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STATEMENTS RELATING TO THE ATOMIC BOMB

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CONTENTS

A. STATEMENTS BY THE PRIME MINISTER AND MR. CHURCHILL ISSUED ON MONDAY, AUGUST 6TH, 1945 ... ... pages 3 to 5

B. STATEMENT ISSUED BY THE DIRECTORATE OF TUBE ALLOYS (DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH) ON SUNDAY, AUGUST 12TH, 1945 ... ... pages 5 to 23

Page

I. INTRODUCTION 5

II. HISTORICAL SURVEY 6

(*a*) Radio-activity 6

(*b*) Artificial Disintegration of Atoms 8

(*c*) Discovery of the Neutron 10

(*d*) Discovery of Fission 11

(*e*) Chain Reaction and the Atomic Bomb 13

III. THE REALISATION OF THE ATOMIC BOMB. BRITISH ACTIVITIES AND ORGANISATION 15

(*a*) Professor Sir George Thomson's Committee 15

(*b*) Directorate of Tube Alloys, D.S.I.R. 18

(*c*) Visit of U.S. Mission to Britain, November 1941 18

(*d*) Visit of British T.A. Mission to U.S.A., February–April 1942 18

(*e*) British T.A. Programme 19

(i) Location of work 19

(ii) Co-ordination of Programmes 21

(iii) Research Contracts. Patents 22

(*f*) Joint British–Canadian–American Slow-Neutron Project in Canada ... 22

(*g*) Transfer of British T.A. Research Groups to U.S.A. 23

A—STATEMENTS BY THE PRIME MINISTER AND MR. CHURCHILL ISSUED ON MONDAY, AUGUST 6th, 1945.

Statement by The Prime Minister.

1. Everybody will have seen the important statements which have been made by President Truman and by Mr. Stimson, the United States Secretary for War, about the atomic bomb. The problems of the release of energy by atomic fission have been solved and an atomic bomb has been dropped on Japan by the United States Army Air Force.

2. President Truman and Mr. Stimson have described in their statements the nature and vast implications of this new discovery. Some account is now required of the part which this country has played in the remarkable scientific advances which have now come to fruition. Before the change of Government Mr. Churchill had prepared the statement which follows and I am now issuing it in the form in which he wrote it.

Statement by Mr. Churchill.

3. By the year 1939 it had become widely recognised among scientists of many nations that the release of energy by atomic fission was a possibility. The problems which remained to be solved before this possibility could be turned into practical achievement were, however, manifold and immense, and few scientists would at that time have ventured to predict that an atomic bomb could be ready for use by 1945. Nevertheless, the potentialities of the project were so great that His Majesty's Government thought it right that research should be carried on in spite of the many competing claims on our scientific manpower. At this stage the research was carried out mainly in our Universities, principally, Oxford, Cambridge, London (Imperial College), Liverpool and Birmingham. At the time of the formation of the Coalition Government, responsibility for co-ordinating the work and pressing it forward lay in the Ministry of Aircraft Production, advised by a committee of leading scientists presided over by Sir George Thomson.

4. At the same time, under the general arrangements then in force for the pooling of scientific information, there was a full interchange of ideas between the scientists carrying out this work in the United Kingdom and those in the United States.

5. Such progress was made that by the summer of 1941 Sir George Thomson's Committee was able to report that, in their view, there was a reasonable chance that an atomic bomb could be produced before the end of the war. At the end of August 1941 Lord Cherwell, whose duty it was to keep me informed on all these and other technical developments, reported the substantial progress which was being made. The general responsibility for the scientific research carried on under the various technical committees lay with the then Lord President of the Council, Sir John Anderson. In these circumstances (having in mind also the effect of ordinary high-explosive which we had recently experienced), I referred the matter on August 30, 1941, to the Chiefs of Staff Committee in the following minute:

> "General Ismay for Chiefs of Staff Committee.
>
> Although personally I am quite content with the existing explosives, I feel we must not stand in the path of improvement, and I therefore think that action should be taken in the sense proposed by Lord Cherwell, and that the Cabinet Minister responsible should be Sir John Anderson.
>
> I shall be glad to know what the Chiefs of Staff Committee think."

The Chiefs of Staff recommended immediate action with the maximum priority.

6. It was then decided to set up within the Department of Scientific and Industrial Research a special division to direct the work, and Imperial Chemical Industries Limited agreed to release Mr. W. A. Akers to take charge of this Directorate, which we called, for purposes of secrecy, the " Directorate of Tube Alloys ". After Sir John Anderson had ceased to be Lord President and became Chancellor of the Exchequer, I asked him to continue to supervise this work, for which he has special qualifications. To advise him, there was set up under his chairmanship a Consultative Council composed of the President of the Royal Society, the Chairman of the Scientific Advisory Committee of the Cabinet, the Secretary of the Department of Scientific and Industrial Research and Lord Cherwell. The Minister of Aircraft Production, at that time Lord Brabazon, also served on this Committee. Under the Chairmanship of Mr. Akers there was also a Technical Committee on which sat the scientists who were directing the different sections of the work, and some others. This Committee was originally composed of Sir James Chadwick, Professor Peierls, and Drs. Halban, Simon and Slade. Later it was joined by Sir Charles Darwin and Professors Cockcroft, Oliphant and Feather. Full use was also made of University and industrial laboratories.

7. On October 11, 1941, President Roosevelt sent me a letter suggesting that any extended efforts on this important matter might usefully be co-ordinated or even jointly conducted. Accordingly all British and American efforts were joined and a number of British scientists concerned proceeded to the United States. Apart from these contacts, complete secrecy guarded all these activities and no single person was informed whose work was not indispensable to progress.

8. By the summer of 1942 this expanded programme of research had confirmed with surer and broader foundations the promising forecasts which had been made a year earlier, and the time had come when a decision must be made whether or not to proceed with the construction of large-scale production plants. Meanwhile it had become apparent from the preliminary experiments that these plants would have to be on something like the vast scale described in the American statements which have been published to-day.

9. Great Britain at this period was fully extended in war production and we could not afford such grave interference with the current munitions programmes on which our warlike operations depended. Moreover, Great Britain was within easy range of German bombers, and the risk of raiders from the sea or air could not be ignored. The United States however, where parallel or similar progress had been made, was free from these dangers. The decision was therefore taken to build the full-scale production plants in America.

10. In the United States the erection of the immense plants was placed under the responsibility of Mr. Stimson, United States Secretary of War, and the American Army administration, whose wonderful work and marvellous secrecy cannot be sufficiently admired. The main practical effort and virtually the whole of its prodigious cost now fell upon the United States authorities, who were assisted by a number of British scientists. The relationship of the British and American contributions was regulated by discussion between the late President Roosevelt and myself, and a Combined Policy Committee was set up.

11. The Canadian Government, whose contribution was most valuable, provided both indispensable raw material for the project as a whole and also necessary facilities for the work of one section of the project which has been carried out in Canada by the three Governments in partnership.

12. The smoothness with which the arrangements for co-operation which were made in 1943 have been carried into effect is a happy augury for our future relations and reflects great credit on all concerned—on the members of the Combined Policy Committee which we set up; on the enthusiasm with which our scientists and technicians gave of their best—particularly Sir James Chadwick who gave up his work at Liverpool to serve as technical adviser to the United Kingdom members of the Policy Committee and spared no effort; and not least, on the generous spirit with which the whole United States organisation welcomed our men and made it possible for them to make their contribution.

13. By God's mercy British and American science outpaced all German efforts. These were on a considerable scale, but far behind. The possession of these powers by the Germans at any time might have altered the result of the war, and profound anxiety was felt by those who were informed. Every effort was made by our intelligence service and by the Royal Air Force to locate in Germany anything resembling the plants which were being created in the United States. In the winter of 1942-1943 most gallant attacks were made in Norway on two occasions by small parties of volunteers from the British Commandos and Norwegian forces, at very heavy loss of life, upon stores of what is called " heavy water ", an element in one of the possible processes. The second of these two attacks was completely successful.

14. The whole burden of execution, including the setting-up of the plants and many technical processes connected therewith in the practical sphere, constitutes one of the greatest triumphs of American—or indeed human—genius of which there is record. Moreover, the decision to make these enormous expenditures upon a project which, however hopefully established by American and British research, remained nevertheless a heartshaking risk, stands to the everlasting honour of President Roosevelt and his advisers.

15. It is now for Japan to realise in the glare of the first atomic bomb which has smitten her, what the consequences will be of an indefinite continuance of this terrible means of maintaining a rule of law in the world.

16. This revelation of the secrets of nature, long mercifully withheld from man, should arouse the most solemn reflections in the mind and conscience of every human being capable of comprehension. We must indeed pray that these awful agencies will be made to conduce to peace among the nations, and that instead of wreaking measureless havoc upon the entire globe, they may become a perennial fountain of world prosperity.

B.—STATEMENT ISSUED BY THE DIRECTORATE OF TUBE ALLOYS (DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH), ON SUNDAY, AUGUST 12TH, 1945.

I. INTRODUCTION.

1. The Prime Minister has issued a statement describng the events leading up to the production, in the United States, of atomic bombs and the dropping, by the United States Army Air Force, of the first of these on Japan. Statements have also been made by President Truman and Mr. Howe. Further statements have been issued by the U.S. and Canadian Governments giving an account of the work carried out in their respective countries which led up to or was associated with this remarkable achievement. These supplementary statements also give an outline of the scientific background without which it is impossible to appreciate the great advance which has been made.

2. The following official statement has been prepared to fulfil a similar purpose in this country. It begins with a very brief account of the outstanding discoveries in that branch of physics, known as " nuclear " physics, which by the year 1939 had led scientists to the belief that it should be possible to find a way of releasing atomic energy on a significant scale and under controlled conditions. It will be seen that scientists of many countries shared in this development and that the contribution of British laboratories was outstanding.

3. There follows an account of the examination of the problem in this country from the beginning of 1940 to the middle of 1941, when a scientific committee reported that there was a good chance that atomic bombs could be produced in time for use in the war. The next section of the statement deals with the organisation of the work in this country and with the scope of the research programmes undertaken. Reference is made to the interchange of information with the corresponding U.S. organisation and to the decision, already referred to in the Prime Minister's statement, that full-scale plants for the production of atomic bombs should be built not in this country but in U.S.A. There is a short reference to the decision to transfer to Canada one section of the work. This was at first a joint Anglo-Canadian project but became later, with the co-operation of the U.S. Government, a tri-partite enterprise.

4. In the Prime Minister's statement there is a reference to the setting up in Washington, after discussions between President Roosevelt and Mr. Churchill, of a Combined Policy Committee. This committee accepted certain recommendations from its scientific advisers for a closer integration of the scientific work, which involved the transfer to U.S.A. and Canada of many of the scientists working on this project in the U.K. The present statement ends with a note on the effect of this on the British programmes.

5. This statement is intended to be read in conjunction with the American and Canadian statements. It is, therefore, confined as far as possible to work in the U.K. and to the share taken by British scientists in the American and Canadian projects. Consequently no reference is made to the gigantic scale of the American scientific and technical effort the successful outcome of which constitutes, as Mr. Churchill has already said, one of the greatest triumphs of human genius of which there is record.

II. Historical Survey.

6. The discovery of the fission of uranium and its application in the atomic bomb is no isolated event but follows a series of discoveries which, since the end of last century, have been the basis of the modern science of physics. This work has been done in many countries and is the result of full and free collaboration between scientists, among whom those working in Britain have played a most important part.

7. Classical ideas on the nature and properties of matter culminated in the atomic theory of the nineteenth century. It was accepted that all matter was made up of discrete, indestructible particles or atoms, which were classified into 92 different species or elements. From the atoms of one or more of these elements all the different chemical compounds that exist in nature are built up. But it was regarded as a cardinal point that the atoms of any one element could in no way be changed or converted into those of another.

(*a*) *Radio-Activity.*

8. The fundamental break with this theory occurred when the French physicist H. Becquerel, in 1896, discovered that one of the elements—uranium —was continuously emitting radiation of an unknown type which could

penetrate matter and affected a photographic plate. Further study of this new-found property of uranium led to the isolation of another element —radium—from the uranium deposits in Joachimstal by Pierre and Marie Curie in 1898. Radium showed, to a much greater degree, this same property of emitting radiation and it was clear that the phenomenon of " radio-activity," as it was called, was altogether different from those associated with normal chemical reactions between atoms. In 1902 Rutherford and Soddy, who were then working at McGill University, Montreal, suggested that it could only be explained by the assumption that the atoms of uranium, radium and other radio-active elements, which had by then been discovered, were unstable and were continuously breaking up at rates which were characteristic for each element.

9. This suggestion was conclusively proved by detailed experimental work in the course of which the nature and properties of the radiation from radio-active elements were discovered. Part of this radiation, the so-called " alpha-rays," consists of helium atoms, carrying a positive charge of electricity, and these were found to be of the greatest value as a tool for further exploration of the structure of atoms.

10. It was, in fact, research on the penetration of matter by " alpha-rays " which led Rutherford, at Manchester University in 1911, to the fundamental discovery that the whole mass of each atom was concentrated in a minute central nucleus which carried a positive electric charge. Round this nucleus, but at relatively very great distances, revolved elementary negative electric charges—the " electrons "—in numbers sufficient to neutralise exactly the positive charge of the nucleus. The mass of these electrons was negligible compared with that of the nucleus. In terms of classical electro-magnetic theory, however, such a system would be unstable and the energy of the revolving electrons would, in a very short time, be lost as radiation. Niels Bohr, of Copenhagen, put forward a theory in 1913 which combined Rutherford's model of the " nuclear atom " with the quantum theory of energy which had been enunciated by Planck, to explain limitations of the classical electro-magnetic theory.

11. The resulting Rutherford-Bohr model of the atom proved to be of the greatest value in explaining the results of experimental work in every branch of physics and, in particular, the relationship between the different elements as regards their ordinary physical and chemical properties. These are determined entirely by the electrons revolving round the nucleus and are therefore practically independent of the mass of the nucleus. It was, therefore, immediately understood that any element, with a given charge on the nucleus, could exist in more than one modification with different atomic masses but almost identical physical and chemical properties.

12. The existence of such modifications of any element, which were known as " isotopes," had first been suggested by Soddy in 1910 as a result of studies of the decay products of the natural radio-active elements. Aston, at Cambridge, followed up work, which had been started by J. J. Thomson and developed the so-called " mass-spectrograph " which subjected a stream of electrically charged atoms—or ions—to a crossed electric and magnetic field and brought those of different mass to a focus at different points. It was proved, with the help of this instrument, that the great majority of elements consisted of a mixture of two or more isotopes and that the relative weight of the atom of any given isotope of any element was very nearly a simple multiple of the weight of a hydrogen nucleus, or proton.

13. Because the isotopes of an element have almost identical chemical properties it is in general extremely difficult to separate them or even to change

appreciably their relative concentration. We must take recourse to processes which depend on the nuclear mass of the atoms, making use of the difference in mass between isotopes. This difference is usually only a small fraction of the total mass. Moreover, while some of these methods, such as that used in the mass-spectrograph, are not difficult to apply, they can ordinarily deal only with very small quantities of material, too small to be of much practical use. In 1932 Urey and Brickwedde of Columbia University, New York, showed that hydrogen itself is not a simple element but contains a small amount (about 1/5000) of an isotope known as " heavy hydrogen " or deuterium which has almost double the mass of a proton. Because, in this case, the ratio of the masses of the isotopes is as two to one the physical and chemical properties of hydrogen and deuterium are sensibly different and it was found possible to separate them, in a pure state, in large amounts by normal technical methods.

14. The atoms of nearly all the elements are stable and it is only in the case of the radio-active elements that spontaneous disintegration of the nucleus takes place. Although it was known that, when this occurred, energy was released, atom for atom, on a scale incomparably greater than that connected with any known chemical reaction, it was recognised to be of no practical use because the rate of decay can in no way be influenced and it was obvious that any hope of understanding the conditions which might make such influence possible would depend on an understanding of the structure of the atomic nucleus.

(b) *Artificial disintegration of atoms*

15. The first decisive step in the solution of this problem was taken by Rutherford who, in 1919, showed experimentally that the charged alpha particles from radium C could, in rare instances, collide with the nucleus of an atom of the common element nitrogen in such a way that it broke up and, as a result of the collision, the nuclei of two other atomic species or elements (oxygen and hydrogen) were formed.

16. While the discovery of radio-activity had shown that some of the elements could, spontaneously, break up to form other elements Rutherford had now shown that the particles emitted in this process could be used to break up, or transmute, the atoms of other elements which were normally stable.

17. This development was pursued in the following years by Rutherford and Chadwick, who found that many other light elements could be transmuted in a similar way. In each case a proton was ejected, and generally the process of transmutation was accompanied by the release of a considerable amount of energy. It thus appeared that the proton was a common constituent of atomic nuclei and one of the fundamental particles of which matter is built up. Moreover, the release of energy in these processes was a further indication of the store of energy resident in atomic nuclei.

18. In parallel with this development, Rutherford, with Chadwick and other colleagues and students of the Cavendish Laboratory, attacked many other questions concerning the properties of atomic nuclei and their structure, laying the experimental foundations of a whole new branch of physics, now known as nuclear physics, arising from Rutherford's discoveries, first of the nature of the phenomenon of natural radioactivity; secondly, of the existence of the atomic nucleus; and thirdly, that some nuclei could be transmuted by bombardment with alpha particles.

19. A further very important step was taken here in 1932 when Cockroft and Walton carried out an experiment in which hydrogen nuclei, produced

artificially in an electric discharge and accelerated to a high velocity by means of an applied voltage, were used to bombard another stable element, lithium. The atoms of this element were found to disintegrate, and transmutation, the dream of the alchemists, had been achieved in a completely controlled laboratory experiment.

20. In this transmutation, and in others which followed this new discovery, the release of energy was enormous for such a minute event as a reaction involving a single nucleus. Nevertheless, the number of nuclear reactions was so small that the amount of energy generated by the reaction was extremely small compared with the total input of energy used to produce the bombarding particles. The practical value of these nuclear reactions as a source of energy was still completely negligible.

21. The reason is not far to seek; not only are these nuclear reactions very rare events, but the reactions are not self-propagating. This is quite different from the chemical reactions with which we are familiar in our daily life, such as the combustion of coal or oil. Once started, these propagate themselves and the reactions develop and spread, involving the whole bulk of material: thus the lighting of a fire releases enough heat to ignite the neighbouring fuel, which in turn releases more heat to ignite more fuel, and so on. This is not the case for the nuclear reactions which have so far been mentioned; the particles which are formed in them are insufficient to affect neighbouring nuclei so as to maintain the reaction and propagate it. It is clear that if we wish to tap the hidden reserves of energy in atomic nuclei and put them to practical use we must find a reaction which can propagate itself; for example, a reaction in which particles are emitted of the same kind that initiated it and in sufficient numbers to affect neighbouring nuclei, which in their turn emit new particles to react with other nuclei, thus beginning a chain-reaction which spreads through the whole mass.

22. It is convenient at this point to consider the form of this reserve of energy in atomic nuclei. As long ago as 1905 Einstein showed that, according to the theory of relativity, there is no essential difference between mass and energy, but that energy has mass and mass represents energy. For many years the proof that energy and mass were equivalent depended on indirect, although conclusive, evidence. The reason for this lack of immediate evidence is the extreme size of the ratio between mass and energy. A very small mass corresponds to a very large amount of energy. For example, a mass of one ounce transformed entirely into heat energy would be sufficient to convert nearly a million tons of water into steam. The fantastic size of the figure for conversion of mass to energy explains why a loss of mass has never been observed in ordinary chemical processes; the heat given off in combustion has, we believe, mass associated with it, but its amount is so small that it cannot be detected by the most sensitive balance.

23. Very striking and direct evidence for the equivalence of mass and energy was furnished by the experiments on the artificial transmutation of atoms. It was shown that in these nuclear reactions a release of energy was always accompanied by a decrease of mass and that the equivalence between mass and energy was exactly as predicted by Einstein. It thus appears that in these nuclear reactions matter is being partially converted into energy and that the reserve of energy of the atomic nucleus is hidden in the most obvious place, its own mass. There is therefore a store of energy resident in matter which is enormously greater than that available to us from any known chemical process. It is clear that since no such extraordinary sources are known on this earth there can be no appreciable conversion of matter into energy. On the other hand, it is now generally accepted that it is this

store of energy in matter itself which maintains the heat of the sun and of other stars, through a cycle of nuclear charges in which matter is converted into energy.

24. In the newly-discovered reactions, involving atomic nuclei rather than the outer screen of electrons, there was an enormous release of energy of this type for each atom that was successfully bombarded. The scientific importance of the results was immense but the apparent practical value was still negligible because only one successful collision could be obtained in many thousands and the total input of energy in producing the bombarding particles was far greater than the energy release from the very few successful collisions.

25. This low efficiency is, in part, due to the very small size of the nucleus compared with that of the atom as a whole. The massive central nucleus of an atom, with its surrounding cloud of electrons, has often been compared with the sun in the planetary system and a direct collision between the bombarding particle and the nucleus, which would be needed to break up the latter, is an inherently improbable event. But when both the nucleus and the bombarding particle are positively charged there will be a force of repulsion between them which will greatly lessen the chance of a direct collision. Only particles of very high energy can overcome this force and nearly all the bombarding particles will lose their energy in collisions with the electrons surrounding the atomic nuclei before they have a chance of reaching the nucleus itself.

(c) *Discovery of the Neutron*

26. In 1932 Chadwick, working in the Cavendish laboratory, made a discovery of fundamental importance. The observation was first made by Bothe and Becker in Germany that, when the element beryllium was bombarded with the alpha-particles emitted by polonium—a natural radio-active element—a very penetrating radiation was emitted. Joliot and his wife, Irene Curie-Joliot, in Paris, carried these observations further and finally, as a result of detailed measurements of the masses and energies of recoil particles, Chadwick was able to prove that this apparent radiation consisted of fundamental particles which had a mass almost the same as that of a proton, but had no electric charge. These new-found particles were called " neutrons " and it was at once realised that they, together with protons, were likely to be the ultimate constituents of the nuclei of atoms of all elements. The nucleus of any atom could be built up from the number of protons required to give the observed positive electric charge together with the additional number of neutrons to bring the nuclear mass up to the observed value.

27. The discovery of the neutron was, however, of even greater practical importance in that its lack of electric charge made it an ideal projectile for carrying out nuclear transformations. The use of neutrons as a means of exploring the structure and reactions of atomic nuclei was taken up vigorously in physics laboratories throughout the world. Neutron sources could be made either by mixing radium or polonium with beryllium so as to take advantage of the nuclear reaction already mentioned or by the use of an instrument, known as the " cyclotron," which had been developed by E. O. Lawrence of the University of California, Berkeley. This instrument has been of very great value in the production of high-energy beams of charged atoms or nuclei and many nuclear reactions, which could be carried out with such beams, were found to produce neutrons.

28. In the meantime an important contribution to the rapid advance in the new science of nuclear physics was made by Joliot and Mme. Irene Curie-Joliot who, in 1933, showed that certain elements, which are normally stable, undergo nuclear reactions when bombarded by alpha-rays and yield new

atomic nuclei which are isotopes of known elements but which are not stable and decay in the way characteristic of the natural radio-active elements. This decay was associated with the emission of " beta-rays " which, since the early work on radio-activity, had been recognised as being negatively charged electrons whose mass is negligible compared with those of either the proton or the neutron. In any radio-active series the emission of an electron, while leaving the atomic mass number unchanged, results in the increase, by one unit, in the net positive charge of the nucleus.

29. In 1934 E. Fermi, and the school of physicists then working with him at Rome, began an intensive study of the reactions produced when the nuclei of all atomic species were subjected to neutron bombardment. In the course of this work the heaviest known elements were examined and, in particular, uranium—with the atomic number 92—was subjected to neutron bombardment. The results of this work showed that new isotopes were formed which were unstable and were subject to radio-active decay. It therefore seemed that, by bombardment of the heaviest known atom with neutrons, it was possible to produce in the laboratory atoms of higher atomic number, 93 and upwards, than were found in nature.

30. Further experimental work, however, led to certain difficulties in this explanation and it was found to be impossible to account for the existence, in the normal arrangement of atomic species, of the very large number of so-called " trans-uranium " elements that were discovered. At this time it was generally accepted that these new elements were all, in fact, of higher atomic number than uranium and elaborate chemical tests had proved that they certainly could not be identified with any of the elements immediately below uranium in atomic number or weight.

(d) *Discovery of Fission*

31. Professor O. Hahn and Dr. Strassmann in Berlin became interested in this problem at the end of 1938 and, from the particular point of view of their chemical nature, carefully re-examined the new elements. In January, 1939, they published a most important paper in which they reported positive chemical evidence to show that one, at least, of the new isotopes which were believed to be of higher atomic number and mass than uranium was, in fact, an isotope of the element barium which has an atomic number and mass not very different from half that of uranium.

32. Immediately afterwards Dr. O. Frisch and Professor Lise Meitner pointed out that this discovery could only mean that, when uranium was bombarded by neutrons, a nuclear reaction took place of a kind utterly different from any so far studied and that the uranium nucleus split into two parts of roughly equal mass. This phenomenon, for which they proposed the name " nuclear fission," could be explained in terms of the theory of nuclear reactions which had been developed by Professor Bohr in the preceding years. They also pointed out that the fragments of the uranium nucleus would fly apart with great energy and this prediction was given a direct proof by experiments carried out by Dr. Frisch in Copenhagen. Confirmation of the reality of the fission process with uranium, and of the great energy released which accompanied it, was obtained by Professor Joliot in Paris independently (and at nearly the same time) and by other physicists throughout the world as soon as the original work was known to them.

33. Very shortly afterwards, in the spring of 1939, Professor Joliot and his collaborators Drs. Halban and Kowarski gave an experimental proof of the additional fact, which was expected on theoretical grounds, that when the fission of uranium takes place a number of free neutrons is also produced. Their first experiments showed this number to be about 3. Experiments

of the same types were carried out by Drs. Anderson, Fermi, Hanstein, Szilard and Zinn in the U.S.A., and independent confirmation was obtained of the fact that more than one free neutron is produced for each fission of a uranium nucleus.

34. It was immediately recognised that this discovery was of the very greatest significance and that, for the first time, there was an experimental basis for the hope that the useful realisation of the enormous store of atomic energy in matter could be achieved. Not only did the fission reaction provide the large amount of energy that was calculated from the difference in mass of the reactants and products, but the liberation of more than one new neutron each time that a uranium nucleus underwent fission made possible the continuation of the reaction by the development of a chain process once the initial step had been taken. Such a chain process would enable the reaction, in a suitable mass of uranium, to take place at an ever-increasing rate and would involve so many atoms that there would be a sensible, and indeed possibly an overwhelming, liberation of energy. The whole process could, furthermore, be started by the application of only a minute fraction of the energy that would be liberated and the difficulty, hitherto encountered in nuclear reactions, of obtaining an overall gain in energy would be eliminated.

35. It was therefore only natural that there should be an outburst of activity in most of the physics laboratories of the world with a spate of publications in the scientific press. This continued until the outbreak of war, when an increasing sense of the great potential value of this work imposed restrictions.

36. Certain important facts emerged from the work that was published during this period and theoretical conclusions and expectations were announced but it is hardly possible to give any strictly chronological account of them. The work was done in so many laboratories and the results, sometimes in a very preliminary form, were communicated to so many journals and published at such varying intervals after communication that details of priority cannot be clearly settled. But reference should be made to the visit which Professor Bohr paid to the U.S.A. from January till May, 1939. He was able to report directly to American physicists the experiments carried out by Hahn, Frisch and Meitner and their suggested interpretation of the results. In addition, while in the U.S.A., Bohr developed and published, in collaboration with Professor J. A. Wheeler of Princeton University, New Jersey, a theory of the fission process.

37. One important prediction which was made from this theory related to the different behaviour of the various isotopes of uranium. This element consists, for much the greater part (99.3 per cent.), of atoms of mass number 238 but there is also an isotope (0.7 per cent.) of mass 235 and a very small proportion (0.008 per cent.) of an isotope of mass 234. The first two, which are conveniently designated by the symbols U.238 and U.235 respectively, are the most important in connection with the uranium fission project. Bohr predicted, in February, 1939, that the common isotope, U.238, would be expected to undergo fission only when the bombarding neutrons had a high energy but that the rarer U.235 isotope would behave differently in that it would not only show this reaction with high energy neutrons but in addition would be particularly liable to undergo fission when the energy, and therefore the velocity, of the bombarding neutrons was very low. This prediction was, in fact, confirmed in March, 1940, by experiments carried out by Nier of Minnesota and Booth, Dunning and Grosse of Columbia University, New York. They used a sample of uranium in which the content of U.235 had been increased above the normal value by means of Nier's mass-spectrograph.

38. It is relevant, at this point, to refer to a different phenomenon shown by the U.238 isotope when bombarded by neutrons of one rather narrowly defined energy value which is intermediate between the very high energy required to cause fission of this isotope and the very low energy which is most effective in causing fission of U.235. Neutrons which have this so-called " resonance " energy are very strongly absorbed by the U.238 nucleus but fission does not follow. Instead the new nucleus, which now has a mass number 239, emits two electrons in successive steps and is thereby converted first to an isotope of an element with atomic number 93 (for which the name " neptunium " has been suggested) and then to one of an element with atomic number 94. This latter has, provisionally, been named " plutonium " and the isotope formed from U.238 after resonance capture of a neutron may be represented by the symbol Pu.239. Neptunium and plutonium are true " trans-uranium " elements, of the type suggested by Fermi, and are not found in nature. Of the two, Pu.239 is of particular interest in connection with the general problem of fission and the release of atomic energy because it could be expected, from the Bohr-Wheeler theory, to show the same sort of properties as U.235 and to be capable of undergoing fission with the greatest ease when bombarded by neutrons of very low energy.

39. Reference must also be made to the fact that the three nuclear species U.235, U.238 and Pu.239 are not the only ones that can undergo fission. The two elements next below uranium in the atomic series were also shown to have this same property. Thorium, with atomic number 90 and consisting of one isotope only of atomic mass 232, behaves in the same way as U.238 and fission can only be brought about when the bombarding neutrons have very high energy. The very rare radio-active element protactinium, with atomic number 91 and atomic mass 231, behaves, as regards fission, in a manner intermediate between U.235 and U.238. These facts, again, are all explicable in terms of the Bohr-Wheeler theory which enumerates certain general rules covering the behaviour to be expected with regard to fission of any heavy nucleus, known or unknown.

(e) *Chain reaction and the Atomic Bomb*

40. The foregoing survey of the development of atomic and nuclear physics, through necessarily brief and incomplete, has traced the growth of the idea that there are enormous reserves of energy in all matter; that these are of a nature quite different from those involved in chemical processes, such as the burning of coal or oil or the detonation of T.N.T. or other explosives, and that the nuclear reactions by which they are released are more comparable to those occurring in the sun or stars or in the natural radio-active elements found on the earth.

41. While this idea has been formed and steadily strengthened since the discovery of the phenomenon of radio-activity at the end of last century it is only since the discovery, reported at the beginning of 1939, of the special phenomenon of fission that a way has been clearly seen by which this atomic or nuclear energy in matter could be released, controlled and put to use by man.

42. In recent years the enormous effort expended on the solution of this problem, practically all of which has been borne by the U.S.A., has been concentrated on the development of an atomic bomb. Considerations of security make it impossible to disclose many of the details of this work but, in what follows, some indication is given of the share in it which has been carried out in Britain. Before doing this, however, it may be worth summarising the nature of the problems relating to the use of fission, either to produce a violent explosion or to liberate atomic energy under controlled con-

ditions, as they appeared when the work was organised, with a new sense of its urgency and importance, at the beginning of the war.

43. It was generally accepted that a chain reaction might be obtained in uranium which would yield enormous amounts of energy. This, on a basis of equal weights, would be millions of times greater than that produced by the combustion of coal or oil. But it was realised that, if this chain reaction was to be divergent and self-sustaining, certain critical conditions must be satisfied. In the first place the system as a whole must be of such a size that there was not too great a probability that neutrons, produced in the fission process, would escape from the system and so be unable to take any further part in the chain process. Secondly the system must not contain more than a limited amount of material that would absorb neutrons and, in this way again, remove their chance of contributing to the divergent fission chain reaction. Thirdly, the fact was appreciated that, if the reaction was not to " run away," it was essential to make use of neutrons of very low energy in the individual steps of the chain process. Only then would it be possible to introduce methods which would allow the rate of development of the process to be controlled. The neutrons produced when fission occurs have very high energies but this is dissipated as a result of elastic collisions with the nuclei of other atoms that may be present. Professor Joliot and his co-workers in Paris, Professor Fermi and other physicists in the U.S.A. and Professor Sir George Thomson and his colleagues in London were giving thought to the possibility of using a mixture of uranium and some suitable " slowing-down " medium arranged in such a way that the fast neutrons produced by fission would lose their energy by elastic collisions before initiating further fission in the uranium. A suitable " slowing-down " medium must, above all, not have any large probability of capturing a neutron and its atoms should be of as small mass as possible in order to get the maximum rate of loss of energy in the neutrons through elastic collisions. The most suitable materials to fulfil both these conditions were " heavy hydrogen " or its compound " heavy water," helium, beryllium and carbon.

44. At the beginning of 1940 Dr. Frisch and Professor Peierls, of Birmingham University, and Professor Sir James Chadwick, of Liverpool University, independently called attention to the possibility of producing a military weapon of unprecendented power. They pointed out that the slow neutron chain reaction would not produce explosive effects much greater than those obtained with ordinary explosives but that if a chain reaction with fast neutrons could be realised the explosive effects might be enormous. It was realised that ordinary uranium would not be suitable, for even if a fast chain reaction could be realised with it a very large quantity of metal would be required. On the other hand, the isotope U235, if it could be separated, offered great possibilities. It seemed that the amount required to make a bomb would not be very large, certainly between one and one hundred kilograms, and rough calculations of the energy released showed that the explosion of such a bomb might be equivalent to many thousands of tons of T.N.T.

45. The explosion of an atomic bomb is very different in its mechanism from the ordinary chemical explosion for it can occur only if the quantity of U235 is greater than a certain critical amount. This is because the reaction depends on the conservation of the neutrons produced in the fissions. In a block of pure, or nearly pure, U235 the neutrons will either be absorbed in the mass of metal, producing new fissions, or they will escape into the outer air, thus being wasted and useless for propagating the reaction. The proportion of neutrons which escape can be reduced by increasing the size of the block of metal, since the production of neutrons is a volume effect and will therefore

increase more rapidly with size than the loss by escape, which is a surface effect. It follows that if the explosion is possible it will require a certain minimum amount of material, which is called the critical size. The chain reaction will develop so fully that an explosion occurs only if the quantity of U235 is greater than this critical amount. Quantities less than this are quite stable and perfectly safe. On the other hand, if the amount of material exceeds the critical size it is unstable and a reaction will develop and multiply itself with enormous rapidity, resulting in an explosion of unprecedented violence. Thus all that is necessary to detonate a bomb of U235 is to bring together two pieces each less than the critical size but which when in contact form an amount exceeding it.

46. If an appreciable fraction of the atoms in a mass of U235 undergo fission within a very short time the amount of energy liberated will be so great that the mass will attain a temperature of many million degrees and a pressure of many millions of atmospheres. It will consequently expand with very great rapidity. As the density of the mass decreases the neutrons can escape more easily from it, and the chain reaction will come to an end. In order to release an appreciable fraction of the available energy, it is therefore necessary that the reaction should develop so rapidly that a substantial part of the material can react before the system has time to fly apart. The neutrons produced in the fission process are fast enough to fulfil this condition (but not if they are slowed down by artificial means as mentioned in the paragraphs above).

47. The interval of time between the beginning and the end of the nuclear reaction is exceedingly brief. In this interval the mass will have expanded so much that the nuclear reaction breaks off, owing to the escape of neutrons. During this interval a substantial part of the mass of U235 should undergo fission, releasing a large amount of energy. If only one pound of U235 is affected this release of energy will be as much as from 8000 tons of T.N.T.

III. The Realisation of the Atomic Bomb. British Activities and Organisation

(a) *Professor Sir George Thomson's Committee.*

48. A committee of scientists, with Professor Sir George Thomson as chairman, was set up in April, 1940, originally under the Air Ministry and later under the Ministry of Aircraft Production. This committee was instructed to examine the whole problem, to co-ordinate work in progress and to report, as soon as possible, whether the possibilities of producing atomic bombs during this war, and their military effect, were sufficient to justify the necessary diversion of effort for this purpose.

49. The first step to be taken was to establish the nuclear data on which depended the possibility of an atomic bomb and which determined its size. This work had already begun at Liverpool early in 1940 under Professor Sir James Chadwick and it was now pushed on more rapidly with Drs. Frisch and Rotblat as his senior collaborators. As the work developed and further problems appeared, it was extended to the Cavendish Laboratory, Cambridge, under Drs. Feather and Bretscher. This also had the advantage of providing an insurance against possible interruption from the effects of enemy bombing, to which the Liverpool laboratory was somewhat exposed. The many theoretical aspects of the problem were investigated by Professor Peierls, assisted by Dr. Fuchs and others. They used the experimental data provided by Liverpool and Cambridge to calculate the critical size of the bomb, they examined the mechanics of the reaction, and calculated the amount of energy likely to be released in an atomic explosion, studying the conditions for increasing the amount.

50. This was clearly only one side of the problem for it would not have been of immediate practical use to show that an atomic bomb was feasible provided that a certain quantity of U.235 were available unless it could also be shown that there was a reasonable possibility of separating such a quantity of U.235 from ordinary uranium and in a reasonable time. This aspect of the problem was also considered by the Committee. In the early stages of the work not much actual experiment could be done owing to the scarcity of men and of facilities, but one method of separation was examined at Liverpool and shown to be unpromising. There are of course several methods available for separating isotopes on a laboratory scale. These were examined very carefully by the Committee, having in mind that it was essential to select and concentrate on what was likely to be the most economical method, owing to the fact that the manpower and industrial resources of Britain were already wholly engaged on production for immediate war needs. The Committee came to the conclusion that the gaseous diffusion method was by for the most promising for large scale production. It is based on physical principles which have long been fully understood and which are easily amenable to calculation, and it seemed likely to make fewer demands for highly-skilled precision work.

51. Research on this method of separation was taken up by a team of workers under the direction of Dr. F. E. Simon in the Clarendon laboratory, Oxford. They were aided on the theoretical aspects by Professsor Peierls and his group, and on the chemical side by Professor W. N. Haworth and a group of men under his direction in the Chemistry Department, Birmingham University. The Metropolitan-Vickers Electrical Company and Imperial Chemical Industries Ltd. were consulted on the many technical questions which were involved. Some experimental work on the diffusion method was also started at Imperial College, London University.

52. By the early summer of 1941, the Committee decided that the feasibility of a military weapon based on atomic energy was definitely established and that this weapon had unprecedented powers of destruction, that a method of producing the amounts of material required was in view, and that a fair estimate of the industrial effort needed to accomplish the project could be given. Accordingly, the Committee drew up a report dated July 15, 1941, which summarized its findings and which made recommendations for the prosecution of the project on a large scale. By agreement between the Minister of Aircraft Production and the Lord President of the Council, this report was referred to the Scientific Advisory Committee of the War Cabinet of which Lord Hankey was the Chairman.

53. It is proper at this point to consider in general terms what had been done and what remained to be done. The experiments on the nuclear properties of uranium had confirmed that ordinary uranium itself would be useless for the purpose of an atomic bomb and that it would be necessary to use the isotope U.235 which is present in ordinary uranium only to the extent of 0.7 per cent. They had further shown that if pure or nearly pure U.235 were available in sufficient bulk a chain reaction could develop which would result in an explosion of extreme violence. The data which had been obtained were sufficient to give an estimate of the amount of U.235 required, but this estimate was very rough and the critical size was known only to a factor of three. The theoretical work had confirmed the early result that the amount of energy released in an atomic explosion would be very large compared with the effect of ordinary bombs. Calculations had been made on the effect of " tampers " and on the best size of bomb. The method of assembly of the material for use as a weapon and the method of fuzing had been considered, but no experiments had been made. On the problem of production of this material, U.235, it had been decided to concentrate on the gaseous

diffusion method, and research and development on some aspects had shown considerable promise. A scheme had been put forward by Dr. Simon and Professor Peierls which had proceeded to the first stage of design. Leading experts of industrial firms had been consulted who had agreed that it should be possible to build a satisfactory plant, although difficulties were to be anticipated. Estimates were given for the cost of a plant to provide adequate quantities of U.235 and for the time required to build it.

54. In short, the Committee was completely convinced that an atomic bomb depending on the fission of U.235 was feasible and that its effect would be comparable with that of some thousands of tons of T.N.T. and that a method of separation of U.235 from ordinary uranium could be realised on a large scale, so that sufficient quantities of the material could be obtained. Admittedly, a great deal of work remained to be done on all aspects of the project. More precise nuclear data were required so that, for example, the critical size could be estimated with better precision; some points needed confirmation; methods of assembly and of fuzing of the material had to be thoroughly examined. The main problem, however, was the design and construction of a plant for the production of the material, and this most essential part of the project was only in its early stages.

55. A different but important aspect of the application of the fission of uranium was also reviewed by the Committee. This was the possibility, mentioned in a previous section of this statement, of finding conditions under which a mixture of uranium and some suitable " slowing-down " medium might give a neutron chain reaction in which the release of energy was obtained in a controlled way. This work was being carried out at Cambridge by Drs. Halban and Kowarski.

These two French physicists had been sent by Professor Joliot to this country at the time of the fall of France in June 1940. They brought with them the 165 litres of " heavy-water "—practically the whole world stock of this material—which the French Government had bought from the Norsk Hydro Company just before the invasion of Norway. Drs. Halban and Kowarski were instructed by Professor Joliot to make every effort to get in England the necessary facilities to enable them to carry out, with the co-operation of the British Government, and in the joint interest of the Allies, a crucial experiment which had been planned in Paris and for which the " heavy-water " had been acquired. Facilities were provided at the Cavendish Laboratory, Cambridge, and, by December, 1940, they produced strong evidence that, in a system composed of uranium oxide (as actually used) or uranium metal with " heavy-water " as the slowing-down medium, a divergent slow neutron fission chain reaction would be realised if the system were of sufficient size. It seemed likely that, if uranium metal were used, this critical size would involve not more than a few tons of " heavy-water ".

56. The Committee concluded that this work had great potential interest for power production but that this particular application was not likely to be developed in time for use in the war. It was, however, recognised that the slow neutron work had a bearing on the military project, for the plutonium which would be produced in such a system could be extracted chemically and might be capable of use in an atomic bomb instead of U.235. The difficulties in the way of building a slow neutron system seemed to be prohibitive at that time. In order to produce the quantities of plutonium which it was guessed, from analogy with U.235, might be required for a bomb, many tons of uranium and many tons of heavy water would have been necessary. The latter particularly would have demanded a major industrial effort.

57. During this period, April, 1940—July 1941, similar problems were occupying the minds of American scientists. Contact was maintained partly by the transmission of reports through the normal scientific liaison machine and partly by visits in both directions by scientists on general scientific missions. Professor Bainbridge, of the National Defence Research Committee of America (N.D.R.C), was in England in April 1941, and Professor Lauritsen (N.D.R.C.), was in England in July of the same year on general scientific matters. Both were invited to attend meetings of Sir George Thomson's Committee.

(b) *Directorate of the Tube Alloys, D.S.I.R.*

58. The Scientific Advisory Committee of the War Cabinet, of which Lord Hankey was the Chairman, endorsed the view of Sir George Thomson's Committee on the importance of the atomic bomb, with the result that Mr. Churchill, who had been kept informed on the developments by Lord Cherwell, asked Sir John Anderson, in September, 1941, to undertake personal responsibility for the supervision of this project as one of great urgency and secrecy. To advise him he set up, under his chairmanship, a Consultative Council of which the members were the Chairman of the Scientific Advisory Committee of the War Cabinet (Lord Hankey and later Mr. R. A. Butler), the President of the Royal Society (Sir Henry Dale), the Secretary of the Department of Scientific and Industrial Research (Sir Edward Appleton) and Lord Cherwell. To ensure continuity the Minister of Aircraft Production, Lord Brabazon of Tara, served on this Council at the beginning.

59. The direction of the work was entrusted to a new Division of the Department of Scientific and Industrial Research and thus fell under the general administrative charge of Sir Edward Appleton as Secretary of the Department. It was known, for reasons of security, as the Directorate of Tube Alloys. Mr. W. A. Akers was, at Sir John Anderson's request, released by the Board of Imperial Chemical Industries, Ltd., to act as Director, with direct access to the Minister on all questions of policy. Mr. Akers had, as his deputy and principal assistant, Mr. M. W. Perrin, who was also lent by I.C.I. Mr. Akers was advised by a Technical Committee, under his chairmanship, composed of the scientists who were directing the different sections of the work and some others. The original members were Professor Sir James Chadwick, Professor Peierls and Drs. Halban, Simon and Slade, with Mr. Perrin as secretary. Later it was joined by Sir Charles Darwin and Professors Cockcroft, Oliphant and Feather.

(c) *Visit of U.S. Mission to Britain, November,* 1941.

60. In November, 1941, at the time when the new T.A. (Tube Alloys) organisation was set up, an American mission, composed of Professors Pegram and Urey, of Columbia University, came to this country to study the experimental and theoretical work which had been done on the T.A. project, to learn our ideas for future work and to agree on arrangements for complete and rapid interchange of information. They visited all the establishments where T.A. work was in progress and took part in a meeting of the new T.A. Technical Committee at which progress was reviewed and new programmes discussed.

(d) *Visit of British T.A. Mission to U.S.A., February-April,* 1942.

61. Under the new organisation a great extension of the scale of work, both in university and industrial laboratories, was started. In the U.S.A. also a greatly intensified T.A. effort had followed the return of Professors Pegram and Urey from England. A mission composed of Mr. Akers, Dr. Halban, Professor Peierls and Dr. Simon visited America at the beginning of 1942

to ensure that the programmes planned for the U.K. were co-ordinated as efficiently as possible with the American work.

62. Every section of the American programme was examined in detail and it was already clear that the new American T.A. organisation intended to make the fullest use of the enormous resources available in the universities and in industry.

(e) *British T.A. Programme.*

63. It was clear in 1942 that, even though granted very high priority, the scale upon which T.A. research and development could be undertaken in the U.K. must be far smaller than in America. A large proportion of the qualified physicists was occupied in other urgent war work and the industrial resources of Britain were engaged, at that time, in war production to a much greater extent than was the case in the U.S.A.

64. Consequently it was necessary to limit the field of T.A. investigation. Broadly the programmes chosen were:

Determination of essential nuclear physical data.

Theoretical investigations into the chain reaction in an atomic bomb, the dimensions and design of a bomb and its blast effect.

The gaseous diffusion U.235 separation process. This included theoretical and experimental research on the process, the design and construction of prototype machines, the manufacture of materials needed, studies on materials of construction, etc.

Investigation of slow neutron divergent systems, especially with " heavy water " as the slowing-down medium.

The manufacture of uranium metal for the slow neutron systems or " piles ".

The manufacture of " heavy water ".

(i) *Location of Work*

65. *Experimental determination of nuclear physical data.*

The research teams at Liverpool and Cambridge Universities were considerably strengthened and small programmes were started at Bristol and Manchester Universities.

Professor Sir James Chadwick exercised general supervision over all this work.

Slow Neutron systems.

This work continued at Cambridge under Drs. Halban and Kowarski with the collaboration of Dr. Bretscher.

Theoretical investigations into chain reaction, etc.

Professor Peierls and his team continued their studies at Birmingham, with collaboration, on special problems, with Professor Dirac of Cambridge.

Later, when Professor Peierls moved to U.S.A., Dr. A. H. Wilson led this group.

66. *The Gaseous Diffusion Process*

University Research

The experimental work was under the general direction of Dr. Simon. His extended team at the Clarendon Laboratory had, as leaders, Mr. Arms and Drs. Kurti and Kuhn. The theoretical study of the process remained in the hands of Professor Peierls and his group at Birmingham. Also at Birmingham University Professor Haworth, who had been very active in T.A. from the

days of the Thomson Committee, had a group working on a number of chemical problems connected with the diffusion project.

Research and Development in Industrial Establishments.

67. The Metropolitan-Vickers Electrical Co. Ltd. accepted a contract for the design and construction of certain prototype machines embodying the principles worked out by Dr. Simon and Professor Peierls. The successful construction of these machines was a considerable technical achievement in view of the novel features contained in them. They were later abandoned in favour of a simpler design which offered certain advantages in operation.

68. Imperial Chemical Industries Ltd. (I.C.I.) were entrusted with the contract for the development of the diffusion plant as a whole, and the work was carried out by the Billingham Division of that company. This programme was a very extensive one as it covered everything involved in the design of a complete plant, including the working out of flow-sheets, research on materials of construction and the development of new types of valves, instruments, etc., to meet novel conditions.

69. In this work they were assisted by the Metals Division of I.C.I., which studied various manufacturing processes. I.C.I. Metals Ltd. had, as sub-contractors, Percy Lund Humphries and Co. Ltd. and the Sun Engraving Co. Ltd., co-ordinated by Dr. Banks whose services were made available by the Printing and Allied Trades Research Association. Metallisation Ltd. also made a valuable contribution to this section of the work. Processes for the manufacture of the many special chemicals required were worked out by the General Chemicals Division of I.C.I. assisted by the Dyestuffs Division. The Mond Nickel Co. Ltd., under a separate contract, made a very successful investigation of certain metallurgical problems.

70. Although some of these research programmes will be carried on a little longer, largely in order to establish optimum conditions, I.C.I. Billingham Division has been able to close down the main programme after producing flow-sheets and designs for diffusion plants operating over a fairly wide range of conditions. In broad outline the plant is, of course, similar to the American diffusion plant now in operation, but it embodies certain novel features.

The manufacture of Uranium Metal.

71. I.C.I. (General Chemicals) Ltd. undertook the manufacture of uranium metal and succeeded in developing a satisfactory method. The conversion of the metal into rods, as required for a " pile ", was tackled by I.C.I. Metals Division. It soon became apparent that many problems required study in connection with the physical, metallurgical and chemical properties of the metal. Research on these points was undertaken by the National Physical Laboratory, Dr. Simon at Oxford with a sub-group at Birmingham, the British Non-Ferrous Metals Research Association, Dr. Orowan at Cambridge and the Alkali Division of I.C.I.

Heavy Water.

72. I.C.I. Billingham Division, which had some experience in the separation of " heavy water " on a laboratory scale, was asked to prepare a scheme for the production of this material on a large scale. After examining various methods they reported that the most suitable process to adopt in this country, if speed of construction and certainty of operation were paramount, was the electrolytic process incorporating the vapour phase catalytic exchange principle introduced by Professor Taylor of Princeton University, U.S.A. Flow-sheets and designs were prepared for a plant in which the exchange system was of a novel design believed to be simpler and more efficient than any of those hitherto used or suggested.

Electro-Magnetic method.

73. Through the interchange of information we were aware of the remarkable development work which was being carried on at the University of California under Professor E. O. Lawrence, with the object of converting the mass spectrograph, used for the separation of isotopes in minute quantities, into a large-scale production apparatus. But it was decided not to start any corresponding research in this country as the physicist most suitable for this work, Professor Oliphant of Birmingham, was engaged in other urgent war work.

74. In July 1943 it was possible to release him from that work so that it was decided to start a research programme at Birmingham on this method. Before work had really started Professor Oliphant visited America in connection with discussions on a closer integration of British and American T.A. efforts, in which it was agreed, as described below, that the most efficient course to follow, in the joint interest, was for Professor Oliphant and most of his team to move to U.S.A. The British electro-magnetic programme was therefore abandoned.

75. After Professor Oliphant's return to this country in March 1945 it was decided to arrange for research to be started on some of the electrical engineering problems involved in this type of plant. With this object research contracts have been placed with the British Thomson-Houston Company, the General Electric Company and Metropolitan-Vickers Electrical Company. In addition the first and last of these companies had already given considerable assistance by lending to the British T.A. organisation the services of Dr. K. J. R. Wilkinson, Dr. T. E. Allibone and other physicists and engineers.

(ii) *Co-ordination of Programmes.*

76. It will be seen, from the account of the diffusion plant research project, that many university and industrial teams were concerned, so that proper co-ordination of the work became an important matter. The same applied to the work on the production of uranium metal and its metallurgy. It was also evident that some of the chemical research carried out for one project would be of interest in connection with another. To ensure satisfactory co-ordination of the work certain committees and panels were set up.

77. The diffusion work was dealt with by the Diffusion Project Committee reporting to the T.A. Technical Committee.

The members of this Diffusion Committee were:—

Mr. W. A. Akers, Director T.A. (D.S.I.R.)—Chairman.
Major K. Gordon (later Dr. G. I. Higson), I.C.I. Billingham Division—Deputy Chairman.
Dr. F. E. Simon, Oxford University.
Mr. H. S. Arms, Oxford University.
Professor R. Peierls (later Dr. A. H. Wilson), Birmingham University.
Mr. J. D. Brown, I.C.I. Billingham Division.
Dr. J. B. Harding, I.C.I. Billingham Division.
Mr. C. F. Kearton, I.C.I. Billingham Division.
Mr. S. Labrow, I.C.I. Billingham Division.
Mr. J. R. Park, I.C.I. Billingham Division.
Mr. N. Elce, Metropolitan-Vickers Electrical Co.
Mr. H. Smethurst, Metropolitan-Vickers Electrical Co.
Mr. M. J. S. Clapham, I.C.I. Metals Division.
Mr. S. S. Smith, I.C.I. Metals Division
Mr. M. W. Perrin, T.A. Directorate (D.S.I.R.)—Secretary.

78. The chemical research was co-ordinated by a panel reporting to the T.A. Technical Committee. The constitution of this Panel was:—

Professor W. N. Haworth, Birmingham University—Chairman.
Dr. R. E. Slade, I.C.I.—Vice-Chairman.
Dr. F. E. Simon, Oxford University.
Dr. J. P. Baxter, I.C.I. General Chemical Division.
Dr. J. Ferguson, I.C.I. Alkali Division.
Mr. J. R. Park, I.C.I. Billingham Division.
Mr. M. W. Perrin, T.A. Directorate (D.S.I.R.)—Secretary.

79. Uranium metal production and metallurgical matters were handled by a Metal Panel, whose members were:—

Mr. E. Colbeck, I.C.I. Alkali Division—Chairman.
Dr. W. O. Alexander, I.C.I. Metals Division.
Dr. N. P. Allen, National Physical Laboratory.
Mr. G. L. Bailey, British Non-Ferrous Metals Research Association.
Dr. A. M. Roberts, I.C.I. General Chemicals Division.
Dr. F. E. Simon, Oxford University.
Mr. D. C. G. Gattiker, T.A. Directorate (D.S.I.R.)—Secretary.

(iii) *Research Contracts. Patents.*

80. The contracts under which research is carried on in university laboratories contain clauses reserving exclusively to the Government all discoveries, inventions and other results arising from the work. In the case of researches carried on by industrial firms all results, inventions and developments in detail applicable within the T.A. field become exclusively the property of the Government. Where an invention is also usable outside the T.A. field provision has been made whereby its use outside the field can be made available to industry. It is within the discretion of the Government to decide whether or not a particular use is within or without the field. Questions relating to inventions and patents are dealt with by a small Patents Committee composed of:—

Mr. A. Blok, D.S.I.R.—Chairman.
Mr. W. A. Akers, Director T.A. (D.S.I.R.).
Mr. M. W. Perrin, T.A. Directorate (D.S.I.R.).

(f) *Joint British-Canadian-American Slow-Neutron Project in Canada.*

81. Towards the end of 1942 it was decided that the slow-neutron research in progress at Cambridge would proceed more quickly and efficiently if it were transferred to a place geographically nearer to Chicago where the corresponding American work was being carried out.

82. A proposal was made to the Canadian Government that a joint British-Canadian research establishment should be set up in Canada, to work in close touch with the American group. The Canadian Government welcomed the suggestion, with the result that, at the beginning of 1943, a large research establishment was set up in Montreal under the general direction of the National Research Council of Canada.

83. Practically the whole of the Cambridge group, under Dr. Halban, was moved to Montreal, where the research staff was rapidly augmented by many Canadian scientists, several new recruits from the United Kingdom and a certain number from the United States. The laboratory was at first directed by Dr. Halban. He resigned this position early in 1944 and Professor J. D. Cockcroft was appointed to succeed him.

84. During the Spring of 1944 the Americans joined actively in that project which now became a joint British-Canadian-American enterprise. Its scope was enlarged and in 1944 a site was selected on the Ottawa river, near

Petawawa, Ontario, for the construction of a pilot scale "pile" using "heavy water," supplied by the U.S. Government, as the slowing-down medium.

85. This joint enterprise in Canada has been described more fully in statements issued by the Canadian Government. It represents a great contribution, both in men and money, by that Government to the development of this new branch of science and its application.

(g) *Transfer of British T.A. Research Groups to U.S.A.*

86. In August, 1943, Sir John Anderson visited America and discussed with the U.S. authorities the means by which the co-operation between the two countries might best be placed upon a more formal basis. Further discussions took place subsequently between President Roosevelt and Mr. Churchill which led to the setting up of a Combined Policy Committee in Washington.

87. Professor Sir James Chadwick who was appointed Scientific Adviser to the British members of this committee examined, with those responsible for the scientific and technical direction of the American project, the question whether there were any further steps which could be taken, in the pooling of scientific and technical effort, which would accelerate the production of atomic bombs in the U.S.A.

88. As a result of these discussions it was decided to move to America a large number of the scientists working in England on T.A. in order that they might work in the appropriate American groups.

89. At this time Professor Bohr escaped from Denmark and the British Government appointed him as an adviser on scientific matters. His scientific advice on the T.A. project has been available both in this country and in the United States to the two Governments.

90. Professor Oliphant and his team from Birmingham University were moved to Berkeley to work with Professor Lawrence's group engaged in research on the electro-magnetic isotope separation project. They were joined by other physicists from Britain including Professor Massey of University College, London, Dr. T. E. Allibone and Dr. K. J. R. Wilkinson who worked partly at Berkeley and partly at the electro-magnetic separation plant itself. Dr. Emeleus of Imperial College, London, Dr. J. P. Baxter and others were transferred to the electro-magnetic plant. Dr. Frisch from the Liverpool nuclear physics group and Dr. Bretscher from the corresponding Cambridge section, together with some members of their teams, were moved into the great American T.A. research establishment at Los Alamos, which is described in American statements on the project. They were joined, at that time or later, by a number of other British scientists including Professor Peierls and Dr. Penney, of Imperial College, London University. Professor Sir Geoffrey Taylor also paid several visits to this establishment.

91. The effect of these transfers, and others which were made to the Montreal project, was to close down entirely all work in the U.K. on the electro-magnetic process and to reduce almost to nothing the nuclear physical research. Nevertheless there is no doubt that this was the proper course to follow in the light of the decision which had been taken to give the highest priority to the production, in the shortest possible time, of an atomic bomb for use in this war.

DIRECTORATE OF TUBE ALLOYS

(Department of Scientific and Industrial Research).

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WARTIME INFORMATION BOARD (CANADA)
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August 6th, 1945.

STATEMENT BY THE HONOURABLE
C. D. HOWE, CANADIAN MINISTER
OF MUNITIONS AND SUPPLY.

The President of the United States has just announced that the Armed Forces of his country have dropped the first atomic bomb on Japan and that at a single stroke destroyed a large part of Hiroshima.

2. This statement is pregnant with significance and while it will take some time properly to assess its full implications it is probable that it will go down in history as one of the most important scientific and military announcements ever made by the head of a great nation.

3. The real significance does not lie in the fact that this new bomb has accomplished an almost incredible feat of destruction, important as that fact may be; its significance is that this bomb is a sign which all can appreciate that the basic problems of the release of energy by atomic fission have been solved, and that the unbelievably large amounts of energy which scientists have long believed to be associated with matter can now be made available.

4. The fact that scientists and engineers have succeeded in releasing this energy on a practical scale ushers in, as the President has said, "a new era in man's understanding of nature's forces". The first application of this new source of energy has been for purposes of war but not all its uses are destructive and we may justifiably expect notable developments along the paths of peace. These industrial applications will require many years of research and development before they come into general use.

5. It is a particular pleasure for me to announce that Canadian scientists and Canadian institutions have played an intimate part and have been associated in an effective way with this great scientific development.

6. While the strictly Canadian effort cannot be compared, either in personnel involved or monies spent, with the truly stupendous effort which the United States has made, nevertheless Canadian scientists and engineers in co-operation with distinguished workers from Britain and America have played a part that guarantees us a front line position in the scientific advance that lies ahead.

7. There is in Canada today under the administration of the National Research Council by far the largest and most distinguished group of research workers ever assembled within our borders. In one National Research Council laboratory in Montreal there is a staff of about 350 - the list of research scientists numbers 140 and includes many internationally known names. Over half of the staff are Canadians; the others have been sent here by the British government and include a few distinguished French scientists. In addition there are sizeable scientific groups working in the Divisions of Chemistry, Physics, and Engineering of the National Research Council at Ottawa, and in the Metallurgical Laboratories of the Department of Mines and Resources, Ottawa, and particular problems are being worked on at McMaster, Toronto, and McGill Universities. The other universities have co-operated in lending important members of their staff and the University of Montreal has made valuable space available for the laboratory I have mentioned.

8. Canada has also undertaken, as part of the co-operative effort, to build a pilot plant for the purpose of investigating one of the methods of making material which is required for the atomic bomb, and 10,000 acres west of the Petawawa Military Camp were expropriated and the necessary industrial facilities, townsite and laboratories are nearing completion.

9. As part of the overall enterprise and in order to guarantee a Government supply of uranium, which is the raw material on which this new source of power at present depends, the Government, with the knowledge and approval of the Governments of the United Kingdom and of the United States, took over the Eldorado Mining and Refining Company. The Government also took steps to provide for new surveys and explorations in search of uranium or other ore-

ments were made with most of the provinces to the end that all supplies of uranium might be obtained for the Crown and ultimately used under whatever arrangements are made for controlling the release of atomic energy in the interests of mankind.

10. Steps have been taken by the three Governments concerned to safeguard the patent position by acquiring the rights to any inventions made in this field by their personnel engaged on the work and by other appropriate measures.

11. Canada has been associated with scientific development in this field since the days when Rutherford made his first discovery at McGill University. Until recently scientific activities were confined to the work of individual university professors and some small scale experiments at the National Research Council in 1940, but our scientists had followed the work done in Europe, where the phenomenon of fission was discovered in 1939, and the subsequent developments which took place in many different countries.

12. When it became apparent that the production of a bomb for use in the present war was a distinct possibility if sufficient effort could be focused on the problem, the U.S. authorities decided to put forth their utmost endeavours, and the magnitude and effectiveness of their efforts during the last three years has been almost unbelievable.

13. The British, who had taken an active and leading part in the research from the beginning and were in close contact with the corresponding research being done in America, proposed towards the end of 1942 that one important section of the work should be carried on in Canada as a joint enterprise. An agreement was made whereby a research laboratory was organized under the administration of the National Research Council, and, as already stated, a large and distinguished group of British and Canadian scientists have been operating in Montreal for the past two and a half years.

14. By 1943 progress had been so successful that it became probable a bomb could be produced and during that summer the three partner Governments, the United States, the United Kingdom and Canada, regarding the closest co-operation to be in the interests of the Allied Powers, agreed that all work should be more intimately integrated, and a Combined Policy Committee was set up under the chairmanship of Secretary of War Stimson to exercise general supervision of the joint effort of the countries concerned. The Honourable Mr. C.D. Howe was named as Canada's representative on this committee. A joint technical subcommittee, consisting of Sir James Chadwick of England, Major General L. R. Groves of the U. S., and the President of the National Research Council of Canada, was appointed to assume responsibilities for the scientific policy of the project in Canada, which became a joint United States, United Kingdom, Canadian project with responsibility for one phase of the overall project. Steps were then taken to design and construct the pilot plant mentioned above. The National Research Council staff was made responsible for the basic design data. Defence Industries Limited undertook the general engineering on a no fee basis, and the Fraser Brace Company were awarded the construction contracts; the work has gone on at a rapid rate and the plant is now in active operation.

15. It has been necessary to take extraordinary security precautions and while we are anxious to give the people all possible information it is obvious that until some appropriate methods are devised to control this new source of energy that has been developed it will not be possible to divulge the technical processes of production or of military application.

16. The President has announced that he will make recommendations to Congress as to how future control of production and use of atomic power may be achieved and the Canadian Government has similar studies under way and will be prepared to enter into agreements to that end.

17. The international aspect of this new development, with its possibilities both of good and evil, will be foremost in the minds of many and it is to be hoped that some means will be found to use it for the benefit of mankind, not for our destruction, but for the maintenance of peace.

18. I have given only a general review of Canada's participation in this most significant scientific development. I would like to emphasize, however, that quite apart from the military and political aspects we can all, I think, take pride in the fact that for the first time a sizeable group of Canadian scientists under the auspices of a Canadian institution have been actively engaged in the pioneering phases of what may well prove to be one of the major scientific advances in history.

A GENERAL ACCOUNT OF THE DEVELOPMENT OF METHODS OF USING ATOMIC ENERGY FOR MILITARY PURPOSES UNDER THE AUSPICES OF THE UNITED STATES GOVERNMENT 1940 - 1945

by H. D. Smyth

Chairman of the Department of Physics
of Princeton University
Consultant to Manhattan District
U. S. Corps of Engineers

Written at the request of Major General L. R. Groves
United States Army. Publication authorized as of
August 1945

FOREWORD

The story of the development of the atomic bomb by the combined efforts of many groups in the United States is a fascinating but highly technical account of an enormous enterprise. Obviously military security prevents this story from being told in full at this time. However, there is no reason why the administrative history of the Atomic Bomb project and the basic scientific knowledge on which the several developments were based should not be available now to the general public. To this end this account by Professor H. D. Smyth is presented.

All pertinent scientific information which can be released to the public at this time without violating the needs of national security is contained in this volume. No requests for additional information should be made to private persons or organizations associated directly or indirectly with the project. Persons disclosing or securing additional information by any means whatsoever without authorization are subject to severe penalties under the Espionage Act.

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

L. R. Groves
Major General, USA

War Department
Washington, D. C.

August 1945

PREFACE

The ultimate responsibility for our nation's policy rests on its citizens and they can discharge such responsibilities wisely only if they are informed. The average citizen cannot be expected to understand clearly how an atomic bomb is constructed or how it works but there is in this country a substantial group of engineers and scientific men who can understand such things and who can explain the potentialities of atomic bombs to their fellow citizens. The present report is written for this professional group and is a matter-of-fact, general account of work in the United States since 1939 aimed at the production of such bombs. It is neither a documented official history nor a technical treatise for experts. Secrecy requirements have affected both the detailed content and general emphasis so that many interesting developments have been omitted.

References to British and Canadian work are not intended to be complete since this is written from the point of view of the activities in this country.

The writer hopes that this account is substantially accurate, thanks to cooperation from all groups in the project; he takes full responsibility for such errors as may occur.

H. D. Smyth

July 1, 1945

TABLE OF CONTENTS

	Foreword
	Preface
Chapter I	Introduction
Chapter II	Statement of the Problem
Chapter III	Administrative History up to December 1941
Chapter IV	Progress up to December 1941
Chapter V	Administrative History 1942 - 1945
Chapter VI	The Metallurgical Project at Chicago in 1942
Chapter VII	The Plutonium Production Problem as of February 1943
Chapter VIII	The Plutonium Problem, January 1943 to June 1945
Chapter IX	General Discussion of the Separation of Isotopes
Chapter X	Diffusion Separation
Chapter XI	Electromagnetic Separation
Chapter XII	The Work on the Atomic Bomb
Chapter XIII	General Summary
	Appendices

CHAPTER I

INTRODUCTION

1.1. The purpose of this report is to describe the scientific technical developments in this country since 1940 directed toward the mi: tary use of energy from atomic nuclei. Although not written as a "popul: account of the subject, this report is intended to be intelligible to scientists and engineers generally and to other college graduates with a good grounding in physics and chemistry. The equivalence of mass and ene is chosen as the guiding principle in the presentation of the background material of the "Introduction".

The Conservation of Mass and of Energy

1.2. There are two principles that have been cornerstones of t structure of modern science. The first -- that matter can be neither created nor destroyed but only altered in form -- was enunciated in the eighteenth century and is familiar to every student of chemistry; it has to the principle known as the law of conservation of mass. The second -- that energy can be neither created nor destroyed but only altered in form emerged in the nineteenth century and has ever since been the plague of i ventors of perpetual-motion machines; it is known as the law of conservat of energy.

1.3. These two principles have constantly guided and disciplin the development and application of science. For all practical purposes t were unaltered and separate until some five years ago. For most practica purposes they are still so, but it is now known that they are, in fact, t phases of a single principle for we have discovered that energy may sometimes be converted into matter and matter into energy. Specifically, suc a conversion is observed in the phenomenon of nuclear fission of uranium, process in which atomic nuclei split into fragments with the release of a enormous amount of energy. The military use of this energy has been the object of the research and production projects described in this report.

The Equivalence of Mass and Energy

1.4. One conclusion that appeared rather early in the developm of the theory of relativity was that the inertial mass of a moving body i: creased as its speed increased. This implied an equivalence between an i: crease in energy of motion of a body, that is, its kinetic energy, and an increase in its mass. To most practical physicists and engineers this appeared a mathematical fiction of no practical importance. Even Einstei:

could hardly have foreseen the present applications, but as early as 1905 he did clearly state that mass and energy were equivalent and suggested that proof of this equivalence might be found by the study of radioactive substances. He concluded that the amount of energy, E, equivalent to a mass, m, was given by the equation

$$E = mc^2$$

where c is the velocity of light. If this is stated in actual numbers, its startling character is apparent. It shows that one kilogram (2.2 pounds) of matter, if converted entirely into energy, would give 25 billion kilowatt hours of energy. This is equal to the energy that would be generated by the total electric power industry in the United States (as of 1939) running for approximately two months. Compare this fantastic figure with the 8.5 kilowatt hours of heat energy which may be produced by burning an equal amount of coal.

1.5. The extreme size of this conversion figure was interesting in several respects. In the first place, it explained why the equivalence of mass and energy was never observed in ordinary chemical combustion. We now believe that the heat given off in such a combustion has mass associated with it, but this mass is so small that it cannot be detected by the most sensitive balances available. (It is of the order of a few billionths of a gram per mole.) In the second place, it was made clear that no appreciable quantities of matter were being converted into energy in any familiar terrestrial processes, since no such large sources of energy were known. Further, the possibility of initiating or controlling such a conversion in any practical way seemed very remote. Finally, the very size of the conversion factor opened a magnificent field of speculation to philosophers, physicists, engineers, and comic-strip artists. For twenty-five years such speculation was unsupported by direct experimental evidence, but beginning about 1930 such evidence began to appear in rapidly increasing quantity. Before discussing such evidence and the practical partial conversion of matter into energy that is our main theme, we shall review the foundations of atomic and nuclear physics. General familiarity with the atomic nature of matter and with the existence of electrons is assumed. Our treatment will be little more than an outline which may be elaborated by reference to books such as Pollard and Davidson's Applied Nuclear Physics and Stranathan's The Particles of Nuclear Physics.

Radioactivity and Atomic Structure

1.6. First discovered by H. Becquerel in 1896 and subsequently studied by Pierre and Marie Curie, E. Rutherford, and many others, the phenomena of radioactivity have played leading roles in the discovery of the general laws of atomic structure and in the verification of the equivalence of mass and energy.

Ionization by Radioactive Substances

1.7. The first observed phenomenon of radioactivity was the blackening of photographic plates by uranium minerals. Although this ef: is still used to some extent in research on radioactivity, the property radioactive substances that is of greatest scientific value is their abi: to ionize gases. Under normal conditions air and other gases do not con electricity -- otherwise power lines and electrical machines would not operate in the open as they do. But under some circumstances the molecu: of air are broken apart into positively and negatively charged fragments, called ions. Air thus ionized does conduct electricity. Within a few m after the first discovery of radioactivity Becquerel found that uranium the power to ionize air. Specifically he found that the charge on an electroscope would leak away rapidly through the air if some uranium sal were placed near it. (The same thing would happen to a storage battery sufficient radioactive material were placed near by.) Ever since that ti the rate of discharge of an electroscope has served as a measure of inte of radioactivity. Furthermore, nearly all present-day instruments for s ing radioactive phenomena depend on this ionization effect directly or i directly. An elementary account of such instruments, notably electrosco Geiger-Müller counters, ionization chambers, and Wilson cloud chambers i given in Appendix 1.

The Different Radiations or Particles

1.8. Evidence that different radioactive substances differ in their ionizing power both in kind and in intensity indicates that there differences in the "radiations" emitted. Some of the radiations are muc more penetrating than others; consequently, two radioactive samples havi the same effect on an "unshielded" electroscope may have very different effects if the electroscope is "shielded," i.e., if screens are interpose between the sample and the electroscope. These screens are said to abso the radiation.

