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CIVILIAN APPLICATIONS OF ATOMIC ENERGY*

By Sir John Cockcroft, Leader of the U.K. Delegation

In the Chair : Dr. H. J. Bhabha. Director. Tata Institute of Fundamental Research, Bombay.

The chairman said that Sir John Cockcroft and his work were so well known that there was hardly any need to speak about him or his work. The subject of civil applications of atomic energy was a fascinating one. It was indeed fortunate that a person of Sir John Cockcroft's eminence and experience in this field was giving a talk on this subject. He was sure that the large audience would listen with much interest to what the lecturer would say.

Sir John Cockcroft said that the military applications of uranium fission may very well in the long run be transcended by the importance to world economy by the tapping of the enormous stores of energy which were locked up in many atomic nuclei. These energies were really very great in comparison with the energies of conventional fuels. At the present time it has been possible to make use of one method of tapping this energy and that by making use of the controlled nuclear chain reaction which was first achieved by Professor Fermi in Chicago. In the ten years or so since that discovery they had learnt a geat deal about the characteristics of atomic piles of this kind and they were confident that it could be applied to the development of useful power. The first type of atomic pile was typified by the Harwell B. E. P. O. This consisted of a reacting core of about 800 tons of graphite. The reacting core was about 30 feet in linear dimensions. It was a graphite cube made up of bricks of graphite. In between these were interspersed bars of uranium metal sheathed in aluminium cans. The uranium bars were of one inch diameter and about 12 inches long. When 25 tons of uranium metal were loaded into this core the nuclear chain reaction started up. Before this about 100,000 spontaneous fissions of uranium nuclei were occurring in a second in the heavy form of uranium but when 25 tons were loaded the fission of uranium was followed by more fissions due to the chain reaction. The pile was surrounded by a big shield of about 6.5 feet in thickness of concrete. This was to prevent the radiations from the fission process escaping through the shield and harming personnel near about.

As a result of the fission, the radioactive waste products, the so-called fission products, which accumulated in the uranium bars gave out radiation even after the chain reaction was shut down.

The characteristics of this kind of pile is that neutrons given out in the fission process of uranium are slowed down by bumping

* Based on a lecture given by Sir John Cockcroft during the C.A.C.D.S. Conference. The lecture was illustrated by lantern slides.

amongst the atoms in the graphite until they reach energies comparable with those of the graphite atoms and when they are slowed down in this way, the fission in the light form of uranium occurs very effectively. It is possible to produce and build a second type of atomic power which is known as a fast reactor. In this type of reactor neutrons from the fission process produce further fissions before they are slowed down and therefore it consists essentially of a core containing uranium in which the proportion of the light uranium is very much increased. Surrounding this is a shield and there may also be a blanket containing uranium 238.

In between the two types of reactors mentioned above, the graphite reactor which works with slow neutrons and the fast reactor, one can build intermediate types of reactors in which the fissions are produced by neutrons of intermediate energy. One can also build other types of piles with slow neutrons using fuel which consisted of uranium in which the light form is very much increased in proportion. For example they could build the so-called homogeneous reactor in which the enriched fuel in some liquid medium generated the heat. This liquid could then be circulated through the heat exchanger. There are, therefore, a vast variety of atomic piles of this kind.

There are always far more forms of dry wall reactors than there are actual reactors and this was due to the fact that any single atomic pile is rather an expensive piece of apparatus to build. One of the most important characteristics of any kind of atomic pile is the neutron balance. In the fission of uranium 235 about 2.35 neutrons are given out on the average and it is a necessary condition of the chain reaction being built up that at least one of these neutrons serves to produce the fission and, therefore, the neutron balance-sheet of the reactor is of great importance. In the case of a graphite reactor the number of neutrons per fission is 2.5. As the neutrons come out of the uranium metal bars they produce a few further neutrons by fission and therefore there will be about 2.56 neutrons to start with. One of these neutrons is required to produce a further fission and then there will be a whole number of processes which absorb the remaining neutrons. For example, in a graphite reactor (of the kind he was talking about) some are absorbed wastefully without producing fission. They are just captured and about 0.2 neutrons is lost that way. Then about 0.9 are absorbed in the heavy uranium to produce a secondary fuel plutonium. This, however, is not wastage of neutrons because plutonium is a very good secondary fuel. Some are absorbed in the graphite, some in the materials such as aluminium and some escape. If all these are added up one is left with 0.02 neutrons which forms the so-called excess. It is necessary that there should always be a certain surplus of neutrons in order to make the chain reaction develop and to control the process.

