A public discussion on the future of nuclear energy was organized by the Director General of the International Atomic Energy Agency in Vienna on 22 September 1959 in conjunction with the third regular session of the Agency's General Conference. The three eminent scientists who participated in the discussion - Dr. Homi J. Bhabha of India, Sir John Cockcroft of the United Kingdom and Dr. Bertrand Goldschmidt of France - are members of the Agency's Scientific Advisory Committee. The Secretary of the Committee, Dr. Henry Seligman, Deputy Director General of IAEA, acted as moderator. The meeting was presided over by the Director General, Mr. Sterling Cole.

The discussion began with opening statements by the three scientists surveying recent developments, current trends and future possibilities. After these general statements, they answered a number of questions from the audience.

A record of the discussion, including the opening statements as well as the questions and answers, is contained in this special number of the IAEA Bulletin.

STATEMENT BY SIR JOHN COCKCROFT

The period since the 1958 Geneva Conference has been spent in accumulating experience of the operation of the first prototype nuclear power stations and in building the large output commercial nuclear power stations which are to come into operation in the early 1960s. There has been some narrowing of the field of reactor development and no essentially new types have appeared. One reason for this has been the appreciation of the long time scale and the enormous amount of research and development effort which is required to see any new type through successive stages of development to final production and operation.

The experience of operation of the first prototype nuclear power stations, Calder Hall, Chapelcross, Shippingport and Marcoule continues to be good. Up to the present over 1 billion units of electricity has been generated in the UK from the two nuclear power stations. Apart from the time required for scheduled changes of the fuel charge, which has been progressively reduced from ten weeks to five weeks, the reactors have operated for about 90 per cent of the possible time. Since future power stations will be able to change their fuel elements under load there appears to be a good chance that nuclear power stations could achieve very high load factors if the loads are available, as they are likely to be for some time in the UK.

The main faults experienced have been conventional ones, not associated with nuclear questions. There was a runaway of a turbine during commissioning at Calder Hall, due to the seizure of a control valve. There have been troubles with meters on circulating fans at Calder Hall, troubles of the stripping of turbine blades at Shippingport, due to failure of a water separation unit, and a partial melt-out at Marcoule.

The Shippingport operators have reported that their station has been simpler to operate than a coal fired station, and that it can be started up and shut down more rapidly than a coal fired station. In the UK we have found that we can take out power stations from a low load up to a full load in about half an hour, the time being limited by ordinary thermal stresses.

The experience gained has resolved many of the technological uncertainties of nuclear power. Thus we have found that the accumulation of stored energy in graphite which could lead to spontaneous temperature rises if allowed to go too far, can be greatly reduced by increasing the operating temperature of the graphite. The chemical reactions between graphite and hot CO_2 have behaved as expected and are not

giving us any trouble. Experiments on provoking reactor oscillations have shown that no difficult problems of control arise but that additions to the control systems will be required for the very large reactors of the future.

Problem of Burn-up

The principal technological problem remaining is that of burn-up. We have to be able to extract the maximum amount of heat possible from nuclear fuel which reactivity limitations allow. It is not always appreciated that when we talk of burn-ups of 3 000 MW days per ton for uranium metal fuel elements or 10 000 MW days per ton for uranium oxide fuel elements these are somewhat arbitrary figures since reactivity limitations will allow a 50 per cent greater burn-up in some natural uranium reactors using graphite moderators whilst the burn-up with oxide fuel element in light water moderator reactors is limited mainly by the degree of enrichment.

The actual burn-up achieved will depend on the efforts of the metallurgists in overcoming radiation damage of fuel elements.

The actual incidence of fuel element faults has been extremely low. In the UK there have been about 27 faults in 100 000 fuel elements for burn-ups ranging up to 1 200 MW days per ton and their causes are now well recognized. The Shippingport operators reported only one or two incipient failures of their fuel elements in one year's operation, and their peak burn-up in the uranium oxide fuel element has reached 10 000 MW days per ton with an average of 2 000 MW days per ton. Nevertheless a large effort is being devoted towards extending this experience to higher burn-ups since this appears now to be one of the main keys to economic operation of nuclear power stations.

A great deal of attention has also been paid to the safety of nuclear power stations. It is now recognized, largely as a result of the Windscale accident experience that the principal reactor hazard following an accident would be likely to result from the melt-out of a limited number of fuel elements leading to a release of radio-iodine and radio-strontium, other isotopes being less important. Modern reactors have a much higher degree of containment than Windscale which had virtually none for radio-iodine so that at the worst the proportion leaking out to atmosphere from modern stations would be much less. In the unlikely event of some being released, the absorption of radio-iodine on grass would require the temporary stoppage of milk supplies to human beings from nearby farms, though the milk could be fed to animals. It might also be necessary to move population within a small radius of a kilometre or so, whilst radio-iodine leakage was occurring. Hazards of this kind would not be catastrophic but until we have accumulated more experience it is wise to maintain a cautious siting policy to avoid the possible disturbance of large numbers of people.

The placing of contracts for the construction of conventional nuclear power stations has slowed down somewhat during the last year. Up to the present 1 875 MW have been ordered by the Electricity Boards and Calder Hall and Chapelcross will contribute about 300 MW, and preparations are being made to order two more large-output power stations. The latest figures for the US programme total about 1 000 MW by 1963. Euratom forecasts under 3 000 MW by 1966. Outside Europe and the US, only Japan has so far indicated her intention of ordering a large scale nuclear power station.

