XEROX 1482/45

A. H. Compton

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November 18, 1944.

Dear Mr. Compton:

In July 1944 you appointed the undersigned a committee to prepare a brief prospectus on Nucleonics. The purpose of the prospectus is to help in the formulation of sound national post-war policies appropriate to the size and importance of this field from the military, scientific and industrial standpoints.

The results obtained in the Metallurgical Project are so outstanding and are fraught with such future consequences that improper post-war policies might prove to be very damaging, or even disastrous, to the United States and to the fate of mankind.

You expressed the thought that the men in the Metallurgical Project are in the most favored position of any in the United States to intelligently speculate on the future of Nucleonics — at least within the scope of the activities of the Metallurgical Project.

The committee has obtained ideas from many workers within the Metallurgical Project and, to the extent that these are considered to be pertinent to the present prospectus, they are given brief mention.

It is our hope that the attached prospectus will prove helpful in formulating long-range policies, particularly as they may relate to matters in which both governmental and non-governmental interests are involved.

Respectfully submitted,

Enrico Fermi

James Franck

T. R. Hogness

Zay Jeffries, Chairman

R. S. Mulliken, Secretary

R. S. Stone

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CLASSIFICATION CANCELLED
DATE 2/17/61
For The Atomic Energy Commission
Chief, Declassification Branch

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PROSPECTUS ON NUCLEONICS

I. INTRODUCTION

Many of us have watched the birth and development of the electronics industry. From laboratory experiments a few decades ago electronics has evolved into one of the most lusty of the sciences and industries. In ELECTRONICS, a trade and technical publication, 1618 companies are listed as electronics companies. Billions of dollars are being spent for electronic devices for war. The field seems to be headed for great post-war developments.

The word "electronics", as is well known, relates to electrons, the negatively charged particles whose normal home is in the outer parts of atoms. As is likewise well known, the center or core of every atom is an exceedingly small but relatively heavy positively charged group of particles called its nucleus. In this prospectus, we are going to present some thoughts on the potentialities of that expanding field of science and industry which deals with atomic nuclei.

We propose to use the word "nucleonics" as a name for this field. Reflecting the modern trend toward close correlation between science and industry, and following the lead of "electronics", we propose that the word "nucleonics" shall refer to both science and industry in the nuclear field.

The science of nucleonics began with the discovery of natural radioactivity by Becquerel in 1896 and it is, therefore, about the same age as the science of electronics. There is also a nucleonics industry which is as old as the commercial production of radium.

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The radium, radon, mesothorium, and polonium industries may be regarded as parts of the nucleonics industry.

Major steps forward in the science of nucleonics were the first achievement of transmutation of the elements in 1919, the discovery of artificial or induced radioactivity, and the development of the cyclotron in the early nineteen-thirties.

Then, during the winter of 1938-39, when Hahn and his associates discovered atomic fission, the horizons of nucleonic science were so greatly enlarged that, even now, no one can foretell the consequences. It was discovered that the nucleus of uranium can be split in two and and that the splitting is accompanied by the evolution of energy tens of millions of times larger than that of the most energetic chemical reactions. Soon afterwards, some observations on the details of this "nuclear fission" led to the faint hope that a means could be found to utilize the liberated energy for practical purposes. This was the reason for the establishment of the Metallurgical Project and other related projects in this and other countries. How the hope of releasing at will and utilizing nuclear energy, which had seemed fantastic only four years ago, has now been realized, and what problems for the future arise from this momentous discovery, will be discussed in several sections of this prospectus.

The Metallurgical Project was established for military purposes and has been operated as a secret military research and development project. The field of nucleonics, however, embraces a scope far greater than the military. In this prospectus, we shall make the attempt, speculatively, to foreshadow something of the immensity of the future development of nucleonics and of its effects on mankind.

As a springboard for our excursion into the future, we shall review in Section II the pre-war history of nucleonics, including the discovery of fission. In Section III we shall outline the crescendo of the war-time history of nucleonics within the Metallurgical Project, culminating in the first achievement of a nuclear power plant.

In Sections IV and V we shall speculate freely about what it may be possible to achieve with the new methods and new tools that we can now visualize. In Section VI we shall try to assess the political implications, both national and international, of the coming age of nucleonics; and we shall conclude in Section VII with a discussion and suggestions on the post-war organization of nucleonics research and industrial nucleonics in this country.

II. THE EARLY HISTORY OF NUCLEONICS

Electrons and Nuclei

As mentioned in Section I, all atoms consist of a number of negative electrons moving around a tiny central positively charged body, the nucleus, which contains practically the whole mass of the atom. This "nuclear theory of atomic structure", first proposed by Rutherford forty years ago, has been since verified by numerous experiments and its correctness established beyond any reasonable doubt.

The chemical properties of different elements and compounds are a result of the arrangement of their outer electron "shells". All energy produced by respiration, combustion, explosion, or other chemical processes, originates in changes in the arrangement of these electrons. From this point of view, the advance of mankind from reliance on its own muscle power to the use of combustion engines and high explosives has tapped no new source of energy. We have only learned how to concentrate the electronic energies and how to release them at will when desired.

The property of the nucleus which determines the number and arrangement of the electrons around it is its electric charge. This consists of a whole number of units of positive charge*. An equal number of outside electrons (which bear one unit of negative charge each)* is required to make the whole atom electrically neutral, as it is in its normal condition. Different chemical elements are distinguished each by the number of units of positive charge on the nuclei of its atoms, that is by the "nuclear charges" of the nuclei. Arranged by increasing values of their nuclear charges from 1 (hydrogen) to 92 (uranium) the various kinds of atoms form the "natural system" or "periodic system" of chemical elements.

While the nuclear charge of every atom of a given element is the same, the nuclei of different atoms of an element may nevertheless vary in mass (atomic weight). However, as we shall see later, all nuclei are built up of unit particles of almost exactly the same mass, so that their masses, too, can be expressed by whole numbers. Thus, each element in the periodic system is characterized by one whole number - its nuclear charge - which determines all its chemical

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*The unit of charge about which we are talking is an exceedingly minute quantity of electricity, equal to that found on an electron. All electrons bear this same electrical charge, and no case is known of any particle bearing a smaller charge. This smallest known quantity of electricity is therefore the fundamental unit of electrical charge, disclosed to us by Nature.

properties, and by any one of several whole numbers which express, in terms of a natural unit of mass, the nuclear masses of the different forms in which this element occurs. These different forms of an element are called its "isotopes".

Natural Radioactivity

That the atomic nucleus is a site of energies a million or more times larger than those available in the outer electronic shells has been apparent since the discovery of radioactivity by Becquerel in 1896.

After the discovery of X-rays, a few months before Becquerel's work, many investigators became interested in the bluish-green phosphorescence seen in the X-ray tubes. Becquerel decided to re-investigate some uranium salts which he had prepared some fifteen years before and which had had phosphorescent properties. After exposure to light, one of the salts was wrapped in black paper and placed below a photographic plate. A blackening of the plate was observed after several hours exposure; this indicated the emission of a radiation capable of penetrating through black paper. Subsequently, it was shown that the photographic action was independent of previous illumination; it was exhibited by all salts of uranium and by the metal itself.

Rutherford studied the radiations given out by uranium and concluded that the rays could be classed into two groups. The first kind, called alpha rays, were found to be comparatively easily absorbed and to produce a very intense ionization in air*. The second kind,

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*By "ionization" is meant the formation of charged particles or "ions". This comes about by the pulling off of one or more outer electrons from an atom or molecule, leading to the formation of both positively and negatively charged particles.

called beta rays, were much more penetrating, but less ionizing. Later, a third type of radiation was found to be given out from radium and was named gamma rays by Villard. We now know that alpha rays are rapidly moving nuclei of helium, beta rays fast moving electrons, while gamma rays are very penetrating super-X-rays.

Most of the chemical elements were examined by Marie and Pierre Curie for "radioactivity" in order to learn whether the phenomenon was a gneral property of matter. Thorium, alone among the known elements, was found by Curie and Schmidt to possess an activity comparable to that of uranium. Mme. Curie in her studies on various uranium and thorium compounds and minerals found that some uranium minerals exhibited a much higher activity than uranium metal. Mme. Curie followed through her hypothesis that small amounts of materials of higher activity were present in these particular uranium minerals. Success was attained and two new strongly radioactive elements, radium and polonium, were added to the list of chemical elements. The discovery of these elements was made possible only because of the employment of their radiations as guides for their separation and concentration. Naturally the discovery of radium stimulated research on the systematic analysis of uranium minerals which led to the detection of new radioactive elements, actinium and radio-lead. The latter, also called Radium D, was found to behave exactly like lead except for activity. Soddy introduced the word "isotopes", mentioned above, to designate the various elements which had the same chemical properties but different radioactive properties. Later, it was found by Aston that ordinary elements also consist of mixtures of isotopes, with identical "electronic" properties, but different mass.

Naturally the discovery of the large number of radioactive elements presented a confusing problem. Some of them seemed to die away at a steady rate, others lost their activity in a few days or even in a few hours. From the compiled mass of data, Rutherford and Soddy brought order based on their transformation theory expounded in 1903. This idea stated that the nuclei of radioactive elements, unlike those of ordinary elements, are not stable but undergo spontaneous disintegration with the expulsion of either an alpha or a beta particle. The atom resulting from the disintegration has entirely different chemical properties from the parent atom. The daughter element in turn may be unstable, and disintegrate by the emission of either an alpha or a beta particle, and so on. Three such disintegration series have been identified, originating in uranium, thorium, and actinium respectively, and terminating in three stable isotopes of lead.

