Atomic Power

By Denis Taylor: *Dr. Taylor was formerly Chief UNESCO Advisor at the University College, Nairobi, Kenya and is now Professor of Electrical Engineering in the University of Strachlyde, Scotland. He is a leading scientist in the electronics field. He was among the British scientists who developed radar during the second World War. He has also headed the Plessey group of companis for a long time.*

1. Atomic Structure

The existence of atoms was known for a very long time before anything was understood about their structure. Rutherford initiated the action which threw the first light on this problem. Working in 1910 in his laboratory in Manchester, England, he had the idea that the alpha-particles emitted by radium might be used as delicate probes to learn something about the structure of atoms. He used a thin metal foil and allowed the alpha-particles to shoot through the foil. His idea was to learn something about the internal forces in the atom. The results were very surprising! A few particles were deflected much more strongly than the rest, and very few, perhaps one in a thousand bounced right back.

Rutherford was quick to realize what an astounding result he had obtained. As he expressed it himself — "it was like seeing an artillery sheel bounce back from a piece of paper, and indicated at once the tremendous forces which must exist inside the atom".

These experiments led Rutherford to appreciate the large amounts of energy locked up in the atom. They also allowed him to put forward ideas on atomic structure, which were later put on a mathematical basis by the Danish physicist Niels Bohr. According to these ideas, the atom, formerly likened to a solid billiard ball became a transparent sphere of emptyness, thinly populated with electrons. The substance of the atom, according to these ideas shrunk to a core of unbelieveable smallness. For example, enlarged many millions of times, an atom could be, say, enlarged to the size of a football, but its nucleus would still be hardly visible. Yet, it is that nucleus, which radiates the powerful electric field which holds and controls the electrons around it, and like a strong spring pushes other nuclei away.

Later experiments performed, notably by Cahdwick, one of Rutherford's associates during his Cambridge University days (when Rutherford was Head of the famous Cavendish Laboratories, Cambridge, England), showed that the nucleus was built up of two elementary particles, not one as had first been supposed. These elementary particles are protons carrying unit positive charge of electricity and neutrons of about the same mass, but carrying no charge. The positive charge on the nucleus was just balanced by the total negative charge on the outer electronic structure so that the atom as a whole is uncharged.

In effect, all the mass of the atom resides in the nucleus and so if the nucleus contains n_1 protons and n_2 neutrons, its total mass, which is usually called the mass number $= n_1 + n_2$ unit masses. The total charge on the nucleus, which is called the atomic number $= n_1$. It is usual to employ a 'shorthand' method to describe an atomic species X, say, with a mass number A and an atomic number Z as $_ZX^A$. Thus, we may note that ordinary carbon is $_6C^{12}$, because its mass number $(A) = 12$ and its nucleus contains 6 protons and 6 neutrons. However, carbon can also exist as $_6C^{13}$, i.e. a heavier species, because its mass number is 13, and its nucleus contains 6 protons and 7 neutrons. Carbon $_6C^{13}$ is a stable isotope of $_6C^{12}$.

2. Neutron/Proton Ratio for Stability

If we plot the number of neutrons against the number of protons for all the stable isotopes, i.e. all the elements found in nature which are stable, we can consider how the neutron/proton ratio varies throughout the periodic system for stability. The natural question to ask is, what would happen if a substance could be produced which has more than the required number of neutrons for stability for a nucleus of that size. Will the nucleus produced be unstable? The answer is yes! This is, in fact, the method of producing radioactive isotopes, which are materials which are unstable and which spontaneously decay into stable substances with the emission of particles (alpha- or beta-particles) and/or gamma-radiation.