Recession in Nuclear Power

The recession in the nuclear power programme is partly due to the changing picture of fuel supply in the world. This appears to be mainly due to a large scale switch of industry from coal to oil resulting in a temporary surplus of coal in some countries. Thus in the UK oil consumption has increased during the last eight years by the equivalent of 20 million tons of coal per annum whilst total energy requirements have only increased by about the same amount.

A second factor in the situation in Britain has been the increase in the estimated cost of nuclear power and a decrease in the estimated cost of future coal fired stations. The UK Electricity Board forecast at Geneva in 1958, that the cost of nuclear power at a site in Southern England away from coal fields would be about equal to coal costs at about 0.6d. per unit, for interest rates of five per cent. Due to a rise in interest rates and some increases in the cost of graphite, and other components, the current forecast figures are now 0.65d. to 0.7d. for nuclear power while the estimated cost of power from coal fired stations has slightly decreased.

The date and rate at which nuclear power stations will become competitive will depend very much on the rate at which capital costs per kilowatt of nuclear power stations is reduced. In the UK we have seen capital cost reductions of the order of 30 per cent during a period of three years. Technological developments such as higher temperature operation are likely to produce a further fall of about 20 per cent by 1966 and still further technological development such as the Fast Breeder Reactor are thought by some to promise a further 20 per cent reduction together with a major reduction in fuel costs due to breeding. However, at this distance ahead - ten years or so - the crystal ball is apt to be a little cloudy so that forecasts should be taken with some reserve.

There is however, one factor favouring nuclear power costs which seem reasonably certain. Uranium prices are now confidently predicted by experts to fall from current figures of 12 dollars a pound to below eight dollars a pound in the middle 1960s and this could result in a fall of up to ten per cent in overall nuclear power costs. There are also some possible bonuses such as increased burn-up and load factors higher than those assumed.

A Temporary Phase

If we combine these favourable factors with the undoubted fact that electricity demands of the world are still rising exponentially with a doubling time of ten years we must agree with the Chairman of Euratom that the recession in Nuclear Power Construction can only be a temporary phase.

The development of nuclear marine propulsion has been taken a step forward by the commissioning of the USSR Icebreaker "Lenin" and we look forward to the commission of the US "Savannah". The problem of economic ship propulsion still seems to us to be as difficult as ever. The cost of the Savannah propulsion unit was stated at Geneva last year to be 15 million dollars as compared with a normal propulsion unit cost of about five million dollars. This reflects the general difficulty of making small nuclear power units competitive.

The central problem of commercial nuclear propulsion is the reduction of capital costs. It is apparent already from our studies that this reduction will have to be made over a wide range of reactor components and that this lies largely within the field of conventional engineering. No nuclear brainwaves will solve this problem.

The work of the last year on the development of thermonuclear power has been concentrated on the understanding of the physics of hot plasmas rather than on the design of thermonuclear reactors to achieve break-through. For it has become abundantly clear that the key to thermonuclear power is to be able to prevent the loss of energy from hot plasmas due to instabilities and radiation mechanisms which appear to set in when we approach interesting plasma densities and temperatures. It has been observed for example, that one comparatively modest device was losing energy by ultra-violet radiation from impurity atoms at the rate of 1 000 MW. Other losses are due to failure of the magnetic containment leading to electrons hitting the walls. These losses have been reported both from pinch machines and mirror machines. We will have to understand much more about the properties of plasma before we can hope to suppress this misbehaviour, and begin to design true thermonuclear reactors. We should also remember that our magnetic bottles of the future will have to withstand plasma pressures of up to 100 atmospheres and that we need six inches of steel to contain such pressures in fission reactors; so thermonuclear power will not be without its design problems. I think therefore that my previous guess that thermonuclear power is at least 20 years away is still a valid one.

Radioisotopes

The applications of radioisotopes, the by-products of atomic energy, continue to expand with a growth rate of about 20 per cent per annum in the UK. A new development has been the production of radio-cobalt sources in units of 100 000 curies as a by-product of reactor operations. These large sources have already found a commercial application to large-scale sterilization of medical appliances, surgical dressings, and goat hair used for carpets. The Wantage Radiation Laboratory will soon install a source of 150 000 curies to irradiate two tons of materials per hour with a dose of 2.5 million rads - a dose which would be lethal to all bacteria. I believe that the US are building an installation to house a one-million curie source for the study of sterilization of food. Investigations on the large-scale disinfestation of grain have shown that it is technically feasible to install similar large radioactive sources in silos to destroy insect pests. The economics of this are now being studied in the UK by pest infestation experts. Since the world loses over 60 million tons of cereals a year by pests, this may well be an important future application of atomic energy.

I am sure there will be many more large-scale commercial applications of radioisotopes. We have arranged for IAEA fellowships to be made available at the Wantage Radiation Laboratory for the study of these problems; it will be for individual countries, in the light of their own situations, to see what use they can make nationally of these new tools and techniques.

STATEMENT BY DR. HOMI J. BHABHA

I would like to take this opportunity to say a few words about the economics of nuclear power in the under-developed countries. The more we look into it, the more we find that there are interesting factors which have not been fully appreciated before, but at the same time, the more complex and diverse the problem becomes.

For one thing, the word "under-developed" - I use this word specifically in the sense of areas in which production is low per capita - covers a very wide spectrum, ranging from countries whose per capita income varies from US $43 to four or five times as much just as in the case of the so-called industrialized countries the per capita national income may vary from some $300 per annum to six times as much. The countries also vary very greatly in their size and population, which ranges from a few millions to a few hundred millions, and in the natural resources of fuel which they possess. The countries of the Middle East, for example, are extremely rich in oil while most of the countries of South Asia are extremely poor in oil, both absolutely and even more on a per capita basis. Similarly the coal reserves of the under-developed areas vary very greatly from one to the other.