The energies with which the disintegrating nuclei of radioactive elements sent out alpha and beta particles could be measured. It was found that they were tremendously large - millions of times larger than the energies liberated by the most violent transformations of the outer electron shells. Thus physicists had their first glimpse of the immense stores of energy hidden in the nuclei. They contemplated these nuclear explosions in awe, but found no more means to provoke or stop them than if they were observing the eruption of a volcano, or the birth of a Nova star in the sky. It became an established belief that radioactive transformations are utterly inaccessible to all external influences.

However, it was asked whether the impact of the radiations emitted by naturally radioactive elements cannot be used to break the nuclei of other, normally stable elements and so bring about the fulfillment of the old dream of transmutation of elements. Because of the great energy and momentum of the alpha particle, it was considered likely to be the most effective tool to promote disintegration. Many experiments were made, but failure always resulted until Rutherford was successful in transforming nitrogen into oxygen in 1919.

In his experiments, alpha particles were obtained from a radioactive deposit in a box, and absorbed in the gas filling the latter. A fluorescent screen was placed over a hole in the box. When the gas through which the alpha particles passed was nitrogen, scintillations were observed on the screen even when the path of the ~~these~~ alpha particles in the gas was so long that absorption should have been complete. Rutherford concluded that these scintillations were due to particles ejected with great speed from the nitrogen nucleus hit by an alpha particle. These particles behaved as if they were rapidly moving protons (hydrogen nuclei).

The nuclear process or "reaction" involved in this first artificial disintegration may be written as

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

meaning that a helium nucleus of mass 4 (an alpha particle) striking a nitrogen nucleus of mass 14, produces an oxygen nucleus of mass 17 and a hydrogen nucleus of mass 1. The latter is known as a "proton", and is of special importance, since it has the smallest mass of any nucleus, equal to the natural unit of mass. Following this first artificial transmutation of nitrogen, many similar transmutations of other light elements were carried out.

The experiments on radioactivity and transmutation showed that the nuclei of heavy elements are complex, with protons and electrons indicated as the primary constituents. (Alpha particles could be regarded as particularly stable groupings of four protons and two electrons.)

In 1932, however, two new elementary particles were discovered - the positron (positively charged electron) by Anderson, and the neutron (chargeless particle of about the same mass as a proton), by Chadwick. These discoveries led to a revision of our concepts of nuclear structure. Neutrons and protons were now supposed by Heisenberg to be the only primary components of the nuclei; electrons (in the form of beta rays) or positrons were assumed to be created at the moment of nuclear disintegration by the conversion of a neutron into a proton or vice versa. The word "nucleon" has recently been suggested to designate either a proton or a neutron. This makes the mass number of any nucleus equal to the number of nucleons in its nucleus.

Artificial Radioactivity

This brings the story to 1934, which might be considered the birth year of artificial radioactivity. It was at this time that Mlle. Irene Curie, a daughter of Mme. Curie, and her future husband, M. Joliot announced that atoms produced by artificial disintegration are not always stable. Specifically, they found that, after they had "bombarded" the element boron with alpha particles, positrons were given out and this continued for some time after the bombardment had been stopped. What happens is that the boron atom absorbs an alpha particle and gives out a neutron, leaving a nitrogen nucleus of charge 7 but with mass 13, one unit lighter than ordinary nitrogen, which is N^{14}. This new type of nitrogen is radioactive and its atoms disintegrate gradually one by one each with the emission of a positron.

Fermi reasoned that neutrons, which bear no electric charge, should be more effective in producing nuclear transmutation and artificial radioactivity than the positively charged alpha particles, which are repelled by the positively charged nuclei. In 1934, he made the first announcement that artificial radioactivity can be produced by neutron bombardment. The usual reaction observed was that the nucleus of the bombarded atom captured the neutron, producing an unstable nucleus, which was then stabilized by emitting a beta particle. This resulted in the formation of an element one unit higher in mass and one unit higher in nuclear charge than the parent atom in the periodic system.

Before the discovery of artificial radioactivity, the field of applied nucleonics was restricted to the use of radium, mesothorium, and other natural radioelements for medicinal purposes and for a few industrial applications. In some cases, radioactive elements could be used as "tracers", (also called"indicators"or "stand-ins")- e.g. radiolead could be added to ordinary lead, and the mobility of atoms in solid or liquid lead ("self-diffusion") could be studied by following the spread of radioactivity. However, only one or two heavy elements have natural radioactive isotopes. Sometimes, a radioactive <u>homologue</u> could be used instead of an <u>isotope</u>, e.g. radium could be used to a certain extent as a tracer for barium, because these two elements belong to the same group in the periodic system and thus behave alike in many, although not all, chemical transformations.

The discovery of artificial radioactivity brought about a vast enlargement in the possibilities of applied nucleonics, because it led to the preparation of a large number of radioactive isotopes of the lighter and medium atomic weight elements. Such isotopes are known now for a large proportion of all elements in the periodic system, although not all of them are equally convenient for use as tracers, because some disintegrate too rapidly and others too slowly. Chemistry, medicine and biology are already making considerable use of these new tools.

Chemists can now add to various reaction components a few "tagged" atoms of their radioactive isotopes and then follow their fate by means of the extremely sensitive radioactive detection methods. Biology has been enabled to study the rate of renewal of the constituents of the animal body, e.g. of phosphorus in the bones, by observing the appearance and disappearance of radioactivity in the body cells after feeding animals with "tagged" foods. Medicine has profited by an enlarged choice of radioactive elements for treatment. Some of these elements are selectively absorbed by certain cells in the organism - e.g. radioactive iodine by the thyroid - thus making possible a new type of localized "inside" radiation treatment.

The Transuranic Elements

Among the elements which Fermi exposed to neutron bombardment were uranium and thorium, the two original radioactive elements. Uranium was the last known element in the periodic system (element 92). If its nucleus would undergo the above-mentioned transformation (capture of a neutron and emission of a beta particle) its nuclear charge should increase to 93 and a new "transuranic" element (element 93) unknown in nature, should arise. First experiments with uranium and thorium showed that their atoms actually are affected by neutron bombardment; but it was several years before the true nature of the ensuing transformations was clearly understood. When this understanding finally was gained, it became the starting point of the present tremendous development of pure and applied nucleonics.

Uranium, as found in nature, consists of a mixture of three isotopes, yet after its bombardment with neutrons, not three, but four different types of artificial radioactivity were found. To clarify the situation, chemical separations were attempted.

In the chemistry of radioactive elements, a commonly used method of identification consists of adding a known inactive element to the product, and then separating it again, for example by precipitation. If the radioactivity belongs to a radioactive isotope of the same element, or to a close relative of the latter, it will follow the added "carrier" into the precipitate.

Element 93 ~~would~~ might appear in the periodic table in the same group with manganese. Addition of manganese as a carrier was therefore tried first. When a manganese salt was added to the uranium salt solution, and manganese precipitated as manganese dioxide, some of the active substance separated with manganese. This seemed to confirm the theory that one of the products of neutron bombardment was element 93.

But what were the other ones? In the meantime, their number had increased from four to nine, and it was necessary to postulate elements up to number 97, if all of them were to be interpreted as "transuraniums".

Fission

In 1938, Curie and Savitch found a new active substance in the products from neutron-bombarded uranium, which could be precipitated with lanthanum as a carrier, thus suggesting that it might be actinium (since actinium and lanthanum belong in the same group in the periodic classification). It did not occur to them that the material might be lanthanum itself. Lanthanum, element 57, was too distant from uranium (element 92) in the periodic system. We have seen that all natural and artificial transmutations which had been observed up to that time had led to the production of "daughter elements" removed only one or two places from the "mother substance" in the periodic system.

Hahn and Meitner repeated the work of Curie and Savitch. They added barium as a carrier and found that certain active substances could be precipitated from a neutron-exposed uranium solution along with the barium, and that these substances transformed themselves after a certain time into other active substances that could be precipitated with the lanthanum. The material which could be precipitated with the barium they first designated as a radium isotope, and the lanthanum-like substance as an actinium isotope. But how were they to explain the conversion of uranium into radium, which would require the driving out of two alpha particles in the nuclear reaction, whereas no alpha particles were detected. In order to prove that the materials actually were radium and actinium, Hahn and Strassmann performed a series of rigorous experiments; but the startling result of these experiments was that the "barium-like" substance was found to be truly barium and not radium; while the "lanthanum-like" substance was nothing else but lanthanum itself. This led to the startling idea that uranium was being split by neutron bombardment into two atoms of medium atomic weight, accompanied by the release of enormous amounts of energy. This new type of nuclear transformation was given the name of <u>fission</u>.

The first word of the fission idea was brought to America by Professor Niels Bohr, who arrived on January 16, 1939 to spend some time at Princeton. The exciting news was soon spread among American physicists, and many hastened to test the idea by direct experiments to look for the shooting out of energetic heavy fission fragments during neutron bombardment of uranium. Within a month confirming results came from four laboratories in this country. Meantime, Meitner and Frisch in Bohr's laboratory had obtained similar results on January 15. Soon it became clear that the whole group of products previously considered as "transuranic elements" was a mixture of isotopes of elements of medium atomic weight. There was one exception, however. Abelson at Berkeley exposed to neutrons a uranium layer which was so thin that it could not hold the fission products, and found that the uranium layer exhibited after the bombardment a single beta-activity, which he attributed to a new unstable uranium isotope U^{239}, decaying to a true transuranic element 93.

Nuclear Disintegration by Artificially Accelerated Particles

We have spoken so far only of nuclear disintegrations produced directly or indirectly by radiations from naturally radioactive substances. Similar results have, however, also been obtained by means of charged particles (ions) accelerated artificially by various electric or magnetic devices.

