TEN YEARS OF NUCLEAR POWER

Ten years have elapsed since the world's first nuclear power station began to supply electricity in Russia, and this in turn marked the end of a twelve-year stage following the first controlled nuclear chain reaction at Chicago.

These periods mark major stages in the development of atomic energy from the realm of abstract ideas to that of everyday industrial application. They followed a period of fundamental research and laboratory work, culminating in Enrico Fermi's demonstration of a system whereby the forces of the atom could be brought under control. Then it was necessary to find ways and means of using the chain reaction for practical purposes and on an industrial scale. And after this had been shown in 1954 to be technically possible, it had still to be developed into an economic process.

All this involved finding answers to innumerable theoretical and technical questions, ranging from major problems of reactor physics, reactor design and construction, to subsidiary matters of auxiliary equipment. Not only was there a whole new range of materials to be dealt with on an industrial scale, which had been known hitherto only in the laboratory, but a new dimension was introduced into industrial operations by massive radioactivity. Even the familiar industrial metals might behave strangely after prolonged exposure to intense radiation under the working conditions of a nuclear power station. Radiation brought the further problem of shielding and of devising means of carrying out complicated chemical and metallurgical processes on a large scale, with reasonable economy and yet with complete safety for the personnel.

It is difficult to find a precedent for the effort which has been deployed during this past decade by the nations which have taken the lead in developing nuclear power. This is because "atomic energy" is not a particular branch of science or technology, employing its own specialists. Rather the atom provides a great variety of techniques for workers in many fields. It can assist in making the most delicate biological tests, or it can drive a large power station or move millions of tons of earth. So the nuclear power station represents the combined effort of physicists, chemists, metallurgists, engineers and many others.

The nuclear power station has proved itself from the technical and engineering standpoint. The third phase of development has been to bring it to the stage of being economically competitive with alternative sources of energy, and it would appear that we are now reaching that goal - though more slowly than had been envisaged ten years ago.

The world is displaying a remarkable appetite for energy - particularly electrical energy - and the rate of investment in new power resources, in advanced countries, tends to be higher than the rate of new investment generally. The possibility of a growing shortage of reasonably-priced fossil fuels has been a perennial source of anxiety. Available resources have repeatedly been extended to meet the growing need; by new discoveries, such as the oilfields of the Middle East and North Africa; by new methods of exploitation, such as mechanized coal extraction and under-sea drilling for oil; and by new methods of utilization. But we are relying on finite resources, and as the best of them are used up, the tendency is for costs to rise.

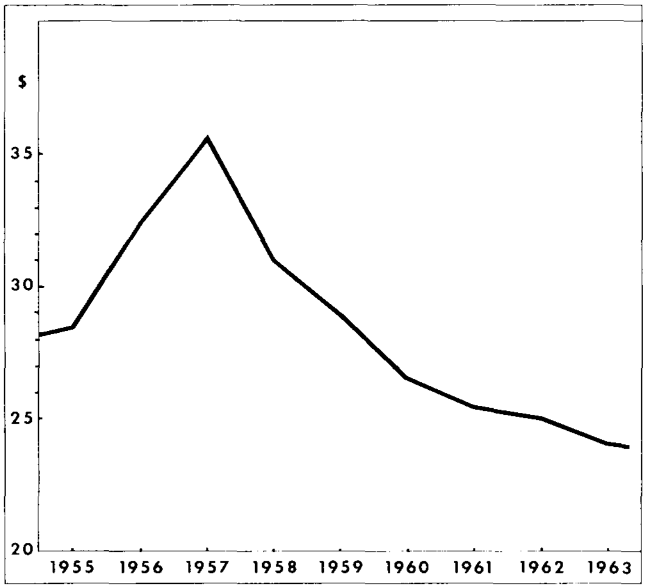
It was in a period when fears of shortage were dominant that commercial nuclear power received its first great impetus. Inevitably thoughts turned to the new power which had been developed for war, as a means of filling what was being referred to as "the power gap". When nuclear energy first became a reality, there was much facile speculation about cheap and virtually unlimited power, and the combination of fears of shortage of conventional energy and hopes of abundance of nuclear energy, caused over-sanguine views of the latter to prevail until about the end of 1957.

The industrially advanced countries embarked on large programmes of research and development with two principal motives - that of filling their own power requirements, and that of developing a nuclear engineering industry which might cater for export markets as well as for domestic needs. The first consideration was uppermost in Britain, the second in the United States.

Several nations decided, about 1950, to press ahead boldly with the development of nuclear power. At that time Western Europe, and particularly Great Britain, was suffering from a coal shortage which was expected to become increasingly acute. In 1955 Britain announced a programme of nuclear power station construction to make good the deficiency. Over a period of ten years, twelve stations were to be built with a total capacity of 1500 to 2000 MW. This was to be additional to the construction of Calder Hall and other stations of the same type, which were built primarily to produce plutonium, but supplied electricity as a by-product. Then the target was raised still higher, so that now nuclear stations are to provide about 5000 MW by 1969, or twelve per cent of Britain's energy production.