1.9. Studies of absorption and other phenomena have shown that fact there are three types of "radiation" given off by radioactive substa There are alpha particles, which are high-speed ionized helium atoms (actually the nuclei of helium atoms), beta particles, which are high-spe electrons, and gamma rays, which are electromagnetic radiation similar to X-rays. Of these only the gamma rays are properly called radiations, and even these act very much like particles because of their short wave-lengt Such a "particle" or quantum of gamma radiation is called a photon. In general, the gamma rays are very penetrating, the alpha and beta rays les so. Even though the alpha and beta rays are not very penetrating, they h enormous kinetic energies for particles of atomic size, energies thousand times greater than the kinetic energies which the molecules of a gas have reason of their thermal motion, and thousands of times greater than the energy changes per atom in chemical reactions. It was for this reason th Einstein suggested that studies of radioactivity might show the equivalen of mass and energy.

The Atom

1.10. Before considering what types of atoms emit alpha, beta, and gamma rays, and before discussing the laws that govern such emission, we shall describe the current ideas on how atoms are constructed, ideas based partly on the study of radioactivity.

1.11. According to our present view every atom consists of a small heavy nucleus approximately 10^{-12} cm in diameter surrounded by a largely empty region 10^{-8} cm in diameter in which electrons move somewhat like planets about the sun. The nucleus carries an integral number of positive charges, each 1.6×10^{-19} coulombs in size. (See Appendix 2 for a discussion of units.) Each electron carries one negative charge of this same size, and the number of electrons circulating around the nucleus is equal to the number of positive charges on the nucleus so that the atom as a whole has a net charge of zero.

1.12. Atomic Number and Electronic Structure. The number of positive charges in the nucleus is called the atomic number, Z. It determines the number of electrons in the extranuclear structure, and this in turn determines the chemical properties of the atom. Thus all the atoms of a given chemical element have the same atomic number, and conversely all atoms having the same atomic number are atoms of the same element regardless of possible differences in their nuclear structure. The extranuclear electrons in an atom arrange themselves in successive shells according to well-established laws. Optical spectra arise from disturbances in the outer parts of this electron structure; X-rays arise from disturbances of the electrons close to the nucleus. The chemical properties of an atom depend on the outermost electrons, and the formation of chemical compounds is accompanied by minor rearrangements of these electronic structures. Consequently, when energy is obtained by oxidation, combustion, explosion, or other chemical processes, it is obtained at the expense of these structures so that the arrangement of the electrons in the products of the process must be one of lowered energy content. (Presumably the total mass of these products is correspondingly lower but not detectably so.) The atomic nuclei are not affected by any chemical process.

1.13. Mass Number. Not only is the positive charge on a nucleus always an integral number of electronic charges, but the mass of the nucleus is always approximately a whole number times a fundamental unit of mass which is almost the mass of a proton, the nucleus of a hydrogen atom. (See Appendix 2.) This whole number is called the mass number, A, and is always at least twice as great as the atomic number except in the cases of hydrogen and a rare isotope of helium. Since the mass of a proton is about 1800 times that of an electron, the mass of the nucleus is very nearly the whole mass of the atom.

1.14. Isotopes and Isobars. Two species of atoms having the same atomic number but different mass numbers are called isotopes. They are chemically identical, being merely two species of the same chemical element. If two species of atoms have the same mass number but different atomic numbers, they are called isobars and represent two different chemical elements.

Radioactivity and Nuclear Change

1.15. If an atom emits an alpha particle (which has an atomic ber of two and a mass of four), it becomes an atom of a different elemen with an atomic number lower by two and a mass number lower by four. The emission by a nucleus of a beta particle increases the atomic number by and leaves the mass number unaltered. In some cases, these changes are companied by the emission of gamma rays. Elements which spontaneously c or "disintegrate" in these ways are unstable and are described as being "radioactive." The only natural elements which exhibit this property of mitting alpha or beta particles are (with a few minor exceptions) those very high atomic numbers and mass numbers, such as uranium, thorium, rad and actinium, i.e., those known to have the most complicated nuclear str tures.

Half-Lives; The Radioactive Series

1.16. All the atoms of a particular radioactive species have same probability of disintegrating in a given time, so that an appreciab sample of radioactive material, containing many millions of atoms, alway changes or "disintegrates" at the same rate. This rate at which the mat changes is expressed in terms of the "half-life," the time required for half the atoms initially present to disintegrate, which evidently is con for any particular atomic species. Half-lives of radioactive materials from fractions of a second for the most unstable to billions of years fo those which are only slightly unstable. Often, the "daughter" nucleus i its radioactive "parent" is itself radioactive and so on down the line f several successive generations of nuclei until a stable one is finally reached. There are three such families or series comprising all togethe about forty different radioactive species. The radium series starts fro isotope of uranium, the actinium series from another isotope of uranium, the thorium series from thorium. The final product of each series, afte or twelve successive alpha and beta particle emissions, is a stable isot of lead.

First Demonstration of Artificial Nuclear Disintegration

1.17. Before 1919 no one had succeeded in disturbing the stabi of ordinary nuclei or affecting the disintegration rates of those that we naturally radioactive. In 1919 Rutherford showed that high-energy alpha particles could cause an alteration in the nucleus of an ordinary element Specifically he succeeded in changing a few atoms of nitrogen into atoms oxygen by bombarding them with alpha particles. The process involved may written as

$$He^4 + N^{14} \longrightarrow O^{17} + H^1$$

meaning that a helium nucleus of mass number 4 (an alpha particle) striki nitrogen nucleus of mass number 14 produces an oxygen nucleus of mass num 17 and a hydrogen nucleus of mass number 1. The hydrogen nucleus, known the "proton," is of special importance since it has the smallest mass of nucleus. Although protons do not appear in natural radioactive processes

there is much direct evidence that they can be knocked out of nuclei.

The Neutron

1.18. In the decade following Rutherford's work many similar experiments were performed with similar results. One series of experiments of this type led to the discovery of the neutron, which will be discussed in some detail since the neutron is practically the theme song of this whole project.

1.19. In 1930 W. Bothe and H. Becker in Germany found that if the very energetic natural alpha particles from polonium fell on certain of the light elements, specifically beryllium, boron or lithium, an unusually penetrating radiation was produced. At first this radiation was thought to be gamma radiation although it was more penetrating than any gamma rays known, and the details of experimental results were very difficult to interpret on this basis. The next important contribution was reported in 1932 by Irene Curie and F. Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it ejected protons of very high energy. This was not in itself inconsistent with the assumed gamma-ray nature of the new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such an hypothesis. Finally (later in 1932) J. Chadwick in England performed a series of experiments showing that the gamma ray hypothesis was untenable. He suggested that in fact the new radiation consisted of uncharged particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. Such uncharged particles are now called neutrons.

1.20. The one characteristic of neutrons which differentiates them from other subatomic particles is the fact that they are uncharged. This property of neutrons delayed their discovery, makes them very penetrating, makes it impossible to observe them directly, and makes them very important as agents in nuclear change. To be sure, an atom in its normal state is also uncharged, but it is ten thousand times larger than a neutron and consists of a complex system of negatively charged electrons widely spaced around a positively charged nucleus. Charged particles (such as protons, electrons, or alpha particles) and electromagnetic radiations (such as gamma rays) lose energy in passing through matter. They exert electric forces which ionize atoms of the material through which they pass. (It is such ionization processes that make the air electrically conducting in the path of electric sparks and lightning flashes.) The energy taken up in ionization equals the energy lost by the charged particle, which slows down, or by the gamma ray, which is absorbed. The neutron, however, is unaffected by such forces; it is affected only by a very short-range force, i.e., a force that comes into play when the neutron comes very close indeed to an atomic nucleus. This is the kind of force that holds a nucleus together in spite of the mutual repulsion of the positive charges in it. Consequently a free neutron goes on its way unchecked until it makes a "head-on" collision with an atomic nucleus. Since nuclei are very small, such collisions occur but rarely and the neutron travels a long way before colliding. In the case of a collision of the "elastic" type, the ordinary laws of momentum apply as they do in the elastic collision of billiard balls. If the nucleus that is struck is heavy, it ac-

quires relatively little speed, but if it is a proton, which is approxi-
mately equal in mass to the neutron, it is projected forward with a larg
fraction of the original speed of the neutron, which is itself correspon
ly slowed. Secondary projectiles resulting from these collisions may be
tected, for they are charged and produce ionization. The uncharged natu
the neutron makes it not only difficult to detect but difficult to contr
Charged particles can be accelerated, decelerated, or deflected by elect
or magnetic fields which have no effect on neutrons. Furthermore, free
trons can be obtained only from nuclear disintegrations; there is no nat
supply. The only means we have of controlling free neutrons is to put m
in their way so that they will be slowed and deflected or absorbed by co
lisions. As we shall see, these effects are of the greatest practical i
portance.

The Positron and the Deuteron

1.21. The year 1932 brought the discovery not only of the neu
but also of the positron. The positron was first observed by C. D. Ande
at the California Institute of Technology. It has the same mass and the
magnitude of charge as the electron, but the charge is positive instead
negative. Except as a particle emitted by artificially radioactive nucl
is of little interest to us.

1.22. One other major discovery marked the year 1932. H. C.
F. G. Brickwedde, and G. M. Murphy found that hydrogen had an isotope of
number 2, present in natural hydrogen to one part in 5000. Because of i
special importance this heavy species of hydrogen is given a name of its
deuterium, and the corresponding nucleus is called the deuteron. Like t
alpha particle it is not one of the fundamental particles but does play
important role in certain processes for producing nuclear disintegration.

Nuclear Structure

1.23. The idea that all elements are made out of a few fundam
particles is an old one. It is now firmly established. We believe that
are three fundamental particles -- the neutron, the proton, and the elect
A complete treatise would also discuss the positron, which we have mentic
the neutrino and the mesotron. The deuteron and alpha particle, which ha
already been mentioned, are important complex particles.

1.24. According to our present views the nuclei of all atomic
species are made up of neutrons and protons. The number of protons is eq
to the atomic number, Z. The number of neutrons, N, is equal to the diff
ence between the mass number and the atomic number, or A - Z. There are
sets of forces acting on these particles, ordinary electric coulomb force
repulsion between the positive charges and very short-range forces of at-
traction between all the particles. These last forces are only partly un
stood, and we shall not attempt to discuss them. Suffice it to say that
bined effects of these attractive and repulsive forces are such that only
certain combinations of neutrons and protons are stable. If the neutrons
protons are few in number, stability occurs when their numbers are about
equal. For larger nuclei, the proportion of neutrons required for stabil

is greater. Finally, at the end of the periodic table, where the number of protons is over 90 and the number of neutrons nearly 150, there are no completely stable nuclei. (Some of the heavy nuclei are almost stable as evidenced by very long half-lives.) If an unstable nucleus is formed artificially by adding an extra neutron or proton, eventually a change to a stable form occurs. Strangely enough, this is not accomplished by ejecting a proton or a neutron but by ejecting a positron or an electron; apparently within the nucleus a proton converts itself to a neutron and positron (or a neutron converts itself into a proton and electron), and the light charged particle is ejected. In other words, the mass number remains the same but the atomic number changes. The stability conditions are not very critical so that for a given mass number, i.e., given total number of protons and neutrons, there may be several stable arrangements of protons and neutrons (at most three or five) giving several isobars. For a given atomic number, i.e., given number of protons, conditions can vary still more widely so that some of the heavy elements have as many as ten or twelve stable isotopes. Some two hundred and fifty different stable nuclei have been identified, ranging in mass number from one to two hundred and thirty-eight and in atomic number from one to ninety-two.

1.25. All the statements we have been making are based on experimental evidence. The theory of nuclear forces is still incomplete, but it has been developed on quantum-mechanical principles sufficiently to explain not only the above observations but more detailed empirical data on artificial radioactivity and on differences between nuclei with odd and even mass numbers.

Artificial Radioactivity

1.26. We mentioned above the emission of positrons or electrons by nuclei seeking stability. Electron emission (beta rays) was already familiar in the study of naturally radioactive substances, but positron emission was not found in the case of such substances. In fact, the general discussion presented above obviously was based in part on information that cannot be presented in this report. We shall, however, give a brief account of the discovery of "artificial" radioactivity and what is now known about it.

1.27. In 1934, Curie and Joliot reported that certain light elements (boron, magnesium, aluminum) which had been bombarded with alpha particles continued to emit positrons for some time after the bombardment was stopped. In other words, alpha-particle bombardment produced radioactive forms of boron, magnesium, and aluminum. Curie and Joliot actually measured half-lives of 14 minutes, 2.5 minutes, and 3.25 minutes, respectively, for the radioactive substances formed by the alpha-particle bombardment.

1.28. This result stimulated similar experiments all over the world. In particular, E. Fermi reasoned that neutrons, because of their lack of charge, should be effective in penetrating nuclei, especially those of high atomic number which repel protons and alpha particles strongly. He was able to verify his prediction almost immediately, finding that the nucleus of the bombarded atom captured the neutron and that there was thus produced an unstable nucleus which then achieved stability by emitting an electron. Thus,

the final, stable nucleus was one unit higher in mass number and one un higher in atomic number than the initial target nucleus.

1.29. As a result of innumerable experiments carried out sin 1934, radioactive isotopes of nearly every element in the periodic tabl now be produced. Some of them revert to stability by the emission of p trons, some by the emission of electrons, some by a process known as K- electron capture which we shall not discuss, and a small number (probab three) by alpha particle emission. Altogether some five hundred unstab nuclear species have been observed, and in most cases their atomic numb and mass numbers have been identified.

1.30. Not only do these artificially radioactive elements pl important role throughout the project with which we are concerned, but t future value in medicine, in "tracer" chemistry, and in many other field research can hardly be overestimated.

Energy Considerations

Nuclear Binding Energies

1.31. In describing radioactivity and atomic structure we hav deliberately avoided quantitative data and have not mentioned any appli- cations of the equivalence of mass and energy which we announced as the guiding principle of this report. The time has now come when we must sp of quantitative details, not merely of general principles.

1.32. We have spoken of stable and unstable nuclei made up of assemblages of protons and neutrons held together by nuclear forces. It general principle of physics that work must be done on a stable system t break it up. Thus, if an assemblage of neutrons and protons is stable, must be supplied to separate its constituent particles. If energy and m are really equivalent, then the total mass of a stable nucleus should be than the total mass of the separate protons and neutrons that go to make up. This mass difference, then, should be equivalent to the energy requi to disrupt the nucleus completely, which is called the binding energy. I member that we said that the masses of all nuclei were "approximately" wh numbers. It is the small differences from whole numbers that are signifi

1.33. Consider the alpha particle as an example. It is stable since its mass number is four and its atomic number two it consists of tw protons and two neutrons. The mass of a proton is 1.00758 and that of a tron is 1.00893 (see Appendix 2), so that the total mass of the separate ponents of the helium nucleus is

$$2 \times 1.00758 + 2 \times 1.00893 = 4.03302$$

whereas the mass of the helium nucleus itself is 4.00280. Neglecting the two decimal places we have 4.033 and 4.003, a difference of 0.030 mass un

This, then, represents the "binding energy" of the protons and neutrons in the helium nucleus. It looks small, but recalling Einstein's equation, $E = mc^2$, we remember that a small amount of mass is equivalent to a large amount of energy. Actually 0.030 mass units is equal to 4.5×10^{-5} ergs per nucleus or 2.7×10^{19} ergs per gram molecule of helium. In units more familiar to the engineer or chemist, this means that to break up the nuclei of all the helium atoms in a gram of helium would require 1.62×10^{11} gram calories or 190,000 kilowatt hours of energy. Conversely, if free protons and neutrons could be assembled into helium nuclei, this energy would be released.

1.34. Evidently it is worth exploring the possibility of getting energy by combining protons and neutrons or by transmuting one kind of nucleus into another. Let us begin by reviewing present-day knowledge of the binding energies of various nuclei.

Mass Spectra and Binding Energies

1.35. Chemical atomic-weight determinations give the average weight of a large number of atoms of a given element. Unless the element has only one isotope, the chemical atomic weight is not proportional to the mass of individual atoms. The mass spectrograph developed by F. W. Aston and others from the earlier apparatus of J. J. Thomson measures the masses of individual isotopes. Indeed, it was just such measurements that proved the existence of isotopes and showed that on the atomic-weight scale the masses of all atomic species were very nearly whole numbers. These whole numbers, discovered experimentally, are the mass numbers which we have already defined and which represent the sums of the numbers of the protons and neutrons; their discovery contributed largely to our present views that all nuclei are combinations of neutrons and protons.

1.36. Improved mass spectrograph data supplemented in a few cases by nuclear reaction data have given accurate figures for binding energies for many atomic species over the whole range of atomic masses. This binding energy, B, is the difference between the true nuclear mass, M, and the sum of the masses of all the protons and neutrons in the nucleus. That is,

$$B = (ZM_p + NM_n) - M$$

where M_p and M_n are the masses of the proton and neutron respectively, Z is the number of protons, $N = A - Z$ is the number of neutrons, and M is the true mass of the nucleus. It is more interesting to study the binding energy per particle, B/A, than B itself. Such a study shows that, apart from fluctuations in the light nuclei, the general trend of the binding energy per particle is to increase rapidly to a flat maximum around $A = 60$ (nickel) and then decrease again gradually. Evidently the nuclei in the middle of the periodic table -- nuclei of mass numbers 40 to 100 -- are the most strongly bound. Any nuclear reaction where the particles in the resultant nuclei are more strongly bound than the particles in the initial nuclei will release energy. Speaking in thermochemical terms, such reactions are exothermic. Thus, in general, energy may be gained by combining light nuclei to form heavier ones or by breaking very heavy ones into two or three smaller frag-

ments. Also, there are a number of special cases of exothermic nuclear integrations among the first ten or twelve elements of the periodic table where the binding energy per particle varies irregularly from one element another.

1.37. So far we seem to be piling one supposition on another. First we assumed that mass and energy were equivalent; now we are assuming that atomic nuclei can be rearranged with a consequent reduction in their total mass, thereby releasing energy which can then be put to use. It is time to talk about some experiments that convinced physicists of the truth these statements.

Experimental Proof of the Equivalence of Mass and Energy

1.38. As we have already said, Rutherford's work in 1919 on artificial nuclear disintegration was followed by many similar experiments. Gradual improvement in high voltage technique made it possible to substitute artificially produced high-speed ions of hydrogen or helium for natural alpha particles. J. D. Cockcroft and E. T. S. Walton in Rutherford's laboratory were the first to succeed in producing nuclear changes by such methods. In 1932 they bombarded a target of lithium with protons of 700 kilovolts energy and found that alpha particles were ejected from the target as a result of the bombardment. The nuclear reaction which occurred can be written symbolically as

$$ {}_3Li^7 + {}_1H^1 \longrightarrow {}_2He^4 + {}_2He^4 $$

where the subscript represents the positive charge on the nucleus (atomic number) and the superscript is the number of massive particles in the nucleus (mass number). As in a chemical equation, quantities on the left must add up to those on the right; thus the subscripts total four and the superscripts eight on each side.

1.39. Neither mass nor energy has been included in this equation. In general, the incident proton and the resultant alpha particles will each have kinetic energy. Also, the mass of two alpha particles will not be precisely the same as the sum of the masses of a proton and a lithium atom. According to our theory, the totals of mass and energy taken together should be the same before and after the reaction. The masses were known from mass spectra. On the left ($Li^7 + H^1$) they totalled 8.0241, on the right (2 He) 8.0056, so that 0.0185 units of mass had disappeared in the reaction. The experimentally determined energies of the alpha particles were approximately 8.5 million electron volts each, a figure compared to which the kinetic energy of the incident proton could be neglected. Thus 0.0185 units of mass had disappeared and 17 Mev of kinetic energy had appeared. Now 0.0185 units of mass is 3.07×10^{-26} grams, 17 Mev is 27.2×10^{-6} ergs and c is 3×10 cm/sec. (See Appendix 2.) If we substitute these figures into Einstein's equation, $E = mc^2$, on the left side we have 27.2×10^{-6} ergs and on the right side we have 27.6×10^{-6} ergs, so that the equation is found to be satisfied to a good approximation. In other words, these experimental results prove that the equivalence of mass and energy was correctly stated by Einstein.

Nuclear Reactions

Methods of Nuclear Bombardment

1.40. Cockcroft and Walton produced protons of fairly high energy by ionizing gaseous hydrogen and then accelerating the ions in a transformer-rectifier high-voltage apparatus. A similar procedure can be used to produce high-energy deuterons from deuterium or high-energy alpha particles from helium. Higher energies can be attained by accelerating the ions in cyclotrons or Van de Graaff machines. However, to obtain high-energy gamma radiation or -- most important of all -- high-energy neutrons, nuclear reactions themselves must be used as sources. Radiations of sufficiently high energy come from certain naturally radioactive materials or from certain bombardments. Neutrons are commonly produced by the bombardment of certain elements, notably beryllium or boron, by natural alpha particles, or by bombarding suitable targets with protons or deuterons. The most common source of neutrons is a mixture of radium and beryllium where the alpha particles from radium and its decay products penetrate the Be^9 nuclei, which then give off neutrons and become stable C^{12} nuclei (ordinary carbon). A frequently used "beam" source of neutrons results from accelerated deuterons impinging on "heavy water" ice. Here the high-speed deuterons strike the target deuterons to produce neutrons and He^3 nuclei. Half a dozen other reactions are also used involving deuterium, lithium, beryllium, or boron as targets. Note that in all these reactions the total mass number and total charge number are unchanged.

1.41. To summarize, the agents that are found to initiate nuclear reactions are -- in approximate order of importance -- neutrons, deuterons, protons, alpha particles, gamma rays and, rarely, heavier particles.

Results of Nuclear Bombardment

1.42. Most atomic nuclei can be penetrated by at least one type of atomic projectile (or by gamma radiation). Any such penetration may result in a nuclear rearrangement in the course of which a fundamental particle is ejected or radiation is emitted or both. The resulting nucleus may be one of the naturally available stable species, or -- more likely -- it may be an atom of a different type which is radioactive, eventually changing to still a different nucleus. This may in turn be radioactive and, if so, will again decay. The process continues until all nuclei have changed to a stable type. There are two respects in which these artificially radioactive substances differ from the natural ones: many of them change by emitting positrons (unknown in natural radioactivity) and very few of them emit alpha particles. In every one of the cases where accurate measurements have been made, the equivalence of mass and energy has been demonstrated and the mass-energy total has remained constant. (Sometimes it is necessary to invoke neutrinos to preserve mass-energy conservation.)

Notation

1.43. A complete description of a nuclear reaction should include the nature, mass and energy of the incident particle, also the nature (mass

number and atomic number), mass and energy (usually zero) of the target particle, also the nature, mass and energy of the ejected particles (or radiation), and finally the nature, mass and energy of the remainder. B all of these are rarely known and for many purposes their complete speci cation is unnecessary. A nuclear reaction is frequently described by a notation that designates first the target by chemical symbol and mass nu if known, then the projectile, then the emitted particle, and then the r mainder. In this scheme the neutron is represented by the letter n, the ton by p, the deuteron by d, the alpha particle by α, and the gamma ray Thus the radium-beryllium neutron reaction can be written $Be^9(\alpha,n)C^{12}$ and deuteron-deuteron reaction $H^2(d,n)He^3$.

Types of Reaction

1.44. Considering the five different particles (n, p, d, α, γ both as projectiles and emitted products, we might expect to find twenty combinations possible. Actually the deuteron very rarely occurs as a pr particle, and the photon initiates only two types of reaction. There ar however, a few other types of reaction, such as (n,2n), (d,H^3), and fiss which bring the total known types to about twenty-five. Perhaps the (n, reaction should be specifically mentioned as it is very important in one cess which will concern us. It is often called "radiative capture" sinc neutron remains in the nucleus and only a gamma ray comes out.

Probability and Cross Section

1.45. So far nothing has been said about the probability of n clear reactions. Actually it varies widely. There is no guarantee that neutron or proton headed straight for a nucleus will penetrate it at all. depends on the nucleus and on the incident particle. In nuclear physics, is found convenient to express probability of a particular event by a "c section." Statistically, the centers of the atoms in a thin foil can be sidered as points evenly distributed over a plane. The center of an ato projectile striking this plane has geometrically a definite probability passing within a certain distance (r) of one of these points. In fact, i there are n atomic centers in an area A of the plane, this probability is $n\pi r^2/A$, which is simply the ratio of the aggregate area of circles of ra r drawn around the points to the whole area. If we think of the atoms as impenetrable steel discs and the impinging particle as a bullet of negli diameter, this ratio is the probability that the bullet will strike a st disc, i.e., that the atomic projectile will be stopped by the foil. If i the fraction of impinging atoms getting through the foil which is measur the result can still be expressed in terms of the equivalent stopping cr section of the atoms. This notion can be extended to any interaction bet the impinging particle and the atoms in the target. For example, the pr bability that an alpha particle striking a beryllium target will produce neutron can be expressed as the equivalent cross section of beryllium for type of reaction.

1.46. In nuclear physics it is conventional to consider that t

impinging particles have negligible diameter. The technical definition of cross section for any nuclear process is therefore:

$$\frac{\text{number of processes occurring}}{\text{number of incident particles}} = (\text{number of target nuclei per cm}^2) \times (\text{nuclear cross section in cm}^2).$$

It should be noted that this definition is for the cross section per nucleus. Cross sections can be computed for any sort of process, such as capture, scattering, production of neutrons, etc. In many cases, the number of particles emitted or scattered in nuclear processes is not measured directly; one merely measures the attenuation produced in a parallel beam of incident particles by the interposition of a known thickness of a particular material. The cross section obtained in this way is called the total cross section and is usually denoted by σ.

1.47. As indicated in paragraph 1.11, the typical nuclear diameter is of the order of 10^{-12} cm. We might therefore expect the cross sections for nuclear reactions to be of the order of $\pi d^2/4$ or roughly 10^{-24} cm^2 and this is the unit in which they are usually expressed. Actually the observed cross sections vary enormously. Thus for slow neutrons absorbed by the (n, γ) reaction the cross section in some cases is as much as 1000×10^{-24} cm^2, while the cross sections for transmutations by gamma-ray absorption are in the neighborhood of $(1/1000) \times 10^{-24}$ cm^2.

Practicability of Atomic Power in 1939

Small Scale of Experiments

1.48. We have talked glibly about the equivalence of mass and energy and about nuclear reactions, such as that of protons on lithium, where energy was released in relatively large amounts. Now let us ask why atomic power plants did not spring up all over the world in the thirties. After all, if we can get 2.76×10^{-5} ergs from an atom of lithium struck by a proton, we might expect to obtain approximately half a million kilowatt hours by combining a gram of hydrogen with seven grams of lithium. It looks better than burning coal. The difficulties are in producing the high-speed protons and in controlling the energy produced. All the experiments we have been talking about have been done with very small quantities of material, large enough in numbers of atoms, to be sure, but in terms of ordinary masses infinitesimal — not tons or pounds or grams, but fractions of micrograms. The amount of energy used up in the experiment was always far greater than the amount generated by the nuclear reaction.

1.49. Neutrons are particularly effective in producing nuclear disintegration. Why weren't they used? If their initial source was an ion beam striking a target, the limitations discussed in the last paragraph applied. If a radium and beryllium source was to be used, the scarcity of radium was a difficulty.

The Need of a Chain Reaction

1.50. Our common sources of power, other than sunlight and wa power, are chemical reactions — usually the combustion of coal or oil. release energy as the result of rearrangements of the outer electronic structures of the atoms, the same kind of process that supplies energy t bodies. Combustion is always self-propagating; thus lighting a fire wit match releases enough heat to ignite the neighboring fuel, which release more heat which ignites more fuel, and so on. In the nuclear reactions have described this is not generally true; neither the energy released n the new particles formed are sufficient to maintain the reaction. But w can imagine nuclear reactions emitting particles of the same sort that initiate them and in sufficient numbers to propagate the reaction in neighboring nuclei. Such a self-propagating reaction is called a "chain action" and such conditions must be achieved if the energy of the nuclea: actions with which we are concerned is to be put to large-scale use.

Period of Speculation

1.51. Although there were no atomic power plants built in the thirties, there were plenty of discoveries in nuclear physics and plenty speculation. A theory was advanced by H. Bethe to explain the heat of th sun by a cycle of nuclear changes involving carbon, hydrogen, nitrogen, a oxygen, and leading eventually to the formation of helium.* This theory now generally accepted. The discovery of a few (n,2n) nuclear reactions (i.e., neutron-produced and neutron-producing reactions) suggested that a self-multiplying chain reaction might be initiated under the right conditions. There was much talk of atomic power and some talk of atomic bom But the last great step in this preliminary period came after four years stumbling. The effects of neutron bombardment of uranium, the most compl element known, had been studied by some of the ablest physicists. The re sults were striking but confusing. The story of their gradual interpreta

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*The series of reactions postulated was

(1) $_6C^{12} + {}_1H^1 \longrightarrow {}_7N^{13}$

(2) $_7N^{13} \longrightarrow {}_6C^{13} + {}_1e^0$

(3) $_6C^{13} + {}_1H^1 \longrightarrow {}_7N^{14}$

(4) $_7N^{14} + {}_1H^1 \longrightarrow {}_8O^{15}$

(5) $_8O^{15} \longrightarrow {}_7N^{15} + {}_1e^0$

(6) $_7N^{15} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4$

The net effect is the transformation of hydrogen into helium and positrons (designated as $_1e^0$) and the release of about thirty million electron volts energy.

is intricate and highly technical, a fascinating tale of theory and experiment. Passing by the earlier inadequate explanations, we shall go directly to the final explanation, which, as so often happens, is relatively simple.

Discovery of Uranium Fission

1.52. As has already been mentioned, the neutron proved to be the most effective particle for inducing nuclear changes. This was particularly true for the elements of highest atomic number and weight where the large nuclear charge exerts strong repulsive forces on deuteron or proton projectiles but not on uncharged neutrons. The results of the bombardment of uranium by neutrons had proved interesting and puzzling. First studied by Fermi and his colleagues in 1934, they were not properly interpreted until several years later.

1.53. On January 16, 1939 Niels Bohr of Copenhagen, Denmark, arrived in this country to spend several months in Princeton, N. J., and was particularly anxious to discuss some abstract problems with A. Einstein. (Four years later Bohr was to escape from Nazi-occupied Denmark in a small boat.) Just before Bohr left Denmark two of his colleagues, O. R. Frisch and L. Meitner (both refugees from Germany), had told him their guess that the absorption of a neutron by a uranium nucleus sometimes caused that nucleus to split into approximately equal parts with the release of enormous quantities of energy, a process that soon began to be called nuclear "fission." The occasion for this hypothesis was the important discovery of O. Hahn and F. Strassmann in Germany (published in Naturwissenschaften in early January 1939) which proved that an isotope of barium was produced by neutron bombardment of uranium. Immediately on arrival in the United States Bohr communicated this idea to his former student J. A. Wheeler and others at Princeton, and from them the news spread by word of mouth to neighboring physicists including E. Fermi at Columbia University. As a result of conversations between Fermi, J. R. Dunning, and G. B. Pegram, a search was undertaken at Columbia for the heavy pulses of ionization that would be expected from the flying fragments of the uranium nucleus. On January 26, 1939 there was a Conference on Theoretical Physics at Washington, D. C., sponsored jointly by the George Washington University and the Carnegie Institution of Washington. Fermi left New York to attend this meeting before the Columbia fission experiments had been tried. At the meeting Bohr and Fermi discussed the problem of fission, and in particular Fermi mentioned the possibility that neutrons might be emitted during the process. Although this was only a guess, its implication of the possibility of a chain reaction was obvious. A number of sensational articles were published in the press on this subject. Before the meeting in Washington was over, several other experiments to confirm fission had been initiated, and positive experimental confirmation was reported from four laboratories (Columbia University, Carnegie Institution of Washington, Johns Hopkins University, University of California) in the February 15, 1939 issue of the Physical Review. By this time Bohr had heard that similar experiments had been made in his laboratory in Copenhagen about January 15th. (Letter by Frisch to Nature dated January 16, 1939 and appearing in the February 18th issue.) F. Joliot in Paris had also published his first results in the

Comptes Rendus of January 30, 1939. From this time on there was a steac flow of papers on the subject of fission, so that by the time (December 1939) Turner wrote a review article on the subject in the Reviews of Moc Physics nearly one hundred papers had appeared. Complete analysis and c cussion of these papers have appeared in Turner's article and elsewhere.

General Discussion of Fission

1.54. Consider the suggestion of Frisch and Meitner in the li of the two general trends that had been discovered in nuclear structure: first, that the proportion of neutrons goes up with atomic number; secor that the binding energy per particle is a maximum for the nuclei of inte mediate atomic number. Suppose the U-238 nucleus is broken exactly in h then, neglecting the mass of the incident neutron, we have two nuclei of atomic number 46 and mass number 119. But the heaviest stable isotope c palladium (Z = 46) has a mass number of only 110. Therefore to reach st bility each of these imaginary new nuclei must eject nine neutrons, becc $_{46}Pd^{110}$ nuclei; or four neutrons in each nucleus must convert themselves protons by emitting electrons, thereby forming stable tin nuclei of mass number 119 and atomic number 50; or a combination of such ejections and versions must occur to give some other pair of stable nuclei. Actually, was suggested by Hahn and Strassmann's identification of barium (Z = 56, A = 135 to 140) as a product of fission, the split occurs in such a way to produce two unequal parts of mass numbers about 140 and 90 with the emission of a few neutrons and subsequent radioactive decay by electron mission until stable nuclei are formed. Calculations from binding-energ data show that any such rearrangement gives an aggregate resulting mass siderably less than the initial mass of the uranium nucleus, and thus th great deal of energy must be released.

1.55. Evidently, there were three major implications of the phenomenon of fission: the release of energy, the production of radioac atomic species and the possibility of a neutron chain reaction. The ene release might reveal itself in kinetic energy of the fission fragments a the subsequent radioactive disintegration of the products. The possibil of a neutron chain reaction depended on whether neutrons were in fact em — a possibility which required investigation.

1.56. These were the problems suggested by the discovery of fission, the kind of problem reported in the journals in 1939 and 1940 a since then investigated largely in secret. The study of the fission pro itself, including production of neutrons and fast fragments, has been la carried out by physicists using counters, cloud chambers, etc. The stud identification of the fission products has been carried out largely by c who have had to perform chemical separations rapidly even with sub-micro scopic quantities of material and to make repeated determinations of the lives of unstable isotopes. We shall summarize the state of knowledge a June 1940. By that time the principal facts about fission had been dis- covered and revealed to the scientific world. A chain reaction had not obtained, but its possibility — at least in principle — was clear and several paths that might lead to it had been suggested.

State of Knowledge in June 1940

Definite and Generally-Known Information on Fission

1.57. All the following information was generally known in June 1940, both here and abroad:

(1) That three elements -- uranium, thorium, and protoactinium -- when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium (Z = 34) to lanthanum (Z = 57).

(2) That most of these fission fragments were unstable, decaying radioactively by successive emission of beta particles through a series of elements to various stable forms.

(3) That these fission fragments had very great kinetic energy.

(4) That fission of thorium and protoactinium was caused only by fast neutrons (velocities of the order of thousands of miles per second).

(5) That fission in uranium could be produced by fast or slow (so-called thermal-velocity) neutrons; specifically, that thermal neutrons caused fission in one isotope, U-235, but not in the other, U-238, and that fast neutrons had a lower probability of causing fission in U-235 than thermal neutrons.

(6) That at certain neutron speeds there was a large capture cross section in U-238 producing U-239 but not fission.

(7) That the energy released per fission of a uranium nucleus was approximately 200 million electron volts.

(8) That high speed neutrons were emitted in the process of fission.

(9) That the average number of neutrons released per fission was somewhere between one and three.

(10) That high-speed neutrons could lose energy by inelastic collision with uranium nuclei without any nuclear reaction taking place.

(11) That most of this information was consistent with the semi-empirical theory of nuclear structure worked out by Bohr and Wheeler and others; this suggested that predictions based on this theory had a fair chance of success.

Suggestion of Plutonium Fission

1.58. It was realized that radiative capture of neutrons by U-238 would probably lead by two successive beta-ray emissions to the formation of a nucleus for which Z = 94 and A = 239. Consideration of the Bohr-Wheeler theory of fission and of certain empirical relations among the nuclei by L. A. Turner and others suggested that this nucleus would be a fairly stable alpha emitter and would probably undergo fission when bombarded by thermal neutrons. Later the importance of such thermal fission to the maintenance of

the chain reaction was foreshadowed in private correspondence and discus
In terms of our present knowledge and notation the particular reaction s
gested is as follows:

$$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} \longrightarrow {}_{93}Np^{239} + {}_{-1}e^{0}$$

$$_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + {}_{-1}e^{0}$$

where Np and Pu are the chemical symbols now used for the two new elemer
neptunium and plutonium; ${}_{0}n^{1}$ represents the neutron, and ${}_{-1}e^{0}$ represents
ordinary (negative) electron. Plutonium 239 is the nucleus rightly gues
to be fissionable by thermal neutrons. It will be discussed fully in la
chapters.

General State of Nuclear Physics

1.59. By 1940 nuclear reactions had been intensively studied over ten years. Several books and review articles on nuclear physics ha been published. New techniques had been developed for producing and cor trolling nuclear projectiles, for studying artificial radioactivity, and separating sub-microscopic quantities of chemical elements produced by n clear reactions. Isotope masses had been measured accurately. Neutron-capture cross sections had been measured. Methods of slowing down neutr had been developed. Physiological effects of neutrons had been observed they had even been tried in the treatment of cancer. All such informati was generally available; but it was very incomplete. There were many ga and many inaccuracies. The techniques were difficult and the quantities materials available were often sub-microscopic. Although the fundamenta principles were clear, the theory was full of unverified assumptions and culations were hard to make. Predictions made in 1940 by different phys of equally high ability were often at variance. The subject was in all-many respects an art, rather than a science.

Summary

1.60. Looking back on the year 1940, we see that all the pre-requisites to a serious attack on the problem of producing atomic bombs controlling atomic power were at hand. It had been proved that mass and energy were equivalent. It had been proved that the neutrons initiating fission of uranium reproduced themselves in the process and that therefo multiplying chain reaction might occur with explosive force. To be sure one knew whether the required conditions could be achieved, but many sci had clear ideas as to the problems involved and the directions in which solutions might be sought. The next chapter of this report gives a stat of the problems and serves as a guide to the developments of the past fi years.

CHAPTER II

STATEMENT OF THE PROBLEM

Introduction

2.1. From the time of the first discovery of the large amount energy released in nuclear reactions to the time of the discovery of ura fission, the idea of atomic power or even atomic bombs was discussed off on in scientific circles. The discovery of fission made this talk seem less speculative, but realization of atomic power still seemed in the di future and there was an instinctive feeling among many scientists that i might not, in fact, ever be realized. During 1939 and 1940 many public ments, some of them by responsible scientists, called attention to the e: mous energy available in uranium for explosives and for controlled power that U-235 became a familiar by-word indicating great things to come. T possible military importance of uranium fission was called to the attent of the government (see Chapter III), and in a conference with representa: of the Navy Department in March 1939 Fermi suggested the possibility of achieving a controllable reaction using slow neutrons or a reaction of a: explosive character using fast neutrons. He pointed out, however, that data then available might be insufficient for accurate predictions.

2.2. By the summer of 1940 it was possible to formulate the p: lem fairly clearly, although it was still far from possible to answer the various questions involved or even to decide whether a chain reaction eve could be obtained. In this chapter we shall give a statement of the prob in its entirety. For purposes of clarification we may make use of some k ledge which actually was not acquired until a later date.

The Chain-Reaction Problem

2.3. The principle of operation of an atomic bomb or power pla utilizing uranium fission is simple enough. If one neutron causes a fiss that produces more than one new neutron, the number of fissions may incre tremendously with the release of enormous amounts of energy. It is a que tion of probabilities. Neutrons produced in the fission process may esca entirely from the uranium, may be captured by uranium in a process not re sulting in fission, or may be captured by an impurity. Thus the question whether a chain reaction does or does not go depends on the result of a c petition among four processes:

(1) escape,
(2) non-fission capture by uranium,
(3) non-fission capture by impurities,
(4) fission capture.

If the loss of neutrons by the first three processes is less than the sur

produced by the fourth, the chain reaction occurs; otherwise it does not. Evidently any one of the first three processes may have such a high probability in a given arrangement that the extra neutrons created by fission will be insufficient to keep the reaction going. For example, should it turn out that process (2) -- non-fission capture by uranium -- has a much higher probability than fission capture, there would presumably be no possibility of achieving a chain reaction.

2.4. An additional complication is that natural uranium contains three isotopes: U-234, U-235, and U-238, present to the extent of approximately 0.006, 0.7, and 99.3 percent, respectively. We have already seen that the probabilities of processes (2) and (4) are different for different isotopes. We have also seen that the probabilities are different for neutrons of different energies.

2.5. We shall now consider the limitations imposed by the first three processes and how their effects can be minimized.

Neutron Escape; Critical Size

2.6. The relative number of neutrons which escape from a quantity of uranium can be minimized by changing the size and shape. In a sphere any surface effect is proportional to the square of the radius, and any volume effect is proportional to the cube of the radius. Now the escape of neutrons from a quantity of uranium is a surface effect depending on the area of the surface, but fission capture occurs throughout the material and is therefore a volume effect. Consequently the greater the amount of uranium, the less probable it is that neutron escape will predominate over fission capture and prevent a chain reaction. Loss of neutrons by non-fission capture is a volume effect like neutron production by fission capture, so that increase in size makes no change in its relative importance.

2.7. The critical size of a device containing uranium is defined as the size for which the production of free neutrons by fission is just equal to their loss by escape and by non-fission capture. In other words, if the size is smaller than critical, then -- by definition -- no chain reaction will sustain itself. In principle it was possible in 1940 to calculate the critical size, but in practice the uncertainty of the constants involved was so great that the various estimates differed widely. It seemed not improbable that the critical size might be too large for practical purposes. Even now estimates for untried arrangements vary somewhat from time to time as new information becomes available.

Use of a Moderator to Reduce Non-fission Capture

2.8. In Chapter I we said that thermal neutrons have the highest probability of producing fission of U-235 but we also said that the neutrons emitted in the process of fission had high speeds. Evidently it was an oversimplification to say that the chain reaction might maintain itself if more neutrons were created by fission than were absorbed. For the probability both of fission capture and of non-fission capture depends on the speed of the neutrons. Unfortunately, the speed at which non-fission capture is most

probable is intermediate between the average speed of neutrons emitted i fission process and the speed at which fission capture is most probable.

2.9. For some years before the discovery of fission, the cust way of slowing down neutrons was to cause them to pass through material atomic weight, such as hydrogenous material. It was E. Fermi and L. Szi who proposed the use of graphite as a moderator for a chain reaction. T process of slowing down or moderation is simply one of elastic collisior between high-speed particles and particles practically at rest. The mor nearly identical the masses of neutron and struck particle the greater t loss of kinetic energy by the neutron. Therefore the light elements are effective as "moderators", i.e., slowing down agents, for neutrons.

2.10. It occurred to a number of physicists that it might be sible to mix uranium with a moderator in such a way that the high-speed sion neutrons, after being ejected from uranium and before re-encounteri uranium nuclei, would have their speeds reduced below the speeds for whi non-fission capture is highly probable. Evidently the characteristics c good moderator are that it should be of low atomic weight and that it sh have little or no tendency to absorb neutrons. Lithium and boron are exc on the latter count. Helium is difficult to use because it is a gas and no compounds. The choice of moderator therefore lay between hydrogen, deuterium, beryllium, and carbon. Even now no one of these substances c excluded from the list of practical possibilities.

Use of a Lattice to Reduce Non-fission Capture

2.11. The general scheme of using a moderator mixed with the anium was pretty obvious. A specific manner of using a moderator was fi suggested in this country, so far as we can discover, by Fermi and Szila The idea was to use lumps of uranium of considerable size imbedded in a of moderator material. Such a lattice can be shown to have real advanta over a homogeneous mixture. As the constants were more accurately deter it became possible to calculate theoretically the type of lattice that w be most effective.

Reduction of Non-fission Capture by Isotope Separation

2.12. In Chapter I it was stated that for neutrons of certain intermediate speeds (corresponding to energies of a few electron volts) has a large capture cross section for the production of U-239 but not fo fission. There is also a considerable probability of inelastic (i.e., n capture-producing) collisions between high-speed neutrons and U-238 nucl Thus the presence of the U-238 tends both to reduce the speed of the fas neutrons and to effect the capture of those of moderate speed. Although may be some non-fission capture by U-235, it is evident that if we can s rate the U-235 from the U-238 and discard the U-238, we can reduce non-f capture and can thus promote the chain reaction. In fact, the probabili fission of U-235 by high-speed neutrons may be great enough to make the of a moderator unnecessary once the U-238 has been removed. Unfortunate U-235 is present in natural uranium only to the extent of about one part 140. Also, the relatively small difference in mass between the two isot

makes separation difficult. In fact, in 1940 no large-scale separation of isotopes had ever been achieved except for hydrogen, whose two isotopes differ in mass by a factor of two. Nevertheless, the possibility of separating U-235 was recognized early as being of the greatest importance, and such separation has, in fact, been one of the two major lines of Project effort during the past five years.

Production and Purification of Materials

2.13. It has been stated above that the cross section for capture of neutrons varies greatly among different materials. In some it is very high compared to the maximum fission cross section of uranium. If, then, we are to hope to achieve a chain reaction, we must reduce effect (3) -- non-fission capture by impurities -- to the point where it is not serious. This means very careful purification of the uranium metal and very careful purification of the moderator. Calculations show that the maximum permissible concentrations of many impurity elements are a few parts per million -- in either the uranium or the moderator. When it is recalled that up to 1940 the total amount of uranium metal produced in this country was not more than a few grams (and even this was of doubtful purity), that the total amount of metallic beryllium produced in this country was not more than a few pounds, that the total amount of concentrated deuterium produced was not more than a few pounds, and that carbon had never been produced in quantity with anything like the purity required of a moderator, it is clear that the problem of producing and purifying materials was a major one.

Control of the Chain Reaction

2.14. The problems that have been discussed so far have to do merely with the realization of the chain reaction. If such a reaction is going to be of use, we must be able to control it. The problem of control is different depending on whether we are interested in steady production of power or in an explosion. In general, the steady production of atomic power requires a slow-neutron-induced fission chain reaction occurring in a mixture or lattice of uranium and moderator, while an atomic bomb requires a fast-neutron-induced fission chain reaction in U-235 or Pu-239, although both slow- and fast-neutron fission may contribute in each case. It seemed likely, even in 1940, that by using neutron absorbers a power chain reaction could be controlled. It was also considered likely, though not certain, that such a chain reaction would be self-limiting by virtue of the lower probability of fission-producing capture when a higher temperature was reached. Nevertheless, there was a possibility that a chain-reacting system might get out of control, and it therefore seemed necessary to perform the chain-reaction experiment in an uninhabited location.

Practical Application of the Chain Reaction

2.15. Up to this point we have been discussing how to produce and control a nuclear chain reaction but not how to make use of it. The technological gap between producing a controlled chain reaction and using it as a large-scale power source or an explosive is comparable to the gap between the discovery of fire and the manufacture of a steam locomotive.

2.16. Although production of power has never been the princip object of this project, enough attention has been given to the matter to reveal the major difficulty: the attainment of high-temperature operati An effective heat engine must not only develop heat but must develop hea a high temperature. To run a chain-reacting system at a high temperatur and to convert the heat generated to useful work is very much more diffi than to run a chain-reacting system at a low temperature.

2.17. Of course, the proof that a chain reaction is possible not itself insure that nuclear energy can be effective in a bomb. To ha an effective explosion it is necessary that the chain reaction build up tremely rapidly; otherwise only a small amount of the nuclear energy wil utilized before the bomb flies apart and the reaction stops. It is also necessary that no premature explosion occur. This entire "detonation" p lem was and still remains one of the most difficult problems in designin high-efficiency atomic bomb.

Possibility of Using Plutonium

2.18. So far, all our discussion has been primarily concerned the use of uranium itself. We have already mentioned the suggestion tha element of atomic number 94 and mass 239, commonly referred to as pluton might be very effective. Actually, we now believe it to be of value com ble to pure U-235. We have mentioned the difficulty of separating U-235 the more abundant isotope U-238. These two isotopes are, of course, che cally identical. But plutonium, although produced from U-238, is a diff chemical element. Therefore, if a process could be worked out for conve some of the U-238 to plutonium, a chemical separation of the plutonium f uranium might prove more practicable than the isotopic separation of U-2 from U-238.

2.19. Suppose that we have set up a controllable chain reacti in a lattice of natural uranium and a moderator -- say carbon, in the fo of graphite. Then as the chain reaction proceeds, neutrons are emitted the process of fission of the U-235 and many of these neutrons are absor by U-238. This produces U-239, each atom of which then emits a beta par cle, becoming neptunium ($_{93}Np^{239}$). Neptunium, in turn, emits another be particle, becoming plutonium ($_{94}Pu^{239}$), which emits an alpha particle, d ing again to U-235, but so slowly that in effect it is a stable element. after the reaction has been allowed to proceed for a considerable time, mixture of metals is removed, it may be possible to extract the plutoniu chemical methods and purify it for use in a subsequent fission chain rea of an explosive nature.

Combined Effects and Enriched Piles

2.20. Three ways of increasing the likelihood of a chain reac have been mentioned: use of a moderator; attainment of high purity of ma rials; use of special material, either U-235 or Pu. The three procedure not mutually exclusive, and many schemes have been proposed for using sm amounts of separated U-235 or Pu-239 in a lattice composed primarily of ordinary uranium or uranium oxide and of a moderator or two different

moderators. Such proposed arrangements are usually called "enriched piles."

Use of Thorium or Protoactinium or Other Material

2.21. All our previous discussion has centered on the direct or indirect use of uranium, but it was known that both thorium and protoactinium also underwent fission when bombarded by high-speed neutrons. The great advantage of uranium, at least for preliminary work, was its susceptibility to slow neutrons. There was not very much consideration given to the other two substances. Protoactinium can be eliminated because of its scarcity in nature. Thorium is relatively plentiful but has no apparent advantage over uranium.

2.22. It is not to be forgotten that theoretically many nuclear reactions might be used to release energy. At present we see no way of initiating or controlling reactions other than those involving fission, but some such synthesis as has already been mentioned as a source of solar energy may eventually be produced in the laboratory.

Amounts of Materials Needed

2.23. Obviously it was impossible in the summer of 1940 to make more than guesses as to what amounts of materials would be needed to produce:

(1) a chain reaction with use of a moderator;
(2) a chain-reaction bomb in pure, or at least enriched, U-235 or plutonium.

A figure of one to one hundred kilograms of U-235 was commonly given at this time for the critical size of a bomb. This would, of course, have to be separated from at least 140 times as much natural uranium. For a slow-neutron chain reaction using a moderator and unseparated uranium it was almost certain that tons of metal and of moderator would be required.

Availability of Materials

2.24. Estimates of the composition of the earth's crust show uranium and thorium both present in considerable quantities (about 4 parts per million of uranium and 12 parts per million of thorium in the earth's crust). Deposits of uranium ore are known to exist in Colorado, in the Great Bear Lake region of northern Canada, in Joachimstal in Czechoslovakia, and in the Belgian Congo. Many other deposits of uranium ore are known, but their extent is in many cases unexplored. Uranium is always found with radium although in much larger quantity. Both are often found with vanadium ores. Small quantities of uranium oxide have been used for many years in the ceramics industry.

2.25. Thorium is also rather widely distributed, occurring as thorium oxide in fairly high concentration in monazite sands found to sc extent in this country but particularly in Brazil and in British India.

2.26. Early rough estimates, which are probably optimistic, v that the nuclear energy available in known deposits of uranium was adequ to supply the total power needs of this country for 200 years (assuming utilization of U-238 as well as U-235).

2.27. As has already been mentioned, little or no uranium met been produced up to 1940 and information was so scant that even the melt point was not known. (For example, the Handbook of Physics and Chemistr 1943-1944 says only that the melting point is below 1850°C whereas we nc know it to be in the neighborhood of 1150°.) Evidently, as far as urani was concerned, there was no insurmountable difficulty as regards obtaini raw materials or producing the metal, but there were very grave question to how long it would take and how much it would cost to produce the nece quantities of pure metal.

2.28. Of the materials mentioned above as being suitable for erators, deuterium had the most obvious advantages. It is present in or hydrogen to the extent of about one part in 5000. By 1940 a number of d ferent methods for separating it from hydrogen had been developed, and a liters had been produced in this country for experimental purposes. The large-scale production had been in a Norwegian plant, from which several hundred liters of heavy water (D_2O, deuterium oxide) had come. As in th case of uranium, the problem was one of cost and time.

2.29. Beryllium in the form of beryllium silicates is widely found but only in small quantities of ore. Its use as an alloying agent become general in the last few years; for such use, however, it is not n sary to produce the beryllium in metallic form. In 1940 only 700 pounds the metal were produced in this country.

2.30. As far as carbon was concerned, the situation was obvio quite different. There were many hundreds of tons of graphite produced year in this country. This was one of the reasons why graphite looked v desirable as a moderator. The difficulties lay in obtaining sufficient quantities of graphite of the required purity, particularly in view of t expanding needs of war industry.

Time and Cost Estimates

2.31. Requirements of time and money depended not only on many known scientific and technological factors but also on policy decisions. Evidently years of time and millions of dollars might be required to achi the ultimate objective. About all that was attempted at this time was ma estimates as to how long it would take and how much it would cost to clar the scientific and technological prospects. It looked as if it would not a very great undertaking to carry along the development of the thermal-ne

chain reaction in a graphite-uranium lattice to the point of finding out whether the reaction would in fact go. Estimates made at the time were that approximately a year and $100,000 would be required to get an answer. These estimates applied to a chain-reacting system of very low power without a cooling system or any means for using the energy released.

Health Hazards

2.32. It had been known for a long time that radioactive materials were dangerous. They give off very penetrating radiations -- gamma rays -- which are much like X-rays in their physiological effects. They also give off beta and alpha rays which, although less penetrating, can still be dangerous. The amounts of radium used in hospitals and in ordinary physical measurements usually comprise but a few milligrams. The amounts of radioactive material produced by the fission of uranium in a relatively small chain-reacting system may be equivalent to hundreds or thousands of grams of radium. A chain-reacting system also gives off intense neutron radiation known to be comparable to gamma rays as regards health hazards. Quite apart from its radioactive properties, uranium is poisonous chemically. Thus, nearly all work in this field is hazardous -- particularly work on chain reactions and the resulting radioactive products.

Method of Approach to the Problem

2.33. There were two ways of attacking the problem. One was to conduct elaborate series of accurate physical measurements on absorption cross sections of various materials for various neutron-induced processes and various neutron energies. Once such data were available, calculations as to what might be done in the way of a chain reaction could be made with fair accuracy. The other approach was the purely empirical one of mixing uranium or uranium compounds in various ways with various moderators and observing what happened. Similar extremes of method were possible in the case of the isotope-separation problem. Actually an intermediate or compromise approach was adopted in both cases.

Power vs. Bomb

2.34. The expected military advantages of uranium bombs were far more spectacular than those of a uranium power plant. It was conceivable that a few uranium bombs might be decisive in winning the war for the side first putting them into use. Such thoughts were very much in the minds of those working in this field, but the attainment of a slow-neutron chain reaction seemed a necessary preliminary step in the development of our knowledge and became the first objective of the group interested in the problem. This also seemed an important step in convincing military authorities and the more skeptical scientists that the whole notion was not a pipe dream. Partly

for these reasons and partly because of the extreme secrecy imposed abou time, the idea of an atomic bomb does not appear much in the records bet the summer of 1940 and the fall of 1941.

Military Usefulness

2.35. If all the atoms in a kilogram of U-235 undergo fission energy released is equivalent to the energy released in the explosion of 20,000 short tons of TNT. If the critical size of a bomb turns out to b practical -- say, in the range of one to one hundred kilograms -- and al other problems can be solved, there remain two questions. First, how la percentage of the fissionable nuclei can be made to undergo fission befo the reaction stops; i.e., what is the efficiency of the explosion? Seco what is the effect of so concentrated a release of energy? Even if only percent of the theoretically available energy is released, the explosion still be of a totally different order of magnitude from that produced by previously known type of bomb. The value of such a bomb was thus a ques for military experts to consider very carefully.

Summary

2.36. It had been established (1) that uranium fission did oc with release of great amounts of energy; and (2) that in the process ext neutrons were set free which might start a chain reaction. It was not c trary to any known principle that such a reaction should take place and it should have very important military application as a bomb. However, idea was revolutionary and therefore suspect; it was certain that many t nical operations of great difficulty would have to be worked out before a bomb could be produced. Probably the only materials satisfactory for bomb were either U-235, which would have to be separated from the 140-ti more abundant isotope U-238, or Pu-239, an isotope of the hitherto unkno element plutonium, which would have to be generated by a controlled chai reacting process itself hitherto unknown. To achieve such a controlled reaction it was clear that uranium metal and heavy water or beryllium or bon might have to be produced in great quantity with high purity. Once material was produced a process would have to be developed for using it and effectively. In some of the processes, health hazards of a new kind would be encountered.

Policy Problem

2.37. By the summer of 1940 the National Defense Research Comm had been formed and was asking many of the scientists in the country to w on various urgent military problems. Scientific personnel was limited (a though this was not fully realized at the time). It was, therefore, real difficult to decide at what rate work should be carried forward on an ato

bomb. The decision had to be reviewed at frequent intervals during the subsequent four years. An account of how these policy decisions were made is given in Chapters III and V.

CHAPTER III

ADMINISTRATIVE HISTORY UP TO DECEMBER 1941

Interest in Military Possibilities

3.1. The announcement of the hypothesis of fission and its ex mental confirmation took place in January 1939, as has already been rec in Chapter I. There was immediate interest in the possible military use the large amounts of energy released in fission. At that time American- nuclear physicists were so unaccustomed to the idea of using their scier for military purposes that they hardly realized what needed to be done. sequently the early efforts both at restricting publication and at getti government support were stimulated largely by a small group of foreign-b physicists centering on L. Szilard and including E. Wigner, E. Teller, V Weisskopf, and E. Fermi.

Restriction of Publication

3.2. In the spring of 1939 the group mentioned above enlisted Niels Bohr's cooperation in an attempt to stop publication of further da by voluntary agreement. Leading American and British physicists agreed, F. Joliot, France's foremost nuclear physicists, refused, apparently bec of the publication of one letter in the Physical Review sent in before a Americans had been brought into the agreement. Consequently publication tinued freely for about another year although a few papers were withheld voluntarily by their authors.

3.3. At the April 1940 meeting of the Division of Physical Sciences of the National Research Council, G. Breit proposed formation o censorship committee to control publication in all American scientific j nals. Although the reason for this suggestion was primarily the desire control publication of papers on uranium fission, the "Reference Committ as finally set up a little later that spring (in the National Research C cil) was a general one, and was organized to control publication policy all fields of possible military interest. The chairman of the committee L. P. Eisenhart; other members were G. Breit, W. M. Clark, H. Fletcher, E. B. Fred, G. B. Pegram, H. C. Urey, L. H. Weed, and E. G. Wever. Vari subcommittees were appointed, the first one of which had to do with uran fission. G. Breit served as chairman of this subcommittee; its other me were J. W. Beams, L. J. Briggs, G. B. Pegram, H. C. Urey, and E. Wigner. general, the procedure followed was to have the editors of various journ send copies of papers in this field, in cases where the advisability of lication was in doubt, either directly to Breit or indirectly to him thr Eisenhart. Breit then usually circulated them to all members of the sub committee for consideration as to whether or not they should be publishe and informed the editors as to the outcome. This arrangement was very s cessful in preventing publication and was still nominally in effect in J 1945, in modified form. Actually the absorption of most physicists in t country into war work of one sort or another soon reduced the number

of papers referred to the committee practically to the vanishing point. It is of interest to note that this whole arrangement was a purely voluntary one; the scientists of the country are to be congratulated on their complete co-operation. It is to be hoped that it will be possible after the war to publish these papers at least in part so that their authors may receive proper professional credit for their contributions.

Initial Approaches to the Government. The First Committee

3.4. On the positive side --- government interest and support of research in nuclear physics --- the history is a much more complicated one. The first contact with the government was made by Pegram of Columbia in March 1939. Pegram telephoned to the Navy Department and arranged for a conference between representatives of the Navy Department and Fermi. The only outcome of this conference was that the Navy expressed interest and asked to be kept informed. The next attempt to interest the government was stimulated by Szilard and Wigner. In July 1939 they conferred with A. Einstein, and a little later Einstein, Wigner, and Szilard discussed the problem with Alexander Sachs of New York. In the fall Sachs, supported by a letter from Einstein, explained to President Roosevelt the desirability of encouraging work in this feild. The President appointed a committee, known as the "Advisory Committee on Uranium" and consisting of Briggs as chairman, Colonel K. F. Adamson of the Army Ordnance Department, and Commander G. C. Hoover of the Navy Bureau of Ordnance, and requested this committee to look into the problem. This was the only committee on uranium that had official status up to the time of organization of the National Defense Research Committee in June 1940. The committee met very informally and included various additional scientific representatives in its meetings.

3.5. The first meeting of the Uranium Committee was on October 21, 1939 and included, besides the committee members, F. L. Mohler, Alexander Sachs, L. Szilard, E. Wigner, E. Teller, and R. B. Roberts. The result of this meeting was a report dated November 1, 1939 and transmitted to President Roosevelt by Briggs, Adamson, and Hoover. This report made eight recommendations, which need not be enumerated in detail. It is interesting, however, that it specifically mentions both atomic power and an atomic bomb as possibilities. It specifically recommended procurement of 4 tons of graphite and 50 tons of uranium oxide for measurements of the absorption cross section of carbon. Others of the recommendations either were of a general nature or were never carried out. Apparently a memorandum prepared by Szilard was more or less the basis of the discussion at this meeting.

3.6. The first transfer of funds ($6,000) from the Army and Navy to purchase materials in accordance with the recommendation of November 1st is reported in a memorandum from Briggs to General E. M. Watson (President Roosevelt's aide) on February 20, 1940. The next meeting of the "Advisory Committee on Uranium" was on April 28, 1940 and was attended by Sachs, Wigner, Pegram, Fermi, Szilard, Briggs, Admiral H. G. Bowen, Colonel Adamson, and Commander Hoover. By the time of this meeting two important new factors had come into the picture. First, it had been discovered that the uranium fission caused by neutrons of thermal velocities occurred in the U-235 isotope only.

Second, it had been reported that a large section of the Kaiser Wilhelm stitute in Berlin had been set aside for research on uranium. Although general tenor of this meeting seems to have been that the work should be pushed more vigorously, no definite recommendations were made. It was pointed out that the critical measurements on carbon already under way a Columbia should soon give a result, and the implication was that definit commendations should wait for such a result.

3.7. Within the next few weeks a number of people concerned, ticularly Sachs, urged the importance of greater support and of better o ization. Their hand was strengthened by the Columbia results (as report for example, in a letter from Sachs to General Watson on May 15, 1940) s ing that the carbon absorption was appreciably lower than had been previ thought and that the probability of carbon being satisfactory as a moder was therefore considerable. Sachs was also active in looking into the q tion of ore supply. On June 1, 1940, Sachs, Briggs, and Urey met with A Bowen to discuss approaching officials of the Union Minière of the Belgi Congo. Such an approach was made shortly afterwards by Sachs.

3.8. The general status of the problem was discussed by a spe advisory group called together by Briggs at the National Bureau of Stand on June 15, 1940. This meeting was attended by Briggs, Urey, M. A. Tuve Wigner, Breit, Fermi, Szilard, and Pegram. "After full discussion, the commendation of the group to the Uranium Committee was that funds should sought to support research on the uranium-carbon experiment along two li

(A) further measurements of the nuclear constants involved in the proposed type of reaction;
(B) experiments with amounts of uranium and carbon equal to about one fifth to one quarter of the amount that could be estimated as the minimum in which a chain reaction would sustain itself.

"It was estimated that about $40,000 would be necessary for fur measurements of the fundamental constants and that approximately $100,00(worth of metallic uranium and pure graphite would be needed for the inter mediate experiment." (Quotations from memorandum of Pegram to Briggs, da August 14, 1940)

The Committee Reconstituted under NDRC

3.9. Before any decisions made at this meeting could be put in effect, the organization of the National Defense Research Committee was announced in June 1940 and President Roosevelt gave instructions that the Uranium Committee should be reconstituted as a subcommittee of the NDRC, porting to Vannevar Bush (chairman, NDRC). The membership of this recons tuted Uranium Committee was as follows: Briggs, Chairman; Pegram, Urey, Beams, Tuve, R. Gunn and Breit. On authorization from Briggs, Breit cons Wigner and Teller frequently although they were not members of the commit

From that time until the summer of 1941 this committee continued in control with approximately the same membership. Its recommendations were transmitted by Briggs to the NDRC, and suitable contracts were made between the NDRC and various research institutions. The funds, however, were first supplied by the Army and Navy, not from regular NDRC appropriations.

Support of Research

3.10. The first contract let under this new set-up was to Columbia University for the two lines of work recommended at the June 15th meeting as described above. The project was approved by the NDRC and the first NDRC contract (NDCrc-32) was signed November 8, 1940, being effective from November 1, 1940 to November 1, 1941. The amount of this contract was $40,000.

3.11. Only very small expenditures had been made before the contract went into effect. For example, about $3,200 had been spent on graphite and cadmium, this having been taken from the $6,000 allotted by the Army and Navy in February, 1940.

3.12. We shall not attempt to review in detail the other contracts that were arranged prior to December 1941. Their number and total amount grew gradually. Urey began to work on isotope separation by the centrifuge method under a Navy contract in the fall of 1940. Other contracts were granted to Columbia University, Princeton University, Standard Oil Development Company, Cornell University, Carnegie Institution of Washington, University of Minnesota, Iowa State College, Johns Hopkins University, National Bureau of Standards, University of Virginia, University of Chicago, and University of California in the course of the winter and spring of 1940-1941 until by November 1941 the total number of projects approved was sixteen, totalling about $300,000.

3.13. Scale of expenditure is at least a rough index of activity. It is therefore interesting to compare this figure with those in other branches of war research. By November 1941 the total budget approved by NDRC for the Radiation Laboratory at the Massachusetts Institute of Technology was several million dollars. Even a relatively small project like that of Section S of Division A of the NDRC had spent or been authorized to spend $136,000 on work that proved valuable but was obviously not potentially of comparable importance to the uranium work.

Committee Reorganized in Summer of 1941

3.14. The Uranium Committee as formed in the summer of 1940 continued substantially unchanged until the summer of 1941. At that time the main committee was somewhat enlarged and subcommittees formed on isotope

separation, theoretical aspects, power production and heavy water.* It thereafter called the Uranium Section or the S-1 Section of NDRC. Thou formally disbanded until the summer of 1942, this revised committee was largely superseded in December 1941 (see Chapter V).

The National Academy Reviewing Committee

3.15. In the spring of 1941, Briggs, feeling that an impartia view of the problem was desirable, requested Bush to appoint a reviewin committee. Bush then formally requested F. B. Jewett, President of the National Academy of Sciences, to appoint such a committee. Jewett comp appointing A. H. Compton, chairman; W. D. Coolidge, E. O. Lawrence, J. Slater, J. H. Van Vleck, and B. Gherardi. (Because of illness, Gherard unable to serve.) This committee was instructed to evaluate the milita portance of the uranium problem and to recommend the level of expenditu which the problem should be investigated.

3.16. This committee met in May and submitted a report. (Th port and the subsequent ones will be summarized in the next chapter.) basis of this report and the oral exposition by Briggs before a meeting the NDRC, an appropriation of $267,000 was approved by the NDRC at its of July 18, 1941, and the probability that much larger expenditures woul necessary was indicated. Bush asked for a second report with emphasis engineering aspects, and in order to meet this request O. E. Buckley of Bell Telephone Laboratories and L. W. Chubb of the Westinghouse Electri and Manufacturing Company were added to the committee. (Compton was in America during the summer and therefore did not participate in the summe meetings of the committee.) The second report was submitted by Coolidge a result of new measurements of the fission cross section of U-235 and creasing conviction that isotope separation was possible, Compton and Le suggested to J. B. Conant of NDRC, who was working closely with Bush, in September 1941, that a third report was desirable. Since Bush and Conan learned during the summer of 1941 that the British also felt increasingl optimistic, the committee was asked to make another study of the whole s For this purpose the committee was enlarged by the addition of W. K. Lew R. S. Mulliken, and G. B. Kistiakowsky. This third report was submitted Compton on November 6, 1941.

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* Uranium Section: Briggs, chairman; Pegram, vice-chairman; S. K. son, Beams, Breit, E. U. Condon, H. D. Smyth, Urey.

Separation Subsection: Urey, chairman; Beams.

Power Production Subsection: Pegram, chairman; Allison, Fermi, Smy Szilard.

Heavy Water Subsection: Urey, chairman; T. H. Chilton.

Theoretical Aspects Subsection: Fermi, chairman; Breit, C. H. Ecka Smyth, Szilard, J. A. Wheeler.

Information received from the British

3.17. Beginning in 1940 there was some interchange of information with the British and during the summer of 1941 Bush learned that they had been reviewing the whole subject in the period from April to July. They too had been interested in the possibility of using plutonium; in fact, a suggestion as to the advisability of investigating plutonium was contained in a letter from J. D. Cockcroft to R. H. Fowler dated December 28, 1940. Fowler, who was at that time acting as British scientific liaison officer in Washington, passed Cockcroft's letter on to Lawrence. The British never pursued the plutonium possibility, since they felt their limited manpower should concentrate on U-235. Chadwick, at least, was convinced that a U-235 bomb of great destructive power could be made, and the whole British group felt that the separation of U-235 by diffusion was probably feasible.

3.18. Accounts of British opinion, including the first draft of the British report reviewing the subject, were made available to Bush and Conant informally during the summer of 1941, although the official British report of July 15th was first transmitted to Conant by G. P. Thomson on October 3rd. Since, however, the British review was not made available to the committee of the National Academy of Sciences, the reports by the Academy committee and the British reports constituted independent evaluations of the prospects of producing atomic bombs.

3.19. Besides the official and semi-official conferences, there were many less formal discussions held, one of these being stimulated by M. L. E. Oliphant of England during his visit to this country in the summer of 1941. As an example of such informal discussion we might mention talks between Conant, Compton, and Lawrence at the University of Chicago semi-centennial celebration in September 1941. The general conclusion was that the program should be pushed; and this conclusion in various forms was communicated to Bush by a number of persons.

3.20. In the fall of 1941 Urey and Pegram were sent to England to get first-hand information on what was being done there. This was the first time that any Americans had been to England specifically in connection with the uranium problem. The report prepared by Urey and Pegram confirmed and extended the information that had been received previously.

Decision to Enlarge and Reorganize

3.21. As a result of the reports prepared by the National Academy committee, by the British, and by Urey and Pegram, and of the general urging by a number of physicists, Bush, as Director of the Office of Scientific Research and Development (of which NDRC is a part), decided that the uranium work should be pushed more aggressively.

3.22. Before the National Academy issued its third report and before Pegram and Urey visited England, Bush had taken up the whole uranium question with President Roosevelt and Vice-President Wallace. He summarized for them the British views, which were on the whole optimistic, and pointed

out the uncertainties of the predictions. The President agreed that it desirable to broaden the program, to provide a different organization, t provide funds from a special source, and to effect complete interchange information with the British. It was agreed to confine discussions of general policy to the following group: The President, Vice-President, S tary of War, Chief of Staff, Bush, and Conant. This group was often ref to as the Top Policy Group.

3.23. By the time of submission of the National Academy's thi report and the return of Urey and Pegram from England, the general plan the reorganization was beginning to emerge. The Academy's report was mo conservative than the British report, as Bush pointed out in his letter November 27, 1941, to President Roosevelt. It was, however, sufficientl optimistic to give additional support to the plan of enlarging the work. proposed reorganization was announced at a meeting of the Uranium Sectio before the Pearl Harbor attack and will be described in Chapter V.

Summary

3.24. In March 1939, only a few weeks after the discovery of uranium fission, the possible military importance of fission was called the attention of the government. In the autumn of 1939 the first governm committee on uranium was created. In the spring of 1940 a mechanism was up for restricting publication of significant articles in this field. W the NDRC was set up in June 1940, the Uranium Committee was reconstitute under the NDRC. However, up to the autumn of 1941 total expenditures we latively small. In December 1941, after receipt of the National Academy port and information from the British, the decision was made to enlarge reorganize the program.

CHAPTER IV

PROGRESS UP TO DECEMBER 1941

The Immediate Questions

4.1. In Chapter II the general problems involved in producing chain reaction for military purposes were described. Early in the summe 1940 the questions of most immediate importance were:

(1) Could any circumstances be found under which the chain reaction would go?

