RECENT DEVELOPMENTS IN NUCLEAR ENGINEERING*

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THE second Geneva Conference on the Peaceful Uses of Atomic Energy revealed the progress in nuclear engineering which has been made during the three years since the first conference.

British experience in operating Calder Hall now extends over two years. The total electrical power generation up to September 1958 has been 938 million kWh., representing a full load power factor of 67 per cent on reactor No. 1 and 81 per cent on reactor No. 2. These high load factors have been achieved in spite of the fact that in this prototype design it is necessary to shut down and release the carbon dioxide pressure before a fuel rod can be changed, this operation taking an appreciable time. During the life-time of the first charge of fuel, only three fuel elements out of the ten thousand developed faults, and so far there has only been one fault in the second charge. In the first charge of reactor No. 2 there have been four positively identified faulty fuel elements, and six channels have been discharged for examination because of rather large signals from the faulty fuel element detector equipment. The fault is usually due to a slight leakage developing in the weld of the magnox alloy can. This allows slow penetration of the carbon dioxide coolant, with resulting oxidization and a slow outleakage of fission products. This usually develops rather slowly, so that fuel elements can be changed when convenient over a period of a week or two. We have had one or two incidences of a more rapid development of a leakage due to a defective weld.

Apart from shutdowns due to the necessity to change faulty fuel elements and to change the whole charge at the end of its life, reactors and power units can go on operating for very long periods; indeed, one reactor operated continuously for six months. Maintenance can be carried out on a single cooling circuit or associated electrical equipment by closing off this circuit and reducing power for an hour or so. There is, in fact, little to go wrong in a graphite-moderated reactor except the fuel elements. No automatic control rod circuits are installed in the Calder Hall reactors, but the circuit has proved to be remarkably stable. The temperature of the fuel element stays constant to ± 1 deg., and there is a similar stability of power-level. In some very large reactors the distribution of power generated in different parts of the reactor can vary slowly over a period of days, due to the accumulation of the fission gas, radioxenon. As a result of this, an increase in power density on one section of the reactor can burn up more xenon and so increase the reactivity, and the opposite effect can occur in another part of the reactor. These very slow spatial oscillations have not so far been observed in Calder Hall.

Initially, with a new charge, the temperature coefficient of reactivity associated with increases of temperature of fuel elements and of moderator is negative and the system is entirely self-stabilizing. As the radiation of the fuel proceeds, the increasing quantity of plutonium fuel modifies the delayed temperature coefficient associated with the moderator temperature, making it increasingly positive; but the prompt coefficient of temperature associated with the fuel-element temperature remains negative. After an irradiation of about 400 MW. days per ton, the moderator temperature coefficient is about $+ 4 \times 10^{-5}$ in K/degree centigrade. It is expected to reach a saturation-level of about 15×10^{-5} with very long irradiation. The overall effect of this limiting value of the temperature coefficient would be that small increases in power-level could be doubled in a time of about two minutes if no movement of control rods were made to correct this. So after a thermal power-level change of 200–201 MW., the level would increase to 202 MW. in two minutes and to 204 MW. in four minutes.

These effects of the positive temperature coefficient occurring over such relatively long periods of time do not require any changes in the normal control of a station, and indeed they are not generally observable to the operator since general small circuit fluctuations require small corrective action to be taken on a similar time-scale. These are examples of the wide range of operational experience we have gained during the past two years. This experience has given us great confidence in this type of power station.

The Shippingport nuclear power station uses a pressurized water reactor to produce 230 MW. of heat, leading to 60 MW. of electricity. This power station went into operation on December 18, 1957, and a brief account of its operational characteristics was given at the recent Geneva Conference on the Peaceful Uses of Atomic Energy. The time taken to get the power station on load from ambient temperature is 8 hr., this being set by thermal stress. The reactor operation has a high negative coefficient of reactivity. On one occasion the condenser vacuum was lost and the turbine shut down automatically. The negative temperature coefficient reduced the reactor output to essentially zero without any movement of control rods, the only effect on the plant being an increase of system pressure from 2,000 to 2,160 lb. sq. in.

