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UNITED STATES ATOMIC ENERGY COMMISSION

THE FUTURE OF ATOMIC ENERGY

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This document consists of 6 + 1 pages.
Date Released: May 27, 1946

Technical Information Division, Oak Ridge Directed Operations
AEC, Oak Ridge, Tenn., 10-11-48--850-11425

THE FUTURE OF ATOMIC ENERGY

By E. Fermi

The attention of the public in the problems of atomic energy has been centered so far primarily on the military side of the development. It is natural that it should be so, since on one hand the military use is to the present time the only application that has attained practical results. On the other hand, the issues raised by it for the national and international policies are novel and difficult and call for a quick solution. There are, however, a number of possibilities for the peace time uses of atomic energy which in the long run may prove more important than the bomb.

If we try to look into the future, and we take the optimistic point of view that mankind may succeed to organize itself so as to eliminate the fear and the danger of the destructive potentialities of atomic weapons, one might speculate as to what may happen to atomic energy as a constructive new force.

Any such speculation, of course, can be at the present time only very sketchy. One might point out to some probable developments, but it would be impossible to make the list even approximately complete. An attempt to do this would be now as difficult as it would have been one century ago to guess the development of electricity.

PRODUCTION OF POWER

The first point that I propose to discuss is the use of nuclear reactions for the production of controlled and usable power. Chain reacting "piles", in which energy is produced at an easily controllable rate, have been operated for over three years. Starting with the first pile, which was run only up to 200 watts, the power has been stepped-up in successive units by enormous factors. The piles operated at Hanford for the synthesis of plutonium produce energy in amounts comparable to that of the largest hydroelectric plants. The energy that is produced in the piles built until now, however, is delivered at such a low temperature that it is of no practical use. In the Hanford plants it actually is wasted for the extremely unconstructive purpose of heating, by a small amount, the waters of the Columbia River.

The physical basis of the chain reaction is the fission of uranium. This is a violent disintegration of the uranium nucleus that takes place when a neutron strikes it. The original nucleus separates into two approximately equal fragments, which fly apart with an enormous velocity and a relatively extremely large release of energy. What makes the chain reaction possible, however, is not the fact that a large amount of energy is released but the fact that in the process also some neutrons are emitted besides the two fragments. If we assume, for the purpose of this discussion, that two neutrons are emitted in each fission and we assume further that the conditions are such that practically all the neutrons originating into the system end up by giving rise to fission, we have the conditions that would lead to an explosive chain reaction. If, indeed, we introduce in a system of this type one initial neutron, this will give rise to a fission in which two neutrons will be produced. In their turn they will give rise to a second fission and produce two neutrons each and so on. The number of neutrons will then double at each step or "generation" so that their number will rapidly multiply until the reaction reaches extreme violence and great amounts of heat are developed. This sudden release of energy produces the atomic explosion. The system as just discussed is said to have a "reproduction factor" of 2 because at each generation one neutron gives rise to 2 new neutrons.

FAST NEUTRON AND SLOW NEUTRON REACTIONS

In designing a bomb one tries to achieve conditions in which the fission energy is released as fast as possible. This requires that the "generation" time be as short as possible and that at each generation the number of neutrons should increase by the largest possible factor. In order to make the generation time short one will use fast neutrons and in order to make the reproduction factor as large as possible one will try to adjust things in such a way that a large percentage of the neutrons end up by producing a new fission and thereby the largest possible number of new neutrons.

If we want, instead, to produce a controllable chain reaction, the reproduction factor will have to be very close to 1 and there will be no need to have a short generation time. Indeed it would be, if anything, more desirable that the generation time be rather long because this would make control more easy. It is possible therefore to use slow neutrons in a controlled chain reaction. There is one more fundamental difference between the bomb and a controlled chain reaction. The fast reaction on which the bomb is working is operated using "valuable" fissionable materials like U^{235} which is separated from uranium at Oak Ridge, Tennessee, or plutonium which is a new element which is actually fabricated at Hanford, Washington.