A radical change came over the situation, however, in 1957-58. New sources of oil were discovered ocean freight rates were reduced, and the fuel shortage abruptly changed to a surplus. Coal mines had been gradually improving their methods and equipment and raising their output. In several countries - such as Western Germany - a process of rationalization took place as soon as the pressure on coal supplies eased. Uneconomic pits were now closed, and more machines were introduced. A marked improvement in output resulted - e.g. in West Germany the average annual increase in underground production was about 7 per cent, from 1957 to 1961. This was well above the rate of increase for industry as a whole.

The relative abundance of coal and oil, together with the improvements in methods, naturally resulted



Crude Petroleum price (per barrel) in the United Kingdom. (UN Monthly Bulletin of Statistics)

in a world-wide fall in the prices of conventional fuels. Another feature of the period was a rise in interest rates. Since capital costs of nuclear stations are substantially higher than those of conventional stations, higher interest charges favour the latter.

Thus, within a few years predictions that nuclear power would be competitive with conventional power in important areas by about 1965 were seen to be premature. The sense of urgency relaxed, and national programmes for nuclear power slowed down. Views of the long-term fuel situation were also somewhat modified. In 1962, a survey of energy resources was made by the World Power Conference with the assistance of national governments, which estimated the reserves of fossile fuels - coal, brown coal and lignite, peat, petroleum, oil in shale and bituminous sand and natural gas - which could probably be economically recovered. The total coal equivalents amounted to about $3\frac{1}{2}$ million million tons, which is seven hundred to eight hundred times the coal equivalent of the whole energy at present used annually by the world. On the other hand, the rate of consumption increases steadily, having risen by more than 60 per cent during the previous decade, and there is no sign of this growth ending.

The conclusion drawn from the survey is that for the world as a whole there is no shortage of energy. The problem is one of economics. Costs must differ considerably in different areas owing to uneven distribution of resources and the heavy costs often involved in the transport of materials and energy in their various forms.

It is against this background that the most recent developments in nuclear power have taken place. In some areas it already appears to be at least marginally competitive, and the nations which have undertaken intensive development programmes have been confirmed in their confidence - the variable factor being that of timing.

National Programmes

The primary objects of the national programmes of research and development at the outset were to gain knowledge and experience, to train personnel at all levels, and to lay the foundations of the nuclear engineering and allied industries. The experience already won in the production of nuclear weapons provided a starting-point for several of the leading countries, but some others which had not been through that stage were quick to catch up.

Ten years ago, there were many diverse possibilities to choose from in planning a power reactor. The fuel, the coolant, the moderator, the use of fast neutrons or thermal neutrons for the fission process, the use of "breeder" systems - all offer a number of alternatives. At the outset, however, the emphasis was necessarily on simplicity, and refinements such as "breeding" were for a later stage of industrial application.

The choice of a system was influenced to some extent by differing national circumstances. The United States possessed large diffusion plant capacity, originally built for military purposes. This plant separates the fissile uranium, U^{235}, from natural uranium, and has provided the United States with "enriched" fuel for power reactors - that is, fuel which contains a higher proportion of U^{235} than is found in natural uranium. On this basis, boiling-water and pressurized-water reactors have been developed with considerable success.

Britain and France, having no such readily available source of enrichment, preferred to concentrate their initial efforts on gas-cooled graphite-moderated reactors using natural uranium fuel. These have higher capital costs than the American water systems, but lower fuel costs. The USSR has also built or undertaken several water reactors and Canada is developing reactors using heavy-water moderator and natural uranium fuel.

In addition, there have been in a number of countries experiments and prototypes of many other reactors, some of them variants or refinements of established systems, some based on radically different, more advanced principles.

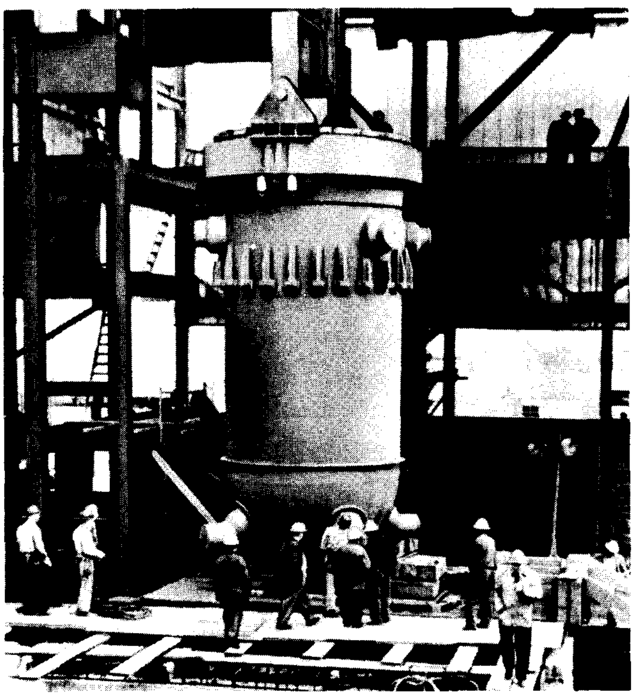
The following particulars of some national programmes are not intended as a complete or detailed catalogue, but rather as illustrative of lines of development of power reactors in everyday operation.

