Prof. Stakman. While studying the cereal rusts, he undertook scientific missions to Europe, to Alaska, and throughout the United States and Mexico for the U. S. Department of Agriculture. Inquiry into disease problems of rubber production in Liberia and establishment of a research laboratory for the Firestone Plantations Company in 1930 necessitated travel in West Africa and also a survey of rubber production in the Far East. During World War II, in the interests of national defense in the Western Hemisphere, Stakman joined a Department of Agriculture Commission to study native rubber in South America and the possibilities of increasing *Hevea* rubber production there. In 1941 he was a member of the Rockefeller Foundation's commission to survey agricultural needs in Mexico, and two years later he helped in the implementation of the Foundation's program for agricultural improvement. More recently he has assisted the Foundation in a survey of agricultural problems and status of education and research in the natural sciences in various countries of Central and South America. Late in 1948 he became a member of a commission of scientists from the National Academy appointed to assist Gen. MacArthur in a survey of scientific research institutions in Japan.

While Dr. Stakman is known primarily as a plant pathologist and agriculturalist, he also is a renowned educator. Graduate students and postdoctorate fellows from every continent in the world have studied in his laboratories and have gained an insight not only into the scientific fields of biology and agriculture but also into the broad cultural life of an American university and the history and development of the peoples of the United States. They have found intelligent consideration and sympathetic understanding of their own national or racial cultures and intense interest in their present and future problems.

The honor and responsibilities of the Association's presidency for 1949 have been well placed in the scientist Elvin Charles Stakman.

Research and the Development of Atomic Energy

Robert F. Bacher, *Member, U. S. Atomic Energy Commission*

RESEARCH IS THE BACKBONE of the development of atomic energy. While the development of atomic energy also depends upon a host of technological improvements and upon the strength of industrial development and management, the guidance of research is a necessary requirement. Today, the research carried on under the atomic energy project ranges through physics, chemistry, metallurgy, the biological sciences, medicine, and most of the branches of engineering. The shortage of trained scientific and technical personnel, due at least in part to these greatly expanded activities, has prompted the Atomic Energy Commission to establish fellowship programs in the physical sciences and in biology and medicine and to set up technical training programs in radiation effects and the use of radioactive isotopes.

The main work of the U. S. Atomic Energy Commission is carried on in several Divisions: the Division of Production, which includes the production of raw materials from which fissionable materials are made and the production of fissionable materials themselves; the Division of Military Application, which covers the research, development, and production of atomic weapons; two Research Divisions, one for the physical sciences and one for the biological and medical sciences; and the Division of Reactor Development. In addition, there are, of course, many supporting activities which are an important and necessary part of the general administrative organization.

Most of the work in atomic energy is conducted by contract with industrial companies, universities, research organizations, and other government agencies. The greater part of it is carried out in installations especially erected for that purpose, although some of it is located in installations owned by the various contractors. The Atomic Energy Commission plans and coordinates this work. It is very important, for example, that work in the production of fissionable materials keep abreast of the developments of atomic weapons and vice versa, and that research in reactor development take account of recent experiences in the production of fissionable materials in reactors.

Since a large part of the work of the atomic energy project is carried on in several large installations, these installations have formed centers for management. At Oak Ridge, for example, there is a Manager who is responsible for all of the activities there as well as for several other contracts either closely associated with the Oak Ridge work or located nearby. Similarly, there are Managers at Chicago, where the

Address delivered at the November 18, 1948, meeting of the Washington (D.C.) Academy of Sciences.

Argonne National Laboratory is located; at Santa Fe, New Mexico, site of the Los Alamos Laboratory; at Richland, Washington, where the Hanford plutonium plant is located; and at New York, for the operation of the Brookhaven National Laboratory and many contracts associated with the procurement and processing of raw materials.

