ATOMIC ENERGY THE NEXT HUNDRED YEARS

By

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ATOMIC ENERGY: THE NEXT HUNDRED YEARS

TONIGHT we, like the humble wayfarer ascending the trackless slope, are stopping for a moment to assay our position. Our wayfarer set out on his upward journey joyously, with the unbounded enthusiasm of youth and with the confidence that he would find the pass that leads him to the sunlit heights beyond. But as the ascent becomes steeper, the path more treacherous, he finds himself baffled and uncertain. The peaks ahead are shrouded in clouds; the passes are obscured; and he pursues a tortuous path to avoid the precipices at his feet. He is alarmed. But he cannot retrace his steps; the falling rubble has rendered the return trail impassable. He looks down into the valley whence he came; he contemplates his ascent with pride but somewhat ruefully asks himself how he ever found the temerity to undertake the venture.

Like the wayfarer, we, too, are uncertain of the path ahead, look back at our ascent, and try, from our experience of it, to predict what the terrain ahead may be.

In essaying the subject of atomic energy in the next hundred years, I am looking back from a high promontory and thinking of the beginning of the upward journey more than a hundred years ago when there occurred something in a measure parallel to the recent discovery of nuclear fission. The discovery of the relationship between electricity and magnetism was much less dramatic, but in the relative scale of technical advancement it, too, marked the beginning of an epoch.

In the early years of the nineteenth century, the steam engine of Watt was rapidly replacing the sluggish streams of England, the horse, and the arm of man employed in turning the wheels of the newly developed spinning machines and in throwing the flying bobbin of the loom. At the same time in this country Fulton was applying the steam engine to the propulsion of ships. English collieries were employing steam power to pump water from the mines, and a few of these were employing the same power to haul coal to the docks.

The older informal groups of artisans—the one-horse, one-cow businessmen—could not afford the investment of the new machinery and were being forced to the larger cities to work out their twelve and fourteen hours a day for a living. The industrial revolution was fast gaining momentum.

At the same time, Wellington's squares had withstood the onslaught of Napoleon's cavalry. Napoleon had been banished to St. Helena. The Hôtel des Invalides and the hospitals of England were filled with wounded. Catastrophic changes were taking place in the political organization of Europe, and yet in this time a former journeyman bookbinder and apprentice to science writes to a friend: "I heard for news that Napoleon was at liberty again. Being no politician, I did not trouble myself much about it." Thus did Michael Faraday, who was to become known as the "Prince of Experimenters," live remote from the concerns of ordinary men, completely devoted to his experiments. It was this complete absorption in science that gave him his opportunities and made him the great experimentalist he was. As a bookbinder he had become a reader and had learned what there was to know about the science of his day. Eventually he became apprentice to the famous natural philosopher, Sir Humphrey Davy of the Royal Institution.

In this position he found an opportunity to examine into the laws which lay behind the phenomena that had so often inspired him with reverent wonder. The lightning had always been to him an entrancing mystery, but now he became aware that laws according to which it operated might be traced.

In 1820 Faraday learned that Oersted, a Danish natural philosopher, had discovered that an electric current flowing through a coiled wire could influence the pointing of the compass needle. For Faraday this phenomenon was of far greater importance than the Battle of Waterloo. In the past, when he had learned of significant experiments, he had repeated them in his own laboratory for his own deeper and broader understanding of the phenomenon. So he repeated Oersted's experiment, but he did not have the opportunity to expand on this experiment for some years to come. The Royal Institution had fallen into financial difficulties, and the directors decided that science might better be employed in aiding the industries of an expanding England rather than making fruitless inquiries into the eccentricities of a compass needle on the work table of a Danish physicist. But in the ten years that he was forced to devote to industrial problems of the time, Faraday's mind was not idle. His many discoveries incidental to his industrial work are still landmarks in the history of science.

In 1831, after eleven years of industrial work, the financial position of the Royal Institution had improved, and Faraday, having in these years gained independence, resigned his direct connection with industry and thereby gave up the possibility of acquiring a fortune, which was estimated by Tyndall as amounting to as much as £150,000, to resume his work on electricity and magnetism.