There are various factors which affect this balance of neutrons at the end of all these processes. For example, if the temperature of the reactor is increased more neutrons are absorbed in the moderator. If the temperature is increased more neutrons may be absorbed in uranium 238. Furthermore, as the chain reaction proceeds the waste products of fission accumulate and they begin to absorb neutrons and the higher the power level of the reactor the more neutrons they absorb. Therefore the need for enough spare neutrons when the reactor starts from cold at zero power to provide for all these additional sources of loss.

The Technological Problems of Nuclear Reactors

The technological problems of nuclear reactors may be divided into four main groups. First of all, there are the problems for the nuclear physicist. He has to predict what the size of the reacting core should be, how much graphite is required, how much uranium is required, what the lattice spacing has to be and so on. He has to advise on the thickness of the concrete shield surrounding the reactor. The intensity of the neutrons varies ; in the reacting core they are maximum at the centre. Then the intensity goes down through the reflector and then it drops very rapidly in going through the sheet and the experimental physicist has to be able to predict that. It is not possible to calculate most of these quantities with any degree of precision and the calculations have all got to be supplemented by experiments. In particular it is necessary to build small special critical reactors in order to predict what the critical size is likely to be.

The next question is that of the control of the chain reaction. When the chain reaction is in equilibrium and the pile is developed to give power at a steady rate, the neutron balance has to vanish, otherwise a large number of neutrons would accumulate. The reaction is controlled by moving into the core the so-called control rods containing the neutron absorber. At the Harwell pile horizontal control rods were used. They were moved in by trolleys. When they were moved in the rate of absorption of neutrons increased and, therefore, the chain reaction could not build up. To start the pile the control rods were withdrawn until a surplus of neutrons of the order of one in a thousand was made available. Then the chain reaction could be built up in a short time of the order of one minute.

When the power level is increased from 100 k.w. by withdrawing the control rods there will be an exponential rise of the power level which overshoots and then comes down to a steady level. The uranium temperature follows a little bit later. There are also automatic control mechanisms which enable it to maintain the power level constant, once they settle down with very high precision, a precision of about one part in a thousand or so.

There is another very important factor in the operation of piles which has to be noted. The fuel rods, after the piles have been running for a time, accumulate a very large amount of the radioactive waste products and it is most important that these waste products do not escape into the atmosphere and so one has a rather elaborate system to prevent this happening. The uranium rods are surrounded by aluminium sheets and in the first place there should be no leak in them. However, if the pile develops power after a time radiations begin to escape into the cooling air which may be detected by one of the very sensitive detectors of radioactivity. Furthermore fission filters are put in to stop any radioactive particles escaping into the outer atmosphere. As a result of this one gets very good warning of any failure long before it becomes dangerous and one could shut down the pile and extract it. It might be mentioned that there are 20,000 fuel elements in the Harwell pile and on the average there were about two failures a year so that at present it was not a serious problem.

There are important chemical and metallurgical problems. The reactor, it may be recalled, contains uranium metal bars sheathed in aluminium cans. The inside of the reactor is permeated with an intense flux of neutrons flying about with very high speeds in all directions. There are about ten to twelve neutrons crossing each square centimeter per second. These neutrons knock out atoms from their normal positions in the lattice; they produce interstitial atoms and this tends to change the metallurgical properties of uranium metal which tends to distort. It is therefore necessary to develop uranium fuel elements which will not distort even when they remain in the atomic pile for a long time. It is only possible to aid this development satisfactorily by producing certain experimental fuel elements and testing them in an experimental reactor; better still in a reactor having a much higher intensity of neutron bombardment such as in the Chalk River reactor.

Then the chemist has to consider what kind of corrosion reactions will occur: there would be interaction between the uranium metal and the sheet or between the cooling medium flowing past the fuel element and one has to remember that a chemical reaction may be speeded up by a factor of thousand or so in the presence of the intense radiation in the centre of the pile and all these things have to be checked.