All of the major contracts of the Atomic Energy Commission are administered through one or another of these offices under the guidance of the various Divisions indicated above. Each of these Managers reports to one of the Division Directors in Washington whose responsibility covers most completely the work carried on by his office. These Division Directors report to a General Manager, who is responsible for carrying out Commission policy. Since every field office must carry on work in a large number of areas, a considerable amount of coordination is needed both by that responsible Division Director and by the Manager. It is the Commission's aim to have very close contact between the Planning Division in Washington and those working directly in the field.

The core of the Commission's work is the procurement and processing of raw materials, the production of fissionable materials, and their utilization either in nuclear reactors or in atomic weapons. As is well known, uranium plays a unique role as a raw material in the production of atomic energy. Natural uranium contains a small fraction—1 part in 140—of uranium of mass 235, which possesses the ability to produce nuclear fission with low-energy neutrons. It is this property, sometimes referred to as the property of nuclear inflammability, which allows one to make a nuclear reactor from natural uranium and graphite or from uranium and heavy water. Other materials, including thorium and the more abundant isotope of uranium of mass 238, are able to produce nuclear fission only with higher-energy neutrons and cannot by themselves maintain a nuclear chain reaction.

Since natural uranium has this unique property, it is a highly important element in the development of atomic energy. In the past, very little effort was put into the search for sources of uranium and into its extraction from low-grade ores. Prior to the development of atomic energy, uranium was used mainly for the extraction of radium and, once the radium had been extracted, was of little or no use. Gen. McNaughton, of Canada, once told me that when he became president of the National Research Council of Canada in 1935, one of his first problems was how to utilize the large amounts of uranium from which the radium had been extracted. That little problem seems to have been solved.

Today, our ideas of the amount of uranium available in the world are necessarily fragmentary. The intensive search for uranium has just begun. In the past, only high-grade deposits were mined; now, new information is being sought on how uranium may be extracted from low-grade ores, and at the same time the location and assessment of low-grade ore bodies are being determined. An intensive effort is being made in this direction, and it accounts for one of the major lines of research and development at present.

Under the general category of production, uranium ore is processed, purified, and made either into uranium hexafluoride for use in the diffusion plants at Oak Ridge or into uranium metal for insertion in the nuclear reactors at Hanford. Each of the steps in this process has been subject to a great many changes as a result of research and development and, indeed, the production of uranium hexafluoride and the production of uranium metal were, in their earliest stages, research processes.

One of the major aims of the production program is to obtain a purified fissionable material, since this can be used either in a variety of nuclear reactors or for the production of atomic weapons. One method of obtaining fissionable material is to separate uranium 235 from the natural uranium by a gaseous diffusion method which was developed during the war and put into operation in 1945. For this purpose a very large plant was constructed at Oak Ridge. This plant contains miles and miles of piping and many hundreds of pumps. The separation of uranium 235 from uranium 238 is accomplished in a very large number of steps and depends essentially upon the fact that, due to its smaller mass, a molecule of uranium hexafluoride (UF_6) containing uranium 235 has a slightly greater chance of diffusion through a tiny hole than one containing uranium 238. As you may guess, this probability is not much greater, and the operation must be conducted many times in order to achieve any sensible separation of isotopes. That this is a practical method of isotope separation is a tribute to technology and industry. Of course, research has played a tremendous role in the development of the gaseous diffusion method, and today, a great amount of process development is going on which constantly improves the efficiency and reliability of the operations.

Another method of isotope separation which was pursued vigorously during the war is the electromagnetic method. Here the separation of isotopes depends upon the curvature of the paths of ions of different masses in a uniform magnetic field. It is the old principle of the mass spectrograph used on an industrial scale. Today, the plant constructed at Oak Ridge during the war for the separation of uranium isotopes by the electromagnetic method is largely in stand-by condition. Work on new developments is going forward, however, and a small part of the wartime installation is operated to test new improvements. In addition, the research and development work on separation of uranium isotopes by the electromagnetic method is coupled with the separation in small amounts of the isotopes of many other elements. Small quantities of these are needed in many cases to sort out the nuclear properties of the various isotopes, since these nuclei are as different one from another as those of ordinary atoms. Some of these separate stable isotopes are important as tracers, but more of that later.