(2) Could the isotope U-235 be separated on a large scale?

(3) Could moderator and other materials be obtained in sufficient purity and quantity?

Although there were many subsidiary problems, as will appear in the acco of the progress made in the succeeding eighteen months, these three ques determined the course of the work.

The Chain Reaction

Program Proposed June 15, 1940

4.2. In June 1940, nearly all work on the chain reaction was centrated at Columbia under the general leadership of Pegram, with Fermi Szilard in immediate charge. It had been concluded that the most-easily duced chain reaction was probably that depending on thermal neutron fissi a heterogeneous mixture of graphite and uranium. In the spring of 1940 I Szilard and H. L. Anderson had improved the accuracy of measurements of t capture cross section of carbon for neutrons, of the resonance (intermedi speed) absorption of neutrons by U-238, and of the slowing down of neutro carbon.

4.3. Pegram, in a memorandum to Briggs on August 14, 1940, wro "It is not very easy to measure these quantities with accuracy without th of large quantities of material. The net results of these experiments in spring of 1940 were that the possibility of the chain reaction was not de nitely proven, while it was still further from being definitely disproven On the whole, the indications were more favorable than any conclusions th could fairly have been claimed from previous results."

4.4. At a meeting on June 15th (see Chapter III) these results were discussed and it was recommended that (A) further measurements be ma

on nuclear constants, and (B) experiments be made on lattices of uranium and carbon containing amounts of uranium from one fifth to one quarter the estimated critical amounts.

Progress up to February 15, 1941

4.5. Pegram's report of February 15, 1941 shows that most of the work done up to that time was done on (A), while (B), the so-called intermediate experiment, was delayed by lack of materials.

4.6. Paraphrasing Pegram's report, the main progress was as follows:

(a) The slowing down of neutrons in graphite was investigated by studying the intensity of activation of various detectors (rhodium, indium, iodine) placed at various positions inside a rectangular graphite column of dimensions 3 x 3 x 8 feet when a source of neutrons was placed therein. By suitable choice of cadmium screens the effects of resonance and thermal neutrons were investigated separately.* A mathematical analysis, based on diffusion theory, of the experimental data made it possible to predict the results to be expected in various other arrangements. These results, coupled with theoretical studies of the diffusion of thermal neutrons, laid a basis for future calculations of the number of thermal and resonance neutrons to be found at any point in a graphite mass of given shape when a given neutron source is placed at a specified position within or near the graphite.

(b) The number of neutrons emitted in fission. The experiments on slowing down neutrons showed that high-energy (high-speed) neutrons such as those from fission were practically all reduced to thermal energies (low speeds) after passing through 40 cm or more of graphite. A piece of uranium placed in a region where thermal neutrons are present absorbs the thermal neutrons and -- as fission occurs -- re-emits fast neutrons, which are easily distinguished from the thermal neutrons. By a series of measurements with and without uranium present and with various detectors and absorbers, it is possible to get a value for the constant η, the number of neutrons emitted per thermal

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*The presence of neutrons can be detected by ionization chambers or counters or by the artificial radioactivity induced in various metal foils. (See Appendix 1.) The response of each of these detectors depends on the particular characteristics of the detector and on the speed of the neutrons (e.g., neutrons of about 1.5 volts energy are particularly effective in activating indium). Furthermore, certain materials have very large absorption cross sections for neutrons of particular ranges of speed (e.g., cadmium for thermal neutrons). Thus measurements with different detectors with or without various absorbers give some indication of both the number of neutrons present and their energy distribution. However, the state of the art of such measurements is rather crude.

neutron absorbed by uranium. This is not the number of neutrons emitted fission, but is somewhat smaller than that number since not every absorp causes fission.

(c) Lattice theory. Extensive calculations were made on the probable r of neutrons escaping from lattices of various designs and sizes. This w fundamental for the so-called intermediate experiment, mentioned above a item (B).

Initiation of New Programs

4.7. Early in 1941 interest in the general chain-reaction pro by individuals at Princeton, Chicago, and California led to the approval certain projects at those institutions. Thereafter the work of these gr was coordinated with the work at Columbia, forming parts of a single lar program.

Work on Resonance Absorption*

4.8. In Chapter II it is stated that there were advantages in lattice structure or "pile" with uranium concentrated in lumps regularly distributed in a matrix of moderator. This was the system on which the Columbia group was working. As is so often the case, the fundamental id is a simple one. If the uranium and the moderator are mixed homogeneous the neutrons on the average will lose energy in small steps between pass through the uranium so that in the course of their reduction to thermal city the chance of their passing through uranium at any given velocity, at a velocity corresponding to resonance absorption, is great. But, if uranium is in large lumps spaced at large intervals in the moderator, th amounts of energy lost by neutrons between passages from one lump of ura to another will be large and the chance of their reaching a uranium lump with energy just equal to the energy of resonance absorption is relative small. Thus the chance of absorption by U-238 to produce U-239, compare the chance of absorption as thermal neutrons to cause fission, may be re sufficiently to allow a chain reaction to take place. If one knew the e values of the cross sections of each uranium isotope for each type of ab sorption and every range of neutron speed, and had similar knowledge for moderator, one could calculate the "optimum lattice," i.e., the best siz shape and spacing for the lumps of uranium in the matrix of moderator. such data were only partially known, a direct experimental approach appea

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*The term "resonance absorption" is used to describe the very strong sorption of neutrons by U-238 when the neutron energies are in certain de nite portions of the energy region from 0 to 1000 electron volts. Such r nance absorption demonstrates the existence of nuclear energy levels at c responding energies. On some occasions the term resonance absorption is to refer to the whole energy region in the neighborhood of such levels.

to be in order. Consequently it was proposed that the absorption of neutrons by uranium should be measured under conditions similar to those expected in a chain-reacting pile employing graphite as moderator.

4.9. Experiments of this type were initiated at Columbia, and were continued at Princeton in February 1941. Essentially the experiment consisted of studying the absorption of neutrons in the energy range extending from a few thousand electron volts down to a fraction of an electron volt (thermal energies), the absorption taking place in different layers of uranium or uranium oxide spheres embedded in a pile of graphite.

4.10. In these experiments, a source of neutrons was provided by a beam of protons (accelerated by a cyclotron) impinging in a beryllium target. (The resulting yield of neutrons was equivalent to the yield from a radium-beryllium source of about 3500 curies strength.) The neutrons thus produced had a wide, continuous, velocity distribution. They proceeded from this source into a large block of graphite. By placing the various uranium or uranium-oxide spheres inside the graphite block at various positions representing increasing distances from the source, absorption of neutrons of decreasing average speeds down to thermal speeds was studied. It was found that the total absorption of neutrons by such spheres could be expressed in terms of a "surface" effect and a "mass" effect.

4.11. These experiments, involving a variety of sphere sizes, densities, and positions were continued until the spring of 1942, when most of the group was moved to Chicago. Similar experiments performed at a later date at the University of Indiana by A. C. G. Mitchell and his co-workers have verified and in some cases corrected the Princeton data, but the Princeton data were sufficiently accurate by the summer of 1941 to be used in planning the intermediate-pile experiments and the subsequent experiments on operating piles.

4.12. The experimental work on resonance absorption at Princeton was done by R. R. Wilson, E. C. Creutz, and their collaborators, under the general leadership of H. D. Smyth; they benefited from the constant help of Wigner and Wheeler and frequent conferences with the Columbia group.

The First Intermediate Experiments

4.13. About July 1941 the first lattice structure of graphite and uranium was set up at Columbia. It was a graphite cube about 8 feet on an edge, and contained about 7 tons of uranium oxide in iron containers distributed at equal intervals throughout the graphite. A preliminary set of measurements was made on this structure in August 1941. Similar structures of somewhat larger size were set up and investigated during September and October, and the so-called exponential method (described below) of determining the multiplication factor was developed and first applied. This work was done by Fermi and his assistants, H. L. Anderson, B. Feld, G. Weil, and W. H. Zinn.

4.14. The multiplication-factor experiment is rather similar to that already outlined for the determination of ν, the number of neutrons produced

per thermal neutron absorbed. A radium-beryllium neutron source is pla near the bottom of the lattice structure and the number of neutrons is sured at various points throughout the lattice. These numbers are then pared with the corresponding numbers determined when no uranium is pres the graphite mass. Evidently the absorption of neutrons by U-238 to pr U-239 tends to reduce the number of neutrons, while the fissions tend t crease the number. The question is: Which predominates? or, more prec Does the fission production of neutrons predominate over all neutron-re processes other than escape? Interpretation of the experimental data this crucial question involves many corrections, calculations, and appr tions, but all reduce in the end to a single number, the multiplication k.

The Multiplication Factor k

4.15. The whole success or failure of the uranium project de on the multiplication factor k, sometimes called the reproduction facto k could be made greater than one in a practical system, the project wou succeed; if not, the chain reaction would never be more than a dream. clear from the following discussion, which applies to any system contai fissionable material. Suppose that there is a certain number of free n present in the system at a given time. Some of these neutrons will the initiate fissions and will thus directly produce new neutrons. The mul cation factor k is the ratio of the number of these new neutrons to the of free neutrons originally present. Thus, if in a given pile comprisi uranium, carbon, impurities, containers, etc., 100 neutrons are produce fission, some will escape, some will be absorbed in the uranium without ing fission, some will be absorbed in the carbon, in the containers or purities, and some will cause fission, thereby producing more neutrons. the fissions are sufficiently numerous and sufficiently effective indiv more than 100 new neutrons will be produced and the system is chain rea If the number of new neutrons is 105, k = 1.05. But if the number of ne trons per 100 initial ones is 99, k = .99 and no chain reaction can main itself.

4.16. Recognizing that the intermediate or "exponential" exp described above was too small to be chain reacting, we see that it was of great interest whether any larger pile of the same lattice structure be chain reacting. This could be determined by calculating what the va k would be for an infinitely large lattice of this same type. In other the problem was to calculate what the value of k would be if no neutron leaked away through the sides of the pile. Actually it is found that, chain-reacting system is well above the critical size -- say two or thr times as great -- and is surrounded by what is called a reflector, the tive value of k differs very little from that for infinite size provide k is near 1.00. Consequently, it has become customary to characterize t chain-reaction potentialities of different mixtures of metal and moderat the value of k_∞ the multiplication constant obtained by assuming infinit of pile.

4.17. The value of k_∞ as reported by Fermi to the Uranium Sect in the fall of 1941 was about 0.87. This was based on results from the

Columbia intermediate experiment. All agreed that the multiplication factor could be increased by greater purity of materials, different lattice arrangements, etc. None could say with certainty that it could be made greater than one.

Experiments on Beryllium

4.18. At about the same time that the work on resonance absorption was started at Princeton, S. K. Allison, at the suggestion of A. H. Compton, began work at Chicago under a contract running from January 1, 1941 to August 1, 1941. The stated objectives of the work were to investigate (a) the increase in neutron production when the pile is enclosed in a beryllium envelope or "reflector", and (b) the cross sections of beryllium. A new contract was authorized on July 18, 1941 to run to June 30, 1942. This stated the somewhat broader objective of investigating uranium-beryllium-carbon systems generally. The appropriations involved were modest: $9,500 for the first contract, and $30,000 for the second contract.

4.19. As has already been pointed out in Chapter II, beryllium has desirable qualities as a moderator because of its low atomic weight and low neutron-absorption cross section; there was also the possibility that a contribution to the number of neutrons would be realized from the (n, 2n) reaction in beryllium. The value of the cross section was not precisely known; furthermore it was far from certain that any large amount of pure beryllium could be obtained. Allison's problem was essentially similar to the Columbia problem, except for the use of beryllium in place of graphite. Because of the scarcity of beryllium it was suggested that it might be used in conjunction with graphite or some other moderator, possibly as a reflector.

4.20. In the Chicago experiments, neutrons produced with the aid of a cyclotron were caused to enter a pile of graphite and beryllium. Allison made a number of measurements on the slowing down and absorption by graphite which were valuable checks on similar experiments at Columbia. He finally was able to obtain enough beryllium to make significant measurements which showed that beryllium was a possible moderator comparable to graphite. However, beryllium was not in fact used at all extensively in view of the great difficulty of producing it in quantity in the required structural form.

4.21. This Chicago project as described above became part of the Metallurgical Laboratory project established at the University of Chicago early in 1942.

Theoretical Work

4.22. Both the intermediate experiments at Columbia and the continued resonance-absorption work at Princeton required skilful theoretical interpretation. Fermi worked out the theory of the "exponential" pile and Wigner the theory of resonance absorption; both these men were constantly conferring and contributing to many problems. Wheeler of Princeton, Breit of Wisconsin, and Eckart of Chicago -- to mention only a few -- also made contributions to general pile theory and related topics. Altogether one can say that by the end of 1941 the general theory of the chain reaction for slow neutrons was

almost completely understood. It was the numerical constants and techno: cal possibilities that were still uncertain.

4.23. On the theory of a fast neutron reaction in U-235 a goo(of progress had also been made. In particular, new estimates of the cri size were made, and it was predicted that possibly 10 percent of the tot energy might be released explosively. On this basis one kilogram of U-2: would be equivalent to 2000 tons of TNT. The conclusions are reviewed b in connection with the National Academy Report. It is to be remembered there are two factors involved; (1) how large a fraction of the available fission energy will be released before the reaction stops; (2) how destr such a highly concentrated explosion will be.

Work on Plutonium

4.24. In Chapter I mention is made of the suggestion that the ment 94, later christened plutonium, would be formed by beta-ray disinte tions of U-239 resulting from neutron absorption by U-238 and that pluto would probably be an alpha-particle emitter of long half-life and would go fission when bombarded by neutrons. In the summer of 1940 the nuclea physics group at the University of California in Berkeley was urged to u neutrons from its powerful cyclotron for the production of plutonium, and separate it from uranium and investigate its fission properties. Variou pertinent experiments were performed by E. Segrè, G. T. Seaborg, J. W. K and M. H. Wahl at Berkeley prior to 1941 and were reported by E. O. Lawr to the National Academy Committee (see below) in May 1941 and also in a m randum that was incorporated in the Committee's second report dated July 1941. It will be seen that this memorandum includes one important idea n specifically emphasized by others (paragraph 1.58), namely, the productio large quantities of plutonium for use in a bomb.

4.25. We quote from Lawrence's memorandum as follows:

> Since the first report of the National Academy of Sciences Comm on Atomic Fission, an extremely important new possibility has been opened for the exploitation of the chain reaction with unseparated isotopes of uranium. Experiments in the Radiation Laboratory of the University of California have indicated (a) that element 94 is forme as a result of capture of a neutron by uranium 238 followed by two s cessive beta-transformations, and furthermore (b) that this transura element undergoes slow neutron fission and therefore presumably beha like uranium 235.
>
> It appears accordingly that, if a chain reaction with unseparat isotopes is achieved, it may be allowed to proceed violently for a period of time for the express purpose of manufacturing element 94 in substantial amounts. This material could be extracted by ordinar chemistry and would presumably be the equivalent of uranium 235 for chain reaction purposes.
>
> If this is so, the following three outstanding important possi- bilities are opened:

1. Uranium 238 would be available for energy production, thus increasing about one hundred fold the total atomic energy obtainable from a given quantity of uranium.

2. Using element 94 one may envisage preparation of small chain reaction units for power purposes weighing perhaps a hundred pounds instead of a hundred tons as probably would be necessary for units using natural uranium.

3. If large amounts of element 94 were available it is likely that a chain reaction with fast neutrons could be produced. In such a reaction the energy would be released at an explosive rate which might be described as a "super bomb".

Radioactive Poisons

4.26. As previously stated, the fragments resulting from fission are in most cases unstable nuclei, that is, artifically radioactive materials. It is common knowledge that the radiations from radioactive materials have deadly effects akin to the effects of X-rays.

4.27. In a chain-reacting pile these radioactive fission products build up as the reaction proceeds. (They have, in practice, turned out to be the most troublesome feature of a reacting pile.) Since they differ chemically from the uranium, it should be possible to extract them and use them like a particularly vicious form of poison gas. This idea was mentioned in the National Academy report (see paragraph 4.48) and was developed in a report written December 10, 1941, by E. Wigner and H. D. Smyth, who concluded that the fission products produced in one day's run of a 100,000 kw chain-reacting pile might be sufficient to make a large area uninhabitable.

4.28. Wigner and Smyth did not recommend the use of radioactive poisons nor has such use been seriously proposed since by the responsible authorities, but serious consideration was given to the possibility that the Germans might make surprise use of radioactive poisons and defensive measures were planned.

Isotope Separation

Small-Scale Separation by the Mass Spectrograph

4.29. In Chapter I the attribution of thermal-neutron fission of uranium to the U-235 isotope was mentioned as being experimentally established. This was done by partly separating minute quantities of the uranium isotopes in A. O. Nier's mass spectograph and then studying the nuclear properties of the samples. Additional small samples were furnished by Nier in the summer of 1941 and studied by N. P. Heydenburg and others at M. A. Tuve's laboratory at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. But results of such experiments were still preliminary, and it was evident that further study of larger and more completely separated

samples was desirable.

4.30. The need of larger samples of U-235 stimulated E. O. Lawrence at Berkeley to work on electromagnetic separation. He was remarkably successful and by December 6, 1941 reported that he could deposit in one hour one microgram of U-235 from which a large proportion of the U-238 had been removed.

4.31. Previously, at a meeting of the Uranium Committee, Smyth of Princeton had raised the question of possible large-scale separation of isotopes by electromagnetic means but had been told that it had been investigated and was considered impossible. Nevertheless, Smyth and Lawrence at a chance meeting in October 1941 discussed the problem and agreed that it might yet be possible. Smyth again raised the question at a meeting of the Uranium Committee on December 6th and at the next meeting (December 18, 1941) there was a general discussion of large-scale electromagnetic methods in connection with Lawrence's report of his results already mentioned. The consequences of this discussion are reported in Chapter XI.

The Centrifuge and Gaseous Diffusion Methods

4.32. Though we have made it clear that the separation of U-235 from U-238 might be fundamental to the whole success of the project, little has been said about work in this field. Such work had been going on since the summer of 1940 under the general direction of H. C. Urey at Columbia. Since this part of the uranium work was not very much affected by the reorganization in December 1941, a detailed account of the work is reserved for Chapters IX and X. Only a summary is presented here.

4.33. After careful review and a considerable amount of experimenting on other methods, it had been concluded that the two most promising methods of separating large quantities of U-235 from U-238 were by the use of centrifuges and by the use of diffusion through porous barriers. In the centrifuge, the forces acting on the two isotopes are slightly different because of their differences in mass. In the diffusion through barriers, the rates of diffusion are slightly different for the two isotopes, again because of their differences in mass. Each method required the uranium to be in gaseous form, which was an immediate and serious limitation since the only suitable gaseous compound of uranium then known was uranium hexafluoride. In each method the amount of enrichment to be expected in a single production unit or "stage" was very small; this indicated that many successive stages would be necessary if a high degree of enrichment was to be attained.

4.34. By the end of 1941 each method had been experimentally demonstrated in principle; that is, single-stage separators had effected the enrichment of the U-235 on a laboratory scale to about the degree predicted theoretically. K. Cohen of Columbia and others had developed the theory for the single units and for the series or "cascade" of units that would be needed. Thus it was possible to estimate that about 5000 stages would be necessary for one type of diffusion system and that a total area many acres of diffusion barrier would be required in a plant separating a

kilogram of U-235 each day. Corresponding cost estimates were tens of millions of dollars. For the centrifuge the number of stages would be smaller, but it was predicted that a similar production by centrifuges would require 22,000 separately driven, extremely high-speed centrifuges, each three feet in length -- at a comparable cost.

4.35. Of course, the cost estimates could not be made accurately since the technological problems were almost completely unsolved, but these estimates as to size and cost of plant did serve to emphasize the magnitude of the undertaking.

Thermal Diffusion in Liquids

4.36. In September 1940, P. H. Abelson submitted to Briggs a 17-page memorandum suggesting the possibility of separating the isotopes of uranium by thermal diffusion in liquid uranium hexafluoride. R. Gunn of the Naval Research Laboratory was also much interested in the uranium problem and was appointed a member of the Uranium Committee when it was reorganized under the NDRC in the summer of 1940. As a result of Abelson's suggestion and Gunn's interest, work was started on thermal diffusion at the National Bureau of Standards. This work was financed by funds from the Navy Department and in 1940 was transferred to the Naval Research Laboratory, still under the direction of Abelson, where it has continued.

4.37. We shall discuss the thermal-diffusion work further in a later chapter, but we may mention here that significant results had already been obtained by the end of 1941 and that in January 1942, using a single separation column, a separation factor had been obtained which was comparable or superior to the one obtained up to that time in preliminary tests on the diffusion and centrifuge methods.

The Production of Heavy Water

4.38. It was pointed out in Chapter II that deuterium appeared very promising as a moderator because of its low absorption and good slowing-down property but unpromising because of its scarcity. Interest in a deuterium moderator was stimulated by experimental results obtained in Berkeley demonstrating that the deuterium absorption cross section for neutrons was, in fact, almost zero. Since oxygen has a very low absorption coefficient for neutrons, it was usually assumed that the deuterium would be used combined with oxygen, that is, in the very convenient material: heavy water. Work at Columbia on possible methods of large-scale concentration of heavy water was initiated in February 1941 under the direction of H. C. Urey (under an OSRD contract). Early in 1941, R. H. Fowler of England reported the interest of the British group in a moderator of deuterium in the form of heavy water and their conviction that a chain reaction would go in relatively small units of uranium and heavy water.

4.39. Urey and A. von Grosse had already been considering the concentration of heavy water by means of a catalytic exchange reaction between hydrogen gas and liquid water. This process depends on the fact that, when isotopic equilibrium is established between hydrogen gas and water, the water

contains from three to four times as great a concentration of deuterium
does the hydrogen gas. During 1941, this exchange reaction between wate
hydrogen was investigated and extensive work was done toward developing
scale methods of producing materials suitable for catalyzing the reactio

4.40. The further development of this work and of other metho
producing heavy water are discussed in Chapter IX. Like the other isoto
separation work at Columbia, this work was relatively unaffected by the
organization in December 1941. It is mentioned in preliminary fashion h
indicate that all the principal lines of approach were under investigati
1941.

Production and Analysis of Materials

4.41. By the end of 1941 not very much progress had been made
the production of materials for use in a chain reacting system. The Nat
Bureau of Standards and the Columbia group were in contact with the Meta
Hydrides Company of Beverly, Massachusetts. This company was producing
uranium in powdered form, but efforts to increase its production and to
the powdered metal into solid ingots had not been very successful.

4.42. Similarly, no satisfactory arrangement had been made fo
taining large amounts of highly purified graphite. The graphite in use
Columbia had been obtained from the U. S. Graphite Company of Saginaw, M
It was of high purity for a commercial product, but it did contain about
part in 500,000 of boron, which was undesirable.

4.43. Largely through the interest of Allison the possibility
increasing the production of beryllium had been investigated to the exte
ascertaining that it would be difficult and expensive, but probably possi

4.44. Though little progress had been made on procurement, muc
progress had been made on analysis. The development of sufficiently acc
methods of chemical analysis of the materials used has been a problem of
first magnitude throughout the history of the project. although sometime
overshadowed by the more spectacular problems encountered. During this p
C. J. Rodden and others at the National Bureau of Standards were princip
responsible for analyses; H. T. Beans of Columbia also cooperated. By 19
several other groups had started analytical sections which have been con-
tinuously active ever since.

4.45. To summarize, by the end of 1941 there was no evidence t
procurement of materials in sufficient quantity and purity was impossible
the problems were far from solved.

Exchange of Information with the British

4.46. Prior to the autumn of 1941 there had been some exchange of reports with the British and some discussion with British scientific representatives who were here on other business. In September 1941, it was decided that Pegram and Urey should get first-hand information by a trip to England. They completed their trip in the first week of December 1941.

4.47. In general, work in England had been following much the same lines as in this country. As to the chain-reaction problem, their attention had focussed on heavy water as a moderator rather than graphite; as to isotope separation, they had done extensive work on the diffusion process including the general theory of cascades. Actually the principal importance of this visi and other interchanges during the summer of 1941 lay not in accurate scientifi data but in the general scientific impressions. The British, particularly J. Chadwick, were convinced that a U-235 chain reaction could be achieved. They knew that several kilograms of heavy water a day were being produced in Norway, and that Germany had ordered considerable quantities of paraffin to be made using heavy hydrogen; it was difficult to imagine a use for these materials other than in work on the uranium problem. They feared that if the Germans got atomic bombs before the Allies did, the war might be over in a few weeks. The sense of urgency which Pegram and Urey brough back with them was of great importance.

The National Academy Committee Report

4.48. The appointment of a National Academy committee was mentioned in Chapter III. The committee's first report in May 1940 mentioned (a) radioactive poisons, (b) atomic power, and (c) atomic bombs, but the emphasis was on power. The second report stressed the importance of the new results on plutonium, but was not specific about the military uses to which the fission process might be put. Both these reports urged that the project be pushed more vigorously.

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

> Since our last report, the progress toward separation of the isotopes of uranium has been such as to make urgent a consideration of (1) the probability of success in the attempt to produce a fission bomb, (2) the destructive effect to be expected from such a bomb, (3) the anticipated time before its development can be completed and production be underway, and (4) a preliminary estimate of the costs involved.

1. Conditions for a fission bomb

A fission bomb of superlatively destructive power will result from bringing quickly together a sufficient mass of element U-235. This seems to be as sure as any untried prediction based upon theory and experiment can be.

Our calculations indicate further that the required masses can be brought together quickly enough for the reaction to become efficient...

2. Destructive effect of fission bombs

a. Mass of the bomb

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

b. Energy released by explosive fission

Calculations for the case of masses properly located at the initial instant indicate that between 1 and 5 percent of the fission energy of the uranium should be released at a fission explosion. This means from 2 to 10 x 10^8 kilocalories per kg of uranium 235. The available explosive energy per kg of uranium is thus equivalent to about 300 tons of TNT.

3. Time required for development and production of the necessary U-235

a. Amount of uranium needed

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

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

b. Separation of U-235

The separation of the isotopes of uranium can be done in the necessary amounts. Several methods are under development, at least two of which seem definitely adequate, and are approaching the stage of practical test. These are the methods of the centrifuge and of diffusion through porous barriers. Other methods are being investigated or

need study which may ultimately prove superior, but are now farther from the engineering stage.

c. Time required for production of fission bombs

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

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

4. Rough estimate of costs

(The figures given in the Academy report under this heading were recognized as only rough estimates since the scientific and engineering data to make them more precise were not available. They showed only that the undertaking would be enormously expensive but still in line with other war expenditures.)

4.50. The report then goes on to consider immediate requirements and desirable reorganization.

Summary

4.51. At the end of Chapter I we summarized the knowledge of nuclear fission as of June 1940, and in Chapter II we stated the outstanding problems as of the same date. In the light of these statements we wish to review the eighteen months' progress that has just been recounted. The tangible progress was not great. No chain reaction had been achieved; no appreciable amount of U-235 had been separated from U-238; only minute amounts of Pu-239 had been produced; the production of large quantities of uranium metal, heavy water, beryllium, and pure graphite was still largely in the discussion stage. But there had been progress. Constants were better known; calculations had been checked and extended; guesses as to the existence and nuclear properties of Pu-239 had been verified. Some study had been made of engineering problems, process effectiveness, costs, and time schedules. Most important of all, the critical size of the bomb had been shown to be almost certainly within practical limits. Altogether the likelihood that the problems might be solved seemed greater in every case than it had in 1940. Perhaps more important than the actual change was the psychological change. Possibly Wigner, Szilard, and Fermi were no more thoroughly convinced that atomic bombs were possible than they had been in 1940, but many other people had become familiar with the idea and its possible consequences.

Apparently, the British and the Germans, both grimly at war, thought the p lem worth undertaking. Furthermore, the whole national psychology had cha Although the attack at Pearl Harbor was yet to come, the impending threat war was much more keenly felt than before, and expenditures of effort and that would have seemed enormous in 1940 were considered obviously necessar precautions in December 1941. Thus it was not surprising that Bush and hi associates felt it was time to push the uranium project vigorously. For t purpose, there was created an entirely new administrative organization whi will be described in the next chapter.

CHAPTER V

ADMINISTRATIVE HISTORY 1942-1945

5.1. In Chapter III the administrative history of the uranium up to December 1941 was reviewed. Chapter IV reported the progress of t scientific work up to the same date. The present chapter describes the ministrative reorganization that took place in December 1941 and various changes that occurred after that time.

Reorganization of NDRC Uranium Section - Transfer to OSRD

5.2. Two major decisions were required in the further plannin the uranium or atomic-bomb program. These decisions were made by Vannev Bush, Director of the Office of Scientific Research and Development (whi cluded NDRC), after conference with various scientists and administrators cerned. (See Chapter III.) The decisions were: first, that the possibi of obtaining atomic bombs for use in the present war was great enough to justify an "all out" effort for their development; second, that the exis organization, the NDRC Uranium Section (known as the S-1 Section, and co ing of L. J. Briggs, Chairman; G. B. Pegram, Vice-Chairman; H. T. Wensel Technical Aide; S. K. Allison, J. W. Beams, G. Breit, E. U. Condon, R. G H. D. Smyth, and H. C. Urey) was not properly organized for such an effo

5.3. At a meeting of the National Defense Research Committee November 28, 1941, Dr. Bush explained why he felt that it was desirable set up the uranium program outside NDRC. The members of NDRC agreed to transfer. Accordingly, the NDRC as an organization had no further conne with the uranium program, which was administered for some time thereafte the OSRD directly through an OSRD S-1 Section, and later through an OSRD Executive Committee.

5.4. At a meeting of the S-1 Section of OSRD on December 6, 19 J. B. Conant, speaking for Bush, announced the proposed "all out" effort the reorganization of the group. The S-1 Section itself had not been for consulted on the proposed reorganization, but there is no doubt that most its members were strongly in favor of the new proposals. The membership the reorganized S-1 Section was as follows:

J. B. Conant, Representative of V. Bush
L. J. Briggs, Chairman
G. B. Pegram, Vice-Chairman
A. H. Compton, Program Chief
E. O. Lawrence, Program Chief
H. C. Urey, Program Chief
E. V. Murphree, Chairman of the separately organized Planning Board
H. T. Wensel, Technical Aide
S. K. Allison
J. W. Beams

G. Breit
E. U. Condon
H. D. Smyth

Formation of the Planning Board

5.5. At the time the S-1 Section was reorganized, Bush also set up a Planning Board to be responsible for the technical and engineering aspects of the work, for procurement of materials and for construction of pilot plants and full-size production plants. This Planning Board consisted of E. V. Murphree (Chairman), W. K. Lewis, L. W. Chubb, G. O. Curme, Jr., and P. C. Keith.

Functions of the Planning Board and OSRD S-1 Section

5.6. It was arranged that contracts for the scientific parts of the work would be recommended to Bush not by the full S-1 Section but by Briggs and Conant after conferences with the program chiefs involved and that recommendations on engineering contracts would be made to Bush by the Planning Board. (The contracts which had been made on behalf of the old Uranium Section had been administered through the NDRC.) Contracts for the development of diffusion and centrifuge separation processes were to be recommended by the Planning Board, which would be responsible for the heavy-water production program also. Bush stated that the Planning Board "will be responsible for seeing to it that we have plans on which to proceed with the next step as expeditiously as possible."

5.7. The scientific aspects of the work were separated from the procurement and engineering phases. The Program Chiefs -- H. C. Urey, E. O. Lawrence, and A. H. Compton -- were to have charge of the scientific aspects. Initially it was proposed that Urey should have charge of the separation of isotopes by the diffusion and the centrifuge methods and of the research work on the production of heavy water. Lawrence was to have charge of the initial production of small samples of fissionable elements, of quantity production by electromagnetic separation methods, and of certain experimental work relating to the properties of the plutonium nucleus. Compton was to have charge of fundamental physical studies of the chain reaction and the measurement of nuclear properties with especial reference to the explosive chain reaction. As an afterthought, he was authorized to explore also the possibility that plutonium might be produced in useful amounts by the controlled chain-reaction method. It was understood, however, that this division of responsibility was to be more precisely defined in later conferences. (The written records of that period do not always give adequate accounts of what was in the minds of the men concerned. In deference to security requirements, references to the importance of plutonium and even to the bomb itself were often omitted entirely.)

5.8. The effect of the reorganization was to put the direction of the projects in the hands of a small group consisting of Bush, Conant, Briggs, Compton, Urey, Lawrence, and Murphree. Theoretically, Compton, Lawrence, Urey, and Murphree were responsible only for their respective divisions of the

program. Each met with Conant and Briggs or occasionally with Bush to d his specific problems, or even the overall program.

Meeting of Top Policy Group - Approval of Reorganization

5.9. A meeting of the Top Policy Group, consisting of Vice-Pr dent Henry A. Wallace, Secretary of War Henry L. Stimson, and Dr. V. Bus held on December 16, 1941. General George C. Marshall and Dr. J. B. Con also members of the group, were absent; Mr. H. L. Smith of the Budget Bu attended. Bush described the reorganization that was in progress and hi plans were approved. In a memorandum to Conant describing this meeting, wrote, "It was definitely felt by the entire group that OSRD should pres fast as possible on the fundamental physics and on the engineering plann and particularly on the construction of pilot plants." Bush estimated t cost of this aspect of the work would be four or five million dollars, a stated the Army should take over when full-scale construction was starte presumably when pilot plants were ready. He suggested the assignment of technically trained Army officer to become familiar with the general nat of the uranium problem. It was made clear at this meeting that the inte national relations involved were in the hands of the President, with Bus sponsible for liaison on technical matters only.

Meeting of OSRD S-1 Section on December 18, 1941

5.10. On December 18, 1941, a meeting of the reorganized S-1 Section was held. Conant was present and discussed the new policy, whic called for an all-out effort. He emphasized that such an effort was jus only by the military value of atomic bombs and that all attention must b centrated in the direction of bomb development. The whole meeting was p vaded by an atmosphere of enthusiasm and urgency. Several methods of el magnetic separation were proposed and discussed, and a number of new con were recommended.

Meeting of OSRD S-1 Section on January 16, 1942

5.11. Another meeting of the OSRD S-1 Section was held on Jan 16, 1942. Informal discussions of the various production methods took p and tentative estimates were made as to when each method would produce r These forecasts actually were no more than guesses since at that time th scientific information available was very incomplete and the problems of ing such data as did exist to the construction and operation of producti plants had hardly been approached.

Rearrangement of the Work Early in 1942

5.12. In the middle of January 1942, Compton decided to conce the work for which he was responsible at the University of Chicago. The Columbia group under Fermi and its accumulated material and equipment an Princeton group which had been studying resonance absorption were moved Chicago in the course of the spring. Certain smaller groups elsewhere r mained active under Compton's direction. Under Lawrence the investigati large-scale electromagnetic separation was accelerated at the University

California at Berkeley and a related separation project was started at Princeton. Research and development on the diffusion process and on the production of heavy water continued at Columbia under Urey; under the general supervision of Murphree, the centrifuge work continued at the University of Virginia under Beams while the Columbia centrifuge work was transferred to the laboratories of the Standard Oil Development Co. at Bayway, New Jersey.

Report to the President by Bush on March 9, 1942

5.13. In a report dated February 20, 1942, Conant recommended that all phases of the work be pushed at least until July 1, 1942. Similarly, on March 9, 1942, Dr. Bush sent a report to the President reflecting general optimism but placing proper emphasis on the tentative nature of conclusions. His report contemplated completion of the project in 1944. In addition, the report contained the suggestion that the Army be brought in during the summer of 1942 for construction of full-scale plants.

Reviews of the Program by Conant

5.14. The entire heavy-water program was under review in March and April 1942. The reviews followed a visit to the United States in February and March 1942 by F. Simon, H. Halban, and W. A. Akers from England. In a memorandum of April 1, 1942 addressed to Bush, Conant reviewed the situation and reported on conferences with Compton and Briggs. His report pointed out that extremely large quantities of heavy water would be required for a plutonium production plant employing heavy water instead of graphite as a moderator. For this reason, he reported adversely on the suggestion that Halban be invited to bring to this country the 165 liters of heavy water which he then had in England.

5.15. In a memorandum written to Bush on May 14, 1942 (shortly before a proposed meeting of Program Chiefs), Conant estimated that there were five separation or production methods which were about equally likely to succeed: the centrifuge, diffusion, and electromagnetic methods of separating U-235; the uranium-graphite pile and the uranium-heavy-water pile methods of producing plutonium. All were considered about ready for pilot plant construction and perhaps even for preliminary design of production plants. If the methods were to be pushed to the production stage, a commitment of five hundred million dollars would be entailed. Although it was too early to estimate the relative merits of the different methods accurately, it was presumed that some methods would prove to be more rapid and efficient than others. It was feared, however, that elimination of any one method might result in a serious delay. It was thought that the Germans might be some distance ahead of the United States in a similar program.

5.16. Conant emphasized a question that has been crucial throughout the development of the uranium project. The question was whether atomic bombs would be decisive weapons or merely supplementary weapons. If they were decisive, there was virtually no limit to the amount of effort and money that should be put into the work. The question was complicated by the uncertainty as to how effective the atomic bombs would be.

Change from OSRD S-1 Section to OSRD S-1 Executive Committee

5.17. In May 1942, Conant suggested to Bush that instead of en couraging members of the section individually to discuss their own phase: the work with Conant and Briggs, the OSRD S-1 Section should meet for ge discussions of the entire program. Bush responded by terminating the OS S-1 Section and replacing it with the OSRD S-1 Executive Committee, cons: of the following:

J. B. Conant, Chairman
L. J. Briggs
A. H. Compton
E. O. Lawrence
E. V. Murphree
H. C. Urey

H. T. Wensel and I. Stewart were selected to sit with the Committee as Te cal Aide and Secretary respectively.

5.18. The following members of the old OSRD S-1 Section were a pointed as consultants to the new Committee:

S. K. Allison
J. W. Beams
G. Breit
E. U. Condon
H. D. Smyth

5.19. The functions of the new OSRD S-1 Executive Committee we

(a) To report on the program and budget for the next eighteen months, for each method.

(b) To prepare recommendations as to how many programs should be continued.

(c) To prepare recommendations as to what parts of the program should be eliminated.

5.20. Recommendations relative to matters of OSRD S-1 policy a relative to the letting of OSRD S-1 contracts were made on the basis of a majority vote of the Committee. Conant refrained from voting except in c of a tie vote. While Bush alone had the authority to establish OSRD poli and commit OSRD funds, he ordinarily followed the recommendations of the Executive Committee.

Report to the President by Bush and Conant on June 17, 1942

5.21. On June 13, 1942, Bush and Conant sent to Vice-President Henry A. Wallace, Secretary of War Henry L. Stimson, and Chief of Staff G George C. Marshall a report recommending detailed plans for the expansion continuation of the atomic-bomb program. All three approved the report.

June 17, 1942, the report was sent by Bush to the President, who also approved. The report, which is too long to present in full, contained four principal parts, which dealt with: (a) The status of the development as appraised by the senior scientists; (b) Recommendations by the program chiefs and Planning Board; (c) Comments by Bush, Conant, and General W. D. Styer; (d) Recommendations by Bush and Conant. We may paraphrase parts (a) and (c) as follows:

(a) The status of the program.

(1) It was clear that an amount of U-235 or plutonium comprising a number of kilograms would be explosive, that such an explosion would be equivalent to several thousand tons of TNT, and that such an explosion could be caused to occur at the desired instant.

(2) It was clear that there were four methods of preparing the fissionable material and that all of these methods appeared feasible; but it was not possible to state definitely that any given one of these is superior to the others.

(3) It was clear that production plants of considerable size could be designed and built.

(4) It seemed likely that, granted adequate funds and priorities, full-scale plant operation could be started soon enough to be of military significance.

(c) Comments by Bush, Conant, and General Styer.

Certain recommendations had been made by Lawrence, Urey, Compton, and Murphree. These recommendations had been reviewed by Bush, Conant, and General Styer (who was instructed by General Marshall to follow the progress of the program) and their comments concerning the program were as follows:

(1) If four separate methods all appeared to a highly competent scientific group to be capable of successful application, it appeared certain that the desired end result could be attained by the enemy, provided he had sufficient time.

(2) The program as proposed obviously could not be carried out rapidly without interfering with other important matters, as regards both scientific personnel and critical materials.

A choice had to be made between the military result which appeared attainable and the certain interference with other war activities.

(3) It was unsafe at that time, in view of the pioneering nature of the entire effort, to concentrate on only one means of obtaining the result.

(4) It therefore appeared best to proceed at once with those phases of the program which interfered least with other important war activities. Work on other phases of the program could proceed after questions of interference were resolved.

5.22. The June 13, 1942, report to the President and Bush's transmittal letter dated June 17, 1942, were returned to Bush with the in itialled approval of the President. A copy of the report was then sent b Bush to General Styer on June 19, 1942.

Selection of Colonel J. C. Marshall

5.23. On June 18, 1942, Colonel J. C. Marshall, Corps of Engin was instructed by the Chief of Engineers to form a new district in the Co of Engineers to carry on special work (atomic bombs) assigned to it. Thi district was designated the Manhattan District and was officially establi on August 13, 1942. The work with which it was concerned was labeled, fo security reasons, the "DSM Project" (Development of Substitute Materials)

Selection of General L. R. Groves

5.24. On September 17, 1942, the Secretary of War placed Briga General L. R. Groves of the Corps of Engineers in complete charge of all activities relating to the DSM Project.

Military Policy Committee; Functioning of the OSRD Committees

5.25. A conference was held on September 23, 1942, among those persons designated by the President to determine the general policies of project, and certain others. Those present were Secretary of War Henry L Stimson, Chief of Staff General George C. Marshall, Dr. J. B. Conant, Dr. Bush, Major General Brehon Somervell, Major General W. D. Styer, and Brig General L. R. Groves. (Vice-President Henry A. Wallace was unable to att A Military Policy Committee was appointed consisting of Dr. V. Bush as Ch man with Dr. J. B. Conant as his alternate, Major General W. D. Styer, an Rear Admiral W. R. Purnell. General Groves was named to sit with the com and act as Executive Officer to carry out the policies that were determin The duties of this committee were to plan military policies relating to m als, research and development, production, strategy, and tactics, and to mit progress reports to the policy group designated by the President.

5.26. The appointment of the Military Policy Committee was approved by the Joint New Weapons Committee, established by the U. S. Joint Chiefs of Staff and consisting of Dr. V. Bush, Rear Admiral W. R. Purnell, and Brig. General R. G. Moses.

5.27. The creation of the Military Policy Committee in effect placed all phases of the DSM Project under the control of Dr. Bush, Dr. Conant, General Styer, Admiral Purnell, and General Groves.

5.28. The OSRD S-1 Executive Committee held meetings about once every month from June 1942 to May 1943 and once after that time, in September 1943. These meetings were normally attended by General Groves, after September 1942, and Col. Marshall, and frequently by representatives of the industrial companies concerned with the production plants. Recommendations of the Committee were not binding but were usually followed. Thus it served as an advisory body to Dr. Bush and General Groves, and as an initial liaison group between the scientific, industrial, and military parts of the DSM Project. The S-1 Executive Committee has never been formally dissolved, but it has been inactive since the fall of 1943.

5.29. The procurement and engineering functions of the Planning Board were taken over by the Manhattan District in the summer of 1942 and that board then became inactive.

5.30. By the spring of 1943 it was felt that the Manhattan District was in a position to take over research and development contracts from the OSRD. Such a transfer was effected as of May 1, 1943, and marked the end of the formal connection of OSRD with the uranium project.

5.31. In July 1943 Conant and R. C. Tolman were formally asked by General Groves to serve as his scientific advisers. They had already been doing so informally and have continued to do so. Coordination of the various scientific and technical programs was accomplished by meetings between General Groves and the leaders of the various projects, in particular, Compton, Lawrence, Oppenheimer (see Chapter XII), and Urey.

Subsequent Organization; the Manhattan District

5.32. Since 1943 there have been no important changes in the form of the organization and few of importance in the operating personnel. General Groves has continued to carry the major responsibility for correlating the whole effort and keeping it directed toward its military objectives. It has been his duty to keep the various parts of the project in step, to see that raw materials were available for the various plants, to determine production schedules, to make sure that the development of bomb design kept up with production schedules, to arrange for use of the bombs when the time came, and to maintain an adequate system of security. In discharging these duties General Groves has had the help of his tremendous organization made up of civilian scientists and engineers and Engineer officers and enlisted men. Many of the civilians have been mentioned already or will be mentioned in later chapters dealing with particular projects. Brigadier General T. F. Farrell has acted as General Groves' deputy in the important later phases of the

of the project. Colonel K. D. Nichols, the District Engineer of the Man hattan District with his headquarters at the Clinton Engineer Works, has connected with the project since 1942. He has been concerned with the research and production problems of both U-235 and plutonium and has alw shown exceptional understanding of the technical problems and their relative importance. Two other officers who should be mentioned are Colonel F. T. Matthias and Colonel S. L. Warren. Colonel Matthias has discharged major responsibilities at the Hanford Engineer Works in an extremely able manner; his duties have been concerned with both the construction and operational phases of the project. Colonel Warren is c of the Medical Section of the Manhattan District and therefore has had ultimate responsibility for health problems in all parts of the project.

Summary

5.33. By the end of 1941 an extensive review of the whole uranium situation had been completed. As a result of this review Bush a his advisers decided to increase the effort on the uranium project and t change the organization. This decision was approved by President Roosev From January 1942 until early summer of 1942 the uranium work was direct Bush and Conant working with the Program Chiefs and a Planning Board. I summer of 1942 the Army, through the Corps of Engineers, was assigned an active part in the procurement and engineering phases, organizing the Manhattan District for the purpose. In September 1942, Dr. Bush, Dr. Co General Styer, and Admiral Purnell were appointed as a Military Policy Committee to determine the general policies of the whole project. Also i September, General Groves was appointed to take charge of all Army activities of the project. The period of joint OSRD and Army control continued through April 1943 with the Army playing an increasingly import role as the industrial effort got fully under way. In May 1943 the resea contracts were transferred to the Corps of Engineers; the period of joint OSRD-Army control ended and the period of complete Army control began.

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

CHAPTER VI

THE METALLURGICAL PROJECT AT CHICAGO IN 1942

Introduction

6.1. As has been made clear in Chapters IV and V, the informat accumulated by the end of 1941 as to the possibility of producing an aton bomb was such as to warrant expansion of the work, and this expansion cal for an administrative reorganization. It was generally accepted that the 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 eleme 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 significa quantities from U-238, either by electromagnetic or statistical methods; whether or not a chain reaction could be established with natural uranium its compounds and could be made to yield relatively large quantities of plutonium; and whether or not the plutonium so produced could be separate from the parent material, uranium. It was hoped also that the program wo provide the theoretical and experimental data required for the design of fast-neutron chain-reacting bomb.

6.2. As has been explained in Chapter V, the problems of isoto 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 "Metallurigical Laboratory" of the University Chicago. In this chapter and the following two chapters we shall describ the work of the Metallurgical Laboratory and the associated laboratories 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 relat importance of the contributions of the various laboratories to the overal success of the atomic-bomb project. This report makes no such attempt, a there is little correlation between the space devoted to the work of a gi group and the ability or importance of that group. In deciding which subdivision of the atomic-bomb project should be discussed first and most fu 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 kep secret. Such criteria, applied to the objectives and accomplishments of t 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 b considered to mark the end of an epoch at the Metallurgical Laboratory. Furthermore, in preparation for the reviewing committee's visit a compre hensive report had been prepared. That report was generally known as th "Feasibility Report" and has been used extensively in preparing this cha

Plan of this Chapter

6.7. In this chapter we shall present the material in the orde the objectives given above. In Part I we shall discuss progress towards initial objectives, including (a) procurement of materials, (b) the expe imental proof of the chain reaction, (c) the chemistry of plutonium and s of the problems of separation, (d) some of the types of auxiliary experi that were performed, and finally (e) the "fast neutron" work. Necessaril the work described in detail is only a sampling of the large amount of theoretical and experimental work actually performed. In Part II we shal 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 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 needed in highly purified metallic form or at least as highly purified uranium oxide. The other materials which were going to be needed were ei 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 seeme less advantageous and almost as difficult to get. Therefore the procurem efforts for a moderator were centered on graphite. As has been explained Chapter V, procurement of uranium and graphite was not primarily the responsibility of the Metallurgical Laboratory but was handled through E. Murphree and others on the "planning board." In fact, the obvious intere of the Metallurgical Laboratory in the problem led to continual interventi by its representatives. A great deal of the credit for the eventual succe 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 commerical 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 t 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 w expected to be at the rate of 500 pounds per day by January 1943. The pur of the metal was good, and the cost had dropped to $22 per pound.

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

6.16. Neither the Westinghouse process nor the Metal Hydrides Process was entirely satisfactory. Intensive activity designed to acceler ate 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 o 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 a the end of the year, under the general direction of Colonel Ruhoff, former with the Mallinckrodt Chemical Works. From the point of view of the Metallurgical Project no further serious delays or difficulty have occurre 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 co 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 urani oxide from Mallinckrodt was available to permit building intermediate pi No. 9. As in previous experiments, a radium-beryllium neutron source wa 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 distanc from the neutron source, (hence the name often used for experiments of t type, "exponential pile") and that, from such rates of decrease, the multiplication constant k for an infinitely large pile of the same latti proportions could be calculated. For the first time the multiplication constant k so calculated from experimental results came out greater than (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 a 1.05 could be obtained in a pile containing highly purified uranium oxid 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 auxiliar experiments done during this period. There was one, however, -- the stu of delayed neutrons -- that we shall discuss because it is a good exampl the kind of experiment that had to be performed and because it concerned effect, not heretofore mentioned, that is of great importance in control a chain-reacting pile.

6.24. From previous investigations, some of which were alread 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 emiss of beta rays from shortlived radioactive substances. Several half-lives been observed, the longest being of the order of a minute.

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

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

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 release 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 respons for developing the instruments and controls, and a great many others in 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 pil to prove that there were conditions under which a chain reaction would o but the ultimate objective of the laboratory was to produce plutonium by chain reaction. Therefore we are interested in the relation between the power at which a pile operates and the rate at which it produces plutoni The relation may be evaluated to a first approximation rather easily. A running stably must be producing as many neutrons as it is losing. For thermal neutron absorbed in U-235 a certain number of neutrons, η, is em One of these neutrons is required to maintain the chain. Therefore, ass the extra neutrons all are absorbed by U-238 to form plutonium, there wi η -1 atoms of Pu^{239} formed for every fission. Every fission releases ro 200 Mev of energy. Therefore the formation of η -1 atoms of plutonium accompanies the release of about 200 Mev. Since η -1 is a small number, can guess that to produce a kilogram a day of plutonium a chain-reacting must be releasing energy at the rate of 500,000 to 1,500,000 kilowatts. first chain-reacting pile that we have just described operated at a maxi of 200 watts. Assuming that a single bomb will require the order of one 100 kilograms of plutonium, the pile that has been described would have kept going at least 70,000 years to produce a single bomb. Evidently th problem of quantity production of plutonium was not yet solved.

The Chemistry of Plutonium

6.33. The second specific objective of the Metallurgical Labor 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 found. Progress towards this objective was necessarily slower than towa the attainment of a chain reaction. Initially little was done at the Met lurgical Laboratory on chemical problems although the extraction problem discussed in a conference soon after the project was organized and the w of Seaborg's group at the University of California on plutonium was encouraged. On April 22-23, 1942, a general conference on chemistry was he 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. 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 p poses; second, to obtain a good understanding of the chemistry necessary the construction and maintenance of the pile. The separation problem was 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 $_{93}Np^{238}$ which disintegrates to $_{94}Pu^{238}$ 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 microchemical 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 fabricatio of uranium rods and tubes, the study of fission products, and the determin tion of the biological effects of radiation. As typical of this kind of w we can cite the development of methods of fabricating and coating uranium metal, under the direction of E. Creutz. Without the accomplishment of th 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 w 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 Wisconsi 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. Conseque ly, 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 suitabl 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 fissio cross section, the energy spectrum of fission neutrons, and the time delay i the emission of fission neutrons. For the most part this work represented s 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 b

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 fabricatio 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, th "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 ur nor heavy water was available. Development of both these types continue however, since if no other type proved feasible they might have to be us Type I c, calling for liquid bismuth cooling, seemed very promising from point of view of utilization of the thermal energy released, but it was 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 produ plants were being planned, it was recognized that a plant of intermediat size was desirable. Such a plant was needed for two reasons: first, as pilot plant; second, as a producer of a few grams of plutonium badly nee for experimental purposes. Designed as an air-cooled plant of 1000-kw capacity, the intermediate pile constructed at Clinton, Tennessee, might l served both purposes if helium cooling had been retained for the main pl Although the plans for the main plant were shifted so that water cooling 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 be a pilot plant except for chemical separation. Actually the main plan was built without benefit of a true pilot plant, much as if the hydroele generators at Grand Coulee had been designed merely from experience gain 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 lo better for eventual full-scale use. A number of specific proposals were for construction of such plants and for the further study of the problems involved. These proposals were based on time and cost estimates which we

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.

CHAPTER VII

THE PLUTONIUM PRODUCTION PROBLEM AS OF FEBRUARY 1943

Introduction

Need of Decisions

7.1. By the first of January 1943, the Metallurgical Laborat achieved its first objective, a chain-reacting pile, and was well on th to the second, a process for extracting the plutonium produced in such It was clearly time to formulate more definite plans for a production p The policy decisions were made by the Policy Committee (see Chapter V) recommendations from the Laboratory Director (A. H. Compton), from the Executive Committee, and from the Reviewing Committee that had visited in December 1942. The only decisions that had already been made were t first chain-reacting pile should be dismantled and then reconstructed o site a short distance from Chicago and that a 1000-kilowatt plutonium p should be built at Clinton, Tennessee.

The Scale of Production

7.2. The first decision to be made was on the scale of produ that should be attempted. For reasons of security the figure decided u may not be disclosed here. It was very large.

The Magnitude of the Problem

7.3. As we have seen, the production of one gram of plutonium day corresponds to a generation of energy at the rate of 500 to 1500 ki watts. Therefore a plant for large-scale production of plutonium will a very large amount of energy. The problem therefore was to design a pl this capacity on the basis of experience with a pile that could operate power level of only 0.2 kilowatt. As regards the plutonium separation w which was equally important, it was necessary to draw plans for an extra and purification plant which would separate some grams a day of plutoniu some tons of uranium, and such planning had to be based on information o tained by microchemical studies involving only half a milligram of pluto To be sure, there was information available for the design of the large- pile and separation plant from auxiliary experiments and from large-scal studies of separation processes using uranium as a stand-in for plutoniu but even so the proposed extrapolations both as to chain-reacting piles as to separation processes were staggering. In peacetime no engineer or scientist in his right mind would consider making such a magnification i single stage, and even in wartime only the possibility of achieving tre- mendously important results could justify it.

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 same 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 Hanfor Engineer Works in the State of Washington. Because of its close connect with fundamentalresearch, the Clinton semi-works was to be operated unde 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 Cl to provide the University with much needed personnel, particularly men w 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 n role in chemistry into a new field involving nuclear physics, it was agr that it would be necessary for them to depend most heavily upon the Meta lurgical Laboratory of the University of Chicago for fundamental researc development data and for advice. The du Pont Company had engineering an industrial experience, but it needed the Metallurgical Laboratory for nu physics and radiochemistry experience. The Metallurgical Laboratory con ducted the fundamental research on problems bearing on the design and op tion of the semi-works and large-scale production plants. It proposed t essential parts of the plutonium production and recovery processes and e ment, answered the many specific questions raised by du Pont, and studie concurred in the final du Pont decisions and designs.

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

Choice of Plant Site

7.11. Once the scale of production had been agreed upon and t responsibilities assigned, the nature of the plant and its whereabouts h be decided. The site in the Tennessee Valley, known officially as the C Engineer Works, had been acquired by the Army for the whole program as re mended in the report to the President (see Chapter V).

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

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 eral problem of the uranium project as it appeared in the summer of 194(now wish to give precise definition to the problem of the design of a le scale plant for the production of plutonium. The objective had already delimited by decisions as to scale of production, type of plant, and sit As it then stood, the specific problem was to design a water-cooled gra moderated pile (or several such piles) with associated chemical separati plant to produce a specified, relatively large amount of plutonium each the plant to be built at the Hanford site beside the Columbia River. Ne to say, speed of construction and efficiency of operation were prime cor siderations.

Nature of the Lattice

7.19. The lattices we have been describing heretofore consist lumps of uranium imbedded in the graphite moderator. There are two obje tions to such a type of lattice for production purposes: first, it is d ficult to remove the uranium without disassembling the pile; second, it difficult to concentrate the coolant at the uranium lumps, which are the points of maximum production of heat. It was fairly obvious that both t difficulties could be avoided if a rod lattice rather than a point latt 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 struc turally and mechanically, but there was real doubt as to whether it was sible to build such a lattice which would still have a multiplication fa k greater than unity. This became a problem for both the theoretical an experimental physicists. The theoretical physicists had to compute what the optimum spacing and diameter of uranium rods; the experimental physi had to perform exponential experiments on lattices of this type in order check the findings of the theoretical group.

Loading and Unloading

7.20. Once the idea of a lattice with cylindrical symmetry wa cepted, it became evident that the pile could be unloaded and re-loaded out disassembly since the uranium could be pushed out of the cylindrical channels in the graphite moderator and new uranium inserted. The decisi had to be made as to whether the uranium should be in the form of long r which had advantages from the nuclear-physics point of view, or of relati short cylindrical pieces, which had advantages from the point of view of handling. In either case, the materials would be so very highly radioact that unloading would have to be carried out by remote control, and the ur loaded uranium would have to be handled by remote control from behind shi ing.

Possible Materials; Corrosion

7.21. If water was to be used as coolant, it would have to be conveyed to the regions where heat was generated through channels of some sort. Since graphite pipes were not practical, 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 en is by no means a small one. How much water was needed depended, of cour on the maximum temperature to which the water could safely be heated and maximum temperature to be expected in the intake from the Columbia River certainly the water supply requirement was comparable to that of a fair- city. Pumping stations, filtration and treatment plants all had to be p vided. Furthermore, the system had to be a very reliable one; it was ne sary to provide fast-operating controls to shut down the chain-reacting in a hurry in case of failure of the water supply. If it was decided to "once-through" cooling instead of recirculation, a retention basin would required so that the radioactivity induced in the water might die down b 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, therefore the minimum time that the water must be held for absolute safe had to be determined.

Controls and Instrumentation

7.27. The control problem was very similar to that discussed connection with the first chain-reacting pile except that everything was a larger scale and was, therefore, potentially more dangerous. It was n sary to provide operating controls which would automatically keep the pi operating at a determined power level. Such controls had to be connecte with instruments in the pile which would measure neutron density or some property which indicated the power level. There would also have to be e gency controls which would operate almost instantaneously if the power l showed signs of rapid increase or if there was any interruption of the w supply. It was highly desirable that there be some means of detecting i cipient difficulties such as the plugging of a single water tube or a br the coating of one of the uranium slugs. All these controls and instrum 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 g off from a pile operating at a high power level is so strong as to make 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 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 p sible to load and unload the pile through these shields and to carry the supply in and out through the shields. The shields should not only be r tion-tight but air-tight since air exposed to the radiation in the pile become radioactive.

7.29. The radiation dangers that require shielding in the pil continue through a large part of the separation plant. Since the fissio products associated with the production of the plutonium are highly radi active, the uranium after ejection from the pile must be handled by remo

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 ar almost completely buried in the ground. Each compartment would contain necessary dissolving or precipitating tanks or centrifuges. The slugs v come into the compartment at one end of the canyon; they would then be c solved and go through the various stages of solution, precipitation, oxi tion, or reduction, being pumped from one compartment to the next until solution of plutonium free from uranium and fission products came out ir last compartment. As in the case of the pile, everything would be opera by remote control from above ground, but the operations would be far mor complicated than in the case of the pile. However, as far as the chemic operations themselves were concerned, their general nature was not so fa 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 tine analysis of samples which was necessary in checking the operation c various chemical processes had to be done by remote control. Such testi was facilitated, however, by use of radioactive methods of analysis as w as conventional chemical analyses.

Waste Disposal

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

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

Recovery of Uranium

7.37. Evidently, even if the uranium were left in the pile un all the U-235 had undergone fission, there would still be a large amount U-238 which had not been converted to plutonium. Actually the process i stopped long before this stage is reached. Uranium is an expensive mate and the total available supply is seriously limited. Therefore the poss bility of recovering it after the plutonium is separated must be conside Originally there was no plan for early recovery, but merely the intentio storing the uranium solution. Later, methods of large-scale recovery we 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, therefc remained a major problem of the Metallurgical Laboratory.

The Training of Operators

7.44. Evidently the operation of a full-scale plant of the typ planned would require a large and highly skilled group of operators. Alt du Pont had a tremendous background of experience in the operation of var kinds of chemical plant, this was something new and it was evident that c ating personnel would need special training. Such training was carried c partly in Chicago and its environs, but principally at the Clinton Labora tories.

The Need for Further Information

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

The Research Program

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

> Product Production Studies - These include all aspects of the researc development and semi-works studies necessary for the design, construc and operation of chain-reacting piles to produce plutonium or other materials.
>
> > Pile Characteristics - Theoretical studies and experiments on la structures to predict behavior in high-level piles, such as temp ture and barometric effects, neutron characteristics, pile poiso etc.
> >
> > Control of Reacting Units - Design and experimental tests of dev 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, ma handling operations, etc.

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

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

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

General Physics - Basic instrument (electronic, ionization, opt etc.) research, atomic mass determinations, neutron, α, β, γ ra tion studies, X-ray investigations, etc.

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

Nuclear Chemistry - Tracing of fission products, disintegration stants, chains, investigation of nuclei of possible use to proj

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

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

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

Clinical Investigations - Basic investigations, such as hematol 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 proce

7.47. An examination of this program gives an idea of the gre 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 M. 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. Cantril, 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. Greenewalt, spend much of their time at Chicago. Miles and Greenewalt 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. Whital 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 had been made to build a tonium production plant with a large capacity. This meant a pile devel thousands of kilowatts and a chemical separation plant to extract the pl The du Pont Company was to design, construct, and operate the plant; the Metallurgical Laboratory was to do the necessary research. A site was on the Columbia River at Hanford, Washington. A tentative decision to b a helium-cooled plant was reversed in favor of water-cooling. The princ problems were those involving lattice design, loading and unloading, che of materials particularly with reference to corrosion and radiation, wat supply, controls and instrumentation, health hazards, chemical separatic process, and design of the separation plant. Plans were made for the ne sary fundamental and technical research and for the training of operator Arrangements were made for liaison between du Pont and the Metallurgical Laboratory.

CHAPTER VIII

THE PLUTONIUM PROBLEM
JANUARY 1943 TO JUNE 1945

Introduction

8.1. The necessity for pushing the design and construction of full-scale plutonium plant simultaneously with research and development evitably led to a certain amount of confusion and inefficiency. It beca essential to investigate many alternative processes. It became necessar investigate all possible causes of failure even when the probability of becoming serious was very small. Now that the Hanford plant is producir plutonium successfully, we believe it is fair to say that a large percer of the results of investigation made between the end of 1942 and the end 1944 will never be used -- at least not for the originally intended purp Nevertheless had the Hanford plant run into difficulties, any one of the superfluous investigations might have furnished just the information req to convert failure into success. Even now it is impossible to say that improvements may not depend on the results of researches that seem unimp today.

8.2. It is estimated that thirty volumes will be required for complete report of the significant scientific results of researches cond under the auspices of the Metallurgical Project. Work was done on every mentioned on the research program presented in the last chapter. In the sent account it would be obviously impossible to give more than a brief stract of all these researches. We believe this would be unsatisfactory that it is preferable to give a general discussion of the chain-reacting and separation plants as they now operate, with some discussion of the e developments.

The Chain Reaction in a Pile

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

8.4. The operation of a pile depends on the passage of neutro through matter and on the nature of the collisions of neutrons with the 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., $_{92}U^{239}$ which produces $_{94}Pu^{239}$).

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:

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

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

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

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. A the tendency of the neutrons to be absorbed by the dominant isotope U-2 so great compared to their tendency to produce fission in the 140-times U-235 that the principal design effort had to be directed toward favori fission (as by using a moderator, a suitable lattice, materials of high 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 Metallurgi Laboratory or with its cooperation consist of four categories of materi the uranium metal, the moderator, the coolant, and the auxiliary materi such as water tubes, casings of uranium, control strips or rods, impuri etc. All the piles depend on stray neutrons from spontaneous fission o mic rays to initiate the reaction.

8.9. Suppose that the pile were to be started by simultaneou lease (in the uranium metal) of N high-energy neutrons. Most of these trons originally have energies above the threshold energy of fission of However, as the neutrons pass back and forth in the metal and moderator, suffer numerous inelastic collisions with the uranium and numerous elas collisions with the moderator, and all these collisions serve to reduce energies below that threshold. Specifically, in a typical graphite-mod pile a neutron that has escaped from the uranium into the graphite trav on the average about 2.5 cm between collisions and makes on the average 200 elastic collisions before passing from the graphite back into the u Since at each such collision a neutron loses on the average about one of its energy, a one Mev neutron is reduced to thermal energy (usually t to be 0.025 electron volt) considerably before completing a single tran through the graphite. There are, of course, many neutrons that depart f this average behavior, and there will be enough fissions produced by fa trons to enhance slightly the number of neutrons present. The enhanceme may be taken into account by multiplying the original number of neutron by a factor ε which is called the fast-fission effect or the fast-multip tion factor.

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

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

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 Nϵpf 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 η, 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, Nϵpf, by η, we have the number of new high speed neutrons generated by the original N high speed neutrons in the course of their lives. If Nϵpfη is greater than N, we have a chain reaction and the number of neutrons is continually increasing. Evidently the product ϵpfη = k_∞, 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_∞ as defined above applies to an infinite lattice. From the known values of k_∞ 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 ne 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 pr at Hanford: actual production in the pile, and separation of the pluton from the uranium slugs in which it is formed. We turn now to a discussi of the second part, the separation process.

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

8.18. In addition to radioactive fission products, U-239 and N (intermediate products in the formation of plutonium) are present in the and are radioactive. The concentrations of all these products begin to b up at the moment the pile starts operating. Eventually the rate of radi active decay equals the rate of formation so that the concentrations bec constant. For example, the number of atoms of U-239 produced per second constant for a pile operating at a fixed power level. According to the l of radioactive disintegration, the number of U-239 atoms disappearing pe second is proportional to the number of such atoms present and is thus i creasing during the first few minutes or hours after the pile is put int operation. Consequently there soon will be practically as many nuclei di integrating each second as are formed each second. Equilibrium concentra for other nuclei will be approached in similar manner, the equilibrium co tration being proportional to the rate of formation of the nucleus and to half-life. Products which are stable or of extremely long half-life (e.g plutonium) will steadily increase in concentration for a considerable tim When the pile is stopped, the radioactivity of course continues, but at a tinually 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 appreciably active for days or months. Thus at any time the concentratio of the various products in a recently stopped pile depend on what the pow level was, on how long the pile ran, and on how long it has been shut dow

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 quence of repeated operations (called cycles), thereby limiting the numb different equipment pieces requiring design and allowing considerable pr change without equipment change. Thus, while the basic plant design was with one method in mind, the final choice of a different method led to r barrassments.

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

Combination Processes.

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

8.25. At the time when it became necessary to decide on the p to serve as the basis for the design of the Hanford plant (June 1943), t choice, for reasons given above, was limited to precipitation processes 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 ex all expectations. The high yields and decontamination factors and the r ease of operation have amply demonstrated the wisdom of its choice as a This choice was based on a knowledge of plutonium chemistry which had be gleaned from less than a milligram of plutonium. Further developments m make the present Hanford process obsolete, but the principal goal, which to have a workable and efficient process for use as soon as the Hanford were delivering plutonium, has been attained.

The Argonne Laboratory

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

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 as thermal-fission cross sections of U-235, U-238, and Pu-239, probabili of non-fission neutron absorption by each of these nuclei, and number of trons emitted per fission.

The Clinton Plant

8.34. In Chapter VI we mentioned plans for a "pilot" plant fo production of plutonium to be built at the Clinton site in Tennessee. B January 1943, the plans for this project were well along; construction w started soon afterward. M. D. Whitaker was appointed director of the Cl Laboratories. The pilot-plant plans were made cooperatively by du Pont the Metallurgical Laboratory; construction was carried out by du Pont; p operation was maintained by the University of Chicago as part of the Met lurgical Project.

8.35. The main purposes of the Clinton plant were to produce plutonium and to serve as a pilot plant for chemical separation. As reg research, the emphasis at Clinton was on chemistry and biological effect radiations. A large laboratory was provided for chemical analysis, for search on purification methods, for fission-product studies, for develop of intermediate-scale extraction and decontamination processes, etc. La a "hot laboratory", i.e., a laboratory for remotely-controlled work on h radioactive material, was provided. There is also an instrument shop an laboratory that has been used very actively. There are facilities for b clinical and experimental work of the health division, which has been ve active. There is a small physics laboratory in which some important wor done using higher neutron intensities than were available at the Argonne Laboratory. The principal installations constructed at the Clinton Labo site were the pile and the separation plant; these are briefly described low.

The Clinton Pile

8.36. In any steadily operating pile the effective multiplica factor k must be kept at one, whatever the power level. The best k_{∞} tha been observed in a uranium-graphite lattice could not be achieved in a p cal pile because of neutron leakage, cooling system, cylindrical channel the uranium, protective coating on the uranium, and other minor factors. Granted air-cooling and a maximum safe temperature for the surface of the nium, a size of pile had to be chosen that could produce 1000 kw. The ef tive k would go down with rising temperature but not sufficiently to be a determining factor. Though a sphere was the ideal shape, practical consi tions recommended a rectangular block.

8.37. The Clinton pile consists of a cube of graphite containi horizontal channels filled with uranium. The uranium is in the form of m cylinders protected by gas-tight casings of aluminum. The uranium cylind or slugs may be slid into the channels in the graphite; space is left to mit cooling air to flow past, and to permit pushing the slugs out at the 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, in

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 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°C. Improvements in the air circulation and an elevation of the maximum uranium surface temperature to 150°C brought the power level up to about 800 kw, where it was maintained until the spring of 1944. Starting at that time, a change was made in 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 exce expectations. In ease of control, steadiness of operation, and absence c dangerous radiation, the pile has been most satisfactory. There have bee very few failures attributable to mistakes in design or construction.

8.45. The pile itself was simple both in principle and in prac Not so the plutonium-separation plant. The step from the first chain-rea pile to the Clinton pile was reasonably predictable; but a much greater a more uncertain step was required in the case of the separation process, i the Clinton separation plant was designed on the basis of experiments usi only microgram amounts of plutonium.

8.46. Nevertheless, the separation process worked! The first of slugs from the pile entered the separation plant on December 20, 1943. the end of January 1944, metal from the pile was going to the separation at the rate of 1/3 ton per day. By February 1st, 1944, 190 mg of plutoni had been delivered and by March 1st, 1944, several grams had been deliver Furthermore, the efficiency of recovery at the very start was about 50 pe 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 chem at Clinton working on improving the process and developing it for Hanford The Hanford problem differed from that at Clinton in that much higher con trations of plutonium were expected. Furthermore, though the chemists we to be congratulated on the success of the Clinton plant, the process was plicated and expensive. Any improvements in yield or decontamination or general simplification were very much to be sought.

8.48. Besides the proving of the pile and the separation plant the production of several grams of plutonium for experimental use at Chic Clinton, and elsewhere, the Clinton Laboratories have been invaluable as training and testing center for Hanford, for medical experiments, pile st 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 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, the problem of sealing the uranium slugs in protective metal jackets. Or periodic visits to Chicago the writer could roughly estimate the state of 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 protect uranium from water corrosion, would keep fission products out of water, would transmit heat from the uranium to the water, and would not a too many neutrons. Yet the failure of a single can might conceivably rec shut-down of an entire operating pile.

8.53. Attempts to meet the stringent requirements involved exp mental work on electroplating processes, hot-dipping processes, cementati coating processes, corrosion-resistant alloys of uranium, and mechanical jacketing or canning processes. Mechanical jackets or cans of thin alumi were feasible from the nuclear point of view and were chosen early as the likely solution of the problem. But the problem of getting a uniform, he conducting bond between the uranium and the surrounding aluminum, and the problem of effecting a gas-tight closure for the can both proved very tro some. Development of alternative methods had to be carried along up to t last minute, and even up to a few weeks before it was time to load the ur slugs into the pile there was no certainty that any of the processes unde development would be satisfactory. A final minor but apparently importan modification in the preferred canning process was adopted in October 1944 after the first pile had begun experimental operation. By the summer of 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 o 1945 the second and third Hanford piles were finished and put into operat as were the additional chemical separation plants. There were, of course some difficulties; however, none of the fears expressed as to canning fai film formation in the water tubes, or radiation effects in the chemical p cesses, have turned out to be justified. As of early summer 1945 the pil are operating at designed power, producing plutonium, and heating the Columbia River. The chemical plants are separating the plutonium from th uranium and from the fission products with better efficiency than had bee anticipated. The finished product is being delivered. How it can be use 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 grap in slowing down neutrons and it has a smaller neutron absorption than gra 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 mu 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. T shields, controls, heat exchanger, etc., have operated satisfactorily.