Sir John Cockcroft then gave a brief account of the application of nuclear reactors of this general kind to the production of useful power. The nuclear reactor is considered for this purpose as simply a source of heat, the heat being developed in the uranium metal bars. This heat could be utilised for central heating purposes. At Harwell, the heat is removed by a stream of air flowing past the uranium rods; the air comes out of a large duct put in the passage of the upgoing air. It is a fairly conventional type of heat exchanger. All this refers to the spectacular application of heat from reactors.

The next thing was to adapt modified reactors of this kind to develop useful power. He showed a diagrammatic drawing of a nuclear power station wherein were shown the reactor, the steam generator and the rest of the conventional thermal generating station. The first thing that had to be done in order to generate sufficient power was to develop heat in the uranium metal bar of the reactor at a reasonably high temperature. If one is limited to using aluminium or magnesium for sheathing uranium metal bars then one will probably be limited to a temperature of about 350°—400°C. Then there is the problem of transferring the heat from the hot uranium metal bars to the steam generator and this could be done in a variety of ways. One of the ways is by using a gas such as carbon dioxide which does not react with the components of the reactor or better still helium could be used if it is available. It is necessary to try to evolve as high a rate of heat transfer as possible from the uranium metal bars to the circulating gas because of the very high cost of uranium metal. However, it seems that with an arrangement of this kind using uranium in aluminium or magnesium one can develop steam at a temperature and pressure which would allow an overall thermodynamic efficiency of the order of 25 per cent. to be achieved and that would really not be too bad for a first nuclear power station. One would like to use liquids also for transferring heat. It may perhaps be possible to use liquid metal for transfer of heat or both liquid metal and gas under pressure. But then one runs up against the usual difficulties in piles of this kind, of having very little surplus of neutrons. If the fluid were to absorb neutrons then the chain reaction could not be developed satisfactorily.

One thing that had to be remembered in the nuclear power station of this kind was that the reactor was really additional to the normal components of the power station and, therefore, one must expect that the overall capital cost of a nuclear power station in the first instance would certainly be more than that of the conventional power station. The size of a nuclear power station would be comparable to the size of a conventional power station using coal. The reactor takes the place of the coal handling equipment and the usual boiler is replaced probably by a rather more efficient and smaller boiler. However, it does seem from the preliminary studies that the capital cost of the first nuclear power station might be about twice that of the conventional power station. From the point of view of economy one starts with this disadvantage. However, the cost of electricity generated depends on two main components: the capital cost and secondly the fuel cost. Now what will the fuel cost of the nuclear power station depend on? One has to remember that uranium is a very expensive metal. A nuclear power station of this kind might contain at least 50 tons of metal and it may cost something between five to twenty thousand pounds to a ton. So the initial cost of the uranium including the processing may well be of the order of a million pounds.

If one has fifty tons of metal in the reactor this might be sufficient to produce a power equivalent to that of a very large power generating station of the present day, something perhaps of the order of fifty thousand K.W. The important question is how long will this initial charge of uranium metal which might cost up to a million pounds last? Will it last one year, five years or twenty years? One has to remember that in the nuclear chain reaction one is building up, in the first instance, the light form of the uranium; uranium 235 is only present to the extent of one part in 140 parts of the total. The next point to be noted is that as uranium 235 is burnt up it is being replaced by plutonium. For each uranium 235 nucleus destroyed, on an average, about 0.9 of an atom of plutonium, which is a secondary fuel is produced. Therefore these reactors are to some extent regenerative. The other point to be taken account of is how to reduce radioactive wastage products, the fission products, which tend to absorb neutrons. And the question then is how long can the reaction proceed before it is necessary to change the charge. This would depend on how the balance of neutrons and the balance sheet change with time. There is some advantage in changing uranium 235 nucleus into plutonium nucleus. On the other hand, the fission products absorb neutrons and therefore the balance between these two factors will determine whether this charge will last one, five or ten years.

An attempt could be made to make an estimate of the cost of a nuclear power station. It assumes that the capital cost of the nuclear power station is twice that of a conventional power station.

The lecturer showed a slide and from it he said it was clear that the cost of electricity generated from a nuclear power station might perhaps be twelve to fifteen per cent. more than the average cost of electricity produced by present-day power stations. One may however expect that with increasing experience, first of all the capital charge would come down and secondly the cost of processing of the uranium metal core would also come down. The general tendency, therefore, for the cost of nuclear power is to fall whereas for that from the usual power station is to steadily rise.