Several other methods of isotope separation were explored during the war, and some of them were actually acted upon and plants constructed. A thermal diffusion plant was operated for a short time at Oak Ridge. Research and development work on the separation of isotopes by a centrifuge method was undertaken, but no plant was ever constructed. New means for the separation of isotopes beyond those already tried or now in active use depend upon fundamental research for their foundation.

The production of fissionable materials in a nuclear reactor is accomplished in a very spectacular way. The whole idea of a nuclear reactor and the operation of a self-sustaining nuclear reaction is, indeed, a revolutionary one. Since the first self-sustaining nuclear reaction was achieved at the Metallurgical Laboratory in Chicago, just about 6 years ago, several reactors for research, development, and production purposes have been constructed. Nuclear reactors were developed during the war solely for the purpose of producing a new element—plutonium—which is a fissionable material and may, therefore, be used as an ingredient for the production of atomic weapons. Plutonium is produced from the excess neutrons which are generated in the fission process. Some of these neutrons produce more fissions in uranium 235; others are absorbed by the uranium 238, producing uranium 239, which is radioactively unstable and emits two beta particles one after the other, becoming plutonium—element 94, mass 239. In order to produce plutonium, even in small quantity, a large number of fissions must take place. Since each nuclear fission produces an amount of energy roughly 2,000,000 times that produced in the combustion of a hydrocarbon molecule, the production of plutonium is accompanied by the liberation of large quantities of energy. So far, this energy has been wasted, but potentially it may be very useful. The large reactors constructed at the Hanford plant, out on the Columbia River, are plutonium producers. The considerable quantity of energy which they produce from nuclear fission warms the Columbia River slightly but is put to no constructive use.

After uranium has been irradiated for some time in the nuclear reactor or pile, it becomes highly radioactive with fission products and also contains a very small amount of plutonium. In order to separate this from the fission products in uranium, a rather elaborate remote-control chemical plant is needed. This separation would not be extraordinarily difficult if this material were not highly radioactive. But to operate a complicated plant without being able to get into it at a critical time poses many problems. Research and development have not only been the foundation for the construction of nuclear reactors but have played an important rôle in the many developments which have taken place in the chemical processing.

The development of the first atomic bomb required research into properties of fissionable materials and a rather imposing amount of development work. Since that time, research and development on weapons have been carried on at the Los Alamos Laboratory, and many new facts about weapons have been learned. This work has led during the past year to successful tests of several newly developed weapons which were carried out in the Pacific last spring. The research and development carried on in connection with the weapons work ranges all the way from fundamental work in nuclear physics and chemistry to weapons development work and ordnance engineering.

A recent example of fundamental work at Los Alamos is, I believe, of unusual interest. Using a very small quantity of helium of mass 3, the condensation of that material was recently achieved. This is a point of considerable scientific interest because the properties of the condensed He^3 were expected to be very different from those of normal helium of mass 4, and it was even thought by some that it might not be possible to condense this material. It does, indeed, show quite different properties from ordinary helium at these low temperatures. The boiling point of He^3 is observed to be 3.19° above absolute zero compared to 4.3° for normal helium, and its vapor pressure at low temperature is very much greater than that observed for He^4. At 1.2° K, the vapor pressure is 35 times that observed for normal helium.

He^3 has been found to occur in very small amounts in natural helium. It is also obtained by the radioactive decay of hydrogen of mass 3, or tritium, which can be produced by the bombardment of lithium in a nuclear reactor. Both of these isotopes, which are of unusual interest for nuclear experimentation, have recently been made available in small quantities as part of the Commission's isotope distribution program. As you may know, the nuclear magnetic moments of both He^3 and H^3 have recently been studied and determined with some precision. The nucleus of H^3 is the simplest one showing radioactive decay. It has a half-life of 12 years, and the maximum energy of the beta particle is now believed to be about 18 kv. Recent measurements of the maximum energy of the emitted beta particle and of the half life now make it appear that there is no serious disagreement with the theoretically expected relation between these two quantities. In spite of the extreme softness of this radiation, it now seems likely that H^3 may be extraordinarily useful as a tracer isotope.