USA

Early reactor research in the United States was devoted to such purposes as plutonium production and naval propulsion units, and in 1953 the first prototype PWR, using light water and enriched uranium came into operation. This research provided a starting-point from which in that year a five-year experimental programme was launched for the development of nuclear power for civil purposes. Although the United States is for the most part well endowed with conventional power resources, it has the widest and most varied programme of research and development of any nation.

In addition to the construction of several experimental power reactors, construction of a prototype was undertaken at Shippingport, to be linked to the electricity grid. Two years later a power demonstration programme was added, whereby the US Atomic Energy Commission and industry co-operated in building and operating a number of nuclear power plants to supply electricity. Under one method, the Commission built and operated the reactors and sold the steam to utility companies; alternatively, the Commission helped the companies to design and build their own reactors, and made no charge for the use of Government-leased fuel for the first few years. In 1958, the Commission published detailed evaluations of the different reactor systems.

The 235 ton reactor vessel being lowered into position at Shippingport, USA (US AEC photo)



Research and development has since continued on a wide front, with a variety of systems being tested in experimental or demonstration reactors. These have included heavy-water moderated, organic moderated, sodium-graphite, high-temperature gas-cooled and fast reactor systems.

But most of the practical achievement to date has been with the pressurized-water and boiling-water systems, which use light water as the coolant and moderator, and enriched uranium fuel. Three stations have already operated extensively, viz. Shippingport (PWR), Dresden (BWR) and Yankee (PWR). More recently three other important stations have come into service - Consolidated Edison, or Indian Point (PWR), Big Rock Point (BWR) and Humboldt Bay (BWR).

Shippingport has a PWR of 60 MW(e); construction began in 1955 and full-power operation was reached at the end of 1957. It was not designed to produce economic power, but was intended as a large-scale laboratory for studying the problems of building and operating a full-scale plant. By advancing the technology of light-water cooled reactors, Shippingport could show the way towards potential cost reductions which could yield better results than the mere optimization of existing techniques. Six years of operating experience have shown that central power stations equipped with pressurized-water reactors can meet the essential criteria of ability to be integrated into a major supply system, no excess idle time for refuelling and maintenance and satisfactory radiation safety. The response of the plant to load transients has been reported to be superior to that of conventional plants on the same supply system, and standard radiation control procedures have been "more than adequate" in maintaining effective radiation safeguards.

The Yankee PWR, now of 175 MW(e), first came into operation in November 1960 and has been more successful than was hoped. It was intended as a demonstration plant, before nuclear power could be expected to be competitive in cost. However, the average power costs for electricity produced from the first core were less than 9.5 mills per kilowatt-hour. Conventional plant of about the same size, and built at the same time in New England (where the Yankee station is situated) has costs of about 8 mills. The operating company reported that "the cost of Yankee power comes closer to being competitive at this early stage than we had dared to hope".

The Indian Point reactor of 275 MW(e) uses fully enriched uranium fuel in combination with thorium as a fertile material. In the course of the fission process, thorium is converted into fissile uranium, thus providing further fuel. The reactor produces saturated steam, which is then superheated with oil fuel. This station was financed by the company, without subsidy of any kind, and the best proof of its success is that the company shortly afterwards decided that it wished to build a second nuclear station on the same terms, but this time of 1000 MW.

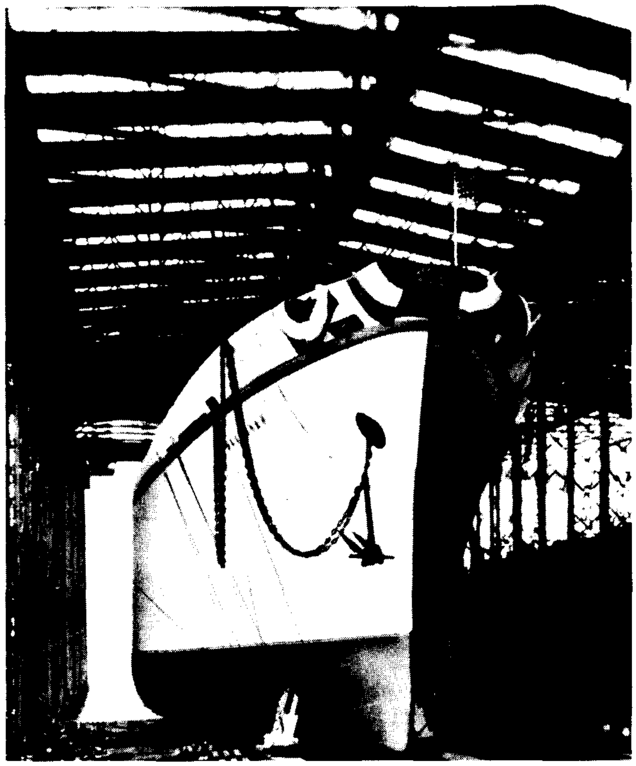
The Dresden station has been on a similar commercial footing, as it was built under fixed-sum contract by an industrial organization, and has been reported to have given uniformly excellent performance under normal conditions of electricity supply, where reliability is a prime requirement. From this point of view, it is said to be as good as the best coal-fired plant in the Commonwealth-Edison supply system.