The simplest way to produce very rapidly moving ions is to accelerate them between two electrodes, to which a very high potential has been applied. However, to achieve nuclear disintegration, potentials of several million volts are usually required. Machines which produce such high potentials have been successfully constructed; but the greatest success in atom-smashing has been achieved by means of an apparatus devised by E. O. Lawrence in California, which is based on the resonance principle and does not require a high voltage. In this apparatus, known as the "cyclotron", ions are accelerated by successive "kicks", in the same way that a bell ringer brings a massive church bell to swinging by striking it regularly at appropriate intervals. In order to keep the ions within the apparatus between the "kicks", they are made to spin around on circles by the attraction of an electromagnet. The cyclotron contains two half-circular hollow electrodes placed between the poles of a powerful electromagnet. Ions are produced in the center of the apparatus, from which all the air is first pumped out, and start moving on a circle in the field of the magnet. When they pass from the first electrode into the second one they are accelerated by a potential applied to the two electrodes; by the time they have completed a half-circle and are about to enter the first electrode again, the direction of the electric potential has been reversed and they receive another "kick". This acceleration is repeated again and again until the ions, having spiralled around long enough to reach a tremendous velocity, emerge by penetrating through a thin window at the outside of the apparatus. The cyclotron may be used to speed up protons, deuterons, (nuclei of a heavy isotope of hydrogen with an atomic mass 2) or alpha particles, depending upon what gas is placed in the apparatus; and also to produce neutrons by letting speeded-up deuterons or protons "bombard" a "target" which thereupon yields a supply of neutrons.

III. NUCLEONICS SINCE 1939

The reason why Hahn's discovery of uranium fission set ablaze the imagination of all nuclear physicists was twofold. In the first place, fission releases ten times as much energy as did the previously known nuclear transformations of naturally and artificially radioactive elements. In the second place, it is capable of propagating itself - that is, some of the products formed by the fission of a uranium atom are capable of inducing the fission of another similar atom, which in its turn brings about the fission of a third one, and so on.

To understand the first point, one should recall one of the great achievements of Einstein's theory of relativity-- the law of equivalence of mass and energy. According to this law, the giving out of energy in any process necessarily means a decrease of the mass of the substance involved. Consequently, the amount of energy given out in any process can be predicted if the mass of the material involved is known before and after the process occurs. If one calculates from exact measurements of the atomic weight the average mass of a neutron or proton in different atoms in the periodic system, one finds that this mass decreases at first rapidly with increasing atomic weight but that the curve soon flattens out, and begins to climb again. This means that very light and very heavy elements contain excess energy, which would become available if the light ones could be condensed into somewhat heavier ones, <u>or</u> if the heavy elements could be broken into lighter ones.

A transformation of the first type - the condensation of hydrogen into helium - is now believed to be the main source of the sun's energy, and is thus the origin of all energy which mankind utilizes in the form of food, fuel, or falling water. Transformations of the second type - those involving the spontaneous breaking up of heavy nuclei - are the essence of natural radioactivity. The series of transmutations leading from uranium through radium and radon to lead represent a descent, step by step, towards the center of the periodic system. However, this spontaneous descent stops with lead, in spite of the fact that lead is still far above the level of the most stable elements, which are situated in the region of iron, and so still contains within it vast stores of locked-up energy. In the case of artificial radioactivity, too, the changes do not go very far.

In contrast, however, the fission of a uranium atom into two atoms of medium weight represents a direct transition from the highest peak of the energy curve into a region close to its bottom. Thus, fission releases almost the maximum amount of energy which one can hope ever to obtain from a single nuclear transformation (unless some day we learn how to change matter completely into energy!)

Despite this large energy effect, fission would be of no more use for practical purposes than were all previously known nuclear reactions, if it were not for the second above mentioned peculiarity of this process - its capacity for self-propagation. All the progress that mankind has achieved in the past in the production and utilization of chemical energy, other than that of muscular work of man or domesticated animals, has been founded on the creation of self-propagating processes of energy change. When man learned how to strike fire, he discovered the first "chain reaction," i.e., a process in which only the first step has to be brought about by a supply of external energy, and which then propagates itself automatically, each link in the chain supplying the active material to start the next link (or several such links, in which case the chain becomes branched and the reaction swells in volume like an avalanche.) All our power engines are devices for controlled chain reactions, while all our explosives are systems contrived to produce branched chain reactions with the maximum chance of rapid development.

It has long been clear to all physicists that the practical utilization of nuclear energy hinges upon the realization of a nuclear chain reaction whose self-propagation would avoid the necessity of a very large external energy supply for the first step in the process. When the fission of uranium by neutrons was discovered, speculations immediately appeared that here is a nuclear reaction which may prove to be capable of chain propagation. The reason for believing this was that the relative content of neutrons in the stable atoms in the middle of the periodic system is smaller than in the heavy atoms like uranium. A splitting of uranium into two medium weight elements would give products containing too many neutrons. It thus appeared likely that in the process of fission one or several neutrons may remain behind as free neutrons instead of being incorporated into the fission products. At the moment when this anticipation was confirmed (in the Spring of 1939), the nuclear chain reaction, with all its tremendous implications, became a concrete possibility.

One might expect that the creation of one new neutron for each fission act would suffice to maintain a chain. Since experiments have shown that the average number of neutrons set free in each fission, - the "multiplication factor" - is actually as high as 2.3, one might conclude that the fission of uranium, once started, would become a branched chain reaction and terminate in a tremendous explosion of the whole available mass of uranium. That this is not so - that a lump of uranium is a perfectly safe object to handle near a neutron source - is the result of a number of chain-breaking processes. The first is the escape of neutrons through the external surfaces of the material. Then there is the effect of impurities, which "catch" neutrons by an action analogous to that of anti-knocks in the gasoline engine.

Most important of all, there is the different behaviour of the different forms (isotopes) of uranium itself. The main isotope of this element, U^{238}, that is uranium of mass 238, can undergo fission only by very fast neutrons. Neutrons set free by uranium fission are very rapid immediately after their liberation, but most of them are slowed down by collisions with uranium atoms before they succeed in initiating a new fission. Once neutrons have been slowed down, the atoms of U^{238} become "traps" which catch neutrons without fission. The rare isotope U^{235}, however, can undergo fission also by slow neutrons. The probability of its fission is so high that a slow neutron moving in a mass of uranium has about an equal chance of being caught by a U^{238} nucleus or of causing fission in a U^{235} nucleus, even though the first isotope is more than a hundred times more abundant than the second one. Thus, the presence of U^{238} cuts the multiplication factor for slow neutrons in uranium by approximately one-half - from 2.3 to 1.15. The latter value is dangerously close to 1 - the lowest value which allows chain propagation - and it seemed nip and tuck whether the influences of impurities and of the escape of neutrons from the material could be reduced so far as to keep the multiplication factor greater than one, as is necessary for a chain reaction.

An obvious way out of this difficulty was to prepare the isotope U^{235} free from U^{238}, or at least to enrich ordinary uranium in U^{235} so as to give the chain reaction a better chance. This is easier said than done, since the separation of large quantities of two heavy isotopes is a tremendously difficult undertaking. Scientists all over the world had just begun tackling this problem when war threw a veil of secrecy over this subject.

The Metallurgical Project was organized however, not to develop this solution of the chain reaction problem, but to see whether a chain reaction can be achieved even without the separation of isotopes. It was suggested as early as 1939 that a favorable relation between the number of fission acts and the chain-breaking neutron absorption acts in ordinary uranium can be achieved by construction of an arrangement in which spherical lumps or cylindrical bars of uranium spaced at regular intervals were surrounded by a "moderator", somewhat like plums in a pudding. By a moderator is meant a mass of substance which efficiently slows down the fast neutrons that are produced by fission and emerge from the uranium lumps, but which does not itself absorb these neutrons. The function of the moderator is to slow down the neutrons and allow them then to diffuse back into the uranium, there to produce fission. Experiments with structures of this type (which soon became known as *piles*) began in March, 1940 at Columbia University, and a year later at the University of Chicago. These projects and also a third started at Princeton University were combined at the beginning of 1942 and concentrated at Chicago to form the present Metallurgical Project.

The moderator must contain a light element, since neutrons are slowed down most efficiently by collisions with light nuclei, but rebound from heavy ones as a ball rebounds from a wall. In this respect hydrogen would be the ideal moderator, but unfortunately it has also the capacity of absorbing neutrons rather strongly, so that the possibility of its use is doubtful. Heavy hydrogen (deuterium) is the next most efficient moderator, and does not strongly absorb neutrons. Thus heavy water is an obvious choice for use as pile moderator, and the preparation of large quantities of heavy water for this purpose was early taken under consideration,. The construction of a large-scale heavy water plant by the Germans in Norway, revealed by British bombing reports, may be a significant indication of parallel thinking on the other side of the front line.

The difficulty of obtaining the required quantities of heavy water caused postponement of the actual construction of heavy water piles in America. In the meantime, the development of piles with less efficient but more easily obtainable moderators proceeded rapidly. Beryllium metal was suggested but soon abandoned because of high costs; since the next element in the periodic system, boron, is an efficient neutron absorber, the choice then fell on carbon. In the form of pure graphite, this element has given the best practical solution of the moderator problem. First determinations of the multiplication factors for a uranium-graphite pile at Columbia in the summer of 1941 gave the comparatively low value of 0.87; but since theoretical calculations predicted 1.07 as an attainable value for this system, the work was continued at Chicago. Successive improvements in the purification of the materials and in the construction of the pile, helped to push the multiplication factor closer and closer to one, until on December 2, 1942, in the experimental pile at the West Stands of the University of Chicago Stadium, the chain reaction was finally achieved.

Barring disclosures from the other side, this date will live in the history of mankind as the day when "nuclear fire" was first lit by man.

After the achievement of this fundamental success, plans rapidly matured for the transition from the laboratory state of development to a pilot plant and then to a large scale plant. The Army took over the whole project in the spring of 1943; a commercial firm undertook contracts for the construction of a 1000 kilowatt pilot plant and for the later construction and operation of a high-power production plant.

