal.

## APPENDIX 3

DELAYED NEUTRONS FROM URANIUM FISSION

As was pointed out in Chapter VI, the control of a chain-reacting pile is greatly facilitated by the fact that some of the neutrons resulting from uranium fission are not emitted until more than a second after fission occurs. It was therefore important to study this effect experimentally. Such experiments were described by Snell, Madzel and Ibsen in a report dated May 15, 1942 from which we quote as follows:

The present experiment consists of two interrelated parts--one concerned with the decay curve, and one concerned with the intensity of the delayed neutrons measured in terms of that of the "instantaneous" fission neutrons.

The Decay Curve of the Delayed Neutrons

The neutron source was the beryllium target of the University of Chicago cyclotron struck by a beam of up to 20  $\mu$ A of 8 Mev deuterons. Near the target was placed a hollow shell made of thinned iron and containing 106 lbs. of  $U_2O_3$ . This was surrounded by about 2" of paraffin. The interior of the shell was filled with paraffin, except for an axial hole which accommodated a  $BF_3$ -filled proportional counter. The counter was connected through an amplifier to a scaling circuit ("scale of 64") equipped with interpolating lights and a Cenco impulse counter. A tenth-second timer, driver by a synchronous motor, and hundredth-second stop watch were mounted on the panel of the scaler, close to the interpolating lights and impulse counter. This group of dials and lights was photographed at an appropriately varying rate by a Sept camera which was actuated by hand. The result was a record on movie film of times and counts, from which the decay curves were plotted.

The actual procedure was as follows: During bombardment the stop watch was started and the timer was running continuously; the counter and amplifier were on, but the pulses leaving the amplifier were grounded. The scaler was set at zero. After a warning signal the cyclotron was shut off by one operator, while another operator switched the output of the amplifier from ground into the scaler, and started taking photographs. It was easy to take the first photograph within half a second of turning off the cyclotron. Sixty to a hundred photographs were taken during a typical run. The necessity of using both a stop watch and a timer arose from the fact that the hundredth-second precision of the stop watch was needed for the small time intervals between photographs during the initial part of the run, but the watch ran down and stopped before the counting was complete. The timer then gave sufficient precision for the later time intervals.



Some forty runs were taken under varying experimental conditions. Short activations of one or two seconds were given for best resolution of the short periods. Long, intense bombardments lasting 15-20 minutes, as close as possible to the target, were made to make the long period activities show up with a maximum intensity. Some 5-minute bombardments were made, keeping the cyclotron beam as steady as possible, to study the relative saturation intensities of the various activities; in these activations the cyclotron beam was reduced to 1 or 2  $\mu$ A to prevent the initial counting rate from becoming too high for a counter (300 per sec. was taken as a reasonable upper limit for reliable counting). Two  $\text{BF}_3$  counters were available, one having a thermal neutron cross section of 2.66 sq. cm., and the other 0.43 sq. cm. After a strong activation, we could follow the decay of the delayed neutrons for some 13 minutes. Background counts (presumably chiefly due to spontaneous fission neutrons) were taken and were subtracted from the readings. They amounted to about 0.4 counts per sec. for the large counter.

A study of all the decay curves gives the following as a general picture of the neutron-emitting activities present:

TABLE 1

<u>Half-life</u>	<u>Relative initial intensity activated to saturation</u>
57 $\pm$ 3 sec.	0.135
24 $\pm$ 2 sec.	1.0
7 sec.	1.2
2.5 sec.	1.2

Any activity of period longer than 57 sec. failed to appear even after the most intense bombardment we could give, lasting 20 minutes. The relative initial intensities given are the average values obtained from three curves.

These results give the following equation for the decay curve, of the delayed neutrons after activation to saturation:

$$\text{Activity} = \text{constant} (1.2e^{-0.28t} + 1.2e^{-0.099t} + 1.0e^{-0.029t} + 0.135e^{-0.012t})$$

where  $t$  is in seconds.

The second part of the experiment measured the total number of neutrons emitted in the time interval 0.01 sec. to 2.0 min. after the cyclotron was turned off. Assuming that all the delayed neutrons observed were in the four groups measured in the first part of the experiment, this second result indicated that  $1.0 \pm 0.2$  per cent of the neutrons emitted in uranium fission are delayed by at least 0.01 sec. and that about 0.07 per cent are

delayed by as much as a minute. By designing the effective value of  $k$ , the multiplication factor, for a typical operating pile to be only 1.01 with all the controls removed and the total variation in  $k$  from one control rod to be 0.002, the number of delayed neutrons is sufficient to allow easy control.