It becomes clear therefore that no generalization about the applicability or non-applicability of atomic energy in the under-developed areas can be made which is not seriously in error in certain parts, just as no such generalization can be made about the applicability of atomic energy in the industrially developed areas.

Situation in India

I shall concern myself primarily with the situation in India, which we have studied carefully, and where a number of factors have shown themselves to operate, which negate all the generalizations which one might expect to be true about the applicability of atomic energy in under-developed areas.

Unlike in the case of China, India's coal reserves are rather limited, the proved reserves being about 43 000 million tons, although the probable reserves may be three times as much. This, however, makes the Indian reserves of coal per capita only 1/35th of those of the United States. Secondly, those reserves are not evenly distributed throughout the country but are concentrated in about four States; 55 per cent lie in the States of Bengal and Bihar in the north-eastern corner of India, and about 25 per cent in the State of Madhya Pradesh. Of the actual production, 80 per cent comes from Bengal and Bihar and only 12 per cent from

Madhya Pradesh. Thus, large areas of the Gangetic plane, of northern and western India, and of southern India, are devoid of coal, which has to be hauled over a distance of over 500 miles to those areas from the coal fields. Thus, the thermal stations in Bombay and Ahmedabad receive their coal from Bengal and Bihar over a distance of some 1 500 miles, while Delhi receives its coal from the same area over a distance of 800 miles. Even when the coal fields nearest to those places are developed fully, coal will still have to be hauled over 500 to 600 miles to these places, This naturally puts up the price of coal to two to three times its value at the pit-head resulting in a corresponding increase in the cost of power. This aspect is well known and is taken into account in most calculations of cost of power. What is equally important, however, is the capital investment required for the transport system, to transport the coal. This point is usually ignored.

When a private group or company thinks of establishing a power station it is concerned only with the capital costs that it itself has to bear, that is with the cost of the power station. It assumes that someone else will find the money to develop additional mines and produce the necessary coal if the demand is there, and that yet another party will meet the demand for transport by finding the investment necessary for increasing the facilities in railways. For a private group, therefore, the higher cost of nuclear power stations compared with thermal power stations is a very important factor which militates against the use of nuclear power stations. While there are large utilities in India which supply an extensive amount of power, future power production will be increasingly the responsibility of the State. As in the case of several

European countries, the railways are entirely State-owned in India. Thus, when the State thinks of increasing power production in the future, it has to think not only of the investment it will have to make in power stations, but of the balancing investment it will have to make in developing new collieries and in providing additional transport required for transporting the coal. The Indian railways are already fully loaded and any large installation of power in areas remote from the coal fields will of necessity require new investment in the railways. We have made some calculations of the amount of this investment on the assumption that good quality coal has to be hauled over a distance of about 700 miles. This investment turns out to be about Rs. 450 or about £33 per kW installed. This is not negligible compared to the cost per kW of really efficient modern thermal stations. It is nearly 50 per cent of the capital cost of small-sized thermal stations such as might be erected in several parts of India. I will not take time to go into similar details regarding the investment in coal mines. Suffice it to say that we estimate that the total national cost per kW installed of thermal power at places some 700 miles from the nearest coal field comes to about Rs. 1 350 (that is £100) per kW for large stations and nearly Rs. 1 600 per kW for small ones. This is comparable to the cost of about Rs. 1 700 per kW for natural uranium power stations of large size and comparable with or higher than the capital cost of enriched uranium stations of a comparable size.

Cost of Power

What about the cost of power itself? The cost of power naturally depends on the interest rate charged on the capital investment and on the depreciation. Several foreign economists seem to contend that as capital is in short supply in under-developed countries interest rates must naturally be high and some have suggested interest rates as fantastically high as 10 per cent. The proof of the pudding is, however, in the eating. The fact is that 11 State Governments in India raised loans in 1958 totalling some Rs. 500 million at 4 1/4 per cent interest and the loans were over-subscribed by the public. Similarly the Government of India raised loans totalling Rs. 1 650 million at interest rates varying from 3 1/2 per cent to 4 per cent and these were also likewise fully subscribed. Thus, it is plain that in all calculations in India as far as local costs are concerned, we would be fully justified in taking interest rates at 4 1/2 per cent. This has a very important bearing on the relative costs of nuclear and thermal power. As regards depreciation, one can do it by the straightline method, assuming a life of 20 years for the plant, in which case one would have to lay by 5 per cent per annum, or one could calculate it on a sinking-fund basis, assuming compound interest on what has already been put into the fund at 4 1/2 per cent. On this basis one would have to lay by 3. 29 per cent per annum for depreciation. It is readily seen that on this basis and with a fuel cost of Rs. 300 000 per ton, that is something more than £20 000 per ton, the cost of power comes out to some 3. 5 cents (about 7 mills) of a rupee per unit. The comparable cost of thermal power comes to 3. 6 cents of a rupee. Thus the power costs are very comparable in actual Indian conditions.