The estimated capital costs of Dresden and Yankee were respectively $250 and $224 per kilowatt of net installed electric capacity, and the initial fuel costs were placed at about 4 mills per kilowatt-hour. However, construction firms have since offered, on plants of 400 MW or larger, warranted costs in the range $132 - $210 for capital construction, and about 1.8 - 2.25 mills for fuel. The reduction in capital costs is largely due to the envisaged increase in plant size, and that of fuel costs to improved fabrication methods and longer burn-up of the uranium fuel.

Practically every water reactor has exceeded the original power rating. Dresden, designed for 629 MW(t) was increased to 700 MW(t); Yankee, from 392 to 485, and the second core to 540 MW(t). Although this improvement over design estimates - which has occurred also with other systems in other countries - is encouraging, it has been pointed out that it also reveals deficiencies of knowledge on the part of the designers. One of the purposes of demonstration plants, however, is to provide the experience which will make good such deficiencies.

Other United States reactors have been built to meet military and other special requirements, and although not "economic" in the ordinary commercial sense, they have provided striking evidence of the versatility and reliability of nuclear power. At the end of 1961, a pressurized-water reactor was shipped to McMurdo Sound in the Antarctic, and furnished 1500 kW(e) for all the United States scientific activities in the region, thus solving a major problem of fuel transport.

An outstanding technical success has been achieved with nuclear propulsion for warships, and notably submarines. The first nuclear submarine Nautilus put to sea in January 1955 and over a period of 26 months travelled 69 138 miles on the first reactor core; on the second core it travelled 93 000



Launching of N.S. Savannah, July 1959 (USA Maritime Administration photo).

miles in a similar period. The submarine Sargo crossed the Arctic under the ice.

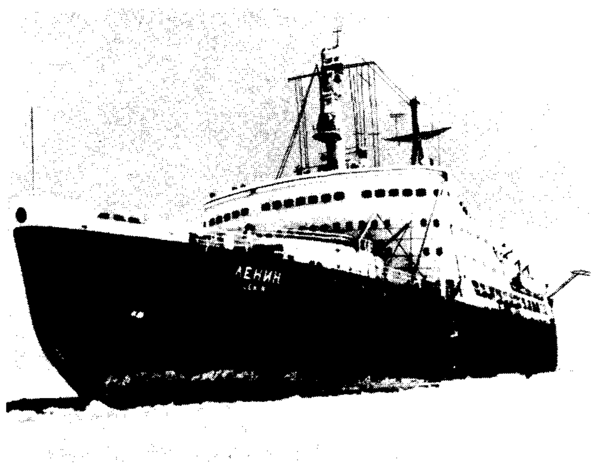
The naval reactors - small, compact, and incorporating many special features - are far too expensive to be applicable to merchant ships, but their success has encouraged research and development in commercial marine propulsion. The Savannah is a merchant ship of 22 000 tons equipped with a PWR of 69 MW(t), which provides a shaft horsepower of 22 314 and a maximum speed of 24 knots. The trials showed that the ship could maintain high speed on long runs. The Savannah, like the Shippingport reactor, was never intended to be economic, but was built as an experimental prototype with much special equipment for purposes of investigation.

USSR

The USSR completed construction of an industrial-type power station in 1954, and in June of that year electricity was being generated. The reactor is a small pressurized-water system, with graphite moderator, using enriched uranium fuel containing 5 per cent U^{235}. The thermal output is 30 MW and the electrical output 5 MW.

The object was to solve the scientific and engineering problem of building an industrial power station which would be reliable in operation. The cost of the electricity produced was much higher than that of electricity from large thermal stations, but the aim was to gain technical and economic experience, and to provide training. It fulfilled this purpose by proving itself, during ten years' operation, both reliable and efficient, and paved the way for the construction of larger reactors of higher performance.

As a result, a PWR of 100 MW(e) is in operation in Siberia, and two further large stations, of 210 MW(e) and 100 MW(e) respectively, the latter using nuclear superheat, have just been completed.



The nuclear-powered ice-breaker Lenin

A unique development has been that of the ice-breaker "Lenin", which was launched in December 1957. This powerful ship has a practically unlimited range of navigation without refuelling, and is capable of navigating in any zone in the Arctic. It is of 16 000 tons displacement, with a maximum speed in clear water of 18 knots. A compact power plant of high capacity was required, capable of operating smoothly under difficult conditions of tossing, vibration and impact loads. This was provided by three separate pressurized-water reactors using enriched uranium fuel; the core height is only about 1.6 metres and the diameter one metre. A single reactor would have been more economical, but three were provided (one as a reserve) for extra reliability. With this plant, the turbines deliver 44 000 horsepower.

The "Lenin" has completed a number of voyages successfully. In the first three years the ship sailed 50 000 miles, mostly under difficult ice conditions. Its reactors operated for three years without a reloading of nuclear fuel.