## APPENDIX 4

THE FIRST SELF-SUSTAINING CHAIN-REACTING PILE

In Chapter VI the construction and operation of the first self-sustaining chain-reacting pile were described briefly. Though details must still be withheld for security reasons, the following paragraphs give a somewhat fuller description based on a report by Fermi. This pile was erected by Fermi and his collaborators in the fall of 1942.

Description of the Pile. The original plan called for an approximately spherical pile with the best materials near the center. Actually control measurements showed that the critical size had been reached before the sphere was complete, and the construction was modified accordingly. The final structure may be roughly described as an oblate spheroid flattened at the top, i.e., like a door knob. It was desired to have the uranium or uranium oxide lumps spaced in a cubic lattice imbedded in graphite. Consequently, the graphite was cut in bricks and built up in layers, alternate ones of which contained lumps of uranium at the corners of squares. The critical size was reached when the pile had been built to a height only three quarters of that needed according to the most cautious estimates. Consequently only one more layer was added. The graphite used was chiefly from the National Carbon Company and the Speer Graphite Company. The pile contained 12,400 lbs. of metal, part of which was supplied by Westinghouse, part by Metal Hydrides, and part by Ames. Since there were many more lattice points than lumps of metal, the remaining ones were filled with pressed oxide lumps.

For purposes of control and experiment there were ten slots passing completely through the pile. Three of those near the center were used for control and safety rods. Further to facilitate experiment, particularly the removal of samples, one row of bricks carrying uranium and passing near the center of the pile was arranged so that it could be pushed completely out of the pile.

This whole graphite sphere was supported by a timber framework resting on the floor of a squash court under the West Stands of Stagg Field.

Predicted Performance of the Pile. The metal lattice at the center of the pile and the two other major lattices making up the bulk of the rest of the pile had each been studied separately in exponential experiments #18, #27, and #29. These had given a multiplication factor of 1.07 for the metal lattice and 1.04 and 1.03 for the oxide lattices, the difference in the last two resulting from difference in the grade of graphite used. It is to be remembered that these figures are multiplication factors for lattices of infinite size. Therefore a prediction of the actual effective multiplication factor  $k_{\text{eff}}$  for the pile as constructed depended on the validity of the deduction of  $k$  from the exponential experiments, on a proper averaging for the different lattices, and on a proper deduction of  $k_{\text{eff}}$  from the average  $k$  for infinite size. Although the original design of

the pile had been deliberately generous, its success when only partly completed indicated that the values of the multiplication factors as calculated from exponential experiments had been too low. The observed effective multiplication factor of the part of the planned structure actually built was about 1.0006 when all neutron absorbers were removed.

Measurements Performed during Construction. A series of measurements was made while the pile was being assembled in order to be sure that the critical dimensions were not reached inadvertently. These measurements served also to check the neutron multiplication properties of the structure during assembly, making possible a prediction of where the critical point would be reached.

In general, any detector of neutrons or gamma radiation can be used for measuring the intensity of the reaction. Neutron detectors are somewhat preferable since they give response more quickly and are not affected by fission-product radiations after shut down. Actually both neutron detectors (boron trifluoride counters) and gamma-ray ionization chambers were distributed in and around the pile. Certain of the ionization chambers were used to operate recording instruments and automatic safety controls.

In the pile itself measurements were made with two types of detector. A boron trifluoride counter was inserted in a slot about 43" from the ground and its readings taken at frequent intervals. In addition, an indium foil was irradiated every night in a position as close as possible to the effective center of the pile, and its induced activity was measured the following morning and compared with the readings of the boron trifluoride counter.

The results of such measurements can be expressed in two ways. Since the number of secondary neutrons produced by fission will increase steadily as the pile is constructed, the activity  $A$  induced in a standard indium foil at the center will increase steadily as the number of layers of the pile is increased. Once the effective multiplication factor is above one,  $A$  would theoretically increase to infinity. Such an approach to infinity is hard to observe, so a second way of expressing the results was used. Suppose the lattice spacing and purity of materials of a graphite-uranium structure are such that the multiplication factor would be exactly one if the structure were a sphere of infinite radius. Then, for an actual sphere of similar construction but finite radius, the activation of a detector placed at the center would be proportional to the square of the radius. It was possible to determine a corresponding effective radius  $R_{eff}$  for the real pile in each of its various stages. It followed, therefore, that, if the factor  $k_{00}$  were precisely one on the average for the lattice in the pile, the activity  $A$  of the detector at the center should increase with increasing  $R_{eff}$  in such a way that  $R_{eff}^2/A$  remained constant, but, if  $k_{00}$  for the lattice were greater than one, then as the pile size approached the critical value, that is, as  $k_{eff}$  approached one,  $A$  should approach infinity and therefore  $R_{eff}^2/A$  approach zero. Therefore by extrapolating a curve of  $R_{eff}^2/A$  vs. size of the pile, i.e., number of layers, to where it cut the axis, it was possible to predict at what layer  $k_{eff}$  would become one. Such



a curve, shown in Fig. 1, indicated at what layer the critical size would be reached. The less useful but more direct and dramatic way of recording the results is shown in Fig. 2, which shows the growth of the neutron activity of the pile as layers were added.