However, Sir John Cockcroft thought that one should not attach too much weight to calculations of this kind at this stage and the important thing was to get on and build a nuclear power station. After a few years' experience one would know what the costs are likely to be. One important thing to be noted is that after one has taken out the charge from an atomic power station there will be in the uranium metal rods a very considerable amount of secondary fuel, plutonium, and this is of value both for military and for civil purposes. In particular, the plutonium will form the fuel for the next type of nuclear power station. This second type of nuclear power station which would probably follow the natural uranium type of power station must be described as the power breeder reactor. The object of this type of power station is to burn up a much higher proportion of the uranium than is likely to be burnt in the first type of power station. He would expect this new type of power unit to be able to burn up at least ten per cent. and preferably much more of the total uranium. With the help of slides he illustrated the deterioration which sets in the fuel elements of the nuclear reactors; what happens to the fuel element after some exposure; what happens after still more exposures; what happens to the improved metal when the metallurgists have worked on it and improved its properties. He showed the neutron balance sheet and said that what is required in the future type of reactor—the power breeder reactor—was production of more plutonium than with the primary fuel and therefore instead of having 0.9 neutrons available to produce plutonium the attempt should be to make this as near 1 as possible. It is desirable to increase it to 1.2 or 1.4. If that could be done then for each primary fuel atom burnt 1.2 to 1.4 secondary fuel atoms are produced. Now in order to do that one has to build the fast reactor rather than the thermal one typified by the graphite reactor.

In the United States they have already built a small experimental breeder reactor. They have announced that it has a reacting core, about the size of a regulation football, constructed mainly of uranium 235. The heat is removed from this core by a liquid matter. Surrounding this core where the nuclear chain reaction proceeds is a blanket containing uranium 238 where secondary fuel is produced.

The lecturer showed a slide wherein a fast reactor power station was represented diagrammatically. The heat was transferred by a liquid matter (liquid sodium-potassium-halide) flowing through pipes going through heat exchangers. There was another liquid metal circuit going through this heat exchanger transferring the heat to steam generators. There were two liquid metal circuits. The reason for this was that the liquid metal circulating through the reacting core becomes highly radioactive and it is undesirable that this should contaminate the steam and the generator if there happens to be any leak.

He then gave some of the charactetristics of this experimental breeder reactor. Heat is transferred by liquid sodium-potassium-halide and the temperature is about 660°F. It develops steam at a pressure of 400 lb./sq. in. and generates about 250 K.W. of electricity. This then was a beginning in developing nuclear power. They have not yet given out whether this nuclear power station has succeeded in breeding, that is to say in producing more secondary fuel than it consumes the primary one.

He then showed a slide showing a schematic drawing of what a power breeder reactor of this kind may look like. The reacting core might contain either uranium 235 or preferably plutonium. Plutonium would be a much better fuel to start breeding reactors with the heat being transferred again by liquid metal going through heat exchangers. The reacting core is surrounded either by ordinary uranium or by thorium. If thorium is used in order to produce another secondary fuel, surrounding it again there would be a standard sheet. One of the characteristics of this kind of reactor is that a very large amount of heat, something corresponding perhaps to about 100,000 k.w. is developed in a very small volume and therefore, if anything happens to this coolant, say due to the failure of the pump, the fuel will melt very rapidly. Therefore, reactors of this kind which develop a lot of power in a very small space present the designers with quite serious technical problems. It is far too early at the present time to say what the cost of power from power breeder reactors is likely to be. One could say with certainty that the primary cost of the fuel is likely to be entirely unimportant if one achieves the real breeding and can build up at least cent. per cent. of the total uranium. The important factor in the cost of power in that case would be the cost of processing of the spent fuels. The reacting core of the pile after it is operated for some time will have to be taken out and sent to chemical processing plants where the radioactive fission products could be extracted. The cost of power from this kind of system will, therefore, depend on the cost of chemical extraction.

The lecturer showed slides of Harwell Chemistry Laboratory where the chemical extraction processes are worked out on a laboratory scale in the first place and also the active chemical engineering laboratory. The processes of extracting radioactive fission products have to be carried out with very special precautions behind thick concrete sheets because of the immense radioactivity of all the materials.