Enrico Fermi, the Italian physicist made important contributions here. It occurred to him to use Chadwick's neutrons as bullets — in the same way as Rutherford had earlier used alpha-particles to penetrate the strong electric field barrier around the nuclei of elements. Having no electric charge, the neutrons would not be influenced by the barrier, and when a neutron broke into a nucleus, it should transform the bombarded element into a new species, which in some cases would be radioactive. This proved to be the case. Thus, applying the neutron-bombardment to ordinary sodium (N_a), as common salt (N_aCl) say, we get:

$$\underset{\text{ordinary sodium}}{N_a^{23} + {}_0n^1} \longrightarrow \underset{\text{a radioactive form of sodium}}{N_a^{24}}$$

The product of the reaction (N_a^{24}) is chemically the same as ordinary sodium, but being unstable, it emits beta-particles and gamma-radiation in this case, which allow its presence to be detected, if necessary at a distance. It can therefore be used as a radioactive tracer, and as such has important applications in research and industry.

It should be noticed that as a neutron is captured in this process, the product of the reaction is always heavier than the original material bombarded. It was therefore a wonderfully exciting time when the method was applied to the heaviest element existing on this earth, namely uranium, to produce completely new elements, elements heavier than had existed before on this earth. We call them the 'transuranic elements'.

Fermi's attempts to produce transuranic elements led to something that was not expected at all. It was some time before this was sorted out, and this was largely due to Lise Meitner, a German physicist working at Copenhagen, and Otto Frisch, now Professor of Physics at Cambridge, England.

Let us consider this problem. A uranium nucleus contains 92 protons, which are, of course, positively charged and which therefore repel one another. They would fly apart if it were not for the presence of the neutrons in the nucleus which have no electric charge and which help to hold the neucleus together by what are called nuclear forces. The nuclear forces of attraction and the electric forces of repulsion are, we now know, precariously balanced and a small disturbance can make the nucleus unstable. This can happen if we bombard the uranium nucleus with a neutron. The neutron may be captured, the balance is upset and the nucleus stretches into an elongated shape — developes a waistline, and may break into two parts which fly apart at great speed. This phenomenon, which is called fission, can and does take place, but it was not expected. The two fragments produced (we call them 'fission fragments') are stopped by friction in the surrounding material and produce heat, and it is this heat which we make use of in atomic power, i.e. the power from the atom.

The important point here is that the 'fission process' can lead to a chain reaction, because at each fission, a few (2 or 3) loose neutrons are produced as well as the two large fission fragments. These neutrons under suitable conditions can produce further fissions, and if we suppose 2 neutrons are produced per fission, it will be seen that a single neutron, produces two neutrons at the first generation, four neutrons at the second generation, eight neutrons at the third generation and so on.

In order to get a reaction of this sort to take place, we have to arrange for the neutrons to bombard the uranium atoms at the correct velocity. The neutrons emitted in the ordinary fission process are moving at a very high velocity. They have to be slowed down before fissions of the type we have been discussing can take place. We use a 'moderator' for this purpose, and we arrange the uranium fuel elements which are usually cylindrical in shape in a matrix of graphite, which acts as the moderator, or slowing down medium, the dimensions of the matrix being chosen to give the correct slowing down of the fission neutrons.

3. Control of a Nuclear Reactor

We now need to consider how to maintain the operating power level constant. This is achieved by inserting into the reactor core (as the assembly of moderator and fuel elements is called), quite close to the fuel elements, rods of material such as cadmium or boron, which have the property of absorbing neutrons strongly.

If many neutrons are absorbed, not sufficient are left to produce a second generation of splitting nuclei as large as the first, and the reaction quickly dies out. If the second generation is exactly equal to the first, the reaction and therefore the power level remains steady. If, on the other hand, the second generation is larger than the first, the number of nuclei undergoing fission gradually rises and the reactor begins to "run away" in power. By suitable arrangement of the neutron-absording rods (they are usually called control rods), the rate of growth or decay of the reaction required can be obtained.

When a reactor plant is in operation, it is necessary to adjust the criticality with the help of these control rods. To start a reactor, the control rods are moved out slowly, so as to reduce the death rate of neutrons until multiplication is obtained. The instruments then tell us when the neutron population has reached the required size. Then the control rods are lowered until the neutron population is steady. Control is thus a fairly simple matter.