Oersted had found that an electric current could produce a magnetic field. Faraday reasoned that if magnetism could be produced from electricity, why should not electricity be produced from magnetism. This is the mode of reasoning employed by many a great scientist—that is, the reversal of phenomena. (One of the big problems today is formulated on this kind of reasoning. Radiant energy can be produced from a change in mass. Employing the famous Einstein equation as the quantitative basis for this reasoning, physicists are now trying to produce matter from radiant energy. This is one of the reasons why we build million-dollar cyclotrons.)

The dramatic day for Faraday came August 29, 1831, when he wound two independent coils of wire on an iron ring. By passing an electric current through one, he hoped to detect a current in the other by means of a crude current-measuring instrument. The effect he obtained was not what he had expected. He found that a current passed through the second independent coil only at the moment when he made or broke the connection in his primary coil. Thus he demonstrated that electricity was made only during the period that the magnetism in the iron ring was being either increased or decreased. This experiment led to many others. He found that, by moving a magnet in and out of a coil of wire, thus changing the magnetic field, an electric current could be generated. He had discovered the principle underlying the electric motor and electric generator. Having renounced all interest in practical applications of his science, he did not go on to develop the simple dynamo, which was practically what he had constructed for a scientific demonstration. Within a very few years this was done by others. Alternating current was first produced, and shortly afterward the commutator was patented and the principle of the direct current electric generator founded.

After these famous experiments, Faraday enjoyed ten productive years. Then unfortunately his mind began to fail, and his significant contributions to science ceased. He died in the year 1867, at the age of seventy-six.

In the meantime, the revolution of 1848 had taken place in Germany, and we had fought our own War between the States. The breech-loading gun had been invented. Science and industry were growing at an ever accelerating pace.

The steam engine had presented problems which stimulated the development of the science of thermodynamics and inspired such men as Carnot, Clapeyron, Joule, Thomson (later Lord Kelvin), and Clausius.

Shortly after the death of Faraday, the carbon filament electric lamp was invented by two Germans and developed in 1880 by Thomas Edison. The demand for electric power was on the increase.

The science of physics had been flourishing, but it was gradually coming to an impasse; the gross aspects of electricity, magnetism, light, and thermodynamics were pretty well understood, and it was getting to be increasingly difficult to find the crucial and the exciting experiment. Chemistry, on the other hand, was beginning to develop toward its own industrial age. The synthesis of indigo had been accomplished, and the German dye industry was being founded. Alfred Nobel was discovering dynamite and other high explosives, which in a later year he was to recognize as so efficient in mass killing that he sincerely believed that surely men would have sense enough to avoid another war. Atoms were being hooked together at will to make new and astonishing compounds, such as salvorsan for the cure of syphilis.

But how the atom is constituted seemed to be beyond the scope of the scientist's imagination at that time. Calculation showed that the atom was so small it could never be seen under a microscope, and therefore some physicists felt that the atom would never be understood and that the physical sciences were fast approaching a dead end. They did not reckon with the experiments of Becquerel, the Curies, and Lord Rutherford.

While the science of physics began to lag, the electric-light industry was beginning to flourish. The lamplighter—the streetlighter—was being replaced by the man who serviced the inclosed electric-arc lamps which had been installed at the street intersections of our larger cities.

By making electric street-lighting possible, Faraday enabled me to earn my first nickel. The relatively intense light emitted by the street-corner arc lamp attracted the phototropic beetle. Flying toward the luminous arc, the beetles struck the glass mantle, were stunned, and fell to the ground. As a boy, I collected these stunned beetles and sold them to a small company which converted them by electroplating (a development of Faraday's) into ornaments for ladies' hatpins. I received five cents for a coffeepot full.