What about hydro power? The rainfall in India is seasonal. There is heavy rainfall for three months of the year while in the remaining nine months hardly any rain falls in most parts of India. The use of hydro power therefore requires the building of large storage reservoirs which can store enough water to supply power throughout the year. This means very large investment in building large dams. Taking a number of typical hydro projects we find that the average cost works out at about Rs. 1 800 per kW installed. This is as high as the capital investment in nuclear power stations. But the investment is mainly in civil engineering work. The cost of the turbo-alternators is relatively a small part of it. For this reason it is best to install more electrical generating capacity than could be kept working at 100 per cent or even 80 per cent load factor throughout the year. This is a new point which comes out very strikingly if one looks into the figures for some of our hydro projects. For example, the installed capacity of the Koyna project is 240 MW; due to limitations of water, the capacity at 80 per cent load factor is only 180 MW. Although the nominal cost of this project is about Rs. 1 380 per kW, the effective cost at 80 per cent load factor would be round about Rs. 1 700. There are other hydro power projects in India in which the effective cost per kW is as high as Rs. 2 200 or even Rs. 2 800 per kW, that is nearly 60 per cent higher than that of nuclear power stations. Thus, if hydro power is to be installed, a very large capital investment has to be made in any case, which in many cases is quite comparable with, if not higher than, the cost of nuclear power stations.

The seasonal nature of rainfall has the effect that it is necessary to support hydro power by thermal power. The following passage from a recent report prepared for the Government of the State of Madras speaks eloquently of the position:

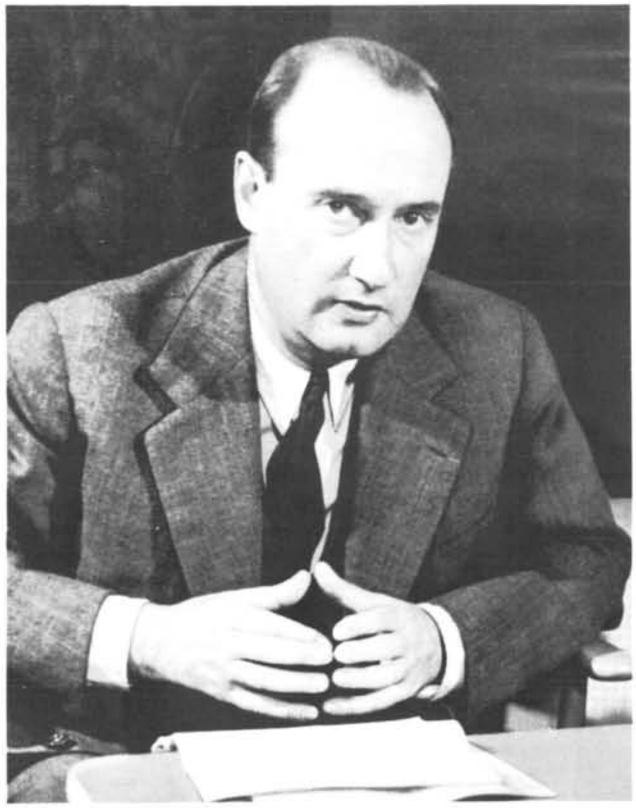
> "From this analysis, it can be seen that though the installed capacity of the grid amounted to 256 000 kW in 1956, the effective capacity in terms of dependable firm power was much less - about 143 000 kW. In exceptionally bad years of drought, and we had a succession of them in the recent past - or when the south-west monsoon is delayed, the storages in these reservoirs are exhausted, necessitating drastic power cuts. There were power cuts in 1953, 1956, 1957 and the one in 1958 went up to 75 per cent during the month of June, and practically paralyzed all established industries in the hydro-electric area."

Need for a Beginning

All that I have said is not intended to prove that nuclear power in certain parts of India today is definitely much cheaper than conventional thermal power or hydro power. It is only intended to show that the capital investment required for nuclear power is quite comparable with the capital investment we have been used to making for hydro projects, and is not much higher than the national investment required for thermal power stations at places remote from coal fields. Bearing in mind the limited reserves of coal and hydro power in the country, which are enough only to see us through the expansion of the next 10 or 20 years, it is clear that an important beginning with nuclear power has to be made now, so that it may be in a position to take on a major part of the increase after 15 years. I may mention in this connexion that we have decided to build our first nuclear power station with an installed capacity of approximately 250 MW, and preliminary work on it has already started.

The position in other under-developed areas may be quite different. The example that I have given of India is intended to show that one should study each problem on its merits and not jump to facile conclusions that nuclear power cannot be economical today in under-developed countries. I consider it one of the tasks of the Agency to take up various under-developed areas for detailed study, to see the sizes of power stations which would be required there and to work out the relative economics. This may turn out to be a fruitful study, not only for the areas which are studied, but also for those countries which will be called upon to supply power stations, at least for the next couple of decades.

STATEMENT BY DR. BERTRAND GOLDSCHMIDT



As I am taking the floor after two physicists, I should like to give you the point of view of the chemist by indicating, on the one hand, the importance of the part played by chemistry and metallurgy in the development of atomic energy and, on the other, the growing influence which radiation and radioisotopes produced in atomic reactors will be exerting in the industry, and especially the chemical industry, of the future.

In these two fields there have been no important changes since the Geneva Conference a year ago, and I shall be attempting to sketch the broad outline of development rather than imparting new information.

Nuclear Materials Industries

Let us begin with the preparation of the nuclear materials needed in building atomic power stations and of the most essential of these, namely uranium. During the past fifteen years or so a considerable uranium mining and metallurgical industry has been developed, which in terms of turnover is this year of the same order of size as the aluminium industry and which consumes almost 4 per cent of the world's production of sulphuric acid. Thanks to this industry which has grown up and the fall in the price of uranium to which it has led, the supply of uranium to nuclear power stations over the next 20 years will present no problem and the cost of the nuclear fuel will be a minor element in the price of the electricity produced.