The Health Division

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

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

1) Adoption of pre-employment physical examinations an frequent re-examinations, particularly of those exposed to radiation.

2) Setting of tolerance standards for radiation doses development of instruments measuring exposure of personnel; giving advic on shielding, etc.; continually measuring radiation intensities at vario locations in the plants; measuring contamination of clothes, laboratory waste water, the atmosphere, etc.

3) Carrying out research on the effects of direct expos of persons and animals to various types of radiation, and on the effects ingestion and inhalation of the various radioactive or toxic materials su as fission products, plutonium and uranium.

Routine Examinations

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

8.66. At the same time it was recognized that the white blood-corpuscle count is not an entirely reliable criterion. Some work on anim indicated that serious damage might occur before the blood count gave any indication of danger. Accordingly, more elaborate blood tests were made 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 pe The first of these instruments was a simple electroscope about the size a shape of a fountain pen. Such instruments were electrostatically charged 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 α-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 gases (at Clinton and at Hanford) would be likely to spread radioactive fission products in dangerous concentrations. Since the behavior of these gases 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 sorption in U-238 leads to the formation of plutonium, the desired produc

8.73. The course of a nuclear chain reaction in a graphite-moc ated heterogeneous pile can be described by following a single generatio neutrons. The original fast neutrons are slightly increased in number b fission, reduced by resonance absorption in U-238 and further reduced by sorption at thermal energies in graphite and other materials and by escaj the remaining neutrons, which have been slowed in the graphite, cause fi in U-235, producing a new generation of fast neutrons similar to the pre generation.

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

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

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

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

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

CHAPTER IX

GENERAL DISCUSSION OF THE SEPARATION OF ISOTOPES

Introductory 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 separat 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 ma and structures differ, the nuclear charges are identical and therefore t external electronic structures are practically identical. For most prac 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 a in continual motion and that their average kinetic energy depends only o the temperature, not on the chemical properties of the molecules. Thus a gas made up of a mixture of two isotopes the average kinetic energy of light molecules and of the heavy ones is the same. Since the kinetic en of a molecule is $1/2\ mv^2$, where m is the mass and v the speed of the mol it is apparent that on the average the speed of a lighter molecule must greater than that of a heavier molecule. Therefore, at least in princip any process depending on the average speed of molecules can be used to separate isotopes. Unfortunately, the average speed is inversely propor to the square root of the mass so that the difference is very small for gaseous compounds of the uranium isotopes. Also, although the average sp differ, the ranges of speed show considerable overlap. In the case of th 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 st or pulled with a string. But they are subject to gravitational fields ar if ionized, may be affected by electric and magnetic fields. Gravitation 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 isotope. 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:

$$r = \frac{n_1'/n_2'}{n_1/n_2}$$

This definition may be applied to one stage of a separation plant or to entire plant consisting of many stages. We are usually interested eithe in the "single stage" separation factor or in the "overall" separation factor of the whole process. If r is only slightly greater than unity, 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 $m_1 = 235$, $m_2 = 238$, 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 9 percent U-235 from natural uranium the overall value of r must be about

Yield

9.9. In nearly every process a high separation factor means a low yield, a fact that calls for continual compromise. Unless indicatio 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 pl 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 l 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 impoverishe 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 gases 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" α, 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° 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 separa isotopes (except, perhaps, the isotopes of hydrogen) by diffusion proces Actually, however, such methods may be used successfully — even for ura 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 foll 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 industria process. The separation of alcohol and water (between which the differe in boiling point is in the neighborhood of 20° C.) is commonly carried o in a simple still using but a single evaporator and condenser. The condensed material (condensate) may be collected and redistilled a number o 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 operatio 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 t streams being in intimate contact and constantly exchanging molecules. molecules of the fraction having the lower boiling point have a relativel greater tendency to get into the vapor stream and vice versa. Such count current distillation methods can be applied to the separation of light a 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 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 force 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. Beams 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 therm convection set up a countercurrent flow, and thermal diffusion caused th preferential flow of the heavy molecules outward across the interface be tween the two currents.

9.23. The theory of thermal diffusion in gases is intricate en 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 accomplis by ordinary chemical reactions. It has in fact been found that in simpl exchange reactions between compounds of two different isotopes the so-ca equilibrium constant is not exactly one, and thus that in reactions of t type separation can occur. For example, in the catalytic exchange of hydrogen atoms between hydrogen gas and water, the water contains betwee three and four times as great a concentration of deuterium as the hydrog gas in equilibrium with it. With hydrogen and water vapor the effect is the same general type but equilibrium is more rapidly established. It i possible to adapt this method to a continuous countercurrent flow arrang ment like that used in distillation, and such arrangements are actually i use for production of heavy water. The general method is well understoo and the separation effects are known to decrease in general with increas molecular weight, so that there is but a small chance of applying it suc fully to heavy isotopes like uranium.

Electrolysis Method

9.25. The electrolysis method of separating isotopes resulted f the discovery that the water contained in electrolytic cells used in the regular commercial production of hydrogen and oxygen has an increased con centration of heavy water molecules. A full explanation of the effect ha not yet been worked out. Before the war practically the entire productio 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 s far (diffusion, distillation, centrifugation, thermal diffusion, exchange reactions, and electrolysis) have all been tried with some degree of succ 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.

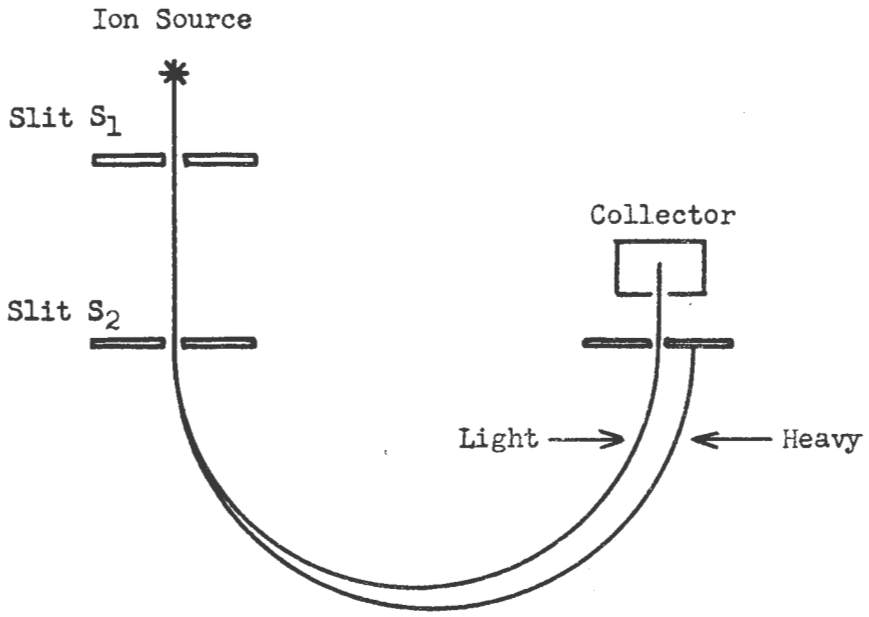
9.27. The criteria set up for judging separation processes are rather similar for the six statistical methods. In every case the separation factor is small so that many successive stages of separation are required. In most cases relatively large quantities of material can be handled in plants of moderate 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

radii proportional to their momenta. Therefore the light ions will move in smaller semicircles than the heavy, and with proper positioning of th collector, only the light ions will be collected.



9.30. Postponing detailed discussion of such a separation devi we may point out the principal considerations that limit the amount of material that passes through it. They are threefold: First, it is difficult to produce large quantities of gaseous ions. Second, a sharpl limited ion beam is usually employed (as in the case shown) so that only a fraction of the ions produced are used. Third, too great densities of ions in a beam can cause space-charge effects which interfere with the separating action. Electromagnetic methods developed before 1941 had ve high separation factors but very low yields and efficiencies. These wer the reasons which -- before the summer of 1941 -- led the Uranium Commit to exclude such methods for large-scale separation of U-235. (See Chapt IV.) Since that time it has been shown that the limitations are not insuperable. In fact, the first appreciable-sized samples of pure U-235 were produced by an electromagnetic separator, as will be described in a later chapter.

Other Isotope-Separation Methods

9.31. In addition to the isotope-separation methods described above, several other methods have been tried. These include the ionic-mobility method, which, as the name implies, depends on the following fac In an electrolytic solution two ions which are chemically identical but of different mass progress through the solution at different rates under

the action of an electric field. However, the difference of mobility will be small and easily obscured by disturbing effects. A. K. Brewer of the Bureau of Standards reported that he was able to separate the isotopes of potassium by this method. Brewer also obtained some interesting results with an evaporation method. Two novel electromagnetic methods, the isotron and the ionic centrifuge, are described in Chapter XI. The isotron produced a number of fair-sized samples of partly separated uranium. The ionic centrifuge also produced some uranium samples showing separation, but its action was erratic.

Cascades and Combined Processes

9.32. In all the statistical methods of separating isotopes many successive stages of separation are necessary to get material that is 90 percent or more U-235 or deuterium. Such a series of successive separating stages is called a cascade if the flow is continuous from one stage to the next. (A fractionating tower of separate plates such as has been described is an example of a simple cascade of separating units.) A complete analysis of the problems of a cascade might be presented in general terms. Actually it has been worked out by R. P. Feynman and others for a certain type of electromagnetic separator and by K. Cohen, I. Kaplan, and others for diffusion processes. At present we shall make only two points about multiple stage or "cascade" plants.

9.33. The first point is that there must be recycling. Considering a U-235 separation plant, the material fed into any stage above the first has already been enriched in U-235. Part of this feed material may be further enriched in passing through the stage under consideration. The remainder will typically become impoverished but not so much impoverished as to be valueless. It must be returned to an earlier stage and recycled. Even the impoverished material from the first (least enriched) stage may be worth recycling; some of the U-235 it still contains may be recovered (stripped).

9.34. The second point is that the recycling problem changes greatly at the higher (more enriched) stages. Momentarily disregarding recycling and assuming steady stage operation, we see that the net flow of uranium through the first stage must be at least 140 times as great as through the last stage. The net flow in any given stage is proportional to the relative concentration of U-238 and thus decreases with the number of stages passed. Also we shall see that any given sample of material is recycled many times so that the amount of material processed in any stage is far greater than the net flow through that stage but is proportional to it.

9.35. We mention these points to illustrate a phase of the separation problem that is not always obvious, namely, that the separation

process which is best for an early stage of separation is not necessari best for a later stage. Factors such as those we have mentioned differ only from stage to stage but from process to process. For example, recy is far simpler in a diffusion plant than in an electromagnetic plant. A plant combining two or more processes may well be the best to accomplish overall separation required. In the lower (larger) stages the size of t equipment and the power required for it may determine the choice of proc In the higher (smaller) stages these factors are outweighed by convenien of operation and hold-up time, which may point to a different process.

The Heavy Water Plants; the Centrifuge Pilot Plant

9.36. The next two chapters are devoted to descriptions of th three methods used for large-scale separation of the uranium isotopes. These are the only isotope-separation plants that have turned out to be major importance to the project up to the present time. At an earlier s it seemed likely that the centrifuge might be the best method for separa the uranium isotopes and that heavy water would be needed as a moderator We shall describe briefly the centrifuge pilot plant and the heavy water production plants.

The Heavy Water Plants

9.37. Two methods were used for the concentration of deuteriu These were the fractional distillation of water and the hydrogen-water exchange reaction method.

9.38. The first of these follows well established fractional distillation methods except that very extensive distillation is required because of the slight difference in boiling point of light and heavy wate Also, because of this same small difference, the amount of steam required is very large. The method is very expensive because of these factors, bu plants could be constructed with a minimum of development work. Plants were started by du Pont in January 1943, and were put into operation abou January 1944.

9.39. The second method for the preparation of heavy water depends upon the catalytic exchange of deuterium between hydrogen gas and water. When such an exchange is established by catalysts, the concentrat of the deuterium in the water is greater than that in the gas by a factor about three as we have already seen.

9.40. In this process water is fed into a tower and flows coun currently to hydrogen and steam in an intricate manner. At the bottom of the tower the water is converted to hydrogen gas and oxygen gas in electr lytic cells and the hydrogen is fed back to the bottom of the tower mixed with steam. This steam and hydrogen mixture passes through beds of catal

and bubbles through the downflowing water. Essentially, part of the deuterium originally in the hydrogen concentrates in the steam and then is transferred to the downflowing water. The actual plant consists of a cascade of towers with the largest towers at the feed end and the smallest towers at the production end. Such a cascade follows the same general principle as those discussed above in connection with separation problems in general. This process required the securing of very active catalysts for the exchange reactions. The most effective catalyst of this type was discovered by H. S. Taylor at Princeton University, while a second, less active catalyst was discovered by A. V. Grosse. In the development of these catalysts R. H. Crist of Columbia University made the necessary determinations of physical constants and H. R. Arnold of du Pont did the development work on one of the catalysts.

9.41. This process was economical in operation. The plant was placed at the works of the Consolidated Mining & Smelting Co., at Trail, British Columbia, Canada, because of the necessity of using electrolytic hydrogen. The construction of the plant was under the direction of E. V. Murphree and F. T. Barr of the Standard Oil Development Co.

The Centrifuge Pilot Plant

9.42. For a long time in the early days of the project the gaseous diffusion method and the centrifuge method were considered the two separation methods most likely to succeed with uranium. Both were going to be difficult to realize on a large scale. After the reorganization in December 1941 research and development on the centrifuge method continued at the University of Virginia and at the Standard Oil Development Company's laboratory at Bayway. To make large centrifuges capable of running at very high speeds was a major task undertaken by the Westinghouse Electric and Manufacturing Company of East Pittsburgh.

9.43. Because of the magnitude of the engineering problems involved, no large scale production plant was ever authorized but a pilot plant was authorized and constructed at Bayway. It was operated successfully and gave approximately the degree of separation predicted by theory. This plant was later shut down and work on the centrifuge method was discontinued. For this reason no further discussion of the centrifuge method is given in this report.

Isotope Separation Compared With Plutonium Production

9.44. The most important methods of isotope separation that have been described were known in principle and had been reduced to practice before the separation of uranium isotopes became of paramount importance. They had not been applied to uranium except for the separation of a few micrograms, and they had not been applied to any substance on a scale comparable to that now required. But the fundamental questions were of costs, efficiency, and time, not of principle; in other words, the problem was

fundamentally technical, not scientific. The plutonium production probl did not reach a similar stage until after the first self-sustaining chai reacting pile had operated and the first microgram amounts of plutonium been separated. Even after this stage many of the experiments done on t plutonium project were of vital interest for the military use either of U-235 or plutonium and for the future development of nuclear power. As consequence, the plutonium project has continued to have a more general interest than the isotope separation projects. Many special problems ar in the separation projects which were extremely interesting and required high order of scientific ability for their solution but which must still kept secret. It is for such reasons that the present non-technical repo has given first emphasis to the plutonium project and will give less spa to the separation projects. This is not to say that the separation prob was any easier to solve or that its solution was any less important.

Summary

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

CHAPTER X

THE SEPARATION OF THE URANIUM ISOTOPES BY GASEOUS DIFFUSION

Introduction

10.1. It was in February 1940 that small amounts of concentra fractions of the three uranium isotopes of masses 234, 235, and 238 were tained by A. O. Nier using his mass spectrometer and were turned over to E. T. Booth, A. von Grosse, and J. R. Dunning for investigation with the Columbia University cyclotron. These men soon demonstrated that U-235 w the isotope susceptible to fission by thermal neutrons. It was natural, therefore, that this group, under the leadership of Dunning, became more terested than ever in the large-scale separation of the uranium isotopes

10.2. The diffusion method was apparently first seriously rev by Dunning in a memorandum to G. B. Pegram, which was sent to L. J. Brig in the fall of 1940. This memorandum summarized preliminary investigati that had been carried on by E. T. Booth, A. von Grosse and J. R. Dunning Work was accelerated in 1941 with financial help provided by a contract H. C. Urey had received from the Navy for the study of isotope separatio principally by the centrifuge method. During this period F. G.Slack of Vanderbilt University and W. F. Libby of the University of California jo the group. An OSRD contract (OEMsr-106) calling specifically for diffus studies went into effect on July 1, 1941 and ran for a year. The work c tinued on an expanding scale under a series of OSRD and Army contracts t the spring of 1945. Up until May 1943 Dunning was in immediate charge o work; Urey was in charge of statistical methods in general. From that t until February 1945 Urey was in direct charge of the Columbia part of th diffusion work, with Dunning continuing as director of one of the princi divisions. On March 1, 1945, the laboratory was taken over from Columbi Carbide and Carbon Chemicals Corporation. Early in 1942, at the suggest of E. V. Murphree, the M. W. Kellogg Company was brought in to develop p for large-scale production of diffusion-plant equipment and eventually t build a full-scale plant. To carry out this undertaking, a new subsidia company was formed called the Kellex Corporation. In January 1943, Carb and Carbon Chemicals Corporation was given the responsibility for operat the plant.

10.3. As stated in Chapter IV, by the end of 1941 the possibi of separating the uranium hexafluorides had been demonstrated in princip by means of a single-stage diffusion unit employing a porous barrier (fo example, a barrier made by etching a thin sheet of silver-zinc alloy wit hydrochloric acid). A considerable amount of work on barriers and pumps also been done but no answer entirely satisfactory for large-scale opera had been found. Also, K. Cohen had begun a series of theoretical studie which reference has already been made, as to what might be the best way use the diffusion process, i.e., as to how many stages would be required, what aggregate area of barrier would be needed, what volume of gas would

to be circulated, etc.

10.4. Reports received from the British, and the visit by the British group in the winter of 1941-1942, clarified a number of points. At that time the British were planning a diffusion separation plant themselves so that the discussions with F. Simon, R. Peierls, and others were particularly valuable.

The Principles of Separation by Diffusion

A Single Diffusion Stage

10.5. As was explained in the last chapter, the rate of diffusion of a gas through an ideal porous barrier is inversely proportional to the square root of its molecular weight. Thus if a gas consisting of two isotopes starts to diffuse through a barrier into an evacuated vessel, the lighter isotope (of molecular weight M_1) diffuses more rapidly than the heavier (of molecular weight M_2). The result (for a short period of time, at least) is that the relative concentration of the lighter isotope is greater on the far side of the barrier than on the near side. But if the process is allowed to continue indefinitely, equilibrium will become established and the concentrations will become identical on both sides of the barrier. Even if the diffusate gas (the gas which has passed through the barrier) is drawn away by a pump, the relative amount of the heavy isotope passing through the barrier will increase since the light isotope on the near side of the barrier has been depleted by the earlier part of the diffusion.

10.6. For a single diffusion operation, the increase in the relative concentration of the light isotope in the diffused gas compared to the feed gas can be expressed in terms of the separation factor r or the enrichment factor, r-1, both defined in paragraph 9.8 of the last chapter. A rather simple equation can be derived which gives r-1 in terms of the molecular weights and the fraction of the original gas which has diffused. If this fraction is very small, the equation reduces to $r = \alpha$, the "ideal separation factor" of paragraph 9.14. If the fraction diffused is appreciable, the equation shows the expected diminution in separation. For example, if half the gas diffuses, $r-1 = .69\ (\alpha - 1)$, or for uranium hexafluoride $r = 1.003$ compared to the value of 1.0043 when a very small fraction of the original gas has diffused.

The Cascade

10.7. To separate the uranium isotopes, many successive diffusion stages (i.e., a cascade) must be used since $\alpha = 1.0043$ for $U^{235}F_6$ and $U^{238}F_6$, a possible gas for uranium separation. Studies by Cohen and others have shown that the best flow arrangement for the successive stages is that in which half the gas pumped into each stage diffuses through the barrier, the other (impoverished) half being returned to the feed of the next lower stage. For such an arrangement, as we have seen, the ideal separating effect between the feed and output of a single stage is $0.69\ (\alpha - 1)$. This is often called ε, the

"overall enrichment per stage." For the uranium hexafluorides, $\mathcal{E} = 0.0$ theory; but it is somewhat less in practice as a result of "back diffus of imperfect mixing on the high pressure side, and of imperfections in barrier. The first experimental separation of the uranium hexafluoride E. T. Booth, H. C. Paxton, and C.B. Slade) gave results corresponding t $\mathcal{E} = 0.0014$. If one desires to produce 99 percent pure $U^{235}F_6$, and if uses a cascade in which each stage has a reasonable overall enrichment then it turns out that roughly 4000 stages are required.

Gas Circulation in the Cascade

10.8. Of the gas that passes through the barrier of any give stage, only half passes through the barrier of the next higher stage, t other half being returned to an earlier stage. Thus most of the materi that eventually emerges from the cascade has been recycled many times. culation shows that for an actual uranium-separation plant it may be ne to force through the barriers of the first stage 100,000 times the volu gas that comes out the top of the cascade (i.e., as desired product U^{23} The corresponding figures for higher stages falls rapidly because of re in amount of unwanted material ($U^{238}F_6$) that is carried along.

The Problem of Large-Scale Separation

Introduction

10.9. By the time of the general reorganization of the atomic project in December 1941, the theory of isotope separation by gaseous di sion was well understood. Consequently it was possible to define the te cal problems that would be encountered in building a large-scale separat plant. The decisions as to scale and location of such plant were not ma until the winter of 1942-1943, that is, about the same time as the corre ing decisions were being made for the plutonium production plants.

The Objective

10.10. The general objective of the large-scale gaseous diffu plant was the production each day of a specified number of grams of uran containing of the order of ten times as much U-235 as is present in the quantity of natural uranium. However, it was apparent that the plant wo be rather flexible in operation, and that, considerable variations might made -- as desired -- in, say, degree of enrichment of the final product.

The Process Gas

10.11. Uranium hexafluoride has been mentioned as a gas that be suitable for use in the plant as "process gas"; not the least of its tages is that fluorine has only one isotope so that the UF_6 molecules of given uranium isotope all have the same mass. This gas is highly reactiv and is actually a solid at room temperature and atmospheric pressure. Th fore the study of other gaseous compounds of uranium was urgently underta

As insurance against failure in this search for alternative gases, it was necessary to continue work on uranium hexafluoride, as in devising methods for producing and circulating the gas.

The Number of Stages

10.12. The number of stages required in the main cascade of the plant depended only on the degree of enrichment desired and the value of overall enrichment per stage attainable with actual barriers. Estimates were made which called for several thousand stages. There was also to be a "stripping" cascade of several hundred stages, the exact number depending on how much unseparated U-235 could economically be allowed to go to waste.

Barrier Area

10.13. We have seen that the total volume of gas that must diffuse through the barriers is very large compared to the volume of the final product. The rate at which the gas diffuses through unit area of barrier depends on the pressure difference on the two sides of the barrier and on the porosity of the barrier. Even assuming full atmospheric pressure on one side and zero pressure on the other side, and using an optimistic figure for the porosity, calculations showed that many acres of barrier would be needed in the large-scale plant.

Barrier Design

10.14. At atmospheric pressure the mean free path of a molecule is of the order of a ten-thousandth of a millimeter or one tenth of a micron. To insure true "diffusive" flow of the gas, the diameter of the myriad holes in the barrier must be less than one tenth the mean free path. Therefore the barrier material must have almost no holes which are appreciably larger than 0.01 micron (4×10^{-7} inch), but must have billions of holes of this size or smaller. These holes must not enlarge or plug up as the result of direct corrosion or dust coming from corrosion elsewhere in the system. The barrier must be able to withstand a pressure "head" of one atmosphere. It must be amenable to manufacture in large quantities and with uniform quality. By January, 1942, a number of different barriers had been made on a small scale and tested for separation factor and porosity. Some were thought to be very promising, but none had been adequately tested for actual large-scale production and plant use.

Pumping and Power Requirements

10.15. In any given stage approximately half of the material entering the stage passes through the barrier and on to the next higher stage, while the other half passes back to the next lower stage. The diffused half is at low pressure and must be pumped to high pressure before feeding into the next stage. Even the undiffused portion emerges at somewhat lower pressure than it entered and cannot be fed back to the lower stage without pumping. Thus the total quantity of gas per stage (comprising twice the amount which flows through the barrier) has to be circulated by means of pumps.

10.16. Since the flow of gas through a stage varies greatly w: the position of the stage in the cascade, the pumps also vary greatly in or number from stage to stage. The type and capacity of the pump requir for a given stage depends not only on the weight of gas to be moved but the pressure rise required. Calculations made at this time assumed a fo pressure of one atmosphere and a back pressure (i.e., on the low pressur side of the barrier) of one tenth of an atmosphere. It was estimated th thousands of pumps would be needed and that thousands of kilowatts would required for their operation. Since an unavoidable concommitant to pumpi gas is heating it, it was evident that a large cooling system would have be provided. By early 1942, a good deal of preliminary work had been don on pumps. Centrifugal pumps looked attractive in spite of the problem of sealing their shafts, but further experimental work was planned on comple sealed pumps of various types.

Leaks and Corrosion

10.17. It was clear that the whole circulating system comprisi pumps, barriers, piping, and valves would have to be vacuum tight. If an lubricant or sealing medium is needed in the pumps, it should not react w the process gas. In fact none of the materials in the system should reac with the process gas since such corrosion would lead not only to plugging the barriers and various mechanical failures but also to absorption (i.e. virtual disappearance) of uranium which had already been partially enrich

Actual vs. Ideal Cascade

10.18. In an ideal cascade, the pumping requirements change fr stage to stage. In practice it is not economical to provide a different of pump for every stage. It is necessary to determine how great a depart from the ideal cascade (i.e., what minimum number of pump types) should b employed in the interest of economy of design, repair, etc. Similar comp mises are used for other components of the cascade.

Hold-up and Start-up Time

10.19. When first started, the plant must be allowed to run un- disturbed for some time, until enough separation has been effected so tha each stage contains gas of appropriate enrichment. Only after such stabilization is attained is it desirable to draw off (from the top stage) any of the desired product. Both the amount of material involved (the hol up) and the time required (the start-up time) are great enough to constit major problems in their own right.

Efficiency

10.20. It was apparent that there would be only three types of material loss in the plant contemplated, namely: loss by leakage, loss by corrosion (i.e., chemical combination and deposition), and loss in plant waste. It was expected that leakage could be kept very small and that -- after an initial period of operation -- loss from corrosion would be small The percentage of material lost in plant waste would depend on the number

stripping stages.

Detailed Design

10.21. Questions as to how the barrier material was to be used (whether in tubes or sheets, in large units or small units), how mixing was to be effected, and what controls and instruments would be required all were still to be decided. There was little reason to expect them to be unanswerable, but there was no doubt that they would require both theoretical and experimental study.

Summary of the Problem

10.22. By 1942 the theory of isotope separation by gaseous diffusion had been well worked out, and it became clear that a very large plant would be required. The major equipment items in this plant were diffusion barriers and pumps. Neither the barriers nor the pumps which were available at that time had been proved generally adequate. Therefore the further development of pumps and barriers was especially urgent. There were also other technical problems to be solved, these involving corrosion, vacuum seals, and instrumentation.

Organization

10.23. As we mentioned at the beginning of this chapter, the diffusion work was initiated by J. R. Dunning. The work was carried on under OSRD auspices at Columbia University until May 1, 1943, when it was taken over by the Manhattan District. In the summer of 1943 the difficulties encountered in solving certain phases of the project led to a considerable expansion, particularly of the chemical group. H. C. Urey, then director of the work, appointed H. S. Taylor of Princeton associate director and added E. Mack, Jr. of Ohio State, G. M. Murphy of Yale, and P. H. Emmett of Johns Hopkins to the senior staff. Most of the work was moved out of the Columbia laboratories to a large building situated near by. Early in 1944, L. M. Currie of the National Carbon Company became another associate director to help Urey in his liaison and administrative work.

10.24. As has been mentioned, the M. W. Kellogg Company was chosen in 1942 to plan the large-scale plant. For these purposes Kellogg created a special subsidiary called Kellex Corporation, and put P. C. Keith in charge of it. The new subsidiary not only planned and procured materials for the large-scale plant, but also carried on research and development in its Jersey City laboratories and later in the large building referred to in the paragraph above. The plant was constructed by the J. A. Jones Construction Company, Incorporated, of Charlotte, North Carolina.

10.25. In January 1943, Carbide and Carbon Chemicals Corporation were chosen to be the operators of the completed plant. Their engineers soon began to play a large role not only in the planning and construction but also in the research work.

Research, Development, Construction, and Production - 1942 to 1945

Production of Barriers

10.26. Even before 1942, barriers had been developed that wer thought to be satisfactory. However, the barriers first developed by E. Booth, H. C. Paxton, and C. B. Slade were never used on a large scale be of low mechanical strength and poor corrosion resistance. In 1942, unde general supervision of Booth and F. G.Slack and with the cooperation of various scientists including F. C. Nix of the Bell Telephone Laboratorie barriers of a different type were produced. In particular, a barrier de veloped by E. O. Norris and E. Adler was thought sufficiently satisfacto to be specified for plant use. Other barriers had been developed by com the ideas of several men at the Columbia laboratories (by now christened SAM Laboratories), Kellex, Bell Telephone Laboratories, Bakelite Corpora Houdaille-Hershey Corporation, and others. Several of these barriers we actually adopted for the plant and installed in many stages. Many modif tions have been tried and by the summer of 1945 a considerably different barrier than that first suggested was preferred, particularly in respect ease of manufacture. By 1945 the problem was no longer one of barely me minimum specifications, but of making improvements resulting in greater of output or greater economy of operation.

10.27. Altogether the history of barrier development reminds writer of the history of the "canning" problem of the plutonium project. each case the methods were largely cut and try, and satisfactory or near satisfactory solutions were repeatedly announced; but in each case a rea satisfactory solution was not found until the last minute and then prove be far better than had been hoped.

Pumps and Seals

10.28. The early work on pumps was largely under the supervisi of H. A. Boorse of Columbia University. When Kellex came into the pictur in 1942, its engineers took leading positions in the development of pumps and seals. It must be remembered that these pumps are to be operated und reduced pressure, must not leak, must not corrode, and must have as small volume as possible. Many different types of centrifugal blower pumps and reciprocating pumps were tried. In one of the pumps for the larger stage the impeller is driven through a coupling containing a very novel and ingenious type of seal. Another type of pump is completely enclosed, its centrifugal impeller and rotor being run from outside, by induction.

Miscellaneous Developments

10.29. As in the plutonium problem, so here also, there were m questions of corrosion, etc., to be investigated. New coolants and lubri cants were developed by A. L. Henne and his associates, by G. H. Cady, by W. T. Miller and his co-workers, by E. T. McBee and his associates, and b scientists of various corporations including Hooker Electrochemical Co., du Pont Co. and the Harshaw Chemical Co. Methods of pretreating surfaces

against corrosion were worked out. Among the various instruments designed or adapted for project use, the mass spectrograph deserves special mention. The project was fortunate in having the assistance of A. O. Nier of the University of Minnesota, whose mass spectrograph methods of isotope analysis were sufficiently advanced as to become of great value to the project, as in analyzing samples of enriched uranium. Mass spectrographs were also used in pretesting parts for vacuum leaks and for detecting impurities in the process gas in the plant.

Pilot Plants

10.30. Strictly speaking, there was no pilot plant. That is to say, there was no small-scale separation system set up using the identical types of blowers, barriers, barrier mountings, cooling, etc., that were put into the main plant. Such a system could not be set up because the various elements of the plant were not all available prior to the construction of the plant itself. To proceed with the construction of the full-scale plant under these circumstances required foresight and boldness.

10.31. There was, however, a whole series of so-called pilot plants which served to test various components or groups of components of the final plant. Pilot plant No. 1 was a 12-stage plant using a type of barrier rather like that used in the large-scale plant, but the barrier material was not fabricated in the form specified for the plant and the pumps used were sylphon-sealed reciprocating pumps, not centrifugal pumps. Work on this plant in 1943 tested not only the barriers and general system of separation but gave information about control valves, pressure gauges, piping, etc. Pilot plant No. 2, a larger edition of No. 1 but with only six stages, was used in late 1943 and early 1944, particularly as a testing unit for instruments. Pilot plant No. 3a, using centrifugal blowers and dummy diffusers, was also intended chiefly for testing instruments. Pilot plant No. 3b was a real pilot plant for one particular section of the large-scale plant.

Plant Authorization

10.32. In December 1942, the Kellogg Company was authorized to proceed with preliminary plant design and in January 1943 the construction of a plant was authorized.

The Site

10.33. As stated in an earlier chapter, a site in the Tennessee Valley had originally been chosen for all the Manhattan District plants, but the plutonium plant was actually constructed elsewhere. There remained the plutonium pilot plant already described, the gaseous diffusion plant, the electromagnetic separation plant (see Chapter XI), and later the thermal diffusion plant which were all built in the Tennessee Valley at the Clinton site, known officially as the Clinton Engineer Works.

10.34. This site was examined by Colonel Marshall, Colonel Nichols, and representatives of Stone and Webster Engineering Corporation in July 1942, and its acquisition was recommended. This recommendation was endorsed by the OSRD S-1 Executive Committee at a meeting in July 1942. Final approval was

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 acqu the tract, which is on the Clinch River about thirty miles from Knoxvill Tennessee, and eventually considerably exceeded 70 square miles. The pl tonium pilot plant is located in one valley, the electromagnetic separat plant in an adjoining one, and the diffusion separation plant in a third

10.35. Although the plant and site development at Hanford is impressive, it is all under one company dealing with but one general ope tion so that it is in some respects less interesting than Clinton, which a great multiplicity of activity. To describe the Clinton site, with its great array of new plants, its new residential districts, new theatres, school system, seas of mud, clouds of dust, and general turmoil is outsi 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 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 ther 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 from 1940 to 1945, not lightened by such exciting half-way marks as the f chain-reacting pile at Chicago. Perhaps more than any other group in the project, those who have worked on gaseous diffusion deserve credit for co age and persistence as well as scientific and technical ability. For sec reasons, we have not been able to tell how they solved their problems -- in many cases found several solutions, as insurance against failure in th plant. It has been a notable achievement. In these five years there hav been periods of discouragement and pessimism. They are largely forgotten 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 isotope 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. S the amount of separation that could be effected by a single stage was very small, several thousand successive stages were required. It was found tha

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 M. W. Kellogg Company was chosen to design the plant and set up the Kellex Corporation for the purpose. The plant was built by the J.A. Jones Construction Company. The Carbide and Carbon Chemicals Corporation was selected as operating company.

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 ISOTOPES

Introduction

11.1. In Chapter IV we said that the possibility of large-sca separation of the uranium isotopes by electromagnetic means was suggeste in the fall of 1941 by E. O. Lawrence of the University of California an H. D. Smyth of Princeton University. In Chapter IX we described the pri ciples of one method of electromagnetic separation and listed the three limitations of that method: difficulty of producing ions, limited fract of ions actually used, and space charge effects.

11.2. By the end of December 1941, when the reorganization of whole uranium project was effected, Lawrence had already obtained some samples of separated isotopes of uranium and in the reorganization he wa 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 physic of the chain reaction to the large-scale production of plutonium, the ob of Lawrence's division immediately shifted to the effecting of large-scal separation of uranium isotopes by electromagnetic methods. This change w prompted by the success of the initial experiments at California and by t development at California and at Princeton of ideas on other possible met Of the many electromagnetic schemes suggested, three soon were recognized being the most promising: the "calutron" mass separator, the magnetron-t separator later developed into the "ionic centrifuge," and the "isotron" method of "bunching" a beam of ions. The first two of these approaches w 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 laborat in Pittsburgh) on a small scale through the winter of 1944-1945. Work on isotron was continued at Princeton until February 1943, when most of the group was transferred to other work. Most of this chapter will be devote 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 therm diffusion plant built to provide enriched feed material for the electro- magnetic 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 abundances of isotopes, not to separate large samples. Using vapor from uranium bromide Nier had prepared several small samples of separated isotopes of uranium, but his rate of production was very low indeed, since his ion current amounted to less than one 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 potenti able to effect much larger scale separations than had ever before been a proached. It was evidently desirable to explore the whole field of elec magnetic separation. With this end in view, Lawrence mobilized his grou 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. C. Aebersold, W. M. Brobeck, F. A. Jenkins, K. R. MacKenz W. B. Reynolds, D. H. Sloan, F. Oppenheimer, J. G. Backus, B. Peters, A. Helmholz, T. Finkelstein, and W. E. Parkins, Jr. Lawrence called back s of his former students, including R. L. Thornton, J. R. Richardson, and others. Among those working at Berkeley for various periods were L. P. from Cornell, E. U. Condon and J. J. Slepian from Westinghouse, and I. L muir and K. H. Kingdon from General Electric. During this early period Oppenheimer was still at Berkeley and contributed some important ideas. the fall of 1943 the group was further strengthened by the arrival of a number of English physicists under the leadership of M. L. Oliphant of t University of Birmingham.

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

Immediate Objectives

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

11.9. The factors that control the effectiveness of an ion sou 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 formulate 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 wo be too technical to present here.

11.10. Turning to the problem of effecting more complete utili- zation of the ions, we must consider in some detail the principle of oper of the calutron. The calutron depends on the fact that singly charged io moving in a uniform magnetic field perpendicular to their direction of motion are bent into circular paths of radius proportional to their momen Considering now just a single isotope, it is apparent that the ions passi through the two slits (and thus passing into the large evacuated region i 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 isotope in question follow curved paths of the same diameter, ions starting out in slightly different directions tend to meet again -- or almost meet again — after completing a semicircle. 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 238 instead of 235) behave similarly, except that they follow circles of slightly different diameter. Samples of the two isotopes are caught in collectors at the two different positions of re-convergence. Now the utilization of a greater fraction of the ions originally produced may be accomplished 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.*

*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 be described in a previous paragraph. Later developments proceeded princip along these two lines: construction and installation of a properly engi neered separation unit for the 37-inch magnet, and design and constructi 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 util zation 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 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 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 need to get an amount of production of military significance. Therefore, con sideration was given to various systems of combining groups of units in economical arrangements. A scheme was worked out which was later used i 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 intensiv study — and for a longer period than in the case of the electromagnetic method. Both of these methods — gaseous diffusion and centrifuge — loo feasible for large-scale production of U-235, but both would require hund of stages to achieve large-scale separation. Neither had actually produc any appreciable amounts of separated U-235. No large-scale plant for plutonium production was under way, and the self-sustaining chain reactic which was to produce plutonium had not yet been proved attainable. But i the case of the electromagnetic method, after the successful separation c 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 con- structed. Many skilled operators would probably be needed. Altogether, that time it looked very expensive, but it also looked certain and rela- tively quick. Moreover, the smallness of the units had the advantage tha development could continue, modifications could be made in the course of construction or, within limits, after construction, and capacity could al 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 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 come, (7) th 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 o 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 speci. plans and recommendations.

Technical Decisions Required

11.21. (a) The Number of Stages. As in all methods, a compr must be made between yield and separation factor. In the electromagneti system, the separation factor is much higher than in other systems so th the number of stages required is small. There was a possibility that a single stage might be sufficient. Early studies indicated that attempts 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 th had been acquired on the variables such as those mentioned above had to b translated into decisions on the following principal points before design could actually begin: (1) the size of a unit as determined by the radius curvature of the ion path, the length of the source slit, and the arrange- ment of sources and receivers; (2) the maximum intensity of magnetic fiel required; (3) whether or not to use large divergence of ion beams; (4) th number of ion sources and receivers per unit; (5) whether the source shou be at high potential or at ground potential; (6) the number of acceleratii electrodes and the maximum potentials to be applied to them; (7) the powe 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 b 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 constructi of this unit was approved at about the same time that the first plant unit 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 mont 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 uni

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 area 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; b 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 Smit and his students had done a considerable amount of work -- and with evid of success -- on the separation of the isotopes of lithium by just such method. This was reported to Lawrence in Washington at one of the Decem 1941, meetings of the Uranium Committee. Lawrence immediately got in to with Smith, with the result that Smith worked on the method at Berkeley from February 1942 to June 1942. J. Slepian of the Westinghouse Researc Laboratory in East Pittsburgh came to Berkeley in the winter of 1941-194 at Lawrence's invitation and became interested in a modification of the magnetron which he called an ionic centrifuge. Slepian stayed at Berkel 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 curren In the case of the ionic centrifuge, uranium samples have been collected showing appreciable separation, but the results have not been clear-cut consistent.

The Situation as of Early 1943

11.31. With the virtual elimination of the isotron and the ion centrifuge from the development program, the calutron separator became th only electromagnetic method worked on intensively. Construction of initi 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 on 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 less speculative venture to build an electromagnetic plant unit hastily than would have been the case for the pile. Further research and develop could proceed advantageously even while initial units of the plant were b built and operated.

Construction and Operation; March 1943 to June 1945

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 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 the ion-producing arcs had not been investigated with any very great thoroughness at Berkeley, but as the process developed, a good deal of w was done on these salts, and a search was made for a uranium compound th would be better than that originally used. Some valuable studies were a 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 wa essential to recover the separated uranium from the receivers with maxim efficiency; whereas recovery of the scattered unseparated uranium from o parts of the unit was less important. But if higher stage units are use even the starting material contains a high concentration of U-235, and i 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 o the accelerating electrodes, on the walls of the magnet chamber, and on receiver walls.

The Thermal Diffusion Plant

11.37. For nearly a year the electromagnetic plant was the on one in operation. Therefore the urge to increase its production rate wa tremendous. It was realized that any method of enriching -- even slight 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 o U-235 in the feed material was twice the natural concentration (1.4 perc instead of 0.7 percent).

11.38. We have already referred to the work done by P. H. Abe of the Naval Research Laboratory on the separation of the uranium isotop by thermal diffusion in a 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 there proposed that a large-scale thermal diffusion plant should be constructe Such a plant would be cheaper than any of the other large-scale plants, a it could be built more quickly. Its principal drawback was its enormous consumption of steam, which made it appear impracticable for the whole jo 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 a large-scale pla were made available to the Manhattan District. It was decided to erect t large-scale thermal diffusion plant at Clinton (using steam from the powe 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, an 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 1942 sufficient progress had been made to

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

11.45. Research and development work on the calutron were car out principally at the Radiation Laboratory of the University of Califor under the direction of Lawrence. Westinghouse, General Electric, and Al Chalmers constructed a majority of the parts; Stone and Webster built th 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 possib to introduce important improvements even after plant operation had begun

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

11.48. Although research work on the calutron was started lat 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 BOMB

The Objective

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 6.38) 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 appreci separated before a substantial fraction of the available nuclear energy ha been released. (For expansion leads to increased escape of neutrons from system and thus to premature termination of the chain reaction.) Stated d ferently, 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 oth 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 esti the order of magnitude of the time interval between the beginning and end 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 ch 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 conclu has been borne out by various theoretical calculations and also by direct periment. For purposes of producing a non-explosive pile, the trick of us a lattice and a moderator suffices -- by reducing parasitic capture sufficiently. For purposes of producing an explosive unit, however, it turns o that this process is unsatisfactory on two counts. First, the thermal neu trons take so long (so many micro-seconds) to act that only a feeble explo 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 becaus 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 c such variation were not known experimentally and were difficult to take int 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 larg

The Reflector or Tamper

12.13. In a uranium-graphite chain-reacting pile the critical si may be considerably reduced by surrounding the pile with a layer of graphit since such an envelope "reflects" many neutrons back into the pile. A simi lar 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

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 twofold: (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

bombs the total amount of energy released per kilogram of fissionable mate (i.e., the efficiency of energy release) increases with the size of the bo Thus the optimum size of the atomic bomb was not easily determined. A tac cal aspect that complicates the matter further is the advantage of simulta ous destruction of a large area of enemy territory. In a complete apprais of the effectiveness of an atomic bomb, attention must also be given to ef fects on morale.

Method of Assembly

12.19. Since estimates had been made of the speed that would br 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 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 introduce by the importance of achieving sudden and perfect contact between projecti and target, by the use of tampers, and by the requirement of portability. None of these technical problems had been studied to any appreciable exten 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 premature 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 co nection 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 mater had to be extended and improved. In the cases of U-235 and plutonium, tent tive 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 problem that had hardly been touched. Examples were the purification and fabricati 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 th core and tamper materials. Thus it became possible to compute critical si 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 appr 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. Furt more, the best distribution of fissionable material in projectile and targ was determined by theoretical studies.

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

12.28. A great deal of theoretical work was done on the equatio of state of matter at the high temperatures and pressures to be expected i the exploding atomic bombs. The expansion of the various constituent part 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 i 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 considerab amount of work was done in evaluating preliminary experiments. Thus an ana sis was made of the back-scattering of neutrons by the various tamper mater ials proposed. An analysis was also made of the results of experiments on the multiplication of neutrons in subcritical amounts of fissionable materi

Experimental Nuclear Physics Division

12.31. The experiments performed by the Experimental Nuclear Phy ics group at Los Alamos were of two kinds: "differential" experiments as f 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 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 1.). 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 ne trons 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 pr cesses lead to the production of ions and the resulting ionization may be detected using electroscopes, ionization chambers, Geiger-Müller counter. 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 Wils cloud chamber method and the photographic emulsion method give the most direct results but are tedious to apply. More often various combinations selective absorbers are used. Thus, for example, if a foil known to abso neutrons of only one particular range of energies is inserted in the path the neutrons and is then removed, its degree of radioactivity is presumab proportional to the number of neutrons in the particular energy range con cerned. Another scheme is to study the induced radioactivity known to be duced only by neutrons whose energy lies above a certain threshold energy.

12.37. One elegant scheme for studying the effects of neutrons a single, arbitrarily-selected velocity is the "time of flight" method. this method a neutron source is modulated, i.e., the source is made to em 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 (se feet or yards from it). The detector is "modulated" also, and with the s periodicity. The timing or phasing is made such that the detector is resp sive 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. fissions in a layer of uranium deposited on an inner surface of an ionizat 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 tim interval. In other words, the measured effects are due only to the neutro having the appropriate velocity.

12.38. Production of Neutrons. All neutrons are produced as th result of nuclear reactions, and their initial speed depends on the energy balance of the particular reaction. If the reaction is endothermic, that if the total mass of the resultant particles is greater than that of the initial particles, the reaction does not occur unless the bombarding parti has more than the "threshold" kinetic energy. At higher bombarding energi the kinetic energy of the resulting particles, specifically of the neutron goes up with the increase of kinetic energy of the bombarding particle abo the threshold value. Thus the $Li^7(p,n)Be^7$ reaction absorbs 1.6 Mev energy since the product particles are heavier than the initial particles. Any f ther energy of the incident protons goes into kinetic energy of the produc so that the maximum speed of the neutrons produced goes up with the speed 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 ang 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 $Li^7(p,n)Be^7$ 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" (periments on assembled or integrated systems comprising fissionable materi 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 de signed to operate at a very low power level, and it had no cooling system. Its purpose was to provide verification of the effects predicted for react systems containing enriched U-235. The results were very nearly as expect

12.46. The second integral experiment was carried out on a pile containing a mixture of uranium and a hydrogenous moderator. In this firs 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-neutr fission became important. The pile was rebuilt several more times, less hydrogen being used each time. By such a serious of reconstructions, the action character was successively altered, so that thermal neutron fission became less and less important while fast neutron fission became more and 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 thre million electron volts. In other words, questions 1, 2, 3, 4, and 5 of th 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 typ of nuclei. Preliminary results on questions 6, 8, and 9, involving detail 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 mate ials, for fabrication of the bomb core, tamper, etc., and for various othe matters. In all this division's work on enriched fissionable materials esp cial care had to be taken not to lose any appreciable amounts of the materi (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 al

Summary

12.50. 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 SUMMARY

Present Overall Status

13.1. As the result of the labors of the Manhattan District c zation in Washington and in Tennessee, of the scientific groups at Berke Chicago, Columbia, Los Alamos, and elsewhere, of the industrial groups a Clinton, Hanford, and many other places, the end of June 1945 finds us e pecting from day to day to hear of the explosion of the first atomic bom devised by man. All the problems are believed to have been solved at le well enough to make a bomb practicable. A sustained neutron chain react resulting from nuclear fission has been demonstrated; the conditions nec to cause such a reaction to occur explosively have been established and be achieved; production plants of several different types are in operati building up a stock pile of the explosive material. Although we do not when the first explosion will occur nor how effective it will be, announ ment of its occurrence will precede the publication of this report. Eve the first attempt is relatively ineffective, there is little doubt that later efforts will be highly effective; the devastation from a single bo is expected to be comparable to that of a major air raid by usual method

13.2. A weapon has been developed that is potentially destruc beyond the wildest nightmares of the imagination; a weapon so ideally su to sudden unannounced attack that a country's major cities might be dest overnight by an ostensibly friendly power. This weapon has been created by the devilish inspiration of some warped genius but by the arduous labo 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 inter- national scientific world in 1940. To develop the necessary industrial p cesses from these principles has been costly in time, effort, and money, the processes which we selected for serious effort have worked and severa that we have not chosen could probably be made to work. We have an initi advantage in time because, so far as we know, other countries have not b able to carry out parallel developments during the war period. We also h 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 chanc that German scientists and engineers might be developing atomic bombs whi would be sufficiently effective to alter the course of the war. There wa therefore no choice but to work on them in this country. Initially many scientists could and did hope that some principle would emerge which woul prove that atomic bombs were inherently impossible. This hope has faded gradually; fortunately in the same period the magnitude of the necessary dustrial 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 cer 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 tha must be answered in the near future.

13.8. Because of the restrictions of military security there been no chance for the Congress or the people to debate such questions. have been seriously considered by all concerned and vigorously debated a the scientists, and the conclusions reached have been passed along to th highest authorities. These questions are not technical questions; they political and social questions, and the answers given to them may affect mankind for generations. In thinking about them the men on the project been thinking as citizens of the United States vitally interested in the fare of the human race. It has been their duty and that of the responsi high government officials who were informed to look beyond the limits of present war and its weapons to the ultimate implications of these discov This was a heavy responsibility. In a free country like ours, such ques 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 th report. It is a semi-technical report which it is hoped men of science this country can use to help their fellow citizens in reaching wise deci The people of the country must be informed if they are to discharge thei 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 shall mention one method of historical importance comparable with the electroscope but no longer used, and then we shall review the various me now in use for observing alpha particles, beta particles (or positrons), gamma rays, and neutrons, or their effects.

Scintillations

The closestapproach that can be made to "seeing" an atom is to the bright flash of light that an alpha particle or high-speed proton ma when it strikes a fluorescent screen. All that is required is a piece o 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. involved "counting" scintillations but the method is tedious and, as far 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 strikes by reason of the electrical forces between the charged particle a 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 prese the electrons knocked out of the molecules move in one direction and the residual positive ions in another direction. An initial beta particle wi 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 g both a positive and a negative ion, there is a total of 36,000 charges se free by one high-speed electron, but since each charge is only 1.6×10^{-1} coulomb, the total is only about 6×10^{-15} coulomb and is still very minu 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 ab 10^{-16} coulomb, but the electrometer is a very inconvenient instrument to

An alpha particle produces amounts of ionization comparable wit the beta particle. It is stopped more rapidly, but it produces more ions 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 fr

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 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 si alpha particles, it is far more convenient to use a self-amplifying devi that is, to make the ions originally produced make other ions in the sam 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 strong electric field strengths close to i even for relatively small potential differences between it and the other electrode. This strong field quickly accelerates the primary ions forme 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 w that the total number of ions formed is proportional to the number of primary ions formed. Thus after amplification a current pulse can be se on an oscilloscope, the height of which will indicate how effective an ionizer the initial particle was. It is quite easy to distinguish in th way between alpha particles and beta particles and photons, and the circ can be arranged to count only the pulses of greater than a chosen magnit Thus a proportional counter can count alpha particles against a backgrou 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 come point when the primary ions from a single alpha particle, beta particle, 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 curr 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 proportiona 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 be observed in photographic emulsions, but the lengths of path are so s that they must be observed under a microscope, where they appear as a s of developed grains marking the passage of the particle. This method o observation requires practically no equipment but is tedious and of lim usefulness. It is possible, however, to use the general blackening of photographic film as a measure of total exposure to radiation, a proced 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 neutrons, but all of them are indirectly applicable since neutrons prod ions indirectly. This happens in two ways -- by elastic collision and nuclear reaction. As we have already described, a fast neutron in pass through matter occasionally approaches an atomic nucleus so closely as impart to it a large amount of momentum and energy according to the law elastic collision. The nucleus thereby becomes a high-speed charged pa which will produce ionization in an ionization chamber, counter, or clo chamber. But if the neutron has low speed, e.g., thermal, the struck n will not get enough energy to cause ionization. If, on the other hand, neutron is absorbed and the resultant nucleus breaks up with the releas energy, ionization will be produced. Thus, for the detection of high-s neutrons one has a choice between elastic collisions and nuclear reacti but for thermal speeds only nuclear reaction will serve.

The reaction most commonly used is the $_5B^{10}(n,\alpha)_3Li^7$ reactio which releases about 2.5 Mev energy shared between the resultant alpha particle and $_3Li^7$ nucleus. This is ample to produce ionization. This reaction is used by filling an ionization chamber or proportional counte with boron trifluoride gas so that the reaction occurs in the region where ionization is wanted; as an alternative the interior of the chambe or counter is lined with boron. The ionization chamber then serves as s instrument to measure overall neutron flux while the proportional counte records numbers of individual neutrons.

One of the most valuable methods of measuring neutron densitie 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 give time it is removed and its activity measured by an electroscope or count 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 ENERGY

Mass

Since the proton and the neutron are the fundamental particles of which all nuclei are built, it would seem natural to use the mass of or the other of them as a unit of mass. The choice would probably be th ton, which is the nucleus of a hydrogen atom. There are good reasons, h torical and otherwise, why neither the proton nor the neutron was chosen Instead, the mass unit used in atomic and nuclear physics is one sixteen the mass of the predominant oxygen isotope, O^{16}, and is equal to 1.6603 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 slightly different unit of mass.)

Charge

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

Energy

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

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

Conversion Table for Energy Units

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

APPENDIX 3

DELAYED NEUTRONS FROM URANIUM FISSION

As was pointed out in Chapter VI, the control of a chain-reactin pile is greatly facilitated by the fact that some of the neutrons resultin from uranium fission are not emitted until more than a second after fissio occurs. It was therefore important to study this effect experimentally. Such experiments were described by Snell, Nedzel and Ibser in a report dat 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 μA of 8 Mev deuterons. Near the target was placed a hollow shell made of tinned iron and containing 106 lbs. of U_3O_8. 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 μA 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 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

Half-life	Relative initial intensity activated to saturation
57 ± 3 sec.	0.135
24 ± 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 ± 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, t
multiplication factor, for a typical operating pile to be only 1.01 with
the controls removed and the total variation in k from one control rod to
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 sel: sustaining chain-reacting pile were described briefly. Though details : still be withheld for security reasons, the following paragraphs give a what fuller description based on a report by Fermi. This pile was erec Fermi and his collaborators in the fall of 1942.

Description of the Pile. The original plan called for an approxim: spherical pile with the best materials near the center. Actually contr measurements showed that the critical size had been reached before the : was complete, and the construction was modified accordingly. The final structure may be roughly described as an oblate spheroid flattened at t top, i. e., like a door knob. It was desired to have the uranium or ur: oxide lumps spaced in a cubic lattice imbedded in graphite. Consequentl the graphite was cut in bricks and built up in layers, alternate ones o which contained lumps of uranium at the corners of squares. The critic size was reached when the pile had been built to a height only three qu of that needed according to the most cautious estimates. Consequently c one more layer was added. The graphite used was chiefly from the Natio Carbon Company and the Speer Graphite Company. The pile contained 12,4C of metal, part of which was supplied by Westinghouse, part by Metal Hydrides, and part by Ames. Since there were many more lattice points t lumps of metal, the remaining ones were filled with pressed oxide lumps.

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

Predicted Performance of the Pile. The metal lattice at the center the pile and the two other major lattices making up the bulk of the rest 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 i the last two resulting from difference in the grade of graphite used. I to be remembered that these figures are multiplication factors for latti of infinite size. Therefore a prediction of the actual effective multiplication factor k_{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 o k_{eff} from the average k for infinite size. Although the original design

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 $\underline{A}$ 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, $\underline{A}$ 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_{∞} were precisely one on the average for the lattice in the pile, the activity $\underline{A}$ of the detector at the center should increase with increasing R_{eff} in such a way that R^2_{eff}/A remained constant, but, if k_{∞} for the lattice were greater than one, then as the pile size approached the critical value, that is, as k_{eff} approached one, $\underline{A}$ should approach infinity and therefore R^2_{eff}/A approach zero. Therefore by extrapolating a curve of R^2_{eff}/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 wou 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. Th were removed once every day with the proper precautions in order to chec the approach to the critical conditions. The construction was carried i 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 th pile was not in operation, several such cadmium strips were inserted in number of slots, bringing the effective multiplication factor considerat 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 cadm strips were taken out. The remaining one was then slowly pulled out. A 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 pil 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 "relaxatio 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.

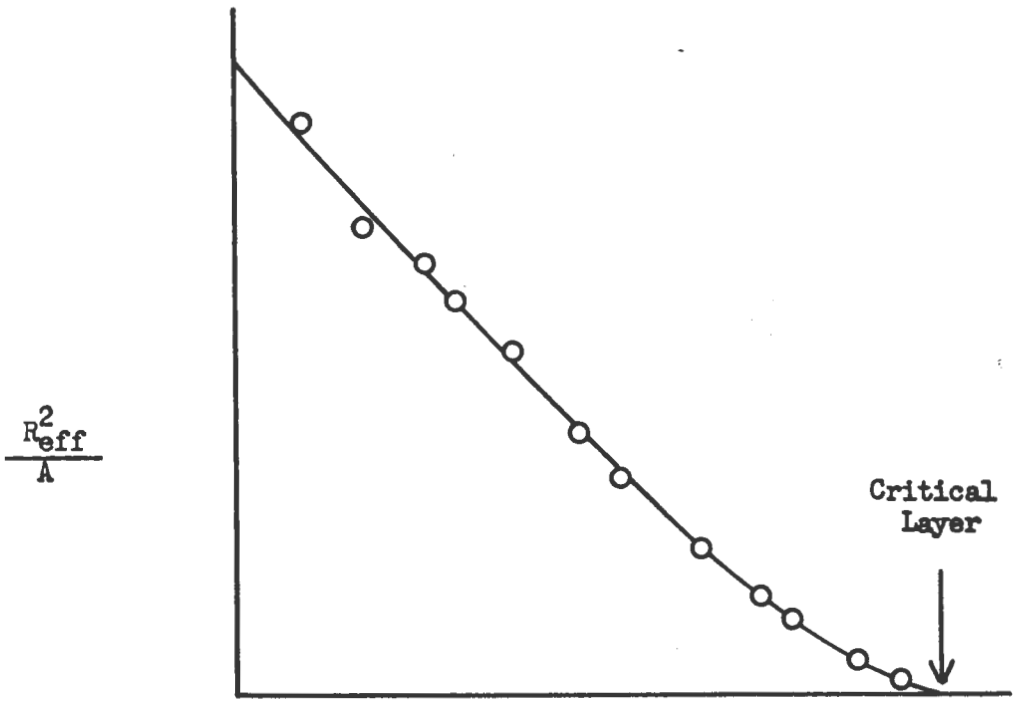


Figure 1

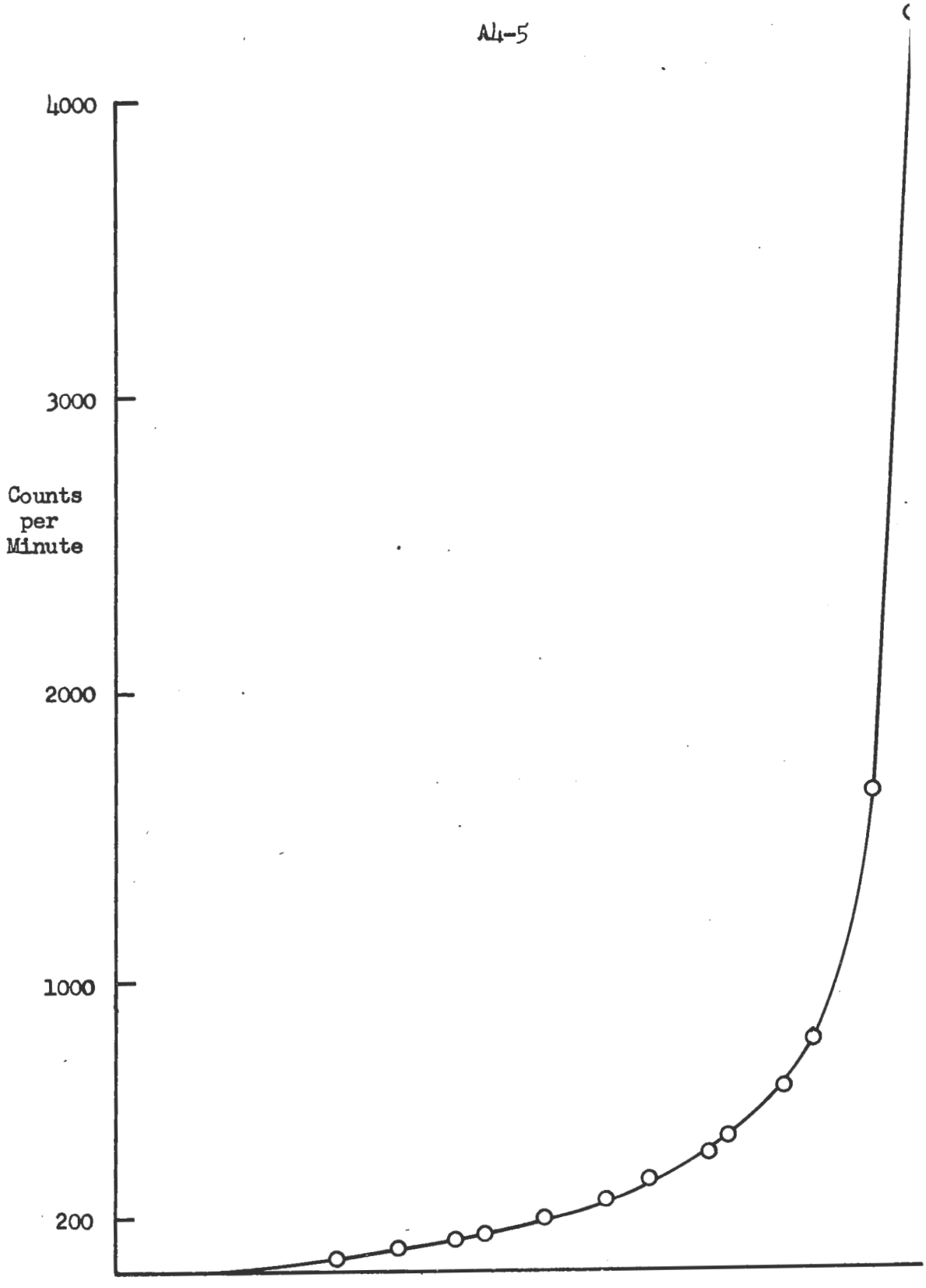

4000
3000
Counts
per
Minute
2000
1000
200
Number of Completed Layers

Figure 2

APPENDIX 5

SAMPLE LIST OF REPORTS

Presented below is a list of titles of representative reports
pared in the Metallurgical Laboratory of the University of Chicago in 19

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 Be 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

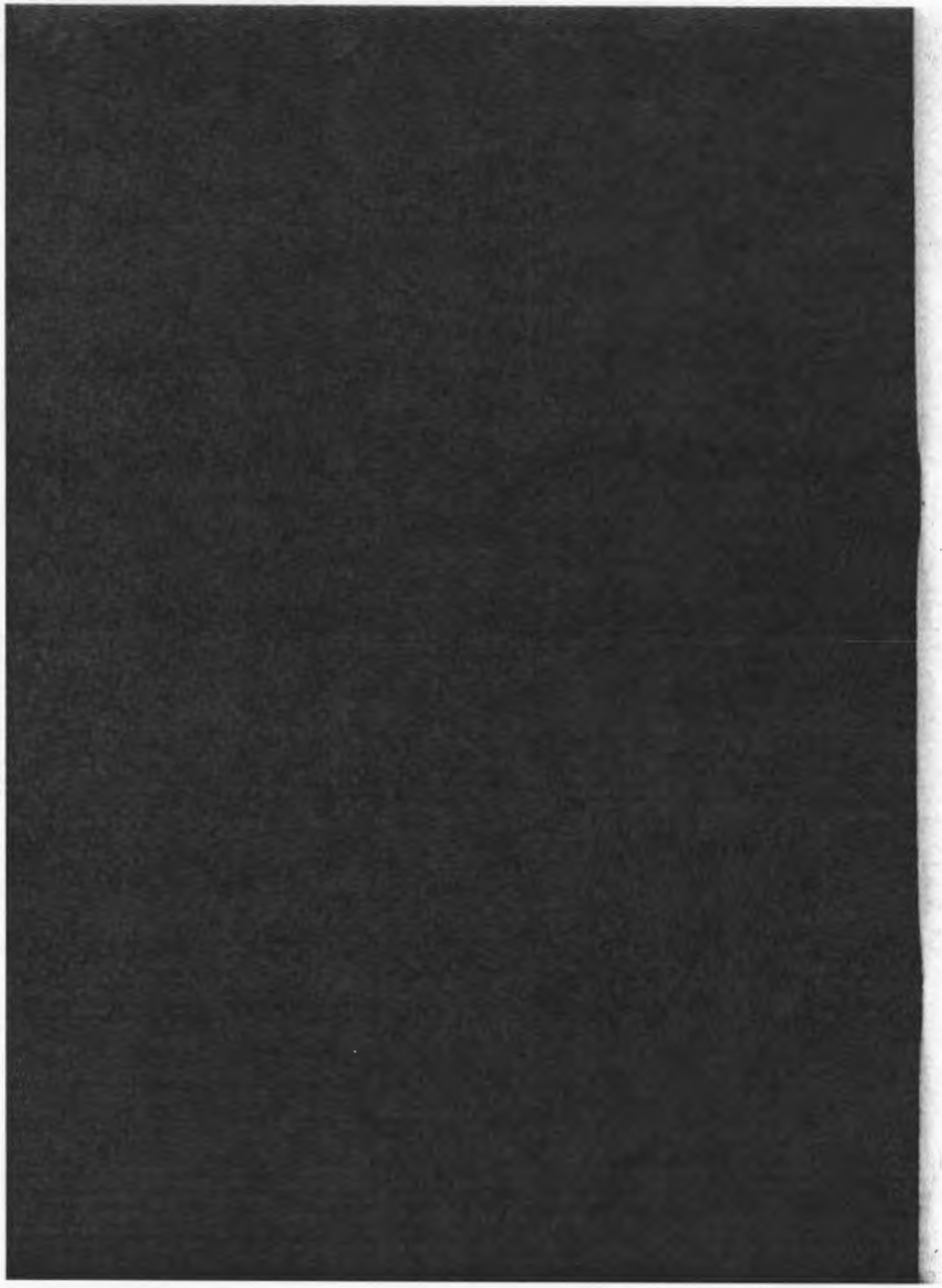
Transuranic and Fission Product Activities

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



A REPORT ON THE INTERNATIONAL CONTROL OF ATOMIC ENERGY

Prepared for

THE SECRETARY OF STATE'S COMMITTEE ON ATOMIC ENERGY

by a Board of Consultants:

Chester I. Barnard
Dr. J. R. Oppenheimer
Dr. Charles A. Thomas
Harry A. Winne
David E. Lilienthal, Chairman

Washington, D. C. March 16, 1946

DEPARTMENT OF STATE

PUBLICATION 2498

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FOREWORD

By The Secretary of State

This "Report on the International Control of Atomic Energy" is in the main the work of a Board of Consultants to the Department of State. The Board carried out its assignment under the general direction of a Committee on Atomic Energy which I set up on January 7, 1946 with Dean Acheson, Under Secretary of State, as Chairman. A letter of transmittal at the beginning of the Report embodies the comments which Mr. Acheson's Committee made on the unanimous findings and recommendations of the Board of Consultants.

In thus transmitting to me the detailed report of the Board, the Committee emphasizes the Board's observation that the Report is not intended as a final plan but "a place to begin, a foundation on which to build". The Committee also states that it regards the consultants' work as "the most constructive analysis of the question of international control we have seen and a definitely hopeful approach to a solution of the entire problem".

The intensive work which this document reflects and the high qualifications of the men who were concerned with it make it a paper of unusual importance and a suitable starting point for the informed public discussion which is one of the essential factors in developing sound policy. The document is being made public not as a statement of policy but solely as a basis for such discussion.

TABLE OF CONTENTS

FOREWORD BY THE SECRETARY OF STATE

Page

Letter of Transmittal VII

Introduction XI

SECTION I. Background of the Problem 1

SECTION II. Principal Considerations in Developing a System of Safeguards 9

Introduction

CHAPTER 1.—The Problem Has Definable Boundaries 11

CHAPTER 2.—The Adequacy of Present Scientific Knowledge 15

CHAPTER 3.—The Constructive Application of Atomic Energy 17

CHAPTER 4.—The Elimination of International Rivalry 21

CHAPTER 5.—"Safe" and "Dangerous" Activities 25

SECTION III. Security Through International Cooperative Development 31

CHAPTER 1.—Functions of Atomic Development Authority 34

CHAPTER 2.—Organization and Policies of Atomic Development Authority 44

SECTION IV. The Transition to International Control 51

OFFICE OF
THE UNDER SECRETARY OF STATE
WASHINGTON

March 17, 1946.

DEAR MR. SECRETARY:

Your committee was appointed on January 7, 1946, with the following terms of reference:

"Anticipating favorable action by the United Nations Organization on the proposal for the establishment of a commission to consider the problems arising as to the control of atomic energy and other weapons of possible mass destruction, the Secretary of State has appointed a Committee of five members to study the subject of controls and safeguards necessary to protect this Government so that the persons hereafter selected to represent the United States on the Commission can have the benefit of the study."

At our first meeting on January 14, the Committee concluded that the consideration of controls and safeguards would be inseparable from a plan of which they were a part and that the Commission would look to the American representative to put forward a plan. At that meeting we also agreed that it was first essential to have a report prepared analyzing and appraising all the relevant facts and formulating proposals. In order that the work should be useful, it was necessary to designate men of recognized attainments and varied background, who would be prepared to devote the major part of their time to the matter.

On January 23, 1946, we appointed as a Board of Consultants for this purpose:

Mr. David E. Lilienthal, Chairman of the Tennessee Valley Authority, who acted as Chairman of the consulting Board,

Mr. Chester I. Barnard, President of the New Jersey Bell Telephone Company,

Dr. J. Robert Oppenheimer, of the California Institute of Technology and the University of California,

Dr. Charles Allen Thomas, Vice President and Technical Director, Monsanto Chemical Company, and

Mr. Harry A. Winne, Vice-President in Charge of Engineering Policy, General Electric Company.

has now completed its report, which is transmitted herewith.

A preliminary draft of this report was first presented to your Committee ten days ago. Extensive discussion between the Committee and the Board led to the development of further considerations embodied in a subsequent draft. Still further discussion resulted in the report now transmitted.

We lay the report before you as the Board has submitted it to us "not as a final plan, but as a place to begin, a foundation on which to build." In our opinion it furnishes the most constructive analysis of the question of international control we have seen and a definitely hopeful approach to a solution of the entire problem. We recommend it for your consideration as representing the framework within which the best prospects for both security and development of atomic energy for peaceful purposes may be found.

In particular, we are impressed by the great advantages of an international agency with affirmative powers and functions coupled with powers of inspection and supervision in contrast to any agency with merely police-like powers attempting to cope with national agencies otherwise restrained only by a commitment to "outlaw" the use of atomic energy for war. In our judgment the latter type of organization offers little hope of achieving the security and safeguards we are seeking.

We are impressed also by the aspect of the plan which concentrates in the hands of the international agency only the activities which it is essential to control because they are dangerous to international security, leaving as much freedom as possible to national and private research and other activity.

We wish to stress two matters brought out in the Board's report—matters of importance in considering the report's proposals as they affect the security of the United States both during the period of any international discussion of them and during the period required to put the plan into full effect.