The new lights which attracted the beetle presented a problem in the measurement of light intensity. The old method of determining illuminating power was inconvenient. The standard international candle for measuring light intensity was not adequate, and a new standard was sought. For this purpose the Reichsanstalt, the German bureau of standards, made studies of the illumination emitted by a hollow, heated sphere, known as a "hohlraum" or a "black body." The distribution of spectral energy emitted by such a black body was measured, and attempts were made, through the medium of thermodynamics, to explain this energy distribution. All attempts to arrive at an adequate explanation failed until 1901, when Max Planck found it. But he did not accomplish this without postulating that light was emitted and received in chunks, that is, quantum-wise. Thus the quantum theory, like thermodynamics, was born from an attempt to understand a practical problem. With the quantum theory, a new age in physics was born.

At first this theory was received with skepticism; it was regarded as a mathematical mechanism conveniently invented by Planck to get the right answer. About twelve years later Niels Bohr used this same theory to explain the light-emitting characteristics of the hydrogen atom, and Albert Einstein proposed his photochemical and photoelectric laws. By experimental verification of these postulations by Millikan and others, physics received new impetus. At this same time Einstein, expanding his earlier theory of relativity, came forth with his now famous equation relating energy to mass; Becquerel had discovered radioactivity; the Curies had isolated radium; and Sir Ernest Rutherford had shown that the atom consists of a small nucleus the diameter of which he had ingeniously measured. An insight into the structure of the atom was being formed.

Meanwhile, Faraday's discovery was beginning to make its influence felt in our modern industrial development. The horse had been replaced by the electric motor in the propulsion of the tramcar; the electrically powered subway was now possible; the electric elevator made possible the architect's dream of such structures as the Empire State Building, the Chrysler Building, and Rockefeller Center.

In the early years of the twentieth century, many discoveries were made which were in turn to lead to the establishment of new industries. Hertz discovered radiowaves, Roentgen discovered X-rays, Richardson led the way to Fleming's patents on the vacuum tube. All these discoveries formed the basis for our present radio and television. Electricity in its many forms was tremendously facilitating communication in the modern world.

In these years Henry Ford developed a cheap horseless carriage, the operation of which depended in large part on the early experiments of Faraday; the magneto had been developed by the German firm of Bosch. We cranked our cars; we repaired our tires every fifty miles.

I can well remember that as a farmboy I was fascinated by a very expensive and powerful Fiat owned by one of our neighbors, and on several occasions, especially in cold weather, I was asked to give a hand in turning over the powerful Italian engine.

To boys like us the labor of cranking a motor was sheer fun, but skeptical industrialists were refusing to believe that the automobile would ever be a significant factor in our national economy. Ironically enough, one of the more sanguine predictions was that the development of the automobile would relieve traffic congestion. The automobile moves faster on Main Street.

Eventually the self-starter eliminated the inconvenience of having to call in the neighbor to turn the crank and accelerated the development of the automobile. Again, all because of Michael Faraday's discoveries.

The industrial development led to the concentration of financial interests and a need for office buildings that rose higher and higher until we have that uniquely American structure, the skyscraper, none of which would have been possible without the electric motor. Little could Faraday in 1831 dream of the extent to which his experiments with an iron ring, copper wire, galvanometer, and an electric battery could alter our Western civilization.

Here I must interject that, had not Faraday carried his experiments to a successful issue, someone else would eventually have done so. Ultimately the result would have been the same. Faraday's work is an example of free, unfettered research which, without aiming at any practical good, may revolutionize our economy.

This was also the period of German prestige. Young students of science in our own universities were eager to carry on their studies in Germany. The prestige of a German Ph.D. degree was the ultimate desideratum for an ambitious young man. Two of these German Ph.D.'s, Irving Langmuir and Steinmetz, were employed by the General Electric Company and laid the foundation for the prestige of that great corporation.

In this period of German ascendancy, Kaiser Wilhelm II called together two hundred industrialists of Germany to form the Kaiser Wilhelm Gesellschaft for the further promotion of science in his country. But before long the Archduke Francis Ferdinand was murdered at Sarajevo, the Battle of Verdun was on, and the recently invented machine gun came into play.

After World I, Europe still maintained its pre-eminence in science. American scientists still flocked there for the adventure and prestige—I was one of these.