GREAT BRITAN

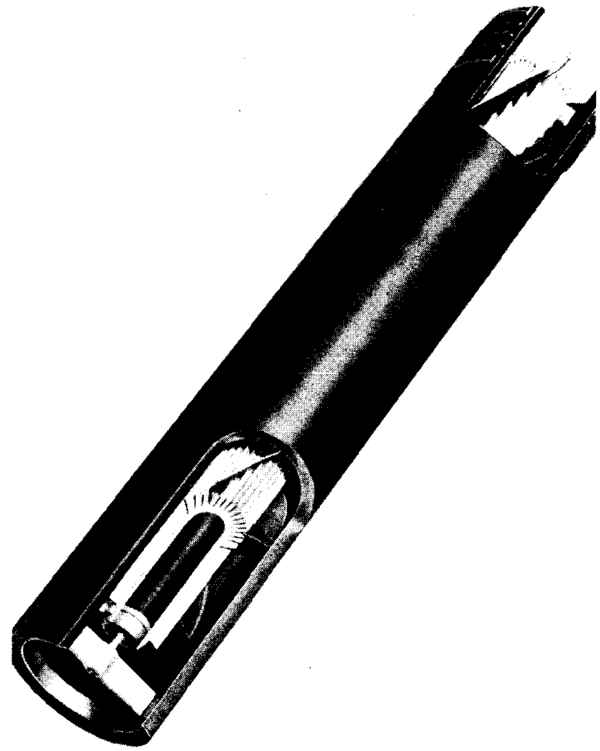
The British programme of nuclear power has developed along three parallel lines:

The construction of reactors designed for the production of plutonium, with some electricity being generated as a by-product;

A series of stations built purely for the commercial production of electricity, based on the same system as the plutonium-producers;

Research and development on more refined systems, leading to construction and operation of prototypes.

Calder Hall, the first of the plutonium stations, employs natural uranium fuel in the form of metal clad in a magnesium alloy (Magnox), with graphite moderator and carbon dioxide coolant. The first reactor went critical in 1956, when electricity supply to the national grid began. At the sister station, Chapel Cross, the first reactor went critical in 1958, and by 1960 the total of eight reactors was working at full power.



A "Magnox" fuel element, in a graphite sleeve (UK AEA photo).

Although the production of electricity has been subordinate, in this sphere the performance of the stations has been somewhat better, technically, than had been hoped. The initial design provided for a reactor power of 180 MW(t), but thanks to the improvement of operating techniques, considerable increases on this figure were achieved, so that reactor powers were raised to about 230 to 250 MW(t). Time spent on maintenance and refuelling was cut down considerably, so that over-all load factors of 94 per cent were attained. Reactor temperatures and pressures were increased, the turbines re-bladed to raise their rating from 21 to 27-30 MW(e) so that the net electrical output was lifted from 34.5 to 45 MW(e).

From the early experience with Calder Hall there resulted a number of engineering improvements to reactors of this family. One much-quoted change was an increase of fifty per cent in the thicknesses of steel which could be successfully welded to form the reactor pressure-vessel. This made possible cores of larger diameter, a more uniform output of heat across the core, and higher gas pressures. Other improvements resulted from the study of heat transfer surfaces and modifications of fuel element surfaces. Successful methods have been developed to refuel later reactors while they are on load, without interruption to power output.

In 1955 a programme of nuclear power station construction purely for the supply of electricity was announced. This envisaged the completion of twelve stations by 1965, with a total capacity of about 1500 to 2000 MW. In 1957 the target was increased to provide 5000 to 6000 MW, which would represent about one-quarter of Britain's total requirements.

However, although the technical performance of the early stations has fully come up to expectations, the earliest cost estimates do not appear to have been realized. At the beginning it was predicted that capital costs should not exceed £120 per installed kilowatt plus about £30 for the initial fuel investment (as against about £55 per kilowatt for a comparable thermal station in Great Britain), and that the early nuclear stations should produce electricity at about 0.6 pence per kilowatt-hour.

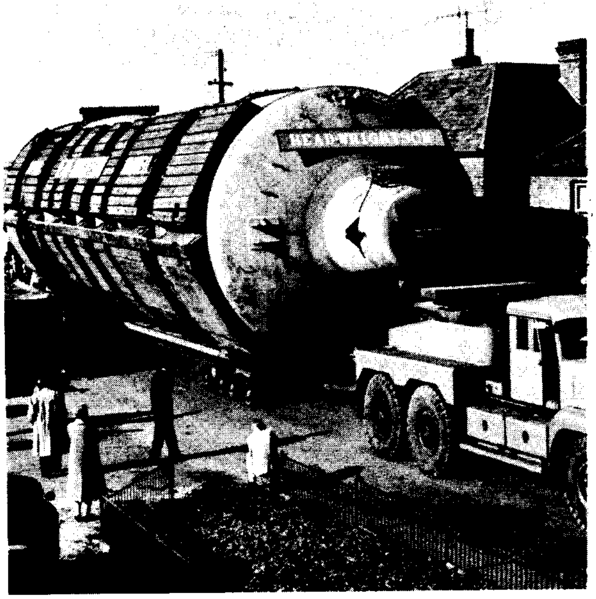
All this was highly problematical and uncertain at a time when no nuclear station was yet in operation and many of the design details had still to be settled. It was not surprising, therefore, that when the fuel shortage eased, the programme should have been slowed a little and spread over a longer period. Experience was also revealing the advantages of building fewer but larger stations.