What happens, you may ask, if the rods get pulled out completely, either through carelessness or sabotage. Well, that is provided for! There are additional rods, designated 'safety rods', which automatically drop into their holes if the neutron population rises above a pre-set level, or if any thing goes wrong.

4. Principle of 'Breeding'

Ordinary natural uranium comprises two stable isotopes ${}_{92}U^{235}$ and ${}_{92}U^{238}$ in the ratio 1: 140. The lighter material (${}_{92}U^{235}$) is fissionable (or fissile) and behaves in the way I have explained. However, the heavier isotope (${}_{29}U^{238}$) behaves differently. In this case the following reaction takes place:

$$U^{238} \quad + \quad n \rightarrow U^{239}$$

and the uranium 239 decays to give neptunium and then plutonium:

$$U^{239} \rightarrow Np^{239} \rightarrow Pu^{239}$$

Plutonium 239 is like uranium 235 a fissile material. It can therefore be used like U^{235} as a fuel in a nuclear reactor. This gave rise to the idea of designing a breeder-like reactor, which produces more fuel than it burns. Breeder reactors have been shown to be feasible and must be employed to bring the cost of electricity produced from the atom down to the minimum figure.

5. The Calder Hall Atomic Power Station

The world's first full-scale commercial size power station utilizing the power from the atom is at Calder Hall in England and it operated for the first time in September 1956*. It comprises 4 gas-cooled, graphite-moderated, natural uranium reactors. Each reactor has a design power of 180 megawatts thermal and exports 35 megawatts of electricity, and so the complete station generates in excess of 140 megawatts of electricity. As already explained, a plant of this kind can be used for the production of plutonium, and, in fact, when the station was first constructed the production of plutonium was its major purpose, electrical energy was produced only as a by-product. If no value is attributed to the plutonium produced, Calder Hall produces electricity at about one penny a unit (i.e. a kilowatt hour). This is not competitive with the coal-fired stations, and so it was appreciated from the very start that in the later plants, the costs would have to be reduced.