Controllable chain reactions can instead be obtained using natural uranium. Indeed this material was used in producing the first chain reaction for the simple reason that at that time the "valuable" fissionable materials were not available. It also is used in all the industrial piles that have been constructed so far. Natural uranium consists primarily of a mixture of U^{238} representing about 99.3 per cent of the total and U^{235} representing about .7 per cent. It is well known that it is this small amount of U^{235} that makes the reaction possible since U^{238} does not react giving rise to fission when bombarded by slow neutrons. Actually a chain reaction can be obtained quite easily using pure U^{235} since thereby one avoids the parasitic absorption due to the U^{238}. When ordinary unseparated uranium is used the problem is appreciably more difficult since the positive excess in the neutron balance in each generation is in this case very small and all unavoidable losses must be kept to a minimum so as to end up with a reproduction factor larger than unity. From this point of view, therefore, the presence of U^{238} is very undesirable. On the other hand U^{238} plays a very essential role in the plutonium production. Indeed U^{238} is transformed during the reaction into plutonium by the mechanism represented in the following nuclear process:

$$U^{238} + n \longrightarrow U^{239}$$
$$U^{239} \longrightarrow N_p^{239} + 0^-$$
$$N_p^{239} \longrightarrow Pu^{239} + 0^-$$

The first of these reactions represents the absorption of a neutron by the nucleus 238 which is thereby transformed into the isotope U^{239}. U^{239} is an unstable isotope of uranium which spontaneously disintegrates by emitting an electron and transforming into the new element neptunium of atomic charge 93 and weight 239 as indicated in the second reaction. The transformation of uranium into neptunium takes place in a time of the order of one half hour. Also Np^{239} which is thereby formed is unstable and spontaneously emits an electron transforming in a few days into the final reaction product Pu^{239} as indicated by the last equation. If we examine the overall balance of a chain reaction of this type, it is clear therefore that U^{235} will gradually be destroyed to keep the reaction going; whereas U^{238} will slowly be transformed into Pu^{239}.

CONTROL OF A PILE

In order to operate a chain reacting pile at a steady level the reproduction factor must be equal to one. If it is larger than one the intensity increases, if it is smaller the intensity drops. For this reason the operator must have means to adjust the reproduction factor to any desired value in the vicinity of one. This usually is achieved by means of organs called control rods. They are rods made of some material having a strong absorption for neutrons which the operator can insert into the pile at a depth that can be accurately adjusted. The number of neutrons absorbed by the rods and thereby removed from the reaction will depend on how deep the rod reaches into the pile. Consequently, the reproduction factor will also depend upon the position of the rod and will have its largest value when the rod is outside and its smallest value when the rod is completely inside. Conditions are usually adjusted in such a way that the reproduction factor is equal to 1 when the rod is in some intermediate position called "critical position" and it takes values larger than 1 if the rod is pulled further out than the critical position and smaller than 1 if the rod is pushed further in. If the operator wishes to increase the rate of reaction, the rod is pulled out so that the reproduction factor exceeds 1 by some small amount and the number of neutrons gradually increases. If the operator wants to reduce the rate of reaction, all he has to do is to insert the rods somewhat further than the critical position. The reproduction factor will then be less than 1 and the rate of reaction will gradually decrease. If he wants to keep the power at a steady level, he will place the rods at the critical position.

It is clear from this that the problem of controlling the rate of reaction in the pile can be solved in a very simple way. Experiment actually has shown that the controlling problem can be solved very easily also in practice. Indeed, to keep a pile, whether capable of producing a large or small amount of power, running at a steady level is an art that can be completely mastered in a few hours. It is also easily possible to keep the intensity of the pile steady at any desired level by moving the rods with mechanical devices operated automatically. In this case all the operator has to do is watch the control panel.

HIGH TEMPERATURE PILES

The chief technical difficulty which stands at present in the way of production of atomic energy for practical uses is the following. In all the reacting units that have been constructed until now the energy is produced at a very low temperature. This undoubtedly is due to a great extent to the fact that the primary purpose for which the piles have been constructed during the war was not production of useful power but the production of plutonium. For this reason no effort was made in the direction of constructing a pile with materials capable of standing a very high temperature since such development undoubtedly would have retarded very considerably the achievement of the essential objectives.