The first Russian large-scale nuclear power station came into operation during the period of the Geneva Conference. The power station is to consist of six identical 100-MW. electrical units. The heat source is a graphite-moderated water-cooled reactor, apparently scaled up from the 5-MW. power station reported at the 1955 Geneva Conference. The reactor has pressure tubes of stainless steel to separate the high-pressure coolant from the graphite. The fuel is natural uranium. Steam reaches the turbines at a pressure of 90 lb./sq. in. at 185° C. The power station seems to be a dual-purpose plant. It is the first major contribution to the U.S.S.R. 2,000-MW. programme of nuclear power stations.

None of these three power stations was designed as a commercial nuclear power station. They are either

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*Substance of a lecture to the Danish Society of Civil Engineers, delivered on October 6.

prototypes or dual-purpose reactors, and their capital costs per kW. hr. are high.

The second generation of nuclear power stations are very different. They have usually been designed specifically as power stations for electricity authorities. In Britain they include four graphite-moderated carbon dioxide cooled reactor power stations due for completion at dates ranging from 1960 to 1962 with outputs ranging from 275 to 500 MW. for a two-reactor station. In the United States there are under construction two pressurized-water and one boiling-water reactor power stations having outputs ranging from 134 MW. electrical to 275 MW.(e), the latter being boosted by 110 MW. of oil superheating. In addition, a 100-MW.(e) electrical fast reactor is being constructed. All these are due for completion by the end of 1960. The French are building two graphite-moderated carbon dioxide cooled reactor power stations of 63 MW. and 170 MW., respectively, for completion by about the same period. Italy is to build one British type of power station and one station similar to the U.S. Dresden power station, using a boiling-water reactor as heat source. The Russians are building two 420-MW. stations, each using two pressurized-water reactors. They are also building a 400-MW. power station using four graphite-moderated reactors in which the steam is superheated inside the reactor.

The British stations are typified by the Somerset power station, which is to generate 500 MW.(e). Each reactor contains about three times as much uranium as in the Calder Hall reactors. The pressure of the carbon dioxide coolant is 85 per cent higher than Calder Hall. The fuel element surface temperature is 430° C. compared with 408° C. at Calder Hall. The heat-transfer surfaces of the fuel elements have also been improved over Calder Hall. The effect of this increased pressure, increased temperature and improved surface has been to increase the average rating from the 1·4 MW./ton in Calder Hall, to 2·6 MW./ton at Hinckley Point. This has resulted in reactor capital costs being reduced by about 20 per cent from the first of the four power stations, and is now of the order of £110 per kilowatt exclusive of costs of fuel and site preparation. For the purpose of economic forecast, the fuel elements have been assumed to achieve an average heat output of 3,000 MW. per ton. Reactivity changes due to substitution of plutonium for uranium-235 and accumulation of fission products will not limit the life of fuel elements before appreciably longer burnups. The limit will probably be set at first by metallurgical imperfections. We have so far accumulated experience of burnup of metallic fuel elements to about 1,200 MW. days/ton in Calder Hall. Fuel elements are undamaged at this burnup and we are steadily extending our experience. The Electricity Authority reactors will operate fuel elements at higher temperatures and ratings. The main new phenomenon to be looked for is swelling of the uranium due to collection of fission gases in bubbles. This could lead to appreciable changes of volume, though we do not expect these to exceed about 10 per cent. The magnesium alloy cans have been designed to withstand volume changes of about 25 per cent. Recently we have shown that the observed swelling in small specimens can be much influenced by temperature cycles, and by restraining the amplitude of the cycling the swelling can be substantially reduced.

It has been stated by the Electricity Authority that with a 75 per cent load factor, 5 per cent interest rate and 20-year write off, and a burnup of 3,000 MW. days/ton, the Somerset nuclear power station just about breaks even, since it is situated in an area remote from coal-fields and conventional fuel costs are consequently high.

The American design thought to be most competitive is typified by the Dresden 180-MW. power station. This is served by a dual-cycle boiling-water reactor. The steam – water mixture produced in the reactor core flows from the reactor vessel to a primary steam drum at the reactor pressure of 1,000 lb./sq. in. The steam then flows to the turbine through the primary steam lines, and the water flows to the secondary steam generator where additional energy is removed to produce steam at a low pressure of 500 lb./sq. in. Valuable information on the stability characteristics of boiling-water reactors has been obtained from the experimental boiling-water reactors at the Argonne Laboratory, at Arco and at Vallecitos.