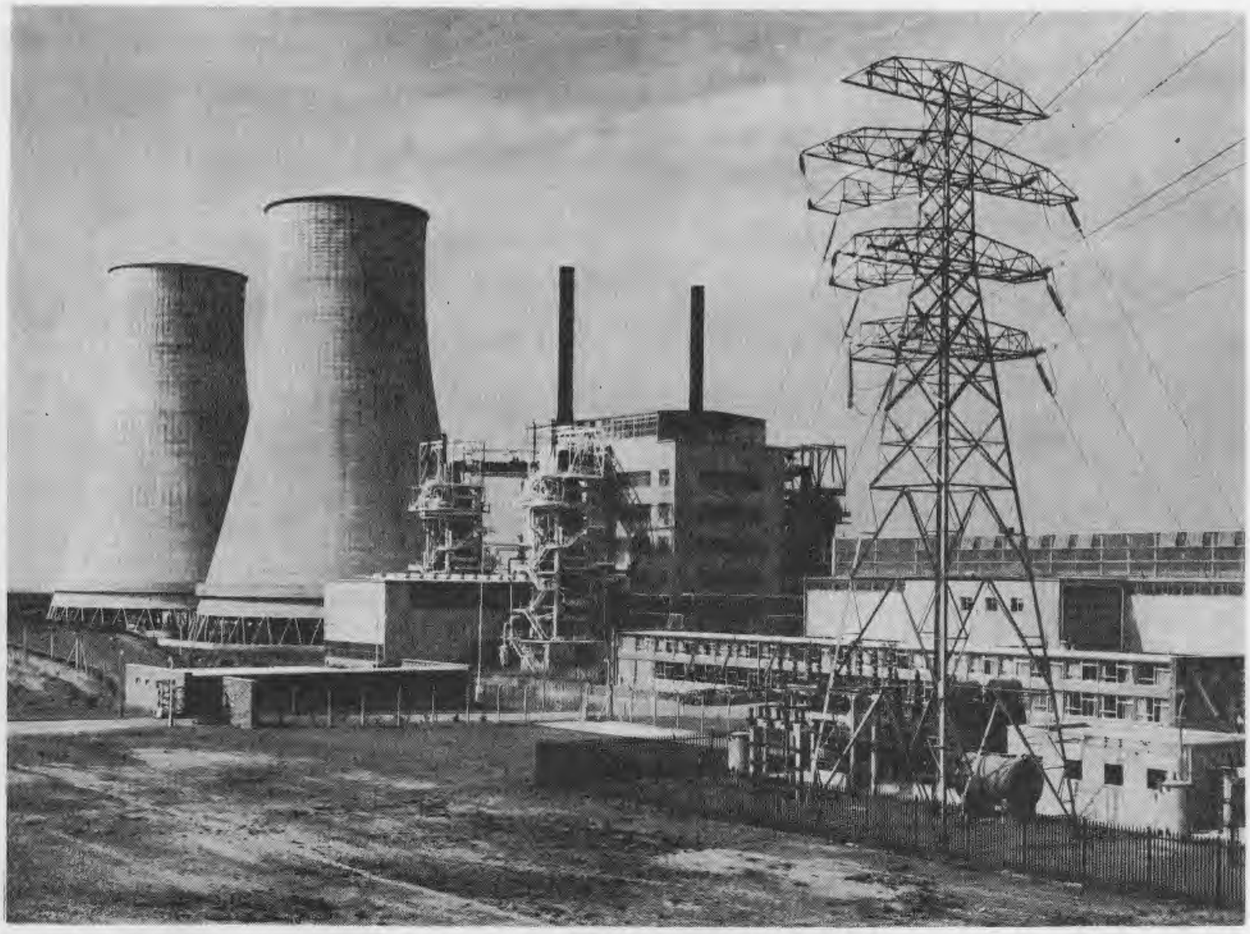


Fig. 1 — *The original Calder Hall Nuclear Power Station*

Fig.1 shows a view of one of the reactors at Calder Hall. The heat exchangers at each of the corners of the reactor building can be seen, as well as the cooling towers. In the foreground is one of the pylons which will carry the electricity to the national grid.

Since this time Britain has gone ahead with a similar station to Calder in a double-size station at Chapelcross, and we have also gone ahead with the construction of C.E.G.B. stations to provide an additional installed capacity of 2,500 megawatts. The majority of these stations have been completed and are providing electricity. As an example Fig.2 shows the construction of the Nuclear Power station at Trawsfyndd (North Wales) which was completed in 1964. This has a capacity of 500 megawatts. As can be seen this is large-scale engineering and very large cranes and other mechanical aids are employed. Fig.3 shows a typical control room for a nuclear power station. In this case the picture shows the control room at Bradwell whose two reactors were commissioned in 1962.

Since 1956, the size of the nuclear power station constructed has gradually increased, and the cost of nuclear power produced electricity has gradually come down, but it was not until the advent of the so-called Advanced Gas-Cooled Reactor (A.G.R.) that atom-produced electricity began to be more economic than electricity produced by conventional means.

In the A.G.R., the uranium metal fuel elements are replaced by uranium dioxide, the higher gas temperatures permitting a more efficient steam cycle and allowing several economies. Initially a reactor of this type was first operated in 1963. This was a 100 megawatt reactor experiment. Its objects were to obtain data on fuel element life, on the kinetic

---

* It was operating well in September 1966, and so has given more than its 10 years of design life.

behaviour of the core and the steam plant, and operating and control experience on a reactor system which is a development of the Calder Hall type of reactor. Higher fuel element ratings are achieved by fabricating the fuel in the form of clusters of small pencils, thereby increasing the surface to volume ratio.

The gas flow pattern is novel. Cold gas from the circulators passes down between the core and the pressure vessel. It returns up the core through the fuel element channels into a hot box through the inner coaxial duct into the heat exchanger. This latter comprises a superheater, evaporator and economiser as usual. An interesting feature of the A.G.R. is the internal neutron shield, situated between the graphite core-fuel element assembly and the hot box which considerably reduce the induced reactivity at the dome of the vessel, so making it feasible to open the vessel when the reactor has reached the end of its life.