But before long the Swastika and the "Heil Hitler" of the Nazis was stifling the development of science. Similar conditions prevailed in Italy under Mussolini. Nevertheless, the older scientific momentum was so great in these countries that the most important discoveries of all time were made there in these strenuous years.

The first of these discoveries was made by Chadwick of England in 1933. He found an elementary particle known as the neutron which differs little in weight or mass from the nucleus of the hydrogen atom, the proton; it has, however, no electric charge. It has the property of being able to wander about in matter without being affected by the electrostatic attractions and repulsions of the electrically charged particles constituting the atom. It walks through matter almost as though the matter consists of empty space. It is equally as difficult to confine it in a bottle as it is to understand it.

The next great discovery was made by Fermi in spite of

Mussolini. And science is beginning to move fast—on its own, without government stimulus or control.

Enrico Fermi, a theoretical physicist at the University of Rome, although he was not, properly speaking, an experimentalist, decided that it would be fun to play with an experimental problem. The University of Rome had a supply of radium which was not being extensively used and was therefore available. Fermi decided to use this supply of radium as a source of the neutrons discovered by Chadwick and to try to determine what the effects of these unusual particles would be on the transformation of atomic nuclei. In the course of his experiments he used these neutrons to bombard uranium in an effort to make new elements heavier than those now known. He reasoned that, should such elements be formed from neutrons, they would be radioactive. His expectations were fulfilled, and he was able to make new radioactive elements but not, as it turned out, to identify them.

Fermi's original identification of new elements was based upon the production of a substance which had radioactive characteristics not attributable to any of the elements already known. There was no question about the fact that he had something new. This new finding stimulated a great deal of activity in the field directed toward determining to what these new radioactive characteristics were due. He had opened up a new field of science and was awarded the Nobel prize in 1938. He used the occasion of going to Sweden to receive the award to get away from Mussolini and the Fascist regime to come to the United States. Eventually he entered the service of our government. And as a result the United States holds the patents for the controlled release of atomic energy.

A great part of Fermi's findings could not be interpreted. The phenomenon of bombarding uranium with neutrons had not yet been explained to anyone's satisfaction and exercised the curiosity and the imagination of many scientists.

One of Professor Fermi's contemporaries and friends in science was Professor Otto Hahn, who had the same interests as Fermi. He too had tried these same experiments but could not understand them. While Fermi was getting his Nobel prize and making the transition from Italian to American citizenship, Hahn and his co-worker, Strassman, were diligently working away at this problem in the Kaiser Wilhelm Institute for Chemistry at Berlin-Dahlem. In trying to separate the radioactive products of this neutron reaction, they rather inadvertently found evidence that one of the products was barium. This seemed incredible, because no phenomenon before observed indicated such a result. Yet barium they found it to be, beyond all dispute. The results of these findings Hahn transmitted to his friend, Lise Meitner, now a refugee in Stockholm, and together with Frisch she repeated and confirmed these experiments. The results of perhaps the most epoch-making experiment in history are recorded in a short article in *Naturwissenschaften* of January 6, 1939, one of the essential paragraphs of which reads: "Our radium isotope has the property of barium; as chemists we are forced to conclude that with these new substances we are dealing not with radium [as was previously assumed] but with barium."

The many scientists versed in the field of nuclear chemistry and nuclear physics immediately saw the implications of a phenomenon vastly different from any previously observed.

At this time Niels Bohr was visiting the United States to attend a meeting of physicists at Columbia University, which Fermi also attended. In the midst of the meeting, Bohr received a cablegram from Lise Meitner telling about her confirmation of Hahn's experiments and suggesting the implications with regard to the tremendous energy which could be released if the interpretation was correct.

Within a few weeks the experiment was verified by scientists at Columbia University, and the atomic age was on.