The contract price of the Dresden nuclear reactor was quoted as about £85 per kilowatt exclusive of research and development costs and fuel charges. The actual costs were stated to be higher than the contract price. The Dresden reactor had a fuel charge of 60 tons of uranium containing 1·5 per cent uranium-235 in the form of uranium oxide clad with zirconium. A burnup of 10,000 MW. days/ton is assumed in the economic forecast. Fuel is costed at American prices of the order of £50,000 per ton, and is to be hired at 4 per cent from the U.S. Atomic Energy Commission. The operator has, in addition, to pay for the uranium-235 burnt. On this basis, fuel costs are likely to be at least 3 mils per kWh. and overall costs were stated to be 7·5 mils. Since, however, the actual capital costs were not stated, this does not mean that commercial nuclear power has arrived in the United States. Indeed, it was stated at Geneva that in the United States nuclear power stations could not reach parity with commercial power before the stations which would start to be built in the late 1960's. This reflects the low present cost of power generated from cheap Kentucky coal or natural gas or hydro-power.

In other countries the date for reaching parity will depend on the cost of indigenous or imported fuel, the interest rates and the load factor available. The World Bank reported at Geneva an interesting study in the economics of nuclear power for a 130–150 MW. station to be erected in southern Italy. Bids were obtained from nine industrial organizations in the United States, Great Britain and France. The results were summarized in Geneva. Nuclear power costs for the most favoured bid were expected to be about 10 per cent above the cost of power from oil- (coal-) fired stations using oil (coal) at £9 10s. per long ton. This assumes a return on investment of 14 per cent and a load factor of 80 per cent.

The Geneva Conference also gave a forecast of the developments in progress towards the third generation of nuclear power stations, which may come into operation in the late 1960's. The major United Kingdom objective will be to reduce capital costs 20–30 per cent below those achieved from the improvement in the second-generation power stations. Capital costs can be reduced by increase of rating, so that more output can be obtained for a given volume of reactor. However, the reactor is already contributing less than 40 per cent of the whole cost. Heat exchangers and the conventional power house contribute more than half the cost. So their costs must also be substantially reduced. This can only be done by increasing the temperature of operation and improving steam conditions.

In Britain an advanced gas-cooled reactor nuclear power station is being built as a reactor experiment to produce the advanced techniques which will be necessary to achieve this. The reactor will use uranium oxide fuel canned in beryllium. This should enable surface fuel temperature to be run to 600° C., giving an outlet temperature for bulk gas of between 500° and 570° C. The fuel elements will consist of a bundle of rods of small diameter. The reactor rating will then be increased from the 2·3 MW. per ton at Hinkley Point to about 8 MW. per ton. The reactor experiment will develop 100 MW. thermal and 28 MW. electrical. Since the plant will be purely experimental, a single-pressure steam cycle will be used with the modest steam condition of 600 lb./sq. in. An appreciably higher efficiency should be obtained with the more complex steam cycle which will be possible in the full-scale power station designed to use this advanced technology.

The use of uranium oxide fuel will require a slight degree of enrichment of the uranium—roughly 1·2 per cent of uranium-235 in the reactor experiment and a lower enrichment for full-scale stations. The enrichment could be provided by plutonium oxide from the second generation of nuclear power stations. Uranium oxide fuel is now being intensively studied, and especially valuable reports came from Chalk River. The fuel has great stability to irradiation, though it cracks as a result of thermal shock, so that it relies on the can for restraint. American companies, backed by a guarantee from the U.S. Atomic Energy Commission, are promising a burnup of 10,000 MW. days/ton, and small specimens are reported to have withstood 25,000 MW. days/ton without appreciable damage.

The present Canadian philosophy of power reactor development is to use a heavy-water moderator, allowing natural uranium oxide fuel to be used. It is then hoped to achieve a burnup of the order of 8,000 MW. days/ton and to write off the fuel at the end of the cycle. In this way it is hoped to achieve fuel costs declining from 1·5 mils to 1 mil and so achieve competitive nuclear power in Canada. The heavy-water gas, or water or steam-cooled reactor is undoubtedly one of the serious competitors for a place in the nuclear power station of the future.