The first matter concerns the disclosure of information not now generally known. The report points out that the plan necessitates the disclosure of information but permits of the disclosure of such information by progressive stages. In our opinion various stages may upon further study be suggested. It is enough to point out now that there could be at least four general points in this progression. Certain information, generally described as that required for an understanding of the workability of proposals, would have to be made available at the time of the discussions of the proposals in the United Nations Atomic Energy Commission, of the report of the Commission in the Security

recommendations of the United Nations. We have carefully considered the content of this information, and in our discussions with the Board have defined it within satisfactory limits. We estimate the degree of its importance and the effect of its disclosure to be as follows: If made known to a nation otherwise equipped by industrial development, scientific resources and possessing the necessary raw materials to develop atomic armament within five years, such disclosure might shorten that period by as much as a year. Whether any nation—we are excluding Great Britain and Canada—could achieve such an intensive program is a matter of serious doubt. If the program were spread over a considerably longer period, the disclosure referred to would not shorten the effort appreciably.

The next stage of disclosure might occur when the proposed international organization was actually established by the action of the various governments upon the report of the United Nations. At this time the organization would require most of the remaining scientific knowledge but would not require the so-called technical know-how or the knowledge of the construction of the bomb.

By the time the organization was ready to assume its functions in the field of industrial production it would, of course, require the technological information and know-how necessary to carry out its task. The information regarding the construction of the bomb would not be essential to the plan until the last stage when the organization was prepared to assume responsibility for research in the field of explosives as an adjunct to its regulatory and operational duties.

The second matter relates to the assumption or transfer of authority over physical things. Here also the plan permits of progress by stages beginning in the field of raw material production, progressing to that of industrial production, and going on to the control of explosives.

The development of detailed proposals for such scheduling will require further study and much technical competence and staff. It will be guided, of course, by basic decisions of high policy. One of these decisions will be for what period of time the United States will continue the manufacture of bombs. The plan does not require that the United States shall discontinue such manufacture either upon the proposal of the plan or upon the inauguration of the international agency. At some stage in the development of the plan this is required. But neither the plan nor our transmittal of it should be construed as meaning that this should or should not be done at the outset or at any specific time. That decision, whenever made, will involve considerations of the highest policy affecting our security, and must be made

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Your Committee, Mr. Secretary, awaits your further instructions as to whether you believe it has performed the task you assigned to it and may now be discharged or whether you wish it to go further in this field under your guidance.

Respectfully submitted,

DEAN ACHESON
Chairman
VANNEVAR BUSH
JAMES B. CONANT
LESLIE R. GROVES,
Major General, USA.
JOHN J. MCCLOY

The Honorable
JAMES F. BYRNES,
Secretary of State,
Washington, D. C.

INTRODUCTION

The board of consultants met for the first time on January 23rd, conferring briefly with the Secretary of State's Committee on Atomic Energy respecting the board's assignment to study the problem of international control of atomic energy. For more than seven weeks since that time we devoted virtually our entire time and energies to the problem we were directed to study and report upon. We visited the plants and installations at Oak Ridge, Tennessee, and Los Alamos, New Mexico, and spent days consulting with numerous scientists, industrial experts, and geologists, authorities in the technical fields concerned with atomic energy. Since February 25th this board has met almost continuously, developing and writing the following report. Our absorption in this task does not, of course, assure the soundness of the recommendation which is the product of our deliberations. But it is relevant as a measure of how important and urgent we feel it to be that the Government and the people of the United States develop a rational and workable plan, before the already launched international atomic armament race attains such momentum that it cannot be stopped.

We have concluded our deliberations on this most difficult problem, not in a spirit of hopelessness and despair, but with a measure of confidence. It is our conviction that a satisfactory plan can be developed, and that what we here recommend can form the foundation of such a plan. It is worth contrasting the sense of hope and confidence which all of us share today with the feeling which we had at the outset. The vast difficulties of the problem were oppressive, and we early concluded that the most we could do would be to suggest various alternative proposals, indicate their strengths and limitation, but make no recommendations. But as we steeped ourselves in the facts and caught a feel of the nature of the problem, we became more hopeful. That hopefulness grew not out of any preconceived "solution" but out of a patient and time-consuming analysis and understanding of the facts that throw light on the numerous alternatives that we explored. Five men of widely differing backgrounds and experiences who were far apart at the outset found themselves, at the end of a month's absorption in this problem not only in complete agreement that a plan could be devised but also in agreement on the essentials

We have described the process whereby we arrived at our recommendation, to make it clear that we did not begin with a preconceived plan. There is this further reason for describing this process. Others would have a similar experience if they were able to go through a period of close study of the alternatives and an absorption in the salient and determining facts. Only then, perhaps, may it be possible to weigh the wisdom of the judgment we have reached, and the possibilities of building upon it.

The plan of the report itself may be briefly described, as an aid in reading it:

In Section I. we examined the reasons that have led to a commitment for the international control of atomic energy and the early proposal for realizing this objective by a system of inspection.

In Section II. the essential characteristics of a workable plan for security are stated, and the considerations that favor the development of a plan are set out. By the time this discussion is concluded, the outlines of a workable plan as we see it are apparent.

In Section III. the essentials of an organization that puts such principles into effect are described.

In Section IV. we consider the problems of the transition period leading from the present to the full operation of the plan.

We have tried to develop a report that will be useful, *not as a final plan, but as a place to begin, a foundation on which to build.* Many questions that at later stages should and must be asked we have not touched upon at all. We recognize that securing the agreement of other nations to such a plan will raise questions the precise contours of which can hardly be drawn in advance of international meetings and negotiation. We have not, of course, undertaken to discuss, much less to try to settle, problems of this character. The newly created Atomic Energy Commission of the United Nations, when its deliberations begin, will deal with many of these in joint discussion. Indeed, this process of joint international discussion is itself an integral part of any program for safeguards and security.

We desire here to express our great indebtedness to the Secretary of the Secretary of State's Committee on Atomic Energy, Mr. Herbert S. Marks, Assistant to the Undersecretary of State, and to the Secretary of this board, Mr. Carroll L. Wilson. They have contributed in many ways to the work of the board. Whatever value our work may prove to have owes a great deal to their acumen, diligence, and high quality of judgment. We wish especially to thank General Groves and his associates in the Manhattan District and the liaison services. We are also indebted to a number of other officers and staff members of the Manhattan Project for their cooperation. As a result of this cooperation we have had unlimited access to the entire range of facts and activities involved in our assignment, and this has been most helpful.

It has not been possible for security reasons to set forth in this report all of the facts which we have taken into account, but we believe that those which are set forth are a sufficient basis for a useful appraisal of our conclusions and recommendations.

WASHINGTON, D. C.
March 16, 1946

SECTION 1

Background of the Problem

This report is a preliminary study of the international control of atomic energy. It has been prepared to contribute to the clarification of the position of the U. S. Representative on the United Nations Commission on atomic energy set up by resolution of the United Nations General Assembly to inquire into all phases of this question.

The Commitment for International Control.

We were given as our starting point a political commitment already made by the United States to seek by all reasonable means to bring about international arrangements to prevent the use of atomic energy for destructive purposes and to promote the use of it for the benefit of society. It has not been part of our assignment to make a detailed analysis of the arguments which have led the Government of the United States in concert with other nations to initiate these steps for international action. By way of background, however, it is useful to review some of the main reasons which have influenced the people of the United States and its Government in this course. These reasons were first definitely formulated in the Agreed Declaration of November 15, 1945, issued by the President of the United States and the Prime Ministers of the United Kingdom and Canada. An understanding of the declarations in that document will itself throw considerable light on the criteria by which any specific proposals for international control may be judged.

The Agreed Declaration cites three reasons for seeking international control. This Declaration recognizes that the development of atomic energy, and the application of it in weapons of war, have placed at the disposal of mankind "means of destruction hitherto unknown." The American people have been quick to recognize the really revolutionary character of these weapons, particularly as weapons of strategic bombardment aimed at the destruction of enemy cities and the eradication of their populations. Enough has been said to make unnecessary a repetition of the probable horrors of a war in which atomic weapons were used by both combatants against the cities of their enemy. But it is hardly possible to overestimate the deep im-

The second point recognized in the Agreed Declaration is that there can be no adequate military defense against atomic weapons. A great mass of expert testimony is involved in an appreciation of the firmness of this point, but it appears to be accepted without essential reservation, and subject only to an appropriate openmindedness, about what the remote future of technical developments in the arts of war may bring.

The third point, and again we quote from the Agreed Declaration, is that these are weapons "in the employment of which no single nation can in fact have a monopoly." Of the three, this is perhaps the most controversial. Strong arguments have been brought forward that the mass of technical and scientific knowledge and experience needed for the successful development of atomic weapons is so great that the results attained in the United States cannot be paralleled by independent work in other nations. Strong arguments have also been put forward that the degree of technical and industrial advancement required for the actual realization of atomic weapons could hardly be found in other parts of the world. These arguments have been met with great and widespread skepticism. It is recognized that the basic science on which the release of atomic energy rests is essentially a world-wide science, and that in fact the principal findings required for the success of this project are well known to competent scientists throughout the world. It is recognized that the industry required and the technology developed for the realization of atomic weapons are the same industry and the same technology which play so essential a part in man's almost universal striving to improve his standard of living and his control of nature. It is further recognized that atomic energy plays so vital a part in contributing to the military power, to the possible economic welfare, and no doubt to the security of a nation, that the incentive to other nations to press their own developments is overwhelming.

Thus the Agreed Declaration bases is policy on the revolutionary increase in the powers of destruction which atomic weapons have injected into warfare, and on the fact that neither countermeasures nor the maintenance of secrecy about our own developments offers any adequate prospect of defense.

There are perhaps other considerations which have contributed to the popular understanding of the necessity for international control, although they do not appear explicitly in the Agreed Declaration. The United States is in a rather special position in any future atomic warfare. Our political institutions, and the historically established

to surprise use of atomic weapons. This suggests that although our present position, in which we have a monopoly of these weapons, may appear strong, this advantage will disappear and the situation may be reversed in a world in which atomic armament is general.

The atomic bomb appeared at the very end of hostilities at a time when men's thoughts were naturally turning to devising methods for the prevention of war. The atomic bomb made it clear that the plans which had been laid at San Francisco for the United Nations Organization would have to be supplemented by a specific control of an instrument of war so terrible that its uncontrolled development would not only intensify the ferocity of warfare, but might directly contribute to the outbreak of war. It is clear, too, that in the solution of this relatively concrete and most urgent problem of protecting mankind from the evils of atomic warfare, there has been created an opportunity for a collaborative approach to a problem which could not otherwise be solved, and the successful international solution of which would contribute immeasurably to the prevention of war and to the strengthening of the United Nations Organization. On the one hand, it seemed unlikely that the United Nations Organization could fulfill its functions without attempting to solve this problem. On the other hand, there was hope and some reason to believe that in attempting to solve it, new patterns of cooperative effort could be established which would be capable of extension to other fields, and which might make a contribution toward the gradual achievement of a greater degree of community among the peoples of the world. Although these more general considerations may appear secondary to the main purposes of this report, they are not irrelevant to it. There is another phrase of the Agreed Declaration which rightly asserts "that the only complete protection for the civilized world from the destructive use of scientific knowledge lies in the prevention of war."

The proposals which we shall make in this report with regard to the international control of atomic energy must of course be evaluated against the background of these considerations which have led to the universal recognition of the need for international control. We must ask ourselves to what extent they would afford security against atomic warfare; to what extent they tend to remove the possibility of atomic weapons as a cause of war; to what extent they establish patterns of cooperation which may form a useful precedent for wider application. We ourselves are satisfied that the proposals in this report provide the basis of a satisfactory answer to these questions.

688651—46——2

So much for the main outline of the political action that led to the setting up of the United Nations Commission on atomic energy. There is a further aspect of the general background that also requires discussion at the outset. When the news of the atomic bomb first came to the world there was an immediate reaction that a weapon of such devastating force must somehow be eliminated from warfare; or to use the common expression, that it must be "outlawed". That efforts to give specific content to a system of security have generally proceeded from this initial assumption is natural enough. But the reasoning runs immediately into this fact: The development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent. From this it follows that although nations may agree not to use in bombs the atomic energy developed within their borders, the only assurance that a conversion to destructive purposes would not be made would be the pledged word and the good faith of the nation itself. This fact puts an enormous pressure upon national good faith. Indeed it creates suspicion on the part of other nations that their neighbors' pledged word will not be kept. This danger is accentuated by the unusual characteristics of atomic bombs, namely their devastating effect as a surprise weapon, that is, a weapon secretly developed and used without warning. Fear of such surprise violation of pledged word will surely break down any confidence in the pledged word of rival countries developing atomic energy if the treaty obligations and good faith of the nations are the only assurances upon which to rely.

Such considerations have led to a preoccupation with systems of inspection by an international agency to forestall and detect violations and evasions of international agreements not to use atomic weapons. For it was apparent that without international enforcement no system of security holds any real hope at all.

In our own inquiry into possibilities of a plan for security we began at this point, and studied in some detail the factors which would be involved in an international inspection system supposed to determine whether the activities of individual nations constituted evasions or violations of international outlawry of atomic weapons.

We have concluded unanimously that there is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled *only* by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are *not merely technical*, but primarily the inseparable political, social, and organizational problems involved in enforcing agreements between nations each free to develop atomic energy but

poses are the heart of the difficulty. So long as intrinsically dangerous activities may be carried on by nations, rivalries are inevitable and fears are engendered that place so great a pressure upon a system of international enforcement by police methods that no degree of ingenuity or technical competence could possibly hope to cope with them. We emphasize this fact of national rivalry in respect to intrinsically dangerous aspects of atomic energy because it was this fatal defect in the commonly advanced proposals for outlawry of atomic weapons coupled with a system of inspection that furnished an important clue to us in the development of the plan that we recommend later in this report.

We are convinced that if the production of fissionable materials by national governments (or by private organizations under their control) is permitted, systems of inspection cannot by themselves be made "effective safeguards . . . . to protect complying states against the hazards of violations and evasions."

It should be emphasized at this point that we do not underestimate the need for inspection as a component, and a vital one, in any system of safeguards—in any system of effective international controls. In reading the remainder of this section it is essential to bear in mind that throughout the succeeding sections of this report we have been concerned with discovering what other measures are required in order that inspection might be so limited and so simplified that it would be practical and could aid in accomplishing the purposes of security.

The remainder of this section, however, is concerned with outlining the reasons for our conclusion that a system of inspection superimposed on *an otherwise uncontrolled exploitation of atomic energy by national governments* will not be an adequate safeguard.

The Technical Problem of Inspection.

Although, as we have said, a system of inspection cannot be judged on technical grounds alone, an understanding of the technical problem is necessary in order to see what an inspection system would involve. The general purpose of such inspection (that is, inspection as the sole safeguard) would be to assure observance of international agreements according to which certain national activities leading more or less definitely to atomic armament would be renounced, and others which have as their purpose peaceful applications of atomic energy would be permitted. The fact that in much of their course these two types of activity are identical, or nearly identical, makes the problem one of peculiar difficulty.

nical Committee reporting to the War Department on the technical aspects of this problem.* We are indebted to this uniquely qualified group of experts for helpful discussions and for making available to us many of their reports, without which we should doubtless have been very much slower to understand the situation.

As a result of our work with this Committee, we are clear: that every stage in the activity, leading from raw materials to weapon, needs some sort of control, and that this must be exercised on all of the various paths that may lead from one to the other; that at no single point can *external* control of an operation be sufficiently reliable to be an adequate sole safeguard; that there is need for a very extensive and technically highly qualified and varied staff if the job is to be done at all; that the controlling agency must itself be active in research and development, and well informed on what is an essentially living art; and that, for effective control, the controlling organization must be as well and as thoroughly informed about the operations as are the operators themselves. Finally—and this we regard as the decisive consideration—we believe that an examination of these and other necessary preconditions for a successful scheme of inspection will reveal that *they cannot be fulfilled in any organizational arrangements in which the only instrument of control is inspection.*

A fundamental objection to an agency charged solely with inspection is that it will inevitably be slow to take into account changes in the science and technology of the field. One cannot look intelligently for a factory of whose principle of design and operation one has never heard. One cannot effectively inspect if the purpose of the operator is to conceal the discoveries by which he hopes to evade inspection. In a field as new and as subject to technical variation and change as this, the controlling agency must be at least as inventive and at least as well informed as any agency which may attempt to evade control.

Human Factors in Inspection.

Even more important than the technical difficulties of realizing an adequate system of inspection, against a background of national rivalry in the field of atomic energy, or through an organization whose major or whose sole directive is suppressive, are the many human factors which in such an arrangement would tend to destroy the confidence and the cooperation essential to its success. The first

*Membership of this Technical Committee on Inspection and Control established by the Manhattan District included L. W. Alvarez, R. F. Bacher, L. A. Bliss, S. G. English, A. B. Kinzel, P. Morrison, F. G. Spedding, C. Starr, Col. W. J. Williams, and Manson Benedict, Chairman.

experts and administrators needed for the work. The work itself, which would be largely policing and auditing and attempting to discover evidences of bad faith, would not be attractive to the type of personnel essential for the job. The activity would offer the inspectors a motive pathetically inadequate to their immense and dreary task.

The presence of a large number of "foreigners" necessarily having special privileges and immunities inquiring intimately and generally into industrial and mining operations would be attended by serious social frictions. For adequate inspection the numbers are large. As an example, it has been estimated that for a diffusion plant operated under national auspices, to offer any real hope of guarding against diversion, 300 inspectors would be required. They would have to check not merely accounts and measuring instruments but also individuals personally. Inquiries would need to be made of individuals without regard to rank or general status. Moreover, it would be especially important to check the location and employment of scientists and many technologists, probably including students. Industrial secrets would be at least to some extent open to "prying". The effect of this would vary with countries. It would probably be as obnoxious to Americans as to any others. Its corrosive effect upon the morale and loyalty of the inspecting organization would be serious.

Some of the organizational difficulties involved in intimate inspection "down the line" of one organization by another are known from experiences that are undoubtedly mild compared with what we should anticipate here. The following are illustrative of the political difficulties of practical operation (quite apart from those to be expected in adopting the international system to begin with). Adequate surveillance by inspection as the sole or primary means of control involves a persistent challenge of the good faith of the nations inspected. If this were confined to relations between the chancelleries and general military staffs the difficulty while serious might not be insuperable. But official questioning of the good faith of a nation by concrete action of inspectors among its citizens is another matter and would tend to produce internal as well as external political problems. A somewhat similar problem is involved when a government (or its officials or employees) interferes with the functions of inspectors or molests or threatens them personally, or bribes or coerces them, or *is accused of doing any of these things.* Such incidents could not be avoided.

tion and use of fissionable materials for purposes of war. It is obvious, however, that suspicion by one nation of the good faith of another and the fear engendered thereby are themselves strong incentives for the first to embark on secret illicit operations. The raw materials of atomic energy, potentially valuable for new peacetime purposes and of critical importance for war, are already a matter of extreme competition between nations. The forces growing out of this situation and making for acute rivalry between nations seem to us far more powerful than those which cause the present rivalries with respect to such resources as oil. The efforts that individual states are bound to make to increase their industrial capacity and build a reserve for military potentialities will inevitably undermine any system of safeguards which permits these fundamental causes of rivalry to exist. In short, any system based on outlawing the purely military development of atomic energy and relying solely on inspection for enforcement would at the outset be surrounded by conditions which would destroy the system.

There is much technical information which underlies our belief that inspection can be effective only if it is supplemented by other steps to reduce its scope to manageable proportions, to limit the things that need to be inspected, to simplify their inspection, and to provide a pattern of organization which on the one hand will be of assistance to the controlling agency, and on the other will minimize organizational sources of conflict and the inducements to evasion. Much of this technical information is interwoven with later sections of this report. As the facts on which we base our recommendations for a workable plan of control are discussed, the detailed considerations which led to the conclusion stated in this section will appear more concretely than in the foregoing summary.

SECTION II

Principal Considerations in Developing a System of Safeguards

INTRODUCTION

At the outset of our inquiry we were preoccupied with some way of making an inspection system provide security. This is a preoccupation that is apparently common to most people who have seriously tried to find some answer to the extraordinarily difficult problem presented by the atomic bomb. But as day after day we proceeded with our study of the facts concerning atomic energy, and reflected upon their significance, we were inescapably driven to two conclusions: (a) the facts preclude any reasonable reliance upon inspection as the primary safeguard against violations of conventions prohibiting atomic weapons, yet leaving the exploitation of atomic energy in national hands; (b) the facts suggest quite clearly a reasonable and workable system that may provide security, and even beyond security, foster beneficial and humanitarian uses of atomic energy.

What Should be the Characteristics of an Effective System of Safeguards:

It may be helpful to summarize the characteristics that are desirable and indeed essential to an effective system of safeguards; in other words, the criteria for any adequate plan for security.

a. Such a plan must reduce to manageable proportions the problem of enforcement of an international policy against atomic warfare.

b. It must be a plan that provides unambiguous and reliable danger signals if a nation takes steps that do or may indicate the beginning of atomic warfare. Those danger signals must flash early enough to leave time adequate to permit other nations—alone or in concert—to take appropriate action.

c. The plan must be one that if carried out will provide security; but such that if it fails or the whole international situation collapses, any nation such as the United States will still be in a relatively secure position, compared to any other nation.

d. To be genuinely effective for security, the plan must be one that is not wholly negative, suppressive, and police-like. We are not

must be one that will tend to develop the beneficial possibilities of atomic energy and encourage the growth of fundamental knowledge, stirring the constructive and imaginative impulses of men rather than merely concentrating on the defensive and negative. It should, in short, be a plan that looks to the promise of man's future well-being as well as to his security.

e. The plan must be able to cope with new dangers that may appear in the further development of this relatively new field. In an organizational sense therefore the plan must have flexibility and be readily capable of extension or contraction.

f. The plan must involve international action and minimize rivalry between nations in the dangerous aspects of atomic development.

The facts we have come to think essential, and the elements of our thinking as we moved toward the plan we herein recommend, are set out in this section, in the form of the considerations that are relevant to an effective program for security, and that have led us to devise what we believe is an adequate plan.

CHAPTER I

The Problem Has Definable Boundaries

This problem of building security against catastrophic use of atomic energy is not one without boundaries. This is important. For if the fact were that tomorrow or a year hence we might reasonably expect atomic energy to be developed from clay or iron or some other common material then it is apparent that the problem of protection against the misuse of energy thus derived would be vastly more difficult. But such is not the case. The only scientific evidence worthy of regard makes it clear that in terms of security uranium is indispensable in the production of fissionable material on a scale large enough to make explosives or power. The significance of this fact for effective international control will appear.

As a first step in our work, we undertook a study, with the help of the qualified members of our group, aimed at an understanding of the well-established principles of nuclear physics upon which, among other things, the conclusion is based that uranium is indispensable as the primary source of atomic energy. These scientific principles are not familiar, but they are capable of being appreciated by laymen. Because the specific content of any system of control will be importantly influenced by the scientific principles and facts, we would emphasize the importance of an appreciation of them. For present purposes, we shall state in greatly simplified terms certain conclusions that are drawn from a full technical account of this subject.

Until 1942 the energy which man had learned to control for his useful purposes derived almost exclusively (except for water, wind, and tidal power) from chemical reactions. For practical purposes, chemical combustion was the main source of energy. This energy is the product of rearrangements of electrons in the periphery of atoms and results from the change in *chemical structure* which occurs in the process of combustion.

"Atomic energy," as that term is popularly used, refers to the energy that results from rearrangements in the structure of atomic nuclei of elements. There are very strong forces which hold such nuclei together and account for their stability. The nature of these forces is not adequately understood, but enough is known about their behavior, not only to make it certain that the energy of an atomic

688651—46——4

explain one major fact of decisive importance: Only in reactions of very light nuclei, and in reactions of the very heaviest, has there ever been, to the best of our knowledge, any large-scale release of atomic energy. The reasons for this can be given in somewhat oversimplified form.

As to the light nuclei—The forces which hold all nuclear particles together are attractive. When lighter nuclei combine to make heavier ones, and in particular when the lightest nucleus of all, that of hydrogen, is combined with another light nucleus, these attractive forces release energy. This combination of light elements to form somewhat heavier ones occurs in the stars and of the sun; in the sun effectively what happens is that hydrogen nuclei combine to form the more stable nuclei of helium. Almost all sources of the energy used on earth come to us from the sunlight which this great atomic energy plant provides. But the conditions which make this plant possible are very special, and we do not know how to duplicate them on earth; we may very well never learn to do so. They depend on maintaining matter deep in the interior of the sun at very high temperatures—many millions of degrees. The nuclear reactions themselves provide the energy necessary to keep the matter hot; and it is kept from expanding and cooling by the enormous gravitational forces of attraction which hold the sun together and provide a sort of container in which this temperature and pressure can be maintained. For the foreseeable future the maintenance of such reactions on earth will not be possible; in the immediate future it is certainly not possible.

As to the heaviest nuclei—Although nuclear reactions can be carried out in the laboratory for all nuclei, and although in some cases a given nuclear reaction may release energy even for nuclei of intermediate weight, the properties which make the large-scale release of such energy possible are peculiar, to the very light nuclei and to the very heaviest. And the very heaviest nuclei have a property shared by none of the the other elements. These very heavy nuclei generate energy if they can be caused to split into lighter ones; this unique process is called "fission." Perhaps a dozen nuclear species are known which can be made to undergo fission; under more drastic treatment no doubt the list will be extended. But to make atomic energy takes more than the property of fission. The fission process itself must maintain itself or grow in intensity so that once it is started in a few nuclei a chain of reactions will be set up and a large part of the material will become potentially reacting. The agency which initiates this process is the neutron. In fission neutrons are emitted; and in certain nuclei bombardment by neutrons is enough to cause fission.

for which it is true—that substance is uranium. Uranium is the only natural substance that can maintain a chain reaction. It is the key to all foreseeable applications of atomic energy.

One may ask why there are so few materials which undergo fission, and why so few of these can maintain a chain reaction. The reason lies in the fact that only the heaviest nuclei are sufficiently highly charged to come apart easily, and that only the most highly charged of all are sufficiently susceptible to fission on neutron bombardment to maintain a chain reaction. It is not to be anticipated that this situation will be invalidated by further scientific discovery.

A word needs to be said about the role of thorium, which is slightly more abundant than uranium, and for which fission is also not too difficult to induce. Thorium cannot maintain a chain reaction, either itself or in combination with any other natural material than uranium. Nevertheless, it occupies an important position with regard to safeguards. The reason for this is the following: Without uranium, chain reactions are impossible, but with a fairly substantial amount of uranium to begin with and suitably large quantities of thorium a chain reaction can be established to manufacture material which is an atomic explosive and which can also be used for the maintenance of other chain reactions.

Absolute control of uranium would therefore mean adequate safeguard regarding raw materials. Yet, since any substantial leakage of uranium through the system of controls would make possible the exploitation of thorium to produce dangerous amounts of atomic explosive, provisions governing thorium should be incorporated in the system to compensate for possible margins of error in the control of uranium. The coexistence of uranium and thorium in some natural deposits makes this technically attractive.

There can be little hope of devising a successful scheme of control unless the problem can somehow be limited to the immediate future, by arrangements that have a reasonable prospect of validity for the next decade or two, and which contain sufficient flexibility to accommodate themselves to inevitably changing conditions. We believe that a system of control which disregards all materials except uranium and thorium satisfies these conditions. Indeed if a successful system of control can be commenced now, based upon these materials, and if the time should ever come when other materials lend themselves to the same activities, it should in fact be far easier to include them within the system than it will be to set up the initial control system with which we are now concerned.

rowed by the geological conditions under which uranium and thorium are found, and the fact that at present those elements have only a restricted commercial significance. Although they are distributed with relative abundance throughout the world, and although it is clear that many sources beyond the known supplies will be discovered, it is apparently the view of the authorities that these elements occur in high concentrations only under very special geologic conditions. This would seem to mean that the areas which need to be surveyed, to which access must be had, and which would ultimately have to be brought under control, are relatively limited.

CHAPTER II

The Adequacy of Present Scientific Knowledge

There can be no question that its dynamic changing quality is one of the dominant features of the present situation in the field of atomic energy. Advances in knowledge must be expected in a constant stream. Does this mean that a system of safeguards is impossible because new knowledge will completely change the nature of the problem from year to year or even month to month? The answer is in the negative:

When the atomic bomb was first used there was a widespread belief that its development involved a few simple, static secrets. As it became possible for people to learn how rapidly ideas and techniques had changed in this field in the last years, and how many further developments the future seemed to have in store, the original opinion was replaced by another: that we knew very little of the possibilities and limitations of this field and that it was so rapidly changing that no account of the present technical situation would have much validity. This view has been expressed both in the preamble to a pending Bill, which indicates that too little is known of the technical facts to provide a firm basis for political action, and in such statements as one attributed to a high official, that it would not be long before we could extract atomic energy from common materials such as clay.

Neither the initial view of a static body of knowledge nor the later one of unpredictably rapid change accurately describes the present situation. As the preceding chapter has shown, there is a great deal that we know about nuclear reactions—know solidly, firmly, and with vast, interrelated experimental checks on the soundness of the description. Novelty will of course appear in scientific discoveries, but it will appear for the most part not as a negation of present knowledge but as the result of new types of physical experience made possible by new methods of physical exploration, and in turn requiring new modes of description. This future experience may have something to do with the basic knowledge involved in release of atomic energy, but there is no basis for believing this, and the chances are against it. There is another type of novelty that lies in ingenious applications of the fundamental facts as they are now known. This does not lessen the importance of the underlying facts and of conclusions which can unambiguously be drawn from them.

knowledge in the field of atomic energy is adequate. We know, for example, that uranium occupies a unique role in the production of fissionable substances and that without it atomic explosives cannot be made. We know that there is no evidence whatever that this situation will soon change. We know that a vast scientific and industrial effort is necessary in order to produce atomic bombs. This is not to say that the effort, however vast, cannot be concealed—although we believe that measures can be taken to reduce this danger. We know that the release of atomic energy does demonstrate the convertibility of mass to energy, but we also know that the familiar example of this physical principle—that the annihilation of a kilogram of any kind of matter is equivalent to all the power consumed in the United States in a period of three months—is a statement of a possibility, the realization of which is so remote that for the purposes of devising a system of safeguards it may be entirely disregarded.

We know, too, that many areas in this field which are now unclear will be clarified by further investigations. Within a few years much more could be learned about atomic explosives. Within a relatively few years the technology of atomic energy power plants will become clearer. It seems likely that before very long we shall have discovered many useful therapeutic and technological applications for the radioactive substances which can be made in the production of fissionable materials. Nor can there be much question that ways will be found to cheapen and simplify the processes involved in the production of the fissionable materials themselves.

But what needs most to be emphasized is that the dynamic quality which has so excited popular interest must be seen in its proper perspective in relation to the general field of scientific knowledge. The prophecies as to future discoveries must not be permitted to obscure the fact that there are at key places throughout the field of knowledge firm anchor points around which it should be possible to construct an effective and adequate system of control.

In this report it is possible for us to do little more than record our own sense of the soundness of this statement. Those who must assume responsibility for political action should test for themselves the correctness of our conclusions. This testing will require an examination of difficult and complicated technical facts, but we are confident that the process is one which other laymen with the appropriate help of experts can readily repeat. We are also confident that unless the effort is made it will be impossible to come to grips with the problem of devising political measures to prevent atomic warfare and to promote the beneficent use of atomic energy.

CHAPTER III

Constructive Applications for Atomic Energy

To "outlaw" atomic energy in all of its forms and enforce such a prohibition by an army of inspectors roaming the earth would overwhelm the capacity and the endurance of men, and provide no security. This conclusion has a further implication in a search for a security system. While suppression is not possible where we are dealing with the quest for knowledge, this thirst to know (that cannot be "policed" out of existence) *can* be used, affirmatively, in the design and building of an effective system of safeguards.

Human history shows that any effort to confine the inquiring human mind, to seek to bar the spirit of inquiry, is doomed to failure. From such efforts comes subversion fraught with terrible consequences: Gestapo, inquisitions, wars. The development of atomic energy is one of a long, long line of discoveries that have their well springs in the urge of men to know more about themselves and their world. Like the jiu jutsu wrestler whose skill consists in making his opponent disable himself with his own thrusts, the designers of a system of safeguards for security should and can utilize for enforcement measures that driving force toward knowledge that is part of man's very nature.

If atomic energy had only one conceivable use—its horrible powers of mass destruction—then the incentive to follow the course of complete prohibition and suppression might be very great. Indeed, it has been responsibly suggested that however attractive may be the potentialities for benefit from atomic energy, they are so powerfully outweighed by the malevolent that our course should be to bury the whole idea, to bury it deep, to forget it, and to make it illegal for anyone to carry on further inquiries or developments in this field.

We have concluded that the beneficial possibilities—some of them are more than possibilities, for they are within close reach of actuality—in the use of atomic energy should be and can be made to aid in the development of a reasonably successful system of security, and the plan we recommend is in part predicated on that idea.

That mankind can confidently look forward to such beneficial uses is a fact that offers a clue of not inconsiderable importance to *the kind of security arrangements* that can be made effective.

pressing, is obvious. Such a job lacks any dynamic qualities. It does not appeal to the imagination. Its future opportunities are obviously circumscribed. It might draw the kind of man, let us say, who was attracted to prohibition squads in years past. Compare this type of personnel with those who could be expected to enter a system under which it is clear that the constructive possibilities of atomic energy may also be developed. Atomic energy then becomes a new and creative field in which men may take pride as participants, whatever their particular role. They are in "on the ground floor" of a growing enterprise. Growth, opportunities, future development—these are the characteristics, let us say of the field of air transport that have made it possible for the airlines to attract a high grade and youthful personnel.

The importance of this fact that atomic energy has beneficial uses as well as destructive uses, in terms of the attraction of personnel in a security organization will, of course, depend upon the functions given to that organization. If the security organization has not only enforcement but also *development functions*, then this consideration of beneficial possibilities becomes a most weighty one.

What are the beneficial possibilities? We have had the benefit of a thoughtful, unpublished report on the technical possibilities now apparent in this field. This report was prepared for the Secretary of War's Interim Committee on Atomic Energy by a panel of scientists who worked with a large additional group of leading scientists in the field.* The conclusions there stated represent an appraisal of these possibilities, that is, in our opinion, challenging and at the same time balanced and restrained.

In introducing its conclusions the report observes that "We are probably no more able to foresee the ultimate fruits of development than were Faraday's contemporaries to understand what would come of the discovery of electro-magnetic induction." It gives a further sense of perspective in emphasizing that "The unique preoccupation of the war years in the use of atomic energy for military weapons . . . has probably retarded our understanding of other applications." We believe that this is equally true at present.

The report discusses two "great fields" for beneficial use, "the development of atomic energy as a controlled source of power" and 'the application of radiations and radioactivities to the growth of the

*This panel included A. H. Compton, E. Fermi, E. O. Lawrence, and J. R. Oppenheimer. Their report was prepared in consultation with S. K. Allison, Zay Jeffries, C. C. Lauretsen, I. I. Rabi, C. A. Thomas, H. C. Urey, and with the further help of numerous specialists.

exploitation of atomic energy as a tool for research will outweigh the benefits to be derived from the availability of a new source of power." But this new source of power is itself regarded as of great significance, and is thought to be "the most appropriate focal point for the work of the next few years."

> "We have examined in some detail [the report continues] the technical problems of making available heat and power on the scale of present world consumption from controlled nuclear reactors. We see no significant limitations on this development, either in the availability or in the cost of the fundamental active materials. We see characteristic limitations and characteristic advantages in atomic power which make us regard it in great measure as a supplement to existing sources, and an incentive to new developments, rather than as a competitor, let us say, to coal or to petroleum products. We see no foundation in current science for the hope that atomic power can be effectively used for light, small portable units such as are required for aircraft and for automotive transportation; but we believe that the development of rather large power units for heat and conversion to electrical energy is a program for the near future; that operating units which will serve to demonstrate the usefulness and limitations of atomic power can be in existence within a few years, and that only the gradual incorporation and adaptation of such units to the specific demands of contemporary economy will involve a protracted development."

Finally, the report takes up the opportunities which have been opened in the field of research by the prospect of a plentiful supply of radioactive substances as byproducts of the manufacture of fissionable materials, a circumstance which it has been said may well be as significant for scientific progress as the ready availability of microscopes for every laboratory.

> "It should be understood [the report says] that work specifically focused on atomic power need not and should not interfere with making available to biology, medicine, chemistry, and physics the radiations and activities characteristic of this field . . . We should not be astonished if the greatest benefit of this program were in fact to lie in therapy for some of the neo-plastic diseases, such as cancer, or in the increased understanding of biological systems or of the realities of the physical world, which will in turn open up new fields of human endeavor."

The full report contains descriptions in more concrete terms of some of these possibilities. We are convinced that in the vigorous exploita-

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system of international control.

Under the most favorable conditions, the peril of atomic warfare can be averted only by drawing upon the best human resources of good will, imagination, and ingenuity. All experience teaches that these resources cannot be tapped except by challenging opportunities. One of the most serious dangers to the promotion of effective international action is the danger that our natural preoccupation with the destructive aspects of atomic energy may blind us to its useful aspects. Upon searching investigation, some of the latter may prove illusory. But if the lessons of past scientific and technological progress mean anything, we also know that many of these opportunities will materialize. We believe that only a system of safeguards which is built around these hopeful prospects can succeed. We have tried throughout this report to make explicit the connection between a system of safeguards and these opportunities.

Important, perhaps even decisive, in the proposals we put forth in this report is the fact that many of the constructive activities required in the development of atomic energy involve no risks of providing a material basis for weapons of war. This aspect of the matter is dealt with in detail in Chapter V of this Section.

CHAPTER IV

The Elimination of International Rivalry

It is clear that uranium and thorium are materials of great strategic importance to nations seeking to establish for themselves a powerful position in the field of atomic energy. The fact that rich sources of such materials occur in a relatively few places in the world, as compared, for example, with oil, creates a competitive situation which might easily produce intolerable tensions in international relations. We believe that so long as nations or their subjects engage in competition in the fields of atomic energy the hazards of atomic warfare are very great indeed. We assume the General Assembly of the United Nations, in setting up an Atomic Energy Commission, had this disturbing fact much in mind.

What is true in respect to the dangers from national competition for uranium is similarly true concerning other phases of the development of atomic energy. Take the case of a controlled reactor, a power pile, producing plutonium. Assume an international agreement barring use of the plutonium in a bomb, but permitting use of the pile for heat or power. No system of inspection, we have concluded, could afford any reasonable security against the diversion of such materials to the purposes of war. If nations may engage in this dangerous field, and only national good faith and international policing stand in the way, *the very existence of the prohibition* against the use of such piles to produce fissionable material suitable for bombs would tend to stimulate and encourage surreptitious evasions. This danger in the situation is attributable to the fact that this potentially hazardous activity is carried on by nations or their citizens.

It has become clear to us that if the element of rivalry between nations were removed by assignment of the intrinsically dangerous phases of the development of atomic energy to an international organization responsible to all peoples, a reliable prospect would be afforded for a system of security. For it is the element of rivalry and the impossibility of policing the resulting competition through inspection alone that make inspection unworkable as a sole means of control. With that factor of international rivalry removed, the problem becomes both hopeful and manageable.

right to engage in certain well-defined activities in respect to atomic energy which we believe will be generally agreed to be intrinsically dangerous because they are or could be made steps in the production of atomic bombs. We schematically describe what we regard as intrinsically dangerous steps later in Chapter V. Those activities thus classified as dangerous we conclude are far less dangerous when carried on not by competing nations but by an international organization whose obligation it is to act for all nations. They can, in our opinion, be rendered sufficiently less dangerous to provide an adequate measure of security.

We can illustrate the force of these conclusions in a few simple cases. (*a*) Take the case of uranium ores. If any nation may engage in prospecting for and mining uranium ore, subject to inspection as to the proper, i. e., peaceful use thereof, inspection is a most difficult thing. But if the *only legal ownership and development of uranium ore* is in the hands of an international agency manned by and representing all nations, the problem of detection of evasions is, by a single stroke, reduced tremendously. Indeed, we are persuaded that it is reduced to quite manageable proportions in the light of existing knowledge about uranium ore deposits through the world. For then it would be true that not the purpose of those who mine or possess uranium ore but the *mere fact of their mining or possessing it becomes illegal*, and national violation is an unambiguous danger signal of warlike purposes. The very opening of a mine by anyone other than the international agency is a "red light" *without more;* it is not necessary to wait for evidence that the *product* of that mine is going to be misused.

(*b*) Take another illustration involving the building and operation of a plutonium pile. The product of that operation is a material that can be used for atomic weapons. The product is also useful for power piles. If all such piles are designed and operated exclusively by an international agency, then the building or operation of such a pile or any move in that direction by *any one else* is illegal without respect to the use he says he plans to make of it, and constitutes a plain and simple danger signal calling for action of a preventative character by an international agency.[1] Nor could there be a clearer sign of danger calling for immediate international action or countermeasures than interference with the operation of an international plant.

We conclude that the international development and operation of potentially and intrinsically dangerous activities in connection with

[1] In Section III we discuss what would happen if the international organization should fail or an international plutonium plant should be seized by a nation; we shall not digress from the present point to discuss that here.

proportions because of the elimination of the hazards of rivalry between nations. But there is a further advantage to vesting exclusively in an international agency these activities so hazardous to world security. That advantage grows out of the nature of the development of atomic energy itself.

This is a growing and changing field. New advances in technology may be confidently expected. It therefore becomes absolutely essential that any international agency seeking to safeguard the security of the world against warlike uses of atomic energy should be in the very forefront of technical competence in this field. If the international agency is simply a police activity for only negative and repressive functions, inevitably and within a very short period of time the enforcement agency *will not know enough* to be able to recognize new elements of danger, new possibilities of evasion, or the beginnings of a course of development having dangerous and warlike ends in view. There is a striking example of this. The art of atomic weapons is in its infancy and we are quite ignorant of the possibilities in this field. Such ignorance, such uncertainty of such catastrophic weapons, is itself a source of danger, and its continuation, through the prohibition of further study and development, would in our opinion not only be hard to effect, but would itself be dangerous. Yet the development of atomic weapons can hardly be left to national rivalry.

A further example: The present separation plants for U 235 at Oak Ridge are huge and bulky in the extreme, and use enormous amounts of power. Quite probably this will always be true. But it is not a law of nature. Those in whose hands lies the prevention of atomic warfare must be the first to know and to exploit technical advances in this field.

We have, therefore, concluded that here was an additional reason and a very practical one why a responsibility for the *development* of atomic energy should be vested in the same international agency that has also responsibility for developing and enforcing safeguards against atomic warfare. For unless the international agency was engaged in development activities itself (as, for example, in the design and operation of power piles or in the surveying and exploration of new sources of raw materials) its personnel would not have the power of knowledge or the sensitivity to new developments that would make it a competent and useful protection to the people of the world.

We have therefore reached these two conclusions: (*a*) that only if the dangerous aspects of atomic energy are taken out of national hands and placed in international hands is there any reasonable prospect of devising safeguards against the use of atomic energy for bombs, and (*b*) only if the international agency was engaged in

its functions as a safeguarder of the world's future.

Such a development function also seems essential in terms of attracting to the international agency the kind of scientists and technicians that this problem requires, recognizing that a mere policing, inspecting, or suppressing function would neither attract nor hold them.

CHAPTER V

"Safe" and "Dangerous" Activities

It is true that the internationalization of activities intrinsically dangerous to security reduces the hazards in the way of security and does bring into more manageable form the problems of enforcement and the suppression of atomic weapons. If it were necessary, in such a scheme of safeguards, to vest in an international agency a total monopoly as to all aspects of atomic energy, disadvantages would arise so great as conceivably to make the prospect of effective internationalization itself beyond realization. Such an overall grant of exclusive right to develop, operate, and utilize, conferred upon an international agency, would change many of the industrial and economic practices of this country, for example, and would change them quite disadvantageously.

Such a complete international monopoly would be hard to live under. Its restrictive limitations would chafe, and might in time cause serious loss of support to the security purposes that lay behind the proposal itself. Many of the considerations of complexity, irritation, the engendering of suspicion, the encouragement of deceit that we found militated against a system of safeguards based upon national operation and international inspection would to a lesser degree be repeated by such an all-out proposal for centralization.

This problem need not arise. For there are important areas in the field of atomic energy where there is no need for an international monopoly, and where work may and should be open not exclusively to the international organization, but to private and to national institutions in a quite free manner. These fields are among those of the greatest immediate promise for the beneficial exploitation of atomic energy. They are technically complex and closely related to the central scientific problems. That open and, in some respects, competitive activity is possible in much of the field should go a long way toward insuring contact between the experts of the international organization and those outside it, in industry and in scientific and educational organizations. The same fact should help correct any tendencies that might otherwise develop toward bureaucratic inbreeding and over-centralization, and aid in providing healthy, expanding national and private developments in atomic energy.

developments in the field of atomic energy as safe for national and private exploitation are in themselves rather complex; to the discussion of these we must now turn. These are, of course, activities which without reliance on the conscious determination of the operators, and with a minimum of control and supervision, are physically incapable of contributing to the making of atomic weapons.

A word may be in order about our views on what constitute "dangerous activities"—those that, in our opinion, ought to be subject to an international monopoly. It will be appreciated at the outset that this distinction between the "safe" and the "dangerous" can be useful without being completely sharp or fixed for all time.

In our view, any activity is dangerous which offers a solution either in the actual fact of its physical installation, or by subtle alterations thereof, to one of the three major problems of making atomic weapons:

I. The provision of raw materials,

II. The production in suitable quality and quantity of the fissionable materials plutonium and U 235, and

III. The use of these materials for the making of atomic weapons.

Thus we regard the mining and processing of uranium as a dangerous activity even though it must be supplemented by plants and ordnance establishments if atomic weapons are to result. We regard the facilities for making atomic weapons as dangerous even though some control be exercised over the provision of the fissionable material; and we regard the operation of reactors or separation plants which make the material for bombs or which, by relatively minor operational changes, could make the material for bombs, as dangerous even though they in turn would have to be supplemented by supplies of raw material and by installations for assembling atomic weapons.

We need not regard as dangerous either amounts of material which are small in relation to those needed to make a weapon or installation whose rate of production is small in these terms. A further point which will prove important in establishing the criteria for the safety or danger of an operation is this: U 235 and plutonium can be denatured; such denatured materials do not readily lend themselves to the making of atomic explosives, but they can still be used with no essential loss of effectiveness for the peaceful applications of atomic energy. They can be used in reactors for the generation of power or in reactors useful in research and in the production of radioactive tracers. It is important to understand the sense in which denaturing renders material safer. In the first place, it will make the material unuseable by any methods we now know for effective atomic explosives unless steps are taken to remove the denaturants. In the second place, the development of more ingenious methods in the field of

scientific and technical effort.

It is possible, both for U 235 and for plutonium, to remove the denaturant, but doing so calls for rather complex installations which, though not of the scale of those at Oak Ridge or Hanford, nevertheless will require a large effort and, above all, scientific and engineering skill of an appreciable order for their development. It is not without importance to bear in mind that, although as the art now stands denatured materials are unsuitable for bomb manufacture, developments which do not appear to be in principle impossible might alter the situation. This is a good example of the need for constant reconsideration of the dividing line between what is safe and what is dangerous.

We would, however, propose as criterion that installations using material both denatured and insufficient in quantity for the manufacture of bombs could be regarded as safe, provided the installations did not themselves make large quantities of suitable material. With some safeguards in the form of supervision, installations in which the amounts of material are small, or in which the material is denatured, might also be regarded as safe; but installations using or making large amounts of material not denatured, or not necessarily denatured, we would call dangerous.

Let us see now what we regard as safe activities in this field.

(1) Perhaps the clearest case is the application of radioactive material as tracers in scientific, medical, and technological studies. This is a field in which progress may be expected to be very rapid, and we can see no reason at all for limiting, on grounds of safety, the activities using such tracer materials.

(2) It is easy to design small nuclear reactors which use denatured U 235 or plutonium. These reactors can be operated at a power level low enough to be incapable of producing dangerous quantities of fissionable materials but high enough to provide neutron sources and gamma ray sources of unparalleled intensity. The material in these reactors is neither in quantity nor in quality significant for bomb production; even if one combined the material from many, no practical method of making weapons would be available. On the other hand, reactors of this kind can and almost inevitably will be designed to operate at so low a power level that they cannot be used to produce quantities of fissionable material which are of military significance. Reactors of this general kind have the following important applications:

(*a*) They may be used to make radioactive materials, and as such may be a supplement, and a valuable supplement, to the more dangerous reactors operating at higher power levels;

(*b*) As a source of radiation, primarily of neutron radiation, such reactors are research tools for physics, for chemistry, and for biology. This may, in fact, be one of the most important applications of the release of atomic energy.

(*c*) The high intensity of radiation from such reactors will bring about changes in chemical and biological systems which may be of immense practical value, once they have been understood.

(3) More marginal from the standpoint of safety, but nevertheless important, is another case of an operation which we would regard as safe. This is the development of power from the fission of denatured U 235 and plutonium in high power-level reactors. Such power reactors might operate in the range from 100,000 to 1,000,000 kw. If these fissionable materials are used in installations where there is no additional uranium or thorium, they will not produce further fissionable material. The operation of the reactors will use up the material. If the reactors are suitably designed, a minimum of supervision should make it possible to prevent the substitution of uranium and thorium for the inert structure of the materials of the reactors. In order to convert the material invested in such reactors to atomic weapons, it would be necessary to close down the reactor; to decontaminate the fissionable material of its radioactive fission products; to separate it, in what is a fairly major technical undertaking, from its denaturant; and to establish plants for making atomic weapons. In view of the limited amount of material needed for such a power reactor, and of the spectacular character and difficulty of the steps necessary to divert it, we would regard such power reactors as safe provided there were a minimum of reasonable supervision of their design, construction, and operation. If the material from one such reactor (of a size of practical interest for power production) were diverted, it might be a matter of some two or three years before it could be used to make a small number of atomic weapons.

We attach some importance to reactors of this type because they make it possible in large measure to open up the field of atomic power production to private or national enterprise. It is, in this connection, important to note that the materials required to construct these reactors cannot themselves be produced in installations which we could regard as safe. It is, furthermore, important to note that for every kilowatt generated in safe reactors, about 1 kilowatt must be generated in dangerous ones in which the material was manufactured. Thus if atomic power is in fact developed on a large scale, about half

primary production plants necessary to produce the materials required to construct *safe* power plants will in that process of production produce large amounts of power as a by-product. It is, furthermore, clear that the stockpiling of appreciable quantities of fissionable material suitably denatured, must precede the development of these safe power reactors. We think it fortunate that the actual operation of such reactors will have to await the production of these essential materials, so that there will be time for further study of means by which they may be supervised and their safety insured.

All the above illustrations show that a great part of the field of atomic energy can be opened with relative safety to competitive activity. They also show that the *safe operations are possible only because dangerous ones are being carried out concurrently*. It is not possible to devise an atomic energy program in which safeguards independent of the motivation of the operators preclude the manufacture of material for atomic weapons. But it is possible, once such operations are undertaken on an international basis, to devise others of great value and of living interest in which safety is no longer dependent on the motivation of the operators.

We have enumerated elements of the large field of non-dangerous activities under (1), (2), and (3) above. Among the activities which we would at the present time classify as those dangerous for national exploitation are the following:

(4) Prospecting, mining, and refining of uranium, and, to a lesser extent, thorium.

(5) The enrichment of the isotope 235 by any methods now known to us.

(6) The operation of the various types of reactors for making plutonium, and of separation plants for extracting the plutonium.

(7) Research and development in atomic explosives.

Of these activities, (6), as we have indicated, not only plays an essential part in providing active materials, but involves installations capable of generating power.

It should be added in conclusion that to exclude even safe activities from international operation seems unwise, but these should not be an international monopoly. It would equally be unwise to exclude from knowledge and participation in the dangerous activities experts who are not associated with the international authority. As the next section will show, there are practical means for making this collaboration possible in such a way that security will be promoted rather

the line between what is dangerous and what is safe has been correctly drawn; it will not stay fixed. No international agency of control that is not qualified to make this reexamination can deserve confidence.

SUMMARY

1. If nations or their citizens carry on intrinsically dangerous activities it seems to us that the chances for safeguarding the future are hopeless.

2. If an international agency is given responsibility for the dangerous activities, leaving the non-dangerous open to nations and their citizens and if the international agency is given and carries forward *affirmative development responsibility*, furthering among other things the beneficial uses of atomic energy and enabling itself to comprehend and therefore detect the misuse of atomic energy, there is good prospect of security.

SECTION III

Security Through International Cooperative Development

INTRODUCTION

In the preceding sections of this report we have outlined the course of our thinking in an endeavor to find a solution to the problems thrust upon the nations of the world by the development of the atomic bomb—the problem of how to obtain security against atomic warfare, and relief from the terrible fear which can do so much to engender the very thing feared.

As a result of our thinking and discussions we have concluded that it would be unrealistic to place reliance on a simple agreement among nations to outlaw the use of atomic weapons in war. We have concluded that an attempt to give body to such a system of agreements through international inspection holds no promise of adequate security.

And so we have turned from mere policing and inspection by an international authority to a program of affirmative action, of aggressive development by such a body. This plan we believe holds hope for the solution of the problem of the atomic bomb. We are even sustained by the hope that it may contain seeds which will in time grow into that cooperation between nations which may bring an end to all war.

The program we propose will undoubtedly arouse skepticism when it is first considered. It did among us, but thought and discussion have converted us.

It may seem too idealistic. It seems time we endeavor to bring some of our expressed ideals into being.

It may seem too radical, too advanced, too much beyond human experience. All these terms apply with peculiar fitness to the atomic bomb.

In considering the plan, as inevitable doubts arise as to its acceptability, one should ask oneself "What are the alternatives?" We have, and we find no tolerable answer.

The following pages contain first a brief summary of the plan we recommend, and then an expansion going into some detail.

Summary of Proposed Plan—The proposal contemplates an international agency conducting all intrinsically dangerous operations in the nuclear field, with individual nations and their citizens free to conduct, under license and a minimum of inspection, all non-dangerous, or safe, operations.

We shall refer to it as Atomic Development Authority. It must have authority to own and lease property, and to carry on mining, manufacturing, research, licensing, inspecting, selling, or any other necessary operations.

This chapter is not an attempt to write a corporate charter for such an international agency. It is the aim, rather, to show that such a charter can be written in workable terms, and that the nature of the organization and its functions will have decisive consequences for world security. We are satisfied that the differences between national and international operations can be exploited to make the problem of atomic energy manageable. This idea, we think, can become as familiar as the fact that the differences between individual enterprise and corporate enterprise have important consequences in the conduct of business.

If we are to do anything constructive in relation to atomic energy it must inevitably be novel and immensely difficult. We think that the weeks that we have spent in analysis of the problem have made it appear somewhat less difficult and somewhat less novel. A succession of such processes will be necessary, each building on the preceding analysis, before even the major ramifications of the problem can be understood and the major questions partially answered. What is chiefly important now is to describe the right course of action in terms sufficiently practical and valid to show that the further exploration is worthwhile.

The proposal contemplates an international agency with exclusive jurisdiction to conduct all intrinsically dangerous operations in the field. This means all activities relating to raw materials, the construction and operation of production plants, and the conduct of research in explosives. The large field of non-dangerous and relatively non-dangerous activities would be left in national hands. These would consist of all activities in the field of research (except on explosives) and the construction and operation of non-dangerous power-producing piles. National activities in these fields would be subject to moderate controls by the international agency, exercised through licensing, rules and regulations, collaboration on design, and the like. The international agency would also maintain inspection facilities to assure that illicit operations were not occurring, primarily in the exploitation of raw materials. It would be a further function of the Atomic Development Authority continually to reexamine the boundary between dangerous and non-dangerous activities. For it must be recognized that although the field is subject to reasonable

The development agency itself would be truly international in character. Its staff would be recruited on an international basis. Its functions would be such as to attract a calibre of personnel comparable to our own activities in raw materials during the war and our own primary production and experimental work. It would be set up as one of the subsidiary agencies of the United Nations, but it would have to be created by a convention or charter establishing its policies, functions, and authority in comprehensive terms.

Whatever the formal organization, its integration with national structure would of course be one of the major problems. Measures to assure the proper degree of accountability to the United Nations and to individual nations, measures to assure that individual nations would have ample opportunity to be informed of the agency's activities, measures to make the agency responsive to the changing needs of nations—all these would have to be worked out with extraordinary care and ingenuity. But certainly our experience with business and government institutions, national and international, would afford a wealth of guidance in the development of such measures.

In the actual conduct of its operations the development organization would at all times be governed by a dual purpose, the promotion of the beneficial use of atomic energy and the maintenance of security. We believe that much can be done in a convention or charter to make these purposes concrete and explicit, to draw the line between the dangerous and the non-dangerous, to establish the principles determining the location of stockpiles and plants so that a strategic balance may be maintained among nations, to establish fair and equitable financial policies so that the contributions of nations to, and their receipt of benefits from the organization will be justly apportioned. The most careful and ingenious definitions will be required in order to accomplish these purposes.

In what follows we shall attempt to develop and expand the foregoing statement of essentials.

We can best visualize the Atomic Development Authority in terms of the answer to these concrete questions:

(1) What will be the functions of the agency; what are the things that it will do?

(2) What kind of organization is necessary to carry out these functions?

(3) How will the organization be related to the United Nations and the individual nations that it will represent?

(4) What policies will guide the agency in determining its manifold actions?

CHAPTER 1

Functions of Atomic Development Authority

In the field of raw materials—The first purpose of the agency will be to bring under its complete control world supplies of uranium and horium. Wherever these materials are found in useful quantities the international agency must own them or control them under effective leasing arrangements. One of its principal tasks will be to conduct continuous surveys so that new deposits will be found and so that the agency will have the most complete knowledge of the world geology of these materials. It will be a further function of the agency constantly to explore new methods for recovering these materials from media in which they are found in small quantities.

In this way there will be no lawful rivalry among nations for these vital raw materials. Through its surveys the agency will be better informed about their geology and extraction than any single nation could possibly be. It will be in a better position to discover whether and where illicit operations might occur than any inspection force could possibly be. This is not to say that there is no risk of illicit operations; any plan, any system of safeguards, involves some risk. The question that must be answered in appraising the dangers is whether the risk is so large that it is better to make no attempt at international control and abandon the world to national atomic armament.

As we have pointed out earlier, if the Atomic Development Authority is the only agency which may lawfully operate in the raw materials field, then any visible operation by others will constitute a danger signal. This situation contrasts vividly with the conditions that would exist if nations agreed to conduct mining operations solely for proper purposes; for surreptitious abuse of such an agreement would be very difficult to detect. It is far easier to discover an operation that should not be going on at all than to determine whether a lawful operation is being conducted in an unlawful manner.

For the purpose of its surveys, the international agency would require access to various nations for its geologists and mining engineers. But the known geology of the critical materials is such that it may be possible to limit the degree of access from the start. And, as explora-

tne right of access to any region for re-survey in the light of new knowledge would be necessary.

All the actual mining operations for uranium and thorium would be conducted by the Authority. It would own and operate the refineries for the reduction of the ores to the metal or salt. It would own the stockpiles of these materials and it would sell the by-products, such as vanadium and radium. It would also provide the necessary supplies of uranium and thorium for the present limited commercial uses. All these sales would presumably go through normal commercial channels.

In the field of raw materials as in other activities of the Authority, extremely difficult policy questions, with the most serious social, economic, and political implications, will arise. How shall nations and individuals be compensated for reserves taken over by the Authority? As between several possible mines in different areas, which shall be operated when it is clear that the output of all is not presently required? How can a stragetic balance be maintained between nations so that stockpiles of fissionable materials will not become unduly large in one nation and small in another? We do not suggest that these questions are simple but we believe that practical answers can be found. An attempt to suggest an approach to such answers is made later where the general question of policies of the Authority is discussed.

Production Plants.—The second major function of the Authority would be the construction and operation of useful types of atomic reactors and separation plants. This means that operations, like those at Hanford and Oak Ridge and their extensions and improvements, would be owned and conducted by the Authority. Reactors for producing denatured plutonium will be large installations and by the nature of the process they will yield large amounts of energy as a byproduct. As the technology of power development by this method expands, ways will be found for utilizing this power both as heat and as electricity. The existing plants are not designed to operate at a sufficiently high temperature for the energy to be used for the generation of electrical power. One of the first research and development problems of the Authority would be to develop designs of reactors such that the energy released would be in form usable for the generation of electric power.

These production plants are intrinsically dangerous operations. Indeed they may be regarded as the most dangerous, for it is through such operations that materials can be produced which are suitable for atomic explosives.

production plants. What measures can be taken to assure the minimum degree of danger in design of plants and output? What measures can be taken to assure the minimum danger of diversion? What measures can be taken to assure location of plants that both will permit the disposition of byproduct power and heat in areas where they are most needed and at the same time will maintain a strategic balance between nations so that none may be inspired with fear lest the existence of plants in another would give that nation an advantage if it suddenly developed aggressive intentions? How will the vast amounts of byproduct power be disposed of by an international agency operating geographically within a national economy? Like the questions previously stated, these are not easy to answer. But here again we think that answers can be found and we venture later to suggest a way of going about the process of formulating answers.

Research Activities—We have already referred to the research that the Authority will conduct to extend the field of knowledge in relation to recoverable raw materials. We have referred to research in power development. There will be many other forms of research in which the Authority will have to engage, relating to simplifying reactors and the like.

Here we desire to emphasize that the field of research in its broadest sense is the field in which the greatest opportunities present themselves for national and private activities. For research in relation to the application of discoveries relating to atomic energy is a great area of work which in the context of the general plan of safeguards herein proposed, is non-dangerous. For the reasons already indicated the Authority itself will have to engage in a wide variety of research activities. For example, one of the important things that the Authority will have to do is research in atomic explosives. We are by no means sure that important new discoveries in this field do not lie ahead. Possibly the study of atomic explosives may yield byproducts useful in peaceful activities. But this will not be the main purpose of the Authority's research. Only by preserving its position as the best informed agency will the Authority be able to tell where the line between the intrinsically dangerous and the non-dangerous should be drawn. If it turns out at some time in the future, as a result of new discoveries, that other materials lend themselves to dangerous atomic developments, it is important that the Authority should be the first to know. At that time measures would have to be taken to extend the boundaries of safeguards.

rather must give vigorous encouragement to research in national or private hands. The universities and public technical agencies, industrial enterprises, research institutes, all will have a direct interest in participating in these activities. A good example of the opportunities in this direction is afforded by considering the situation with respect to radioactive isotopes. It will be possible for the Authority to produce these isotopes in primary production plants. The chemical separation and purification of them, however, is an involved industrial process, but involves no threat to security; states or private organizations should be encouraged to go into these activities. But for many purposes it will also be possible to produce these isotopes in small non-dangerous reactors that can be safely operated by nations or private institutions. In the interest of avoiding overexpansion of the international Authority, we think a deliberate effort should be made to encourage the production of isotopes in national hands.

It would be premature, of course, to seek now to draw any hard and fast line between the functions that the Authority should have in producing these isotopes and the functions which ought to be left to nations and their citizens. But it is important to be aware at all times of the necessity for taking advantage of the opportunity for promoting decentralized and diversified national developments and of avoiding unnecessary concentration of functions in the Authority. The field of research is an area in which the keenest awareness of this problem will be essential when the time comes to draft a charter and when thereafter the time comes for establishing the detailed administrative policies of the Authority.

Up to now we have been dealing with the exclusive proprietary functions of the Atomic Development Authority. Except as to the discussion just concluded we have been describing the things it must do wholly withdrawn from national hands. We turn now to a discussion of functions more regulatory than proprietary in character. These are the functions through which the agency will maintain moderate controls over the activities that will be conducted by nations or private agencies. For convenience we shall refer to these activities as "licensing" functions though we think that various devices besides licensing may in fact be developed to do the job.

Licensing Activities—The uranium and thorium which the Authority mines and the fissionable materials which it produces will remain the property of the Authority. By such ownership the Authority could determine the conditions under which these dangerous materials might be used. Through the lease of such denatured materials to

lishment in which such material is used. Moreover, through its own research and development activities and through establishing cooperative relationships with research and development laboratories in this field throughout the world, the Authority would be in a position to determine intelligently safe and unsafe designs of reactors for which it might lease its fissionable materials.

In the following paragraphs we shall refer to three of the general types of activities of great importance in the field of atomic energy which, as already indicated, are or can be made sufficiently safe to be carried on by nations under suitable arrangements with the proposed Authority. These types of activity, as we have pointed out earlier, open up a broad field for national and private exploitation of the useful applications of atomic energy. In particular, they will permit broad scope for research and development in this field by nations and private groups within such nations.

One of the first licensing activities of the Authority might be in the field of research reactors for which it would furnish on lease denatured plutonium or U 235. In carrying on such operations, presumably those desiring to build such research reactors would submit their designs to the Authority both for approval and for advice as to improvements, and would obtain a license to build such a reactor and lease of the denatured fissionable material needed for it. There would be a minimum of danger involved in allowing the construction and operation of research reactors not exceeding a prescribed power level. As we have seen, the amounts of fissionable material which might be produced through their use would be so small that for any individual unit, or even for units in one country which might number a dozen or more, there would be no real danger in terms of producing material sufficient for use in atomic explosives. Presumably the Authority from time to time would send its research personnel, in the dual role of research workers and inspectors, to the laboratories in which these reactors were used, but a minimal inspection would be needed. Moreover, such research reactors would fulfill to a large extent the urgent requirements for further intensive scientific research in this field. Presumably licenses and leases of material would be arranged between the Authority and individual nations so that the Authority would not be dealing directly with private groups within nations.

The Authority would also license and lease in the same manner as described for research reactors the construction and operation of reactors for making radioactive materials. There may well be, as suggested above, a field for the national or private production of such radioactive materials which will require a pile to produce mate-

plutonium or U 235.

Within the next few years, the Authority should also be in a position to license the construction and operation of power piles and to furnish on lease denatured plutonium or U 235. The design of such piles would have to be carefully reviewed, and the construction perhaps should be inspected by the Authority, to insure that the pile was not readily convertible to a dangerous form. For example, there should be no provision within such piles for the introduction of uranium or thorium. Iron or lead might be required as structural materials and if these were made non-removable, there would be a large factor of safety against abuse. Such power reactors would "burn" the active materials and require replenishing from time to time. The fissionable materials for such power reactors would be derived from the operation of the production plants of the Authority. There is no prospect that for several years such power reactors as described here could be licensed, for the reason that there would not be enough fissionable materials produced in the plants of the Authority. Thus there is a reasonable period during which research and development may proceed both in the laboratories of the Authority and in national and private groups throughout the world, as a result of which much more will be known as to the safe and unsafe features of design prior to the time when decisions will be required.

The questions of policy that arise in relation to the licensing activities of the Authority will likewise require the utmost in ingenuity and resourcefulness for their solution. How shall control be exercised lightly enough to assure the free play of national and private enterprise without risk to security? How shall facilities and materials available for national and private exploitation be allocated and at what cost? How may safe activities, assigned to national hands, be withdrawn if new discoveries show them to be dangerous? Again, we do not minimize the difficulties. We say only that we believe them to be of manageable proportions, and that techniques can be devised to facilitate solutions.

Inspection Activities—Throughout this report we have recorded our conviction that international agreements to foreswear the military use of atomic weapons cannot be enforced solely by a system of inspection—that they cannot be enforced in a system which leaves the development of essentially dangerous activities in the field of atomic energy in national hands and subject to national rivalry, and, to insure against diversion of these activities to aggressive ends, relies upon supervision by an agency which has no other function. But inspection in a wide variety of forms has its proper place in the

nizable as inspection, but that may be regarded as one of the virtues of the proposal.

It may at the outset be useful to recall some of the factors which lead us to believe that as a function of the Atomic Development Authority inspection can be effective. We do not by this wish to suggest that the necessary inspection functions are trivial or that they can be carried out without inventiveness and effort. We do believe that the proposals of this report create a framework within which such inventiveness and such effort can be effective.

In the inspection of declared and legal activities—to be sure that they are really legal—it is of the greatest advantage that the operations can themselves be so conducted as to make this inspection and control easy. The Atomic Development Authority will have the double responsibility of technically effective development, and of safety. It would be in a position to insure that in the plan of operations, in the physical layout, in the system of audits, and in the choice of developments, full weight and full consideration can be given to the ease of detecting and avoiding diversion and evasion. Thus, the Authority may conceivably find it unwise to exploit certain types of deposits because of the difficulties they present to adequate auditing. The Authority may have reason to decide on one or another method of the separation of isotopes because it lends itself more readily to control. In the location of its operations, it will be in a position to take into account political and sociological factors which might make control difficult, or to allow such considerations to influence its choice of operating personnel and procedures. We attach great weight to the importance of unifying at the planning stage the requirements of development and control. We also attach great weight to the far-reaching inseparability of the two functions in the personnel of the development authority.

As we have pointed out repeatedly, the Authority will be aided in the detection of illegal operations by the fact that it is not the motive but the operation which is illegal. Any national or private effort to mine uranium will be illegal; any such stockpiling of thorium will be illegal; the building of any primary reactor or separation plant will be illegal. This circumstance is of very great importance for the following reason: It is true that a thoroughgoing inspection of all phases of the industry of a nation will in general be an unbearable burden; it is true that a calculated attempt at evasion may, by camouflage or by geographical location, make the specific detection of an illegal operation very much more difficult. But the total effort needed to carry through from the mine to the bomb, a surreptitious program of

difficult undertakings so great, and the special character of many of these undertakings so hard to conceal, that the fact of this effort should be impossible to hide. The fact that it is the existence of the effort rather than a specific purpose or motive or plan which constitutes an evasion and an unmistakable danger signal is to our minds one of the great advantages of the proposals we have outlined.

We have frequently emphasized the related difficulties of providing in an inspection agency personnel with the qualifications necessary for that work, and with enlightened and constantly improving understanding of the technical realities. We believe that these problems can be solved in an Atomic Development Authority to which is entrusted the technical exploration of the field, and in which inspection activities will be carried out in part by the very personnel responsible for the new developments and in part by the men of the same organization, who have access to, and who have an interest in, the research and development activities of the Authority. We do not wish to overemphasize the advantages that may arise from the free association of the Authority's scientists and experts with those engaged in private or national undertakings, but we believe that if a serious effort is made to cultivate this association it will greatly reduce the chance of evasive national or private action, or of the existence, unknown to the Authority, of technical developments which might constitute a potential danger. As an example of an association which would on technical grounds be most appropriate for the Authority, we may cite the problem of power. The Authority will be engaged in the production of power. It will be engaged in licensing power plants of non-dangerous type for private or national operation. It should take advantage of these associations to be informed about the power requirements which play so large a part in the operation of separation plants.

It will be seen that we do not contemplate any systematic or large-scale inspection activities for the Authority except those directed to the control of raw materials. It is our hope—and we believe it a valid hope—that when the Authority is in full operation it will, through the application of ingenuity to the problem, have obtained a sufficiently complete control over raw materials and the fissionable products so that no elaborate and formal inspection procedures will be needed to supplement it. It is clear that final decision on this matter must take into account the events of the transition period from our present condition to that of the full operation of the Authority. It is also clear that the more rapidly the initial steps leading to the Authority's control of raw materials are taken, the greater the chance of the elimination of the more burdensome forms of inspection.

The geological survey, while in a sense inspection, will be focussed on a world-wide search and survey for the discovery of the essential raw materials. In the conduct of research and development, and through the location of the Authority's laboratories in various parts of the world, the Authority should become cognizant of a wide range of research and development activities in various countries. Therefore, the purpose of inspection would be served in that personnel of the Authority should be currently and intelligently informed regarding national and private research and development activities in this field.

In operating mines, refineries, and primary production plants in various countries, the personnel of the Authority will likewise acquire insight regarding the activities and trends in various countries. In its licensing activities the Authority will maintain contact with the research and development laboratories authorized to use reactors. Exchange of personnel, visits, and even formal inspection, may all be involved.

In licensing power reactors which are somewhat less safe than research reactors, the Authority would send its representatives to inspect or visit these plants at frequent intervals. Such personnel would presumably be trained in the development or engineering branches of the Authority and their primary purpose might well be to furnish engineering services and advice to the operators. The inspection that would actually result would be far more effective than any direct attempt to inspect.

Under the relations described between the Authority and national or private groups using denatured fissionable material, the inspectors would have a right of access deriving from the terms of the license and lease. Furthermore, if the Authority conducted the operations described, it would have within its organization a unique knowledge of the whold field of atomic energy and the changes in that field, which are almost certain to be rapid if it is developed in a healthy manner. To the extent inspection was required it could be done by competent engineers or scientists who would be far more knowledgeable than those inspected and who could furnish useful aid and advice at the same time.

In the course of its activities, the Authority might acquire information which would cause it to suspect evasions or violations in places to which it did not have the right of access for geological survey or for inspection of installations using leased material. Some means would have to be provided so that the Authority by making out a prima facie case would be granted access to the suspected plant or laboratory. This might be arranged through the presentation of such a request to some international body such as the International Court. If the Court

were satisfied with the adequacy of the reasons presented by the Authority, it might then request the nation in which the suspected activities were located to grant access to representatives of the Authority. This seems to us one of the possible means of approach to the limited problem of detection of evasions that would be present even under the Atomic Development proposal. The procedure seems sufficiently limited in its effect upon national sovereignty to be practical. We recognize that the idea raises a host of questions that would have to be answered before the feasibility and effectiveness of the device could be established but we think it worthy of this further exploration.