The following points are important. There is no known practical limitation to the temperature at which energy can be produced by a fission chain reaction. Indeed there is reason to believe that in the explosion of the atomic bombs temperatures perhaps as high as 1,000,000°C. may have been obtained. A practical limitation is imposed only for machines designed to operate at a steady level by the refractory properties of the materials used. In this respect, the choice of the materials is quite critical because not only their ability to stand high temperatures must be taken into account but also one must consider the adverse effect that adding foreign materials in the reaction system has on the nuclear reaction itself. This adverse effect is due to the fact that most materials absorb neutrons sometimes more and sometimes less. Any material that has to be added as a coolant to remove heat from the pile or as a lining for the pipes through which a cooling fluid is conducted determines a loss of neutrons. When this loss is so large that the reproduction factor drops below 1 the reaction stops.

COULD LARGE AMOUNTS OF ENERGY BE RELEASED?

It has been mentioned that the essential fuel in piles of the Hanford type is U^{235} which represents only .7 per cent of the total weight of natural uranium.

The content in fission energy of uranium is roughly 3,000,000 times that of an equal weight of coal. If only .7 per cent of the uranium is utilized, the practical uranium to coal ratio will be about 20,000. These figures point to the great importance of devising methods for the complete utilization of the energy of uranium.

The demand for a practical solution of this problem may not be very pressing in the immediate future since there still are fairly large uranium deposits which can be mined at relatively low cost. If we conceive, however, a development in which large amounts of atomic energy would be produced by U^{235}, the rich deposits of uranium would rapidly be exhausted and further production would have to use very poor ores with a consequent increase of several orders of magnitude in the cost of the primary material. In this case, the importance of a complete utilization of the energy stored in uranium would naturally become much greater. It is clear on the other hand the energy value of one pound of uranium is so great that even an enormous increase of cost of this material may not interfere with its economical use as a source of power. Indeed 3 million tons of coal, equivalent in energy content to one ton of uranium, cost about 8 million dollars. Consequently, as far as cost of the raw materials, uranium and coal would become equivalent for a price of uranium of 4,000 dollars per pound. Before the war the cost of uranium was about 2 dollars per pound so that an increase of the order of a thousand times the pre-war price would not be necessarily uneconomical.

We might conceive that 20 or 30 years from now the general scheme of atomic energy production may be perhaps about as follows. There will be large central installations in which very great amounts of power will be produced and transformed into electrical energy or steam for local power consumption. Besides producing directly power, these large units may also produce some amount of plutonium which will be extracted and distributed to small installations in which plutonium and not uranium will be used as the primary fuel. This plan would have the advantage of permitting wide use of relatively small power units thereby reducing very greatly the difficulties of distribution.

A general scheme of this type has recently been discussed in a report by the State Department outlining a possible organization for the international control of atomic energy. According to this report the large central units in which plutonium is produced, as well as all sources of uranium and thorium, would be controlled and operated by an international organization which would distribute or sell plutonium in a denatured form for use by individual consumers. The authors of this report express the view that it may be possible to denature plutonium so as to make its use for military uses exceedingly difficult and time consuming and express the hope therefore that it may be feasible to exert only a minimum international control on the users of denatured plutonium without danger that it may be diverted secretly to construction of weapons. Such a scheme undoubtedly has some attractive features although the report may be over-optimistic in its estimate of the difficulties to divert denatured plutonium to military uses. There is no denying the fact that the possible use of plutonium for aggressive warfare constitutes a difficulty for the industrial uses of atomic energy that is much greater than any technical difficulty that we can foresee. The problem of preventing this use is essentially political and not technical and I do not see much hope of solving it unless the very basis of the relationships among nations should be thoroughly changed in the future years.

NECESSITY OF SHIELDS

Going back to the technical problems, I would like to mention one more factor of atomic energy units which will prove a serious limitation to their general use. During the process of fission, which is basic to the production of atomic energy, not only energy but also radiations of various kinds particularly neutrons and gamma rays are produced. Unless they are prevented from doing so by a shield, these radiations would escape from the pile and their intensity would be so terrific that they would kill in a very short time any living being who were to approach an unshielded operating unit. It is therefore an essential necessity to shield the pile with such materials as to prevent the escape of lethal radiations. In principle the problem is not at all difficult to solve. It is sufficient, for example, to surround the pile with a concrete wall of several feet thickness in order to eliminate completely any danger. On the other hand there is no way to eliminate the radiations without the use of a very heavy shield. Indeed in many designs of piles that have been discussed the shield represents by far the greatest part of the weight of the installation. The necessity of surrounding the pile with a heavy shield will prevent several uses of atomic power. It does not appear possible for instance to design an atomic power unit light enough to be used in a car or in a plane of ordinary size. Perhaps a large locomotive may be the smallest mobile unit in which an atomic power plant conceivably could be installed.