The piles were originally conceived as energy-producing units. An additional and important function could be the production of a large variety of radioactive fission products, whose potential importance for many branches of science and technology will be described in the next section. However, it was a discovery made in 1941 which gave the real impetus for the war-time development of the Project: it was realized that the pile may lead to the production of a pure fissionable element, thus by-passing the difficulties of isotope separation. It was mentioned above that about one-half of all slow neutrons are absorbed by the main uranium isotope, U^{238}. They are thus lost for the chain reaction in the pile; but the product to the formation of which they lead is at present more eagerly sought than the radioactive fission products or the energy produced by the pile.

This product is the element plutonium - a "transuranium" element not known in nature, and formed from U^{238} by the addition of a neutron and the subsequent loss of two beta particles.

Thus, the processes in a uranium pile can be described by the equations (1) and (2).

(1) U^{235} atom plus slow neutron ⟶ 2 radioactive smaller atoms (fission products) plus fast neutrons,

where the average number of fast neutrons coming out per atom of uranium 235 used up is about 2.3. Of the fast neutrons (energies of the order of a million "electron-volts"), most are slowed down by the graphite so as to become slow neutrons (energies of the order of those of gas molecules in normal air). When the pile is operating steadily, one slow neutron, out of those neutrons produced in the original step (1), finds a U^{235} atom and repeats step (1).

Of the remaining neutrons produced, the majority are captured in the following process:

(2) U^{238} atom plus neutron ⟶ U^{239} atom ⟶ beta ray plus Np^{239} atom ⟶ beta ray plus Pu^{239} atom.

This scheme shows that the direct product of capture of a neutron by U^{238} is an atom of the uranium isotope U^{239}, which, however, is radioactive and quickly decays into an atom of the new atomic species Np^{239}; this in turn decomposes, somewhat more slowly, into an atom of the relatively stable Pu^{239}. Np and Pu are the symbols for two new chemical elements, neptunium and plutonium, of atomic numbers 93 and 94, following uranium (atomic number 92) in the periodic system of the chemical elements. Although they were earlier produced in minute amounts by the operation of the Berkeley cyclotron, it is only by the use of the pile that we can make such new synthetic elements by the gram or by the pound. Like U^{235}, Pu^{239} is fissionable by slow neutrons and also gives a chain reaction. Since it is chemically different from uranium, it can be separated from the latter by chemical methods. However, the small concentration of plutonium in the pile-treated uranium (of the order of 0,1% at the best), and the large variety of the fission products which have to be removed from it, make the purification process uniquely difficult. An extensive study of methods for separating the plutonium has been carried out by the various divisions of the Metallurgical Project, and the final success of this study is a major achievement of the Project. The tremendous radioactivity of the material after its sojourn in the pile has created problems of handling, waste disposal and health which were entirely new for the chemical industry and required a wide employment of remote control methods and automatic devices. All these procedures have now been developed for full scale operation.

One point may be in need of clarification. How does the chain reaction start in the pile? When defining chain reactions in chemistry, we spoke of the external energy required for initiation of the chain. One could thus think that a neutron source (brought into operation by a naturally radioactive element or by cyclotron bombardment) would be required to initiate the reaction in the pile. In fact, however, the pile "ignites" itself if it has the proper size. The neutron production caused by the spontaneous disintegration of uranium, however small its yield, perhaps aided by neutron production caused by cosmic rays, is sufficient to provide the initial reaction impulse; the branching of the chains leads to the rapid expansion of the reaction.

IV. THE DAWN OF THE NUCLEONICS AGE

The aspect of the pile which commands almost exclusive interest in war time is the production of plutonium. However, we can visualize other developments, equally vast in scope and variety, which the newly acquired mastery of nuclear power promises to bring about, and which are bound to come into their own under peacetime conditions.

Important developments are likely to stem from all three functions of the pile mentioned in Section III -- power production, production of new heavy elements, and production of radioactive isotopes of common elements. In addition, the pile can be expected to find applications in science, medicine and technology as a source of intense radiation, providing powerful beams of gamma rays as well as of slow and fast neutrons.

In this section, we will try to present a general view of the approaching "nucleonics age", while the next section will be devoted to a review of some concrete developments of nucleonics which may be anticipated in the nearer future in various fields of human endeavor.

Power production

In trying to assess the future importance of nuclear power, one has to consider three aspects of power production: (1) the amount of available energy, (2) its intensity or concentration, and (3) its availability under conditions which limit the usefulness of the more common energy sources.

That the quantity of nuclear energy available in unstable uranium isotopes is not small is made obvious by the fact that the first plutonium-producing pile is designed to produce energy (in the form of heat) at a rate comparable to the output of large electric generating stations in America. To produce this energy, only about one pound of the unstable uranium isotope U^{235} will have to be consumed daily. At the same time, about one pound of the stable isotope U^{238} will be converted into plutonium. The consumption of one pound of U^{235} per day would correspond to the use of about 140 pounds of ordinary uranium metal per day, or a ton every two weeks. It has been estimated that the total quantity of uranium available in high grade ores on earth is about 20,000 tons, of which about 10,000 tons are on this continent. This latter amount will enable 5 piles of the larger type described above to run for 75 years.

This estimate is based on the assumption that plutonium is regularly removed and utilized for other purposes. If plutonium is allowed to remain in the pile (more exactly, if, after a sufficiently long irradiation time, uranium and plutonium are separated from the fission products and returned into the pile), the process can theoretically be continued until all the U^{238} is consumed. In this way a given supply of uranium would last 140 times as long as was estimated above for the consumption of U^{235}. However, even so, the energy available in 10,000 tons of uranium will not be sufficient to permit this material to replace coal and other combustible materials, or falling water, as an energy source. The present coal consumption is of the order of a billion tons <u>per annum</u>; the nuclear energy content of uranium is, pound for pound about one million times as large as the chemical energy content of coal; thus

10,000 tons of uranium are equivalent to ten billion tons of coal, or to a ten-year consumption of this fuel. Obviously, one cannot hope to replace our main sources of energy — coal, oil, or falling water — by a material available in such limited quantities. However, it is quite likely that methods will be found to produce uranium from ores of lower grade, which are much more common than the relatively rich ores pitchblende and carnotite which now are mined. Uranium is by no means a rare element in the earth's crust, being present in small quantities in many common rocks.

Furthermore, in all probability, uranium will not remain for long the only source of nuclear power. As was mentioned in Section III, very large amounts of energy are contained in all very heavy and very light elements. Thorium, in particular, the nearest neighbor of uranium in the periodic system, is likely to become important as a pile material. Thorium is considerably more abundant than uranium, and large deposits of thorium-bearing monazite sand have been found in various countries, mainly Brazil and India.

Vastly larger quantities of nuclear energy are locked up in the much more abundantly available light elements, particularly hydrogen. It was mentioned in Section III that the sun probably derives most of its energy from a slow conversion of hydrogen into helium. All the energy sources which we have so far tapped on earth represent only an infinitesimal fraction of the solar energy which has reached the earth since its formation, and the latter in turn is only an infinitesimal fraction of the total energy which the sun is radiating into space.

Thus, mankind has been living on driblets of converted nuclear energy during all history.

The conversion of hydrogen into helium is possible in the sun because of the tremendously high temperature prevailing in its interior. One could thus doubt that it will ever be possible to achieve a similar process on earth. However, it used to be said only a short time ago that man is unlikely ever to achieve control of the nuclear energy which was known to be contained in uranium and other heavy elements. In the light of scientific history, it would be unwise to overlook the possibility or even the probability that we shall learn to obtain and control nuclear power from hydrogen, thus making available the water of all the oceans as a fuel or power source. It seems possible that the use of neutrons from a chain reacting pile may provide the key to the release of the nuclear energy of hydrogen. If we learn to unlock this inexhaustible store of power, then indeed, we shall be in the midst of the nucleonics age, and all other sources of energy will become utterly puny in comparison.*

Even though the possibility of obtaining an unlimited quantity of nuclear energy, and making coal, oil, or falling water obsolete as sources of energy, lies in an as yet dimly perceived (but by no means fantastic or necessarily remote) future, there is no uncertainty

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*It has often been suggested that we shall succeed instead in converting the earth, or even the whole solar system, into a super-nova; but our experience in controlling nuclear power from uranium is distinctly reassuring in this respect.

whatsoever about the tremendous superiority of nuclear power over all other sources of energy so far as the concentration of energy and the possible intensity of its release are concerned. As stated previously the amount of energy generated by the fission of one pound of uranium is several million times greater than that available in an equal weight of coal or any other ordinary fuel or explosive. To make this relation more vivid, one may point out that the fission all at once of the atoms in a piece of uranium the size of a dime would represent as energetic an explosion as that of fifty two-ton block-busters exploded simultaneously. One pound of uranium, if it could be exploded under the Empire State Building, would produce enough energy to lift this building several miles high into the air. However, it should be understood that an actual explosion is not possible with ordinary uranium, but only with the isotope U^{235}, and then only by the use of sufficiently large quantities of the material.

According to calculations made before the war, such a nuclear explosion is capable of producing not only a tremendous blast of air, but also a blast of gamma radiation such as to kill all living matter for miles around. Further, the long-lived radioactivity of the fission products should make the neighborhood unfit for habitation for a long time afterwards.

We have considered the quantity of energy available in the unstable nuclei, and its concentration. It remains to say a few words on the third aspect of power production, the availability of this power under conditions where ordinary power is difficult to obtain. A nuclear energy generator can work for a very long period without fuel supply. It is therefore tempting to think of using such generators in deserts or polar countries, on ships in the ocean, or even in excursions into space — in short, under conditions where the weight of fuel to be transported is a handicap for the utilization of ordinary power engines.