Experience with the Windscale Experimental A.G.R. has been most remarkable. A great deal of success of the reactor can be attributed to the superlative performance of the stainless steel/ceramic fuel. Its high performance without failure augers well for the future. Furthermore, experiments in the core have shown that small fuel can bursts do not lead to catastropic failure of the can and the reactor can be operated for several months without unloading the stringer of the fuel elements.

Another very pleasing conclusion which can he made from the Windscale Experiment is that refuelling at power can be carried out very easily and with relative safety. With the arrangement used, the preparation of the complete stringer, including its installation and checking of its associated instrumentation and the loading on to the fuel machine, the positioning of the machine on the reactor, the coupling to the irradiated stringer to be withdrawn, the sealing and the pressure balancing, all can be carried out without affecting the reactor in any way.

Fig. 2 — *The C.E.G.B. Nuclear power Station at Trawfyndd during the constructional period*

The core of the Windscale A.G.R. is probably the most intensively instrumented of any power reactor prototype* and this has produced more data on operating conditions and limits than has been available for any other nuclear power system. There are 868 thermocouples on the fuel element stringers and all channel gas outlet temperatures are automatically recorded and compared with an alarm by a data logger. This facility has proved to be an invaluable feature particularly at start-up. The complete station is shown in Fig.4.

6. Dungeness 'B'

It was because of the good results of the Windscale A.G.R. Experiment that A.G.R. was one of

---

* See "A.G.R. Control and Instrumentation" by present author and associates, Journal of British Nuclear Energy Society, pp. 197-204, April 1963.

the types of reactor plants considered for the first of the second-generation power stations in Britain. Another was the Boiling Water Reactor (B.W.R.), which has been worked on more particularly in the United States of America. The new station at Dungeness is part of the 5000 megawatt nuclear power stations to become operational in Britain over the period 1970 to 1975.

The enquiry for the Dungeness 'B' power station in its final form left the contracting firms considerable freedom as to what they offered. The successful tenderer (the Atomic Power Construction Company Ltd.) who had already built a number of the first generation gas-cooled stations retained very largely the features of the Windscale A.G.R., were bold in their proposals for gas coolant pressure and turbine output and used a larger fuel element cluster. A section through the station is shown in Fig.5.

The tenders received by C.E.G.B.* were assessed for compliance with the specifications, adjustments being made when the design was in any way outside the limits required. Both gas and water cooled reactors were judged to have a higher availability and adequate flexibility for use on the C.E.G.B. system, but only the A.G.R. could be refuelled on load. This latter is perhaps the largest single factor in favour of the A.G.R., as with the A.G.R. the annual shut-down period, estimated at 19½ days for fuel changing, and so high is the non-availability penalty for high efficiency plant in the U.K., that such a shut-down represents an addition of £8.97/kW in the generating costs of the B.W.R.

Fig. 3 — *The control room of the C.E.G.B. Nuclear Power Station at Bradwell*

The comparison of a number of tenders for the same engineering plant is extremely complicated. A "present worth" basis is used by the C.E.G.B. for the project comparison with all the expenditures and credits during the construction and during the 20 years of amortised life referred as capital sums to date when the first reactor is ready for commercial load. An interest rate of 7½% is charged in accordance with the Board's normal practice for long term investment and 5½% for short term financing as over the construction period. No allowance is made for the changing value of money.

The 20-year amortisation life already mentioned is used as a step of commercial prudence, in view of the limited experience with nuclear power stations. This is, in spite of the fact that the designs submitted were for a 30-year life, and this is the minimum life expected. Similarly, a load factor of 75% is assumed in the C.E.G.B. estimates, whereas the design load is 85%. If more optimistic values are achieved, there is a large effect on the generation costs as shown in Table I.