Research and development work which is not directly connected with the production of fissionable materials or the development and production of atomic weapons forms a large part of the program of work in physical science research, biological and medical research, and in the development of nuclear reactors.

The Commission has a major program of research in biology and medicine. This was first undertaken during the war in connection with the production of radioactive materials and the health hazards accompanying them. It was soon found that, in addition to health problems, there were many inadequately understood medical and biological problems which arose due to the unknown effects of these radioactive materials. During the war, work in these fields was confined largely to that absolutely necessary for the production programs under way. Very little was done to understand the effects of radiation upon living cells.

The health work is now carried out on an even greater scale, since many more problems have arisen in connection with new methods of chemical processing and the greatly increased use of radioactive materials. In addition, a great deal of work is directed toward a better understanding of the effects of radiation upon living matter, and these studies include fundamental research in biology and medicine. Work is now under way to study the way in which radioactive materials are concentrated in various parts of the body, and similar studies have been made on plants.

Radioactive isotopes, which are proving to be an important means of finding new information in many sciences, are of particular importance in the complex problems in biology and medicine. Today, biological and medical workers are by far the greatest users of radioactive isotopes, and the possibilities are growing every day. Work now in progress in the biological sciences ranges from fundamental work on photosynthesis to practical problems on the use of fertilizers. It would be very difficult to overestimate the benefits the world could get from a better understanding of the processes by which plants accumulate solar energy.

An example of the medical uses of radioactive isotopes is some recent work at Tulane University. A study was made of patients with congestive heart failure. Due to the deficiencies in the pumping action of the heart, the saline solution of the blood backs up in various parts of the body, the lungs become water logged, the liver swells up, and there is a general condition of dropsy. By using radioactive sodium, it was definitely shown that the excretion of sodium was subnormal, and a drug was found which increases greatly the salt excretion and relieves the dropsy.

Another example is the work at Columbia University, where radioactive iodine has been used as a diagnostic aid in determining whether patients have a thyroid disorder. Radioiodine has also been used with success in many cases in the treatment of hyperthyroidism, and the same radioisotope has been used in radioautographic studies of primary thyroid cancer to give information which would point to possible therapy. These are but a few examples of the extensive use of one radioactive isotope in medical work.

Sometimes the work in radiation effects leads to an unexpected result. Since the plutonium production reactors are located on the Columbia River, attention has been directed toward studies of salmon. Dr. Donaldson, head of the School of Applied Fisheries at the University of Washington, has found in the course of these studies that new spawning grounds can be successfully established by the transplanting of spawn to suitable pools not previously used.

The work in biology and medicine is carried on in the various National Laboratories at Brookhaven, Oak Ridge, and Argonne, as well as at Rochester, Los Alamos, Berkeley, and at a very large number of universities and medical schools. The Commission is also supporting the Atomic Casualty Survey, a study made of the casualties suffered from the bombs dropped upon Hiroshima and Nagasaki.

In the physical sciences the work supported by the Atomic Energy Commission is predominantly in the fields of physics, chemistry, and metallurgy, although much of this work branches into the engineering phases of these sciences. A great deal of the work in the physical sciences, however, is directed toward fundamental research, since an effort is being made to encourage fundamental work in nuclear science, both in order to obtain a more complete understanding of the atomic nucleus and to provide trained scientists who may later take up applied work in atomic energy.

Our understanding of the atomic nucleus is today all too inadequate. While we have learned how to obtain energy in quantity from certain atomic nuclei, we do not know the origin of the forces holding the atomic nucleus together, and we have no explanation of most of the observed properties of atomic nuclei, such as their angular momenta and magnetic moments. Information on nuclear properties is now being added at an ever-increasing rate, and today, many fundamental properties of nuclei are known of which we were ignorant three years ago.