Production of New Heavy Elements

The synthesis of new heavy elements, both within the pile and on the outside of the pile through the absorption of neutrons pouring out from it, has immense possibilities.

In Section III we have discussed plutonium as the first such element to be produced in measurable quantities, and mentioned its fissionable character (similar to that of U^{235}), which gives it explosive possibilities and consequent military importance. Another element which can be obtained in the pile, the uranium isotope 233, shares these possibilities. In contrast to the uranium isotope 235, which has to be separated from natural uranium by laborious methods of isotope separation, the isotope U^{233} can be produced from thorium (element 90) in the pile in the same way as plutonium is formed from uranium (element 92), and can be separated from its mother substance by chemical methods.

The preparation of U^{233} illustrates how the stray neutrons which escape from a pile can be used. These stray neutrons are part of the neutrons produced in process (1) of Section III and not utilized either in process (2) or in a repetition of (1). If thorium (Th^{232})

is placed in the pile, or around the pile, the following process occurs:

(3) Th^{232} atom plus slow neutron $\longrightarrow$ Th^{233} atom $\longrightarrow$ beta ray plus Pa^{233} atom $\longrightarrow$ beta ray plus U^{233} atom.

Production of new neptunium isotopes (we recall that neptunium is the element 93, situated between uranium and plutonium, and that one of its isotopes is formed as a short lived intermediate in the production of plutonium), as well as that of elements beyond plutonium, is entirely reasonable to expect, and these, too, may prove to be suitable for use in piles or other nuclear power devices.

Production of radioactive isotopes of ordinary elements

In Section II, we have spoken of the use of the few available natural radioactive elements, and of the more abundant artificial radioactive isotopes obtained by neutron bombardment, as "tracers" or "stand-ins" in the investigation of various processes. This technique, which despite the limited availability of its tools, has already contributed a large amount of valuable information to physics, chemistry, and particularly biology and medicine, is scheduled for an unprecedented development when radioactive isotopes of practically all chemical elements become available in large quantities and abundant variety as by-products of the exploitation of piles.

These materials will be produced in two ways. In the first place, fission produces a large assortment of radioactive isotopes of medium atomic weight, such as radioactive barium, radioactive xenon, radioactive cesium and many others. At present, the removal of these tremendously radioactive "contaminations" constitutes a major difficulty and source of danger in the separation of plutonium from uranium after the pile treatment. In the future, these contaminants will constitute by-products as effective as radium is now, and in much larger quantities, both for "tracer" studies and for medical irradiation purposes.

The assortment of radioactive products obtainable in the pile is, however, not restricted to those produced by fission. If a specific isotope is required, it can often be produced "to order" by introducing a suitable material into the pile, or exposing it to stray neutrons escaping from the latter — a method which we have described above when speaking of the production of U^{233} from thorium.

In order to be able to allow a large proportion of neutrons to escape from the pile without running the risk that the chain reaction may be stopped by this "leak", one will need piles with a larger "multiplication factor" than that of the uranium-graphite pile. One way to obtain these is to substitute heavy water (D_2O) for graphite in a type of pile which holds much promise for the future and of which one is in operation. Still better, perhaps, in the long run, will be the use of "enriched" piles where ordinary uranium is replaced by a uranium which has been enriched in U^{235}, or to which have been added Pu^{239}, U^{233}, or perhaps Th^{232}, or other heavy atoms natural or synthetic. These piles can be made much smaller than the ordinary uranium piles whose minimum size is determined by the necessity of preventing too many neutrons from escaping through the walls.

Such enriched piles probably also hold out the most future promise for utilization as power generators, while the larger piles of ordinary uranium may retain their importance as chemical factories for the production of plutonium and radioactive by-products.

<u>Radiation Production</u>

At present, the tremendous radiation which surrounds the operating pile is considered as a nuisance, since it necessitates extensive shielding and remote control operation. However, this radiation, too, can in the future be put to many uses. We have mentioned before the use of stray neutrons for nuclear transformations; but they — as well as the powerful hard gamma rays escaping from the pile — can also be used to bring about chemical transformations. Many possibilities of this type will be mentioned in the next section. One can also envisage a pile as the nucleus of a nuclear health center, equally useful for medical treatment of cancer and similar diseases and for biological research.

V. THE NEARER FUTURE OF NUCLEONICS

We have attempted to give, in the preceding section, a general idea of the tools which the development of nucleonics promises to give mankind: a new source of energy, a source of radiations of extraordinary intensity, several new heavy elements of exceptionally interesting properties, and a vast assortment of radioactive isotopes of ordinary elements. Let us now survey a few of the infinite number of possible applications of these new tools in different spheres of science and technology.

Many of the suggestions enumerated below are speculative and we do not wish to imply that we expect that all will be put into practice. Nevertheless we believe that this group of suggestions, including the most speculative ones, does give a correct and not exaggerated impression of the type of development which is in store.

Physics.

Striking changes can be expected to follow from the availability of nuclear energy in both pure and applied science. The construction of the chain-reacting pile is a notable example of how disinterested research in a field of physics apparently far remote from any practical interest can suddenly yield results of tremendous technological value. The potential practical importance of pure research is likely to be shown in this case even more clearly than in the well-known example of the development of the electrical industries from the discovery of electromagnetism by Faraday.

In the haste of wartime development, further basic experimental and theoretical research on the true nature of atomic nuclei, although it provided the basis for the realization of the nuclear chain reaction in the pile, has of necessity been neglected. After the war, this type of research will come into its own again. Making use of the powerful tools for nuclear transformation made available by the industrial development of the pile, the science of nucleonics will strive to penetrate deeper into the mystery of the nucleus. A better understanding of nuclear structure, acquired in this way, is certain to open new ways for the practical mastery of nuclear forces. The old story of science and technology mutually assisting and promoting each other is likely to be repeated in nucleonics on a more spectacular scale than ever before. We have witnessed a development of this type in the wartime history of nucleonics, where the study of minute quantities of plutonium made accessible by the cyclotron technique has revealed the potentialities of this material as a source of nuclear power, and thus provided the incentive for the construction of large-scale plutonium-producing piles.

While nucleonics promises to become, after the war, the most lively part of theoretical and experimental physics, other branches of physics will undoubtedly benefit from the possibility of using the radiations from the pile, as well as pile-produced radioactive tracers. This will be particularly true of all studies of migration and exchange processes of the type of diffusion or evaporation, as well as of the investigations of the general properties of the crystalline and liquid states.

Chemistry and Chemical Engineering

Pure and applied chemistry are likely to make an even wider use than physics of pile radiation and pile products. In the realm of inorganic chemistry, the study of the transuranic elements is certainly going to be eagerly pursued, particularly when these elements become more readily available. Suffice it to recall that the discovery of a single new element has always been considered an important step forward in the history of chemistry. The cyclotron and the pile have already made possible the discovery and production of two new elements, neptunium and plutonium, and may provide several more. The position of these elements at the extreme end of the periodic system makes their study very important for the better under standing of the latter.

The radiations of an operating pile are known to produce pronounced chemical and other changes in graphites, water, and other materials. In the future, these radiations can be used to bring about transformations of various materials which may be difficult or impossible to obtain in any other way. Such materials could be irradiated inside or outside the pile. A new "super-photochemistry" already is emerging from studies of this type. In contrast to light, the pile radiations (consisting of gamma rays and neutrons) are absorbed by every kind of matter. One may therefore anticipate difficulties in producing selectively the desired transformations; but certainly this will be found possible in some cases. As a result, pile irradiation may replace catalyst action or high temperature in various important chemical or physico-chemical processes, such as nitrogen fixation, hardening of metals or plastics, cracking of petroleum oils, and chain polymerization as in making synthetic rubber.

An improved method of making liquid fuels from coal, lignite, cellulose, and the like, could perhaps be obtained. Natural gas with or without other added constituents, for example, water, carbon dioxide, ammonia, hydrogen sulfide, and so on, could be circulated over artificial radioactive material or through a pile, to produce synthetic rubbers, plastics, lubricating oils, fuels of special characteristics, and so on. It may prove feasible to synthesize certain low volume, high-priced organic chemicals by exposure to pile radiation.

The use of radioactive tracers also will become important for both pure and applied chemistry. In pure chemistry, the possibility of providing a radioactive "stand-in" for practically every ordinary element will give entirely new possibilities for all studies in the field of reaction kinetics, enabling the chemist to follow the fate of all components throughout a chemical process, and to detect transfers of atoms from place to place within a molecule, or from one molecule to another, even in the state of chemical equilibrium, where ordinary chemical methods show no change at all.

The use of the radioactive carbon isotope C^{14}, in particular, promises to create for the first time the possibility of investigating directly the mechanism of organic reactions, and of verifying the concepts which organic chemists have widely used in their work.

In applied chemistry, tracer methods will be important for the study of such processes as corrosion, diffusion, adsorption, and formation and destruction of colloids. They will be used for studying the performance of distillation columns and other equipment used in chemical engineering, for example in the oil industry. Particularly important as a tracer in the oil industry will be the carbon isotope C^{14}. Experimental chemical engineering, including research and development work on the unit operations, general trouble shooting work on chemical processes, and correlation of performance data on chemical process equipment, offers a wide variety of possibilities for useful applications of the tagged atom technique as an analytical method. In the rare gas industry, radioactive rare gases obtained as pile fission products will be very valuable.

In the study of fluid flow, radio-compounds can serve as metering fluids in the usual method of dilution measurement; they have a decided advantage in ease of analysis. Again, the linear velocity of liquid flow in a pipe can be measured by timing the successive appearance of activity at two points along its length. This method is of special value where circumstances are such that sampling is impossible; the activity can be detected through the pipe walls.