As Faraday had watched and wondered at the lightning, scientists and laymen have watched the stars and wondered at the source of their radiant energy. As information about the macrocosm—about the elemental composition of stars and our sun—accrued, so information about the microcosm of the atom was being accumulated. Aston, of England, in 1918 had discovered isotopes. It was found that there is not only one kind of hydrogen atom but three, not one but three kinds of oxygen atoms—all apparently behaving alike in their chemical reactions at the temperatures possible to man, but, as determined later, behaving entirely differently at the temperatures of the stars.

The exact relative masses of most of these isotopes had been measured by Dempster at the University of Chicago. As a result of Dempster's work and by means of the relationship of mass and energy deduced by Einstein, it was now possible to speculate quantitatively on the production of energy in the stars as lighter elements combined to form heavier elements. In this way Bethe, formerly of Munich and now of Cornell, postulated a series of nuclear reactions resulting in the formation of helium from hydrogen, with the release of tremendous amounts of energy to explain the heat of our sun.

The reactions of Bethe for our sun were not applicable to the hotter and younger stars, and other plausible reactions were postulated for these. Thus the reactions which are now to be used for the hydrogen bomb were considered years ago to explain microcosmically the grandeur of the evening sky.

The development of science and technology, and its application in war, in contrast to the development of social thought, has been increasing at an ever accelerating pace. It took eleven years to make the first step toward expounding and developing Oersted's discovery that an electric current was related to magnetism. In this blitzed-up age it took the same length of time to develop the A-bomb, after the process of fission was discovered by Hahn and Strassman—win a war with it and carry out preliminary experiments looking toward far greater achievements than those resulting from Faraday's experiments of a hundred years ago.

Before one can appreciate the significance of the discovery of atomic fission, one needs to have a rudimentary understanding of the process itself. The culmination of the work of Rutherford, Einstein, Bohr, Chadwick, Fermi, Hahn, and hundreds, even thousands, of scientists can be represented as follows.

Imagine the interior of a great cathedral. In the center of this cathedral is suspended a small millet seed. The millet seed corresponds in size to the nucleus of the atom and the walls of the cathedral to the shell or shells of electrons about this nucleus. However, there is this significant difference: In the case of the cathedral, the weight resides in the walls, and the millet seed is negligible. In the case of the atom, almost the total weight resides in the nucleus and the walls are negligible. Matter is made up of aggregates of these atoms consisting of millet seeds and walls—this table, this chair, we ourselves, are made up of aggregates of atoms—but the matter of which we are composed is largely empty space —this great void between the millet seed and the wall. In fact, if we could strip atoms of this outside wall and force these nuclei closer together, we should have an extremely heavy material. Such material is known to exist in some of the stars; there are stars that have matter which is a billion times denser than the matter we know on earth, so dense that the largest crane on earth would be unable to lift a teaspoonful of it. This is the result of the packing-together of the nuclei of atoms, obliterating the void which exists between the wall of the atom and the nucleus. But such matter can exist only under conditions as yet unobtainable on earth.

Nuclear energy arises not from changes in the electrons but rather with the nucleus (not with the walls of the cathedral but with the millet seed).

Let us now use an imaginary mental microscope to enlarge our view of this nucleus. We find that it consists of a combination of two elementary particles—neutrons and protons—closely packed and intermeshed. These particles have very nearly the same weight. The proton is positively charged—that is, it contains one unit of positive electricity. The neutron has no charge at all. There is some kind of not-yet-understood nuclear force—nuclear cement—that holds them together. Now, it is the number of positive charges, the number of protons in this nucleus, which determines the kind of atom it belongs to as a nucleus. For example, all the oxygen atoms which make up part of the air have nuclei which have in them eight protons—eight positive charges—and some neutrons. Some oxygen atoms have eight protons and eight neutrons, some have eight protons and nine neutrons, and some have eight protons associated with ten neutrons. In all three kinds of oxygen atoms there are always eight protons. The three different kinds of oxygen atoms are known as oxygen isotopes. They are all oxygen—that is, the walls of the cathedrals are the same but the millet seed is different.