The modified programme then became as follows:-

Station	Year of commissioning first reactor	Net output capacity MW(e)
Berkeley	1962	275
Bradwell	1962	300
Hinkley Point	1963	500
Trawsfynydd	1964	500
Dungeness	1964	550
Hunterston	1964	300
Sizewell	1965	580
Oldbury	1966	560
Wylfa	1968	1180

All these stations have the "Magnox" fuel, which has the advantage that the materials are relatively cheap and readily available, no enrichment is involved, and the fuel elements are comparatively cheap to fabricate. Against this is the drawback of the rather low operating temperature - about 420°C - imposed by the Magnox, which limits the efficiency and also the development potential of this type of station.

In the design of the early stations, the basic policy was to keep the conception and operation of the reactor unit on the simplest lines, and possible refinements were often omitted, for the sake of mechanical simplicity. Each of the above stations has two reactors.



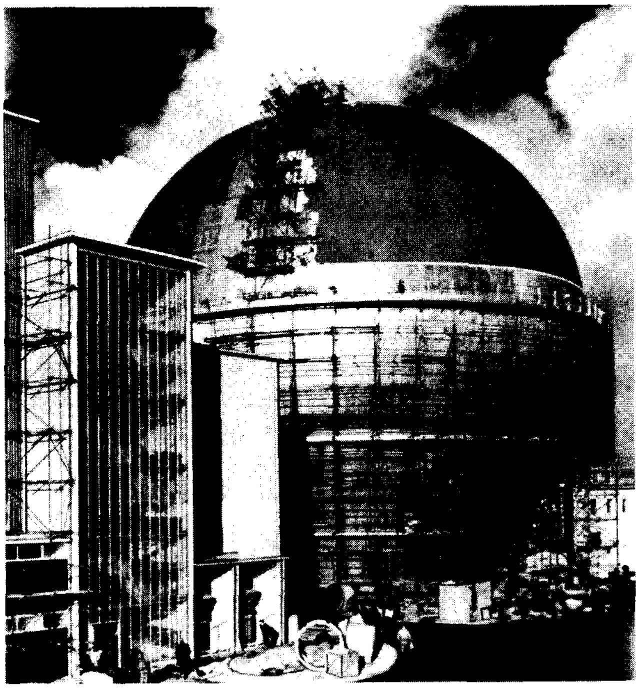
Heat exchanger en route to Bradwell power station, UK (UK AEA photo).

Although Berkeley and Bradwell, being built exclusively for electricity generation, represent an advance upon Calder Hall, tenders for their construction were received in 1955, and the contracts let in the following year - so that they were begun without the benefit of Calder Hall operating experience. Much of the design and manufacture was carried out before full results of necessary research and development became available, so that many changes resulted, and some setbacks. At Berkeley a total delay of fourteen months ensued, and the total cost of design changes was £5 100 000. The capital cost, per kilowatt sent out, rose from the estimated £145 to £173.

At Bradwell the total cost of generation has been estimated at 1.12 pence per kilowatt-hour, made up of 0.80 pence for capital charges and 0.32 pence running costs. These figures are necessarily highly tentative, since they are based on certain assumptions - such as a useful life of 20 years for the reactor, and a fuel burn-up of 3000 megawatt-days per ton of uranium fuel - which have still to be demonstrated in practice.

On the whole, however, these assumptions seem more likely to prove over-cautious than otherwise. The stations have proved flexible and reliable in operation, and further improvements are expected, partly as the result of larger size. Hinkley Point, with higher coolant pressure and higher net electrical output per ton of fuel, is expected to show generating costs of 1.02 pence per kilowatt-hour.

While this programme of Magnox stations has been underway, Britain has been developing an improvement to the system, known as the Advanced Gas-Cooled Reactor, using slightly enriched ceramic fuel elements. A prototype built at Windscale achieved its design output in 1963.



The Advanced Gas-cooled reactor at Windscale, UK, nearing completion in 1961 (UK AEA photo).

Another line of development which was undertaken at an early stage was the fast breeder reactor at Dounreay, which went critical in 1959, and is now being used as a test installation for the development of fuel elements.

FRANCE

France has followed a path very similar to that taken by Great Britain but has done so more slowly, and with more emphasis on the gaining of experience than on the generation of electricity. The choice of the natural uranium, graphite system was also influenced to some extent by availability of materials, as France possessed deposits of uranium ore, and an important graphite industry.

The French programme is one of building a succession of power units - in the experimental phase this was done by the Commissariat à l'Energie Atomique, and in the executive phase by Electricité de France. One plant was to be built every eighteen months, each one showing an increase in power and efficiency.