The growth of this industry would have been impossible but for the introduction on an industrial scale for the first time in the mineral chemical industry of new methods of extraction using either organic solvents or organic ion exchange resins. Thanks to these specially selective processes, which will no doubt also help in their turn in the extraction of other metals from their lean ores, it is nowadays possible to extract uranium from abundant ores with a content of one part per thousand or even less at prices which are only four or five times higher than those quoted before the War for scarce and unusual ores several hundreds of times more concentrated.

Other important nuclear material industries can today be regarded as virtually developed; these are the industries producing graphite, zirconium, and nuclearly pure uranium and thorium metal. These industries are coming close to the complete elimination of elements which readily absorb neutrons and are approaching degrees of purity such as have never yet been achieved in industry. Here again refinement by means of organic solvents is in very many cases the preferred method.

Isotope Separation

Still more original and of a kind previously quite unknown are the isotope separation facilities, which we might call physico-chemical plant. Here are repeated, sometimes on an enormous scale, the hundreds and hundreds of thousands of successive stages involved in the separation of atoms of different kinds which nature has till now always supplied as inseparable pairs - i.e. the two hydrogens, yielding heavy water, and the two uraniums, yielding uranium enriched in uranium-235. In either case, considerable difficulties have had to be overcome and although this field is partly classified, the technical solutions for these difficulties will undoubtedly become more and more useful in other branches of industry. The science and industrial technique of isotope separation is scarcely more than 20 years old. It is difficult to believe that progress cannot be made and if it were considerable it might greatly influence the choice of future lines of development and the economics of nuclear power. The latter will depend for the immediate future mainly on the progress achieved in improving the behaviour of nuclear fuel elements under radiation. The object is to attain higher and higher temperatures for the fuels, and hence for the coolants which carry the energy to the generating turbines, and a larger and larger burn-up of fuel, before deformation becomes too great and the fuel has to be taken out of the reactor. Like pure plutonium, pure uranium metal does not stand up very well to temperature fluctuations and the effect of radiation, as these cause serious deformation, but their oxides, and some of their alloys with other metals, are much more resistant to these effects.

Atomic laboratories throughout the world are studying hundreds of different kinds of uranium and plutonium alloys, together with the kinds of ceramic produced by fritting - i.e. heating to a high temperature under pressure - mixtures of metal oxides with one another or with other metals. These studies are lengthy, delicate and expensive and should culminate in experiments in material-testing reactors, of which there are at present few but will shortly be more, particularly in Europe, thanks to the placing of new units in operation. France has great hopes that uranium alloyed with small quantities of molybdenum or chromium will behave satisfactorily up to 3 000 MW/day/ton; these alloys are doubtless also produced in other laboratories which too often keep silent in a matter of obvious industrial importance.

It would be most desirable if the Agency could help to co-ordinate this research but unfortunately the only real way to co-ordinate research is on the principle "He who pays the piper calls the tune" and, as you know, our Agency is very poor. Perhaps the Agency can try and arrange for programmes to be communicated and published and for information to be given on unsuccessful experiments, which are far more numerous than the successful ones.

Finally, I should like to give you an actual example of the scale and difficulty of the metallurgical problems. Like France, the United Kingdom is studying natural uranium gas-cooled reactors. Two prototypes of an advanced design exist in our two countries - the A.G.R. (Graphite-Moderated Advanced Gas-Cooled Reactor) in the United Kingdom, and the E.L.4 reactor in France which is the fourth of the heavy-water-moderated series. In both systems the required increase in cooling gas temperature makes it necessary to sheathe the nuclear fuel with beryllium which has a much higher melting point than the magnesium previously used.

The metallurgy of beryllium is in its infancy, and its cost is high - $150/kg - partly owing to the danger from beryllium dust which causes certain kinds of accelerated tuberculosis, yet the success of these two reactors depends to some extent on the manufacture, welding and behaviour of these beryllium tubes.

Success might lead to further demand for beryllium, and the need for beryllium supplies, which can easily be satisfied at present from rich but fairly rare ores, might lead to prospecting for poorer but more abundant ores, the study of the chemistry of beryllium extraction and the establishment of a new chemical industry.

Chemistry will definitely have its part to play in some future reactors. Some will use organic coolants and moderators, radiation-resistant hydro-carbons with a high boiling-point, while in others, the so-called homogeneous reactors, the nuclear fuel will be in the form of a dissolved salt, the fission products being removed from the solution by circulation in an appropriate vessel. A reactor of this kind, really chemical in nature and rich in promise, still seems a long way off due to the as yet unsolved problem of corrosion by radiation.

Radiation and Radioactive By-products

Let us now leave the first part of our survey and turn to the question of the industrial use of radioactive by-products and of radiation from the chain reaction in uranium.

It is often forgotten that uranium fission has led to the discovery not only of a source of energy over two million times more concentrated than coal but also of a means of producing transmutations on a scale undreamed of by the most sanguine alchemists of the middle ages.

One of the amazing features of this transmutation is that the large nuclear power stations of the future will produce from uranium tens and even hundreds of kilogrammes of plutonium a new element which does not exist in nature.

Plutonium will be the chosen fuel of the future in "breeder" reactors, which enable a much larger proportion of the world's uranium to be transformed into energy. The separation of plutonium from uranium and of radioactive fission products from irradiated rods has necessitated the construction of veritable alchemists' factories, operated entirely by remote control owing to the danger of intense radiation. These factories are real triumphs of modern technology in their design and operation. Here again, the preferred procedure is extraction by means of an organic solvent, though in certain cases this may be replaced in the future by selective extraction by salts or molten metals, a procedure known as pyrometallurgy, the operation of which under radiation will present completely new industrial problems.