During the construction, appreciably before reaching this critical layer, some cadmium strips were inserted in suitable slots. They were removed once every day with the proper precautions in order to check the approach to the critical conditions. The construction was carried in this way to the critical layer.

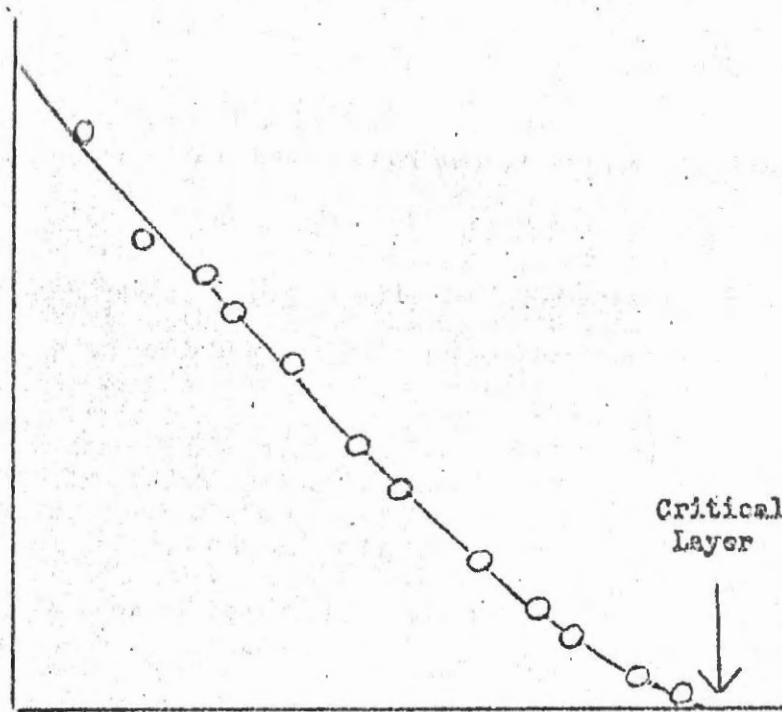
Control. The reaction was controlled by inserting in the pile some strips of neutron absorbing material -- cadmium or boron steel. When the pile was not in operation, several such cadmium strips were inserted in a number of slots, bringing the effective multiplication factor considerably below one. In fact, any one of the cadmium strips alone was sufficient to bring the pile below the critical condition. Besides cadmium strips that could be used for manual operation of the pile, two safety rods and one automatic control rod were provided. The automatic control rod was operated by two electric motors responding to an ionization chamber and amplifying system so that, if the intensity of the reaction increased above the desired level, the rod was pushed in, and vice versa.

Operation of the Pile. To operate the pile all but one of the cadmium strips were taken out. The remaining one was then slowly pulled out. As the critical conditions were approached, the intensity of the neutrons emitted by the pile began to increase rapidly. It should be noticed, however, that, when this last strip of cadmium was so far inside the pile that the effective multiplication factor was just below one, it took a rather long time for the intensity to reach the saturation value. Similarly, if the cadmium strip was just far enough out to make  $k_{eff}$  greater than one, the intensity rose at a rather slow rate. For example, if one rod is only 1 cm. out from the critical position, the "relaxation time," i.e., the time for the intensity to double, is about four hours. These long "relaxation times" were the result of the small percentage of delayed neutrons which have been discussed in Appendix 3, and make it relatively easy to keep the pile operating at a constant level of intensity.

The pile was first operated on December 2, 1942 to a maximum energy production of about 1/2 watt. On December 12th the intensity was run up to about 200 watts, but it was not felt safe to go higher because of the danger of the radiation to personnel in and around the building. During this high intensity run, measurements were made of radiation intensity beside the pile, in the building, and on the sidewalk outside.