There have also been many exciting experiments with cosmic rays and with high-energy particles accelerated in giant machines. During the past year, the first man-made mesons were produced in the big cyclotron in Berkeley, and now it seems that there are probably several kinds of these intermediate mass particles which are produced by high-energy particles. Work upon these fundamental particles of physics is being carried on in Commission-supported laboratories and under a number of contracts with universities which have been supported jointly by the Commission and the Office of Naval Research.

The requirements of nuclear reactors have posed many interesting and difficult problems. Due to their unusual ability to absorb neutrons, it has become necessary to separate rather completely some elements from various materials with which they are usually found and in which they have frequently appeared as impurities because of their similar chemical properties. In some cases it has been necessary to reduce the content of such impurities in reactor materials to a fraction of a part per million. The effects of radiation upon materials in nuclear reactors have prompted a vigorous investigation of the solid state characteristics of certain materials. The whole subject of the solid state is, indeed, a difficult one, and the radiation effects upon materials are today only very incompletely understood. These effects constitute one of the major problems in reactor development, and some further basic understanding will certainly be necessary in the course of this development. The requirements of reactors have also led to the development of several new metals which have not been used previously due to their difficulty in preparation but which may prove to be the structural materials of the future.

The development of nuclear reactors is a subject which is just beginning to come into its own. At the end of the war, the optimism about the development of atomic power struck everywhere, and the technical difficulties were only just beginning to be understood. For example, radiation effects upon materials in reactors had been anticipated, but the seriousness of these effects and the difficulties to which they might lead were only partially foreseen. Radiation effects soon proved to be a reality, and the difficulties to which they led were serious. It became necessary to backtrack considerably in reactor development in order to take account of these effects.

The chemical problems of reprocessing nuclear fuel, or of extracting plutonium from irradiated uranium, have likewise proved to be a major headache. These chemical processes are costly and complicated, and involve tremendous outlays in plant. Disposal of the radioactive wastes obtained from these chemical plants has proved to be extremely difficult. During the past two years, considerable progress has been made in the development of new chemical processes which may prove to be more efficient and which may help in the disposal problem. The disposal of these products, which have sometimes been referred to by the uneuphonious name of atomic garbage, is much more difficult than the disposal of ordinary industrial wastes.

These hurdles in the development of nuclear reactors seem now to have been partially cleared, but we can by no means conclude that the production of electrical power from nuclear reactors is technically feasible, let alone economically feasible.

It seems very likely that new developments will make the production of electrical power from nuclear reactors technically feasible. But exactly how complicated such a plant will be and what its efficiency may be are points which are pretty much unknown. There are, indeed, whole sections of this work that are unexplored. For example, we know that the efficiency of a heat engine depends upon the difference in temperature of the thermal cycle. Nuclear reactors today operate at relatively low temperatures; thus, the temperature difference measured on an absolute scale is indeed small, and the efficiency necessarily low. In order to achieve higher efficiency, it will be necessary to operate nuclear reactors at much higher temperatures. This involves many technical developments, some of which may prove to be desirable for other reasons as well, but much new work is necessary.

The question of economic feasibility is one on which we can only speculate. It is true that various papers have been written on this subject, but it seems most unlikely that the question of economic feasibility can be sensibly commented upon until the technical situation is considerably clearer. We should remember, however, that the course of any new development, once its outlines have been clarified, is always to simplify and thus cheapen the process. Although the development of electrical power from nuclear reactors looks complicated and questionable from the economic standpoint, we can expect that future work will make this development considerably more favorable. In spite of this, it is far too early to make any predictions about the economic feasibility of atomic power.

On the technical side, the situation is much more promising but the developments are going to take some time. On a demonstration basis, electrical power will probably be developed from a nuclear reactor within the next two years. Within the next 8–10 years there will probably exist a prototype of a nuclear reactor for the production of electrical power in quantity. This unit, of course, will be preceded by smaller units. Two of these are now being designed and will soon be under construction, one at the Argonne National Laboratory and the other at the Knolls Atomic Power Laboratory near Schenectady.