We also heard of the progress of three recent experiments employing a different technology. The 10-MW. organic liquid – moderated reactor experiment at Arco uses a diphenyl or terphenyl moderator. This has a comparatively high stability to irradiation, about 100 lb. of polymer being formed per MW. day of heat. Coolant make-up costs 0·75–1·8 mils per electrical kWh., with a present probable value of about 1·2 mils. The use of an organic moderator has the advantage of a low pressure of about 13 atmospheres, with the surface temperature of fuel elements at 420° C. and a temperature of the bulk coolant ranging from 260° to 270° C. Another attractive feature of cooling by organic liquid is the low level of radioactivity of the coolant, which makes possible maintenance of the primary circuit, even during reactor operation. The reactor uses cermet fuel elements consisting of a 20-mil plate of uranium oxide in stainless steel clad in 5 mils of stainless steel. 26 kgm. of uranium-235 are used.

Good operational experience has been reported for this reactor. The system shows considerable promise for ship propulsion and for power stations with output in the 10–30-MW. range. It should have low capital costs, though whether these can be competitive with Diesel propulsion units remains to be seen. Fuel costs at the prices of American enriched fuel and loan charge would be expected to break even with the costs of oil fuel for ship propulsion systems.

The sodium-cooled graphite-moderated reactor experiment at the North American Aviation Company represents another experiment in reactor technology. The use of liquid sodium as a coolant offers the technical advantage of a high operating temperature with moderate pressure. These are offset by the compatibility problems characteristic of liquid sodium and the consequent need to keep the oxygen content at a level of a few parts per million. The graphite moderator has to be separated from the liquid sodium since it is not compatible with it, so that the graphite bricks are canned in zirconium, which is somewhat of a complication. We carried out a detailed design study on this reactor in the United Kingdom and have decided not to proceed with it.

The Oak Ridge homogeneous aqueous 10-MW. reactor experiment was also described. In this reactor a fluid fuel of uranyl sulphate is contained in a zircalloy core vessel. This is surrounded by a blanket containing a slurry of thorium oxide which captures escaping neutrons and so gives the reactor a breeding potential. Two difficulties have occurred in this reactor. First, corrosion of the wall of the core vessel led to a leakage from core to blanket, so the reactor has at present to operate as a one-zone system. Secondly, there are problems concerned with the stability of the liquid fuel. The future of this reactor system will depend on the results of the experimental programme.

The fast reactor constitutes the fourth class of reactor experiments. So far, only experience on the American 1-MW. fast reactor has been reported. The experiment showed that instabilities occurred due to the geometry of the core fuel rods. This has now been redesigned and the difficulty eliminated. 60-MW. reactor experiments are due to be commissioned in the United Kingdom in 1959 and in the United States in 1960, and a 5-MW. reactor experiment is just going into operation in the U.S.S.R.

Fast reactors have a core of very small size and a corresponding very high rating. For this reason their capital costs should be low. On the other hand, the fact of a large rating produces severe technological problems, and only experience with the reactor experiment will show whether they can be solved. Fuel costs should in principle be low, since they would be fuelled by plutonium from second-generation reactors, presumably at the 'civil price' of about £5 per gm. The reactor should have a breeding factor of at least 1·5 and should turn over the fuel in about 1,000 days. The fuel costs will, however, be dominated by the number of times it is necessary to re-process the fuel during its life, and the cost of making the re-processed fuel into new fuel elements. To minimize these costs, the United States and the United Kingdom are developing the so-called pyro-metallurgical processing system, in which the fuel is melted and the unwanted fission products skimmed off, leaving behind some fission products which, when alloyed with plutonium, have been shown to have good stability to radiation. Until we know more about re-cycling costs, the economic future of fast reactors will remain obscure.