16 4

$$\frac{2}{A} \frac{N_{eff}}{A}$$



Number of Completed Layers

Figure 1

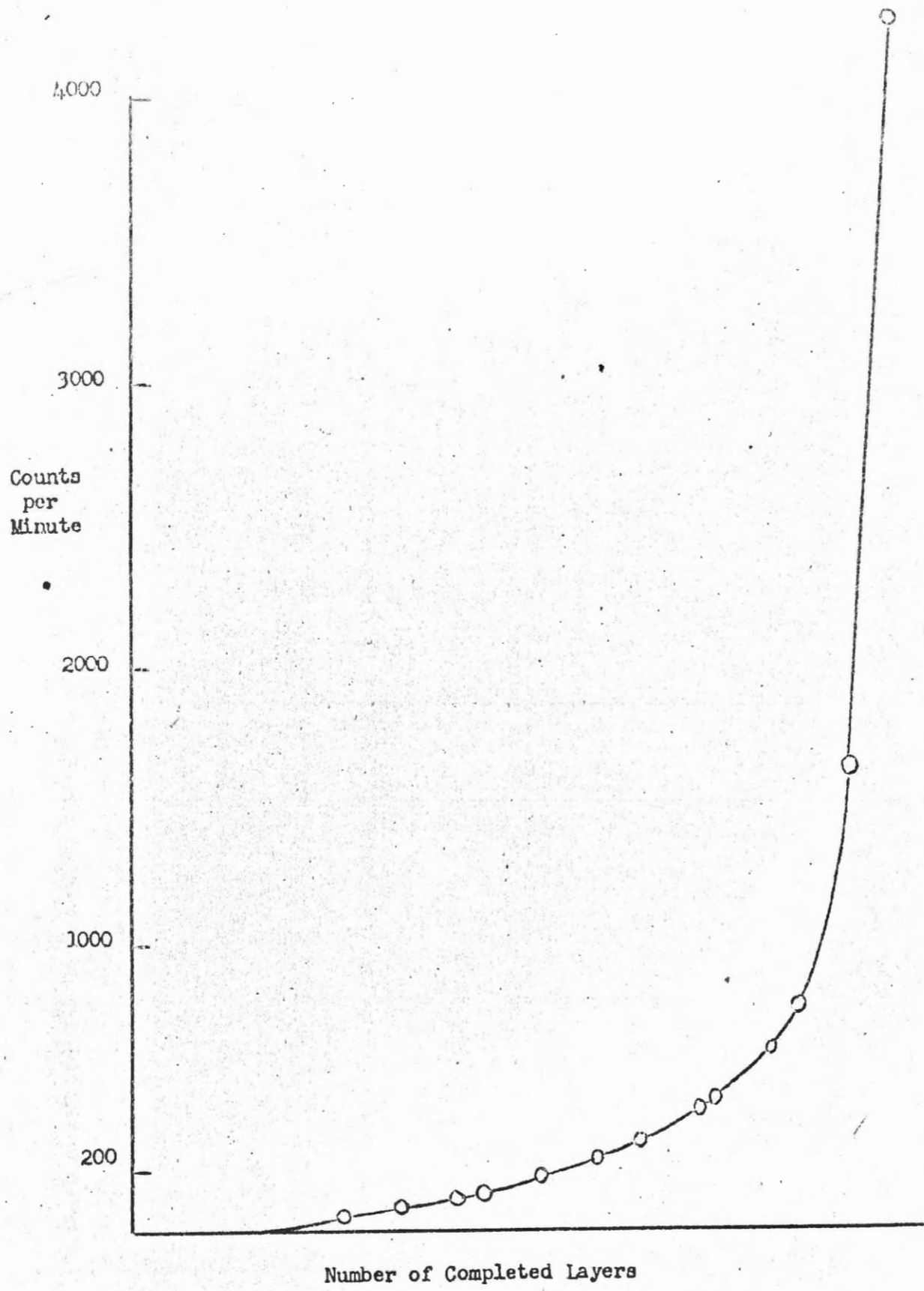


Figure 2

APPENDIX 5

SAMPLE LIST OF REPORTS

Presented below is a list of titles of representative reports prepared in the Metallurgical Laboratory of the University of Chicago in 1942.

A Table for Calculating the Percentage Loss Due to the Presence of Impurities in Alloy

Concerning the Radium-Beryllium Neutron Sources

Preliminary Estimates of the Radiations from Fission Products

Background of Natural Neutrons in Multiplying Pile

Absorption Cross Sections for Rn plus Ec Fast Neutrons

On Mechanical Stresses Produced by Temperature Gradients in Rods and Spheres

Effect of Geometry on Resonance Absorption of Neutrons by Uranium

Protection against Radiations

Planning Experiments on Liquid Cooling

Report on the Possibility of Purifying Uranium by Carbonyl Formation and Decomposition

On the Radioactivity of Cooling Helium

Estimation of Stability of Ether under Various Conditions of Irradiation

Uranium Poisoning

Transuranic and Fission Product Activities

Chemical Effects of Radiation on Air Surrounding the Pile

An Estimate of the Chemical Effects of Radiation on the Cooling Water in the Pile

The Extraction Method of Purification of Uranyl Nitrate

The Diffusion of Fission Products from Cast Metal at 600°C and 1000°C