Of course, the whole development of economic electrical power from nuclear reactors is but one aspect of reactor development. For some purposes, such as the propulsion of a ship, the nuclear reactor has peculiar advantages from the fuel standpoint. Here, the question of size, weight, and complexity of the nuclear reactor and its auxiliary equipment are of paramount importance. While no reactor, operating at the temperature presently used, could possibly prove to be a useful source of power for such a purpose, the use of higher temperatures may reasonably be expected to lead, in the not too distant future, to reactors which are suitable for this purpose. Whether or not the characteristics of such reactors are such that they will prove to be useful sources for ship or submarine propulsion will have to await the outcome of the development work. At the present moment, the prospects in this direction look favorable, and it seems likely that this will be the first application of a mobile nuclear reactor.

Many people have speculated upon the possibility of driving an aircraft by a nuclear reactor. Here there are many intriguing possibilities because of the extraordinary large energy content per pound of purified nuclear fuel. Unfortunately, nuclear reactors as we now know them are heavy. In particular, the shields for protection from the penetrating radiations produced inside must be very thick and heavy. Furthermore, the temperatures needed for aircraft nuclear reactors will probably need to be much higher than those which might be tolerated for driving a ship. In short, the problems here seem to be much more difficult.

The other day I read in a newspaper that someone had said that the theoretical work for the construction of a nuclear-powered aircraft was 99% complete. Probably he was misquoted, since there are certainly some important scientific problems yet to be solved. But the development of a nuclear-powered aircraft is primarily a technical and engineering problem—not a scientific one. Whether such a development will prove to be feasible can be determined only if a very great amount of new technical work is done.

In this connection it is interesting to note that the B-29 which was first used in combat in the later stages of the war was being designed prior to the discovery of nuclear fission. It took just about the same time to go from the discovery of nuclear fission through the production of experimental, pilot plant, and production chain reactors, through the extraction of purified fissionable material, to the development and construction of the atomic bomb that it took to proceed from the design of the B-29 to its actual use. This is by no means due to any lack of ingenuity and industry on the part of airplane manufacturers, but rather to the enormous complexity of the technical and construction problems which must be solved to make an airplane or airplane engine. We cannot expect the nuclear-powered aircraft to appear in the next few years, even if further work does indicate that it is feasible.

One of the most exciting prospects in the development of nuclear reactors is the possibility that one may be able to consume fissionable material, obtaining energy from this process, and at the same time utilize the neutrons thus produced to generate a larger amount of fissionable material than was destroyed. This subject is now being actively pursued. Whether or not it will be possible to achieve is not yet clear. In order to be practical, it will also be necessary to develop highly efficient chemical treatment of the nuclear fuel which must be reprocessed from time to time. It is a very intriguing possibility, and since the amount of new material which can be produced will depend both upon the intrinsic rate of production in the reactor and the amount of fissionable material thus committed, our stock of fissionable material may prove to be an even more precious possession than it seems today.

As you can see, research enters into almost every phase of atomic energy work. There is no sharp distinction between research and development. While there are a few examples where fundamental research can be set off by itself, it is more usual to find that development work often produces new leads for fundamental research and fundamental research shows the way to new possibilities for development and practical utilization of atomic energy.

Much has been made over the point expressed by some that atomic energy is of use only as an instrument of destruction. It is certainly true that our introduction to atomic energy was through the operation of the plutonium production reactor and the development of the atomic bomb. All work during the war was aimed at the development of the atomic bomb, but in the past three years we have seen the actual start of work in many other directions. The future holds quite a different picture. I believe that only those of myopic vision today believe that the long-range developments of atomic energy will not in time contribute very greatly to man's general well-being and cultural advancement if he can but stir up the wisdom needed to handle the tremendous forces which have been unleashed.