It is chemistry too which makes it possible for the liquid effluents of these factories to be discharged in a safe form, containing concentrations of radioactive substances no greater than the concentrations of radium which until recent years were the boast of many mineral waters. The problems of the disposal of radioactive wastes, which are largely chemical problems, are assuming increasing importance in face of the growing sensitiveness of the public to everything affecting environmental radioactivity. The Agency has a considerable role to play in laying down international rules which will help to promote the development of atomic energy by reassuring the public concerning its use; the group of experts on this problem, together with the forthcoming conference which is to be devoted to it, are the first notable manifestations of that role.

In addition to plutonium, nuclear reactors yield substantial quantities of radioactive by-products formed either directly by fission in the nuclear fuel or by the transmutation of elements bombarded by neutrons. By this means it has been possible to reconstitute radioactive isotopes of all the known elements, nuclides which must have existed when the world was formed but which disappeared owing to their instability.

Industrial Use of High-level Radiation

It is not my intention to speak of the many scientific, medical and industrial applications of radioisotopes; instead I will turn to the industrial utilization of high-level sources of radiation, a promising technological field which is just beginning to be developed. The Conference which the Agency has recently held at Warsaw has shown the interest of this subject and I shall attempt to give you a rapid survey of it, laying particular emphasis on its applications to the chemical industry.

The strongest sources of radiation are the reactors themselves. A reactor of 100 000 thermal units gives a radiation equivalent to several hundred tons of radium; during the fifty years which followed the discovery of radium only some two to three kilogrammes of that substance - even one gramme of which is dangerous to handle - were isolated. The revolution which is taking place is shown by those figures and by a comparison of prices. One gramme of radium is worth today some thousands of dollars, whereas an equivalent quantity of radioactive cobalt or caesium costs about one dollar.

Already attempts are being made to use the kinetic energy of fission products to produce chemical reactions, particularly in the gaseous phase, e.g. the formation of oxides of nitrogen and nitric acid from nitrogen and oxygen, or the oxidization of organic products. If these experiments prove successful it may be that nuclear reactors will one day be constructed solely for the purpose of achieving chemical syntheses. We now have the possibility of using in the chemical industry a new factor, ionization by radiation, in addition to the conventional factors of temperature and pressure and we see appearing over the horizon a new branch of industrial chemistry: radiochemistry.

The high-level radiation sources used at present are either liquid metal circuits irradiated inside the reactor and emitting penetrating gamma rays on emerging (such as the mixture of gallium and indium in the Soviet I. R. T. reactor), or plants using the penetrating radiation flux of irradiated fuel rods undergoing cooling, or cobalt-60 sources obtained by it radiating cobalt with neutrons, or sources of caesium-137, a fission product with long half-life which it is relatively easy to separate from the mixture.

At the French Atomic Centre of Saclay we have a casemate which can hold a large part of the rods of the 15 MW EL 3 pile. Part of this casemate is fitted out as a refrigeration chamber in which important experiments can be carried out on the conservation of food by radiation.

Finally, when the required dose and intensity of radiation are relatively low and when penetrating rays are not necessary, it will be possible to use beta ray sources derived from a number of fission products of long half-life such as radio-strontium, for which a genuine usefulness will thus be found, belying its sinister reputation with the public. Such sources are already being used for the industrial treatment of plastic materials by radiation, as well as for bending, i.e. the joining of two plastic materials, the two sorts of molecules shattered by the effect of the radiations recombining with one another in the intermediary phase.

In the United States irradiated polyethylene is already being produced on a commercial scale; this material can then be used as an electric insulator at relatively high temperatures.

In another field reference should be made to the first attempts to reduce by means of radiation the cracking temperature of hydro-carbons. An attempt has also been made to improve the action of catalysts by radiation, though this application seems remote since most of the effects observed disappear on heating to the temperatures required for most industrial treatments.

These chemical applications of high-level radiation only represent a small part of a very large industry which has already got off to a real start in the following fields: food conservation, sterilisation of pharmaceutical products, sterilisation of insects with a view to their destruction, creation of new agricultural species by induced mutation, and improvement of vaccines by destruction of microbes and viruses.

Emerging Technologies

Thus a group of new technologies is emerging, the development and exploitation of which entail fewer resources and which will become more and more widely available, so allowing many more countries to profit from them, in particular those for whom a nuclear power production programme would at present be premature. The Agency will be able to play a role here in promoting technical assistance to countries which wish to enter this field. The volume of work done in this field will increase steadily and it will represent, alongside the growing production of nuclear power, an industrial field of great potential importance, where, as we have attempted to show, chemistry and chemical industry will have a large part to play.

QUESTIONS AND ANSWERS

Question to Sir John Cockcroft:

You spoke of isotopes as by-products of atomic energy. This is certainly true of fission products but in my opinion it is not so true of the isotopes created by neutron bombardment. In view of the fact that isotopes have played such an enormous part in biology and biochemistry in the last ten years, do you think it is now reasonable still to talk about them as by-products of atomic energy?

Answer:

This is really a question of words, but I talked of them as by-products because they are produced in reactors which were constructed for other purposes. To that extent, they are by-products of electrical power or materials testing reactors. I didn't mean to disparage the role of isotopes. In fact, I have often thought that applications to biology and biochemistry have been one of the most important developments of atomic energy so far.

Question to Dr. Bhabha:

Are there any indications of new lines of fundamental research that may bring about major changes in atomic science and technology?