Since the primary purpose of this programme is that of providing experience, each reactor was to be different from its predecessors - e.g. the G2 station employed concrete containment, and horizontal fuel-loading channels; the first of the EDF stations had a steel pressure-vessel and vertical channels. In the light of experience and of technical advances, a new and improved type was developed for each succeeding reactor. Such a policy brings the long-term benefits of wide and detailed experience, but it also involves certain obvious drawbacks. Each reactor must bear a heavy development cost, and the opportunities for economizing by standardizing are restricted.

Very high regularity of operation has not been sought in the early stations. On the contrary, it has been considered that a better knowledge can be gained of materials and components if these are pushed close to the limits of the conditions they are designed to withstand. Nevertheless, the standards of performance are stringent. No essential part is placed in service until a prototype has completed, without the slightest hitch, tests equivalent to a minimum of 2000 years of service. After about four years of operation, G2 and G3 have shown themselves to be very safe.

The construction programme is as follows:-

Station	Power		Operational
	MW(t)	MW(e)	
G2	250	37	1959
G3	250	37	1960
EDF-1	300	68	1963
EDF-2	800	198	1964
EDF-3	1560	480	1966
EDF-4			1968
*EDF-5		500	1971

*Preliminary only

Although the natural uranium/graphite system is the same as that employed in Great Britain, the technology of the French reactors has differed in several important respects. One important departure was the use of pre-stressed concrete to serve as containment as well as a shield against radiation, thus doing away with the need for welded steel pressure-vessels, and permitting a much more compact design, bigger cores and higher gas pressures. Another difference has been in the construction of heat exchangers. Britain has employed few and very large exchangers, and found it convenient to assemble and erect them on site. In France, where contracts tend to be placed with a number of specialist firms, it was more advantageous to manufacture the heat exchangers as smaller units in the factory; this yielded certain economies of repetition.

Progressive improvement has been made in power station efficiency, through design modifications and experience in operation. In the G2 and G3 reactors, the maximum specific power of the uranium fuel was 3.5 MW(t) per ton; with EDF-3 this is being raised to 6.2 MW. The output of the most heavily-loaded channel of G2 was 260 kW; in EDF-3 it is 660 kW. These changes result from a number of modifications in the design and composition of the fuel elements.

The practice of changing fuel while the reactor is on load has been a success, and besides increasing the availability of the reactor, it allows of optimization of the fuel renewal programme. Repetition of designs for reactor components has allowed of some reduction of costs, and experience in the manufacture of fuel elements has reduced the number of rejects.

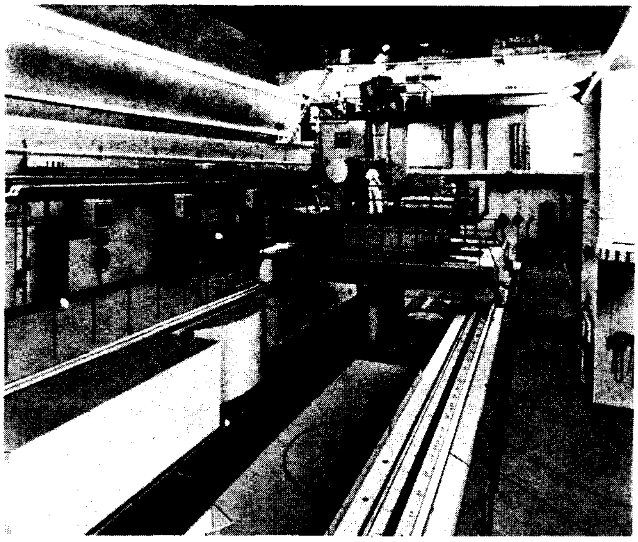
In addition to this series of reactors, EDF is collaborating with a Belgian group in building a 242 MW pressurized-water reactor at Chooz, and the CEA has built an 80 MW(e) prototype heavy-water moderated, gas-cooled reactor and is also developing several other types.

CANADA AND SWEDEN

Canada, where conventional power supplies have been, in the main, cheap and easily available, has adopted a long-range programme intended to ensure that the Canadian manufacturer will eventually be able to design and build nuclear power stations for domestic and export purposes. It has been limited to the one basic technique of heavy-water reactors.

The small NRX reactor completed in 1947 was followed by the NRU in 1957, and then came the NPD, which was taken to full power in 1962. This is a natural uranium, heavy-water reactor of 20 MW(e). The latest in the series is the full-scale CANDU, of 200 MW(e), which is now in the final stage of construction and testing.

Sweden was originally most interested in nuclear power as a possible means of district heating. However, it was later realized that the size of the station and the load factor had such a considerable influence on unit cost that it would not be easy to make the system economic, since the maximum load would be required only for a short period during the winter. In 1958, therefore, two projected stations were combined into one, at Ågesta. This is a pressurized-water reactor using heavy water and natural uranium. It will deliver 10 MW of electricity and 55 MW of heat for residential heating, and came into operation in 1964. Work is also beginning on construction of a base-load boiling-water power station of 200 MW(e) due to operate in 1968.