Biology and Medicine

In medicine and in biological science, both the intense radiation emitted by the pile or by products made in it, and the radioactive tracer isotopes, will be of utmost usefulness. As we have stated before, a working pile may well become a center of biological radiation research and therapy. Radioactive fission products, as well as radioactive isotopes prepared "to order" from pile-irradiated materials, will be widely used for medicinal purposes. Not only will they be available in quantities vastly greater than those in which radium or mesothorium can be obtained now, but they will also allow a much wider selection of radiations with respect to both type of radiation and penetrating power; and they will often permit localized treatment of the type which was illustrated in Section II by the example of radioactive iodine absorbed selectively in the thyroid. One could also produce a radiation center directly in the tissue where irradiation is desired, by introducing locally an element such as boron which strongly absorbs neutrons, and irradiating it with a stream of neutrons.

The use of tracer elements is even more important for biology and medicine than it is for physics and chemistry. In biology, such isotopes as radioactive phosphorus and the non-radioactive rare isotopes of hydrogen, carbon, oxygen and nitrogen have already been used with conspicuous success in determining the mechanism of many complex steps in metabolism. They have also been used in finding out how single atoms or large atomic groups are exchanged in living tissues for fresh ones - a process which goes on continuously even in such permanent structures as teeth or bones. When radioactive carbon (C^{14}), nitrogen, and hydrogen become easily available, the usefulness of the radioactive tracer technique will be vastly increased. It will be applied to the solution of the basic problems of animal and plant metabolism, such as respiration, photosynthesis fat and protein metabolism, as well as to minor puzzles presented by the metabolic role of "micro-nutrients", such as cobalt, whose absence has caused widespread losses of ~~cattle~~ sheep in New Zealand.

Photosynthesis, that is the building up, through the action of light in green leaves, of complex organic compounds such as form the structure of plant and animal tissues, is the most important single biochemical process in nature. No life at all would be possible on earth if we did not have plant life to synthesize organic matter from the inorganice materials carbon dioxide and water. In this process, plants use the energy of sunlight - which as we have seen is itself derived in the final analysis from nuclear energy - and convert it into the chemical energy of combustible organic matter. Not only all animal life, but also all technological developments based on coal and oil, are possible only because of this function of plant life.

Despite extensive studies, we still know practically nothing about the mechanism of this most fundamental process of life, which nobody has yet succeeded in repeating outside the living plant cell. We do not know what intermediate chemical compounds are formed in the course of photosynthesis, nor what is the first product of it. All these questions could perhaps be answered by using tagged radioactive atoms of carbon.

The animal organism reverses the process of photosynthesis; sugar is oxidized to carbon dioxide and water, liberating energy. In this case the process, although it involves a great number of steps, is comparatively well understood, but its understanding has required the work of hundreds of investigators for several decades.

By the use of tracers the effort to obtain this knowledge would have been greatly reduced; and much additional information (for example, concerning the role of copper and other metals in respiration) can still be expected from the application of the tracer technique. Comparatively little is known about the metabolism of fats and proteins; in these fields, more complex than that of sugar metabolism, tracer techniques hold great promise.

Once we understand the oxidation and breakdown of proteins in the animal body, the solution of the reverse problem, that of growth, will be greatly aided. The problem of normal growth is fundamental to that of abnormal growth or cancer.

It is known that plants require some twenty or more elements for their growth, including such "micronutrients" as boron, manganese or cobalt. Because micronutrient experiments on animals are practically impossible, we have no similar information on them. Tracers, however, will make the study of this field easily possible.

What is the mechanism of nerve action? How do pathogenic bacteria carry out their poisonous missions? What is the mechanism of immunological reactions? What is the chemical reaction which controls the beating of the heart? What is the mechanism that stops and starts growth? These are only a few of the current questions to which prompter answers will very probably be obtained by the use of tracers.

In medicine, many artificially activated substances are now being used as tracers, particularly diagnostic work. Radioactive iron, for example, is being used to label and trace red blood cells in shock cases. Activated sodium metaborate is used to check blood circulation time in cases of "immersion foot", diabetes, hardening of the arteries, etc. The strontium isotope Sr^{39} is used as a tracer for calcium to determine the healing of bone fractures. The iodine isotope I^{131} is used for measuring the functioning of pathological thyroid glands.

Another primary biochemical use of tracers is in analysis, for which such adaptations have been made as the radioautograph to determine the actual cells involved in an accumulation or secretion process; the use of gamma radiation to analyze for a tracer species without destruction of the animal or tiss ue analyzed; and analyzing quantitatively by the "isotope dilution" technique for chemical or cellular constituents which cannot be isolated or separated in a quantitative manner.

All these methods and procedures will be facilitated and many new ones will be made possible by the abundantly available isotopic tracers derived from the pile.

Scientists have already induced mutations by means of radiation, so that it is not improbable that geneticists may now be able to produce many more new and economically important types of plant and animal life.

Metallurgy

In metallurgy, the use of radioactive tracers has many possible applications. Some of these are as follows:

Diffusion of an element into itself and into alloys in which the element in question is a component, can be followed if the diffusing atoms are radioactive.

Inclusions, that is small bits of foreign matter in metals, could be identified by adding a radioactive form of suspected components to the melt. The inclusions could furthermore be photographed by microradiographic techniques.

Minor constituents often markedly affect the properties of metals and alloys. Positive identification and location of these minor constituents is usually very difficult by microscopic methods. Microradiographic method could be used in studying the distribution of these minor constituents among different phases in a piece of metal.

Engineering and Construction

In the design and testing of machinery and in many phases of engineering and construction, radioactive tracers and other pile products have promising applications.

They could be applied to problems of wear and lubrication of moving parts. Wear problems are concerned with pick-up of metal or other material from one surface to another. By introducing tracers, the effect of pick-up under various conditions, such as surface treatment, lubrication, loading, temperature, and so on could be studied.

One might introduce small amounts of radioactive gaseous fission products into tanks and other equipment to test for leaks; use the same kinds of active gas for determining convection and air removal rates in ventilation problems for buildings; or use the active gases to determine the permeability of relatively impervious membranes and structures.

Radioactive tracers have already found use in the field of geophysics for tracing flows of liquid or gaseous materials in subterranean deposits, and this use can be extended. Tracers might also be used in measurements of flow in sewers and over dams where the volume is high and ordinary chemicals would have to be used in too large a quantity. Radioactive sodium or other material could be added to drilling muds pumped into oil wells to establish whether the mud is reappearing in adjacent intersecting wells. Questions of underground drainage of oil across property lines could also be attacked by adding oil-soluble active material in one well and looking for it in neighboring ones.

Radioactive materials could be embodied into paints and floor coverings for cutting down static. These paints and coatings might be made using either beta or very soft gamma emitters. They would be particularly useful in explosives plants and in the printing industry.

Hard and soft gamma emitters of reasonably long life made up into radiation "sources" could be used as substitutes for industrial and clinical X-ray machines. The possibility of putting a gamma ray source into body cavities is attractive since better picutres could be obtained than is now possible in some cases. The same would be true of X-ray pictures made of machinery, castings, etc. The small size of the source required would permit its insertion into the inside of complicated hollow castings, and so on.

In the lighting field one can visualize a cold light that would last for many years, produced by mixing radioactive material with luminescent material.

The field of instruments relating to nucleonics will be very large. The need for instruments in this field is, perhaps, greater than that of any other so far uncovered by man.

Prospecting for minerals should be a fruitful field for nucleonics applications. For instance, the presence of beryllium might be determined by the emission of neutrons upon irradiation by gamma rays, and the fluorescence of many minerals under gamma irradiation might likewise be used. In any case where specific nuclear reactions are involved, a suitable device could be set up which would specifically determine these elements.

Agriculture

Nucleonics even promises to go out on the farm and help the farmer of the future, both by irradiation and by the application of tracers. Commercial growers are already producing superior pineapples from a mutation obtained by irradiation. The detection of selenium in fodder plants in certain South Dakota counties where animals have been poisoned because plants they ate had absorbed selenium from the soil, is a typical problem which can be studied by the radioactive tracer technique. The same applies to other poisons, as well as to "micro-nutrients" which are important for the growth of plants. Small amounts of radioactive material might be sprayed on migratory insect pests to aid in determining their origins, routes, and migration speeds. Radioactive isotopes could be used to test fertilizer materials for immediate availability.

Power

We have spoken so far in this section only of the use of the "by-products" of the pile development - radiation and new isotopes.

The present quantitative limitation and the immense intensity of nuclear power have been described in the preceding section. These two characteristics determine the uses to which nuclear power may be put in the immediate future, that is before pile materials other than uranium are utilized.

The limited amount of available uranium precludes a widespread use of pile power for energy production in competition with coal, oil or falling water. However, the tremendous heat generated by a working pile built primarily for other purposes, for example plutonium production, can certainly be utilized in such ways as the central heating of large areas, thus freeing oil for premium uses (aircraft, automobiles, and so on). Since the petroleum supply is definitely conceded to be critical by even the most optimistic geophysicists, plutonium plants might, despite their cost, become an economic necessity on the east coast where oil is now being used for heating both public buildings and private homes. While it is unlikely that piles will be constructed for heating purposes alone, it is quite probable that waste heat will be an important by-product of piles constructed for other purposes such as the fission process itself, or for supplying power for mining or irrigation in inaccessible places.

Piles built with material capable of sustaining high temperatures, for example with beryllium metal as moderator, will offer improved thermodynamic possibilities for power production. Even without such radical efficiency improvement, the pile may conceivably prove useful as an energy source under special conditions where its freedom from fuel supply limitations may outweigh all other considerations, particularly those of costs. That cost is not always the decisive factor in the selection of methods of energy generation, is illustrated by the following example.