Sir John Cockcroft next referred to what contribution nuclear power might in the long run make to augment our power resources. Recently there has been published in the United States a report on material resources. The total energy resources in the world were expressed in terms of a very large unit, 10^{18} British thermal units.* In this very large unit U.S.A. has got 7.6Q in its coal reserves, Canada 2, U.K. 1, China 6, Russia 10, and the rest of the world about 7. This makes a total of about 33Q. A similar table was produced for oil and the total oil reserves were estimated to be about 6Q. The present world consumption of power is about a tenth of a Q a year. So these reserves at the present rate of consumption would last only for about 330 years. But it is well known that the curve of energy consumption is rising very rapidly. The total annual input of energy from major world energy resources and energy consumptions are going up extremely rapidly and, therefore, there does seem to be need for developing within the next fifty years or so another addition to the resources of world energy.

The lecturer said that he would like to say something about other applications of nuclear power stations before he finished his talk. First of all, the application to the propulsion of ships. It is pretty obvious that a large reactor of the type of the Harwell reactor which has a shield weighing five thousand tons is not suitable for driving ships. One can make reactors by using heavy water when the total weight might come down to something of the order of a thousand to fifteen hundred tons, but even so it was pretty heavy to be put inside a ship. In fact, it seemed that the only way to make power units for ships would be to use not uranium in its normal proportion but to use enriched uranium, uranium in which the proportion of U235 is very considerably increased. It was reported that the United States are now building three propulsion units of this general type, two of them to drive submarines and one to drive an aircraft carrier. They are using two quite different kinds of reactors but all of them use enriched fuel U235.

The first kind of reactor is the general type of the heavy water or graphite reactor except that the dimensions would be much greater. A second type of reactor is being built by the General Electric Co. which operates in the intermediate region of energy so that it is known as an intermediate reactor.

If one looks into the economics of nuclear propulsion units for ships it appears again that the capital cost is likely to be several times higher than those of conventional propulsion units. It seems also that the fuel costs are likely to be three or four time as high. For special purposes such as for driving submarines this does not matter very much because it is well known that, in any case, propulsion costs are very much higher than those of normal commercial units.

The lecturer next dwelt on the important applications of nuclear reactors to the production of radioactive isotopes which as is well known have applications in medicine and biology. Carbon 14—radioactive carbon—is of particular importance in studying metabolic processes in living matter. They also have important industrial applications. A typical example is the use of radioactive cobalt for radiography.

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* British thermal unit is the amount of energy required to heat 1 lb. of water by 1 degree Fahrenheit.

At the present time most of the radioactive isotopes are made by inserting materials into piles such as the Harwell pile and leaving them there for different intervals of time. For isotopes which have short half-life periods such as phosphorus or iodine, the material is left in the pile for about a week. On the other hand, if isotopes having long half-life periods are being produced such as the radioactive carbon or radioactive cobalt they are left for much longer periods.

A very important source of radioactive isotopes is the wastage products, (the fission products) and in the long run these would become increasingly important. At present it is possible to produce in atomic piles a source, in a material such as cobalt, the radioactivity of which is equivalent to about thousand grams of radium. This is to say one can produce a source having an activity of thousand Curies. However, if instead of using radioactive cobalt materials such as caesium 137 were used then there is no reason theoretically why one should not have a radioactive source which is a thousand times stronger. There was recently a symposium at Harwell to see what the long term application of those radioactive waste products might be. It looks very probable that in the future one might have sources having activities corresponding to that of a million grams of radium. These may have applications in chemical engineering. They can be used in chemical reactions such as polymerisation. They will be used for sterilising food and so on. There are very many possibilities of the applications but it is far too early to say whether they would be economically justified.

Sir John Cockcroft then showed a film illustrating the handling of radioactive materials at Harwell. He concluded the lecture by saying that great care had to be taken in disposing of the radioactive affluent. Before discharging it into the Thames which is the source of London's water supply they had to be quite certain that the radioactivity level in the water was very low.

Dr. Bhabha said that it was his pleasant duty on behalf of all to thank Sir John Cockcroft for a very interesting and lucid lecture. Sir John Cockcroft had put in a very considerable amount of scientific material into a popular lecture and the chairman was sure that everyone who had assembled to listen to the lecture had found it exceedingly interesting. He recalled that soon after the first atom bomb explosion all the pundits spent their time in convincing others that it was of no use except for destructive purposes. Dr. Bhabha was very glad to note that the prognostics of the peaceful uses of the atomic energy are so hopeful today.