Agesta power station, Sweden

ITALY AND JAPAN

Italy, in contrast to most of the countries described above, has been primarily concerned with a rather pressing problem of power supplies, and has therefore adopted a policy of having nuclear stations built by foreign contractors. In 1958 a contract was placed for a British Magnox-type station, generally similar to Bradwell, to be built at Latina, with a capacity of 200 MW(e). The next year a second contract was given to an American firm for a boiling-water reactor station of 150 MW(e), generally similar to Dresden, to be built at Garigliano. Latina began to supply electricity to the grid in May 1963. and Garigliano a few months later. A third station at Trino is nearing completion. It is an American pressurized-water design similar to the Yankee plant, with a gross electrical capacity of 270 MW.

These contracts have at the same time provided an opportunity for participation by local industry, which has thereby gained valuable experience of three different reactor systems. Imports for the three plants ranged from one-third to one-half of the total investment, to provide for specialized techniques and to supply parts which could not be manufactured economically in Italy.

Japan has followed a course very similar to that taken by Italy, for the same reasons of fuel shortage, which makes it necessary to import increasing quantities of fuel. As the total power requirements and the size of newly installed stations are both increasing steadily, the situation is a favourable one for nuclear power. Japan, however, has special problems of earthquake safety and of population density, the first of which has been met by special design, and the second by careful site selection. Italy has also had to consider each of these problems.

A contract has been given for the construction of a British-type power station at Tokai Mura, with participation by local industry. The station will be of 158 MW(e) and is due for completion in 1965.

Japan is also interested in development of the boiling-water system.

LESSONS OF DECADE

The first decade of nuclear power opened with many alternative possibilities in the choice of reactor systems; it ends with two main lines of development - water reactors and gas-graphite reactors - well established, and many interesting possibilities under study. Within any one system, too, many variations are possible, and the national programmes have been able to demonstrate the relative advantages of some of the alternatives, such as pre-stressed concrete and steel pressure-vessels.

The considerations governing the choice of a reactor system for a civil power station are perhaps as much economic as technical; the water systems using enriched fuel are smaller and lower in capital cost than the gas-graphite systems, but the fuel costs more. From the point of view of satisfactory operation, both have proved themselves. Experience has shown them to be highly reliable - perhaps even more so than conventional stations - safe, and flexible in operation. They are able to shed total load without difficulty, and to give suitable rates of load pick-up. They are capable of being integrated into a major network along with other forms of power generation. The training of operating staff has not proved unduly difficult, and as reactor crews gain experience, they have produced progressively better results, especially in such operations as refuelling.

Each nuclear station has suggested improvements for the succeeding ones. There have been many design and engineering improvements. The composition and form of fuel elements has been closely studied, and the burn-up has exceeded early estimates. Other changes in materials and design have permitted higher operating temperatures and pressures, with higher efficiencies resulting.

The influence of unit size on the economics of nuclear power has been plainly demonstrated. Earlier ideas of compact and economical nuclear plants in the range 30 to 50 MW have had to be regretfully discarded, or at least deferred, and it is the most highly-developed countries which have been able to derive the most from nuclear power. Even with them, reactors of considerably greater power than those already in operation are considered to be the most economical - reactors of 500 MW or more - and not many systems can accommodate such a station. However, the growth of the electricity demand and the development of special applications such as water purification are clearing the way for these very large units.

Costs have been progressively reduced. In the first four years of the British programme, the specific capital cost of the Magnox stations was reduced by one-third. Uranium has also proved to be far more plentiful than appeared probable at the beginning of the decade, and its price has fallen accordingly.

All in all, nuclear power is now just beginning to be competitive with power from conventional sources. As a result of recent bids for large nuclear plants for New Jersey Central (at Oyster Creek) and for Niagara Mohawk (at Nine-Mile Point), it is claimed that nuclear power without subsidies is definitely cheaper in these cases than competing conventional power.

It has been difficult to forecast precisely when and where the "break-even" point would be reached. The first half of the decade saw gallant efforts made to make fine calculations, and to determine "cross-over points" (the time when nuclear power would become cheaper than conventional) by extrapolating from exiguous data.

In the last two or three years, however, enough information has emerged to confirm early confidence that nuclear power, sooner or later, would be paying its way, and we content ourselves with a step-by-step progress. Firm cost data are beginning to emerge, particularly on the side of capital costs, and we have much more information about operating costs. But many unknowns remain, among them the life of the station, the future costs of nuclear fuel, future credit for irradiated fuel, etc.

International comparisons can be particularly misleading, as the bases of calculation on such items as capital charges, taxation, etc., differ very widely. Moreover, the only valid calculation is an individual one for a particular situation, taking in every aspect of local conditions and system requirements.

In determining the choice of a power station, too, energy costs are far from being the sole or even most important determining factor. Even though a nuclear station might show the best long-range results, the size of the initial capital investment can be a serious deterrent. A country with indigenous fuel or hydro-electric resources might prefer to use these in order to save foreign exchange, or to be independent of uranium fuel fabricated elsewhere.

But the decade has clearly demonstrated the technical feasibility of nuclear power, and also the scope for continuing economic improvement, so that its future is no longer in doubt.