We may summarize this discussion by stating that there is definitely a technical possibility that atomic power may gradually develop into one of the principal sources of useful power. If this expectation will prove correct, great advantages can be expected to come from the fact that the weight of the fuel is almost negligible. This feature may be particularly valuable for making power available to regions of difficult access and far from deposits of coal. It also may prove a great asset in mobile power units for example in a power plant for ship propulsion. On the disadvantage side we have some technical limitations to the applicability of atomic power of which perhaps the most serious is the impossibility of constructing light power units; also there will be some peculiar difficulties in operating atomic plants, as for example the necessity of handling highly radioactive substances which will necessitate, at least for some considerable period, the use of specially skilled personnel for the operation. But the chief obstacle in the way of developing atomic power, will be the difficulty of organizing a large scale industrial development in an internationally safe way. This presents actually problems much more difficult to solve than any of the technical developments that are necessary. It will require an unusual amount of statesmanship to balance properly the necessity of allaying the international suspicion that arises from withholding technical secrets, against the obvious danger of dumping the details of the procedures for an extremely dangerous new method of warfare on a world that may not yet be prepared to renounce war. Furthermore, the proper balance should be found in the relatively short time that will elapse before the "secrets" will naturally become open knowledge by rediscovery on part of the scientists and engineers of other countries.

One might be led to question whether the scientists acted wisely in presenting the statesmen of the world with this appalling new problem. Actually there was no choice. Once basic knowledge is acquired any attempt at preventing its fruition would be as futile as hoping to stop the earth from revolving around the sun by degree.

OTHER APPLICATIONS OF ATOMIC POWER

Power production is not the only peaceful use of atomic chain reactions that is in sight. There are other possibilities which may perhaps not compete with the power production in direct economic importance, but perhaps may prove to be ultimately the most fruitful field of development. An operating pile is a source of radioactive materials many orders of magnitude stronger than any source previously obtainable. Radioactive materials are produced partly as a direct consequence of the fission process since the fragments into which the uranium atoms split are radioactive isotopes of elements located in the middle part of the periodic system. These radioactive elements can be purified chemically. Other radioactive substances can be produced as follows. In a going pile neutrons are emitted continuously in very great numbers. Any substance that is inserted in the pile is exposed to an intensive bombardment by these neutrons. When a neutron strikes the nucleus of a substance, several reactions may take place which, in many cases, give rise to the formation of radioactive isotopes. Most elements can be obtained in this way in a radioactive form. The lifetimes of these elements range from a fraction of a second to thousands of years. Among the more significant artificial radio-elements one should mention Carbon 14 with a lifetime of about three thousand years. Radioactive substances can be used for a variety of purposes. The radiations emitted by them are equivalent to the radiations emitted by radium and could be used for medical purposes on a much greater scale than has been possible with radium. Also from the point of view of radiotherapy, the hope has been expressed that it might be possible to take advantage of the fact that the artificial radioactive substances form a variety of chemical elements and one might use the chemical properties in order to achieve a concentration of the active material in the tissue that is to be exposed to the radiations.

Very great hopes have been raised by the possibility of using large amounts of radioactive materials as tracers. Particularly attractive in this respect appears the possibility to use Carbon 14 as a tracer for carbon in organical chemical and bio-chemical work. The use of Carbon 14 in biology is expected to offer means to follow easily the reactions of carbon in the complicated chemical processes of life and it is hoped that the availability of Carbon 14 will be adequate to allow research in this direction to proceed on a very large scale.

It would not be very surprising if the stimulus that these new techniques will give to science were to have an outcome more spectacular than an economic and convenient energy source or the fearful destructiveness of the atomic bomb.