CHAPTER II

Organization and Policies of Atomic Development Authority

In the light of the scientific and technological facts and of broad human and political factors, we have undertaken, up to this point, to describe the kind of functions that an Atomic Development Authority would have to be given in order to be effective. In considering the problems of organizational structure and detailed policies for such an authority it is also clear that the facts concerning atomic energy are decidedly pertinent. But as to these problems, there is much relevant experience in the general field of international organization. Obviously the systematic approach necessary for a solution of these problems must draw heavily on that experience.

But there is an important question of timing. It would be premature now to seek definitive answers to many of the questions as to organization and policy. For in order to have validity the answers will have to be the product of international discussion and deliberation rather than any unilateral statement of a detailed plan.

In considering the type of organizational problem involved in setting up an Atomic Development Authority under the United Nations, it should be readily possible to find helpful analogies in other international operations, public and private, and even in national activities. In the course of our discussions numerous questions concerning these matters have naturally occurred to us as they would to anyone studying the international issues created by atomic energy. It has been necessary to reflect intensively on the possible answers to such questions as a means of testing the soundness of our main conclusions. We present here some of the results of our own discussion and reflection, not in the form of a systematic statement but rather for the purpose of illustrating the types of questions that arise and possible answers which occurred to this group.

One of the key problems of course will be the question of personnel. It will be of the essence to recruit that personnel on a truly international basis, giving much weight to geographical and national distribution. It does not seem to us an unreasonable hope that the organization would attract personnel of high quality. For the field of knowledge is one in which the prospects for future development have become an absorbing interest of the entire world. Certainly

there is a far better chance that the Authority would attract personnel of a high calibre than that any purely policing organization would do so. At any rate, it is clear that the success of the organization would depend upon the quality of the administrators, geologists, mining experts, engineers, physicists, chemists, and other personnel, and every possible effort must be made to establish the kind of organization that will attract them.

It is not alone necessary for the organization to be thoroughly informed in the field of atomic energy. It will also be necessary for the nations of the world to be thoroughly informed at all times about the operations of the Authority. There are many ways of assuring this necessary degree of accountability on the part of the Authority to the nations and peoples whose instrument it will be. Some integral organ of the United Nations, perhaps the Security Council itself, will need to serve as the overseeing body for the Authority. But it could do so in ways generally comparable to those employed by Congressional appropriations and investigating committees and the Bureau of the Budget in relation to governmental institutions in the United States. Detailed measures would have to be worked out to assure the proper connection between such an overseeing or "accountability" body and the Atomic Development Authority itself. Ways will also have to be worked out to assure that individual nations may maintain enough direct contact with the organization to give them a sense of intimate relations with it. This need will be served in part by the fact that the staff of the organization will be recruited from various nationalities. The operations of the Authority in its licensing activities, where it will be dealing directly with individual states, will also be one of the ways in which this objective is accomplished. For in this field there will be constant collaboration between the Authority and individual states in working out the detailed scientific, technological, and political problems which will cluster around the Authority's licensing activities. None of these matters appears to present insuperable difficulties.

The foregoing is intended merely as a statement of the possibilities for actually creating an organization that will have sound relations with the United Nations and with individual states. These possibilities must be made the subject of further exploration as intensive as that which we have directed to the scientific and technological facts concerning atomic energy itself.

Until qualified men set themselves the task of actually writing a charter, chapter by chapter, anything said about policies must be merely by way of preface. The actual statement of policy, like the

form of organization, will have to grow out of the international discussions and deliberations.

The fundamentals governing the Atomic Development Authority must of course be those which have been so well stated in the resolution of January 18, 1946 setting up the United Nations Atomic Energy Commission, that is, the strengthening of security and the promotion of the beneficial use of atomic energy. In our report we have adopted as the first principle in the accomplishment of these fundamental objectives the proposition that intrinsically dangerous activities in the field must not be left open to national rivalry but must be placed in truly international hands. To establish the boundaries between international and national action, we have grasped the fortunate circumstance that a dividing line can be drawn between dangerous and non-dangerous activities. We have emphasized that not the least in the fortunate circumstances that we have observed is the fact that the field of non-dangerous activities is so challenging that it provides an opportunity to avoid such centralization of authority as might make the price of security seem too high. In this connection it is important that a purposeful effort should be made to keep as broad and diversified as possible the field of activities which is left in national and private hands. Every effort must be made to avoid centralizing exclusively in the Authority any more activities than are essential for purposes of security.

These are the kind of basic considerations which we assume the United Nations Atomic Energy Commission would seek to make explicit in its recommendations for the charter of an Atomic Development Authority. Many others can be added to the list. We mention some now which are typical and illustrative and which are drawn from the kind of questions which have arisen in our own discussions.

We would expect that the charter itself should, so far as practicable, define the areas that are clearly dangerous, in which there must be an exclusive international operation, and the areas which now seem clearly non-dangerous, in which there may be national and private operations. One of the most difficult problems will be the creation of charter provisions and administrative machinery governing the manner in which the line will be drawn between safety and danger near the middle of the spectrum of activities where the division becomes less sharp. Another difficult problem will be to provide the means to redefine as either "dangerous" or "safe" when new knowledge shifts the line. In these matters close questions will arise, of course, as to the issues which must be referred for approval to the individual nations, the issues which need only be referred to some organ of the United Nations, like the Security Council, and the issues which can be determined by administrative action of the Atomic Development Authority itself.

In strengthening security, one of the primary considerations will relate to the geographical location of the operations of the Authority and its property. For it can never be forgotten that it is a primary purpose of the Atomic Development Authority to guard against the danger that our hopes for peace may fail, and that adventures of aggression may again be attempted. It will probably be necessary to write into the charter itself a systematic plan governing the location of the operations and property of the Authority so that a strategic balance may be maintained among nations. In this way, protection will be afforded against such eventualities as the complete or partial collapse of the United Nations or the Atomic Development Authority, protection will be afforded against the eventuality of sudden seizure by any one nation of the stockpiles, reduction, refining, and separation plants, and reactors of all types belonging to the Authority.

This will have to be quite a different situation from the one that now prevails. At present with Hanford, Oak Ridge, and Los Alamos situated in the United States, other nations can find no security against atomic warfare except the security that resides in our own peaceful purposes or the attempt at security that is seen in developing secret atomic enterprises of their own. Other nations which, according to their own outlook, may fear us, can develop a greater sense of security only as the Atomic Development Authority locates similar dangerous operations within their borders. Once such operations and facilities have been established by the Atomic Development Authority and are being operated by that agency within other nations as well as within our own, a balance will have been established. It is not thought that the Atomic Development Authority could protect its plants by military force from the overwhelming power of the nation in which they are situated. Some United Nations military guard may be desirable. But at most, it could be little more than a token. The real protection will lie in the fact that if any nation seizes the plants or the stockpiles that are situated in its territory, other nations will have similar facilities and materials situated within their own borders so that the act of seizure need not place them at a disadvantage.

Various auxiliary devices, in addition to a strategic geographic division of plants and facilities and stockpiles, will also be necessary. Some of these have already been referred to. The design of primary production plants should make them as little dangerous as possible. The stockpiles of materials suitable for the production of bombs should be kept as small as possible consistent with sensible economics and engineering. So far as practicable, stocks should be denatured or kept in low concentrations unsuitable for the production of bombs. In other words, the design and operating procedures should definitely

prevent the accumulation of substantial amounts of material quickly convertible into important quantities of explosives.

All these matters must be the subject of the most careful consideration in the writing of the charter itself.

With appropriate world-wide distribution of stockpiles and facilities; with design rendered as little dangerous as possible; with stockpiles of dangerous materials kept at the lowest level consistent with good economics and engineering; there will be no need for a sense of insecurity on the part of any of the major powers. Seizures will afford no immediate tactical advantage. They would in fact be an instantaneous dramatic danger signal, and they would permit, under the conditions stated, a substantial period of time for other nations to take all possible measures of defense. For it should be borne in mind that even if facilities are seized, a year or more would be required after seizure before atomic weapons could be produced in quantities sufficient to have an important influence on the outcome of war. Considering the psychological factors in public opinion, the fixing of danger signals that are clear, simple, and vivid seems to us of utmost importance.

There are other basic problems of only slightly less difficulty which will also need to be dealt with in the international deliberations. These have to do with such matters as compensation to nations and private agencies for the raw materials which the Authority would take over, they have to do with the problem of initial financing, they have to do with allocations and distribution of the materials and the facilities which the Authority will license or sell to individual nations and, through them, to their citizens. One of the difficult problems in this respect will be the question of priority in establishing non-dangerous power plants within various nations and the relation between these licensed activities and the power-producing activities of the Authority itself. A special word needs to be said on this subject.

The needs of nations for new power resources vary not only with industrial conditions, but also with their proximity to water power, coal, and petroleum. As we have emphasized before, the power supply from fissionable materials is of two entirely distinct kinds. Power will be produced in the very process of operating the production plants which make fissionable materials. These plants are of the dangerous kind which must be owned and operated by the Authority. The decisive consideration in determining the location of such plants will have to be strategic; otherwise the physical balance between nations will be impaired. In other words, the distribution of these plants throughout the world will have to be based primarily on security considerations. But there will still be ample room for an individual nation, once it is decided that such a plant can be located within its borders, to determine where the plant shall be situated in relation to its own economic and social needs. It also appears fair to assume that the charter could provide specifically for the Authority to turn the power over to the nation or its designee at the bus bar of the power plant, thus leaving it to each individual state to determine policy in relation to transmission, distribution, and use, or the Authority might deliver steam to the individual state, leaving all electrical operation in national or private hands as determined by the policies of the particular nation. Problems of price will be difficult, but here again it should be possible to state basic policies in the charter which will give reasonable assurance of fairness in the fixing of cost.

The problem of power producing piles should be somewhat less difficult in the case of the non-dangerous plants. In these, fissionable materials will be denatured. The charter should be able to provide for their allocation of this type of plant in accordance with more conventional economic standards. It might be possible to provide that they should be located on the basis of competitive bids among interested nations. On such a basis, countries with ample power resources in water, coal, or oil would limit their bids to those warranted by the costs of alternative sources. Those countries having few or expensive ordinary sources of power might bid higher, but below the cost of other alternatives. In this way the maximum usefulness of fissionable materials with the greatest conservation of other sources of power would be secured.

Many other questions of the same order as those we have discussed can readily be imagined. These are enough to illustrate the nature of the problem.

SECTION IV

The Transition for International Control

When fully in operation, the plan described in the previous section would, in our opinion, provide a great measure of security against surprise attack by atomic weapons. But it will take a considerable time before the plan can be adopted, and once the nations of the world have adopted it, a still further time will be required to put the plan into operation. It is essential to consider what will be the condition of affairs during the necessary period of transition.

In particular we must take note of the nature of the commitment already made for international action in order to determine whether the proposal satisfies the conditions attached to that commitment. In the pronouncements which the United States has made and sponsored in concert with other nations, the commitment for action has always been coupled with the requirement that the process of moving toward the goal of complete international collaboration must be accompanied at each stage by appropriate safeguards. It is the purpose of this section to describe the extent to which the suggested plan will satisfy this requirement.

The period of transition may be broken down into two sub-periods. In the first there will be no Atomic Development Authority. There will be discussions in the Atomic Energy Commission of the United Nations Organization, and as a result of these discussions, proposals will be referred to the United Nations Council and Assembly and to the several nations for further discussion and acceptance. From this process, there will result a charter that has been ratified by the various nations. It is at this stage that the Atomic Development Authority will come into being. All of this will inevitably require time. In the second period, when an Atomic Development Authority is created by the ratification by the several nations of the charter which establishes it, it will have an immense task before it, involving many different fields and many different activities. It would, of course, be possible to leave the ordering and sequence of these activities, or rather of undertaking them, to the discretion of the Authority. It seems far more likely that provisions governing the sequence of

steps by which the Authority will come into full operation will be provided in the charter.

Two different kinds of consideration will be involved in setting up the steps of discussion and operation. On the one hand there are, as we shall see, certain indispensable requirements for the *adoption and the success of the plan itself*, which require that certain steps be taken before others can be effective. On the other hand, there is a wide range of schedules all equally compatible with the operability of the plan and *affecting primarily its acceptability* to the several nations. We shall be concerned in this section with outlining the requirements of the plan as to schedule, and pointing out what other elements are not fixed by the plan itself and in the fixing of which quite new considerations are essential. In other words, we shall attempt to describe those steps which must be undertaken in a particular order if the plan is to become effective at all. We shall also indicate other steps which are a necessary part of bringing the plan into operation, but as to which there is some freedom of choice in determining their sequence. The sequence of the first set of steps is fixed by the plan itself; the sequence of the second set is a matter that will have to be fixed by the negotiation between the nations.

The Position of the U. S. During the Transition

In order to have meaning, the examination of the transition period must take account of the present position of the United States in the field of atomic energy, and that position must be compared with the one that this country would occupy during the period when the plan for international action is being adopted and executed. Today's position must also be compared with the conditions that will prevail when the plan has finally been brought into full operation. We must also consider what our position would be some years hence if we were forced to abandon our present commitment for international action and pursue instead a purely national treatment of the problem.

Today the United States has a monopoly in atomic weapons. We have strategic stockpiles; we have extensive facilities for making the ingredients of atomic bombs and for making the bombs themselves; we have a large group of people skilled in the many arts which have gone into this project; we have experience and know-how obtainable only in the actual practice of making atomic weapons; we have considerable resources of raw material; and we have a broad theoretical knowledge of the field which may appear inadequate in future years, but which enables us to evaluate not only the performance of the past but also what the future is likely to hold.

It is true that some part of our monopoly we hold in common with the United Kingdom and Canada. This applies principally not to material facilities or to weapons, but to the availability of raw materials, to theoretical knowledge, and to some elements of the know-how.

It has been recognized that this monopoly could not be permanent. There have been valid differences of opinion on the time which it would take other nations to come abreast of our present position, or to surpass it; but it is generally admitted that during the next five to twenty years the situation will have changed profoundly.

International control implies an acceptance from the outset of the fact that our monopoly can not last. It implies substituting for a competitive development of atomic armament a conscious, deliberate, and planned attempt to establish a security system among the nations of the world that would give protection against surprise attack with atomic weapons. Above all, it involves the substituting of developments which are known to the world for developments by the several nations which might well remain more or less secret, and where the very fact of secrecy would be a constant source of fear, incitement and friction.

Inherent in the adoption of any plan of international control is a probable acceleration—but only acceleration—of the rate at which our present monopoly will inevitably disappear, since our knowledge and our mastery of practical arts, and to some extent our physical installations, must ultimately be made available to an international agency in the process of establishing control.

Let us consider, for example, the plan we recommend in this report. If adopted and executed in good faith, this will have reached a reasonably full degree of operation in a period of years. At that time nearly all the factors making the present position of the United States in relation to atomic energy a preferred one will have been eliminated. For, when the plan is in full operation, no nation will be the legal owner of atomic weapons, of stockpiles of fissionable material or raw materials, or of the plants in which they can be produced. An attempt will have been made to establish a strategic balance in the geographical distribution of the internationally owned plants and stockpiles.

The security which we see in the realization of this plan lies in the fact that it averts the danger of the surprise use of atomic weapons. The seizure by one nation of installations necessary for making atomic weapons would be not only a clear signal of warlike intent, but it would leave other nations in a position—either alone or in concert—to take counter-actions. The plan, of course, has other security purposes, less tangible but none the less important. For in the very fact

of cooperative effort among the nations of the world rests the hope we rightly hold for solving the problem of war itself.

It is clear that it would be unwise to undertake a plan based on the proposals which we have put forward unless there were some valid hope that they would be entered into and carried through in good faith; nevertheless, we must provide against the hazard that there may not be such good faith and must ask ourselves this question: What will be the state of affairs should the plan be adopted with the intention of evasion or should evasion be undertaken by any nation during the years when it is being put into effect?

The basis of our present monopoly now lies in two rather different things: knowledge, and physical facilities. The ultimate geographical balance toward which a plan for international control must work will witness the loss of both kinds of monopoly. Knowledge will become general, and facilities will neither in their legal possession nor in their geographical distribution markedly favor any one nation. Although both elements of our present hegemony will thus disappear over a period of years, quite different considerations are involved in the sharing of our knowledge and in the balancing of physical facilities.

The Material Aspects of the Transition

The transfer of such facilities to international control; the establishment under international control of similar facilities in other nations; the creation of stockpiles; the gradual building up of groups of men skilled in the various necessary arts—these are changes which from their very nature will require time to bring about, and which can, within not too wide limits, be scheduled and controlled. In the discussions within the United Nations Commission leading up to the adoption of the charter for the Authority, and even more in the early planning phases of the Authority's work, there will have to be some disclosure by us of theoretical information. But these discussions and these plans will not essentially alter the present superiority of the United States. They will not move its stockpiles of uranium or of fissionable material or its bombs or its operating plants, and need not alter the operation of these plants. These disclosures of information, now secret, will not create in any other nation the experience and the know-how which are so great a part of our present position of superiority.

No matter what may be the schedule of operations adopted, this situation cannot change overnight under any circumstances. Nevertheless, it is clear that very serious consideration must be given to the scheduling of those physical and legal changes which over a period of years will bring about a balanced international operation. On the one hand, the general principles underlying this scheduling will have

to be the subject of negotiation, and the outcome will in one form or another have to be written into the charter. The charter may, for instance, provide that some things should not be done before a specified number of years have elapsed, or before the activities of the Authority, let us say, in the field of raw materials, have reached a certain stage of effectiveness. On the other hand, the Authority itself may by charter provision be given responsibility and discretion in the planning of its activities. It may, for instance, be called upon to certify that it is in satisfactory control of the raw materials situation before it undertakes certain of its other functions.

We are aware of the great importance which attaches to a prudent and reasonable scheduling of the step by step transition from our present position. But this problem is of a fundamentally different kind from those that have been discussed in this report. In this report we have attempted to discover and describe the conditions which, as we view the matter, a workable system of international control would have to satisfy.

The consideration of the steps of transition by which the special position of the United States may be relinquished involves quite other values. The sequence, the ordering, and the timing of these steps may be decisive for the acceptability of the international controls, but they will not affect its operability. Therefore, they present problems of negotiation between the nations within the UNO in the course of agreeing upon a charter for the Atomic Development Authority. Such problems of negotiation, in our opinion, are separable from the nature of the objective of the negotiation. They are problems which cannot be solved now, because they depend, among other things, on the motivation of the participating nations, on the political background of the negotiations, and on what may be conceived to be the separate, as opposed to the collective, interests of these nations.

The extent to which special precautions need to be taken to preserve present American advantages must be importantly influenced by the character of the negotiation and by the earnestness which is manifested by the several nations in an attempt to solve the common problems of international control. These questions lie in the domain of highest national policy in international relations.

We are convinced that the first major activities of the Authority must be directed to obtaining cognizance and control over the raw materials situation. This control may of course be subject to limitations, defined in the charter, on the freedom of the Authority in its early operations to alter the national distribution of raw materials. The problems of making a geological survey reliable and not prohibitively difficult are major technical problems. The raw materials control will bring the Authority face to face with the problem of access,

which is both a technical and a political problem. It will bring it face to face with the need for establishing its own research agencies and for their coordination with private and national ones. These undertakings are fundamental for the operation of the Authority and to all of its future prospect of success.

There are other things which no doubt the Authority would wish to do at once. Without much delay it should set up laboratories for the study of nuclear physics and the technological problems that it must expect to encounter in its future work. It should attempt to establish suitable forms of liaison and interchange with private and national institutions working on atomic energy or on its applications or on the fundamental sciences which may be involved. In short, the Authority should get started on its research program and in establishing the patterns of its liaison with other agencies for which it will be responsible in the future.

It would be desirable that even in the earliest days the Authority act to permit the use of radioactive tracer materials and those laboratory reactors which use small amounts of denatured active material, and which seem to provide such valuable tools for research in a variety of fields.

The Authority may need to establish, even in its earliest days, planning boards to make studies of the difficult questions of stockpiling, power development, future plant construction; it may need to set up a system for the interim recording and accounting of operations in the field of raw materials, and in the production plants of the United States.

These seem to us reasonable plans for initial operations. All the other operations of the Authority are certainly subject to scheduling. They may accompany these initial operations, or they may come later. But the control of raw materials is an essential prerequisite for all further progress and it is the first job that the Authority must undertake. It will be a continuing activity, but what we are concerned with is that it should start.

In considering the special position of the United States, there are, as we have seen, the following important components, the discontinuance or transfer of which to the jurisdiction of the Authority will have to be very carefully scheduled by international negotiation: our raw material supplies; the plants at Oak Ridge and Hanford now operating to make atomic explosives; the stockpiles of bombs now in our possession; the stockpiles of undenatured fissionable materials; our atomic bomb plant and laboratory at Los Alamos. Our loss of monopoly in these elements cannot be indefinitely postponed. Some of the things we now have will have to cease; some will have to be transferred to the Authority; some will have to be paralleled by activities elsewhere.

The scheduling will determine the rapidity with which a condition of international balance will replace our present position. Once the plan is fully in operation it will afford a great measure of security against surprise attack; it will provide clear danger signals and give us time, if we take over the available facilities, to prepare for atomic warfare. The significant fact is that at all times during the transition period at least such facilities will continue to be located within the United States. Thus should there be a breakdown in the plan at any time during the transition, we shall be in a favorable position with regard to atomic weapons.

Disclosure of Information as an Essential of International Action.

One of the elements in the present monopoly of the United States is knowledge. This ranges all the way from purely theoretical matters to the intimate practical details of know-how. It is generally recognized that the transmission of any part, or all, of this knowledge to another nation could provide the basis for an acceleration of a rival effort to make atomic weapons. Even that part of our knowledge which is theoretical, which can be transmitted by word of mouth, by formula, or by written note is of value in this context. If such knowledge were available to a rival undertaking it would shorten the time needed for the solution of the practical problems of making atomic weapons, by eliminating certain unworkable alternatives, by fixing more definitely design features which depend on this theoretical knowledge, and by making it possible to undertake the various steps of the program more nearly in parallel, rather than in sequence. It is not, in our opinion, possible to give a reliable estimate of how much such revelation would shorten the time needed for a successful rival effort. It is conceivable that it would not be significantly shortened. It is conceivable that it might be shortened by a year or so. For an evaluation on this point depends on information, which is not available to us, on the detailed plans and policies of such a rival undertaking, as well as on their present state of knowledge. It is, of course, clear that even with all such theoretical knowledge available, a major program, surely lasting many years, is required for the actual production of atomic weapons.

Our monopoly on knowledge cannot be, and should not be, lost at once. Here again there are limitations on the scheduling inherent in the nature of our proposals; and in the nature of the deliberations necessary for their acceptance. But even with the recognition of these limitations, there is a rather wide freedom of choice in the actual scheduling of disclosures. Here considerations of acceptability and of general political background will make a decisive contribution.

It is clear that the information, which this country alone has, can be divided more or less roughly into categories. The acceptance and

operation of the plan will require divulging certain categories of this information at successive times. A schedule can outline the point at which this must occur. In particular, there is a limited category of information which should be divulged in the early meetings of the United Nations Commission discussing these problems. There is a more extensive category which must be divulged some years hence after a charter has been adopted and the Atomic Development Authority is ready to start its operations; and there are other categories that may be reserved until the Authority later undertakes some of the subsequent stages of its operations, for instance, those that involve research on weapons. We are convinced that under the plan proposed in this report such scheduling is possible, though it is clear, as we have pointed out, that many factors beyond the scope of this report, and involving the highest considerations of international policy, will be involved in such schedules. We wish to emphasize that it will involve an initial divulging of information, which is justifiable in view of the importance of early progress on the path of international cooperation.

It is true, as the Secretary of State has said, that there is nothing in the Resolution setting up the Atomic Energy Commission that compels the United States to produce information for the use of the United Nations Commission. But the point that needs to be emphasized is that unless we are prepared to provide the information essential to an *understanding* of the problem, the Commission itself cannot even begin the task that has been assigned to it.

Let us examine in a little more detail the nature of the information which is required in the early stages. What is important for the discussions in the United Nations Organization Commission is that the Members and their technical advisors have an understanding of the problem of the international control of atomic energy and of the elements of the proposals that the United States member will put forward. They must be in a position to understand what the prospects for constructive applications of atomic energy are and to appreciate the nature of the safeguards which the plan we here propose affords. They must be in a position to evaluate alternatives which may arise, and to have insight into the rather complex interrelations of the various activities in this field. Above all they must have a sound enough overall knowledge of the field as a whole to recognize that no relevant or significant matters have been withheld. For the process of reaching common agreement on measures of international control presupposes an adequate community of knowledge of fact. Much of the information which is required for this purpose is already widely known. We are convinced, however, that there are further items now held by us as secret without which the necessary insight will be

difficult to obtain. These items are of a theoretical and descriptive nature and have in large part to do with the constructive applications of atomic energy. In our opinion, they are largely qualitative; and they involve almost nothing of know-how.

On the other hand, when the Atomic Development Authority is in existence and undertakes operations in a given field, it must have made available to it all information bearing on that field—practical as well as theoretical. Thus, if the Authority, as its first major undertaking, attempts to obtain control of raw materials, we must be prepared to make available to it *all* knowledge bearing on this problem. This will, of course, be a common obligation on all participating nations. Conversely, should it by charter agreement be determined that research and development in the field of atomic explosives will be undertaken by the Authority only at a late date, the specific technological information relating to such developments would not be required by it in the earlier phases. It is important to bear in mind that before the Authority can undertake some of its functions, such as the construction of reactors or the development of power, it will have to spend some time in planning these activities and in research directed toward them, and that information must be made available early enough to make such planning and research effective.

These are examples of requirements for information by the Atomic Development Authority at certain stages of its progress. In accepting the plan here recommended for international control, the United States will be committed to making available this information at the time, and in the full measure required by the operating necessities. Once the sequence and timing of stages has been fixed by negotiation and agreement between the nations, a minimum rate of disclosure of information will have been fixed by the agreement as well. A too cautious release of information to the Atomic Development Authority might in fact have the effect of preventing it from ever coming to life. For one of the decisive responsibilities of the Authority is the establishment and maintenance of the security of the world against atomic warfare. It must be encouraged to exercise that responsibility, and to obtain for itself the technical mastery that is essential.

We may further clarify the nature of the disclosures required by this board's proposals by a reference to a report. We have had the opportunity to examine in detail a report of December, 1945, prepared for the Manhattan District by its Committee on Declassification, a committee of seven scientists, including the wartime heads of all the major laboratories of the Project.[1] This Committee was

[1] Membership of this Committee included R. F. Bacher, A. H. Compton, E. O. Lawrence, J. R. Oppenheimer, F. G. Spedding, H. C. Urey, and R. C. Tolman, Chairman.

directed to report on a policy of declassification—that is disclosure—of scientific and technical material now classified as Secret, a policy *which would best promote the national welfare, and protect the national security*. In interpreting its directive the Committee limited itself to a consideration of these objectives *in the absence of any system of international control*. It recommended against declassification at the present time of a very considerable body of technical, technological, industrial, and ordnance information, that is information bearing directly on the manufacture of weapons and the design and operation of production plants. But it recommended the prompt declassification of a large body of scientific fact and of technical information of non-critical nature and wide applicability. It expressed the view that the further declassification of critical items of basic theoretical knowledge would conduce, not only to the national welfare, but to the long-term national security as well—no doubt because of the damaging effect which continued secrecy in these matters could have on our own scientific and technical progress. Corresponding to these distinctions, the Committee divided our secret scientific and technical information into three categories, the first of which it recommended for immediate declassification; the second of which it recommended for eventual declassification in the interests of long-term, national security of the United States; and for the third of which it recommended against declassification in the absence of effective international control. We have tried to see what technical information this board would find essential for the sort of understanding that must be established as a basis for discussion in the UNO Commission, and to compare this with the items listed in the report of the Committee on Declassification. Many of the facts needed are already public; many are included in Class One; the remainder are all in Class Two, and comprise perhaps one-third of the items there listed. It is important again to emphasize that the Declassification Committee's recommendation was aimed at furthering our own long-term national security in the absence of international measures.

We wish to emphasize that the initial disclosures will place in the hands of a nation (should it be acting in bad faith) information which could lead to an acceleration of an atomic armament program. We do not regard this circumstance as in any way peculiar to the plan recommended in this report. It is inherent in the concept of international control. The adoption of any workable scheme of international control may shorten the time during which the United States has a position as favorable as it has today. We cannot be sure of this, but we must be prepared for it.

In this section we have been discussing the problem of transition to international control as it affects the security of the United States. During this transition the United States' present position of monopoly may be lost somewhat more rapidly than would be the case without international action. But without such action the monopoly would in time disappear in any event. Should the worst happen and, during the transition period, the entire effort collapse, the United States will at all times be in a favorable position with regard to atomic weapons. This favorable position will depend upon material things; less and less will it rest upon keeping nations and individuals ignorant.

When fully in operation the plan herein proposed can provide a great measure of security against surprise attack. It can do much more than that. It can create deterrents to the initiation of schemes of aggression, and it can establish patterns of cooperation among nations, the extension of which may even contribute to the solution of the problem of war itself. When the plan is in full operation there will no longer be secrets about atomic energy. We believe that this is the firmest basis of security; for in the long term there can be no international control and no international cooperation which does not presuppose an international community of knowledge.

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THE

ATOMIC BOMBINGS

OF

HIROSHIMA AND NAGASAKI

by

The Manhattan Engineer District

THE ATOMIC BOMBINGS OF HIROSHIMA AND NAGASAKI

Index

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FOREWORD.....
INTRODUCTION.....
THE MANHATTAN PROJECT INVESTIGATING GROUP.....
PROPAGANDA.....
SUMMARY OF DAMAGES AND INJURIES.....
MAIN CONCLUSIONS.....
THE SELECTION OF THE TARGET.....
DESCRIPTION OF THE CITIES BEFORE THE BOMBINGS.....
Hiroshima.....
Nagasaki.....
THE ATTACKS.....
Hiroshima.....
Nagasaki.....
GENERAL COMPARISON OF HIROSHIMA AND NAGASAKI.....
GENERAL DESCRIPTION OF DAMAGE CAUSED BY THE ATOMIC EXPLOSIONS.....
TOTAL CASUALTIES.....
THE NATURE OF AN ATOMIC EXPLOSION.....
CHARACTERISTICS OF THE DAMAGE CAUSED BY THE ATOMIC BOMBS.....
CALCULATIONS OF THE PEAK PRESSURE OF THE BLAST WAVE.....
LONG RANGE BLAST DAMAGE.....
GROUND SHOCK.....
SHIELDING, OR SCREENING, FROM THE BLAST.....
FLASH BURN.....
CHARACTERISTICS OF THE INJURIES TO PERSONS.....
BURNS.....
MECHANICAL INJURIES.....
BLAST INJURIES.....
RADIATION INJURIES.....
SHIELDING FROM RADIATION.....
EFFECTS OF THE ATOMIC BOMBINGS ON THE INHABITANTS OF THE CITIES.....
APPENDIX: Father Siemes' eyewitness account.....

FOREWORD

This report describes the effects of the atomic bombs which were dro on the Japanese cities of Hiroshima and Nagasaki on August 6 and 9, 1945, spectively. It summarizes all the authentic information that is available damage to structures, injuries to personnel, morale effect, etc., which ca released at this time without prejudicing the security of the United State

This report has been compiled by the Manhattan Engineer District of t United States Army under the direction of Major General Leslie R. Groves. Special acknowledgement to those whose work contributed largely to this re is made to:

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INTRODUCTION

Statement by the President of the United States: "Sixteen hours ago an American airplane dropped one bomb on Hiroshima, Japan, and destroyed its usefulness to the enemy. That bomb had more power than 20,000 tons of T.N.T. It had more than two thousand times the blast power of the British Grand Slam, which is the largest bomb ever yet used in the history of warfare".

These fateful words of the President on August 6th, 1945, marked the first public announcement of the greatest scientific achievement in history. The atomic bomb, first tested in New Mexico on July 16, 1945, had just been used against a military target.

On August 6th, 1945, at 8:15 A.M., Japanese time, a B-29 heavy bomber flying at high altitude dropped the first atomic bomb on Hiroshima. More than 4 square miles of the city were instantly and completely devastated. 66,000 people were killed, and 69,000 injured.

On August 9th, three days later, at 11:02 A.M., another B-29 dropped the second bomb on the industrial section of the city of Nagasaki, totally destroying 1½ square miles of the city, killing 39,000 persons, and injuring 25,000 more.

On August 10, the day after the atomic bombing of Nagasaki, the Japanese government requested that it be permitted to surrender under the terms of the Potsdam declaration of July 26th which it had previously ignored.

THE MANHATTAN PROJECT ATOMIC BOMB INVESTIGATING GRO

On August 11th, 1945, two days after the bombing of Nagasaki, a messa was dispatched from Major General Leslie R. Groves to Brigadier General Th F. Farrell, who was his deputy in atomic bomb work and was representing hi operations in the Pacific, directing him to organize a special Manhattan P ect Atomic Bomb Investigating Group.

This Group was to secure scientific, technical and medical intelligen in the atomic bomb field from within Japan as soon as possible after the cessation of hostilities. The mission was to consist of three groups:

1. Group for Hiroshima.
2. Group for Nagasaki.
3. Group to secure information concerning general Japanese activitie in the field of atomic bombs.

The first two groups were organized to accompany the first American troops into Hiroshima and Nagasaki.

The primary purposes of the mission were as follows, in order of impo tance:

1. To make certain that no unusual hazards were present in the bombe cities.
2. To secure all possible information concerning the effects of the bombs, both usual and unusual, and particularly with regard to radioactive fects, if any, on the targets or elsewhere.

General Groves further stated that all available specialist personnel instruments would be sent from the United States, and that the Supreme All Commander in the Pacific would be informed about the organization of the mission.

On the same day, 11 August, the special personnel who formed the part the investigating group to be sent from the United States were selected an ordered to California with instructions to proceed overseas at once to accomplish the purposes set forth in the message to General Farrell. The ma party departed from Hamilton Field, California on the morning of 13 August arrived in the Marianas on 15 August.

On 12 August the Chief of Staff sent the Theater Commander the follow message:

"FOR MACARTHUR, SIGNED MARSHALL:

"GROVES HAS ORDERED FARRELL AT TINIAN TO ORGANIZE A SCIENTIFIC GROUP THREE SECTIONS FOR POTENTIAL USE IN JAPAN IF SUCH USE SHOULD BE DESIRED. FIRST GROUP IS FOR HIROSHIMA, THE SECOND FOR NAGASAKI, AND THE THIRD FOR T PURPOSE OF SECURING INFORMATION CONCERNING GENERAL JAPANESE ACTIVITIES IN

FIELD OF ATOMIC WEAPONS. THE GROUPS FOR HIROSHIMA AND NAGASAKI SHOULD ENTER THOSE CITIES WITH THE FIRST AMERICAN TROOPS IN ORDER THAT THESE TROOPS SHALL NOT BE SUBJECTED TO ANY POSSIBLE TOXIC EFFECTS ALTHOUGH WE HAVE NO REASON TO BELIEVE THAT ANY SUCH EFFECTS ACTUALLY EXIST. FARRELL AND HIS ORGANIZATION HAVE ALL AVAILABLE INFORMATION ON THIS SUBJECT."

General Farrell arrived in Yokohama on 30 August, with the Commanding General of the 8th Army; Colonel Warren, who was Chief of the Radiological Division of the District, arrived on 7 September. The main body of the investigating group followed later. Preliminary inspections of Hiroshima and Nagasaki were made on 8-9 and 13-14 September, respectively. Members of the press had been enabled to precede General Farrell to Hiroshima.

The special groups spent 16 days in Nagasaki and 4 days in Hiroshima, during which time they collected as much information as was possible under their directives which called for a prompt report. After General Farrell returned to the U.S. to make his preliminary report, the groups were headed by Brigadier General J. B. Newman, Jr. More extensive surveys have been made since that time by other agencies who had more time and personnel available for the purpose, and much of their additional data has thrown further light on the effects of the bombings. This data has been duly considered in the making of this report.

PROPAGANDA

On the day after the Hiroshima strike, General Farrell received instructions from the War Department to engage in a propaganda campaign against the Japanese Empire in connection with the new weapon and its use against Hiroshima. The campaign was to include leaflets and any other propaganda considered appropriate. With the fullest cooperation from CINCPAC of the Navy and the United States Strategic Air Forces, he initiated promptly a campaign which included the preparation and distribution of leaflets, broadcasting via short wave every 15 minutes over radio Saipan and the printing at Saipan and distribution over the Empire of a Japanese language newspaper which included the description and photographs of the Hiroshima strike.

The campaign proposed:

1. Dropping 16,000,000 leaflets in a period of 9 days on 47 Japanese cities with population of over 100,000. These cities represented more than 40% of the total population.
2. Broadcast of propaganda at regular intervals over radio Saipan.
3. Distribution of 500,000 Japanese language newspapers containing stories and pictures of the atomic bomb attacks.

The campaign continued until the Japanese began their surrender negotiations. At that time some 6,000,000 leaflets and a large number of newspapers

had been dropped. The radio broadcasts in Japanese had been carried out a regular 15 minute intervals.

SUMMARY OF DAMAGES AND INJURIES

Both the Hiroshima and the Nagasaki atomic bombs exhibited similar effects.

The damages to man-made structures and other inanimate objects was th result in both cities of the following effects of the explosions:

A. Blast, or pressure wave, similar to that of normal explosions.
B. Primary fires, i.e., those fires started instantaneously by the h radiated from the atomic explosion.
C. Secondary fires, i.e., those fires resulting from the collapse of buildings, damage to electrical systems, overturning of stoves, and other primary effects of the blast.
D. Spread of the original fires (B and C) to other structures.

The casualties sustained by the inhabitants of both cities were due t

A. "Flash" burns, caused directly by the almost instantaneous radiat of heat and light at the moment of the explosion.
B. Burns resulting from the fires caused by the explosion.
C. Mechanical injuries caused by collapse of buildings, flying debri and forceable hurling - about of persons struck by the blast pressure wave
D. Radiation injuries caused by the instantaneous penetrating radiat (in many respects similar to excessive X-ray exposure) from the nuclear ex plosion; all of these effective radiations occurred during the first minut after initiation of the explosion, and nearly all occurred during the firs second of the explosion.

No casualties were suffered as a result of any persistent radioactivi of fission products of the bomb, or any induced radioactivity of objects n the explosion. The gamma radiations emitted by the nuclear explosion did of course, inflict any damage on structures.

The number of casualties which resulted from the pure blast effect al (i.e., because of simple pressure) was probably negligible in comparison t that caused by other effects.

The central portions of the cities underneath the explosions suffered almost complete destruction. The only surviving objects were the frames o small number of strong reinforced concrete buildings which were not collap by the blast; most of these buildings suffered extensive damage from inter fires, had their windows, doors, and partitions knocked out, and all other fixtures which were not integral parts of the reinforced concrete frames burned or blown away; the casualties in such buildings near the center of plosion were almost 100%. In Hiroshima fires sprang up simultaneously all the wide flat central area of the city; these fires soon combined in an im "fire storm" (high winds blowing inwards toward the center of a large conf gration) similar to those caused by ordinary mass incendiary raids; the re- sulting terrific conflagration burned out almost everything which had not

already been destroyed by the blast in a roughly circular area of 4.4 square miles around the point directly under the explosion (this point will hereafter in this report be referred to as X). Similar fires broke out in Nagasaki, but no devastating fire storm resulted as in Hiroshima because of the irregular shape of the city.

In both cities the blast totally destroyed everything within a radius of 1 mile from the center of explosion, except for certain reinforced concrete frames as noted above. The atomic explosion almost completely destroyed Hiroshima's identity as a city. Over a fourth of the population was killed in one stroke and an additional fourth seriously injured, so that even if there had been no damage to structures and installations the normal city life would still have been completely shattered. Nearly everything was heavily damaged up to a radius of 3 miles from the blast, and beyond this distance damage, although comparatively light, extended for several more miles. Glass was broken up to 12 miles.

In Nagasaki, a smaller area of the city was actually destroyed than in Hiroshima, because the hills which enclosed the target area restricted the spread of the great blast; but careful examination of the effects of the explosion gave evidence of even greater blast effects than in Hiroshima. Total destruction spread over an area of about 3 square miles. Over a third of the 50,000 buildings in the target area of Nagasaki were destroyed or seriously damaged. The complete destruction of the huge steel works and the torpedo plant was especially impressive. The steel frames of all buildings within a mile of the explosion were pushed away, as by a giant hand, from the point of detonation. The badly burned area extended for 3 miles in length. The hillsides up to a radius of 8,000 feet were scorched, giving them an autumnal appearance.

MAIN CONCLUSIONS

The following are the main conclusions which were reached after thorough examination of the effects of the bombs dropped on Hiroshima and Nagasaki:

1. No harmful amounts of persistent radioactivity were present after the explosions as determined by:

A. Measurements of the intensity of radioactivity at the time of the investigation; and

B. Failure to find <u>any clinical evidence</u> of persons harmed by persistent radioactivity.

2. The effects of the atomic bombs on human beings were of three main types:

A. Burns, remarkable for (1) the great ground area over which they were inflicted and (2) the prevalence of "flash" burns caused by the instantaneous heat radiation.

B. Mechanical injuries, also remarkable for the wide area in which suffered.

C. Effects resulting from penetrating gamma radiation, The effects from radiation were due to instantaneous discharge of radiation at the mome of explosion and not to persistent radioactivity (of either fission product or other substances whose radioactivity might have been induced by proximit to the explosions).

3. The effects of the atomic bombs on structures and installations we of two types:

A. Destruction caused by the great pressure from the blast; and
B. Destruction caused by the fires, either started directly by the gr heat radiation, or indirectly through the collapse of buildings, wiring, et

4. The actual tonnage of T.N.T. which would have caused the same blas damage was approximately of the order of 20,000 tons.

5. In respect to their height of burst, the bombs performed exactly according to design.

6. The bombs were placed in such positions that they could not have d more damage from any alternative bursting point in either city.

7. The heights of burst were correctly chosen having regard to the ty of destruction it was desired to cause.

8. The information collected would enable a reasonably accurate predi tion to be made of the blast damage likely to be caused in any city where a atomic explosion could be effected.

THE SELECTION OF THE TARGET

Some of the most frequent queries concerning the atomic bombs are thos dealing with the selection of the targets and the decision as to when the bombs would be used.

The approximate date for the first use of the bomb was set in the fall of 1942 after the Army had taken over the direction of and responsibility f the atomic bomb project. At that time, under the scientific assumptions wh turned out to be correct, the summer of 1945 was named as the most likely d when sufficient production would have been achieved to make it possible actually to construct and utilize an atomic bomb. It was essential before th time to develop the technique of constructing and detonating the bomb and t make an almost infinite number of scientific and engineering developments a tests. Between the fall of 1942 and June 1945, the estimated probabilities of success had risen from about 60% to above 90%; however, not until July 1 1945, when the first full-scale test took place in New Mexico, was it conclusively proven that the theories, calculations, and engineering were correct and that the bomb would be successful.

The test in New Mexico was held 6 days after sufficient material had b come available for the first bomb. The Hiroshima bomb was ready awaiting s able weather on July 31st, and the Nagasaki bomb was used as soon after the

Hiroshima bomb as it was practicable to operate the second mission.

The work on the actual selection of targets for the atomic bomb was begur in the spring of 1945. This was done in close cooperation with the Commanding General, Army Air Forces, and his Headquarters. A number of experts in variou fields assisted in the study. These included mathematicians, theoretical physicists, experts on the blast effects of bombs, weather consultants, and variou other specialists. Some of the important considerations were:

A. The range of the aircraft which would carry the bomb.
B. The desirability of visual bombing in order to insure the most effective use of the bomb.
C. Probable weather conditions in the target areas.
D. Importance of having one primary and two secondary targets for each mission, so that if weather conditions prohibited bombing the target there would be at least two alternates.
E. Selection of targets to produce the greatest military effect on the Japanese people and thereby most effectively shorten the war.
F. The morale effect upon the enemy.

These led in turn to the following:

A. Since the atomic bomb was expected to produce its greatest amount of damage by primary blast effect, and next greatest by fires, the targets should contain a large percentage of closely-built frame buildings and other construction that would be most susceptible to damage by blast and fire.

B. The maximum blast effect of the bomb was calculated to extend over an area of approximately 1 mile in radius; therefore the selected targets should contain a densely built-up area of at least this size.

C. The selected targets should have a high military strategic value.
D. The first target should be relatively untouched by previous bombing, in order that the effect of a single atomic bomb could be determined.

The weather records showed that for five years there had never been two successive good visual bombing days over Tokyo, indicating what might be expected over other targets in the home islands. The worst month of the year for visual bombing was believed to be June, after which the weather should improve slightly during July and August and then become worse again during September. Since good bombing conditions would occur rarely, the most intense plans and preparations were necessary in order to secure accurate weather forecasts and to arrange for full utilization of whatever good weather might occur. It was also very desirable to start the raids before September.

DESCRIPTION OF THE CITIES BEFORE THE BOMBINGS

Hiroshima

The city of Hiroshima is located on the broad, flat delta of the Ota River, which has 7 channel outlets dividing the city into six islands which project into Hiroshima Bay. The city is almost entirely flat and only

slightly above sea level; to the northwest and northeast of the city some hills rise to 700 feet. A single hill in the eastern part of the city pro about ½ mile long and 221 feet in height interrupted to some extent the spreading of the blast damage; otherwise the city was fully exposed to the bomb. Of a city area of over 26 square miles, only 7 square miles were co pletely built-up. There was no marked separation of commercial, industria and residential zones. 75% of the population was concentrated in the dens built-up area in the center of the city.

Hiroshima was a city of considerable military importance. It contain the 2nd Army Headquarters, which commanded the defense of all of southern Japan. The city was a communications center, a storage point, and an asse area for troops. To quote a Japanese report, "Probably more than a thousa times since the beginning of the war did the Hiroshima citizens see off wi cries of 'Banzai' the troops leaving from the harbor."

The center of the city contained a number of reinforced concrete buil ings as well as lighter structures. Outside the center, the area was congested by a dense collection of small wooden workshops set among Japanese houses; a few larger industrial plants lay near the outskirts of the city. The houses were of wooden construction with tile roofs. Many of the indus buildings also were of wood frame construction. The city as a whole was h susceptible to fire damage.

Some of the reinforced concrete buildings were of a far stronger cons tion than is required by normal standards in America, because of the earth quake danger in Japan. This exceptionally strong construction undoubtedly counted for the fact that the framework of some of the buildings which were fairly close to the center of damage in the city did not collapse.

The population of Hiroshima had reached a peak of over 380,000 earlie the war but prior to the atomic bombing the population had steadily decrea because of a systematic evacuation ordered by the Japanese government. At time of the attack the population was approximately 255,000. This figure based on the registered population, used by the Japanese in computing ratio quantities, and the estimates of additional workers and troops who were br into the city may not be highly accurate. Hiroshima thus had approximately the same number of people as the city of Providence, R.I., or Dallas, Tex.

Nagasaki

Nagasaki lies at the head of a long bay which forms the best natural h bor on the southern Japanese home island of Kyushu. The main commercial ar residential area of the city lies on a small plain near the end of the bay. Two rivers divided by a mountain spur form the two main valleys in which th city lies. This mountain spur and the irregular lay-out of the city tremen dously reduced the area of destruction, so that at first glance Nagasaki ap peared to have been less devastated than Hiroshima.

The heavily build-up area of the city is confined by the terrain to le than 4 square miles out of a total of about 35 square miles in the city as whole.

The city of Nagasaki had been one of the largest sea ports in southern Japan and was of great war-time importance because of its many and varied industries, including the production of ordnance, ships, military equipment, and other war materials. The narrow long strip attacked was of particular importance because of its industries.

In contrast to many modern aspects of Nagasaki, the residences almost without exception were of flimsy, typical Japanese construction, consisting of wood or wood-frame buildings, with wood walls with or without plaster, and tile roofs. Many of the smaller industries and business establishments were also housed in wooden buildings or flimsily built masonry buildings. Nagasaki had been permitted to grow for many years without conforming to any definite city zoning plan and therefore residences were constructed adjacent to factory buildings and to each other almost as close as it was possible to build them throughout the entire industrial valley.

THE ATTACKS

Hiroshima

Hiroshima was the primary target of the first atomic bomb mission. The mission went smoothly in every respect. The weather was good, and the crew and equipment functioned perfectly. In every detail, the attack was carried out exactly as planned, and the bomb performed exactly as expected.

The bomb exploded over Hiroshima at 8:15 on the morning of August 6, 1945. About an hour previously, the Japanese early warning radar net had detected the approach of some American aircraft headed for the southern part of Japan. The alert had been given and radio broadcasting stopped in many cities, among them Hiroshima. The planes approached the coast at a very high altitude. At nearly 8:00 A.M., the radar operator in Hiroshima determined that the number of planes coming in was very small - probably not more than three - and the air raid alert was lifted. The normal radio broadcast warning was given to the people that it might be advisable to go to shelter if B-29's were actually sighted, but no raid was expected beyond some sort of reconnaissance. At 8:15 A.M., the bomb exploded with a blinding flash in the sky, and a great rush of air and a loud rumble of noise extended for many miles around the city; the first blast was soon followed by the sounds of falling buildings and of growing fires, and a great cloud of dust and smoke began to cast a pall of darkness over the city.

At 8:16 A.M., the Tokyo control operator of the Japanese Broadcasting Corporation noticed that the Hiroshima station had gone off the air. He tried to use another telephone line to reestablish his program, but it too had failed. About twenty minutes later the Tokyo railroad telegraph center realized that the main line telegraph had stopped working just north of Hiroshima. From some small railway stops within ten miles of the city there came unofficial and confused reports of a terrible explosion in Hiroshima. All these reports were transmitted to the Headquarters of the Japanese General Staff.

Military headquarters repeatedly tried to call the Army Control Station in Hiroshima. The complete silence from that city puzzled the men at

Headquarters; they knew that no large enemy raid could have occurred, and knew that no sizeable store of explosives was in Hiroshima at that time. young officer of the Japanese General Staff was instructed to fly immediat to Hiroshima, to land, survey the damage, and return to Tokyo with reliabl information for the staff. It was generally felt at Headquarters that not serious had taken place, that it was all a terrible rumor starting from a sparks of truth.

The staff officer went to the airport and took off for the southwest. After flying for about three hours, while still nearly 100 miles from Hiroshima, he and his pilot saw a great cloud of smoke from the bomb. In bright afternoon, the remains of Hiroshima were burning.

Their plane soon reached the city, around which they circled in disbe A great scar on the land, still burning, and covered by a heavy cloud of sm was all that was left of a great city. They landed south of the city, and staff officer immediately began to organize relief measures, after reporti Tokyo.

Tokyo's first knowledge of what had really caused the disaster came fr the White House public announcement in Washington sixteen hours after Hiroshima had been hit by the atomic bomb.

Nagasaki

Nagasaki had never been subjected to large scale bombing prior to the plosion of the atomic bomb there. On August 1st, 1945, however, a number c high explosive bombs were dropped on the city. A few of these bombs hit ir the shipyards and dock areas in the southwest portion of the city. Several the bombs hit the Mitsubishi Steel and Arms Works and six bombs landed at t Nagasaki Medical School and Hospital, with three direct hits on buildings there. While the damage from these few bombs were relatively small, it cre considerable concern in Nagasaki and a number of people, principally school children, were evacuated to rural areas for safety, thus reducing the popul tion in the city at the time of the atomic attack.

On the morning of August 9th, 1945, at about 7:50 A.M., Japanese time, air raid alert was sounded in Nagasaki, but the "All clear" signal was give at 8:30. When only two B-29 superfortresses were sighted at 10:53 the Japanese apparently assumed that the planes were only on reconnaissance and no further alarm was given. A few moments later, at 11:00 o'clock, the observation B-29 dropped instruments attached to three parachutes and at 11:0 the other plane released the atomic bomb.

The bomb exploded high over the industrial valley of Nagasaki, almost midway between the Mitsubishi Steel and Arms Works, in the south, and the Mitsubishi-Urakami Ordnance Works (Torpedo Works), in the north, the two principal targets of the city.

Despite its extreme importance, the first bombing mission on Hiroshima had been almost routine. The second mission was not so uneventful. Again the crew was specially trained and selected; but bad weather introduced som momentous complications. These complications are best described in the bri

account of the mission's weaponeer, Comdr., now Capt., F. L. Ashworth, U.S.N. who was in technical command of the bomb and was charged with the responsibility of insuring that the bomb was successfully dropped at the proper time and on the designated target. His narrative runs as follows:

"The night of our take-off was one of tropical rain squalls, and flashes of lightning stabbed into the darkness with disconcerting regularity. The weather forecast told us of storms all the way from the Marianas to the Empire. Our rendezvous was to be off the southeast coast of Kyushu, some 1500 miles away. There we were to join with our two companion observation B-29's that took off a few minutes behind us. Skillful piloting and expert navigation brought us to the rendezvous without incident.

"About five minutes after our arrival, we were joined by the first of our B-29's. The second, however, failed to arrive, having apparently been thrown off its course by storms during the night. We waited 30 minutes and then proceeded without the second plane toward the target area.

"During the approach to the target the special instruments installed in the plane told us that the bomb was ready to function. We were prepared to drop the second atomic bomb on Japan. But fate was against us, for the target was completely obscured by smoke and haze. Three times we attempted bombing runs, but without success. Then with anti-aircraft fire bursting around us and with a number of enemy fighters coming up after us, we headed for our secondary target, Nagasaki.

"The bomb burst with a blinding flash and a huge column of black smoke swirled up toward us. Out of this column of smoke there boiled a great swirling mushroom of gray smoke, luminous with red, flashing flame, that reached to 40,000 feet in less than 8 minutes. Below through the clouds we could see the pall of black smoke ringed with fire that covered what had been the industrial area of Nagasaki.

"By this time our fuel supply was dangerously low, so after one quick circle of Nagasaki, we headed direct for Okinawa for an emergency landing and refueling".

GENERAL COMPARISON OF HIROSHIMA AND NAGASAKI

It was not at first apparent to even trained observers visiting the two Japanese cities which of the two bombs had been the most effective.

In some respects, Hiroshima looked worse than Nagasaki. The fire damage in Hiroshima was much more complete; the center of the city was hit and everything but the reinforced concrete buildings had virtually disappeared. A desert of clear-swept, charred remains, with only a few strong building frame left standing was a terrifying sight.

At Nagasaki there were no buildings just underneath the center of explosion. The damage to the Mitsubishi Arms Works and the Torpedo Works was spectacular, but not overwhelming. There was something left to see, and the main contours of some of the buildings were still normal.

An observer could stand in the center of Hiroshima and get a view of t most of the city; the hills prevented a similar overall view in Nagasaki. Hiroshima impressed itself on one's mind as a vast expanse of desolation; t nothing as vivid was left in one's memory of Nagasaki.

When the observers began to note details, however, striking differenc appeared. Trees were down in both cities, but the large trees which fell i Hiroshima were uprooted, while those in Nagasaki were actually snapped off. A few reinforced concrete buildings were smashed at the center in Hiroshim but in Nagasaki equally heavy damage could be found 2,300 feet from X. In study of objects which gave definite clues to the blast pressure, such as squashed tin cans, dished metal plates, bent or snapped poles and like, it was soon evident that the Nagasaki bomb had been much more effective than t Hiroshima bomb. In the description of damage which follows, it will be not that the radius for the amount of damage was greater in Nagasaki than Hiro

GENERAL DESCRIPTION OF DAMAGE CAUSED BY THE ATOMIC EXPLOSIONS

In considering the devastation in the two cities, it should be remembe that the cities' differences in shape and topography resulted in great differences in the damages. Hiroshima was all on low, flat ground, and was roughly circular in shape; Nagasaki was much cut up by hills and mountain s with no regularity to its shape.

In Hiroshima almost everything up to about one mile from X was complet destroyed, except for a small number (about 50) of heavily reinforced concr buildings, most of which were specially designed to withstand earthquake sh which were not collapsed by the blast; most of these buildings had their in teriors completely gutted, and all windows, doors, sashes, and frames rippe out. In Nagasaki, nearly everything within 1/2 mile of the explosion was destroyed, including heavy structures. All Japanese homes were destroyed w in 1 1/2 miles from X.

Underground air raid shelters with earth cover roofs immediately below the explosion had their roofs caved in; but beyond 1/2 mile from X they suf fered no damage.

In Nagasaki, 1500 feet from X high quality steel frame buildings were completely collapsed, but the entire buildings suffered mass distortion and panels and roofs were blown in.

In Nagasaki, 2,000 feet from X, reinforced concrete buildings with 10" walls and 6" floors were collapsed; reinforced concrete buildings with 4" w and roofs were standing but were badly damaged. At 2,000 feet some 9" conc walls were completely destroyed.

In Nagasaki, 3,500 feet from X, church buildings with 18" brick walls completely destroyed. 12" brick walls were severly cracked as far as 5,00C feet.

In Hiroshima, 4,400 feet from X, multi-story brick buildings were completely demolished. In Nagasaki, similar buildings were destroyed to 5,30C feet.

In Hiroshima, roof tiles were bubbled (melted) by the flash heat out to 4,000 feet from X; in Nagasaki, the same effect was observed to 6,500 feet.

In Hiroshima, steel frame buildings were destroyed 4,200 feet from X, and to 4,800 feet in Nagasaki.

In both cities, the mass distortion of large steel buildings was observed out to 4,500 feet from X.

In Nagasaki, reinforced concrete smoke stacks with 8" walls, specially designed to withstand earthquake shocks, were overturned up to 4,000 feet from X.

In Hiroshima, steel frame buildings suffered severe structural damage up to 5,700 feet from X, and in Nagasaki the same damage was sustained as far as 6,000 feet.

In Nagasaki, 9" brick walls were heavily cracked to 5,000 feet, were moderately cracked to 6,000 feet, and slightly cracked to 8,000 feet. In both cities, light concrete buildings collapsed out to 4,700 feet.

In Hiroshima, multi-story brick buildings suffered structural damage up to 6,600 feet, and in Nagasaki up to 6,500 feet from X.

In both cities overhead electric installations were destroyed up to 5,500 feet; and trolley cars were destrdyed up to 5,500 feet, and damaged to 10,500 feet.

Flash ignition of dry, combustible material was observed as far as 6,400 feet from X in Hiroshima, and in Nagasaki as far as 10,000 feet from X.

Severe damage to gas holders occured out to 6,500 feet in both cities.

All Japanese homes were seriously damaged up to 6,500 feet in Hiroshima, and to 8,000 feet in Nagasaki. Most Japanese homes were damaged up to 8,000 feet in Hiroshima and 10,500 feet in Nagasaki.

The hillsides in Nagasaki were scorched by the flash radiation of heat as far as 8,000 feet from X; this scorching gave the hillsides the appearance of premature autumn.

In Nagasaki, very heavy plaster damage was observed in many buildings up to 9,000 feet; moderate damage was sustained as far as 12,000 feet, and light damage up to 15,000 feet.

The flash charring of wooden telegraph poles was observed up to 9,500 feet from X in Hiroshima, and to 11,000 feet in Nagasaki; some reports indicate flash burns as far as 13,000 feet from X in both places.

Severe displacement of roof tiles was observed up to 8,000 feet in Hiroshima, and to 10,000 feet in Nagasaki.

In Nagasaki, very heavy damage to window frames and doors was observed up to 8,000 feet, and light damage up to 12,000 feet.

Roofs and wall coverings on steel frame buildings were destroyed out 11,000 feet.

Although the sources of many fires were difficult to trace accurately it is believed that fires were started by primary heat radiation as far as 15,000 feet from X.

Roof damage extended as far as 16,000 feet from X in Hiroshima and in Nagasaki.

The actual collapse of buildings was observed at the extreme range of 23,000 feet from X in Nagasaki.

Although complete window damage was observed only up to 12,000 feet from X, some window damage occured in Nagasaki up to 40,000 feet, and actual breakage of glass occured up to 60,000 feet.

Heavy fire damage was sustained in a circular area in Hiroshima with mean radius of about 6,000 feet and a maximum radius of about 11,000 feet; similar heavy damage occured in Nagasaki south of X up to 10,000 feet, where it was stopped on a river course.

In Hiroshima over 60,000 of 90,000 buildings were destroyed or severely damaged by the atomic bomb; this figure represents over 67% of the city's structures.

In Nagasaki, 14,000 or 27% of 52,000 residences were completely destroyed and 5,400, or 10%, were half destroyed. Only 12% remained undamaged. This destruction was limited by the layout of the city. The following is a summary of the damage to buildings in Nagasaki as determined from a ground survey made by the Japanese:

Destruction of Buildings and Houses (Compiled by Nagasaki Municipality)	Number	Percentage
Total in Nagasaki (before atomic explosion)	50,000	100.0
Blasted (not burned)	2,652	5.3
Blasted and burned	11,494	23.0
Blasted and/or burned	14,146	28.3
Partially burned or blasted	5,441	10.9
Total buildings and houses destroyed	19,587	39.2
Undamaged	30,413	60.8

In Hiroshima, all utilities and transportation services were disrupted for varying lengths of time. In general however services were restored about as rapidly as they could be used by the depleted population. Through railroad service was in order in Hiroshima on 8 August, and electric power was available in most of the surviving parts on 7 August, the day after the bombing. The reservoir of the city was not damaged, being nearly 2 miles from X. However 70,000 breaks in water pipes in buildings and dwellings were caused by the blast and fire effects. Rolling transportation suffered extensive damage. The damage to railroad tracks, and roads was comparatively small, however. The electric power transmission and distribution systems were badly wrecked. The telephone system was approximately 80% damaged, and no service was restored until 15 August.

Despite the customary Japanese lack of attention to sanitation measures, no major epidemic broke out in the bombed cities. Although the conditions following the bombings makes this fact seem surprising, the experience of other bombed cities in both Germany and Japan show Hiroshima and Nagasaki not to be isolated cases.

The atomic explosion over Nagasaki affected an over-all area of approximately 42.9 square miles of which about 8.5 square miles were water and only about 9.8 square miles were built up, the remainder being partially settled. Approximately 36% of the built up areas were seriously damaged. The area most severely damaged had an average radius of about 1 mile, and covered about 2.9 square miles of which 2.4 were built up.

In Nagasaki, buildings with structural steel frames, principally the Mitsubishi Plant, as far as 6,000 feet from X were severely damaged; these buildings were typical of wartime mill construction in America and Great Britain, except that some of the frames were somewhat less substantial. The damage consisted of windows broken out (100%), steel sashes ripped out or bent, corrugated metal or corrugated asbestos roofs and sidings ripped off, roofs bent or destroyed, roof trusses collapsed, columns bent and cracked, and concrete foundations for columns rotated. Damage to buildings with structural steel frames was more severe where the buildings received the effect of the blast on their sides than where the blast hit the ends of buildings, because the buildings had more stiffness (resistance to negative moment at the top of columns) in a longitudinal direction. Many of the lightly constructed steel frame buildings collapsed completely while some of the heavily constructed (to carry the weight of heavy cranes and loads) were stripped of roof and siding, but the frames were only partially injured.

The next most seriously damaged area in Nagasaki lies outside the 2.9 square miles just described, and embraces approximately 4.2 square miles of which 29% was built up. The damage from blast and fire was moderate here, but in some sections (portions of main business districts) many secondary fires started and spread rapidly, resulting in about as much over-all destruction as in areas much closer to X.

An area of partial damage by blast and fire lies just outside the one just described, and comprises approximately 35.8 square miles. Of this area, roughly 1/6th was built up and $\frac{1}{4}$ was water. The extent of damage varied from serious (severe damage to roofs and windows in the main business section of Nagasaki, 2.5 miles from X), to minor (broken or occasionally broken windows at a distance of 7 miles southeast of X).

As intended, the bomb was exploded at an almost ideal location over Nagasaki to do the maximum damage to industry, including the Mitsubishi Steel and Arms Works, the Mitsubishi-Urakami Ordnance Works (Torpedo Works), and numerous factories, factory training schools, and other industrial establishments. with a minimum destruction of dwellings and, consequently, a minimum amount of casualties. Had the bomb been dropped farther south, the Mitsubishi-Urakami Ordnance Works would not have been so severely damaged, but the main business and residential districts of Nagasaki would have sustained much greater damage and casualties.

Calculations show that the structural steel and reinforced concrete fr which survived the blast fairly close to X could not have withstood the est mated peak pressures developed against the total areas presented by the sid and roof of the buildings. The survival of these frames is explained by th fact that they were not actually required to withstand the peak pressure be cause the windows were quickly knocked out and roof and siding stripped off thereby reducing total area and relieving the pressure. While this saved t building frame, it permitted severe damage to building interior and content and injuries to the building occupants. Buildings without large panel oper ings through which the pressure could dissipate were completely crushed, ev when their frames were as strong as those which survived.

The damage sustained by reinforced concrete buildings depended both or the proximity to X and the type and strength of the reinforced concrete cor struction. Some of the buildings with reinforced concrete frames also had reinforced concrete walls, ceilings, and partitions, while others had brick concrete tile walls covered either with plaster or ornamental stone, with p titions of metal, glass, and plaster. With the exception of the Nagasaki M ical School and Hospital group, which was designed to withstand earthquakes and was therefore of heavier construction than most American structures, ma of the reinforced concrete structures could be classified only as fair, wit concrete of low strength and density, with many of the columns, beams, and slabs underdesigned and improperly reinforced. These facts account for som of the structural failures which occured.

In general, the atomic bomb explosion damaged all windows and ripped o bent, or twisted most of the steel window or door sashes, ripped doors from hinges, damaged all suspended wood, metal, and plaster ceilings. The blast concussion also caused great damage to equipment by tumbling and battering. Fires generally of secondary origin consumed practically all combustible ma rial, caused plaster to crack off, burned all wooden trim, stair covering, wooden frames of wooden suspended ceilings, beds, mattresses, and mats, and fused glass, ruined all equipment not already destroyed by the blast, ruine all electrical wiring, plumbing, and caused spalling of concrete columns ar beams in many of the rooms.

Almost without exception masonry buildings of either brick or stone wi the effective limits of the blast were severely damaged so that most of the were flattened or reduced to rubble. The wreckage of a church, approximate 1,800 feet east of X in Nagasaki, was one of the few masonry buildings stil recognizable and only portions of the walls of this structure were left sta ing. These walls were extremely thick (about 2 feet). The two domes of th church had reinforced concrete frames and although they were toppled, they together as units.

Practically every wooden building or building with timber frame within miles of X was either completely destroyed or very seriously damaged, and s nificant damage in Nagasaki resulted as far as 3 miles from X. Nearly all buildings collapsed and a very large number were consumed by fire.

A reference to the various photographs depicting damage shows that al- though most of the buildings within the effective limits of the blast were tally destroyed or severely damaged, a large number of chimneys even close

were left standing, apparently uninjured by the concussion. One explanation is that concrete chimneys are approximately cylindrical in shape and consequently offer much less wind resistance than flat surfaces such as buildings. Another explanation is that since the cities were subject to typhoons the more modern chimneys were probably designed to withstand winds of high velocity. It is also probable that most of the recently constructed chimneys as well as the more modern buildings were constructed to withstand the acceleration of rather severe earthquakes. Since the bombs were exploded high in the air, chimneys relatively close to X were subjected to more of a downward than a lateral pressure, and consequently the overturning moment was much less than might have been anticipated.

Although the blast damaged many bridges to some extent, bridge damage was on the whole slight in comparison to that suffered by buildings. The damage varied from only damaged railings to complete destruction of the superstructure Some of the bridges were wrecked and the spans were shoved off their piers and into the river bed below by the force of the blast. Others, particularily steel plate girder bridges, were badly buckled by the blast pressure. None of the failures observed could be attributed to inadequate design or structural weaknesses.

The roads, and railroad and street railway trackage sustained practically no primary damage as a result of the explosion. Most of the damage to railroads occurred from secondary causes, such as fires and damage to bridges or other structures. Rolling stock, as well as automobiles, trolleys, and buses were destroyed and burned up to a considerable distance from X. Streets were impassable for awhile because of the debris, but they were not damaged. The height of the bomb explosion probably explains the absence of direct damage to railroads and roads.

A large part of the electric supply was interrupted by the bomb blast, chiefly through damage to electric substations and overhead transmission systems. Both gas works in Nagasaki were severely damaged by the bomb. These works would have required 6-7 months to get into operation. In addition to the damage sustained by the electrical and gas systems, severe damage to the water supply system was reported by the Japanese government; the chief damage was a number of breaks in the large water mains and in almost all of the distributing pipes in the areas which were affected by the blast. Nagasaki was still suffering from a water shortage inside the city six weeks after the atomic attack.

The Nagasaki Prefectural report describes vividly the effects of the bomb on the city and its inhabitants:

"Within a radius of 1 kilometer from X, men and animals died almost instantaneously and outside a radius of 1 kilometer and within a radius of 2 kilometers from X, some men and animals died instantly from the great blast and heat but the great majority were seriously or superficially injured. Houses and other structures were completely destroyed while fires broke out everywhere. Trees were uprooted and withered by the heat.

"Outside a radius of 2 kilometers and within a radius of 4 kilometers from X, men and animals suffered various degrees of injury from window glass

and other fragments scattered about by the blast and many were burned by t intense heat. Dwellings and other structures were half damaged by blast.

"Outside a radius of 4 kilometers and within a radius of 8 kilometers living creatures were injured by materials blown about by the blast; the m ity were only superficially wounded. Houses were only half or partially damaged."

The British Mission to Japan interpreted their observations of the de struction of buildings to apply to similar construction of their own as fo

A similar bomb exploding in a similar fashion would produce the follo effects on normal British houses:

Up to 1,000 yards from X it would cause complete collapse.

Up to 1 mile from X it would damage the houses beyond repair.

Up to 1.5 miles from X it would render them uninhabitable without ext sive repair, particularly to roof timbers.

Up to 2.5 miles from X it would render them uninhabitable until first repairs had been carried out.

The fire damage in both cities was tremendous, but was more complete Hiroshima than in Nagasaki. The effect of the fires was to change profoun the appearance of the city and to leave the central part bare, except for reinforced concrete and steel frames and objects such as safes, chimney st and pieces of twisted sheet metal. The fire damage resulted more from the properties of the cities themselves than from those of the bombs.

The conflagration in Hiroshima caused high winds to spring up as air drawn in toward the center of the burning area, creating a "fire storm". wind velocity in the city had been less than 5 miles per hour before the b ing, but the fire-wind attained a velocity of 30-40 miles per hour. These great winds restricted the perimeter of the fire but greatly added to the damage of the conflagration within the perimeter and caused the deaths of m persons who might otherwise have escaped. In Nagasaki, very severe damage caused by fires, but no extensive "fire storm" engulfed the city. In both cities, some of the fires close to X were no doubt started by the ignition highly combustible material such as paper, straw, and dry cloth, upon the i stantaneous radiation of heat from the nuclear explosion. The presence of large amounts of unburnt combustible materials near X, however, indicated t even though the heat of the blast was very intense, its duration was insuff cient to raise the temperature of many materials to the kindling point exc in cases where conditions were ideal. The majority of the fires were of secondary origin starting from the usual electrical short-circuits, broken lines, overturned stoves, open fires, charcoal braziers, lamps, etc., follo collapse or serious damage from the direct blast.

Fire fighting and rescue units were stripped of men and equipment. Al 30 hours elapsed before any rescue parties were observable. In Hiroshima o a handful of fire engines were available for fighting the ensuing fires, an none of these were of first class type. In any case, however, it is not li

that any fire fighting equipment or personnel or organization could have effected any significant reduction in the amount of damage caused by the tremendous conflagration.

A study of numerous aerial photographs made prior to the atomic bombings indicates that between 10 June and 9 August 1945 the Japanese constructed fire breaks in certain areas of the cities in order to control large scale fires. In general these fire breaks were not effective because fires were started at so many locations simultaneously. They appear, however, to have helped prevent fires from spreading farther east into the main business and residential section of Nagasaki.

TOTAL CASUALTIES

There has been great difficulty in estimating the total casualties in the Japanese cities as a result of the atomic bombing. The extensive destruction of civil installations (hospitals, fire and police department, and government agencies) the state of utter confusion immediately following the explosion, as well as the uncertainty regarding the actual population before the bombing, contribute to the difficulty of making estimates of casualties. The Japanese periodic censuses are not complete. Finally, the great fires that raged in each city totally consumed many bodies.