There are two important isotopes of the element uranium, U^{235} and U^{238}. Both of these atoms have the same cathedral walls—the walls are the same but the millet seeds are different. Both nuclei of these two elements have 92 positive charges associated with them, but they differ in the number of neutrons. U^{235} has a total of 235 particles, including protons as well as neutrons; U^{238} has 238 particles. They differ in weight and in their internal nuclear characteristics.

We can imagine that these nuclei are shimmying about, vibrating this way and that, and that their dynamic balance might easily be disturbed. U^{235} is a very nervous fellow—his big brother U^{238} is more stolid.

Now there are some gnats flying about in our atomic cathedral. These are the unbound neutrons, on the loose. Many of these are floating around in this room, many of them are passing through us now without our knowing it. Suppose that one of these stray neutrons strikes the nucleus of the U^{235} atom—the gnat alights on the millet seed—and is absorbed to add one more neutron to the 143 which are already present. This extra neutron disturbs the U^{235} family of protons and neutrons no end. The whole nucleus begins to shimmy harder and becomes so unstable and vibrates so violently that it breaks into two almost equal parts. When it does so, it releases a tremendous amount of energy. The energy was already there, stored up in the nucleus two billion years ago when the elements were formed, but it needed this extra neutron to come in and trigger it off. That is the process of fission.

U^{235} has the only nucleus now present in the earth that behaves this way. There is good reason to believe that there cannot be many such unstable nuclei. On the basis of our present theory, the elements that had atoms of greater mass than the uranium atom at the time of the formation of the elements, some two billion years ago, have already disappeared, because their nuclei were so unstable that in the course of time they gave off small chips in radioactive decay and settled down to a low-temperature equilibrated, or steady-state, existence. Uranium, the element with the heaviest and most complicated nucleus, is on the ragged edge of instability. It is unstable but not unstable enough to have disappeared.

Of the three isotopes of uranium, 234, 235, and 238, the isotope 235 was found to be the closest to the breaking point. (U^{234} will be disregarded in this discussion because of its extreme scarcity—a feature, however, by no means to be neglected in any theory of nuclear structure or of cosmogenesis.)

But U^{235} exists on earth as only 0.7 per cent or 1 part in

140 of all this relatively scarce element. But that is what one might expect, for one would think that scarcity and instability would go hand in hand. Perhaps it was foreordained that we mortals should be given just enough to put the responsibility in our own hands for our continued existence. A very slight change in the conditions that obtained during the formation of our universe might have left us with no U^{235}, no A-bomb, no H-bomb, and no problem of world destruction to worry about. We are being forced to learn the hard way, and to learn fast.

Where nuclear energy differs from ordinary energy such as we know it today, as in the burning of coal, is that nuclear energy is derived from a change in the nucleus, the millet seed, whereas the energy in the burning of coal and in ordinary chemical reactions is produced by a change in the walls of the cathedral rather than in the nucleus. The great changes in energy are derived from changes in the millet seed rather than from changes in the cathedral walls.

The potential energy of U^{235} is so great that one pound of uranium-235 fissioning in this manner produces as much energy as two to three million pounds of coal, or the same amount of energy as would be produced by many more millions of pounds of TNT. This represents a source of energy millions of times greater, pound for pound, than any we have previously known. If we were to announce that we had discovered a new fuel which was twice as concentrated as coal and less than twice as expensive, it would be regarded as a revolutionary discovery because the new fuel could replace coal. Here there is a fuel which is two million times more energetic than coal—the cost is not yet known. The new fuel is still enormously expensive.

However, this new fuel has another great advantage over coal. It is possible to utilize this fuel in such a way that, while burning, it produces more fuel out of cheap materials than is consumed. This process is as if one were to put a ton of coal and a lot of cheap sand into a boiler, and, upon sifting the ashes, after the coal has burned, one were to find more than the original ton of coal left. This process, which the public is now beginning to hear about, is known as the breeder principle. The process of consumption breeds new fuel. An installation for such breeding has been designed at Chicago and Schenectady and is now ready for construction.