---

* The full story is given in "Dungeness 'B' A.G.R. Nuclear Power Station", Report by Central Electricity Generating Board, London (July 1965). See also paper by present author "Advanced Gas-cooled Nuclear Reactor Power Plants", Journal of E.A. Institution of Engineers, 14, pp. 82-93, December 1965.

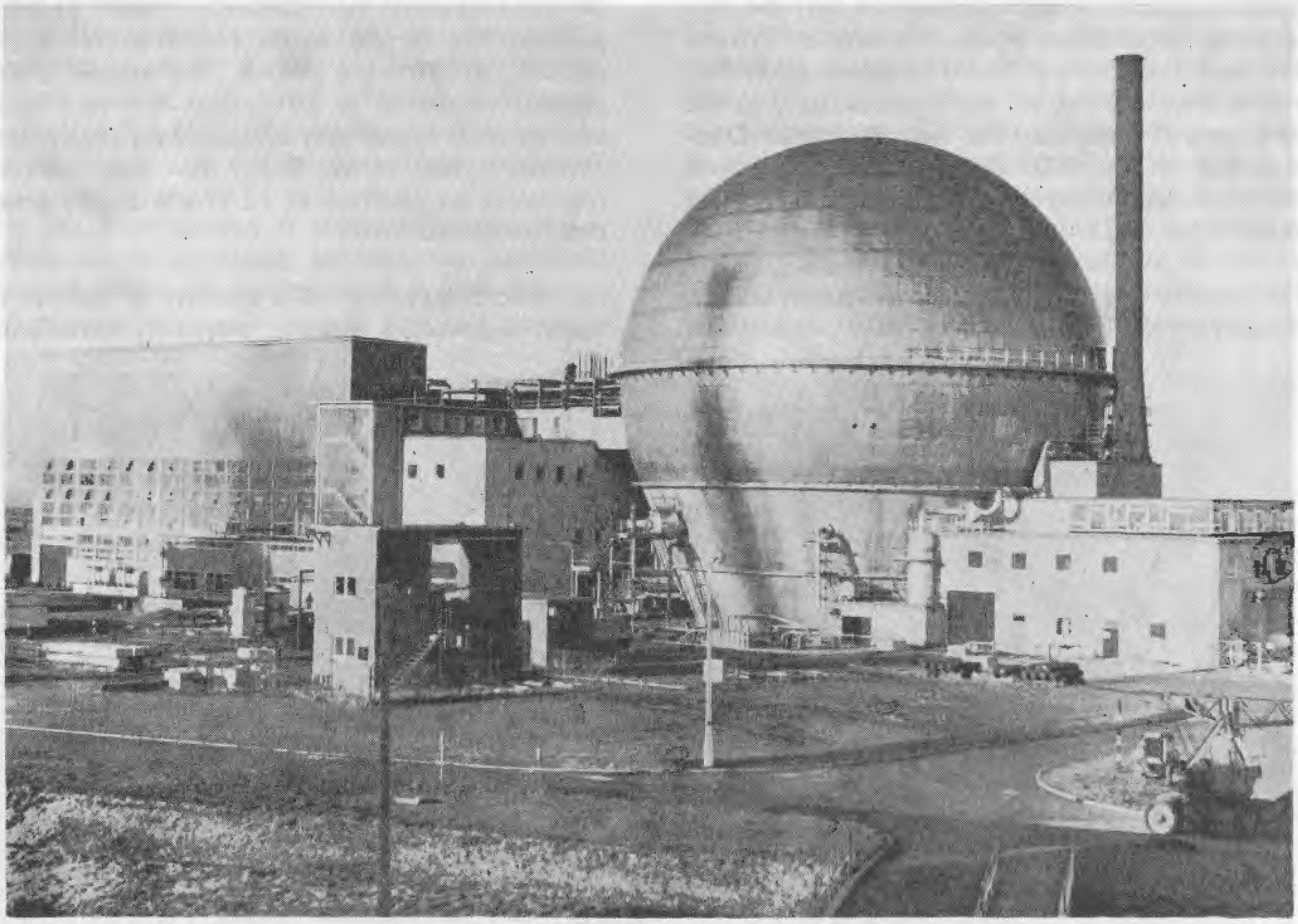
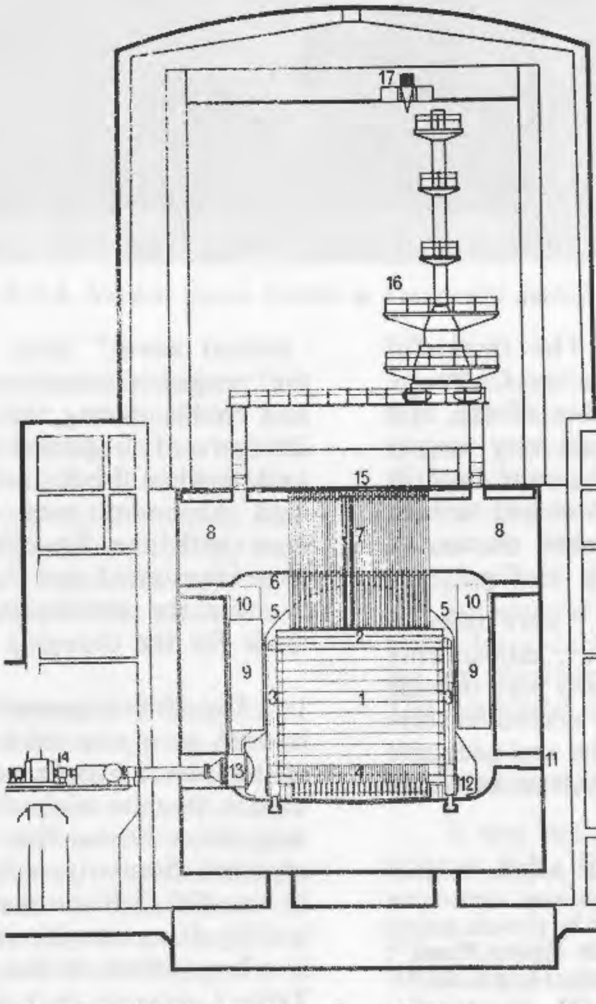