If electrical energy is to be used in the manufacture of metallic aluminum, the cost should be in the neighborhood of 0.2¢ per kilowatt hour. Electrical energy for many industrial uses is practical at around 1¢ per kilowatt hour. Electrical energy for home lighting is economical at 5¢ per kilowatt hour. Large amounts of power are used in automobiles, trucks, buses and airplanes at a cost of around 20¢ per kilowatt hour, without including any labor or up-keep items. We would willingly pay $1 per kilowatt hour, or more, for electrical energy with which to start our automobiles rather than return to the old handcrank. The public also consumes a substantial amount of power for electricity to operate flashlight lamps from small dry batteries. A round figure for the cost of this power is $30 per kilowatt hour. Thus, it is seen that the value of power is not a fixed thing, and it may be that many uses will be found for pile power in which the overall cost of the power is not the controlling factor. On the other hand, we should not conclude that the cost of pile power is necessarily going to be high as compared with other power sources. This is one of the great uncertainties of the future which can only be answered by further experimentation and experience.

Let us consider some aspects of the power situation. It might be possible to put in power plants in the Far North, in the Antarctic, or in desert regions adjacent to important mineral deposits. Other sources of power might be practically unavailable in these areas and piles might make it possible, therefore, to gain added mineral resources for mankind. While these mineral resources were being made available for man's use, one or more of the other by-products might also be produced, which could have the result of making the entire operation economical.

Pile power may also be used for transportation, particularly in regions far distant from fuel supply bases. While pile-powered interplanetary ships still belong to the realm of scientific day-dreaming, pile-powered battleships or submarines have been considered as likely applications of nuclear power in the relatively near future.

It is not impossible to hope that a submarine powered by a pile could make a round trip across the Pacific without once having to surface for refueling or for recharging of its batteries. Of course, much experimentation will have to be completed before a small compact unit of relatively large capacity can be produced for this purpose, but the total uranium needed is so little compared with the reserves available that this application appears to be among the most promising ones.

The generation of nuclear power for driving a fleet of 30 modern battleships would require 30 power plants of roughly 500,000 KW capacity (heat rate) each. Assuming that these operate at only 10% of rated capacity on the average, the total heat dissipation rate would be 1,500,000 KW; the known North American uranium reserve could support such a fleet for about 470 years. Thus the uranium supply is large enough to warrant discussion of its use in battleships. The great weight of the pile and the fact that this weight must necessarily be concentrated in one part of the ship probably will lead to structural design changes in the ship itself, since at present the fuel reserve is widely distributed over the ship.

Explosives

It is clear from what was said in Section IV what terrifying results can be expected from the use of plutonium or other pure fissionable isotopes as explosives. The possibility of their use for military or political purposes inevitably dominates not only the war time development of nucleonics but also all discussion concerning its post-war future.

This is the main reason why, unlike most other scientific discoveries and inventions, the pursuit and organization of nucleonics after the war cannot be left entirely to private scientific and industrial initiative without bringing mankind and our nation in particular into the gravest jeopardy. This consideration has caused us to devote to the military and political implications of nucleonics a separate Section VI, and to present in the final Section VII, a series of recommendations as to how the development of nucleonics should be organized in this country after the war emergency is over.

It is, of course, our most ardent hope that nuclear explosives will never be used to annihilate cities or whole nations. One can hope that if they are used at all, it will be for peacetime engineering undertakings on a scale deemed impossible until now. The development of such peacetime applications of nuclear explosives will hinge on methods of controlling the time and violence of the explosions. When nuclear explosives are brought under control, one may be able to consider seriously such spectacular things as changing the direction of sea currents, destroying or diverting tropical hurricanes, removing the danger of earthquakes or volcanic eruptions by timely release of the accumulated pressure or strain, or of reducing to a few days the time required for the blasting of such waterways as the Panama Canal.

VI. THE IMPACT OF NUCLEONICS ON INTERNATIONAL RELATIONS AND THE SOCIAL ORDER

Military Implications

It is the unanimous opinion of observers acquainted with the active work in nucleonics that developments in this field will be of extraordinary importance in connection with the post-war security problem. We know that the British are actively engaged in this work. A reasonable surmise is that the Germans are about as far along as ourselves and are pressing the subject most vigorously. It would be surprising if the Russians are not also diligently engaged in such work. Until the peace has become stable, we can afford no relaxation in our present developments. Rather, we have to broaden them, so as to include possibilities hitherto neglected under the pressure of immediate needs imposed by the war. Otherwise, we may find to our surprise that our present strong hand is covered by a stronger.

While it is our duty to our nation to see that no such surprise ever takes place, by preserving and extending in the post-war period the lead in the field of pure and applied nucleonics which we believe we have established now, it cannot be emphasized too strongly that no lasting security against a national and international catastrophe can be achieved in this way. Peace based on uncontrolled and perhaps clandestine development of certain phases of nucleonics in a number of sovereign nations will be only an armistice. It is bound to end, sooner or later, in a catastrophe, particularly because nuclear power, beyond any older means of warfare, holds out to the aggressor the temptation of being able to make a successful sudden stroke, even against a vastly more powerful and well prepared nation. Nuclear weapons might be produced in small hidden locations in countries not normally associated with a large scale armament industry, thus evading surveillance. A nation, or even a political group, given the opportunity to start aggression by a sudden use of nuclear destruction devices, will be able to unleash a "blitzkrieg" infinitely more terrifying than that of 1939-40. A sudden blow of this kind might literally wipe out even the largest nation — or at least all its production centers — and decide the issue on the first day of the war. The weight of the weapons of destruction required to deliver this blow will be infinitesimal compared to that used up in a present day heavy bombing raid, and they could easily be smuggled in by commercial aircraft or even deposited in advance by agents of the aggressor.

If a war should start with both sides unprepared for immediate use of nuclear weapons, the nation which has accumulated the larger reserves of critical materials or developed the best ways for their conversion into nuclear explosives will have in exaggerated form the same type of advantage that this country has had in the present war because of superior capacity for airplane construction.

The situation as it has been developing may be described by an analogy somewhat as follows. Since the area of the earth does not increase, the advantage of the attacker constantly increases with increasing technical development. If two people are in a room of 100 by 100 feet and have no weapons except their bare fists, the attacker has only a slight advantage over his opponent. But if each of them has a machine gun in his hands the attacker is sure to be victorious. Similarly, as long as the weapons of war were of the caliber of rifles and guns, the act of attacking gave very little advantage. The situation had already changed substantially with the advent of the airplane; the present war illustrates this point clearly. With the production of nuclear bombs, however, the world situation approaches that of two men with machine guns in a 100 by 100 foot room.

The problem of the elimination of aggression will no doubt be solved eventually in the same way in which modern society has solved the problem of machine guns. It has given the privilege of possessing machine guns only to a well-disciplined group responsible to established authorities. Similarly a central authority, must be set up to exercise the necessary control over nuclear power.

Until such an authority is established, even the most intense and efficient "nucleonic re-armament" of a nation will not be able to give this country enduring safety from a sudden devastating blow.

The most that an independent American nucleonic re-armament can achieve is the certainty that a sudden total devastation of New York or Chicago can be answered the next day by an even more extensive devastation of the cities of the aggressor, and the hope that the fear of such a retaliation will paralyze the aggressor. The whole history of mankind teaches that this is a very uncertain hope, and that accumulated weapons of destruction "go off" sooner or later, even if this means a senseless mutual destruction.

The Dilemma of Technological Progress in a Static World Order

As we approach the nucleonics age, the existing gap between continued technological progress and our relatively static political institutions tends to widen. The tension impelling us toward a solution of this problem on a world-wide scale may rise to extreme heights. As recently stated by Dr. L. L. Mann, "technological advances without moral development are catastrophic. Thus brotherhood, once a vision, is now a necessity."

Two types of solution seem possible. These may briefly be described as forward-looking and backward-looking. The backward-looking approach would call for a moratorium on the progress of science and industry, and in particular nucleonics, in order to give social, economic, and political development a chance to catch up.

The forward-looking approach would combine an intensive development of nucleonics, because of its immense potential benefits to humanity, with an even more intensive effort to solve the most crucial of existing political problems on a world-wide scale. In this approach, widespread scientific education must go hand in hand with education of the general public. The moral development necessary to prevent the misuse of nuclear energy can only be achieved if public opinion becomes fully aware of the catastrophic possibilities inherent in the development of nucleonics, and thus prepared to give its support to the decisions required to prevent the danger. Public opinion will agree to the abandonment of cherished old traditions only if it becomes absolutely clear that their retention will of necessity release forces that will bring about self-destruction of civilization, if not of mankind.

Neither of the two approaches can succeed without international cooperation, and both involve grave risks. The backward-looking approach, if adopted by any individual nation, will inevitably mean national suicide for that nation. For there will be other nations which will be willing and glad to take advantage of this situation by arming themselves for modern and in particular for nucleonic warfare.

Thus, the forward-looking approach, providing for the maximum intensity in the development of nucleonics, appears the only one feasible. But it must be continuously kept in mind that without a worldwide organization for the maintenance of peace, this approach will hasten the coming of the most destructive war in history. In this war, if all are not destroyed, it is likely that one nation will acquire global dominance so that a world organization will in the end be established, but probably in a form not to our liking. To sum up, we believe that the inevitability of the development of nucleonics by some if not all nations shows compellingly, because of its potential military consequences, the necessity for all nations to make every effort to cooperate now in setting up an international administration with police powers which can effectively control at least the means of nucleonic warfare.

The Control of Critical Materials.

Among the ways by which the worldwide development of nucleonics can be kept under control, one of the most important is the supervision over critical materials, particularly those which are of crucial value for military purposes. Even within a nation this is of particular importance, since any group gaining control over such materials might seize and hold power in that nation.