Answer:

I suppose the answer to that question must always be "yes". What we know is such a small fraction of the amount there is to be known. I don't know what more I can say on this. As you know, we have not succeeded in achieving any direct transmutation of nuclear energy into electricity. It may be that there are fundamental aspects of this that will reveal themselves in due course and allow us to generate power directly rather than by the present method, which is simply a new way of boiling water.

Sir John Cockcroft added: I might just add to this last point about the direct generation of electricity that I think that if we ever achieve a fusion reactor which would have a very hot gas electrically conducting, you can quite easily see how you can force that to vibrate and transmit the energy directly into an external circuit. But this depends on first building a fusion reactor.

Question to Sir John Cockcroft:

Do you feel that work on thermonuclear fusion, after some striking initial progress, has now reached a kind of deadlock? If so, do you think that the difficulties are such as would require some basic new idea for a break-through?

Answer:

I don't think that it has reached a deadlock. I think that we have now reached an understanding of what the problems are, and this is the first step towards progress. And as far as the future is concerned, I feel that there is a very good chance that one would overcome those difficulties once they were fully understood.

Question to Dr. Goldschmidt:

How do you see the future of reprocessing of irradiated nuclear fuel? Will there be a tendency to limit the problems of handling and transportation of such radioactive fuel by means of "hot" processing plants near each reactor or do you feel on the contrary that reprocessing will be centralized in large regional plants?

Answer:

I think a distinction must be made between natural uranium and enriched uranium. As regards natural uranium, it is possible that as burn-up improves and the price of uranium continues to fall, a stage will be reached where there will be no advantage in processing the spent uranium except where there is an actual desire to extract plutonium and fission products. There is no doubt that in the present state of technology it is advantageous to combine the facilities for the chemical treatment of spent fuel for several countries, and this is just what the Organisation for European Economic Co-operation is trying to do in setting up the European Chemical Processing Company ("Eurochemic") at Mol, Belgium, with the participation of 11 countries. As regards enriched uranium, on the other hand, which will be relatively easy to transport, it is possible that one will go on having it processed in the countries that supply it, i.e. mainly the United States, but that some countries will later on want to have their own fairly small plant so that they can process spent fuel on the spot.

Question to Dr. Bhabha:

What programme of activities, in particular research activities, do you recommend for countries which are just entering the nuclear energy field?

Answer:

The answer to this question must clearly depend on their needs, but it seems to me that one of the greatest benefits that we have derived from the development of atomic energy is the very powerful tool it has put at our disposal for studying the fundamental problems of life. The pathways by which the complicated molecules, the proteins, enzymes etc., are built up, are something about which we understand very little, and this is a field where isotopes have made progress possible in a few years which might otherwise have taken decades. Scientific contributions to the world's knowledge can be made by many countries which may or may not be developed generally. There are many names which come to one's mind of people from the so-called under-developed countries who have made important contributions to world science. I might mention the Raman Effect, for example. So I imagine that it would be possible for countries to use isotopes in making their own contribution to the great march of biology and medicine.

Question to Sir John Cockcroft:

Is it true that the economic outlook for nuclear power does not seem quite so promising now as it appeared, say, two years ago?

Answer:

I think that due to various causes, which may be temporary, such as an increase in interest rates and a fall in the costs of coal and freight of coal from the United States to Europe, the position of nuclear power is worse by about ten per cent. That is to say, costs have increased by about ten per cent over the last year or two due to these factors. On the other hand, we can see that with the forecast fall in uranium prices we may expect a diminution of ten per cent. So this would tend to balance out these additional costs. Furthermore, we believe from design studies already made that nuclear power stations started in 1961 or 1962 are very likely to have capital costs 20 per cent lower than those of stations for which orders are being placed at the present time. So I think this temporary disadvantage of nuclear power costs will disappear.

Question to Dr. Goldschmidt:

As regards enriched uranium, do you believe that more economic methods of isotope separation, such as ultra-centrifuge, can be developed? As regards heavy water, it has been published recently that a process devised by Dr. Spivak may allow heavy water production at costs between one-half and one-third of the present production cost. What do you think of that news? If it proved true, wouldn't it be a tremendous incentive for building natural uranium reactors?

Answer:

The technology of isotope separation is only about 20 years old; hence, it is by no means out of the question that improvements in the economics of this method can be achieved. Ultra-centrifuging, which has been under study for many years and has in particular been the subject of recent research in Germany and the Netherlands, seems to be a suitable process for separating the final fractions, but this process is as yet by no means developed enough to use in a large facility based on natural uranium.

As regards heavy water, I am surprised at the statement of Dr. Spivak, who, if I am not mistaken, had prolonged discussions about his patents with the United States Government. As far as I know, Dr. Spivak's process is the one used in the United States, and, as the US Government has stated, the price of heavy water is exactly the ex-factory cost price. I should therefore be surprised if that process could enable heavy water to be produced at a third of the present cost. There is no doubt that if heavy water could be produced at a third of the present price it would give natural-uranium, heavy-water reactors an increased advantage.

Question to Dr. Bhabha:

Of the various prototypes of small and medium power reactors which are being developed, which do you regard as the most interesting from the point of view of the under-developed areas with which you are most familiar?

Answer:

In many under-developed areas, the type of power stations that one would require would be so small that nuclear power would not be economical, except in very out-of-the-way places and for very special reasons. But in many other areas the type of power stations that would be required would be of the size of about 50 or 60 MW. And this, as you know, is at the lower limit of the natural-uranium reactors, except perhaps the heavy-water-moderated one. The enriched-uranium reactors would here perhaps be more economical, and there are several possibilities which would allow one to make a choice. There are the pressurized-water reactor, the boiling-water reactor and the organic-moderated reactor, and these three seem, from various papers I have seen, to compete neck-and-neck. I don't think there is a unique choice at the present stage.