To understand the breeder principle, it is necessary to reconsider the process of fission in greater detail. A neutron enters the nucleus of the U^{235} atom, and the nucleus splits into two parts, just as a drop of water divides and splits into two parts under impact. A small spray accompanies the splitting, as in the breaking of a water droplet. But, when the nucleus splits, the spray consists of neutrons which were imbedded in the original nucleus. Neutrons are splashed out in this splitting process. On the average about three neutrons are split out in every process of fission. Beginning with the one neutron which enters the U^{235} nucleus, the splitting U^{235} nucleus produces three neutrons. If there is another U^{235} nucleus in the vicinity and one of these sprayed-out neutrons enters that, it causes another fission; then three more neutrons are produced, and those neutrons in turn enter other U^{235} nuclei and produce still more neutrons. The neutrons increase in number exponentially as more U^{235}

nuclei split. This process takes place within one-millionth of a second. Now it is obvious that, if there are a great number of U^{235} atoms clustered together, they will all be split in this very short time, giving rise to a tremendous amount of energy—all within a millionth of a second. This is the principle of the atom bomb.

To be able to use such tremendous concentrations of energy for peaceful purposes of running our machines, heating and lighting our homes, pumping and evaporating water, one must keep this highly nervous, highly explosive material under control. That is a far more difficult problem that even trying to heat a boiler with TNT. But it can be done—it has been done, but is not yet applicable to industrial uses. The control is effected by removing at exactly the right pace the excess neutrons produced by the reaction.

As I have said, each atom produces three neutrons. Of the three, only one is needed to produce another fission, and only one more neutron from that fission to produce a second fission, and so on. It is imperative to get rid of the two extra neutrons in each case. These are waste neutrons, and they must be absorbed as fast as they are formed so that the rapid chain reaction characteristic of the bomb does not occur. To accomplish this result, other harmless atoms capable of consuming neutrons without undergoing fission are placed in the reaction chamber. Just enough of these are placed in the mixture to absorb two neutrons and leave one free to continue the reaction. Such atoms are boron and cadmium, the former found in borax and the latter in cadmium metal, a material used to plate the brakes of automobiles. These special substances have the property of absorbing neutrons to a high degree and so keeping them under control. With the proper design to provide just enough neutron absorbers, the reaction can be kept under control and a steady release of atomic energy attained. This was the feat that was first accomplished in the West Stands of Stagg Field on December 5, 1942, by Enrico Fermi.

There are ways of utilizing the waste neutrons other than absorbing them by such substances as cadmium and borax. If U^{238}, the principal form of uranium which does not undergo fission, is in the neighborhood of the neutrons, the nucleus of this substance will absorb the neutrons. It will not undergo fission, but it will be transformed into plutonium, and plutonium, like U^{235}, is fissionable. In this way, with the waste neutrons, it is possible to make a new fissionable material, a new fuel.

If one could contrive a process so controlled that the two waste neutrons which are produced in every fission event could be taken up by U^{238} (a cheap substance, incidentally), one would be able to make two atoms of fissionable material for every atom consumed. The return on the original investment would be 100 per cent. There would be twice as much fuel returned as was put in.

But it is not feasible to attain so high an efficiency, because some of the neutrons escape through the walls of the reaction chamber and some are absorbed by the container; but scientists are confident that at least 10 per cent per annum on the original investment will be returned. That is, every time 1 pound of nuclear fuel is burned, 1.1 pounds will be returned. This is an extremely conservative estimate.

It is not obvious to many what an extremely large accumulation of wealth could result from investment at 10 per cent, compounded annually, over a period of years. In 1626 the Dutch bought Manhattan Island from the Indians for $24.00. Had this $24.00 been invested at 10 per cent, and compounded annually, the accumulated principal in 1950 would amount to $600,000 billion. It is no wonder that banks place a time limit for accumulation on forgotten deposits—even with much lower rates of interest.

Suppose 100 pounds of atomic fuel were invested in our boilers in the year 1970. Then by 1971, one year later, 110 pounds would have accumulated, and twenty years later, in 1990, there would be at our disposal approximately 2,000 pounds. In a hundred years, by 2070, more synthesized fuel would be available than would be necessary to satisfy all the heat and power requirements of the whole of the United States. Such an estimate begins with only 100 pounds of fuel. It would be perfectly possible to begin with a great deal more than this and thereby cut down the time necessary to produce, from inexpensive material, all the heat and power that this country could use.