In the first place, worldwide prospecting for the ores of such critical metals as uranium, thorium, beryllium (which may be very important in nucleonics), and perhaps bismuth, will be needed. In addition to prospecting the rocks and earth, sea water, and the sea floor, salt lakes and fossil salt lake beds should be examined as possible sources of these raw materials. Careful studies on the mining of these ores, and the stockpiling of the resulting metals and perhaps also of heavy water (which may be important for use in future piles), will need to be instituted. It is probable that U^{235} and such pile products as U^{233} and plutonium will be rated as vital national or international assets such as gold has been in the past.

If so, it might be possible to work out plans whereby these materials would be made in greater quantities during times of low employment than during times of high employment. Projects for the recovery of uranium and thorium from low-grade deposits may likewise be made part of a sound program for employment in times of low industrial activity. It now seems that there will be no possibility of acquiring too much U^{235}, U^{233}, or plutonium for generations. No one yet knows what other elements may also be valuable in nucleonics, and should also be stockpiled. Future research alone can answer these questions.

In the future nucleonics industry in America it will be possible to give considerable scope to free private enterprise activity and still have the government hold a tight rein on important factors in the nucleonics field. Control of end products need not be so far different from that of gold, except for safety measures. No one may hoard gold, yet the gold industry is quite free. Gold production is in private hands and any one may purchase it for use in the industries and arts. Industrial ethyl alcohol has been in the hands of private enterprise, but its production and sale are under government observation.

Researchers normally have little difficulty in getting gold or ethyl alcohol for experimental purposes. Similar arrangements could be made if the government had control of all potentially dangerous nucleonics end products. The same might be true of certain of the raw materials involved. While stockpiles are being built up there will be a continuous and steady market for all such materials. The military needs could always be given first preference.

In spite of the need of an unusual degree of governmental or international control over materials used in nucleonics, because of their exceptional possibilities for destruction, this control could be kept at the minimum level consistent with safety.

VII. THE POST-WAR ORGANIZATION OF NUCLEONICS IN AMERICA

In the preceding section, we have emphasized the imperative necessity for a worldwide organization to prevent nucleonics from becoming the destroyer of our civilization. Before such an organization is established, as well as later within its framework, it will be of vital importance for this country to retain its leading position, both in nuclear research and in the nucleonics industry. The present section deals with the probable development of nucleonics in America after the war and with the measures which should be taken to strengthen it.

It will be impossible to stop the scientific world from tackling the whole nucleonics field feverishly in the post-war period. With so many things unknown, there will always be the feeling that something big can come from further studies in the nuclear field. Finding of new facts in this field is of the utmost importance in order that we may achieve as good an understanding of the structure of nuclear matter as now obtains for the electron atmosphere surrounding the nucleus. Our present theory is definitely not sufficient for that purpose. When this understanding has been achieved, who knows what sweeping predictions may be made to guide experimenters straight to goals otherwise attainable only by slow and costly cut-and-try methods?

There should, therefore, be government-supported nucleonics laboratories having ample facilities for both fundamental and applied research. A legitimate side-line of such laboratories would be the supplying of special materials to other research centers and to industry.

It seems, however, both unlikely and undesirable that the whole development of nucleonics should be restricted to these government-sponsored laboratories, under the protection of continued wartime secrecy. On the contrary, full information on most phases of the subject should be released just as soon as possible from the standpoint of national security. Probably this would mean soon after the close of the war, for, as recently remarked by Rear Admiral J. A. Furer, "There is no such thing as permanent secrecy of ideas, or even very much lag in the flowering of the same ideas in the brains of the enemy. I plow through vast heaps of intelligence reports and I am pretty well convinced the enemy is trying to do all — or most all — of the things we are, and is certainly thinking along virtually the same lines. True security lies in speed of accomplishment. It is the only way we can keep ahead of the enemy in this complex technical war of measure and counter-measure."

It is inevitable that differences of opinion shall arise over the question of admitting industrial groups to full participation in the development of nuclear power and its by-products. However, without a healthy development of nucleonic <u>industry</u>, nucleonic research alone will be insufficient to guarantee the leading position of this country and its full preparedness for all emergencies.

In the first forty odd years of the history of nucleonics, up to the discovery of atomic fission, practically all work in this field was done at the universities. The discovery of fission laid the groundwork for the Metallurgical Project and other related projects based on cooperation of universities and industrial concerns. Because of the war and the possible important military uses of the pile products, the government took over the support of this work. In doing so, it gained a patent position in this field which is far more comprehensive than is warranted by its own participation in the development and its legitimate interest in that part of the results which are vital for the security of the nation.

By this cooperative wartime effort the progress of nucleonics has been pushed forward greatly with respect to both science and the groundwork for industrial success. No one can say just to what extent the normal development has been accelerated; but we may well be several years ahead of where we would have been had the war emergency not caused the government to press for full exploitation of this field, and science and industry to place all its facilities at the service of the government.

The best way to maintain the lead which America has acquired in this field probably lies in a combination of (a) extensive nuclear research work in universities and specially created nucleonics laboratories, with (b) continued government-sponsored study and development of the problems directly related to military matters, and (c) a healthy growth of an independent nucleonics industry.

A well-developed nucleonics industry will be the best insurance for military potency in the nuclear field, and will strengthen America's hand in its attempts to achieve an international understanding to make impossible the use of nuclear power for destructive purposes.

It may turn out that the first problem of industrial participation in nucleonics development will be not how to exclude undesirable industrial concerns, but how to induce any concern at all to step into a field which, at least at present, offers little prospect of early profit. Probably only large concerns, able to support long range research programs, will be interested at all, and these only if normal patent claims may be made on bonafide company developments. Objectors to this point of view will speak of monopolies contrary to public interest. The answer is that not one but several independent concerns must become active in the field. The resulting diverse viewpoints, healthful competition of ideas, and the economic urge to develop and produce useful things (as against the scientific aim to discover and develop new things) should result in the growth of a nucleonics industry which, in future emergencies, will be as necessary to the security of the nation as the automotive, the airplane, the metal working, the chemical, and the electronics industries are in this war. This point deserves emphasis: the nation will need pure scientific ability and creative talent in nucleonics; but it will also need the physical plant — piles, radiochemical plants and whatever else may develop — in quantity, and this will come only if there is a nucleonics industry. Research alone is not enough, essential though it is.

Public education in the scientific and technical field on the significance of nucleonics, and enlightenment on its consequences in the national and international situation, are urgently needed in order to prepare for the post-war readjustment. After our weapons have once been demonstrated, a calm appraisal of the realities widely spread before the public will help to obtain full support of the work. What will then be most required is wise judgment in determining how the national effort in this direction can be encouraged and guided. For such guidance our democracy must rely upon the common sense of a generally informed public and the expert opinions of a fully informed group of technical men.

The nations putting in the most effort in nucleonics after the war may be expected to succeed ahead of the lagging nations. The nations which establish conditions favorable to extensive research and industrial development in nucleonics may be expected to show a greater advance in the science and art than nations which, intentionally or otherwise, have policies or laws which discourage research and development in this field. As Americans, we have an important stake in the future of nucleonics from the military, industrial, and scientific standpoints. It is, therefore, of vital importance to the future of the United States that proper relationships be established between governmental and non-governmental agencies in this field.

The broad objectives, in our opinion, should be:

1. TO STIMULATE WIDESPREAD RESEARCH IN NUCLEONICS IN THE UNITED STATES.
2. TO ENCOURAGE THE DEVELOPMENT OF A FREE NUCLEONICS INDUSTRY IN THE UNITED STATES.
3. TO COORDINATE THE GOVERNMENTAL ACTIVITIES IN NUCLEONICS WITH THE SCIENTIFIC AND INDUSTRIAL DEVELOPMENTS IN THIS FIELD IN SUCH A WAY AS TO INSURE MAXIMUM NATIONAL SECURITY.
4. TO STRIVE FOR THE ESTABLISHMENT OF AN EFFICIENT INTERNATIONAL SUPERVISION OVER ALL MILITARY ASPECTS OF NUCLEONICS.

While the procedures necessary for the accomplishment of these objectives may not now be fully obvious, and while they may be expected to be changed as experience is gained, we believe these objectives can be substantially achieved. Some suggestions are offered for consideration:

(a) THE PROJECTS RELATING TO PLUTONIUM, U^{235}, AND PERHAPS U^{233} SHOULD BE PROSECUTED BY THE GOVERNMENT, NO MATTER WHEN THE WAR ENDS, to a point sufficient for military appraisal.

(b) THE DEVELOPMENT OF THE NUCLEONICS INDUSTRY BY PRIVATE ENTERPRISE SHOULD BE ENCOURAGED. The military by-products of the industrial developments should be made available to the government, and the use of government information and patents should be made available to industry so far as the military situation may permit.

(c) SCIENTIFIC EDUCATION AND RESEARCH SHOULD BE ENCOURAGED IN EXISTING UNIVERSITY LABORATORIES, AND NEW RESEARCH LABORATORIES for nucleonics with special facilities SHOULD BE CREATED at universities.

(d) A SUITABLE AGENCY, with both government and non-government representatives, SHOULD BE ESTABLISHED to guide and coordinate such nucleonics activities as may affect the military or other interests of the nation.

(e) ENLIGHTENMENT OF PUBLIC OPINION ON THE SCOPE AND SIGNIFICANCE OF NUCLEONICS SHOULD START AS SOON AS POSSIBLE to bring about realization of the dangers for world security caused by the new scientific and technical developments, and to prepare for decisions which will have to be taken to meet this danger.

(f) COOPERATION WITH FRIENDLY NATIONS in all these problems — particularly the last named one — SHOULD BE GIVEN SERIOUS AND PROMPT ATTENTION.