The number of total casualties has been estimated at various times since the bombings with wide discrepancies. The Manhattan Engineer District's best available figures are:

TABLE A

Estimates of Casualties

	Hiroshima	Nagasaki
Pre-raid population	255,000	195,000
Dead	66,000	39,000
Injured	69,000	25,000
Total Casualties	135,000	64,000

The relation of total casualties to distance from X, the center of damage and point directly under the air-burst explosion of the bomb, is of great importance in evaluating the casualty-producing effect of the bombs. This relationship for the total population of Nagasaki is shown in the table below, based on the first-obtained casualty figures of the District:

TABLE B

Relation of Total Casualties to Distance from X

Distance from X, feet	Killed	Injured	Missing	Total Casualties	Killed per square mile
0 - 1,640	7,505	960	1,127	9,592	24,700
1,640 - 3,300	3,688	1,478	1,799	6,965	4,040
3,300 - 4,900	8,678	17,137	3,597	29,412	5,710
4,900 - 6,550	221	11,958	28	12,207	125
6,550 - 9,850	112	9,460	17	9,589	20

No figure for total pre-raid population at these different distances w available. Such figures would be necessary in order to compute per cent mo tality. A calculation made by the British Mission to Japan and based on a preliminary analysis of the study of the Joint Medical Atomic Bomb Investi gating Commission gives the following calculated values for per cent morta at increasing distances from X:

TABLE C

Per-Cent Mortality at Various Distances

Distance from X, in feet	Per-cent Mortality
0 - 1000	93.0%
1000 - 2000	92.0
2000 - 3000	86.0
3000 - 4000	69.0
4000 - 5000	49.0
5000 - 6000	31.5
6000 - 7000	12.5
7000 - 8000	1.3
8000 - 9000	0.5
9000 - 10,000	0.0

It seems almost certain from the various reports that the greatest tol number of deaths were those occurring immediately after the bombing. The causes of many of the deaths can only be surmised, and of course many pers near the center of explosion suffered fatal injuries from more than one of bomb effects. The proper order of importance for possible causes of death burns, mechanical injury, and gamma radiation. Early estimates by the Jap nese are shown in D below:

TABLE D

Cause of Immediate Deaths

City	Cause of Death	Per-cent of Total
Hiroshima	Burns	60%
	Falling debris	30
	Other	10
Nagasaki	Burns	95%
	Falling debris	9
	Flying glass	7
	Other	7

THE NATURE OF AN ATOMIC EXPLOSION

The most striking difference between the explosion of an atomic bomb a that of an ordinary T.N.T. bomb is of course in magnitude; as the President

announced after the Hiroshima attack, the explosive energy of each of the atomic bombs was equivalent to about 20,000 tons of T.N.T.

But in addition to its vastly greater power, an atomic explosion has several other very special characteristics. Ordinary explosion is a chemical reaction in which energy is released by the rearrangement of the atoms of the explosive material. In an atomic explosion, the identity of the atoms, not simply their arrangement, is changed. A considerable fraction of the mass of the explosive charge, which may be uranium 235 or plutonium, is transformed into energy. Einstein's equation, $E = mc^2$, shows that matter that is transformed into energy may yield a total energy equivalent to the mass multiplied by the square of the velocity of light. The significance of the equation is easily seen when one recalls that the velocity of light is 186,000 miles per second. The energy released when a pound of T.N.T. explodes would, if converted entirely into heat, raise the temperature of 36 lbs. of water from freezing temperature ($32^{\circ}F$) to boiling temperature ($212^{\circ}F$). The nuclear fission of a pound of uranium would produce an equal temperature rise in over 200 million pounds of water.

The explosive effect of an ordinary material such as T.N.T. is derived from the rapid conversion of solid T.N.T. to gas, which occupies initially the same volume as the solid; it exerts intense pressures on the surrounding air and expands rapidly to a volume many times larger than the initial volume. A wave of high pressure thus rapidly moves outward from the center of the explosion and is the major cause of damage from ordinary high explosives. An atomic bomb also generates a wave of high pressure which is in fact of much higher pressure than that from ordinary explosions; and this wave is again the major cause of damage to buildings and other structures. It differs from the pressure wave of a block buster in the size of the area over which high pressures are generated. It also differs in the duration of the pressure pulse at any given point: the pressure from a block buster lasts for a few milliseconds (a millisecond is one thousandth of a second) only, that from the atomic bomb for nearly a second, and was felt by observers both in Japan and in New Mexico as a very strong wind going by.

The next greatest difference between the atomic bomb and the T.N.T. explosion is the fact that the atomic bomb gives off greater amounts of radiation. Most of this radiation is "light" of some wave-length ranging from the so-called heat radiations of very long wave length to the so-called gamma rays which have wave-lengths even shorter than the X-rays used in medicine. All of these radiations travel at the same speed; this, the speed of light, is 186,000 miles per second. The radiations are intense enough to kill people within an appreciable distance from the explosion, and are in fact the major cause of deaths and injuries apart from mechanical injuries. The greatest number of radiation injuries was probably due to the ultra-violet rays which have a wave length slightly shorter than visible light and which caused flash burn comparable to severe sunburn. After these, the gamma rays of ultra short wave length are most important; these cause injuries similar to those from over-doses of X-rays.

The origin of the gamma rays is different from that of the bulk of the radiation: the latter is caused by the extremely high temperatures in the bomb, in the same way as light is emitted from the hot surface of the sun or from the wires in an incandescent lamp. The gamma rays on the other hand are

emitted by the atomic nuclei themselves when they are transformed in the fi sion process. The gamma rays are therefore specific to the atomic bomb and are completely absent in T.N.T. explosions. The light of longer wave lengt (visible and ultra-violet) is also emitted by a T.N.T. explosion, but with much smaller intensity than by an atomic bomb, which makes it insignificant far as damage is concerned.

A large fraction of the gamma rays is emitted in the first few microse onds (millionths of a second) of the atomic explosion, together with neutrc which are also produced in the nuclear fission. The neutrons have much les damage effect than the gamma rays because they have a smaller intensity and also because they are strongly absorbed in air and therefore can penetrate only to relatively small distances from the explosion: at a thousand yards the neutron intensity is negligible. After the nuclear emission, strong ga radiation continues to come from the exploded bomb. This generates from th fission products and continues for about one minute until all of the explos products have risen to such a height that the intensity received on the gro is negligible. A large number of beta rays are also emitted during this ti but they are unimportant because their range is not very great, only a few feet. The range of alpha particles from the unused active material and fis sionable material of the bomb is even smaller.

Apart from the gamma radiation ordinary light is emitted, some of whic is visible and some of which is the ultra violet rays mainly responsible fo flash burns. The emission of light starts a few milliseconds after the nuc ar explosion when the energy from the explosion reaches the air surrounding the bomb. The observer sees then a ball of fire which rapidly grows in siz During most of the early time, the ball of fire extends as far as the wave high pressure. As the ball of fire grows its temperature and brightness de crease. Several milliseconds after the initiation of the explosion, the brightness of the ball of fire goes through a minimum, then it gets somewha brighter and remains at the order of a few times the brightness of the sun a period of 10 to 15 seconds for an observer at six miles distance. Most o the radiation is given off after this point of maximum brightness. Also af this maximum, the pressure waves run ahead of the ball of fire.

The ball of fire rapidly expands from the size of the bomb to a radius several hundred feet at one second after the explosion. After this the mos striking feature is the rise of the ball of fire at the rate of about 30 ya per second. Meanwhile it also continues to expand by mixing with the coole air surrounding it. At the end of the first minute the ball has expanded t radius of several hundred yards and risen to a height of about one mile. T shock wave has by now reached a radius of 15 miles and its pressure dropped less than 1/10 of a pound per square inch. The ball now loses its brillian and appears as a great cloud of smoke: the pulverized material of the bomb This cloud continues to rise vertically and finally mushrooms out at an alt tude of about 25,000 feet depending upon metereological conditions. The cl reaches a maximum height of between 50,000 and 70,000 feet in a time of ove 30 minutes.

It is of interest to note that Dr. Hans Bethe, then a member of the Manhattan Engineer District on loan from Cornell University, predicted the existence and characteristics of this ball of fire months before the first test was carried out.

To summarize, radiation comes in two bursts - an extremely intense one lasting only about 3 milliseconds and a less intense one of much longer duration lasting several seconds. The second burst contains by far the larger fraction of the total light energy, more than 90%. But the first flash is especially large in ultra-violet radiation which is biologically more effective. Moreover, because the heat in this flash comes in such a short time, there is no time for any cooling to take place, and the temperature of a person's skin can be raised 50 degrees centigrade by the flash of visible and ultra-violet rays in the first millisecond at a distance of 4,000 yards. People may be injured by flash burns at even larger distances. Gamma radiation danger does not extend nearly so far and neutron radiation danger is still more limited.

The high skin temperatures result from the first flash of high intensity radiation and are probably as significant for injuries as the total dosages which come mainly from the second more sustained burst of radiation. The combination of skin temperature increase plus large ultra-violet flux inside 4,000 yards is injurious in all cases to exposed personnel. Beyond this point there may be cases of injury, depending upon the individual sensitivity. The infrared dosage is probably less important because of its smaller intensity.

CHARACTERISTICS OF THE DAMAGE CAUSED BY THE ATOMIC BOMBS

The damage to man-made structures caused by the bombs was due to two distinct causes: first the blast, or pressure wave, emanating from the center of the explosion, and, second, the fires which were caused either by the heat of the explosion itself or by the collapse of buildings containing stoves, electrical fixtures, or any other equipment which might produce what is known as a secondary fire, and subsequent spread of these fires.

The blast produced by the atomic bomb has already been stated to be approximately equivalent to that of 20,000 tons of T.N.T. Given this figure, one may calculate the expected peak pressures in the air, at various distances from the center of the explosion, which occurred following detonation of the bomb. The peak pressures which were calculated before the bombs were dropped agreed very closely with those which were actually experienced in the cities during the attack as computed by Allied experts in a number of ingenious ways after the occupation of Japan.

The blast of pressure from the atomic bombs differed from that of ordinary high explosive bombs in three main ways:

A. Downward thrust. Because the explosions were well up in the air, much of the damage resulted from a downward pressure. This pressure of course most largely effected flat roofs. Some telegraph and other poles immediately below the explosion remained upright while those at greater distances from the center of damage, being more largely exposed to a horizontal thrust from the blast pressure waves, were overturned or tilted. Trees underneath the explosion remained upright but had their branches broken downward.

B. Mass distortion of buildings. An ordinary bomb can damage only a part of a large building, which may then collapse further under the action of gravity. But the blast wave from an atomic bomb is so large that it can

engulf whole buildings, no matter how great their size, pushing them over a
though a giant hand had given them a shove.

C. Long duration of the positive pressure pulse and consequent small effect of the negative pressure, or suction, phase. In any explosion, the positive pressure exerted by the blast lasts for a definite period of time (usually a small fraction of a second) and is then followed by a somewhat longer period of negative pressure, or suction. The negative pressure is always much weaker than the positive, but in ordinary explosions the short duration of the positive pulse results in many structures not having time t fail in that phase, while they are able to fail under the more extended, though weaker, negative pressure. But the duration of the positive pulse i approximately proportional to the 1/3 power of the size of the explosive charge. Thus, if the relation held true throughout the range in question, 10-ton T.N.T. explosion would have a positive pulse only about 1/14th as lo as that of a 20,000-ton explosion. Consequently, the atomic explosions had positive pulses so much longer than those of ordinary explosives that nearl all failures probably occurred during this phase, and very little damage could be attributed to the suction which followed.

One other interesting feature was the combination of flash ignition an comparative slow pressure wave. Some objects, such as thin, dry wooden sla were ignited by the radiated flash heat, and then their fires were blown ou some time later (depending on their distance from X) by the pressure blast which followed the flash radiation.

CALCULATIONS OF THE PEAK PRESSURE OF THE BLAST WAVE

Several ingenious methods were used by the various investigators to de mine, upon visiting the wrecked cities, what had actually been the peak pressures exerted by the atomic blasts. These pressures were computed for various distances from X, and curves were then plotted which were checked against the theoretical predictions of what the pressures would be. A furt check was afforded from the readings obtained by the measuring instruments which were dropped by parachute at each atomic attack. The peak pressure figures gave a direct clue to the equivalent T.N.T. tonnage of the atomic bombs, since the pressures developed by any given amount of T.N.T. can be calculated easily.

One of the simplest methods of estimating the peak pressure is from crushing of oil drums, gasoline cans, or any other empty thin metal vessel with a small opening. The assumption made is that the blast wave pressure comes on instantaneously, the resulting pressure on the can is more than th case can withstand, and the walls collapse inward. The air inside is compressed adiabatically to such a point that the pressure inside is less by a certain amount than the pressure outside, this amount being the pressure difference outside and in that the walls can stand in their crumpled condit: The uncertainties involved are, first, that some air rushes in through any opening that the can may have, and thus helps to build up the pressure insi and, second, that as the pressure outside falls, the air inside cannot esca sufficiently fast to avoid the walls of the can being blown out again to so extent. These uncertainties are such that estimates of pressure based on this method are on the low side, i.e., they are underestimated.

Another method of calculating the peak pressure is through the bending of steel flagpoles, or lightning conductors, away from the explosion. It is possible to calculate the drag on a pole or rod in an airstream of a certain density and velocity; by connecting this drag with the strength of the pole in question, a determination of the pressure wave may be obtained.

Still another method of estimating the peak pressure is through the overturning of memorial stones, of which there are a great quantity in Japan. The dimensions of the stones can be used, along with known data on the pressure exerted by wind against flat surfaces, to calculate the desired figure.

LONG RANGE BLAST DAMAGE

There was no consistency in the long range blast damage. Observers often thought that they had found the limit, and then 2,000 feet farther away would find further evidence of damage.

The most impressive long range damage was the collapse of some of the barracks sheds at Kamigo, 23,000 feet south of X in Nagasaki. It was remarkable to see some of the buildings intact to the last detail, including the roof and even the windows, and yet next to them a similar building collapsed to ground level.

The limiting radius for severe displacement of roof tiles in Nagasaki was about 10,000 feet although isolated cases were found up to 16,000 feet. In Hiroshima the general limiting radius was about 8,000 feet; however, even at a distance of 26,000 feet from X in Hiroshima, some tiles were displaced.

At Mogi, 7 miles from X in Nagasaki, over steep hills over 600 feet high, about 10% of the glass came out. In nearer, sequestered localities only 4 miles from X, no damage of any kind was caused. An interesting effect was noted at Mogi; eyewitnesses said that they thought a raid was being made on the place; one big flash was seen, then a loud roar, followed at several second intervals by half a dozen other loud reports, from all directions. These successive reports were obviously reflections from the hills surrounding Mogi.

GROUND SHOCK

The ground shock in most cities was very light. Water pipes still carried water and where leaks were visible they were mainly above ground. Virtually all of the damage to underground utilities was caused by the collapse of buildings rather than by any direct exertion of the blast pressure. This fact of course resulted from the bombs' having been exploded high in the air.

SHIELDING, OR SCREENING FROM BLAST

In any explosion, a certain amount of protection from blast may be gained by having any large and substantial object between the protected object and the center of the explosion. This shielding effect was noticeable in the atomic explosions, just as in ordinary cases, although the magnitude of the

explosions and the fact that they occurred at a considerable height in the caused marked differences from the shielding which would have characterized ordinary bomb explosions.

The outstanding example of shielding was that afforded by the hills in the city of Nagasaki; it was the shielding of these hills which resulted in the smaller area of devastation in Nagasaki despite the fact that the bomb there was not less powerful. The hills gave effective shielding only at su distances from the center of explosion that the blast pressure was becoming critical - that is, was only barely sufficient to cause collapse - for the structure. Houses built in ravines in Nagasaki pointing well away from the center of the explosion survived without damage, but others at similar dist in ravines pointing toward the center of explosion were greatly damaged. I the north of Nagasaki there was a small hamlet about 8,000 feet from the ce of explosion; one could see a distinctive variation in the intensity of dam across the hamlet, corresponding with the shadows thrown by a sharp hill.

The best example of shielding by a hill was southeast of the center of explosion in Nagasaki. The damage at 8,000 feet from X consisted of light ter damage and destruction of about half the windows. These buildings were European type and were on the reverse side of a steep hill. At the same di tance to the south-southeast the damage was considerably greater, i.e., all windows and frames, doors, were damaged and heavy plaster damage and cracks the brick work also appeared. The contrast may be illustrated also by the that at the Nagasaki Prefectural office at 10,800 feet the damage was bad e for the building to be evacuated, while at the Nagasaki Normal School to wh the Prefectural office had been moved, at the same distance, the damage was comparatively light.

Because of the height of the bursts no evidence was expected of the shielding of one building by another, at least up to a considerable radius. It was in fact difficult to find any evidence at any distance of such shiel There appeared to have been a little shielding of the building behind the Administration Building of the Torpedo Works in Nagasaki, but the benefits were very slight. There was also some evidence that the group of buildings comprising the Medical School in Nagasaki did afford each other mutual prot tion. On the whole, however, shielding of one building by another was not noticeable.

There was one other peculiar type of shielding, best exhibited by the workers' houses to the north of the torpedo plant in Nagasaki. These were 6,000 to 7,000 feet north of X. The damage to these houses was not nearly bad as those over a thousand feet farther away from the center of explosion It seemed as though the great destruction caused in the torpedo plant had weakened the blast a little, and the full power was not restored for anothe 1,000 feet or more.

FLASH BURN

As already stated, a characteristic feature of the atomic bomb, which quite foreign to ordinary explosives, is that a very appreciable fraction o the energy liberated goes into radiant heat and light. For a sufficiently large explosion, the flash burn produced by this radiated energy will becom

the dominant cause of damage, since the area of burn damage will increase in proportion to the energy released, whereas the area of blast damage increases only with the two-thirds power of the energy. Although such a reversal of the mechanism of damage was not achieved in the Hiroshima and Nagasaki bombs, the effects of the flash were, however, very evident, and many casualties resulted from flash burns. A discussion of the casualties caused by flash burns will be given later; in this section will be described the other flash effects which were observed in the two cities.

The duration of the heat radiation from the bomb is so short, just a few thousandths of a second, that there is no time for the energy falling on a surface to be dissipated by thermal defusion; the flash burn is typically a surface effect. In other words the surface of either a person or an object exposed to the flash is raised to a very high temperature while immediately beneath the surface very little rise in temperature occurs.

The flash burning of the surface of objects, particularly wooden objects, occurred in Hiroshima up to a radius of 9,500 feet from X; at Nagasaki burns were visible up to 11,000 feet from X. The charring and blackening of all telephone poles, trees and wooden posts in the areas not destroyed by the general fire occurred only on the side facing the center of explosion and did not go around the corners of buildings or hills. The exact position of the explosion was in fact accurately determined by taking a number of sights from various objects which had been flash burned on one side only.

To illustrate the effects of the flash burn, the following describes a number of examples found by an observer moving northward from the center of explosion in Nagasaki. First occurred a row of fence posts at the north edge of the prison hill, at 0.3 miles from X. The top and upper part of these posts were heavily charred. The charring on the front of the posts was sharply limited by the shadow of a wall. This wall had however been completely demolished by the blast, which of course arrived some time after the flash. At the north edge of the Torpedo works, 1.05 miles from X, telephone poles were charred to a depth of about 0.5 millimeters. A light piece of wood similar to the flat side of an orange crate, was found leaning against one of the telephone poles. Its front surface was charred the same way as the pole, but it was evident that it had actually been ignited. The wood was blackened through a couple of cracks and nail holes, and around the edges onto the back surface. It seemed likely that this piece of wood had flamed up under the flash for a few seconds before the flame was blown out by the wind of the blast. Farther out, between 1.05 and 1.5 miles from the explosion, were many trees and poles showing a blackening. Some of the poles had platforms near the top. The shadows cast by the platforms were clearly visible and showed that the bomb had detonated at a considerable height. The row of poles turned north and crossed the mountain ridge; the flash burn was plainly visible all the way to the top of the ridge, the farthest burn observed being at 2.0 miles from X.

Another striking effect of the flash burn was the autumnal appearance of the bowl formed by the hills on three sides of the explosion point. The ridges are about 1.5 miles from X. Throughout this bowl the foliage turned yellow, although on the far side of the ridges the countryside was quite green. This autumnal appearance of the trees extended to about 8,000 feet from X.

However, shrubs and small plants quite near the center of explosion ir Hiroshima, although stripped of leaves, had obviously not been killed. Mar were throwing out new buds when observers visited the city.

There are two other remarkable effects of the heat radiated from the h explosion. The first of these is the manner in which heat roughened the su of polished granite, which retained its polish only where it was shielded f the radiated heat travelling in straight lines from the explosion. This ro ening by radiated heat caused by the unequal expansion of the constituent c tals of the stone; for granite crystals the melting temperature is about 6C centigrade. Therefore the depth of roughening and ultimate flaking of the granite surface indicated the depth to which this temperature occurred and ed to determine the average ground temperatures in the instant following th explosion. This effect was noted for distances about $1\frac{1}{2}$ times as great in Nagasaki as in Hiroshima.

The second remarkable effect was the bubbling of roof tile. The size o: bubbles and their extent was proportional to their nearness to the center o explosion and also depended on how squarely the tile itself was faced towar the explosion. The distance ratio of this effect between Nagasaki and Hiro was about the same as for the flaking of polished granite.

Various other effects of the radiated heat were noted, including the lightening of asphalt road surfaces in spots which had not been protected f the radiated heat by any object such as that of a person walking along the Various other surfaces were discolored in different ways by the radiated he

As has already been mentioned the fact that radiant heat traveled only straight lines from the center of explosion enabled observers to determine direction toward the center of explosion from a number of different points, observing the "shadows" which were cast by intervening objects where they shielded the otherwise exposed surface of some object. Thus the center of plosion was located with considerable accuracy. In a number of cases these "shadows" also gave an indication of the height of burst of the bomb and oc sionally a distinct penumbra was found which enabled observers to calculate diameter of the ball of fire at the instant it was exerting the maximum cha or burning effect.

One more interesting feature connected with heat radiation was the cha of fabric to different degrees depending upon the color of the fabric. A n of instances were recorded in which persons wearing clothing of various col received burns greatly varying in degree, the degree of burn depending upon color of the fabric over the skin in question. For example a shirt of alte light and dark gray stripes, each about 1/8 of an inch wide, had the dark stripes completely burned out but the light stripes were undamaged; and a p of Japanese paper exposed nearly $1\frac{1}{2}$ miles from X had the characters which w written in black ink neatly burned out.

CHARACTERISTICS OF THE INJURIES TO PERSONS

Injuries to persons resulting from the atomic explosions were of the following types:

A. Burns, from
   1. Flash radiation of heat
   2. Fires started by the explosions.
B. Mechanical injuries from collapse of buildings, flying debris, etc.
C. Direct effects of the high blast pressure, i.e., straight compression.
D. Radiation injuries, from the instantaneous emission of gamma rays and neutrons.

It is impossible to assign exact percentages of casualties to each of the types of injury, because so many victims were injured by more than one effect of the explosions. However, it is certain that the greater part of the casualties resulted from burns and mechanical injures. Col. Warren, one of America's foremost radioligists, stated it is probable that 7 per cent or less of the deaths resulted primarily from radiation disease.

The greatest single factor influencing the occurrence of casualties was the distance of the person concerned from the center of explosion.

Estimates based on the study of a selected group of 900 patients indicated that total casualties occurred as far out as 14,000 feet at Nagasaki and 12,000 feet at Hiroshima.

Burns were suffered at a considerable greater distance from X than any other type of injury, and mechanical injuries farther out than radiation effects

Medical findings show that no person was injured by radioactivity who was not exposed to the actual explosion of the bombs. No injuries resulted from persistent radioactivity of any sort.

BURNS

Two types of burns were observed. These are generally differentiated as flame or fire burn and so-called flash burn.

The early appearance of the flame burn as reported by the Japanese, and the later appearance as observed, was not unusual.

The flash burn presented several distinctive features. Marked redness of the affected skin areas appeared almost immediately, according to the Japanese, with progressive changes in the skin taking place over a period of a few hours. When seen after 50 days, the most distinctive feature of these burns was their sharp limitation to exposed skin areas facing the center of the explosion. For instance, a patient who had been walking in a direction at right angles to a line drawn between him and the explosion, and whose arms were swinging, might have burns only on the outside of the arm nearest the center and on the inside of the other arm.

Generally, any type of shielding protected the skin against flash burns, although burns through one, and very occasionally more, layers of clothing did occur in patients near the center. In such cases, it was not unusual to find burns through black but not through white clothing, on the same patient.

Flash burns also tended to involve areas where the clothes were tightly dr over the skin, such as at the elbows and shoulders.

The Japanese report the incidence of burns in patients surviving mor than a few hours after the explosion, and seeking medical attention, as hi as 95%. The total mortalities due to burns alone cannot be estimated with degree of accuracy. As mentioned already, it is believed that the majorit all the deaths occurred immediately. Of these, the Japanese estimate that and most of the reports estimate that over 50%, of the deaths were due to burns.

In general, the incidence of burns was in direct proportion to the di tance from X. However, certain irregularities in this relationship result the medical studies because of variations in the amount of shielding from flash burn, and because of the lack of complete data on persons killed out right close to X.

The maximum distance from X at which flash burns were observed is of paramount interest. It has been estimated that patients with burns at Hiroshima were all less than 7,500 feet from the center of the explosion a the time of the bombing. At Nagasaki, patients with burns were observed o to the remarkable distance of 13,800 feet.

MECHANICAL INJURIES

The mechanical injuries included fractures, lacerations, contusions, abrasions, and other effects to be expected from falling roofs, crumbling walls, flying debris and glass, and other indirect blast effects. The appearance of these various types of mechanical injuries was not remarkable t the medical authorities who studied them.

It was estimated that patients with lacerations at Hiroshima were less than 10,600 feet from X, whereas at Nagasaki they extended as far as 12,20C feet.

The tremendous drag of wind, even as far as 1 mile from X, must have r sulted in many injuries and deaths. Some large pieces of a prison wall, fc example, were flung 80 feet, and many have gone 30 feet high before falling The same fate must have befallen many persons, and the chances of a human being surviving such treatment are probably small.

BLAST INJURIES

No estimate of the number of deaths or early symptoms due to blast pressure can be made. The pressures developed on the ground under the explosions were not sufficient to kill more than those people very near the center of damage (within a few hundred feet at most). Very few cases of ruptured ear drums were noted, and it is the general feeling of the medical authorities that the direct blast effects were not great. Many of the Japanese reports, which are believed to be false, describe immediate effect such as ruptured abdomens with protruding intestines and protruding eyes, b no such results were actually traced to the effect of air pressure alone.

RADIATION INJURIES

As pointed out in another section of this report the radiations from the nuclear explosions which caused injuries to persons were primarily those experienced within the first second after the explosion; a few may have occurred later, but all occurred in the first minute. The other two general types of radiation, viz., radiation from scattered fission products and induced radioactivity from objects near the center of explosion, were definitely proved not to have caused any casualties.

The proper designation of radiation injuries is somewhat difficult. Probably the two most direct designations are radiation injury and gamma ray injury. The former term is not entirely suitable in that it does not define the type of radiation as ionizing and allows possible confusion with other types of radiation (e.g., infra-red). The objection to the latter term is that it limits the ionizing radiation to gamma rays, which were undoubtedly the most important; but the possible contribution of neutron and even beta rays to the biological effects cannot be entirely ignored. Radiation injury has the advantage of custom, since it is generally understood in medicine to refer to X-ray effect as distinguished from the effects of actinic radiation. Accordingly, radiation injury is used in this report to mean injury due only to ionizing radiation.

According to Japanese observations, the early symptons in patients suffering from radiation injury closely resembled the symptons observed in patients receiving intensive roentgen therapy, as well as those observed in experimental animals receiving large doses of X-rays. The important symptons reported by the Japanese and observed by American authorities were epilation (loss of hair), petechiae (bleeding into the skin), and other hemorrhagic manifestations, oropharyngeal lesions (inflammation of the mouth and throat), vomiting, diarrhea, and fever.

Epilation was one of the most spectacular and obvious findings. The appearance of the epilated patient was typical. The crown was involved more than the sides, and in many instances the resemblance to a monk's tonsure was striking. In extreme cases the hair was totally lost. In some cases, regrowth of hair had begun by the time patients were seen 50 days after the bombing. Curiously, epilation of hair other than that of the scalp was extremely unusual.

Petechiae and other hemorrhagic manifestations were striking findings. Bleeding began usually from the gums and in the more seriously affected was soon evident from every possible source. Petechiae appeared on the limbs and on pressure points. Large ecchymoses (hemorrhages under the skin) developed about needle punctures, and wounds partially healed broke down and bled freely. Retinal hemorrhages occurred in many of the patients. The bleeding time and the coagulation time were prolonged. The platelets (coagulation of the blood) were characteristically reduced in numbers.

Nausea and vomiting appearing within a few hours after the explosion was reported frequently by the Japanese. This usually had subsided by the following morning, although occasionally it continued for two or three days. Vomiting was not infrequently reported and observed during the course of the

later symptoms, although at these times it generally appeared to be relate other manifestation of systemic reactions associated with infection.

Diarrhea of varying degrees of severity was reported and observed. I more severe cases, it was frequently bloody. For reasons which are not ye clear, the diarrhea in some cases was very persistent.

Lesions of the gums, and the oral mucous membrane, and the throat wer observed. The affected areas became deep red, then violacious in color; a many instances ulcerations and necrosis (breakdown of tissue) followed. B counts done and recorded by the Japanese, as well as counts done by the Ma hattan Engineer District Group, on such patients regularly showed leucopen (low-white blood cell count). In extreme cases the white blood cell count below 1,000 (normal count is around 7,000). In association with the leuco and the oropharyngeal lesions, a variety of other infective processes were seen. Wounds and burns which were healing adequately suppurated and serio necrosis occurred. At the same time, similar ulcerations were observed in larynx, bowels, and in females, the gentalia. Fever usually accompanied t lesions.

Eye injuries produced by the atomic bombings in both cities were the subject of special investigations. The usual types of mechanical injuries were seen. In addition, lesions consisting of retinal hemorrhage and exud were observed and 75% of the patients showing them had other signs of radi injury.

The progress of radiation disease of various degrees of severity is sh in the following table:

Summary of Radiation Injury

Clinical Symptoms and Findings

Day after Explosion	Most Severe	Moderately Severe	Mild
1.	1. Nausea and vomiting after 1-2 hours.	1. Nausea and vomiting after 1-2 hours.	
2.			
3.	NO DEFINITE SYMPTOMS		
4.			
5.	2. Diarrhea		
6.	3. Vomiting	NO DEFINITE SYMPTOMS	
7.	4. Inflammation of the mouth and throat		
8.	5. Fever		
9.	6. Rapid emaciation		
10.	Death		NO DEFINITE SYMPTOMS
11.	(Mortality probably	2. Beginning epilation.	
12.	100%)		
13.			
14.			
15.			
16.			
17.			
18.		3. Loss of appetite	
19.		and general malaise.	1. Epilation
20.		4. Fever.	2. Loss of appetite
21.		5. Severe inflammation	and malaise.
22.		of the mouth and throat	3. Sore throat.
23.			4. Pallor.
24.			5. Petechiae
25.			6. Diarrhea
26.			7. Moderate emacia-
27.		6. Pallor.	tion.
28.		7. Petechiae, diarrhea	
29.		and nose bleeds	(Recovery unless com-
30.			plicated by previous
31.		8. Rapid emaciation	poor health or
		Death	super-imposed in-
		(Mortality probably	juries or infec-
		50%)	tions).

It was concluded that persons exposed to the bombs at the time of detonation did show effects from ionizing radiation and that some of these patients, otherwise uninjured, died. Deaths from radiation began about a week after exposure and reached a peak in 3 to 4 weeks. They practically ceased to occur after 7 to 8 weeks.

Treatment of the burns and other physical injuries was carried out by Japanese by orthodox methods. Treatment of radiation effects by them incl general supportative measures such as rest and high vitamin and caloric di Liver and calcium preparations were administered by injection and blood tr fusions were used to combat hemorrhage. Special vitamin preparations and special drugs used in the treatment of similar medical conditions were use American Army Medical Corps officers after their arrival. Although the ge measures instituted were of some benefit no definite effect of any of the specific measures on the course of the disease could be demonstrated. The of sulfonamide drugs by the Japanese and particularly of penicillin by the American physicians after their arrival undoubtedly helped control the inf tions and they appear to be the single important type of treatment which m have effectively altered the earlier course of these patients.

One of the most important tasks assigned to the mission which investig the effects of the bombing was that of determining if the radiation effect were all due to the instantaneous discharges at the time of the explosion, if people were being harmed in addition from persistent radioactivity. Thi question was investigated from two points of view. Direct measurements of persistent radioactivity were made at the time of the investigation. From these measurements, calculations were made of the graded radiation dosages, i.e., the total amount of radiation which could have been absorbed by any p son. These calculations showed that the highest dosage which would have be received from persistent radioactivity at Hiroshima was between 6 and 25 roentgens of gamma radiation; the highest in the Nagasaki Area was between and 110 roentgens of gamma radiation. The latter figure does not refer to city itself, but to a localized area in the Nishiyama District. In interpr these findings it must be understood that to get these dosages, one would h had to remain at the point of highest radioactivity for 6 weeks continuousl from the first hour after the bombing. It is apparent therefore that insof as could be determined at Hiroshima and Nagasaki, the residual radiation al could not have been detrimental to the health of persons entering and livin in the bombed areas after the explosion.

The second approach to this question was to determine if any persons n in the city at the time of the explosion, but coming in immediately afterwa exhibited any symptoms or findings which might have been due to persistence induced radioactivity. By the time of the arrival of the Manhattan Enginee District group, several Japanese studies had been done on such persons. No of the persons examined in any of these studies showed any symptoms which c be attributed to radiation, and their actual blood cell counts were consist within the normal range. Throughout the period of the Manhattan Engineer District investigation, Japanese doctors and patients were repeatedly reque to bring to them any patients who they thought might be examples of persons harmed from persistent radioactivity. No such subjects were found.

It was concluded therefore as a result of these findings and lack of findings, that although a measurable quantity of induced radioactivity was found, it had not been sufficient to cause any harm to persons living in the two cities after the bombings.

SHIELDING FROM RADIATION

Exact figures on the thicknesses of various substances to provide complete or partial protection from the effects of radiation, in relation to the distance from the center of explosion, cannot be released at this time. Studies of collected data are still under way. It can be stated, however, that at a reasonable distance, say about ½ mile from the center of explosion, protection to persons from radiation injury can be afforded by a layer of concrete or other material whose thickness does not preclude reasonable construction.

Radiation ultimately caused the death of the few persons not killed by other effects and who were fully exposed to the bombs up to a distance of about ½ mile from X. The British Mission has estimated that people in the open had a 50% chance of surviving the effects of radiation at 3/4 of a mile from X.

EFFECTS OF THE ATOMIC BOMBINGS ON THE INHABITANTS OF THE BOMBED CITIES

In both Hiroshima and Nagasaki the tremendous scale of the disaster largely destroyed the cities as entities. Even the worst of all other previous bombing attacks on Germany and Japan, such as the incendiary raids on Hamburg in 1943 and on Tokyo in 1945, were not comparable to the paralyzing effect of the atomic bombs. In addition to the huge number of persons who were killed or injuried so that their services in rehabilitation were not available, a panic flight of the population took place from both cities immediately following the atomic explosions. No significant reconstruction or repair work was accomplished because of the slow return of the population; at the end of November 1945 each of the cities had only about 140,000 people. Although the ending of the war almost immediately after the atomic bombings removed much of the incentive of the Japanese people toward immediate reconstruction of their losses, their paralysis was still remarkable. Even the clearance of wreckage and the burning of the many bodies trapped in it were not well organized some weeks after the bombings. As the British Mission has stated, "the impression which both cities make is of having sunk, in an instant and without a struggle, to the most primitive level."

Aside from physical injury and damage, the most significant effect of the atomic bombs was the sheer terror which it struck into the peoples of the bombed cities. This terror, resulting in immediate hysterical activity and flight from the cities, had one especially pronounced effect: persons who had become accustomed to mass air raids had grown to pay little heed to single planes or small groups of planes, but after the atomic bombings the appearance of a single plane caused more terror and disruption of normal life than the appearance of many hundreds of planes had ever been able to cause before. The effect of this terrible fear of the potential danger from even a single enemy plane on the lives of the peoples of the world in the event of any future war can easily be conjectured.

The atomic bomb did not alone win the war against Japan, but it most certainly ended it, saving the thousands of Allied lives that would have been lost in any combat invasion of Japan.

EYEWITNESS ACCOUNT

Hiroshima -- August 6th, 1945

by

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Up to August 6th, occasional bombs, which did no great damage, had fallen on Hiroshima. Many cities roundabout, one after the other, were destroyed, but Hiroshima itself remained protected. There were almost daily observation planes over the city but none of them dropped a bomb. The citizens wondered why they alone had remained undisturbed for so long a time. There were fantastic rumors that the enemy had something special in mind for this city, but no one dreamed that the end would come in such a fashion as on the morning of August 6th.

August 6th began in a bright, clear, summer morning. About seven o'clock, there was an air raid alarm which we had heard almost every day and a few planes appeared over the city. No one paid any attention and at about eight o'clock, the all-clear was sounded. I am sitting in my room at the Novitiate of the Society of Jesus in Nagatsuke; during the past half year, the philosophical and theological section of our Mission had been evacuated to this place from Tokyo. The Novitiate is situated approximately two kilometers from Hiroshima, half-way up the sides of a broad valley which stretches from the town at sea level into this mountainous hinterland, and through which courses a river. From my window, I have a wonderful view down the valley to the edge of the city.

Suddenly—the time is approximately 8:14—the whole valley is filled by a garish light which resembles the magnesium light used in photography, and I am conscious of a wave of heat. I jump to the window to find out the cause of this remarkable phenomenon, but I see nothing more than that brilliant yellow light. As I make for the door, it doesn't occur to me that the light might have something to do with enemy planes. On the way from the window, I hear a moderately loud explosion which seems to come from a distance and, at the same time, the windows are broken in with a loud crash. There has been an interval of perhaps ten seconds since the flash of light. I am sprayed by fragments of glass. The entire window frame has been forced into the room. I realize now that a bomb has burst and I am under the impression that it exploded directly over our house or in the immediate vicinity.

I am bleeding from cuts about the hands and head. I attempt to get out of the door. It has been forced outwards by the air pressure and has become jammed. I force an opening in the door by means of repeated blows with my hands and feet and come to a broad hallway from which open the various rooms. Everything is in a state of confusion. All windows are broken and all the doors are forced inwards. The book-shelves in the hallway have tumbled down. I do not note a second explosion and the fliers seem to have gone on. Most of my colleagues have been injured by fragments of glass. A few are bleeding but none has been seriously injured. All of us have been fortunate since it is now apparent that the wall of my room opposite the window has been lacerated by long fragments of glass.

We proceed to the front of the house to see where the bomb has landed. There is no evidence, however, of a bomb crater; but the southeast section of the house is very severely damaged. Not a door nor a window remains. The blast of air had penetrated the entire house from the southeast, but the house still stands. It is constructed in a Japanese style with a wooden framework, but has been greatly strengthened by the labor of our Brother Gropper as is frequently done in Japanese homes. Only along the front of the chapel which adjoins the house, three supports have given way (it has been made in the manner of Japanese temple, entirely out of wood.)

Down in the valley, perhaps one kilometer toward the city from us, several peasant homes are on fire and the woods on the opposite side of the valley are aflame. A few of us go over to help control the flames. While we are attempting to put

things in order, a storm comes up and it begins to rain. Over the city, clouds of smoke are rising and I hear a few slight explosions. I come to the conclusion that an incendiary bomb with an especially strong explosive action has gone off down in the valley. A few of us saw three planes at great altitude over the city at the time of the explosion. I, myself, saw no aircraft whatsoever.

Perhaps a half-hour after the explosion, a procession of people begins to stream up the valley from the city. The crowd thickens continuously. A few come up the road to our house. We give them first aid and bring them into the chapel, which we have in the meantime cleaned and cleared of wreckage, and put them to rest on the straw mats which constitute the floor of Japanese houses. A few display horrible wounds of the extremities and back. The small quantity of fat which we possessed during this time of war was soon used up in the care of the burns. Father Rektor who, before taking holy orders, had studied medicine, ministers to the injured, but our bandages and drugs are soon gone. We must be content with cleansing the wounds.

More and more of the injured come to us. The least injured drag the more seriously wounded. There are wounded soldiers, and mothers carrying burned children in their arms. From the houses of the farmers in the valley comes word: "Our houses are full of wounded and dying. Can you help, at least by taking the worst cases?" The wounded come from the sections at the edge of the city. They saw the bright light, their houses collapsed and buried the inmates in their rooms. Those that were in the open suffered instantaneous burns, particularly on the lightly clothed or unclothed parts of the body. Numerous fires sprang up which soon consumed the entire district. We now conclude that the epicenter of the explosion was at the edge of the city near the Jokogawa Station, three kilometers away from us. We are concerned about Father Kopp who that same morning, went to hold Mass at the Sisters of the Poor, who have a home for children at the edge of the city. He had not returned as yet.

Toward noon, our large chapel and library are filled with the seriously injured. The procession of refugees from the city continues. Finally, about one o'clock, Father Kopp returns together with the Sisters. Their house and the entire district where they live has burned to the ground. Father Kopp is bleeding about the head and neck, and he has a large burn on the right palm. He was standing in front of the nunnery ready to go home. All of a sudden, he became aware of the light, felt the wave of heat and a large blister formed on his hand. The windows were torn out by the blast. He thought that the bomb had fallen in his immediate vicinity. The nunnery, also a wooden structure made by our Brother Gropper, still remained but soon it is noted that the house is as good as lost because the fire, which had begun at many points in the neighborhood, sweeps closer and closer, and water is not available. There is still time to rescue certain things from the house and to bury them in an open spot. Then the house is swept by flame, and they fight their way back to us along the shore of the river and through the burning streets.

Soon comes news that the entire city has been destroyed by the explosion and that it is on fire. What became of Father Superior and the three other Fathers who were at the center of the city at the Central Mission and Parish House? We had up to this time not given them a thought because we did not believe that the effects of the bomb encompassed the entire city. Also, we did not want to go into town except under pressure of dire necessity, because we thought that the population was greatly perturbed and that it might take revenge on any foreigners which they might consider spiteful onlookers of their misfortune, or even spies.

Father Stolte and Father Erlinghagen go down to the road which is still full of refugees and bring in the seriously injured who have sunken by the wayside, to the temporary aid station at the village school. There iodine is applied to the wounds but they are left uncleansed. Neither ointments nor other therapeutic agents are available. Those that have been brought in are laid on the floor and no one can give them any further care. What could one do when all means are lacking? Under those circumstances, it is almost useless to bring them in. Among the passersby, there are many who are uninjured. In a purposeless, insensate manner, distraught by the magnitude of the disaster most of them rush by and none conceives the thought of organizing help on his own initiative. They are concerned only with the welfare of their own families. It became clear to us during these days that the Japanese displayed little initiative, preparedness, and organizational skill in preparation for catas-

trophes. They failed to carry out any rescue work when something could have been saved by a cooperative effort, and fatalistically let the catastrophe take its course. When we urged them to take part in the rescue work, they did everything willingly, but on their own initiative they did very little.

At about four o'clock in the afternoon, a theology student and two kindergarten children, who lived at the Parish House and adjoining buildings which had burned down, came in and said that Father Superior LaSalle and Father Schiffer had been seriously injured and that they had taken refuge in Asano Park on the river bank. It is obvious that we must bring them in since they are too weak to come here on foot.

Hurriedly, we get together two stretchers and seven of us rush toward the city. Father Rektor comes along with food and medicine. The closer we get to the city, the greater is the evidence of destruction and the more difficult it is to make our way. The houses at the edge of the city are all severely damaged. Many have collapsed or burned down. Further in, almost all of the dwellings have been damaged by fire. Where the city stood, there is a gigantic burned-out scar. We make our way along the street on the river bank among the burning and smoking ruins. Twice we are forced into the river itself by the heat and smoke at the level of the street.

Frightfully burned people beckon to us. Along the way, there are many dead and dying. On the Misasi Bridge, which leads into the inner city we are met by a long procession of soldiers who have suffered burns. They drag themselves along with the help of staves or are carried by their less severely injured comrades...an endless procession of the unfortunate.

Abandoned on the bridge, there stand with sunken heads a number of horses with large burns on their flanks. On the far side, the cement structure of the local hospital is the only building that remains standing. Its interior, however, has been burned out. It acts as a landmark to guide us on our way.

Finally we reach the entrance of the park. A large proportion of the populace has taken refuge there, but even the trees of the park are on fire in several places. Paths and bridges are blocked by the trunks of fallen trees and are almost impassable. We are told that a high wind, which may well have resulted from the heat of the burning city, has uprooted the large trees. It is now quite dark. Only the fires, which are still raging in some places at a distance, give out a little light.

At the far corner of the park, on the river bank itself, we at last come upon our colleagues. Father Schiffer is on the ground pale as a ghost. He has a deep incised wound behind the ear and has lost so much blood that we are concerned about his chances for survival. The Father Superior has suffered a deep wound of the lower leg. Father Cieslik and Father Kleinsorge have minor injuries but are completely exhausted.

While they are eating the food that we have brought along, they tell us of their experiences. They were in their rooms at the Parish House—it was a quarter after eight, exactly the time when we had heard the explosion in Nagatsuke—when came the intense light and immediately thereafter the sound of breaking windows, walls and furniture. They were showered with glass splinters and fragments of wreckage. Father Schiffer was buried beneath a portion of a wall and suffered a severe head injury. The Father Superior received most of the splinters in his back and lower extremity from which he bled copiously. Everything was thrown about in the rooms themselves, but the wooden framework of the house remained intact. The solidity of the structure which was the work of Brother Gropper again shone forth.

They had the same impression that we had in Nagatsuke: that the bomb had burst in their immediate vicinity. The Church, school, and all buildings in the immediate vicinity collapsed at once. Beneath the ruins of the school, the children cried for help. They were freed with great effort. Several others were also rescued from the ruins of nearby dwellings. Even the Father Superior and Father Schiffer despite their wounds, rendered aid to others and lost a great deal of blood in the process.

In the meantime, fires which had begun some distance away are raging even closer, so that it becomes obvious that everything would soon burn down. Several objects are rescued from the Parish House and were buried in a clearing in front of the Church, but certain valuables and necessities which had been kept ready in case of fire could not be found on account of the confusion which had been wrought. It is high time to flee, since the oncoming flames leave almost no way open. Fukai, the sec-

retary of the Mission, is completely out of his mind. He does not want to leave the house and explains that he does not want to survive the destruction of his fatherland. He is completely uninjured. Father Kleinsorge drags him out of the house on his back and he is forcefully carried away.

Beneath the wreckage of the houses along the way, many have been trapped and they scream to be rescued from the oncoming flames. They must be left to their fate. The way to the place in the city to which one desires to flee is no longer open and one must make for Asano Park. Fukai does not want to go further and remains behind. He has not been heard from since. In the park, we take refuge on the bank of the river. A very violent whirlwind now begins to uproot large trees, and lifts them high into the air. As it reaches the water, a waterspout forms which is approximately 100 meters high. The violence of the storm luckily passes us by. Some distance away, however, where numerous refugees have taken shelter, many are blown into the river. Almost all who are in the vicinity have been injured and have lost relatives who have been pinned under the wreckage or who have been lost sight of during the flight. There is no help for the wounded and some die. No one pays any attention to a dead man lying nearby.

The transportation of our own wounded is difficult. It is not possible to dress their wounds properly in the darkness, and they bleed again upon slight motion. As we carry them on the shaky litters in the dark over fallen trees of the park, they suffer unbearable pain as the result of the movement, and lose dangerously large quantities of blood. Our rescuing angel in this difficult situation is a Japanese Protestant pastor. He has brought up a boat and offers to take our wounded up stream to a place where progress is easier. First, we lower the litter containing Father Schiffer into the boat and two of us accompany him. We plan to bring the boat back for the Father Superior. The boat returns about one-half hour later and the pastor requests that several of us help in the rescue of two children whom he had seen in the river. We rescue them. They have severe burns. Soon they suffer chills and die in the park.

The Father Superior is conveyed in the boat in the same manner as Father Schiffer. The theology student and myself accompany him. Father Cieslik considers himself strong enough to make his way on foot to Nagatsuke with the rest of us, but Father Kleinsorge cannot walk so far and we leave him behind and promise to come for him and the housekeeper tomorrow. From the other side of the stream comes the whinny of horses who are threatened by the fire. We land on a sand spit which juts out from the shore. It is full of wounded who have taken refuge there. They scream for aid for they are afraid of drowning as the river may rise with the sea, and cover the sand spit. They themselves are too weak to move. However, we must press on and and finally we reach the spot where the group containing Father Schiffer is waiting.

Here a rescue party had brought a large case of fresh rice cakes but there is no one to distribute them to the numerous wounded that lie all about. We distribute them to those that are nearby and also help ourselves. The wounded call for water and we come to the aid of a few. Cries for help are heard from a distance, but we cannot approach the ruins from which they come. A group of soldiers comes along the road and their officer notices that we speak a strange language. He at once draws his sword, screamingly demands who we are and threatens to cut us down. Father Laures, Jr., seizes his arm and explains that we are German. We finally quiet him down. He thought that we might well be Americans who had parachuted down. Rumors of parachutists were being bandied about the city. The Father Superior who was clothed only in a shirt and trousers, complains of feeling freezing cold, despite the warm summer night and the heat of the burning city. The one man among us who possesses a coat gives it to him and, in addition, I give him my own shirt. To me, it seems more comfortable to be without a shirt in the heat.

In the meantime, it has become midnight. Since there are not enough of us to man both litters with four strong bearers, we determine to remove Father Schiffer first to the outskirts of the city. From there, another group of bearers is to take over to Nagatsuke; the others are to turn back in order to rescue the Father Superior. I am one of the bearers. The theology student goes in front to warn us of the numerous wires, beams and fragments of ruins which block the way and which are impossible to see in the dark. Despite all

precautions, our progress is stumbling and our feet get tangled in the wire. Father Kruer falls and carries the litter with him. Father Schiffer becomes half unconscious from the fall and vomits. We pass an injured man who sits all alone among the hot ruins and whom I had seen previously on the way down.

On the Misasa Bridge, we meet Father Tappe and Father Luhmer, who have come to meet us from Nagatsuke. They had dug a family out of the ruins of their collapsed house some fifty meters off the road. The father of the family was already dead. They had dragged out two girls and placed them by the side of the road. Their mother was still trapped under some beams. They had planned to complete the rescue and then to press on to meet us. At the outskirts of the city, we put down the litter and leave two men to wait until those who are to come from Nagatsuke appear. The rest of us turn back to fetch the Father Superior.

Most of the ruins have now burned down. The darkness kindly hides the many forms that lie on the ground. Only occasionally in our quick progress do we hear calls for help. One of us remarks that the remarkable burned smell reminds him of incinerated corpses. The upright, squatting form which we had passed by previously is still there.

Transportation on the litter, which has been constructed out of boards, must be very painful to the Father Superior, whose entire back is full of fragments of glass. In a narrow passage at the edge of town, a car forces us to the edge of the road. The litter bearers on the left side fall into a two meter deep ditch which they could not see in the darkness. Father Superior hides his pain with a dry joke, but the litter which is now no longer in one piece cannot be carried further. We decide to wait until Kinjo can bring a hand cart from Nagatsuke. He soon comes back with one that he has requisitioned from a collapsed house. We place Father Superior on the cart and wheel him the rest of the way, avoiding as much as possible the deeper pits in the road.

About half past four in the morning, we finally arrive at the Novitiate. Our rescue expedition had taken almost twelve hours. Normally, one could go back and forth to the city in two hours. Our two wounded were now, for the first time, properly dressed. I get two hours sleep on the floor; some one else has taken my own bed. Then I read a Mass *in gratiarum actionem*, it is the 7th of August, the anniversary of the foundation of our society. Then we bestir ourselves to bring Father Kleinsorge and other acquaintances out of the city.

We take off again with the hand cart. The bright day now reveals the frightful picture which last night's darkness had partly concealed. Where the city stood everything, as far as the eye could reach, is a waste of ashes and ruin. Only several skeletons of buildings completely burned out in the interior remain. The banks of the river are covered with dead and wounded, and the rising waters have here and there covered some of the corpses. On the broad street in the Hakushima district, naked burned cadavers are particularly numerous. Among them are the wounded who are still alive. A few have crawled under the burnt-out autos and trams. Frightfully injured forms beckon to us and then collapse. An old woman and a girl whom she is pulling along with her fall down at our feet. We place them on our cart and wheel them to the hospital at whose entrance a dressing station has been set up. Here the wounded lie on the hard floor, row on row. Only the largest wounds are dressed. We convey another soldier and an old woman to the place but we cannot move everybody who lies exposed in the sun. It would be endless and it is questionable whether those whom we can drag to the dressing station can come out alive, because even here nothing really effective can be done. Later, we ascertain that the wounded lay for days in the burnt-out hallways of the hospital and there they died.

We must proceed to our goal in the park and are forced to leave the wounded to their fate. We make our way to the place where our church stood to dig up those few belongings that we had buried yesterday. We find them intact. Everything else has been completely burned. In the ruins, we find a few molten remnants of holy vessels. At the park, we load the housekeeper and a mother with her two children on the cart. Father Kleinsorge feels strong enough, with the aid of Brother Nobuhara, to make his way home on foot. The way back takes us once again past the dead and wounded in Hakushima. Again no rescue parties are in evidence. At the Misasa Bridge, there still lies the family which the Fathers Tappe and Luhmer had yesterday rescued from the ruins. A piece of tin had been placed over them to shield them from the sun. We cannot take them along for our cart is full. We give

them and those nearby water to drink and decide to rescue them later. At three o'clock in the afternoon, we are back in Nagatsuka.

After we have had a few swallows and a little food, Fathers Stolte, Luhmer, Erlinghagen and myself, take off once again to bring in the family. Father Kleinsorge requests that we also rescue two children who had lost their mother and who had lain near him in the park. On the way, we were greeted by strangers who had noted that we were on a mission of mercy and who praised our efforts. We now met groups of individuals who were carrying the wounded about on litters. As we arrived at the Misasa Bridge, the family that had been there was gone. They might well have been borne away in the meantime. There was a group of soldiers at work taking away those that had been sacrificed yesterday.

More than thirty hours had gone by until the first official rescue party had appeared on the scene. We find both children and take them out of the park: a six-year old boy who was uninjured, and a twelve-year old girl who had been burned about the head, hands and legs, and who had lain for thirty hours without care in the park. The left side of her face and the left eye were completely covered with blood and pus, so that we thought that she had lost the eye. When the wound was later washed, we noted that the eye was intact and that the lids had just become stuck together. On the way home, we took another group of three refugees with us. They first wanted to know, however, of what nationality we were. They, too, feared that we might be Americans who had parachuted in. When we arrived in Nagatsuka, it had just become dark.

We took under our care fifty refugees who had lost everything. The majority of them were wounded and not a few had dangerous burns. Father Rektor treated the wounds as well as he could with the few medicaments that we could, with effort, gather up. He had to confine himself in general to cleansing the wounds of purulent material. Even those with the smaller burns are very weak and all suffered from diarrhea. In the farm houses in the vicinity, almost everywhere, there are also wounded. Father Rektor made daily rounds and acted in the capacity of a painstaking physician and was a great Samaritan. Our work was, in the eyes of the people, a greater boost for Christianity than all our work during the preceding long years.

Three of the severely burned in our house died within the next few days. Suddenly the pulse and respirations ceased. It is certainly a sign of our good care that so few died. In the official aid stations and hospitals, a good third or half of those that had been brought in died. They lay about there almost without care, and a very high percentage succumbed. Everything was lacking: doctors, assistants, dressings, drugs, etc. In an aid station at a school at a nearby village, a group of soldiers for several days did nothing except to bring in and cremate the dead behind the school.

During the next few days, funeral processions passed our house from morning to night, bringing the deceased to a small valley nearby. There, in six places, the dead were burned. People brought their own wood and themselves did the cremation. Father Luhmer and Father Laures found a dead man in a nearby house who had already become bloated and who emitted a frightful odor. They brought him to this valley and incinerated him themselves. Even late at night, the little valley was lit up by the funeral pyres.

We made systematic efforts to trace our acquaintances and the families of the refugees whom we had sheltered. Frequently, after the passage of several weeks, some one was found in a distant village or hospital but of many there was no news, and these were apparently dead. We were lucky to discover the mother of the two children whom we had found in the park and who had been given up for dead. After three weeks, she saw her children once again. In the great joy of the reunion were mingled the tears for those whom we shall not see again.

The magnitude of the disaster that befell Hiroshima on August 6th was only slowly pieced together in my mind. I lived through the catastrophe and saw it only in flashes, which only gradually were merged to give me a total picture. What actually happened simultaneously in the city as a whole is as follows: As a result of the explosion of the bomb at 8:15, almost the entire city was destroyed at a single blow. Only small outlying districts in the southern and eastern parts of the town escaped complete destruction. The bomb exploded over the center of the city. As a result of the blast, the small Japanese houses in a diameter of five kilometers, which compressed 99% of the city, collapsed or were blown up. Those who were in the houses were buried in the ruins. Those who were in the open sustained

burns resulting from contact with the substance or rays emitted by the bomb. Where the substance struck in quantity, fires sprang up. These spread rapidly.

The heat which rose from the center created a whirlwind which was effective in spreading fire throughout the whole city. Those who had been caught beneath the ruins and who could not be freed rapidly, and those who had been caught by the flames, became casualties. As much as six kilometers from the center of the explosion, all houses were damaged and many collapsed and caught fire. Even fifteen kilometers away, windows were broken. It was rumored that the enemy fliers had spread an explosive and incendiary material over the city and then had created the explosion and ignition. A few maintained that they saw the planes drop a parachute which had carried something that exploded at a height of 1,000 meters. The newspapers called the bomb an "atomic bomb" and noted that the force of the blast had resulted from the explosion of uranium atoms, and that gamma rays had been sent out as a result of this, but no one knew anything for certain concerning the nature of the bomb.

How many people were a sacrifice to this bomb? Those who had lived through the catastrophe placed the number of dead at at least 100,000. Hiroshima had a population of 400,000. Official statistics place the number who had died at 70,000 up to September 1st, not counting the missing ... and 130,000 wounded, among them 43,500 severely wounded. Estimates made by ourselves on the basis of groups known to us show that the number of 100,000 dead is not too high. Near us there are two barracks, in each of which forty Korean workers lived. On the day of the explosion, they were laboring on the streets of Hiroshima. Four returned alive to one barracks and sixteen to the other. 600 students of the Protestant girls' school worked in a factory, from which only thirty to forty returned. Most of the peasant families in the neighborhood lost one or more of their members who had worked at factories in the city. Our next door neighbor, Tamura, lost two children and himself suffered a large wound since, as it happened, he had been in the city on that day. The family of our reader suffered two dead, father and son; thus a family of five members suffered at least two losses, counting only the dead and severely wounded. There died the Mayor, the President of the central Japan district, the Commander of the city, a Korean prince who had been stationed in Hiroshima in the capacity of an officer, and many other high ranking officers. Of the professors of the University, thirty-two were killed or severely injured. Especially hard hit were the soldiers. The Pioneer Regiment was almost entirely wiped out. The barracks were near the center of the explosion.

Thousands of wounded who died later could doubtless have been rescued had they received proper treatment and care, but rescue work in a catastrophe of this magnitude had not been envisioned; since the whole city had been knocked out at a blow, everything which had been prepared for emergency work was lost, and no preparation had been made for rescue work in the outlying districts. Many of the wounded also died because they had been weakened by under-nourishment and consequently lacked in strength to recover. Those who had their normal strength and who received good care slowly healed the burns which had been occasioned by the bomb. There were also cases, however, whose prognosis seemed good who died suddenly. There were also some who had only small external wounds who died within a week or later, after an inflammation of the pharynx and oral cavity had taken place. We thought at first that this was the result of inhalation of the substance of the bomb. Later, a commission established the thesis that gamma rays had been given out at the time of the explosion, following which the internal organs had been injured in a manner resembling that consequent upon Roentgen irradiation. This produces a diminution in the numbers of the white corpuscles.

Only several cases are known to me personally where individuals who did not have external burns later died. Father Kleinsorge and Father Cieslik, who were near the center of the explosion, but who did not suffer burns became quite weak some fourteen days after the explosion. Up to this time small incised wounds had healed normally, but thereafter the wounds which were still unhealed became worse and are to date (in September) still incompletely healed. The attending physician diagnosed it as leucopania. There thus seems to be some truth in the statement that the radiation had some effect on the blood. I am of the opinion, however, that their generally undernourished and weakened condition was partly responsible for these findings. It was noised about that

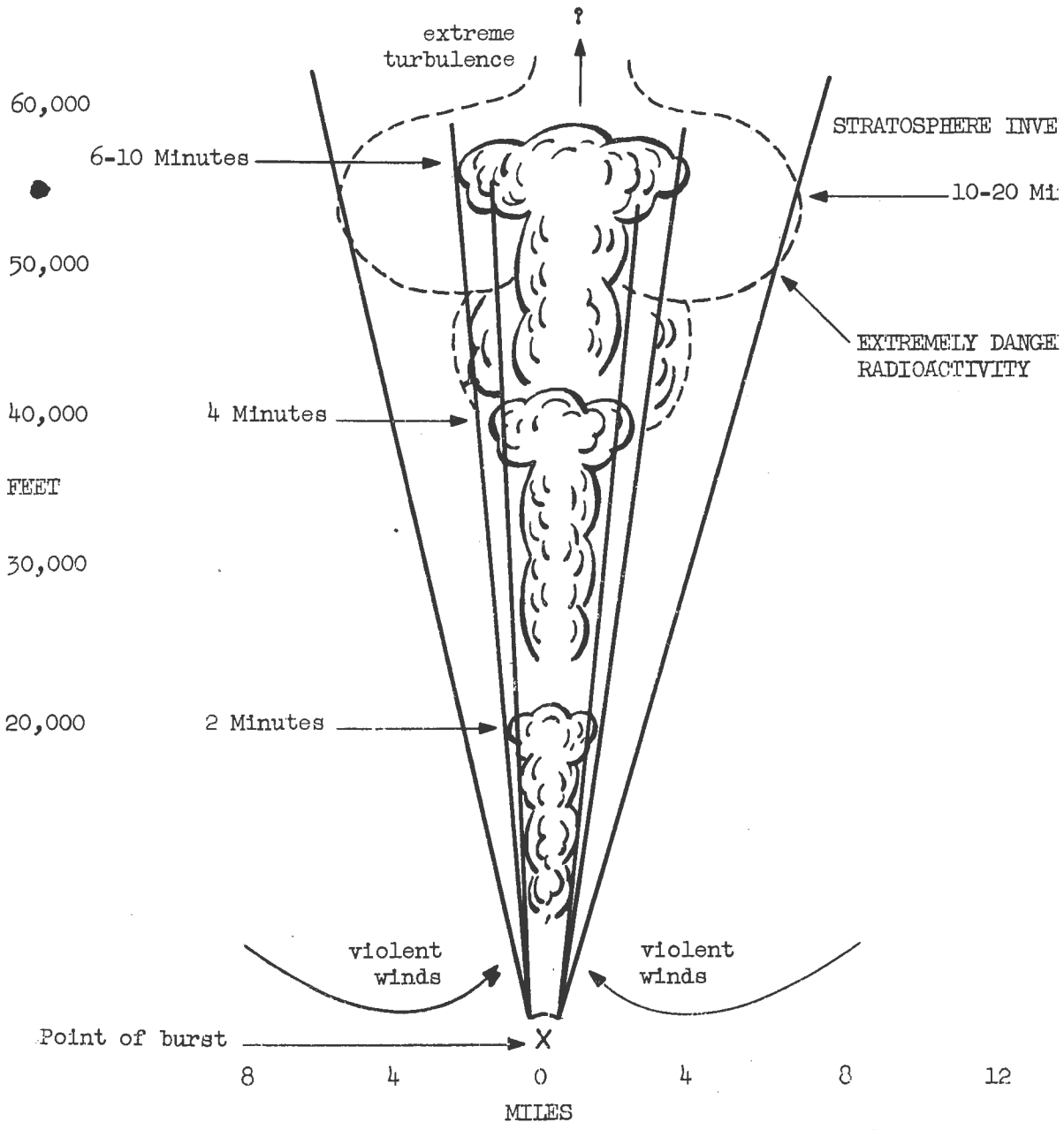
the ruins of the city emitted deadly rays and that workers who went there to aid in the clearing died, and that the central district would be uninhabitable for some time to come. I have my doubts as to whether such talk is true and myself and others who worked in the ruined area for some hours shortly after the explosion suffered no such ill effects.

None of us in those days heard a single outburst against the Americans on the part of the Japanese, nor was there any evidence of a vengeful spirit. The Japanese suffered this terrible blow as part of the fortunes of war ... something to be borne without complaint. During this war, I have noted relatively little hatred toward the allies on the part of the people themselves, although the press has taken occasion to stir up such feelings. After the victories at the beginning of the war, the enemy was rather looked down upon, but when allied offensive gathered momentum and especially after the advent of the majestic B-29's, the technical skill of America became an object of wonder and admiration.

The following anecdote indicates the spirit of the Japanese: A few days after the atomic bombing, the secretary of the University came to us asserting that the Japanese were ready to destroy San Francisco by means of an equally effective bomb. It is dubious that he himself believed what he told us. He merely wanted to impress upon us foreigners that the Japanese were capable of similar discoveries. In his nationalistic pride, he talked himself into believing this. The Japanese also intimated that the principle of the new bomb was a Japanese discovery. It was only lack of raw materials, they said, which prevented its construction. In the meantime, the Germans were said to have carried the discovery to a further stage and were about to initiate such bombing. The Americans were reputed to have learned the secret from the Germans, and they had then brought the bomb to a stage of industrial completion.

* * *

We have discussed among ourselves the ethics of the use of the bomb. Some consider it in the same category as poison gas and were against its use on a civil population. Others were of the view that in total war, as carried on in Japan, there was no difference between civilians and soldiers, and that the bomb itself was an effective force tending to end the bloodshed, warning Japan to surrender and thus to avoid total destruction. It seems logical to me that he who supports total war in principle cannot complain of war against civilians. The crux of the matter is whether total war in its present form is justifiable, even when it serves a just purpose. Does it not have material and spiritual evil as its consequences which far exceed whatever good that might result? When will our moralists give us a clear answer to this question?