Many observers therefore believe that in a hundred years, but not much earlier, the soot and smog of our cities will have disappeared, and, because of the very low transportation cost of nuclear fuel, our industries will be dispersed and the larger cities will have begun to decline in population. The consequent dispersal of population would undoubtedly have most significant results.

But the advantages derived from cheaper and cleaner power will be as nothing compared with the advantages given our society by the tracers or radioactive atoms that can now be produced even in the present low-temperature reactors at our disposal.

As I have said a number of times, to control the nuclear reaction, it is necessary to introduce substances into the reaction mixture to absorb the excess neutrons. These substances are manifold, and those can be chosen that produce useful by-products. These by-products are the radioactive forms of the common elements. Carbon-14, for example, is one of these. This substance is a radioactive form of carbon, an element which constitutes a large fraction of all living organisms. In its gross aspects it behaves like the normal carbon of which we are made, but in its nucleus it differs in that once in every five thousand years such an atom has a fifty-fifty chance of changing, radically, to a nitrogen atom with the emission of radioactive rays. A fifty-fifty chance in five thousand years may not seem very significant, but when one considers that the number of such particles in any finite quantity of matter is so large and our means of detecting radioactivity so sensitive, it becomes apparent that with proper instruments it is possible to smell out this substance in unbelievably small amounts. Thus, an amount of carbon-14 one one-hundredth the weight of a dime will result in about seventy-five billion such disruptions a second. The sensitivity of detection is so great that ten disruptions a second are easily observable.

C^{14} atoms and other radioactive atoms can be incorporated into vitamins, hormones, antibiotics, and drugs, such as digitalis. By means of our new electronic eyes it is possible to follow these substances as they perform in the body and to learn what their actions are. It will also be possible to embody these C^{14} atoms into the molecules that are the building blocks of our growth structure. In that way, we shall perhaps understand normal growth and consequently such abnormal growth as cancer. We shall know much more about disease and health.

Two hundred years before the time of Faraday, two Dutchmen, Zanser and Leeuwenhoek, made the first compound microscopes. It was the compound microscope that made possible the work of Pasteur and the bacteriologists that followed him. Little do we now appreciate what the development of the microscope meant to modern medicine. But the microscope reveals only living organisms containing millions of molecules. The Geiger counter and the radioactive isotope now allow us to "see" effectively and follow molecules. And since the more microscopic our inspection of biological matter can be, the more fundamental will be our information on living systems, we may have high hopes of great things to come. Energy in plenty for all and the increasing accumulation of scientific knowledge will undoubtedly lead to greater marvels than did the experiments of Faraday.

No more than Faraday could predict the electric lamp, the radio, the telephone, the telegraph, and television, can we at this juncture predict the discoveries which will follow upon the discovery of atomic energy. But we have learned from Faraday's work and subsequent developments that the unimaginable will surely come upon us. The ever increasing tempo of advance in science and technology assures us that their advent will come more swiftly than ever before.

But the unpredictable comes only from basic science, not from inventions that merely substitute a chain for a belt, a saw for a knife. In the past these basic discoveries have come from Europe. In all the basic discoveries I have recounted, which led to our great industrial age, not a single major work came out of America. Are we now as a people wise enough to provide favorable conditions for the disinterested observer of natural phenomena, in contrast to the practical inventor? For it is the unfettered experimenter who has in the past and who will in the future make the fundamental discoveries for radical improvement of human life and for the elimination of the struggle for a place in the sun which now threatens to destroy us.

We go back to the youthful Faraday contemplating the thunderstorm. His wonder at it impelled him to go on in an attempt to understand. In his later years, with his failing mind, he realized dimly that he had not reached his goal.

And like the wayfarer, we too bend our backs and push forward in our climb, the goal still obscured in mist.

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