Fig. 4 — *The A.G.R. Windscale Experiment — note the reactor is enclosed in a spherical pressure*



1. *Core and reflector*
2. *Top shield*
3. *Side shield*
4. *Support structure*
5. *Pressure cylinder*
6. *Thermal insulation*
7. *Fuelling and control standpipes*
8. *Concrete pressure vessel*
9. *Boiler*
10. *Steam outlet*
11. *Feed water inlet*
12. *Plenum chamber*
13. *Circulatar*
14. *Circulator drive*
15. *Charge face*
16. *Fuelling machine*
17. *Charge face crane.*

Fig. 5 — *Vertical section through Dungeness 'B' Station*

Table I

Effect of Load Factor and Life on Generating Costs (pence/kWh)

Station Life	*Load Factor*	*AGR (1200 megawatts)*
20 years	75%	0.457
20 years	85%	0.414
30 years	75%	0.414
30 years	85%	0.377

7. Other Considerations

The largest single source of possible saving for the later A.G.R's appears to be the increase of reactor size. Substantiation for the feasibility of A.G.R's having about double the size of the Dungeness 'B' output was obtained in a detailed design study carried out by the UKAEA in 1964. The target saving for a 2 x 1200 MW station with four turbo-generators would be 10% in the cost of the electricity generated compared with a 2 x 600 MW station.

Another matter which is worthy of comment is desalination. Britain has already achieved considerable progress in this field, and British plants are responsible for producing about 70% of the world's daily output of fresh water from the sea. The latest development is linking the Weir-Westgarth multi-stage evaporator plant with an Advanced Gas-Cooled reactor plant to produce both electricity and desalination of sea water, and the proposition would appear to be an excellent one, with many possibilities for export business.

8. Acknowledgments

The photographs used to illustrate this lecture have been supplied by the Central Office of Information, London, to whom acknowledgments are made.