Question to Sir John Cockcroft:

The direct conversion of nuclear energy to electricity is an intriguing possibility. However, little effort has been expended in this area because of the expected low efficiency of the process. What are your views on this mode of conversion? Might it not have a useful application, even if the efficiency were not high, provided that the capital investment for the conversion were extremely low?

Answer:

There are two main lines of development being pursued to convert heat into electricity directly. First, by the use of semi-conductors, and secondly, by thermionic devices. At present, efficiencies of conversion of about 15 per cent have been reported on small-scale apparatus, and it has also been predicted that if the temperature of operation of the thermionic devices could be increased to 2 000 to 2 500 degrees or much higher, then we could get interesting efficiencies of perhaps 30 per cent. I think that these possibilities are very interesting, but I think they will have, in the first place, small-scale applications whilst we are developing the technology. It is not yet possible to foresee that one could use them on an enormous scale for converting a large part of the heat from, say, a nuclear power station directly into electricity. But we are just beginning with this and I wouldn't like to forecast the situation in five years' time.

Question to Dr. Goldschmidt:

Could energy released from nuclear wastes be converted into power or used industrially in large quantities for radiation chemistry purposes?

Answer:

In reply to the second question, there is no doubt in my view that the radioactive by-products from the nuclear fuel rods will be used in an industry still to be established: a radiochemical industry. On the other hand, to the first part of the question I think the answer is "no"; the energy produced in radioactive waste is a fraction, relatively small to start with and decreasing still more over time, of the nuclear energy of the reactor, and for the present this energy is a nuisance because the premises and equipment in which the radioactive wastes are stores have to be cooled.

Question to Dr. Bhabha:

Do you feel that important progress on fusion has been achieved since last year's Geneva Conference? What do you think of the view that full utilization of the fission possibilities may suffice for mankind's needs and that the success of fusion is too problematical to devote much time to it?

Answer:

The answer to the first question seems to me to be that the main progress made has been that one has given up the approach of a race meeting. One has come now to appreciate that the problem has to be tackled basically, to understand it first. There are two main problems: one is containment and the other is the loss of energy from the plasma. The change in approach that has come about is that the matter is now being studied scientifically as a basic problem without attempting to stage a dramatic break-through. This in itself, I think, is considerable progress, though perhaps not scientific progress.

As regards the second question, it is well known that - with breeding, which will undoubtedly be possible in a few years - the total energy available from uranium and thorium in the world is many times, at least 15 to 20 times, the energy available from the known reserves of coal and oil. Hydro power anyway is a negligible part. So, on that basis, fission alone would certainly be able to support power production in the world on the most optimistic basis for several centuries. This, however, does not seem to me to be any reason for not putting in an effort on fusion because, as you know, fusion has certain advantages also. It will not lead to such a production of radioactive waste as is caused by the fission process, and this may in the long run be a very considerable advantage.

Question to Dr. Goldschmidt:

Is there any such thing as safe disposal of radioactive wastes from atomic power stations? If this is so today, when output of waste is relatively small, will it be so tomorrow, when the wastes will be plentiful?

Answer:

There will be no difficulty in storing spent uranium rods and letting them lie for 20 to 30 years; by that time, their radioactivity will have decreased considerably and it will then be possible to process them if the uranium they contain is needed. Their radioactivity is very high at the moment of the extraction of the irradiated rods from the reactor, but it decreases very rapidly after that. Further, it is always possible to concentrate the fission products in a relatively small volume and in solid form. There is no reason to think that there might be any limit to the storage of these solid materials. Personally I hope that we shall reach a situation in which the spent fuels would be processed only in order to extract the long-lived fission products which will be of use in the radiochemical industry I spoke of just now. Thus we hope that in the future the fission products and radioactive wastes will play a beneficent part. Their handling will presumably be rather tricky, but nevertheless I think that in the end they will be of benefit in the development of industry and of civilization.

Question to Sir John Cockcroft:

How does the future of fast breeder reactors compare with that of the Calder Hall type as generators of power from the point of view of (a) technology and (b) economics?

Answer:

I think that from the point of view of technology the main difference would be that the core of this reactor would be very small as compared with the enormous cores at Calder Hall. The fuel will perhaps consist of plutonium oxide mixed with uranium oxide; so it would be essentially ceramic fuel. The heat would be transferred by liquid sodium in order to take away the vast amounts of heat from the very small core.

The technological problems in this are quite severe because since we have taken more heat out of the small core, the irradiation damage problems would be more severe.

On the point of economics, the enthusiasts for fast reactors predict that because of the small size, the capital costs would be perhaps 40 per cent less than the capital costs of the power stations we are just about to order now. They think that if we achieve very high burn-ups, as we may be able to do with these oxide fuels, the fuel costs, because of the breeding, might be perhaps half the present-day fuel costs. And so the enthusiasts think that fast breeder reactors would be able to produce power at very much below the cost of the power we are going to produce in the early 1960's. All this is contingent on having available for the charges of these reactors large amounts of plutonium produced by the earlier power stations. A single reactor may require a charge of about a ton of plutonium, and, at the forecast prices for by-product plutonium, this might cost £5 million. If the costs for plutonium were much higher the investment charges would, of course, be correspondingly increased. So fast reactors do require a base of thermal reactors producing low-cost plutonium as a by-product.