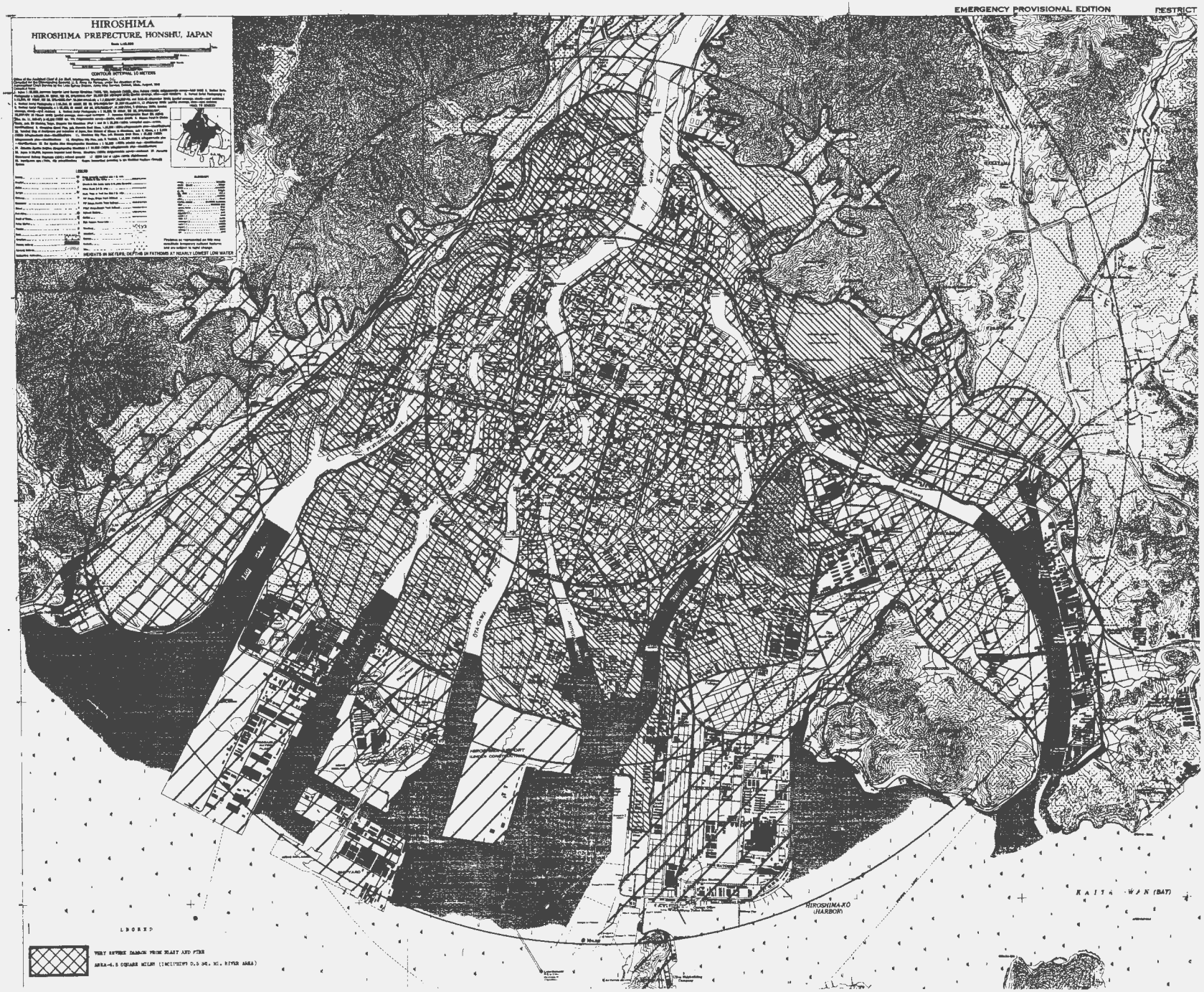


PROBABLE POSITION OF RISING CLOUD
AT INTERVALS AFTER EXPLOSION

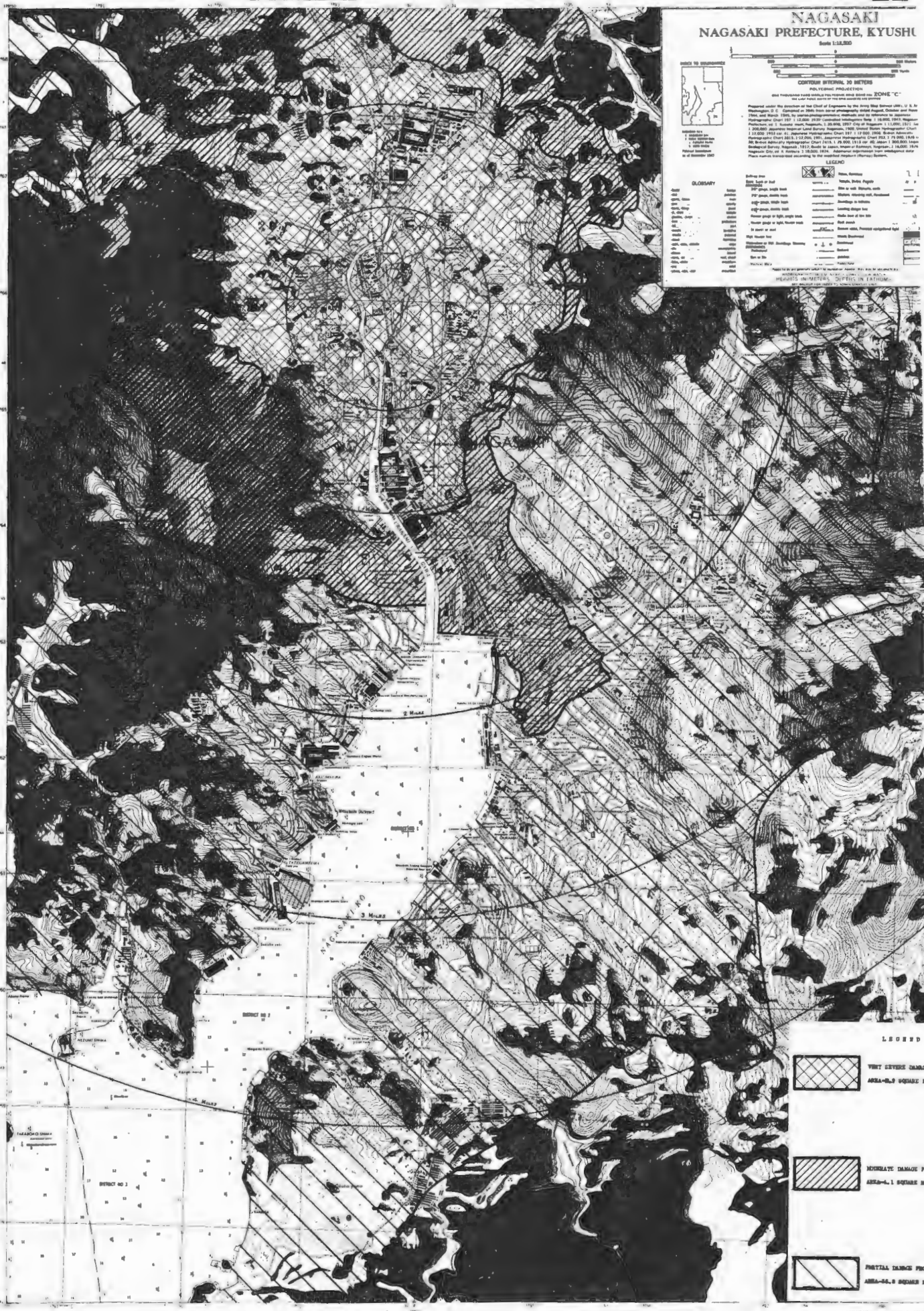
Figure 1

Probable position of rising cloud

at intervals after explosion


HIROSHIMA
HIROSHIMA PREFECTURE, HONSHU, JAPAN
CONTOUR INTERVAL 10 METERS
HEIGHTS IN METERS, DEPTHS IN FATHOMS AT NEARLY LOWEST LOW WATER
LEGEND
VERY SEVERE DAMAGE FROM BLAST AND FIRE
AREA-4.5 SQUARE MILES (INCLUDING 0.5 SQ. MI. RIVER AREA)
HIROSHIMA-KO (HARBOR)
KAITA WAN (BAY)

NAGASAKI



PHOTOGRAPHS

OF THE

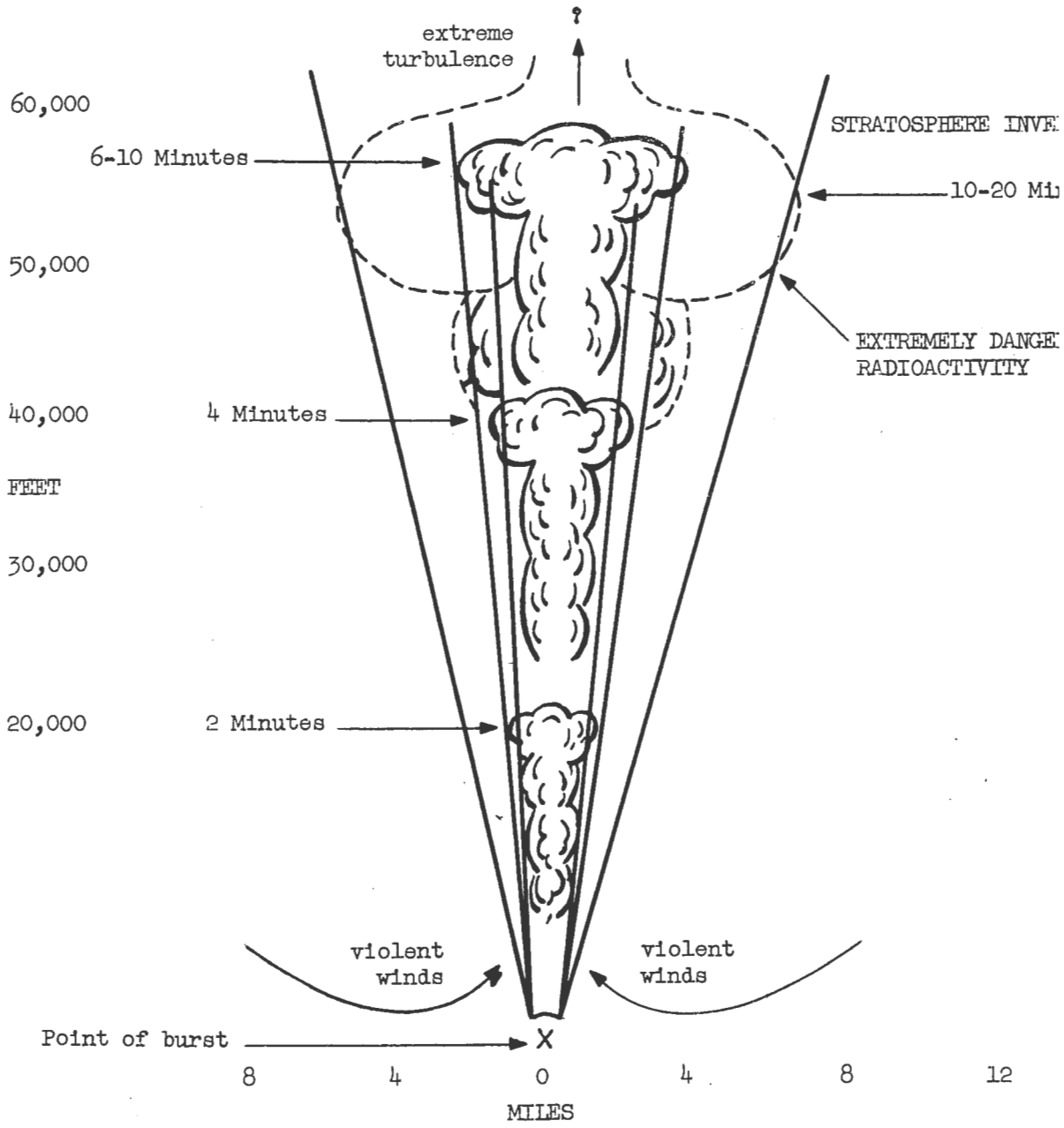
ATOMIC BOMBINGS

OF

HIROSHIMA AND NAGASAKI

by

The Manhattan Engineer District

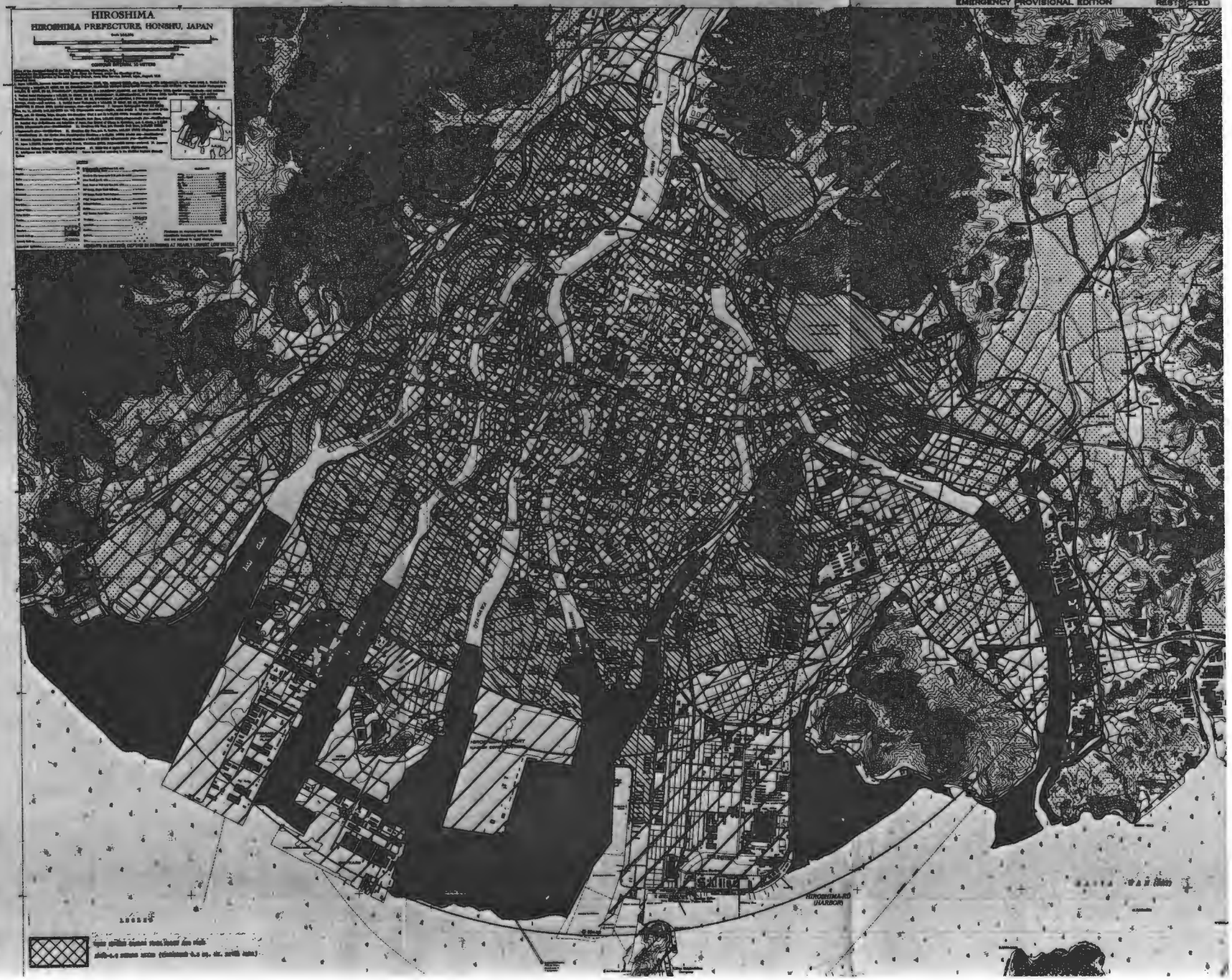


PROBABLE POSITION OF RISING CLOUD
AT INTERVALS AFTER EXPLOSION

Figure 1

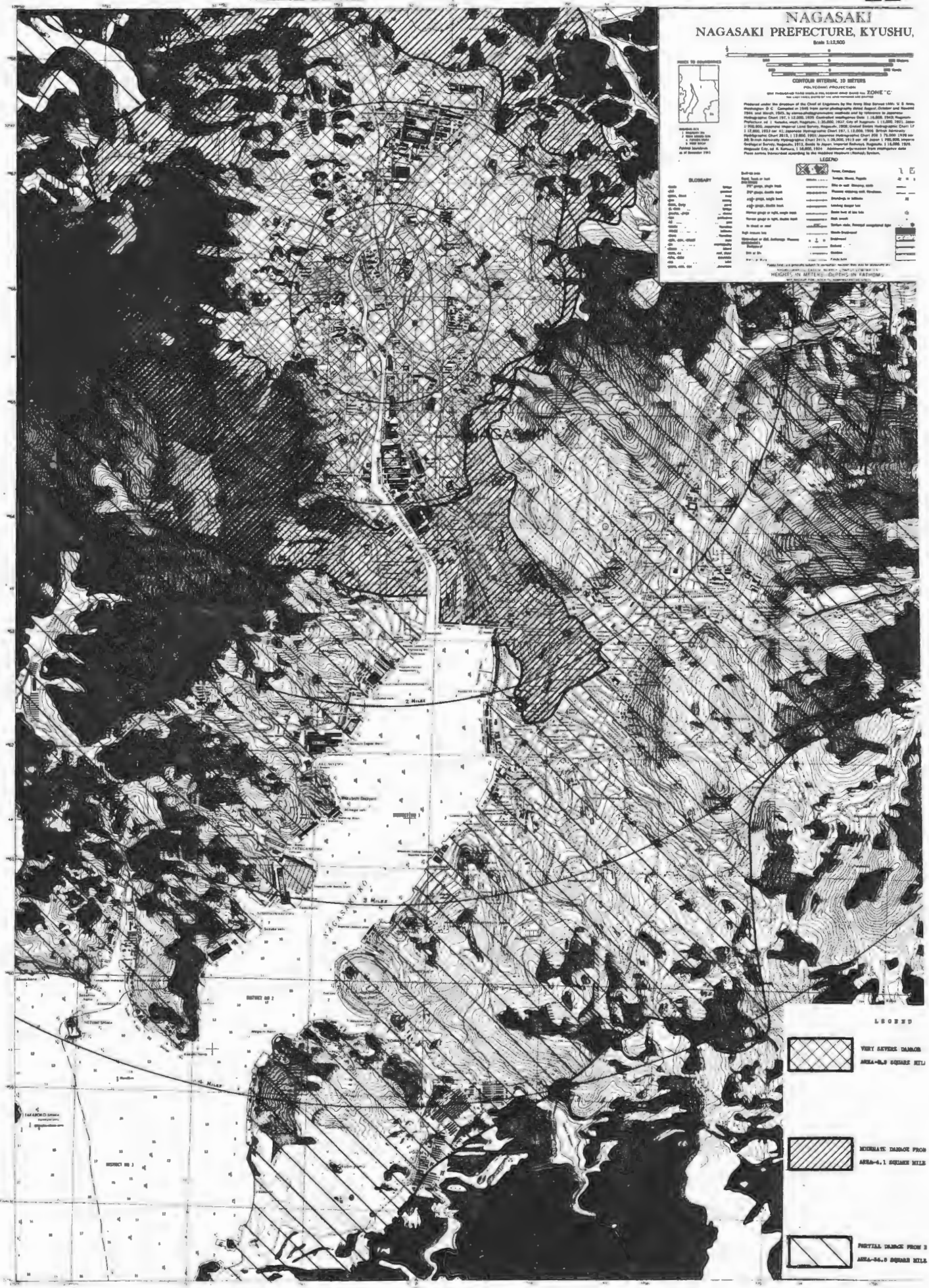
Probable position of rising cloud

at intervals after explosion


HIROSHIMA
HIROSHIMA PREFECTURE, HONSHU, JAPAN
EMERGENCY PROVISIONAL EDITION
RESTRICTED
HIROSHIMA-KO (HARBOR)

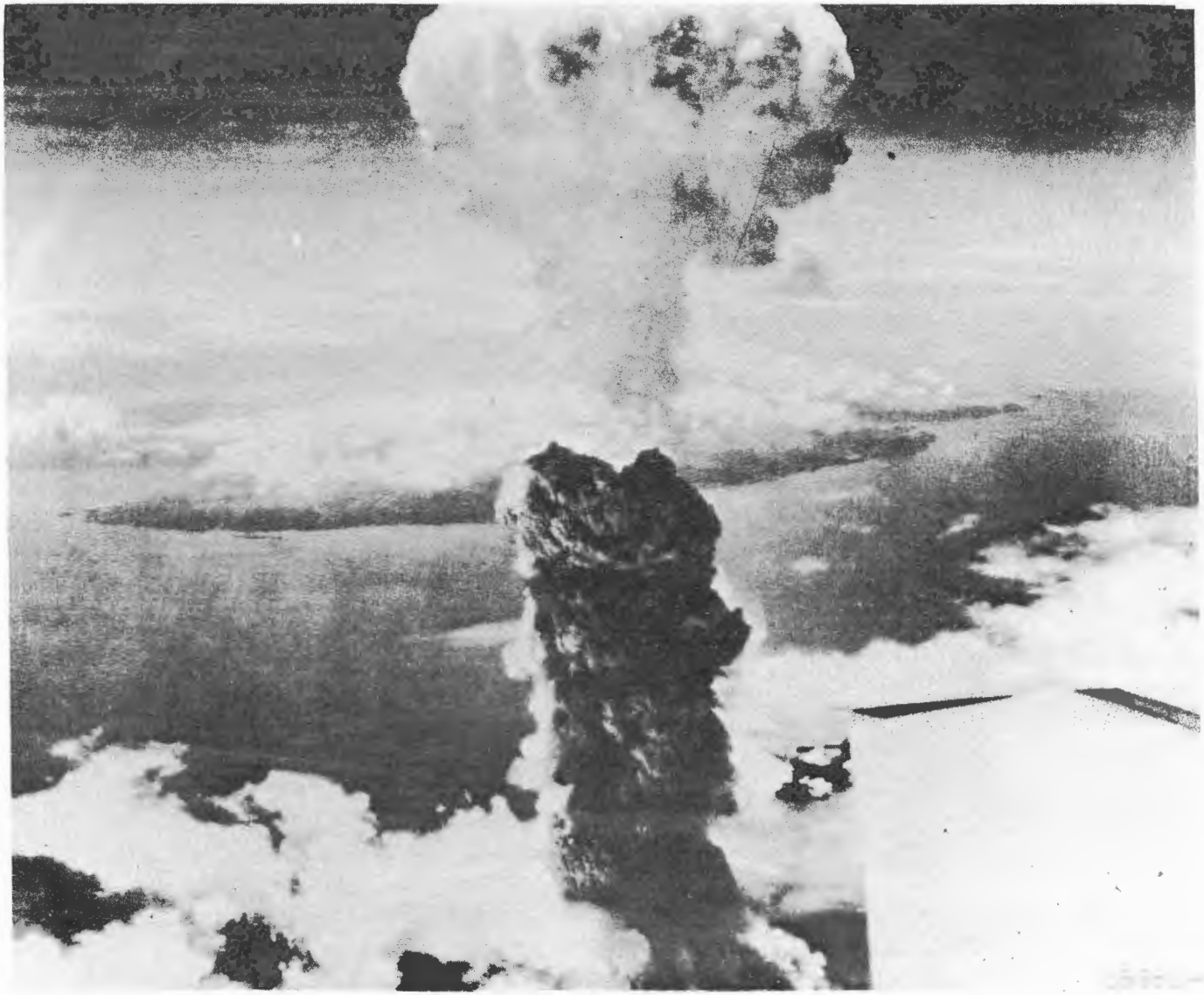
TYPE CLASS I

NAGASAKI



A.M.S. L502
Type C (AMS 1), 1945


2.6 Miles
3.3 Miles



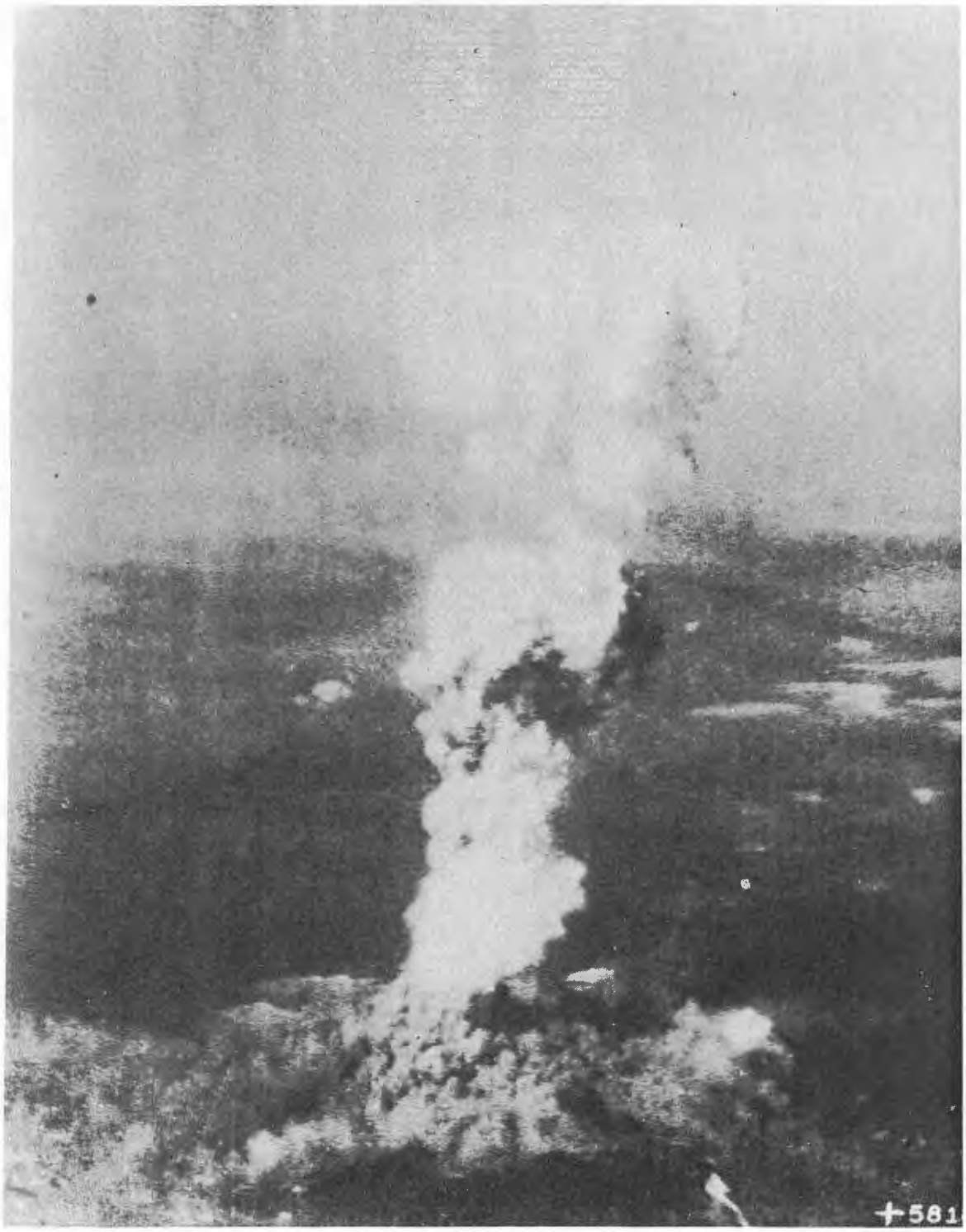


Figure 6

The Atomic Bomb Explosion over Hiroshima.


'O' Point

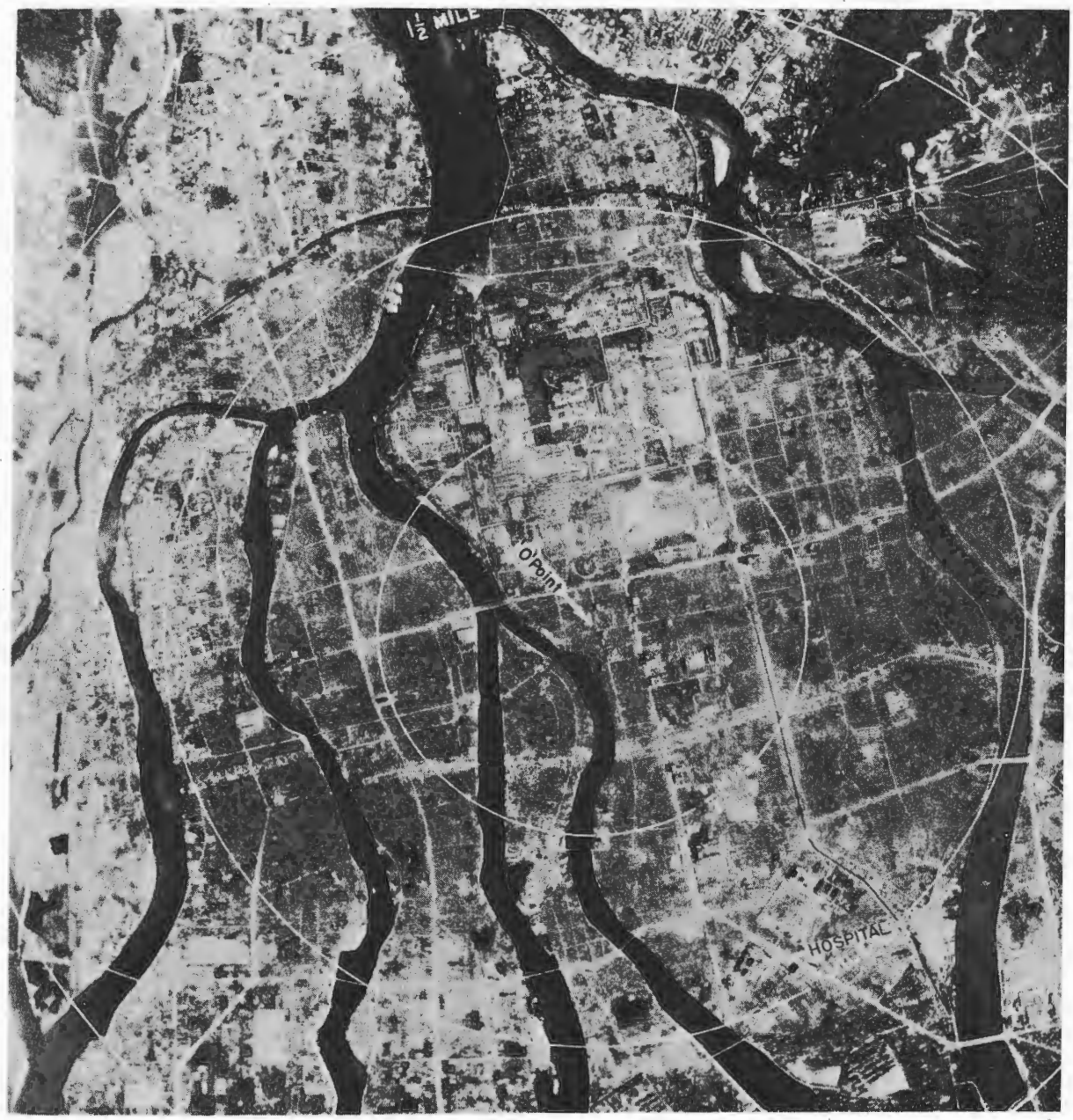


Figure 8

Aerial View of Hiroshima after the Bomb.

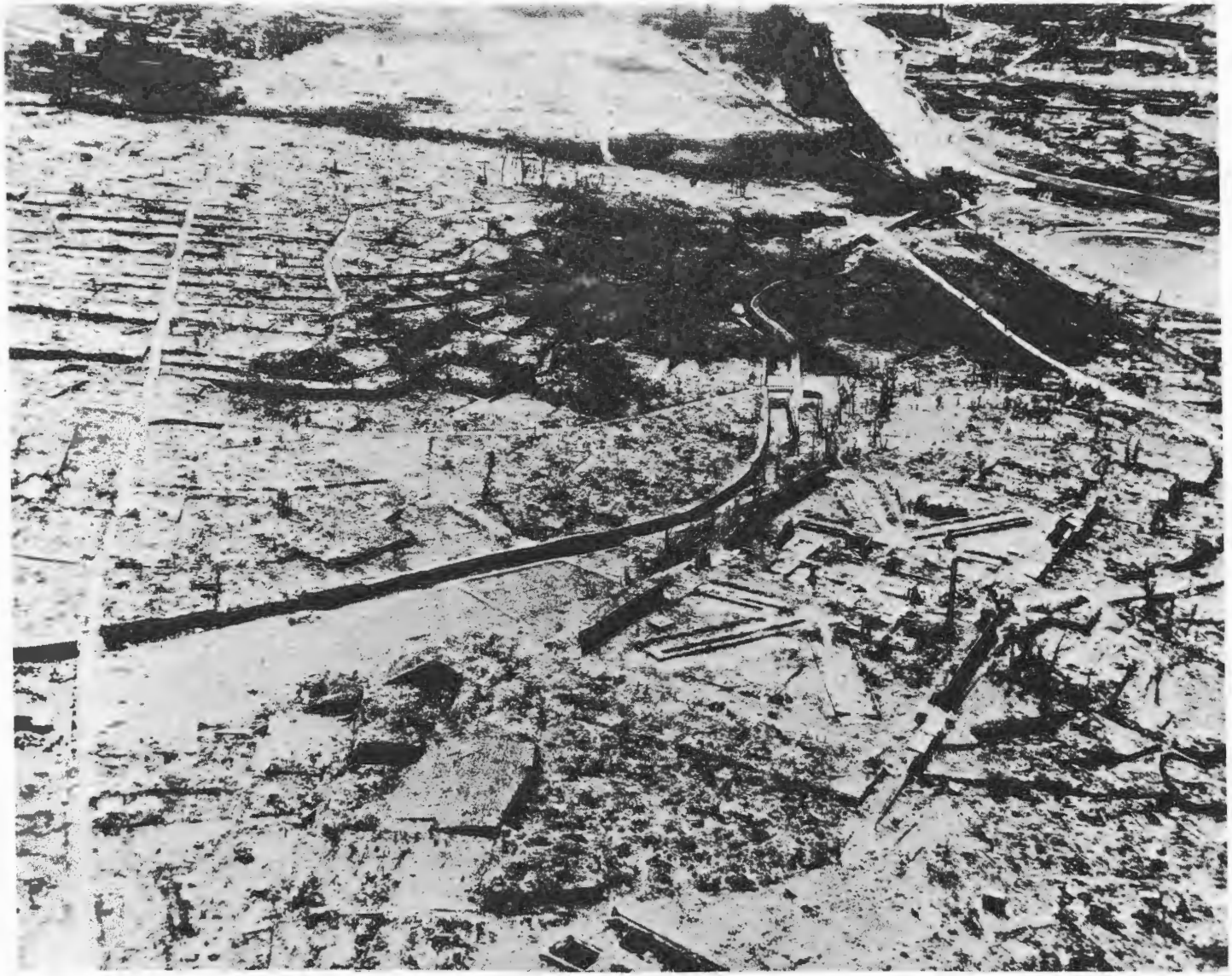


Figure 9

Panoramic view of Nagasaki after the bomb

5

Figure 11

General view of Nagasaki taken from about four miles southeast of X. The chimneys in the background are lo-

Figure 14

Pre-strike aerial view of Nagasaki. X is just northeast of the stadium which is visible in the upper right portion of the photograph. The main targets were the Mitsubishi-

Figure 15

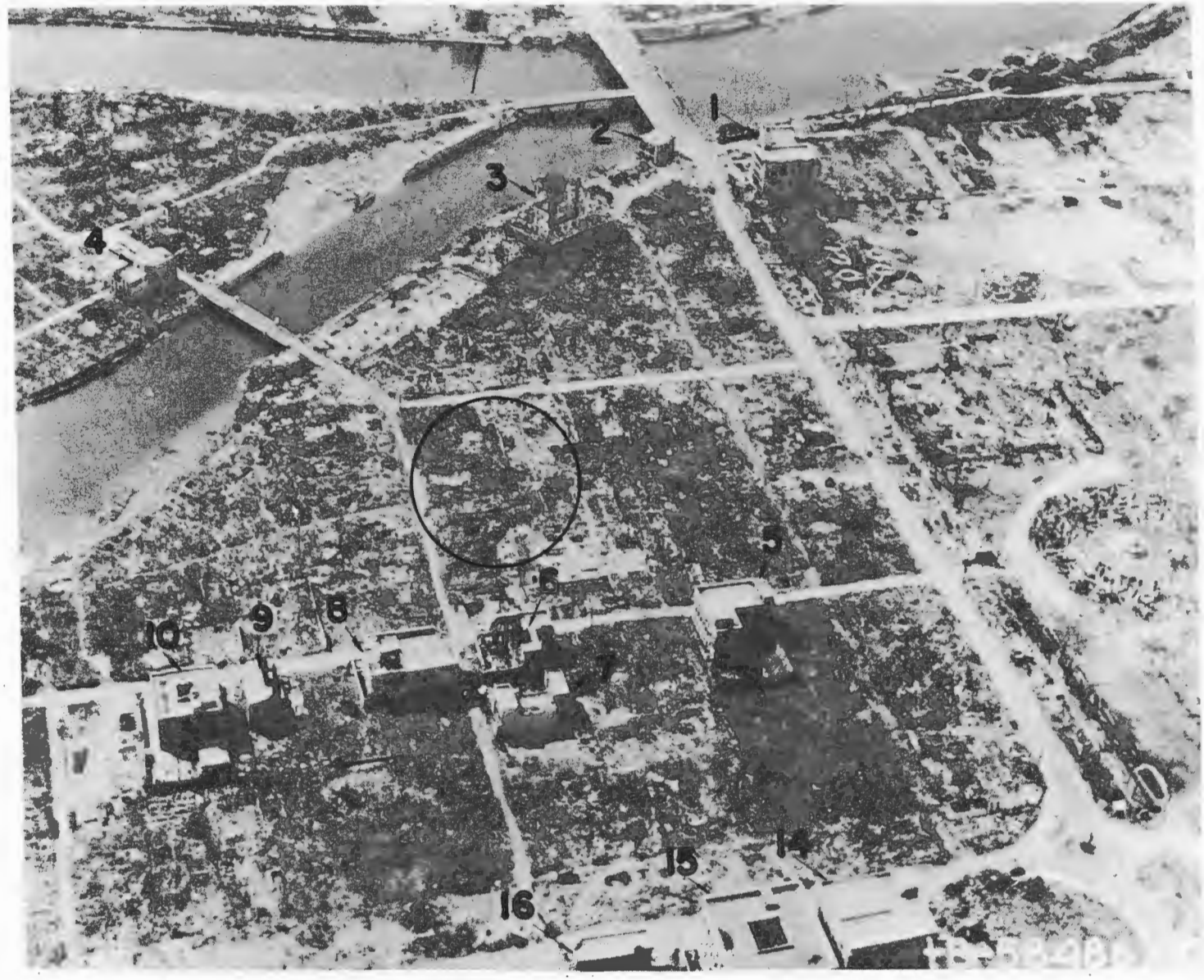
Figure 16

General panoramic view taken from the Nagasaki Medical School and Hospital, looking southeast. In the foreground, at the foot of the hill on which the Medical School is located, the double-track street railway loop to the hospital buildings will be noticed. There was practically no damage to the tracks themselves, but the trolley wires were knocked down and the tracks covered with debris. The whole area shown in this picture was covered with industrial buildings and small residences almost as close together as it was possible to build them. In the background, the skeleton remains of the Mitsubishi Steel and Arms Works can be seen. Note that the reinforced concrete

Figure 17

Figure 18

Figure 19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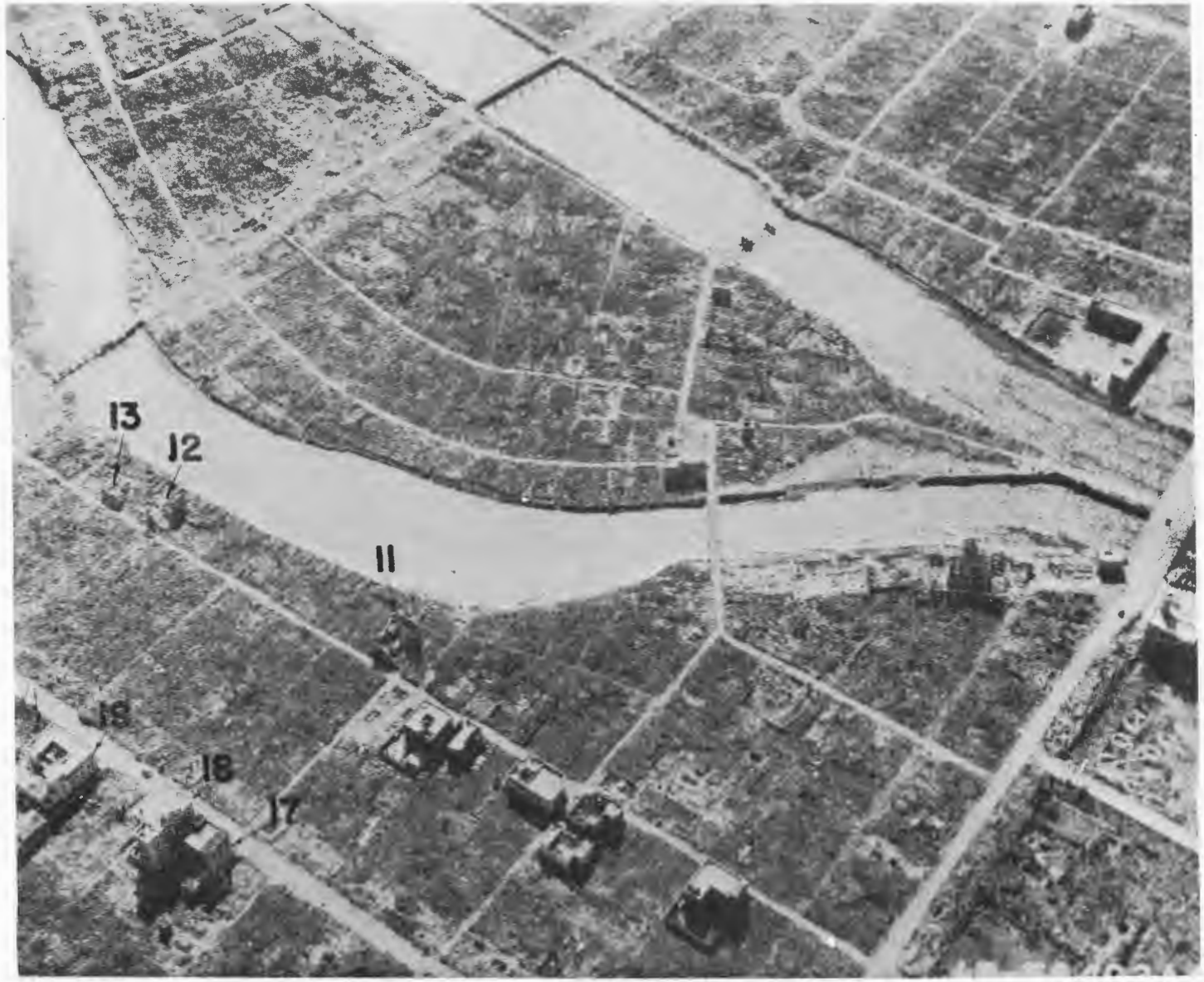

13
12
11
18
18
17


5
14
15
6
H-38


H-39

Figure 24


11
12

Figure 26

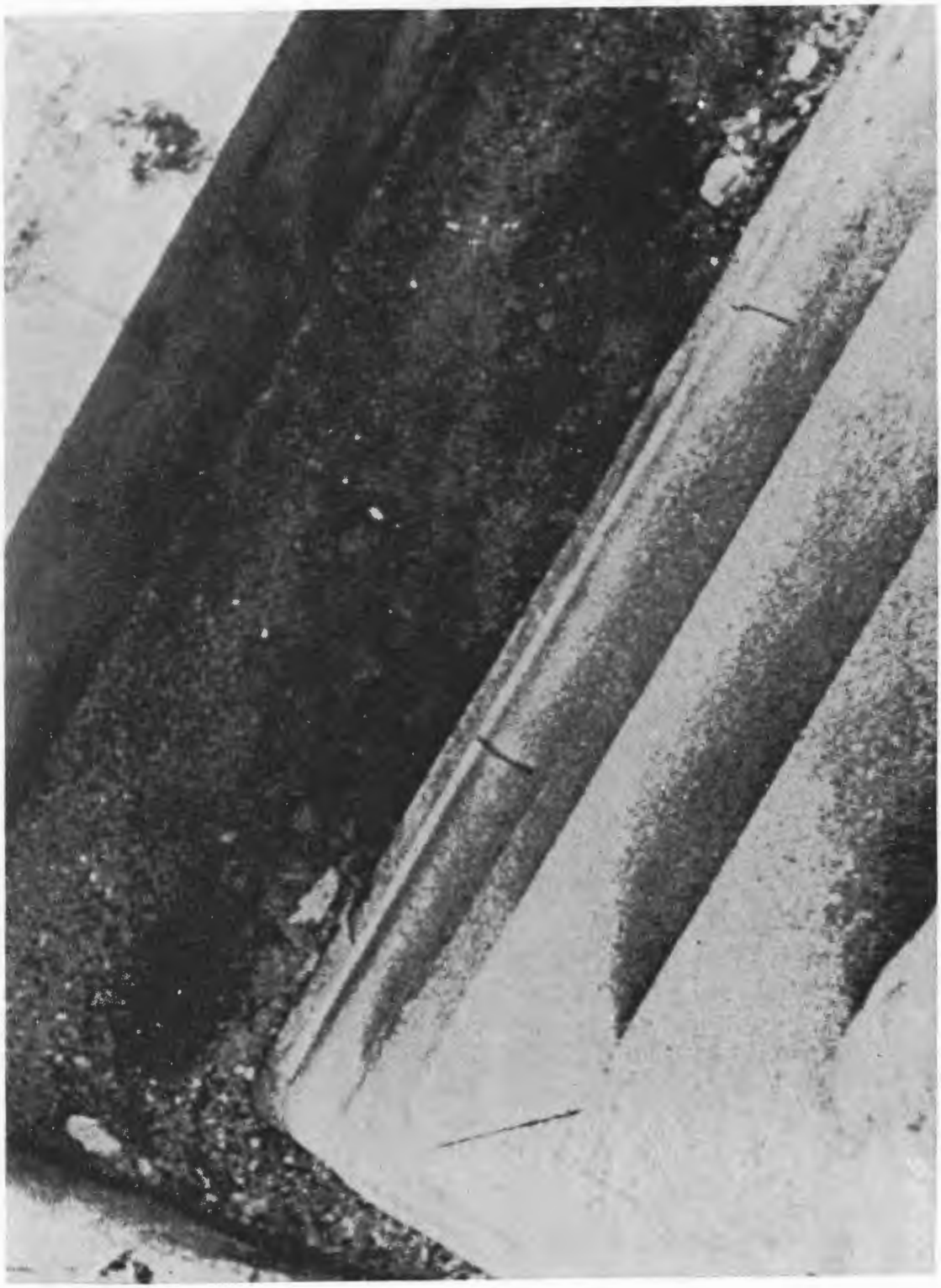
Figure 27

Typical reinforced concrete building 1000 feet northwest of X. The concrete roof slab was supported by concrete beams with no interior columns. The interior beams failed, causing the roof slab to settle as

Figure 28

Bridge, 1000 feet northwest of X in Hiroshima. The blast pressure at this point had a considerable

Figure 30



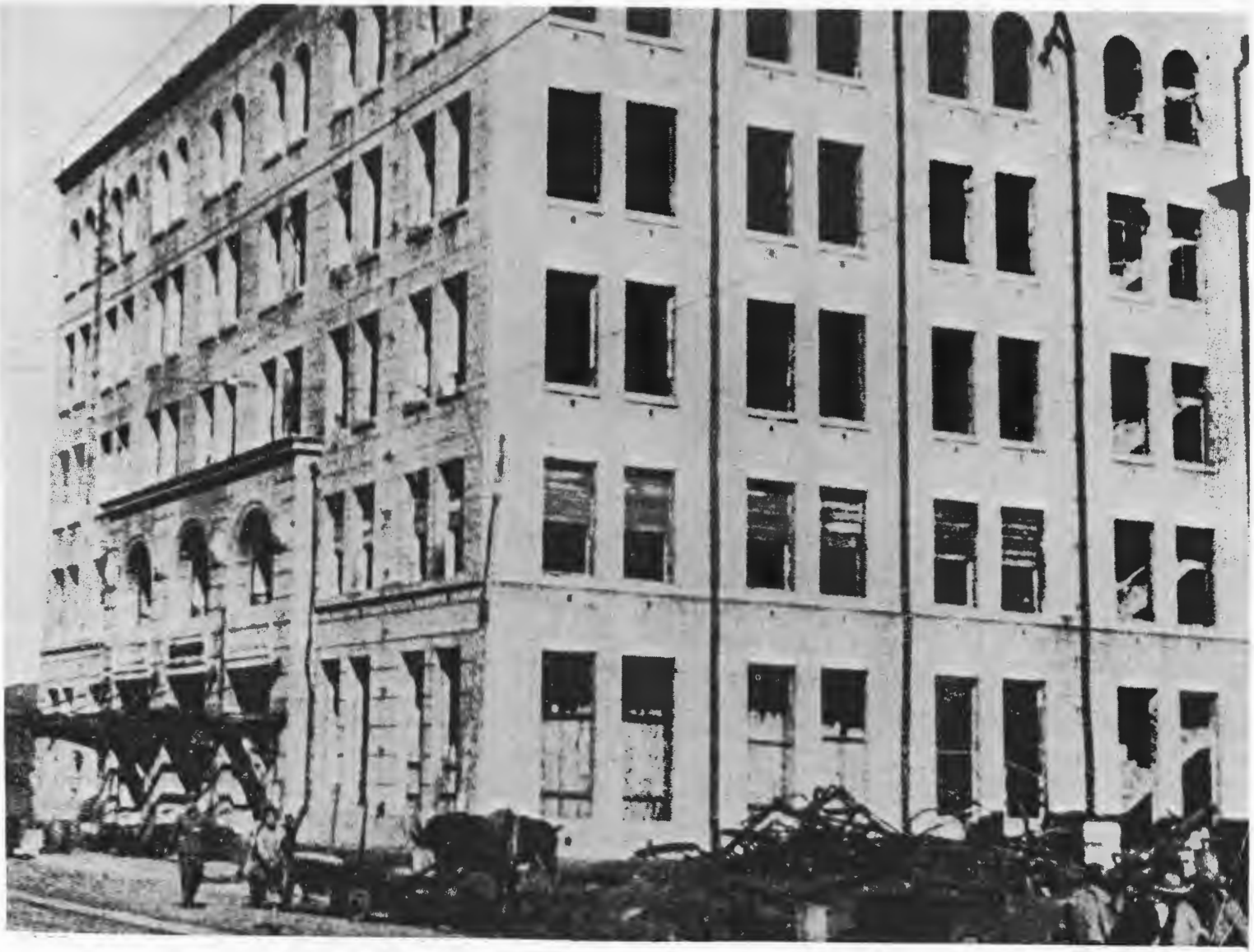


Figure 32


H-35

Figure 24

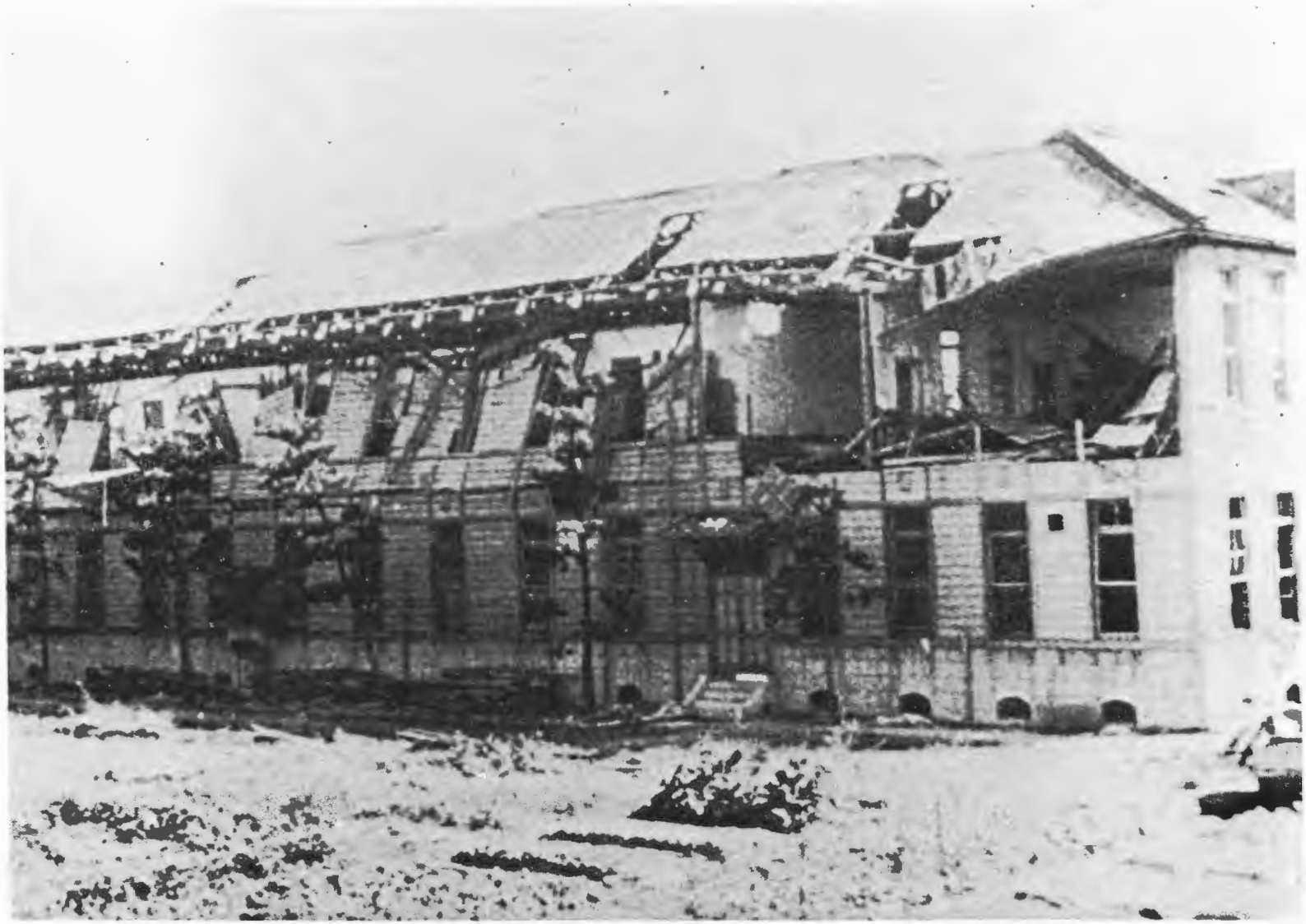
Figure 35

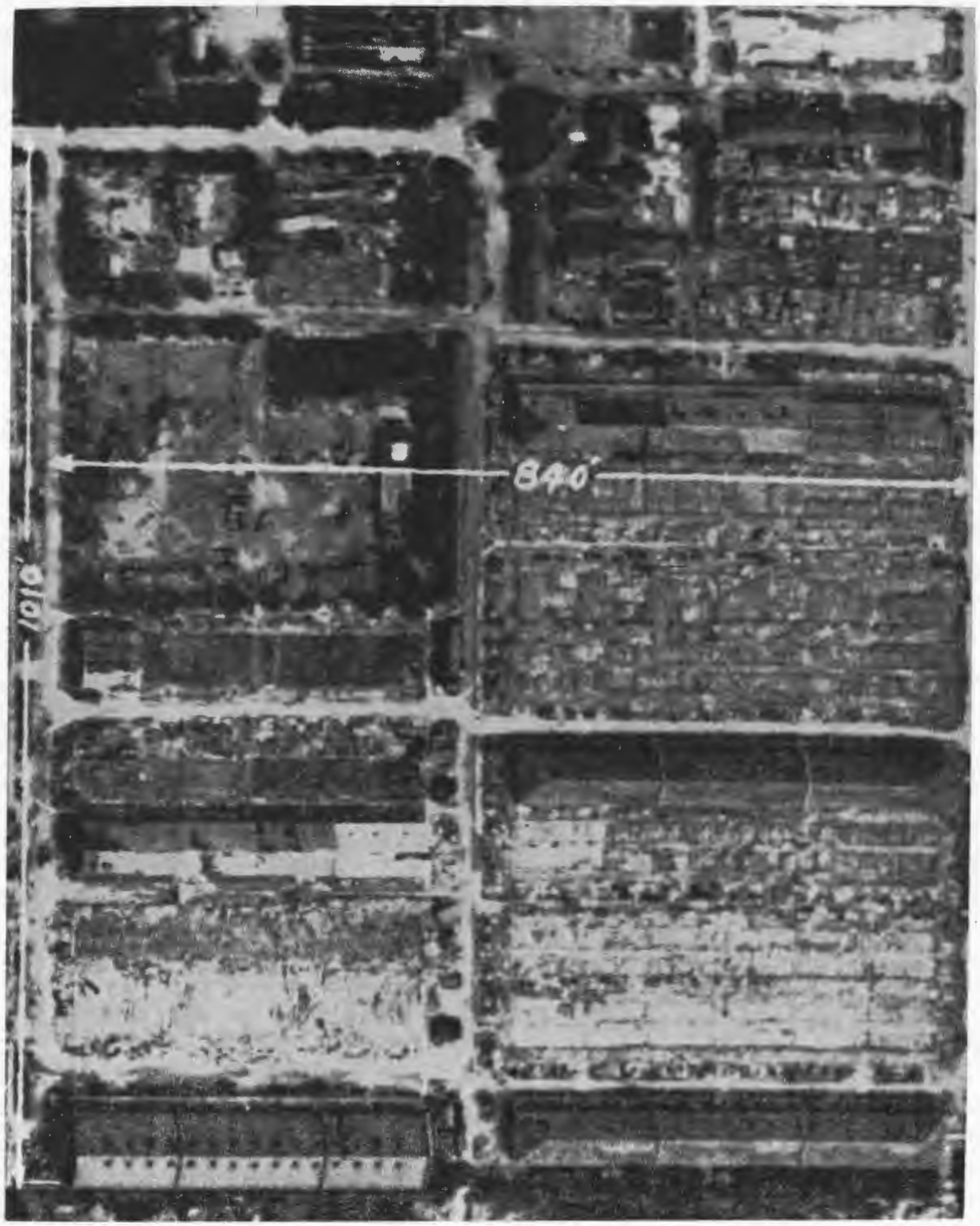
Looking east from the Red Cross Hospital, 0.9 mile south of X. The reinforced concrete Communications Bureau building in the right foreground is one mile from X. Damages to the building were not extensive and were similar to those at the Red Cross Hospital. The two standing walls in the center background are parallel to the direction

Figure 36

University of Hiroshima, 0.8 to 0.9 mile south of X, looking northeast from the Red Cross Hospital. The buildings shown were of reinforced concrete construction and were not severely damaged structurally. Other buildings in this group were of wooden construction and were destroyed by blast

Figure 38




840'
1010'

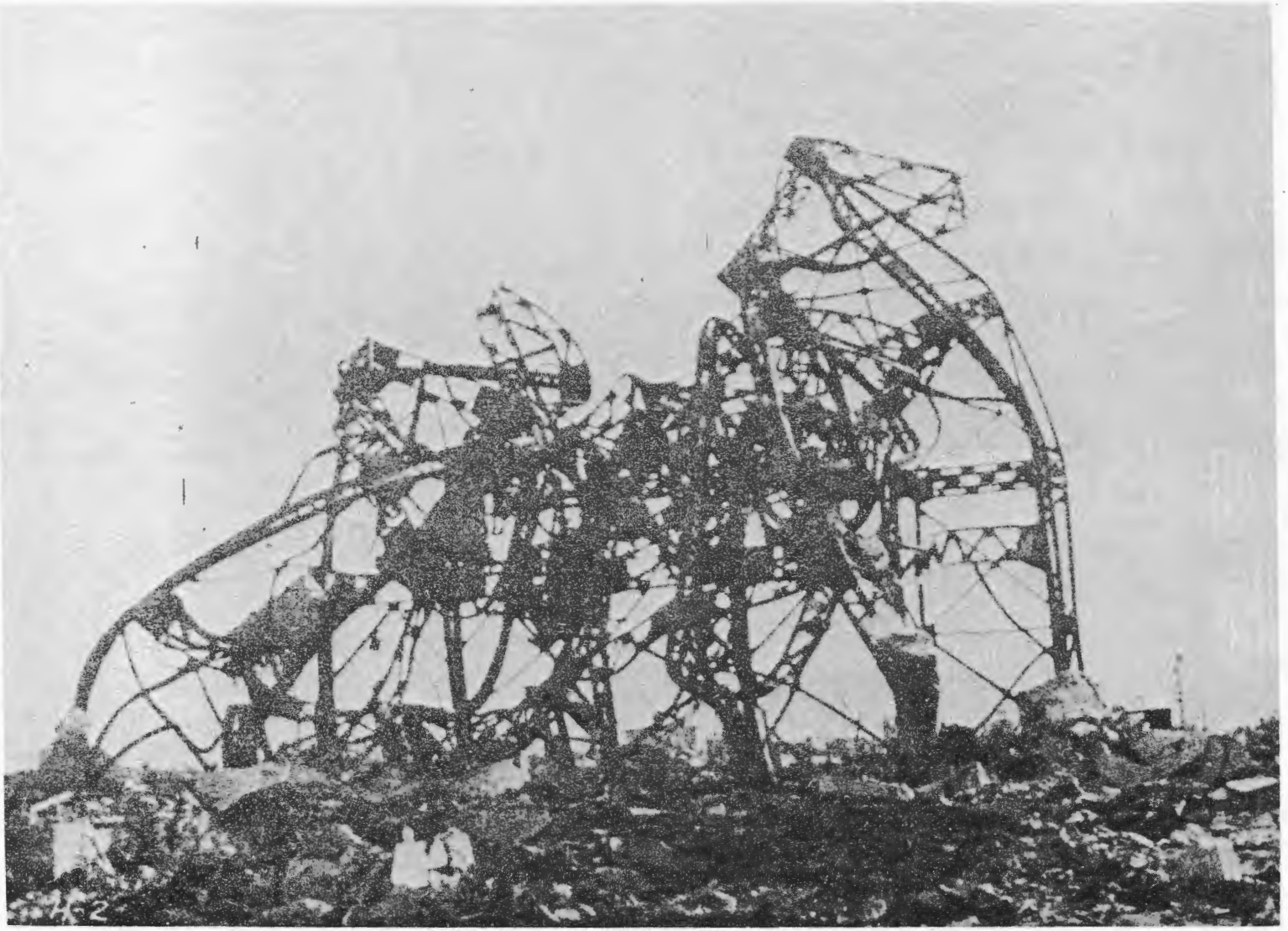


Figure 43

Figure 44

Aerial view of Nagasaki, after the bombing, showing the two principal targets.

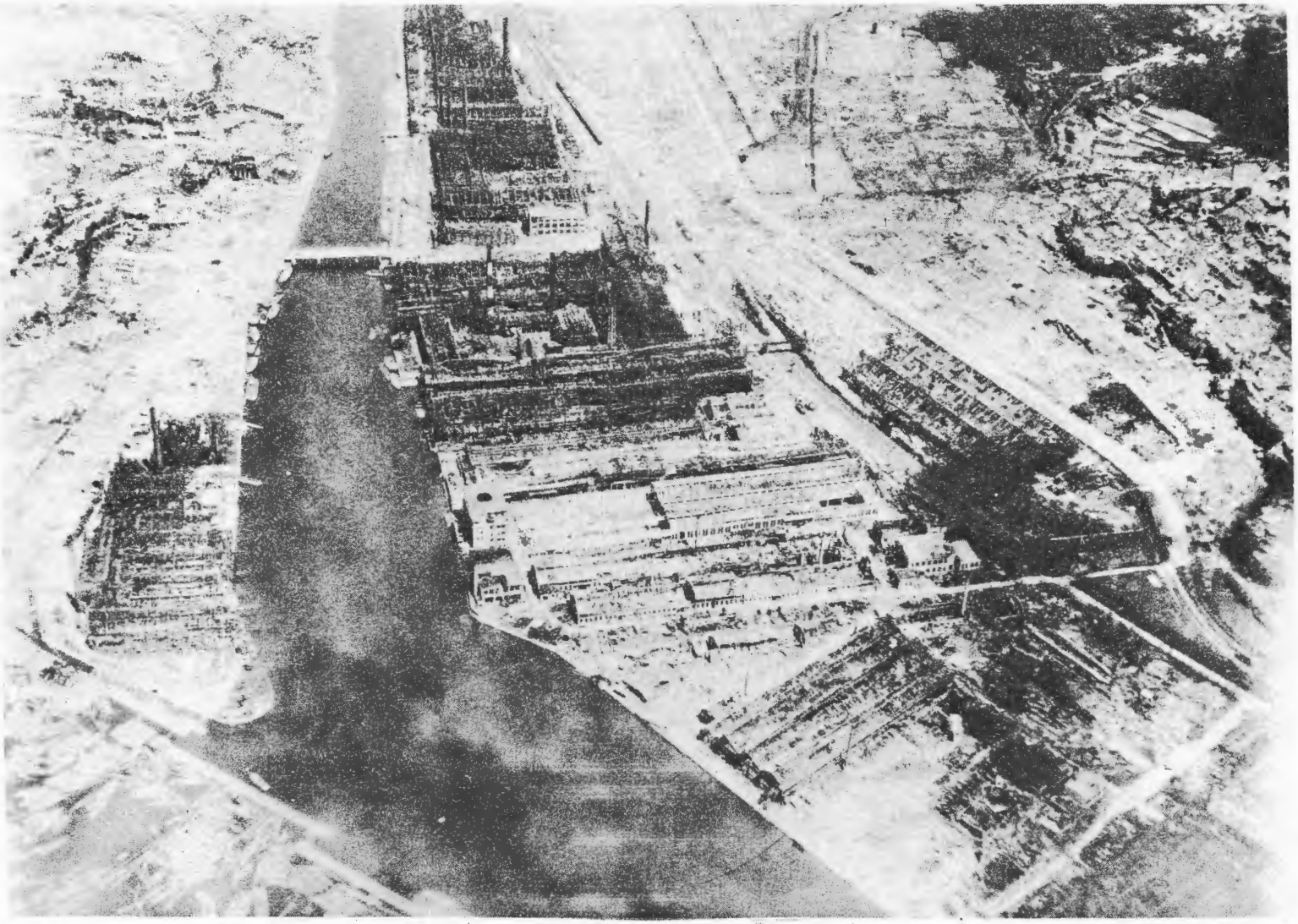


Figure 45

Aerial view of the Mitsubishi Steel and Arms Works in Nagasaki, from 0.3 to 1.2 miles south of X. This view looking north toward X shows that the middle three-fourths of the above plant with the

Figure 46

Panorama of Nagasaki. This aerial view shows the devastation north of X and west of the Urakami River. All of the heavily built-up areas were completely destroyed, and dwellings were ...

Figure 48

Panorama showing the general destruction in the industrial valley of Nagasaki, looking west from

Figure 51

The Nagasaki Medical School and Hospital, from 0.4 to 0.55 mile southeast of X. This view

Figure 52

Nagasaki Medical School and Hospital, showing a room in the hospital building on the south-

Figure 53

Rioma 55


N-5

Figure 59

Aerial view of the Mitsubishi Heavy Ordnance Works (Marunouchi Works) embedding from 0.7 to 1.0

Figure 60

Figure 61

Figure 62

Figure 64

Figure 65

Plume 67

Figure 68

Figure 72

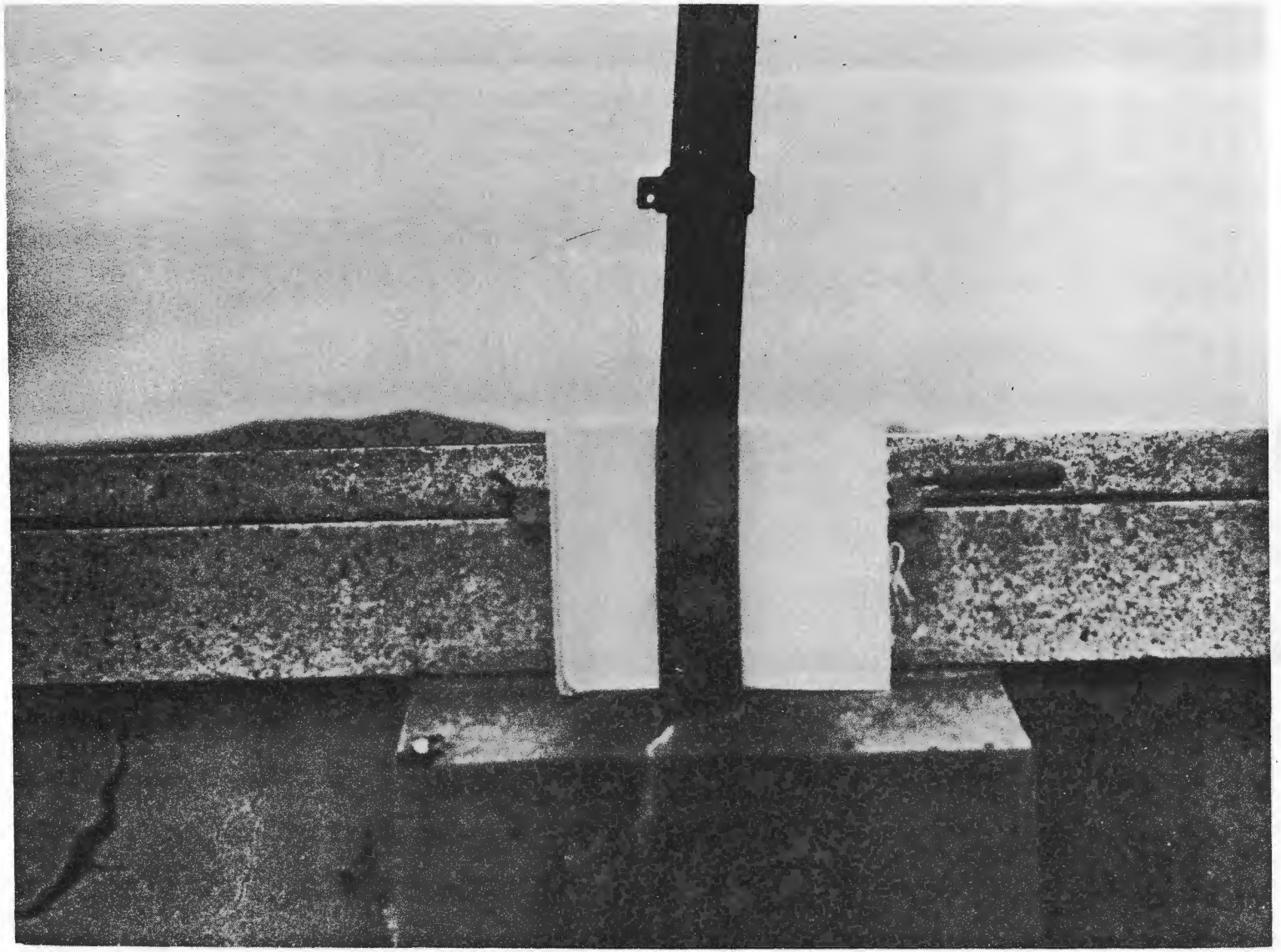
Figure 78

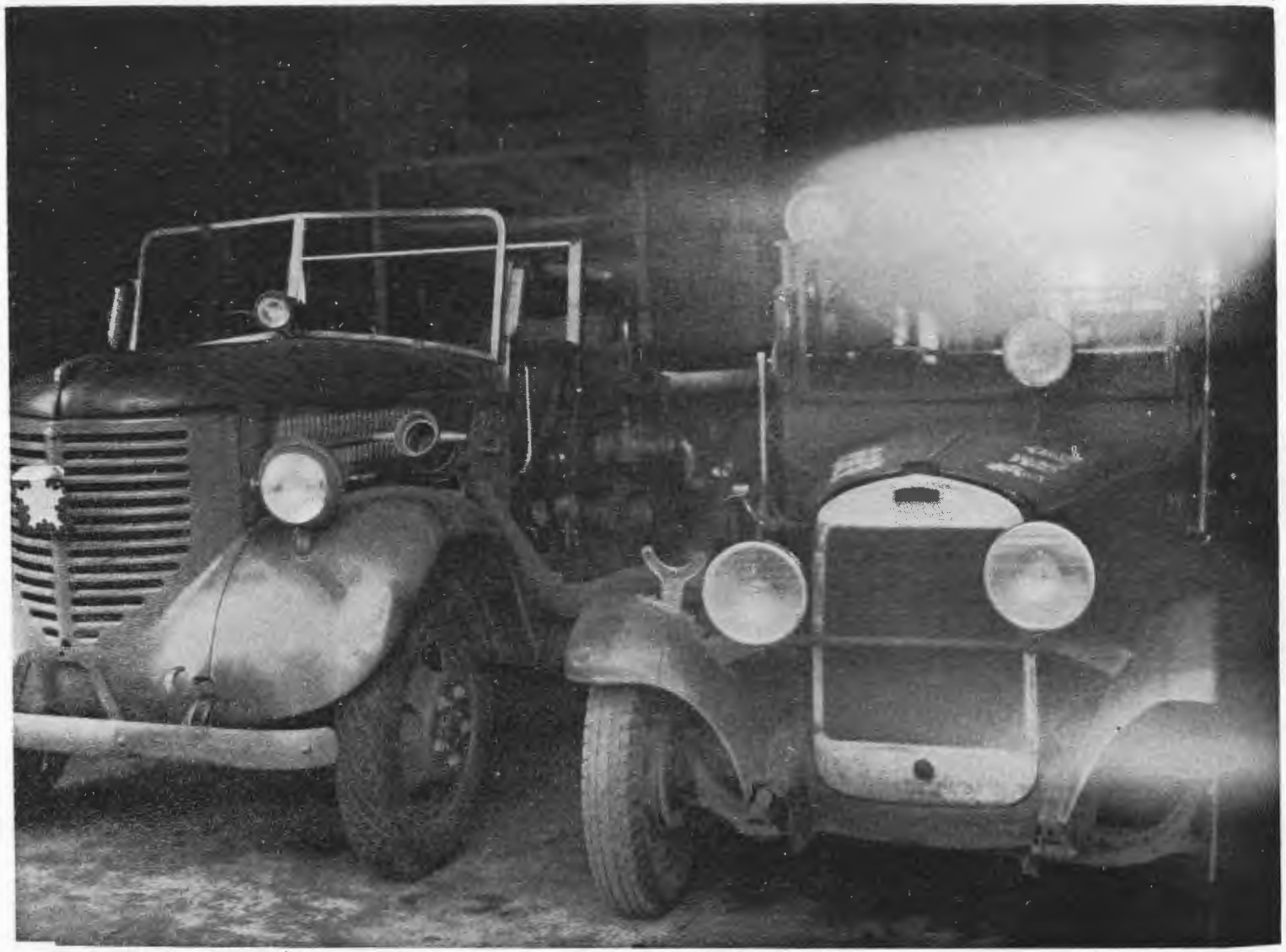
Oct 1970

Figure 81

Figure 82

Figure 83





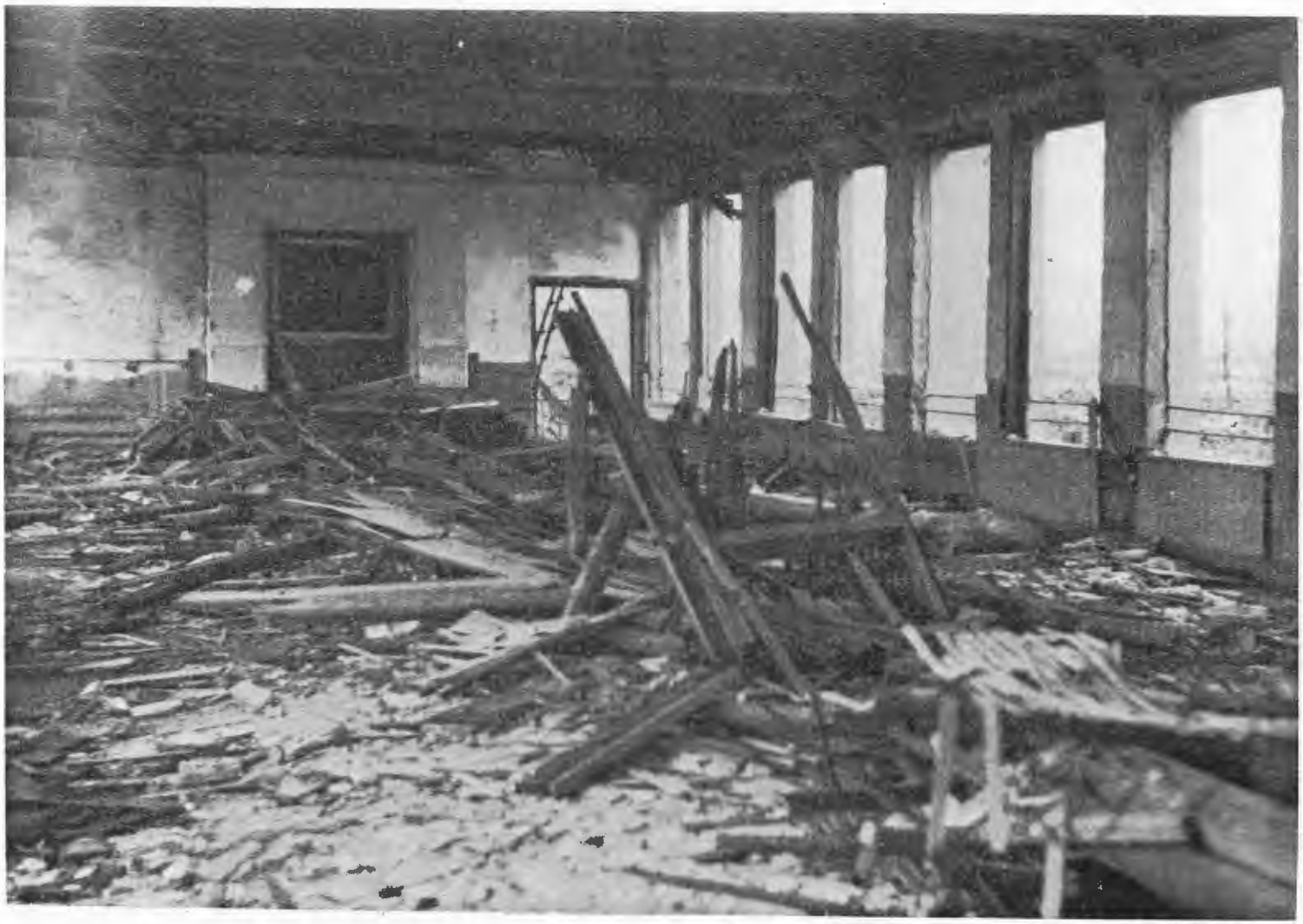


Figure 91

Figure 101