The technical feasibility of the nuclear propulsion of shipping has been abundantly demonstrated by the voyages of the U.S. submarine *Nautilus*, culminating in the remarkable voyage underneath the polar ice cap. The pressurized-water reactor used to develop steam for its propulsion has proved to be highly reliable. We heard at Geneva of the first approaches to commercial nuclear propulsion. The U.S. *Savannah*, a combined passenger-cargo ship coming into commission in 1960, will use a pressurized-water reactor developing 22,000 shaft horse-power. The pressurized-water propulsion unit seems likely to achieve fuel costs based on American prices about equal to those for oil fuel. Present capital costs are, however, three to four times higher than conventional capital costs, and a drastic reduction of these costs is necessary before parity with conventional propulsion is achieved. American engineers expect to build a nuclear tanker using a boiling-water reactor for propulsion by 1962. Since this type of reactor appears to have lower capital costs than the pressurized-water reactor, this should help to bridge the gap, though operating costs will still be well above conventional costs. It seems likely that we shall have to wait five years or more before we shall know whether truly commercial nuclear propulsion is a feasibility. However, there is one immediate application which would be impossible without nuclear power. The opening up of the 6,000-mile seaway north of the U.S.S.R. has had to wait for the practically unlimited endurance of the nuclear propulsion unit. The ice-breaker *Lenin*, which is due to be commissioned in 1959, will have three pressurized-water reactors installed, and two of these will provide 44,000 shaft horse-power for propulsion.

In contrast with the hopeful outlook for marine applications, commercial nuclear aircraft propulsion seems much further away.

EFFECTS OF WEATHER ON PLANT BEHAVIOUR

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CROP yields vary enormously from year to year and from farm to farm, but record crops, produced by the best managers in exceptionally favourable seasons, show how far yields usually fall below the full cropping capacity of the varieties which are at present available. One of the challenges in agronomy is to show how average yields could be increased. Since 'the weather' plays such an important part in determining the behaviour of plants, a more precise knowledge of the effects of environmental factors would be extremely useful in agriculture. In the first place, knowledge of varietal preferences would make it easier to select the variety most likely to yield heavily in any particular site, provided sufficient meteorological data were available to enable the pattern of probable weather conditions to be forecast. Thus the critical matching of variety to district, on which successful agriculture largely depends, would be placed on a firmer footing than by the traditional and time-consuming method of trial and error.

Another advantage of a fuller knowledge of response to environment is that, once the plant's requirements are known, it is sometimes practicable to exercise a degree of control over the environment itself, to provide conditions which are more nearly optimal for growth. An obvious example is the control of soil moisture and soil salinity, by the complementary techniques of irrigation and drainage, which now make it possible for crops to be grown on some two hundred million acres of land throughout the world which could not otherwise be used for agriculture. Less spectacular, though still useful, methods of environmental control on an agricultural scale are the reduction of air speeds by the use of windbreaks, and the reduction of light intensity by the use of shade trees in the production of some plantation crops. In horticulture, the grower often goes much further by using devices like cloches, frames and heated glasshouses which change such factors as temperature, wind speed and, to a lesser extent, light.

Much research is now being done on the effects of environmental factors on plant behaviour[1,2] and the possibilities of controlling these factors in crop production, but the position is frustrating. Apart from the control of water, and reduction of wind and light intensity, there seems to be little hope of affecting the other physical factors of the environment on a field scale. This is particularly the case with the two important factors of temperature and day-length, both of which have profound effects on the behaviour of many crop plants, and it is difficult to see how control of physical factors of the environment (apart from water) can make any substantial contribution to increasing yields of the major food crops in the immediate future. This is an unwelcome conclusion to those who are working on the agronomical uses of environmental control, but one which must nevertheless be accepted.

However, there is another possible approach. If it is impracticable to affect plant behaviour in the field by altering the nature of its environment, might it not be possible to alter the plant's responses to the natural environment ? For example, the use of a chemical treatment to affect the responses of a plant to temperature or day-length would be a much more elegant device than to try to alter those weather factors on a field scale. The results of some recent experiments suggest that this approach is worth considering.

The work has mainly been done on the raspberry (*Rubus idaeus* L.), which is not itself of much importance in world cropping, but was chosen because of its great convenience as an experimental plant. The pattern of the work has been, first, to study the behaviour of the species in the field, in order to distinguish between successive phases in the life-cycle, with particular emphasis on the behaviour of the stem apices. Next, plants have been grown in